PS1-6 A6

ULTRASOUND-GUIDED HIFU NEUROLYSIS OF PERIPHERAL NERVES TO TREAT SPASTICITY AND PAIN

J. L. FOLEY*[1,2], J. W. LITTLE[3], F. L. STARR III[2], C. FRANTZ[2], and S. VAEZY[1,2], [1]Department of Bioengineering, University of Washington, [2]Center for Industrial and Medical Ultrasound, Applied Physics Laboratory, University of Washington, [3]Department of Rehabilitation Medicine, University of Washington. Corresponding e-mail: jlf2@u.washington.edu

Spasticity, a major complication of central nervous system (CNS) disorders signified by uncontrollable muscle contractions, is difficult to treat effectively. Current treatments such as intramuscular blocks, nerve blocks, and surgical interventions, often provide only short-term or partial benefit and can be invasive and of high risk. We report on the use of ultrasound image-guided high intensity focused ultrasound (HIFU) to non-invasively target and suppress the function of the sciatic nerve complex of rabbits *in vivo*, a possible treatment of spasticity and pain. The device included a 3.2 MHz spherically curved transducer (focal length of 3.5 cm, f-number of 1, focal full width half maximum of 5.1 mm (axial) x 0.76 mm (lateral)) with a custom-made polyacrylamide gel coupling medium, integrated with an intraoperative imaging probe (CL10-5, Philips HDI-1000) such that the HIFU focus was within the image plane. The nerve complex was imaged in cross-section and identified between two muscle planes, and the HIFU treatment was directed to the nerve and monitored in real-time (HIFU focal region became hyperechoic during treatment). *In situ* focal acoustic intensity (I_{SATA}, spatial average temporal average) of 2700-3200 W/cm^2, applied using a scanning method (scan rate of 0.5-0.6 mm/second), was effective in achieving complete conduction block in 100% of the 22 nerve complexes (11 rabbits) treated. The force response of the plantarflexion muscles in the rabbit foot to electrical stimulation of the sciatic nerve complex was measured both before and after HIFU treatment using a force gauge perpendicularly coupled to the metatarsal joint of the rabbit foot. The force response was approximately 0.55 N before HIFU treatment, and complete suppression of this force was achieved after HIFU treatment, indicating complete conduction block. The HIFU treatment time for complete nerve block was 36 $\pm$ 14 seconds (mean $\pm$ standard deviation). Gross examination showed blanching of the nerve at the HIFU treatment site and lesion volumes of 1-5 cm^3 encompassing the nerve complex. Histological examination indicated axonal demyelination (osmium and Richard's stain, n=5; Masson's trichrome, n=2) and necrosis of Schwann cells (H&E, n=4) as probable mechanisms of nerve block. Long-term studies, currently under investigation, will determine the duration of the HIFU conduction block and allow us to observe any other biological and neurological effects that may develop over time. Further work could also focus on the treatment of spinal nerve roots that are shown to cause spasticity in muscle groups as a result of CNS injury or disease. With accurate localization and targeting of peripheral nerves and spinal nerves using ultrasound imaging, HIFU could become a promising

tool for the suppression of spasticity and pain.
We acknowledge the support of the Seattle Foundation.

PS1-7 A7

COUNTER-PROPAGATING LAMB WAVE PAIR FOR NONDESTRUCTIVE INSPECTION

T. HOSHIMIYA and M. SUZUKI*, Tohoku Gakuin University.
Corresponding e-mail: d0396104@tjcc.tohoku-gakuin.ac.jp

Two YAG laser beams, divided by a beam-splitter, were focused on a thin aluminum plate by two renticular lenses, and they generated a pair of counter-propagating Lamb waves. Grating-like thermo-elastic line sources generated Lamb waves, the distance d of which was adjusted such that only limited Lamb modes could be generated. FFT and wavelet analyses of the thermoelastic waveforms proved that the S0 and A0 Lamb modes alone were generated. The feasibility of the application of the counter-propagating Lamb modes to nondestructive evaluation (NDE) of a plane metal specimen with a surface defect was considered under several kinds of arrangements. A typical example is an arrangement such that a line source with a periodicity d located at x=0 which produces a Lamb wave traveling to +x direction and that located at x=L which produces a Lamb wave directing to x direction. A scanning scheme is considered in which one transmitter is fixed (at x=0) and the other position (x=L) is scanned toward +x-direction over the surface defect. The second scanning scheme is the scanning with a central position of pair transmitters over the surface defect with the distance L between two transmitters fixed constant. In this experiment, contact sensing with PZT transducer was adopted. Furthermore, noncontact sensing with air-borne ultrasonic transducer will be discussed. The imaging with counter-propagating Lamb waves with 2D scanning was also discussed.
The authors are grateful to Prof. N. Chubachi and Dr. T. Sannomiya for their disucussion on this study.

PS1-8 A8

PERFORMANCE ASSESSMENT OF A NEW KALMAN FILTER-BASED METHOD FOR ULTRASONIC TIME-OF-FLIGHT ESTIMATION

L. ANGRISANI[1], A. BACCIGALUPI[1], and R. SCHIANO LO MORIELLO*[2],
[1]Università di Napoli Federico II - Dipartimento di Informatica e sistemistica,
[2]Università di Napoli Federico II - Dipartimento di Ingegneria Elettrica.
Corresponding e-mail: rschiano@unina.it

There are relevant examples of application fields requiring reliable and speedy measurements of the distance between a device and an external surface. To

achieve this goal, the use of ultrasonic transducers is widely exploited. Ultrasonic based distance meters generally estimate the time-of-flight (TOF) of an ultrasonic pulse generated by a proper transducer. In the paper, the authors propose a digital signal processing method based on the use of the discrete extended Kalman filter (DEKF) for TOF estimation [1]. The discrete Kalman filter (KF) is a recursive solution of the problem of estimating the state of a linear stochastic system or process by using measurements that are linear functions if the state. Similar approaches can be extended to the analysis of non linear systems, provided that suitable techniques of linearization about a nominal trajectory are applied. If the nominal trajectory is defined on the fly as the current best estimate of the actual trajectory, the corresponding filter is named DEKF. In recent scientific works [2], the DEKF has been used to improve the accuracy of ultrasonic based location systems of robots. In particular, TOF data provided by several ultrasonic sensors and collected as temporal readings are properly fused thanks to the exploitation of some nice properties of the DEKF. The authors, instead, propose the DEKF as an original tool to overcome the well-known problem of biased estimate occurring when the echo envelope undergoes shape distortions. The novelty of the method mainly relies upon its capability of jointly estimating the whole set of parameters (A_0, α, T, and τ) that characterize the well-known model of echo envelope, A(t): $A(t)=((t-\tau)/T)^{\alpha}*\exp((t-\tau)/T)$ A_0 accounts for echo amplitude, α and T are peculiar to the specific ultrasonic transducer, and τ is the desired TOF. This way, the achieved TOF estimation inherently accounts for the distortion the ultrasonic echo eventually undergoes, with a consequent positive effect on bias reduction. Details concerning the suggested use of the DEKF and its action in the framework of the adopted measurement procedure will be given in the full paper. Actual research activities is focused on the performance assessment of the proposed digital signal-processing method at varying of typical measurement conditions. In particular, the capability of the method of granting an accurate value of the shape parameters will be used in order to identify the presence of non-planar or non-orthogonal reflection surfaces, able to distort the received echo. Moreover, typical problem of closed tank or reservoir configuration, such reverberation and multiple echoes, will also be taken into account.

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PS1-9 512C-H

DUAL CONFIGURATION HIGH TEMPERATURE HYDROGEN SENSOR ON LGS SAW DEVICES

J. A. THIELE* and M. PEREIRA DA CUNHA, Dept. of Electrical and Computer Eng., University of Maine.
Corresponding e-mail: mdacunha@eece.maine.edu

In the past few years there has been an increasing interest in the langasite family of crystals (LGX) for surface acoustic wave (SAW) applications in communications, frequency control, and sensors. LGX has several interesting properties including: up to about six times higher electromechanical coupling than quartz ST-X; existence of temperature compensated cuts with zero power flow angle and minimal diffraction; up to 26% reduction in phase velocities with respect to quartz ST-X, which allows the fabrication of smaller devices; and the absence of a crystal phase transition up to the crystal melting point (around 1177K). Since this crystal has no phase transition, bulk acoustic wave (BAW) and SAW devices have been explored as temperature and pressure sensors at temperatures up to several hundred °C. In addition to temperature and pressure sensors, a need exists for high temperature sensors capable of detecting target gases. Hydrogen (H_2) detection, in particular, is of paramount importance in applications such as hydrogen fuel cells, fuel leakage from jet engines, and power plants. This paper reports on a dual LGS SAW device configuration for the detection of H_2 gas at 250°C using original all palladium (Pd) electrodes. The Pd electrodes are used for the SAW transduction and reflection functions and to detect H_2. The phase differences between two identical all Pd SAW resonators have been tracked. The dual configuration scheme has been used to minimize temperature cross interference, since the LGS (0°, 138.5°, 26.6°) orientation is not temperature compensated at 250°C. The detection of H_2 gas concentrations produces a three degree differential phase shift with respect to the reference for a 1000ppm H_2 gas concentration, and a one and a half degree phase shift for 500ppm H_2 gas. The SAW resonators respond to the presence of H_2 in a matter of seconds and become stable between 25 to 75 minutes later. The devices have been continuously operated at 250°C for a period of six weeks, with no degradation in the device response. The dual configuration high temperature LGS SAW devices and experiments reported in this work prove the capability of these crystals to withstand prolonged exposure to high temperatures (250°C) and to perform as appropriate high temperature H_2 gas sensors.
Funding for this project was provided by the Maine Space Grant Consortium (MSGC EP-02-08 and MSGC SG-03-15) and the National Science Foundation (NSF ECS-0134335 and NSF EEC-9820332).

PS1-10 512C-H

A THEORETICAL STUDY OF LOVE WAVE SENSORS MASS LOADING AND VISCOELASTICITY SENSITIVITY IN GAS AND LIQUID ENVIRONMENTS

P. MAZEIN*[1], D. REBIÉRE[1], C. DÉJOUS[1], F. JOSSE[2], and J. PISTRÉ[1], [1]Laboratoire IXL (ENSEIRB CNRS UMR5818 Université Bordeaux 1), [2]Microsensor Research Laboratory and Department of Electrical and Computer Engineering, Marquette University.
Corresponding e-mail: mazein@ixl.fr

The sensitivity of Love wave (also known as guided shear horizontal surface acoustic wave (SH-SAW)) sensors to mass loading and/or to viscoelasticity change, in gas and liquid environments, is theoretically investigated. The objective is to present effective design parameters for Love wave sensors. The investigated sensor platform consists of a number of orientations of rotated Y-cut quartz substrate, a guiding layer, and a thin polymethylmetacrylate (PMMA) coating used to simulate the chemically sensitive layer. The platform sensitivity is determined by calculating the relative change in velocity, DV/V, for a small change in PMMA density and/or viscoelasticity. The investigation process consists of computing optimal guiding layer thickness (resulting in the largest perturbation, hence the highest sensitivity), for increasing layer density and shear modulus. The calculated highest sensitivity is reported on a 3D plot as a function of guiding layer density and shear modulus for a given substrate orientation. While the results are obtained for arbitrarily large ranges of density and shear modulus, optimum sensitivity for practical materials such as SiO2, PMMA, SU8, Si3N4, is indicated on the plot. It is observed that optimum thickness values ranging from 0.1 to 10 μm are needed depending on the waveguiding material. It is seen that the device sensitivity, in general, increases as the difference in bulk shear wave velocities between the substrate and the guiding layer. For a given mass sensitivity, the viscoelasticity sensitivity is analyzed and vice versa. The relative importance of mass loading and viscoelasticity are discussed, in terms of chemical sensors and biosensors implementation. In liquid-phase operation, the influence of the liquid viscosity on the sensor response is also studied. Various experiments are conducted to confirm the above results.

PS1-11 513AB

DEDICATED FINITE ELEMENTS FOR ELECTRODE THIN FILMS ON QUARTZ RESONATORS

S. SRIVASTAVA*[1], Y.-K. YONG[1], M. TANAKA[2], and T. IMAI[2], [1]Rutgers University, [2]Seiko Epson, Inc.
Corresponding e-mail: yyong@rci.rutgers.edu

The electrode thin films of a quartz resonator deserve particular attention in a three-dimensional finite element analysis because they give rise to (1) electrical boundary conditions at the electrode-quartz interface, (2) mass loading effects and (3) stiffness effects. Since the films are usually on the quartz surface, their stresses are relatively low in magnitude. In dynamic analyses in which we ask for natural frequencies and mode shapes, there is an urgent need to reduce the number of degrees of freedom because the major difficulty is the expense of computing eigenvalues and eigenvectors. The reduction of number of degrees of freedom is detrimental to accuracy, but negligibly so if properly used. In this paper we develop and show the results of dedicated finite elements for electrode thin films on quartz resonators. The subtle effects of the electrical boundary conditions on the frequency-temperature curves of an AT-cut plate are presented. Two strategies for modeling the electrode thin films and their numerical results are presented. These modeling strategies for the electrode films are important in the finite element modeling of both low and high frequency quartz resonators because (1) they help avoid the inherent effects of elements

with poor aspect ratios in thin films, and (2) they greatly reduce the number of degrees in the finite element models. The films are conductors, hence they form an electric equipotential surface at the film to quartz interface where the electric potential is a specified known value in forced vibration problems and short-circuit eigenvalue problems. For an open circuit eigenvalue problem, the electric potential is unknown. The electrode films also contribute mechanically to the quartz plate in terms of additional stiffness and mass. One strategy for the mechanical modeling of very thin films is to neglect their stiffness and include only the mass effects. In this strategy, no additional degrees of freedom are needed for the film if the mass of such a film is added to the mass degrees of freedom at the film to quartz interface. Results in terms of frequency spectra are presented to show that the strategy is quite accurate for very thin electrode films. For thicker electrode films, their stiffness effects, in addition to the mass effects, must be included to yield accurate frequency spectra. The second strategy is to perform Guyan static condensation of the mechanical degrees of freedom of the electrodes into the degrees of freedom at the film to quartz interface. Results in terms of frequency spectra are presented to show that the second strategy is accurate for both thin and thick electrode films.
Funding by DARPA and SPAWAR is gratefully acknowledged. Clark Nguyen is the program manager.

PS1-12 B1

VISUALIZATION OF IN- AND OUT-OF-PLANE VIBRATIONS IN A MICROMECHANICAL RF-RESONATOR

O. HOLMGREN*[1], K. KOKKONEN[1], T. MATTILA[2], V. KAAJAKARI[2], A. OJA[2], J. KIIHAMÜKI[2], J. V. KNUUTTILA[1], and M. M. SALOMAA[1], [1]Materials Physics Laboratory, Helsinki University of Technology, [2]VTT Information Technology.
Corresponding e-mail: oholmgre@focus.hut.fi

The in- and out-of-plane vibrations of a micromechanical 13.1 MHz bulk acoustic mode silicon resonator [1] have been measured utilizing a scanning Michelson laser interferometer [2]. These RF MEMS resonators possess a high quality factor of 130,000 and a high power handling capacity of 0.12 mW and can therefore be suitable for reference oscillator applications. The resonator consists of a plate released from the substrate and supported at the corners. The device has been fabricated using deep reactive ion etching on a silicon-on-insulator (SOI) wafer. For the sacrificial oxide release etch, a 39×39 grid of holes (d = 2 μm) has been etched to the silicon plate.

The main vibration mode can be characterized as a two-dimensional plate expansion preserving its original square shape. The test resonator exhibits also the Lamé mode (12.1 MHz) in which the square edges bend in antiphase preserving the volume of the plate. Vibrations occur parallel to the plate. However, the resonator also vibrates perpendicular to the surface of the plate due to the Poisson's ratio of the silicon crystal.

The plate vibrations have been visualised employing our scanning laser interferometer. The out-of-plane vibrations were measured directly with the scanning laser interferometer. The lateral vibration components were obtained via the reflection modulation of the probe beam at the edges of the release etch holes. This is achieved by a simple modification to our existing interferometer. Hence a novel vectorial detection of in-plane vibration components can be accomplished.

We have been able to detect the vibration components of the square-extensional mode and Lamé mode in all three directions, and the results are compared with finite element (FEM) simulations. In addition, undesirable parasitic vibrations in the electrode regions have been observed.

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Acknowledgements: OH thanks the Research Council of HUT for a scholarship. This research has been supported by the Academy of Finland through the Programme TULE (Future Electronics Research).

PS1-13 513AB

AN ULTRASONIC LINEAR MOTOR USING A RIDGE WAVEGUIDE

M. TOMINAGA*, J. R. FRIEND, R. KAMINAGA, K. NAKAMURA, and S. UEHA, Precision and intelligence Laboratory, Tokyo Insutitute of Technology.
Corresponding e-mail: tomi34@sonic.pi.titech.ac.jp

For the telecommunications industry, multiplexed optical switching remains difficult and is a current topic of study, with most commercial devices using MEMS electrostatic comb actuators. We propose the development of an ultrasonic motor using a traveling wave generated along a ridge waveguide as one method to address current devices' shortcomings. The ridge waveguide,simply a rectangular prismatic projection from a flat substrate, along which waves propagate ultrasonically, may be fabricated alongside other microcomponents as a part of an integrated MEMS device for optical communication. At any point along the waveguide, the traveling-wave vibration is elliptically polarized and will push a slider placed on the waveguide through friction. The use of a flexural waveguide mode enables us to fabricate the ultrasonic linear motor on a substrate alongside other MEMS devices. This study presents three different methods to excite a traveling wave along the ridge waveguide. In the first version, acrylic, which has a large vibration attenuation, was used for a relatively large rectangular waveguide, at 5 mm in width, 15 mm in height, and 500 mm in length. A traveling wave at 21.7 kHz was successfully generated using a single Langevin transducer attached perpendicularly to the waveguide, transmitting standing-wave vibration energy into the waveguide, progressively attenuated and turned into a traveling-wave along the waveguide's length. The wavelength was 28.2 mm, a vibration velocity of 108 mm/s was obtained along the top of the waveguide,and, using a bronze slider placed on the waveguide, a sliding velocity of 33 mm/s was achieved. In the second configuration, a traveling wave was generated at 81.5 kHz by a Langevin transducer attached perpendicularly to a low-loss aluminum ridge waveguide 3 mm wide, 6 mm in height, and 130 mm long; transmitted along the waveguide's length; and absorbed in a viscoelastic terminator. The standing wave ratio, wavelength, and peak vibration velocity of the traveling wave were 2.7, 23.0 mm, and 110 mm/sec, respectively. A slider velocity of 90 mm/s was achieved in this configuration. In the third configuration, two Langevin transducers were attached at either end of the aluminum ridge waveguide from the previous setup, using a phase difference between the drive signals of the transducers to generate a flexural traveling wave along the ridge at 78.5 kHz, the propagation direction of which could be switched via phase control. At an input-signal phase difference of 60 degrees, a traveling wave with a standing wave ratio of 1.96 was achieved. Reversing the traveling-wave/sliding direction, a standing wave ratio of 1.5 was measured at a phase difference of 320 degrees. A slider velocity of 103 mm/s was achieved in either direction. We finish with discussion and early results on miniaturization of this technology to be applied for optical switching, and compare it with current technology. In particular, the unlimited stroke of the proposed actuator and the flexibility in material choice in its construction will be emphasized.

PS1-14 513AB

COMBINED RADIATION PRESSURE FIELD IN A DUAL-FREQUENCY ULTRASOUND SYSTEM

J. S. THIERMAN*[1], G. T. CLEMENT[2], and K. HYNYNEN[2], [1]Harvard-MIT HST Program, [2]Brigham and Women's Hospital, Harvard Medical School.
Corresponding e-mail: thierman@mit.edu

The radiation force incident on an object in an ultrasound field is often utilized to create local displacements used for making elastographic measurements. This force is proportional to the target properties like absorption and reflection as well as the squared pressure of the ultrasound field. In particular, in a dual-frequency radiation force set-up, the objective is to create a pressure field which beats in time in order to produce a cyclical radiation force which could be used to make dynamic measurements of target mechanical properties. This study looks at the combined pressure field from two ultrasound transducers in a dual-frequency system to determine the radiation pressure field pattern which would be incident on an object in the focal plane. The pressure fields from a concentric element transducer as well as two separate elements with intersecting foci are analyzed. First, the combined pressure field is calculated using a computer simulation of the summed linear fields. Then, the simulation is shown to be in close agreement with experimental measurements of the pressure fields. Finally, the simulation is expanded to compute the radiation pressure for various target sizes and transducer geometries. We present the first direct experimental measurements of the cyclical radiation force from a dual-frequency system. With a 1mm diameter target, we record a magnitude on the order of 1.4 μN which oscillate at frequencies less than 1 Hz using a dual frequency concentric ring transducer (8 cm radius of curvature, 10 cm diameter) driven

at 20 W electrical per element at a frequency of 1.7 MHz + Γf. Then, the we demonstrate that the summed linear pressure field with its grading lobe pattern results in a radiation pressure field which varies greatly depending on the geometry of the transducers and the target size. For example, there is a decrease in radiation pressure as target size increases of up to 97% for target diameters ranging from $1/4\lambda$; to 20λ. In some cases, the resulting radiation force on the target may not cause a cyclical displacement in time that is measurable as has been previously assumed in the literature. Knowledge of the combined pressure field will allow for optimization of the dual-frequency set-up so that the pressure field variation in time is conducive for radiation force experiments.

PS1-15 B4

ON MINIMIZING BULK SCATTERING LOSS IN CRF(DMS) DEVICES

W. WANG[1], X. ZHANG[1], H. WU[1], Y. SHUI*[1], and V. P. PLESSKY[2], [1]Key Lab. on Modern Acoustics, Nanjing University, [2]GVR Trade SA.
Corresponding e-mail: yashui@nju.edu.cn

For widely used DMS (dual mode SAW) filters, it is inevitable to have local non-synchronous area in the device. It is known that the bulk scattering of commonly used in this case leaky waves on these breaks of periodicity is one of the major sources of losses in this type of filters. A few methods to replace the gaps by "distributed gaps" with slowly varying parameters were recently proposed [3, 4]. We utilize FEM/BEM combined Green's function method similar to developed by P. Ventura et al. [1] to investigate this phenomenon and to optimize the "distributed gaps". We use one port resonator with differently defined gaps as a research vehicle and apply the results to two ports DMS filter. We numerically studied the following three kinds of non-synchronous geometry: (1) abruptly change of the period (as in the hiccup resonator [2]) with metallized gap; (2) gradually changing period near gap, but no special gaps ("accordion gap"); (3) gradually changing metallized ratio while keeping the period constant near ends of structures (and smaller). We found that it is possible to keep the frequency position of resonance at the same place, while significantly improving its Q-factor. Through finite electrode Green's function solution, we get the electrical quality factor Q for the resonators and the insertion loss for the DMS filters. By deducting the loss due to the electrical reflection at input and output ports and the surface wave carried outside both reflectors from the insertion loss, we can obtain the energy leakage by the non-synchronous arrangement of the device. Here, we neglected the material loss and electric resistance loss in assumption of the computer experiments. Therefore the results may deviate from the experiments, where other mechanisms of loss are inevitable, but it gives theoretically the loss due to bulk wave radiation by non-synchronous structure. In addition, from the solution of Green's function, we can obtain the electrical potential and charge distribution, mechanical displacement and stress distribution on the

interface between substrate and electrodes. From these distributions, we reconstructed the field distribution beneath the interface, in particular, we have obtained the energy leakage at local district near "gap". Scattering diagrams are calculated for above mentioned cases of gaps. We continue the optimization of gaps and the best "distributed" gap will be presented.

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PS1-16 B5

SAW AND BAW RESPONSE OF C-AXIS ALN THIN FILMS SPUTTERED ON PLATINUM

M. CLEMENT[1], L. VERGARA*[1], J. OLIVARES[1], E. IBORRA[1], J. SANGRADOR[1], A. SANZ-HERVÁS[1], and C. ZINCK[2], [1]Dpto. Tecnología Electrónica, Universidad Politécnica de Madrid, [2]CEA-DRT-LETI/DIHS-CEA/GRE.
Corresponding e-mail: eiborra@etsit.upm.es

AlN thin films are frequently used as piezoelectric material in SAW and BAW devices. The performance of these devices is related to the piezoelectric properties of the AlN films, which are closely correlated with the crystal properties (preferred orientation, texture and grain size). In the case of sputtered AlN films these properties depend strongly on the deposition conditions and the type of substrate. BAW and SAW propagation modes are determined by the piezoelectric coefficients d_{33} and d_{13}, respectively. The relationship between these coefficients, which is constant for single crystals, for AlN thin films could be affected by the defects associated to the polycrystalline nature of the material (residual stress, inversion domains, grain boundaries, etc.) In this communication we compare the longitudinal and transversal piezoelectric properties of AlN films deposited by sputtering on highly textured platinum films. AlN thin films were grown by sputtering an Al target in Ar/N_2 atmospheres under different conditions to obtain films of different crystal qualities. The crystallographic properties were measured by XRD. Perpendicular stress was derived from the XRD measurements while the in-plane residual stress was obtained from the substrate bow after film deposition. The crystal quality of AlN films grown on Pt varies with the process parameters in a similar way as on other substrates: only when enough energy is supplied to the substrate, pure c-axis oriented films are obtained. Grain size, residual stress and FWHM of the rocking-curve of the best films on Pt are much better than on other substrates (other metals, Si and SiO_2), which indicates a strong influence of the surface of the substrate. SAW delay lines and BAW resonators were fabricated to evaluate the electromechanical coupling in the transversal (k_T^2) and longitudinal (k_L^2) directions and the acoustic velocities. SAW devices were made by patterning chromium IDTs by lift-off on top of the AlN films. The use of a metallic substrate affects largely

the SAW response (S_{12} parameter), reducing dramatically the out-of-band losses due to the electromagnetic feedthrough (EMF). The accurate determination of $k_T{}^2$ is carried out by eliminating the influence of the EMF and the parasitic elements from the measurement. Values of $k_T{}^2$ as high as 2.5% are obtained. The BAW resonators were made using bulk micro-machining technique. The piezoelectric device was fabricated on an oxidized silicon wafer covered by a Si_3N_4 thin film. The bottom electrode consisted of a Pt layer. The devices were released by deep reactive ion etching of the silicon wafer. The value of the longitudinal electromechanical coupling ($k_L{}^2$) is derived from the resonator response (S_{11} parameter) and correlated with $k_T{}^2$ derived from the SAW measurements.
This work has been supported by the Ministerio de Ciencia y Tecnología of Spain through project no. MAT2001-350. One of the authors (J.O.) would like to acknowledge financial support by the Ministerio de Ciencia y Tecnología of Spain through the Ramón y Cajal programme.

PS1-17 B6

FEM/BEM IMPEDANCE AND POWER ANALYSIS FOR MEASURED LGS SH-SAW DEVICES

T. D. KENNY*, T. B. POLLARD, E. BERKENPAS, and M. PEREIRA DA CUNHA, Dept. of Electrical and Computer Engineering, University of Maine.
Corresponding e-mail: mdacunha@eece.maine.edu

Pure Shear Horizontal Surface Acoustic Waves (SH-SAW) exist on the X-axis cylinder cuts, Euler angles (0° , θ, 90°), of trigonal class 32 group crystals, which include quartz and the LGX family of crystals (langasite, langatate, and langanite). This pure SH-SAW mode has interesting propagation characteristics, such as: (i) higher phase velocity than the regular SAW or Rayleigh mode, which can be used for higher frequency devices; (ii) reduced attenuation compared to other SAW modes when the surface is immersed in liquid, which can be used for liquid sensor applications; (iii) a power penetration depth into the substrate comparable to the Rayleigh SAW mode, when a metallic finite film thickness or a grating is used for additional guidance of the SH-SAW at the surface; and (iv) calculated and measured electromechanical coupling up to 0.8% along selected LGX substrate orientations. Along these selected LGX orientations, the interdigital transducers (IDTs) used to generate the SH-SAW also excite a significant amount of shear horizontal bulk acoustic wave (SH-BAW) that propagates almost parallel to the surface, with a slightly different phase velocity. The present work uses combined finite and boundary element methods (FEM/BEM) to calculate IDT impedance, while considering both the SH-SAW and SH-BAW contribution. The ratio of transduced SH-SAW power to SH-BAW power is analyzed as a function of device geometry, and IDT metallization material and thickness. The simulations and experimental IDTs range in length from 5 to 60 wavelengths (λ), and in normalized electrode thickness, h/λ, from 0 to 1%. Typically for a 20λ IDT the FEM/BEM simulations indicate that the input power is distributed about evenly between the SH-SAW and SH-BAW modes. The measured impedance of devices fabricated along LGS Euler angles (0° , 22°

, 90°) with aluminum and gold electrodes of thicknesses between 1500 and 2000 agree extremely well (within 2%) with the FEM/BEM IDT impedance calculations accounting for both SH-SAW and SH-BAW generation. The SH-BAW angular plots obtained with the FEM/BEM analysis confirm that this mode excited by the IDTs propagates nearly parallel to the surface. Both our simulations and experimental results consistently indicate that the ratio of SH-SAW to SH-BAW transduced power strongly depend on metal type and thickness. For instance, at $h/\lambda=0.6\%$ nearly 20% less power is radiated as SH-BAW when gold instead of aluminum electrodes are employed.
This work was conducted with support from the National Science Foundation (grants ECS-0233463 and ECS-0134335).

PS1-18 512A-F

EVALUATION OF MATERIAL CONSTANTS AND SAW PROPERTIES IN LACA$_4$O(BO$_3$)$_3$ SINGLE CRYSTALS

H. SHIMIZU*[1], H. TAKEDA[1], T. NISHIDA[1], T. SHIKITA[2], S. OKAMURA[1], and T. SHIOSAKI[1], [1]Graduate School of Materials Science, Nara Institute of Science and Technology (NAIST), [2]Research Development Division, Sakai Chemical Industry Co., Ltd.
Corresponding e-mail: s-hiroyu@ms.aist-nara.ac.jp

Rare-earth calcium oxoborates, $RCa_4O(BO_3)_3$ (R = La-Lu, Y; RCOB) single crystals exhibit excellent non-linear optical properties and can be grown by Czochralski (Cz) technique[1]. We have paid attention to piezoelectric properties of the RCOB crystals. In this study, we prepared RCOB (R = La, LaCOB) crystals using the Cz technique and evaluated the material constants and SAW properties. From our previous report[2], the relationship between the morphology of the grown crystal and crystallographic *abc* - rectangular *XYZ* axes was revealed. This knowledge is very useful to prepare substrates for piezoelectric measurements. The LaCOB crystals belong to the monoclinic symmetry (point group *m*). The total number of material constants which should be determined is 27. They consist of 4 dielectric, 10 piezoelectric, and 13 elastic compliance constants (ϵ_{ij}, d_{ij}, and s_{ij}, respectively). We could suggest substrates in order to determine these constants using length-extensional (transverse effect), thickness-extensional (longitudinal-effect) and thickness-shear modes. Twenty four of 27 constants were determined until now, e.g., ϵ_{11}, ϵ_{22}, ϵ_{33}, ϵ_{13} at 10 kHz were 9.7, 14.3, 9.7, -1.24 and d_{11}, d_{32} were 2.3, -2.3 pC/N at room temperature, respectively. Their 1st order temperature coefficients were 56.3, -273.6, 135.8, -258.4 and -408.3, 409.6 ppm/K, respectively. SAW and Pseudo-SAW (PSAW) on the *X*-, *Y*- and *Z*-cut substrates of LaCOB crystal were characterized. Maximum coupling factor ($k^2 = 0.6\%$) was observed on the *Z*-cut crystal at the *Y*-axis propagation. Relatively low temperature coefficient of time delay (48 ppm/K) was observed on the *Y*-cut crystal at the *Z*-axis propagation. These feature suggested the LaCOB crystal will become performance-competitive with existing $Li_2B_4O_7$ and $La_3Ga_5SiO_{14}$ crystals.

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PS1-19 B8

OPTIMIZED MEMBRANE CONFIGURATION IMPROVES CMUT PERFORMANCE

Y. HUANG*, E. O HÆGGSTRÖM, X. ZHUANG, A. S. ERGUN, and B. T. KHURI-YAKUB, Edward L. Ginzton Laboratory, Stanford University.
Corresponding e-mail: yongli@stanford.edu

An improvement in CMUT performance was achieved by membrane configuration optimization. CMUTs with three different membrane configurations: square, rectangular and tent, were designed and fabricated using a newly developed process based on the wafer-bonding technique. Paired tests showed that improved transmission (TX) and reception (RX) performance could be achieved by using tent or rectangular membranes instead of conventional square membranes in the CMUT.

A CMUT with a fixed element size and a certain operation frequency, can have its performance improved by an optimized membrane design. The improvement originates from three factors: 1) an increased average membrane displacement for a given pressure loading, 2) an increased average membrane deflection relative to the maximum membrane deflection, 3) an increased fill factor.

Since the performance difference between CMUTs with square and hexagon shaped membranes was relative small, a squareCMUT with 88 μm by 88 μm membranes was selected to represent the conventional design. A rectCMUT with 72 μm by 540 μm rectangular membranes and a tentCMUT with 540 μm by 540 μm tent membranes anchored with 15 μm square support posts (70 μm pitch) were designed for comparison. The designs were such that all CMUTs worked in the same frequency region. All membranes were made from 1 μm thick single crystal silicon while the support walls in the squareCMUT and rectCMUTs were 5 μm wide. The fill factor of the square-, rect- and tentCMUTs were 89%, 94% and 95%, respectively. A FEM simulation predicted that, at 20 VDC, the precollapsed average membrane displacement relative to the maximum membrane displacement for the three designs would be 30%, 46% and 52%, respectively.

The ultrasonic characteristics of the CMUTs were obtained by broadband pitch-catch and pulse-echo tests. The experimental TX and RX results were normalized, to ensure a fair comparison, by the electric field intensity. In both TX and RX, the rectCMUTs and tentCMUTs showed a higher output pressure and sensitivity through the entire bias range than the squareCMUTs. The performance improvement gained by the new designs varied with bias. As an example: in TX, at 20 VDC, the output pressure per input voltage of the rectCMUTs and tentCMUTs were 46% and 44% higher than that of the squareCMUT, respectively. The measured max transmission efficiency was 22 kPa/VAC at 90 VDC with the tentCMUT. In RX, at 20 VDC, the sensitivity of the rectCMUT and tentCMUT were 43% and 65% higher than that of the squareCMUT, respectively. The TX and RX spectra of the designs were slightly different in shape, but had a similar uncorrected fractional bandwidth (∼125%).

Since the optimized devices had fewer sub-cells with independent cavities than the conventional design, the optimized CMUT yields were potentially more sensitive to fabrication defects than that of the conventional devices. A newly developed process based on the wafer-bonding technique improved their yields over that of conventional surface micromachining. No difference in yield was observed between the three designs.

PS1-20 511AB

INVERSE CALCULATION METHOD FOR PIEZOCOMPOSITE MATERIALS CHARACTERISATION

G. FÉRIN*[1,2], D. CERTON[2], J. GUYONVACH[2], and N. FÉLIX[1], [1]VERMON, [2]GIP Ultrasons / LUSSI.
Corresponding e-mail: g.ferin@vermon.com

Due to their high permittivity and their low acoustic impedance, the piezocomposite materials are increasingly used for ultrasound imaging probes for medical or N.D.T. applications. The determination of elastic, dielectric and piezoelectric homogenised constants needs to be considered for the optimisation and the performance evaluation of the piezocomposite. All parameters are indeed required for the modelling of piezocomposite devices by finite element models or analytical approaches. Inverse problem method enables the determination of parameters by solving data fitting in the least square sense. The full determination of effective electro-acoustic tensor [c, e, ϵ] is then performed from displacement field measurement obtained in air compared to the simulated one. For the modelling of the plate, the piezocomposite is considered as a homogeneous medium with the same symmetry class than the ceramic phase, 6mm. The mechanical response is calculated using well known analytical approach where the source is introduced from the electrical boundary conditions of the plate. Mechanical losses are taken into account. Calculations are performed in the spatial frequency (k) and time frequency (ω) domain: the ω-k domain. The tested piezocomposite material is manufactured under the form of a classical array without backing and matching layers. Mechanical displacements are produced by pulsed electrical excitation source. The experimental ω-k diagram of the displacement is obtained from the 2D Fourier transform of the x-t diagram of the measured displacement. The sensitivity of the ω-k response of the displacement to each parameter is studied. Results are then used to define, for each material property, the optimal ω-k area which brings out the most information. The numerical inversion scheme used to reconstruct the material properties from the ω-k diagram of the displacement is described and first validated from theoretical displacement fields. We show that the regression procedure is successful, while the initial values of material properties stay ten percent around the real values. Experimental results are presented and discussed for four different configurations using piezocomposite structures

with different piezoceramics and filler materials type. Using these results, an acoustic performance evaluation for the different piezocomposite configurations will be realized.

PS1-21 B10

WIDE FREQUENCY BAND AND HIGH INTENSITY THICKNESS VIBRATION OF HYDROTHERMAL LEAD ZIRCONATE TITANATE POLYCRYSTALLINE FILM

M. ISHIKAWA*[1], M. K. KUROSAWA[1], and S. TAKEUCHI[2], [1]Tokyo Institute of Technology, [2]Toin University of Yokohama.
Corresponding e-mail: m.ishikawa@ae.titech.ac.jp

The ultrasonic characteristics of the transmission sensitivity and high intensity vibration capability of hydrothermal lead zirconate titanate polycrystalline thick film was measured. A hydrothermal PZT was deposited on a titanium substrate by solution including Pb^{2+}, Zr^{4+} and Ti^{4+} in an autoclave at 180 degree Celsius. The deposition rate was about 4mm/6h. The deposit film had a polycrystalline structure. The atomic ratio of the film was Zr:Ti= 80:20. A PZT film about 60μm thick was deposited on a 50μm thick titanium substrate surfaces by the mentioned method. The electrode of Au was deposited on the PZT film surface by the vacuum evaporator on one side in 8$\times$8mm square area. Counter electrode was the titanium substrate. The hydrothermal PZT ultrasonic transducer was fixed in water by a clamp, and a calibrated hydrophone in frequency range between 1 MHz to 20 MHz was set the horizontal distance of 20mm from the hydrothermal PZT ultrasonic transducer. Driving signals of 250 V burst wave between 2 MHz to 20 MHz were applied to the PZT film. Then, after 14 μs from the arriving signal, the hydrophone signal was obtained in all frequency range. The transmission sensitivity in wide frequency range from 2 MHz to 20 MHz was in the deviation of $\pm$6dB. The peak transmission sensitivity was 80 kPa. The frequency response of the thickness mode vibrator was measured by the laser Doppler vibrometer in the bandwidth was 20 MHz. The measuring point was at center of the surface of the electrode at under the condition of a constant driving voltage. The result of measured vibration was the vibration displacement and the vibrator velocity were 13 nm and 2 m/s when the driving voltage was 150 Vo-p at the frequency of 20 MHz. Additionally, the powder density of the deposited PZT polycrystalline thick film was 4.310^3 kg/m^3 and we estimated the phase velocity of longitudinal wave was about 2000m/s, consequently the acoustic impedance was estimated to be about 8.610^6 kg/m^2 s. This amount is 0.3 less than the amount of the ceramics PZT. The experiment shown that this PZT film was broadband ultrasonic transducer that enables ultrasonic waves to transmit in water at 2 MHz to 20 MHz with the transmission sensitivity in the range of $\pm$6dB and high intensity operation as 2m/s in water at 20 MHz. And further the acoustic impedance was very low compared to ceramics PZT. In general, desirable attribute of medical ultrasonic assessment transducer is wide frequency band and low acoustic impedance. And high intensity ultrasonic transmission is

imperative for ultrasonic therapy. We find out about hydrothermal PZT thick film was completely meet the various requests on medical ultrasonic transducer. It is expected that this hydrothermal PZT will be utilized for development of medical ultrasonic transducer that serve double duties as assessment and therapy

PS1-22 B11

REAL-TIME 3D ULTRASOUND WITH MULTIPLE TRANSDUCER ARRAYS

M. P. FRONHEISER*, E. D. LIGHT, and S. W. SMITH, Deptartment of Biomedical Engineering, Duke University.
Corresponding e-mail: mpf3@duke.edu

We modified our real time 3D ultrasound system (Duke U./Volumetrics Medical Imaging) for near simultaneous 3D scanning with multiple 2-D array transducers. The 3D scanner uses 512 transmit channels and 256 receive channels for arrays operating from 2-10 MHz. The real time system scans a 650-1200 pyramid with 16:1 receive mode parallel processing producing up to 60 volumetric scans per second and features up to five image planes as well as 3D rendering, 3D pulsed wave and 3D Color Doppler. To incorporate multiple near simultaneous arrays, we divided the phase delay memory into multiple segments, each segment corresponding to a separate array transducer with unique array geometry. This allows multiple combinations of transthoracic, transabdominal, endoscopic, catheter and ultrasound therapy probes of annular, linear and 2-D arrays limited only by the total number of 512 transmitters, 256 receivers. As a first illustration we modified the transducer cable assembly to incorporate two independent 3D intra-cardiac echo catheters, a 7 Fr (2.3 mm O.D.) side scanning catheter and a 14 Fr forward viewing catheter with tool port each of 85 channels operating at 5 MHz. For applications in treatment of atrial fibrillation, the goal is to implant the side-viewing catheter within the coronary sinus to view the whole left atrium including left pulmonary veins. Meanwhile the forward viewing catheter inserted within the left atrium is directed toward the os of a pulmonary vein for therapy using the integrated tool port. With pre-loaded phasing data, the scanner switches between catheters automatically at the push of a button with a delay of only a few seconds so that the clinician can view the therapy catheter with the coronary sinus catheter and vice versa. At present the automatic switching system has been tested in tissue phantoms. Ultimately, the system will switch between 3D probes on a frame-by-frame basis, line-by-line basis, or on the basis of frequency separation for true simultaneity and enable image fusion of multiple 3D scans.

PS1-23 C6

ULTRA-LOW DRIFT CRYOGENIC SAPPHIRE MICROWAVE OSCILLATOR

P. Y. BOURGEOIS*[1], Y. KERSALÉ[1], N. BAZIN[1], M. CHAUBET[2], and V. GIORDANO[1], [1]Departement LPMO, Institut FEMTO-ST, UMR 6174, [2]Centre National des Etudes Spatiales.
Corresponding e-mail: pybourgeois@lpmo.edu

Ultra–stable oscillators are required for various domains, such as frequency metrology, radars, or test equipments. Cryogenic sapphire ones represents the best solution to be used with the modern cold atoms frequency standards for terrestrial applications.

In our previous works [1], we have obtained frequency instability better than $3 \cdot 10^{-14}$ from $10s$ to $100s$ and less than 10^{-13} up to $1000s$.

The aim of this paper is to show that we recently reached the best long term frequency instability of such ultra stable oscillators.

The heart of each of our cryogenic oscillators is composed of a $50mm \times 20mm$ sapphire cylindrical disk resonator, in which Whispering Gallery Modes are excited. Such resonators are characterized by ultra-low dielectric losses especially at low temperatures (around the liquid helium temperature , *i.e.* $4.2K$) : it enables very high Q-factors, that a traditionnal quartz can not provide. The sapphire crystal is placed in a center of an open cavity which naturally inhibits spurious modes that are present in a closed cavity. In our laboratory, we have undertaken to improve our previous results. A $WGH_{15,0,0}$ mode excited inside the resonator presented a loaded Q-factor of about $450 \cdot 10^6$ with a turnover temperature around $6K$. The room-temperature loop oscillator was built considering this configuration, with the implement of a pound servo loop used to control the phase fluctuations and a power servo loop to control the injected microwave power inside the resonator. The particularity of the electronic circuitry was the use of 2 voltage controlled phase shifter to reduce AM fluctuations. The observed frequency instability was not clearly a frequency drift (frequency random walk). The obtained results show a frequency instability of around 8×10^{-15} until $100s$ of integration time and less than 6×10^{-14}day which is the best long-term stability ever obtained with cryogenic sapphire oscillators.

[1]:P.Y Bourgeois, Y.Kersalé, N. Bazin, J.G. Hartnett, M.Chaubet and V.Giordano "Progress in the building of sapphire-helium clock at LPMO" Proceedings of the Joint meeting 17th E.F.T.F and 2003 IEEE IFCS, Tampa, Fl, USA, pp 355-359.

PS1-24 C7

EVOLUTION OF THE UWA SOLID NITROGEN DUAL-MODE SAPPHIRE MICROWAVE OSCILLATOR

J. ANSTIE, J. HARTNETT*, M. TOBAR, E. IVANOV, and F. VAN KANN, University of Western Australia.
Corresponding e-mail: anstie@physics.uwa.edu.au

Helium temperature cryogenic sapphire based oscillators have been used with great success as secondary frequency standards. Their exceptional frequency stability at small integration times (with instability as low as few parts in 10^{16} over 10 seconds) is ideal for use with cold atomic transition based clocks, including the current generation of caesium fountain clocks. From a cost perspective, however, a helium-based standard is far from ideal. Liquid nitrogen is cheap, widely available and can be easily solidified, making solid nitrogen a more cost effective cryogen.

A key feature of helium-based sapphire resonators is a turning point in the frequency-temperature curve between 6 and 10 K, making them insensitive to temperature fluctuations, to first order. To produce a similar turning point at 50 K, with solid nitrogen, in a single mode resonator usually requires the introduction of additional losses, which compromise the Q factor of the resonator. An alternative solution is to excite two orthogonal modes in a single sapphire crystal and look for the turning point in their beat note. A clock utilising this technique is currently under development at UWA, and last year produced resulted in a frequency instability on the order of 2 parts in 10^{13} over 10 seconds. The clock has since been upgraded. An automatic refill system, that will allow the clock to run continuously, has been added and is currently being tested. Also, a new temperature control system, based on a single mode frequency, has been integrated into the clock and is also undergoing testing. Better coupling to the resonator has been achieved with primary coupling to both modes on the order of unity. As a result, an improvement in the frequency stability of an order of magnitude is expected, with results to be presented at the conference.

PS1-25 C8

SH-SAW TRANSDUCER ANALYSIS ON SINGLE CRYSTAL $KNBO_3$ FOR LIQUID SENSORS

T. B. POLLARD*, T. D. KENNY, and M. PEREIRA DA CUNHA, Dept. of Electrical and Computer Eng., University of Maine.
Corresponding e-mail: mdacunha@eece.maine.edu

The pure shear horizontal surface acoustic wave (SH-SAW) mode is very attractive for liquid phase sensing applications. This particular mode has particle displacements parallel to the device surface and normal to propagation direction, which reduces acoustic power loss in an adjacent liquid media. Potassium Niobate ($KNbO_3$) possesses this type of mode along Z-axis cylinder orientations, Euler angles (Φ, 90°, 0°), with a maximum electromechanical coupling coefficient (K^2=53%) along (0°, 90°, 0°). The SH-SAW propagating in a mechanically and electrically free surface is weakly guided by the surface, showing a power penetration depth of about 200 wavelengths (λ). This number drops two orders of magnitude to about 1λ, when the mechanically free surface is electrically shorted, a very important result for a SAW sensor that needs to detect small perturbations at the surface. For such a strong coupling material few interdigital transducer (IDT) electrodes are required to efficiently excite the SH-SAW. The analysis of the IDT behavior in exciting the SH-SAW and the

shear horizontal bulk acoustic wave (SH-BAW) is thus of primary importance in designing a successful $KNbO_3$ sensor. This work investigates the interdigital transducer (IDT) array on single crystal $KNbO_3$ along Euler angles (0°, 90°, 0°), and the resulting characteristics of the IDT performance including: SH-SAW power penetration depth; power partitioning between the SH-SAW and SH-BAW; spurious SH-BAW power flow angle and magnitude, and overall IDT impedance. In order to verify our experimental results, a boundary element method (BEM) simulator for the pure SH type mode has been developed to obtain the overall charge distribution on the IDT electrodes and to provide a means to analyze the IDT acoustic impedance and power spectral distribution. Based on our experimental results and the numerical analysis performed, we have identified that the Poynting vector decays very rapidly (about 1.5λ) underneath the IDT structure with more than 3 finger pairs. The calculated impedance for a 5 split finger pair 15λ aperture IDT as a function of frequency fits very well the measured curve, matching the measured values within a few percent over the devices bandwidth. We have also identified that the addition of guard electrodes to the IDT and their respective number play a significant role in the overall IDT impedance and device behavior. For instance, our results show that adding 12 guard electrodes to the IDT structure previously mentioned mismatches the IDT impedance, Z_{IDT}, from (49-j0.5)Ω to (32-j0.5)Ω, but broadens Z_{IDT} response by 40% in frequency (SWR$\leq$1.2). A $KNbO_3$ IDT design that exhibits a high SH-SAW to SH-BAW power ratio will better exploit surface perturbations, resulting in a high performance liquid phase sensor.
This work was conducted with support from the National Science Foundation (grants ECS-0233463 and ECS-0329913).

PS1-26 C9

AN EFFICIENT NUMERICAL METHOD IN CALCULATING THE ELECTRICAL IMPEDANCE DIFFERENT MODES OF AT-CUT QUARTZ CRYSTAL RESONATOR

S.-Y. PAO[1], M.-C. CHAO[2], C. S. LAM[2], and P.-Z. CHANG[1], [1]Institute of Applied Mechanics, National Taiwan University, [2]TXC Corporation.
Corresponding e-mail: sypao@mems.iam.ntu.edu.tw

Lee and Brebbia in 1978 presented a finite element analysis (FEA) of AT-cut quartz crystal resonator by including the thickness-shear branches in the length-width directions and the flexural branch in the thickness direction based on Mindlins 2-D elastic equations. The formulation was pure elastic and electrical impedance of different modes could not be calculated since piezoelectric effect and damping were not included. In the years after, many FEA-based studies were conducted using either the full-bown 3-D elastic-piezoelectric model or the simplified Mindlins 2-D elastic-piezoelectric model. Such formulations are quite complicated and numerically time-consuming in computation. Furthermore, one experienced tremendous difficulty in resolving the many eigenmodes in the 3-D analysis.

In this paper, by assuming weak piezoelectric coupling, we first rearrange the electrical potential and damping terms to the right hand side of the elastic-piezoelectric equations of motion. These terms become the forcing terms of the pure elastic equations of motion. Again, we solve for the eigenmodes of the AT-cut quartz crystal resonator again using Lee-Brebbias FEA method based on Mindlins 2-D elastic equations. Then we use the mode superposition method to calculate the weight of each eigenmode. The elastic displacement field with electrical potential effect can then be calculated as the weighting sum of each eigenmode. The electrical charges on the quartz crystal resonator can be obtained from the elastic displacement and electrical potential field at each node point. Finally, we calculate the electrical impedance from the electrical charges and the potential. This method is considered much more efficient than the full-blown 3-D elastic-piezoelectric analysis or the simplified Mindlins 2-D elastic-piezoelectric analysis. We present results from this study and compare with experimental results and previous numerical analyses.

PS1-27 C10

EFFECTS OF ELECTRIC BIAS AND O_2 CONTENT ON PROPERTIES OF ZNO FILMS AND CHRACTERIZATION OF ZNO-BASED FILM BULK ACOUSTIC RESONATOR

D.-Y. KIM*, D.-H. CHO, B.-H. KIM*, J.-B. LEE, J.-P. JUNG, and J.-S. PARK, Dept. of Electrical Engineering, Hanyang University.
Corresponding e-mail: mozzo@ihanyang.ac.kr

Film bulk acoustic resonators (FBARs) are considered to be very promising devices as state-of-the art on passive RF communication components which have occupied the attention. FBARs may possess several advantages in achieving small dimensions and excellent performances at high frequency ($>$ a few GHz) against surface acoustic wave (SAW) devices. Moreover, FBARs could adapt the well-developed Si process without any special revision and incardinate the monolithic microwave integrated circuit (MMIC). Among the various materials, polycrystalline ZnO has been recognized to be a good candidate for FBAR application. FBARs require properties of c-axis preferred growth and high electrical resistivity so that the devices could reveal low insertion loss and little distortion of frequency response. To obtain the c-axis preferred crystal orientation, the atoms on the substrate must have enough mobility to migrate to the columns with the preferred orientation. However, the widely-used RF magnetron sputtering may hardly provide the atoms with enough energy for surface diffusion at room temperature or low temperature. We present a novel method for achieving ZnO films with highly c-axis (002)-textured orientation without deteriorating the electrical resistivity, and hence improving the device performance of ZnO-based FBAR devices. The method proposed involves dc-biased deposition during ZnO growth which is introduced at around room temperature. Applying electric bias during deposition may change the energy of ions participated in film growth.

Therefore, we have focused on the role of ions, especially how $O_2{}^+$ ions affect the growth behavior of ZnO films. The ZnO films have been deposited on Al/Si, Mo/Si, and Si (111) substrates by employing an RF magnetron sputtering system. X-ray diffraction (XRD) spectroscopy is used to characterize the crystal orientation of the films deposited and the corresponding rocking curves are also measured. The texture coefficient (TC) for (002)-orientation and the full-width at half maximum (FWHM) are evaluated. The surface morphology and the roughness are monitored by field-emission scanning electron microscopy (FE-SEM) and atomic force microscopy (AFM), respectively. All the data obtained from ZnO films are characterized in terms of the dc bias voltages applied. ZnO-based FBAR devices are fabricated using a lift-off technique and their frequency response characteristics are measured. From this study, it is suggested that the proposed method would be desirable for the fabrication of ZnO FBAR devices with sufficiently low temperature for MMIC.
This work was performed by the technical support from the center for Electronic Materials and Components (EM&C) of Hanyang University at Ansan campus.

PS1-28 513CD

NON-LINEAR DIELECTRIC RESPONSE IN 111 AND 100 ORIENTED 0.5PB($YB_{1/2}NB_{1/2}$)O_3-0.5PBTIO_3 THIN FILMS

N. BASSIRI GHARB* and S. TROLIER-MCKINSTRY, The Pennsylvania State University.
Corresponding e-mail: nzb102@psu.edu

The effective dielectric and piezoelectric coefficients of piezoelectric films depend on the applied electric field strength and frequency. The application of these films in microelectromechanical systems (MEMS) requires an understanding of these nonlinearities for prediction of the device behavior. The AC electric field dependence of the permittivity and piezoelectric response of ferroelectric thin films in sub-switching conditions can be modeled using Rayleigh-type behavior. (1-x)Pb($Yb_{1/2}Nb_{1/2}$)O_3-xPbTiO_3 (PYbN-PT) presents one of the highest Curie temperatures ($\sim$360°C) near the morphotropic phase boundary (x$\sim$0.5) among the relaxor-PT solid solution systems, which makes is a very good candidate for devices with good temperature stability and wide working temperature range. The highest piezoelectric responses in this material are observed for the 100 orientation. In this work, the nonlinear dielectric response of 111 and 100 oriented thin films of 0.5PYbN-0.5PT are reported as a function of AC electric field and frequency. The responses are modeled with a frequency-dependent modification of Rayleigh law as $\epsilon_r = \epsilon_{r,init}(\omega)+\alpha(\omega)E$ where E_{AC}=E.sin(ωt) is the AC driving field and $\epsilon_{r,init}$ and α are the reversible and irreversible Rayleigh coefficients. This modified model predicts the dielectric properties of the PYbN-PT films in the intermediate AC field and frequency regions relatively well. Furthermore, 100 oriented films show higher irreversible Rayleigh coefficients than 111 oriented films. The ratio of the irreversible to reversible coefficients is also higher in the 100 oriented films, showing a higher contribution to the dielectric constant due

to the irreversible component (movement of the domain walls) in these films with respect to the 111 oriented films. Work on the piezoelectric nonlinearity for these films will also be described.
This work was supported by Office of Naval Reaserch. The authors gratefully acknowledge that some substrates were provided by Dr P.Muralt (EPFL)

PS1-29 513CD

PIEZOELECTRIC ANISOTROPY-PHASE TRANSITION RELATIONS IN PEROVSKITE SINGLE CRYSTALS

M. BUDIMIR*, D. DAMJANOVIC, and N. SETTER, EPFL.
Corresponding e-mail: marko.budimir@epfl.ch

The orientation dependence of the longitudinal piezoelectric coefficient, $d_{33}{}^{42}$, is investigated as a function of temperature in $BaTiO_3$ and $PbTiO_3$ crystals using the Landau-Ginzburg-Devonshire theory. We show that a presence of the ferroelectric-ferroelectric phase transition in $BaTiO_3$ leads to enhanced $d_{33}{}^{42}$ along nonpolar directions. The reason for this is that in the vicinity of a phase transition temperature at which a polarization vector changes its direction (tetragonal-orthorhombic/monoclinic, orthorhombic/monoclinic-rhombohedral), the shear piezoelectric coefficients become high. It is shown for all ferroelectric phases of $BaTiO_3$ that the shear stress deforms the crystal cell and changes the polarization direction in a similar way as the corresponding temperature-induced phase transition. The influence of the piezoelectric shear effect on the anisotropy of $d_{33}{}^{42}$ is particularly pronounced in the orthorhombic/monoclinic phase where the piezoelectric shear coefficients are determined by the presence of both the high-temperature tetragonal and the low-temperature rhombohedral phases. In $PbTiO_3$, which does not exhibit ferroelectric-ferroelectric phase transitions, the shear piezoelectric effect is weak and $d_{33}{}^{42}$ has its maximum along the polar axis at all temperatures.These results can be generalized to include phase transitions induced by electric-field and composition variations and are valid for all perovskite materials, including complex relaxor- ferroelectric perovskites that have recently attracted attention for their exceptionally large piezoelectric properties.
The authors acknowledge financial support of the Swiss National Science Foundation

PS1-30 C3

GRAIN ORIENTATION OF NEW LEAD-FREE PIEZOELECTRIC CERAMIC IN THE SYSTEM OF $(BI_{1/2}NA_{1/2})TIO3\text{-}(BI_{1/2}K_{1/2})TIO_3\text{-}BATIO_3$

N. MARANDIAN HAGH*, M. ALLAHVERDI, and A. SAFARI, Rutgers university.
Corresponding e-mail: nmhagh@rci.rutgers.edu

A new lead-free piezoelectric system of $(Bi_{1/2}Na_{1/2})TiO3-(Bi_{1/2}K_{1/2})TiO_3$-Ba TiO_3 (BiNT-BiKT-BT) has shown promising properties compared to other non-lead piezoelectric systems. Incorporation of BiKT to the binary system of BiNT-BT has improved the coupling coefficients (k_p & k_t) and piezoelectric coefficient (d_{33}). In this ternary system, a d_{33} of about 150 pC/N, coupling coefficient of k_t=45%, relative permittivity of 850, dielectric loss of 2.1%, and remnant polarization of $37\mu C/cm_2$ has been achieved in the bulk polycrystalline body. Texturing of this ternary system has been carried out by using the $SrTiO_3$ templates, which are fabricated via Molten Salt Synthesis (MSS). Texturing of up to 73% in the (00l) direction compare to the polycrystalline body has been shown when heat treatment carried out in 1170C-2h in oxygen atmosphere. The effect of incorporation of a third component (BiKT) on the stability of the templates, degree of texturing, and the electromechanical properties of grain oriented samples are the issues which will be addressed.
The authors would like to acknowledge the financial support of Howartt Foundation (HF) and ONR for accomplishment of this research.

PS1-31 C4

SPATIAL RESITIVITY PROFILING OF MULTILAYER CAPACITORS AS A FUNCTION OF FURNACE CONDITIONS

C. M. WILLIAMS, A. E. HYDRICK, H. M. SCHULZE*, and W. A. SCHULZE*, Alfred University.
Corresponding e-mail: hms1@alfred.edu

Commercial X7R $BaTiO_3$ multilayer ceramic capacitors (MLCCs) were examined to better understand the failure mechanisms involved under typical HALT conditions. These samples were initially examined in their as received state using a semiconductor probing station adapted for use as a DC high resistivity profiling device. The samples were then annealed in various partial pressures of oxygen (PO_2) in an effort to alter oxygen vacancy concentration and change the density of electronic carriers in the samples. Using both DC and AC profiling it was found that there was a decrease in the insulation resistance of the dielectric material as samples were reduced in low PO_2 atmospheres. This was thought to be a possible source of life test failure for $BaTiO_3$. Insulation resistance was also shown to decrease as a function of increasing temperature. HALT testing (small numbers) of reduced MLCCs suggested a threshold level of PO_2 before the onset of degradation.
Special thanks to the International Microelectronics and Packaging Society, S. J. Stein Educational Foundation, for supporting our undergraduate researchers.

PS1-32 513CD

COMPLEX LATTICE QUASICONTINUUM THEORY AND ITS APPLICATION TO FERROELECTRICS

O. KOWALEWSKY*, J. KNAP, and M. ORTIZ, California Institute of Technology.
Corresponding e-mail: olga@caltech.edu

Complex lattice Quasicontinuum theory is being developed and applied to the description of ferroelectric phenomena.

Quasicontinuum theory is a multiscale theory that provides a unified description of materials by combining atomistic and continuum approaches. It provides a seamless transition between atomistics and continuum, but the description of the material is derived directly from the underlying atomic structure, using the computationally expensive atomistics only where needed at the location of atomistic origin phenomena.

Complex Lattice Quasicontinuum theory can be applied to complex lattice crystals consisting of many kinds of atoms. One highlight of it is treatment of each component lattice as separately and independently as possible. The component Quasicontinua are coupled through the microscopic forces within nodal clusters, making the complex atomistics of the heterogeneous lattice the basis of the description.

Ferroelectrics are especially suited to the application of Quasicontinuum theory. The nature of defects in ferroelectric materials is atomistic, but their influence over the material is long ranged due to induced elastic fields. Many different ferroelectric phenomena involving Barium Titanate have been investigated and simulated. In particular the domain wall structure : 180 degree domain wall in tetragonal phase with simultaneous consideration of about eleven million atoms. The results show that even if the effect of the domain wall is long ranged due to long range of the columbic potential, the main switch of the polarization happens in the 4-6 cells adjacent to the wall. This is in accordance with most experiments.

Another example simulated is a crack in Barium Titanate. An originally pure tetragonal phase specimen is being subjected to many incremental loading steps. The results are important and noteworthy. One can see a polarization change around the crack tip which is reminiscent of the pattern building in 90 degree domain walls. More calculations are needed to make a final statement about the nature of polarization change but the calculations are very promising.

PS1-33 513CD

DESIGN, FABRICATION AND CHARACTERIZATION OF TUNABLE PZT FILM BULK ACOUSTIC RESONATORS

C. ZINCK*[1], G. CARUYER[2], A. VOLATIER[2], E. DEFAŸ[1], D. PELLISSIER-TANON[2], L. FIGUIÈRE[3], and M. AID[1], [1]CEA-DRT - LETI/DTS - CEA/ GRE, [2]STMicroelectronics, CCMC Crolles, [3]STMicroelectronics.
Corresponding e-mail: czinck@cea.fr

We present the elaboration and the characterization of Film Bulk Acoustic Resonators using PZT thin film. BAW devices are very promising components for wireless applications, using PZT as piezoelectric material allows to tune the frequency of the device. We have used an analytical model (acoustic) based on Mason model to design the structures. This model allows us to calibrate the ideal thickness of the devices to reach a specific frequency. The model will be detailed. The PZT thin films are elaborated thanks to RF magnetron sputtering, and crystallised in the perovskite phase at 700°C. We have elaborated FBAR devices using bulk micro machining technique (DRIE). The FBAR is mechanically supported by a SiN thin film (0,5μm), and the piezoelectric stack is constituted of Ti (50 nm) / Pt (200 nm) / PZT (350 nm) / Pt (100 nm). A PECVD SiO2 film provides an electrical insulation between the top and the bottom electrode The PZT thin film exhibits a dielectric constant of 800. The first results are promising, the devices exhibit a coupling coefficient between 8 and 12 % without any polarisation. The frequency resonance is at 1,8 GHz. We investigate the effect of DC bias on the frequency resonant.

PS1-34 513CD

CONVERSION OF 45° ROTATED X-CUT $KNBO_3$ PLATES TO Y-CUT PLATES BY COMPRESSION

K. NAKAMURA, N. CHIBA, and S. ITO*, Graduate School of Engineering, Tohoku University.
Corresponding e-mail: nakam18@ec.ecei.tohoku.ac.jp

Ferroelectric potassium niobate ($KNbO_3$) single crystals are expected as lead-free high-coupling piezoelectric materials. The electromechanical coupling factor of the surface acoustic wave (SAW), k_{SAW}, is as high as 73% for Y-cut $KNbO_3$ plates. Since $KNbO_3$ has a pseudo-cubic structure, the domain state is changeable by a mechanical stress as well as an electric field. To the best of our knowledge, however, there has been no report on domain control by applying a mechanical stress onto $KNbO_3$ crystals. The objective of this study is to convert the 45° X-plate with a high coupling factor for the thickness-extensional mode to the Y-plate with a very high coupling factor for the surface acoustic wave. Both plates are in relation of 60° domain each other. Considering the crystal structure, the 45° X-plate may be converted to the Y-plate by applying a compressive force obliquely to the plate surface. To comfirm this and obtain a better understanding of the domain behaviors, a system consisting of a polarizing microscope combined with a stress application mechanism was constructed for observation and video recording of the domain state during linearly increasing the applied stress. When the stress was about 6.6 MPa, a stripe 60° domain nucleated and evolved as expected. Finally the 45° X-plate was almost converted to the Y-plate in about 10 seconds. The recorded moving pictures will be presented. To confirm this conversion, an X-ray diffraction investigation was performed before and after applying the stress. The conversion was also confirmed by observing the electrical admittance characteristics before and after applying the stress. Although a thickness-extensional mode resonance was

originally observed, it turned into the thickness-shear mode resonance, which is a feature of the *Y*-plate. These results would present a useful suggestion for obtaining *Y*-domain $KNbO_3$ films.

PS1-35 D3

COOLING-RATE-DEPENDENT DOMAIN STRUCTURES OF PMN-PT SINGLE CRYSTALS OBSERVED BY CONTACT-RESONANCE PIEZORESPONSE FORCE MICROSCOPY

J. SAKAMOTO*, H. OKINO, and T. YAMAMOTO, National Defense Academy.
Corresponding e-mail: g42014@nda.ac.jp

Domain structures of PMN-PT ($Pb(Mg_{1/3}Nb_{2/3})O_3$-$PbTiO_3$) single crystals have been observed by Piezoresponse Force Microscopy (PFM). Recently, Yan *et al*[1] have found that dielectric properties of PMN-PT single crystals in the ferroelectric phase strongly depended on cooling rate across relaxor-ferroelectric phase transition temperature ($T_{R\text{-}F}$). They expected that if cooling rate across $T_{R\text{-}F}$ changed, the average domain size in ferroelectric phase would change. In order to examine their prospects, we observed domain structures of PMN-PT single crystal using contact-resonance PFM (CR-PFM) in the air at room temperature after thermal treatments with various cooling rates. CR-PFM is a suitable tool for observing delicate domain structures such as microdomains due to its low modulation voltage (typically $0.1V_{p\text{-}p}$).

PMN-PT single crystals with practically morphotropic phase boundary composition were grown by the Bridgman method. The Curie temperature of the specimens was approximately 175 °C, which was estimated from the permittivity measurements. The thermal treatment process is as follows:(1) The sample was heated from room-temperature to 220 °C. The heating rate is 60 °C/h. (2) kept at 220 °C for six hours. (3) cooled down from 220 °C to room-temperature with various cooling rate ranging from 15 °C/h to 60 °C/h. We found that shapes and average sizes of domains depended on the cooling rate. Before thermal treatment, finger-print-patterned domain structures 500 $\sim$ 1000 nm in width were observed. After thermal treatment under the cooling rate 15 °C/h, finger-print-patterned domains were also observed. On the other hand, after thermal treatment under the cooling rate 30 °C/h, circular domains 50 $\sim$ 300 nm in diameter were observed. Furthermore, after thermal treatment under the cooling rate 60°C/h, finer circular domains were observed. Their diameter was 20 $\sim$ 100 nm. Our results corresponded with Yan's prospects qualitatively.

[1] F. Yan, P. Bao, Y. Wang, H. L. W. Chan, and C. L. Choy, Appl. Phys. Lett. 81, 4580 (2002).

The authors are pleased to express our gratitude to Dr. Yohachi Yamashita and Dr. Mitsuyoshi Matsushita for providing excellent PMN-PT single crystals. This work was partly supported by the Nissan Science Foundation.

PS1-36 D4

EFFECTS OF LI2CO3 AND BI2O3 ADDITIVES ON SINTERING TEMPERATURE AND PIEZOELECTRIC PROPERTIES OF PCW-PMN-PZT CERAMICS FOR MULTILAYER PIEZOELECTRIC TRANSFORMER

K. CHUNG*[1], J. YOO[2], H. SONG[2], Y. JEONG[3], H. YOON[4], C. PARK[2], and D. LEE[1], [1]Inha University, [2]Semyung University, [3]KEPRI, [4]Kyungmoon College.
Corresponding e-mail: stream95@hanmail.net

In this study, in order to develop the low temperature sintering ceramics for multilayer piezoelectric transformer, PCW-PMN-PZT ceramics using Li2CO3, Bi2O3 and CuO as sintering aids were manufactured, and their microstructural, dielectric and piezoelectric properties were investigated. When the only CuO was added, specimens could not be sintered below 1000°. However, when Li2CO3 and Bi2O3 were added, specimens could be sintered below 1000°. Li2CO3 and Bi2O3 addition were proved to lower sintering temperature of piezoelectric ceramics due to the effect of Li2O-Bi2O3 liquid phase. Li2CO3 and Bi2O3 added specimens showed higher piezoelectric properties than those of the only CuO added specimens. At 0.2wt% Li2CO3 and 0.3wt% Bi2O3 added specimen sintered at 980°, the dielectric constant(ϵr) of 1610, electromechanical coupling factor(kp) of 0.51 and mechanical quality factor(Qm) of 1367 were shown, respectively. These values are suitable for multilayer piezoelectric transformer application.
This work was supported by KEPRI

PS1-37 D5

SOL-GEL DERIVED PB(ZR,TI)O_3 THIN FILMS: RESIDUAL STRESS, ORIENTATION, AND ELECTRICAL PROPERTIES

R. J. ONG*[1], T. A. BERFIELD[2], N. R. SOTTOS[2], and D. A. PAYNE[1], [1]Department of Materials Science and Engineering and Frederick Seitz Materials Research Laboratory, University of Illinois at Urbana-Champaign, [2]Department of Theoretical and Applied Mechanics, University of Illinois at Urbana-Champaign, [3]Department of Materials Science and Engineering and Frederick Seitz Materials Research Laboratory, [4]Department of Theoretical and Applied Mechanics.
Corresponding e-mail: r-ong@uiuc.edu

Pb(Zr,Ti)O_3 compositions have been under investigation as potential integrated ferroelectric, piezoelectric and capacitor thin films for some time. Sol-gel synthesis and spin-coating are popular routes to the formation of high-quality, dense, crack-free, insulating films. However, electrical properties measured in thin film form can be different than those observed in bulk specimens of the same composition. Pb(Zr,Ti)O_3 films with a nominal composition at the MPB (53/47) were deposited from a 2-methoxyethanol based sol-gel system onto Pt/Ti/SiO_2//Si

substrates via spin-casting. Multiple layers were sequentially deposited and heat-treated to 650C with the use of a PbO overcoat to ensure complete formation of the perovskite phase. Films with a final thickness varying from $<0.2\mu$m to $>0.5\mu$m were fabricated and studied by analytical techniques, including, electron microscopy, XRD, wafer curvature and electrical measurements to relate functional properties with the film?s macroscopic state (phase, stress, orientation). Electron microscopy allowed for the study of phase assemblage and morphology in thin films of various thicknesses. X-ray diffraction studies were used to interrogate not only phase purity in the film, but also film orientation with respect to the substrate. *Ex-situ* wafer curvature measurements allowed for the determination of residual stresses in the $Pb(Zr,Ti)O_3$ films and the $Pt/Ti/SiO_2//Si$ substrates. Final properties of interest such as dielectric constant, dielectric loss, remanent polarization, and coercive field were measured for films of various thicknesses and residual stress states. These measurements were employed as a whole in an attempt to separate the potential causes of property variations in a model $Pb(Zr,Ti)O_3$ thin film system when compared with their ceramic bulk counterparts. While, dielectric constant values of $\sim$1200, loss tangents of $\sim$2%, remanent polarizations of $\sim 18\mu C/cm^2$ and coercive field strengths on the order of 4 MV/m were measured for the thickest films, significant variations were observed as film thickness decreased (and the measured stress increased).
Authors would like to thank National Science Foundation for its support through grant CMS 00-8206. This material is based upon work supported by the U.S. Department of Energy, Division of Materials Sciences under Award No. DEFG02-91ER45439, through the Frederick Seitz Materials Research Laboratory at the University of Illinois at Urbana-Champaign. Research for this publication was carried out in the Center for Microanalysis of Materials, University of Illinois at Urbana-Champaign, which is partially supported by the U.S. Department of Energy under Award No. DEFG02-91-ER45439.

PS1-38 511CF

FREQUENCY TUNING OF VIBRATING MICRO-ELECTRO-MECHANICAL RESONATORS AND FILTERS VIA LASER TRIMMING

M. ABDELMONEUM*[1] and C. NGUYEN[2], [1]Radiation Laboratory, University of Michigan Ann Arbor, [2]DARPA.
Corresponding e-mail: mabdel@eecs.umich.edu

Location dependent laser trimming of the resonance frequencies of micro-scale clamped-clamped beam (CC-beam) and disk vibrating mechanical resonators has been demonstrated in steps ranging from 22 ppm to 28,400pm, with targeting measures that suppress the Q and motional resistance variations. In particular, geometrically symmetrical laser targeting is instrumental in preserving the resonator's high Q, where it is commonly a non-issue for macroscopic vibrating resonators. A semi-empirical model has also been developed that identifies the locations best targeted for laser trimming for a desired shift in frequency.

Among previous approaches to frequency tuning of MEMS resonators and filters, voltage tuning via DC-bias-dependent electrical stiffnesses [1] has been the most common method used to date. However, DC-bias tuning has several drawbacks, including the need for extra interconnect pads, as well as its impact on motional resistance entailing complex trimming process. Hence, a less intrusive tuning method is desirable, such as laser trimming. Although laser trimming has been previously used for precise tuning of macro scale (order of mm to cm) metal resonators [2], it is less useful for trimming their micro-scale renditions, since the stress distributions generated by laser trimming are more debilitating at the micro-scale.

This work solves this problem by strategically targeting laser trims to not only achieve a desired frequency shift, but to also cancel Q-limiting stress distributions. At the center of a CC-beam, negative frequency drift steps as low as -22 ppm are observed. By moving the location of the trimming point off center, the magnitude of the frequency shift increases gradually till a maximum drift of -28,400 ppm is achieved at topography lines above the sense electrode running under the beam. Beyond this point the frequency shift turns positive, meaning that either upward or downward frequency trims are achievable. Unfortunately, unlike larger mm size resonators [2], moving the trimming point off center of a micro-scale resonator reduces its Q by about 25%. Here, the off center laser pulse disturbs the stress distribution along the beam and so increases the beam internal losses, reducing its overall Q. To create a balanced stress distribution, the next trimming point is selected to be at a mirror symmetric location to that of the previous off center point. Doing so, the resonator restores its original Q value with minimum change in device motional resistance.

The model predicting the degree of frequency shift for a given trim location on a CC-beam resonator makes use of a location-dependent effective mass trimming coefficient. Using this model, a two-CC-beam resonator filter has been trimmed to a flat passband using only three laser pulses on the output resonator: one at the beam center, and two symmetric pulses at topography lines, to maximize the frequency shift with minimum Q loss.

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PS1-39 511DE

MECHANICALLY-COUPLED MICROMECHANICAL RESONATOR ARRAYS FOR IMPROVED PHASE NOISE

S. LEE* and C. T.-C. NGUYEN, University of Michigan.
Corresponding e-mail: seungbae@umich.edu

Reductions in phase noise by more than 26 dB have been obtained over previous micromechanical resonator oscillators by replacing the single resonator normally used in such oscillators with a mechanically-coupled array of them [1] to effectively raise the power handling ability of the frequency selective tank by a factor equal to the number of resonators used in the array, and all with virtually no increase in volume or cost, given that all resonators are integrated onto a single die using batch processed MEMS technology. Specifically, a mechanically-coupled array of ten 15.4-MHz 40μmx10μmx2μm free-free beams embedded in a positive feedback loop with a single-ended to differential transimpedance sustaining amplifier achieves phase noises of -109 and -133 dBc/Hz at 1 kHz and far-from-carrier offset frequencies, respectively. When divided down to 10-MHz, these effectively correspond to -112 and -136 dBc/Hz, respectively, which represent more than 17 and 26 dB improvements over recently published work [2]. Unlike bulk quartz crystal oscillators, the phase noise performance of oscillators reference to micro-scale mechanical resonators at close-to-carrier offset frequencies is mainly limited by a combination of the electrical (i.e., capacitively-transduced) and mechanical (i.e., spring-softening [3]) nonlinearities of the micromechanical resonator, rather than by the sustaining electronic device. A direct consequence of this is a $1/f^3$ noise that depends greatly on the resonators deflection amplitude *x*, according to modeling of this phenomenon (to be detailed in the full paper), which predicts that phase noise can be reduced by minimizing the deflection amplitude while maximizing output power. The use of an array of resonators with combined outputs does just this by allowing each resonator to move a smaller amount while still sourcing a substantial combined output. Mechanical coupling of this array insures that all resonators vibrate at exactly the same frequency. The measured frequency spectra of fabricated one-, three-, ten- and hundred-free-free beam resonators show peak values that increase with the number of resonators, as expected, to the point of reducing the overall motional resistance by more than 14X. There is some reduction in Q, from 6,800 to 2,432, for the 100-resonator mechanically-coupled array, but this final Q is still enough for good close-to-carrier performance, and attaining higher power output with small amplitude is presently the more important goal. In particular, the ability of the 100-resonator array to avoid amplitudes past the critical Duffing [3] nonlinear amplitude allows it to attain much better close-to-carrier phase noise (by more than 10 dB) than its 10-resonator counterpart, whose resonators must vibrate at amplitudes larger than the critical point to attain the same far-from-carrier phase noise.

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This work was supported under DARPA Cooperative Agreement No. F30602-01-1-0573.

PS1-40 511DE

DIRECT MOUNTING OF QUARTZ CRYSTAL ON A CMOS PLL CHIP

H. KIM*[1], J. LIM[2], K. CHOI[2], D. KENNY[3], and T. JACKSON[1], [1]Department of Electrical Engineering, The Pennsylvania State University, [2]Department of Computer Science & Engineering, The Pennsylvania State University, [3]Saronix East Development Center.
Corresponding e-mail: hskim@psu.edu

Motivated by the current demand for potable wireless devices, we are attempting to reduce the size of frequency reference source by directly mounting a quartz crystal on a CMOS PLL chip. This paper presents the experiment and its results.

The approach of direct mounting of quartz crystal on a CMOS PLL chip provides number of advantages and challenges. The advantages are:

1. Compact form factor, no separate crystal packaging needed 2. Less stray effects, less power, and less cost due to close mounting of crystal on chip

The challenges are:

1. Crystal mounting affects resonant frequency 2. On-chip digital noise affects resonant frequency 2. On-chip temperature affects resonant frequency 3. Capping of crystal on chip

We have fabricated two PLL prototype chips including the on-chip oscillator circuits and mounted the 155.52 MHz AT-cut mesa quartz crystals on them. The quartz crystals are mounted with conductive epoxy on the chip surface bonding-pad and epoxy is cured in a vacuum oven at 160 °C for 40 minutes. The chip sizes are designed slightly larger than quartz crystal resonator so that whole quartz crystal resonator is located within the perimeter of the chips. The largest chip size is 1.85 mm by 3.7 mm, however, the actual oscillator and PLL circuits occupy only about 10% of total chip area.

We achieved successful mounting and chip designs. The on-chip oscillator generates 155.52 MHz frequency signal without difficulty. We measured 2.98ps RMS jitter over 12 KHz to 20MHz bandwidth and 3.34ps RMS jitter over 10 Hz to 10MHz bandwidth. The SSB phase noise at 10Hz is 65 dBc/Hz, at 10 KHz is 123 dBc/Hz, and at 10MHz is 149 dBc/Hz.

The on-chip PLL uses 8KHz reference frequency to lock 19.44 MHz VCXO output. The PLL circuit consists of frequency divider, frequency comparator, and Opamp. Digital frequency divider and comparator generate on-chip noise that affects the oscillator noise characteristic. We measured 13 ps RMS jitter when the PLL circuit is in operation.

The measurements of various other aspects are currently being carried out and the design improvements are being developed.

This work was supported in part by Pittsburgh Dightal Greenhouse and Saronix

PS1-41 511CF

LARGE ENHANCEMENT OF CPT SIGNALS IN FREQUENCY STANDARDS

Y.-Y. JAU*[1], E. MIRON[2], A. POST[1], N. KUZMA[1], and W. HAPPER[1], [1]Princeton University, [2]NRCN.
Corresponding e-mail: yjau@Princeton.EDU

Coherent population trapping (CPT) spectroscopy has become a useful technique for probing atomic hyperfine resonances. The CPT signal is an on-resonance transmission peak observed when a modulated probing beam is passing through an alkali-metal vapor cell. The CPT - based frequency standards lock the local oscillators to the hyperfine frequency by tuning the oscillator frequency to the CPT resonance. The precision of atomic clocks is proportional to

the linewidth divided by the signal-to-noise ratio (SNR). The conventional CPT clocks have low SNR especially for miniature vapor cells or for higher buffer gas pressure. We have developed a method to improve the CPT signal by 1 to 2 orders of magnitude at the same noise level. We believe that this new method will greatly enhance the implementation of CPT in frequency standards. The results of experimental measurements and theoretical calculations will be presented.
Prof. Michael Romalis

PS1-42 511CF

FREQUENCY TRANSFER OF OPTICAL STANDARDS THROUGH A FIBER NETWORK USING 1550-NM MODE-LOCKED SOURCES

K. HOLMAN*, D. JONES, and J. YE, JILA, NIST and University of Colorado.
Corresponding e-mail: kevin.holman@colorado.edu

With the advent of optical atomic clocks and the associated superior short-term frequency stability, transfer of signals linked to such clock/frequency standards over an appreciable distance with minimal loss of stability has become an important research subject. Using femtosecond frequency combs produced by mode-locked lasers for this purpose allows simultaneous transfer of optical and radio frequency (RF) signals, both phase locked to the optical frequency standard. Optical transfer is realized by detecting the absolute positions of the transferred comb lines, whereas RF transfer is achieved by simply using a fast photodiode to detect the repetition frequency of the transferred laser pulses. The phase coherence of a mode-locked Ti:sapphire laser linked to an optical standard has been transferred to a 1550-nm mode-locked source, which is necessary for distribution over optical fiber networks. We have studied the transfer instability for such a 1550-nm source over a fiber network.

Of course RF signals can be transferred via direct amplitude modulation on an optical carrier. The approach we have taken in this work utilizes a phase stabilized 1550-nm mode-locked laser source for simultaneous distribution of optical and radio frequency standards over a 7-km installed fiber network. The transfer instability for the repetition rate of a 1550-nm mode-locked fiber laser is determined by comparing the pulse rate detected after transmission through a roundtrip of a fiber network with that of the pulses before transmission. To minimize the detection instability, it is critical to minimize the light power incident on the photodetector while maintaining a sufficient signal-to-noise ratio (*SNR*). The stretching of the pulses caused by the fiber dispersion decreases the *SNR* of the detected harmonic. By minimizing the pulse spectral bandwidth, the amount of stretching is reduced, maintaining a sufficient *SNR* without needing to greatly increase the incident light power on the detector. The measured instability is the same as that for optical-carrier transfer over the fiber network, and is nearly an order of magnitude better than that for RF transfer through modulation on an optical carrier, as summarized in the table below.

A natural extension of this work in the time domain is to determine the rms timing jitter introduced during the transfer process. This will be an important step towards exploration of tight synchronization of remotely located pulsed lasers and radio frequency sources. We have also begun investigating optical transfer of frequency standards using mode-locked pulse trains. Preliminary results indicate there is no difference between cw and mode-locked schemes when measured locally. However, due to time gating and other effects we expect mode-locked pulses could offer a significant advantage over long transmission distances. We will present further work on these topics as well as implementation of stabilization loops for both microwave and optical frequency transfer using mode-locked sources.

Instability for RF Transfer

RF Source	1-second Allan Deviation
modulated cw	2e-13
cw optical transfer	2.6e-14
mode-locked fiber laser	2.6e-14

The current address for D. Jones is Dept. of Physics and Astronomy, University of British Columbia, Vancouver, B.C. V6T 1Z1 Canada. Funding for this work is supported by ONR, NASA, NIST, and NSF. K. Holman is a Fannie and John Hertz Foundation graduate fellow.

PS1-43 511DE

A MULTI-RESONANCE ACOUSTIC INTERFACIAL BIOSENSOR (MAIB) FOR MONITORING A FORMATION PROCESS OF BIOLOGICAL THIN FILMS

S. J. KWOUN* and R. M. LEC, School of Biomedical Engineering, Science and Health System, Drexel University.
Corresponding e-mail: sunkwoun@biomed.drexel.edu

Interfacial phenomena in biological processes have been of growing interest in the last decade. In particular, biological thin films and their formation processes have become increasingly important. Biological thin films play significant role in development of biosensors where they provide selective interfaces for detection of various biochemical analytes. Other applications biological thin films find in biotechnology, waste water treatment systems, the food industry, and medical area. In this work, a thickness-shear mode multi-resonance acoustic interfacial biosensor (MAIB) is proposed to study the deposition processes of thin film of collagen and albumin. These two materials form two different types of overlayers. Collagen forms anisotropic and polycrystalline thin films, and albumin forms amorphous films. The whole deposition processes including initial liquid stage to final solid thin film stage were investigated. The theoretical analysis of MAIB has been developed to model the sensor response. When acoustic shear wave (ASW) is excited into liquid media it does not propagate but rather penetrates over a relatively short distance. The penetration depth is function of viscoelastic properties of the film and the frequency of acoustic wave. The responses of the MAIB depended on interfacial processes and could be related to biological, chemical, and physical phenomena. Such processes as interfacial mass accumulation or changes in elastic and lossy modulus were measured and monitored

in real time using MAIB. The MAIB responses (or signatures) were obtained at the fundamental, 3rd, 5th, and 7th harmonic resonant frequencies (10, 30, 50 and 70 MHz). As a result, the viscoelastic properties of thin films at the different distances from the surface of the MAIB were measured. The changes in the MAIB resonant frequencies and attenuation were monitored during the deposition processes and compared with the theoretical results. Interestingly, the harmonic responses of MAIB were different, which indicated the processes of non-uniform spatial processes during the film formation. Also, the MAIB responses showed qualitatively different signatures for collagen and albumin thin films. Finally, the responses of MAIB were compared with images obtained with optical microscope, SEM, and AFM in order to correlate macroscopic MAIB data with microscopic structures and morphological features of thin films. In conclusion, a multi-resonance acoustic interfacial biosensor (MAIB) has exhibited an attractive measurement features for study the kinetics of biological thin film formation processes in real time with high sensitivity and high temporal resolution.
This study has been performed with the support of the NSF under the grant No. 0242662.

PS1-44 D10

SAW SENSORS USING ORTHOGONAL FREQUENCY CODING

D. PUCCIO*[1], D. C. MALOCHA[1], D. GALLAGHER[1], and J. H. HINES[2], [1]ECE Dept., University of Central Florida, [2]Microsensor Systems, Inc.
Corresponding e-mail: dcm@ece.engr.ucf.edu

The SAW sensor offers advantages in that it is wireless, passive, small and has varying embodiments for varying sensor applications. In addition, there are various ways of encoding the sensed data information for retrieval. Single sensor systems can typically use a single carrier frequency and a simple device embodiment, since tagging is not required. In a multi-sensor environment, it is necessary to both identify the sensor as well as obtain the sensor information. The SAW sensor then becomes both a sensor and a tag. For multi-sensor systems, many embodiments use coded reflectors having a single carrier frequency. Previous work by several authors have shown that there are advantages of using spread spectrum techniques for device interrogation and coding, such as enhanced processing gain and greater interrogation power. This paper will present a spread spectrum approach using orthogonal frequency coding (OFC) for encoding the SAW sensor. The encoding technique is similar to M-ary FSK in terms of its implementation where a transducer or reflector is built with the desired code. A second level of coding using a PN sequence can also be employed. The processing gain offered by spread spectrum increases the range of the system and codes are designed to reduce cross correlation for environments where multiple sensors are employed. In addition, it is shown that the time ambiguity in the autocorrelation due to the OFC is significantly reduced as compared to a single frequency tag having the same code length. The OFC approach is general and should be applicable to many differing SAW sensors for temperature,

pressure, liquids, gases, etc. Device embodiments are shown, and a discussion is provided for device design considerations such as the number of chips used, chip length, transducer fractional bandwidth, and chosen piezoelectric material. Measured device results are presented and compared with COM model predictions to demonstrate performance. Devices are then used in computer simulations of multiple transceiver designs and the results are discussed.

PS1-45 D11

TECHNIQUES TO EVALUATE THE MASS SENSITIVITY OF LOVE MODE SURFACE ACOUSTIC WAVE BIOSENSORS

L. A. FRANCIS*[1,2], J.-M. FRIEDT[3], R. DE PALMA[2,4], C. ZHOU[2,4], C. BARTIC[2], P. BERTRAND[1], and A. CAMPITELLI[2], [1]Unité de Physico-Chimie et de Physique des Matériaux, Université catholique de Louvain, [2]Biosensors Group, IMEC, [3]Laboratoire de Microanalyses Nucléaires, Université de Franche-Comté, [4]Department of Chemistry, Physical and Analytical Chemistry, Katholiek Universiteit Leuven.
Corresponding e-mail: francisl@imec.be

With a shear horizontal polarization and a high mass sensitivity, Love mode surface acoustic wave (SAW) biosensors detect and quantify in real-time chemical species sustained in liquid environments. The Love mode is a guided acoustic mode generated in single or multiple layer coatings on a piezoelectric substrate. Love mode biosensors can be tailored in order to achieve desired parameters from both the electrical and sensing points of view. To this end, the fine tuning of these parameters requires a set of proper methods to investigate experimentally the sensing properties and link them with theoretical models that take into account the material characteristics as well as instrumentation and physical effects occurring in the device during a biorecognition experiment.

In this paper, we investigate two experimental approaches that can be used to evaluate the mass sensitivity of Love mode SAW biosensors. The first approach is based on the analysis of the dispersion curve of the sensor, which helps to determine, either by simulation or derivation, the value of the mass sensitivity. In order to obtain the dispersion curve, we have performed a chemical wet etching procedure that enables the continuous monitoring of the transfer function during the etching of the entire guiding layer.

The second approach is based on the addition or removal of layers in known quantities. The mass sensitivity is estimated in different cases: etching of a thin gold layer, copper electrodeposition, surface adsorption of an ionic surfactant or of a biochemical layer.

The results obtained by these techniques are compared to each other and to a theoretical model.

In the theoretical model, the layered structure of the acoustic sensor is described in terms of mechanical transmission lines and the mass sensitivity is calculated using the dispersion relation and the phase and group velocities. The model takes into account the design of the device, the influence of a liquid cell and the parasitic effects linked to the instrumentation. From this model, we extract the theoretical mass sensitivity of a multilayered system.

Future improvements of the model will address Love mode SAW biosensors with piezoelectric, semiconducting or porous guiding layers.

L. Francis thanks the FRIA (Fonds de Formation à la Recherche dans lIndustrie et dans lAgriculture) for its financial support.

Session: P1FC-A
OSCILLATORS AND RESONATORS
Chair: M. Driscoll
Northrop Grumman, USA

P1FC-A-1 M1

THERMO-ACOUSTIC EXCITATION OF MEMS

J. M. PARPIA*, M. ZALALUTDINOV, K. L. AUBIN, R. REICHENBACH, and H. G. CRAIGHEAD, Cornell University.
Corresponding e-mail: jmp9@cornell.edu

We demonstrate that radio-frequency micromechanical resonators can be actuated using a thermo-acoustic drive mechanism. This drive can be effected by a focused laser beam or by means of a microfabricated resistive element in proximity to the MEMS resonator. The drive mechanism exhibits a number of interesting phenomena including self resonance and injection-locking. Injection locking can be acheived by the application of a pilot signal from a synthesiser. The self oscillaing signal can also be "entrained" by closing a feedback loop in which the resonant output of the oscillator is amplified, phase-shifted and fed back as a pilot signal to entrain and stabilize the oscillator. Once injection-locked or "entrained", the pilot signal can be swept over a range that is as wide as 4% of the natural frequency of the resonator. The signal also exhibits excellent frequency stability in its phase-locked loop mode.

P1FC-A-2 M11

THE MICROCOMPUTER COMPENSATED CRYSTAL OSCILLATOR—PRACTICAL APPLICATION OF DUAL-HARMONIC MODE QUARTZ THERMOMETRY

E. JACKSON*, Q-Tech Corporation.
Corresponding e-mail: edward.jackson@q-tech.com

A precision frequency sourced based on dual harmonic mode quartz thermometry - Q-Tech's Microcomputer Compensated Crystal Oscillator ('MCXO') - is described. System architecture, thermometry, compensation method and detailed environmental and long-term performance characteristics are presented. Problems arising from the need to employ frequency synthesis and discrete-time

compensation are addressed. Test results indicate that an initial frequency-temperature accuracy of 1E-8 over a temperature range of -50 to $+85$ deg C, at less than 100 mW power consumption is readily achievable, but that long-term stability depends upon unique resonator Aging characteristics that have not been previously characterized for precision clocks. Dependence of long-term stability on differential aging rate between resonator harmonic modes is developed.

P1FC-A-3 M12

NEW ANALYSIS ON PUSH-PUSH FET OSCILLATORS FOR OUTPUT POWER IMPROVEMENT

J. KWON* and I. S. KIM, KyungHee University.
Corresponding e-mail: ihnkim@khu.ac.kr

This paper newly analyzes conventional Push-Push FET oscillator circuits for output power improvement. We have discovered two circuit problems existed in the conventional Push-Push FET oscillators. So, the two problems will be first introduced for output power improvement. The first problem is in resonator-coupled circuits at the gate port, and the second, such as power combiner and RF power compensation circuit, in output circuits at the drain port. As a result, the problems will be theoretically analyzed including different characteristics of two active devices and isolation property of power combiners. After we investigate the circuit problems analytically on the conventional Push-Push FET oscillators, we suggest a new design method for improving output power level.

P1FC-A-4 M13

LOW-VOLTAGE SURFACE TRANSVERSE WAVE OSCILLATORS FOR THE NEXT GENERATION CMOS TECHNOLOGY

I. D. AVRAMOV*, Institute of Solid State Physics.
Corresponding e-mail: iavramov@pronto.phys.bas.bg

One of the most challenging requirements to next generation CMOS technology is the low-supply voltage, which allows lower overall power consumption and heat dissipation at an increased integration scale on a unity chip area. The current 3.3 V supply voltage standard is expected to be reduced to 2.5, 1.8 and 1.2V in the near future. If such low-voltage CMOS circuits are driven by clock oscillators operating at higher supply voltages, then integrated level shifters are necessary to provide the required clock level. At high clock frequencies, such devices are fairly noisy and generally degrade the phase jitter of a low-noise clock oscillator. As shown in this work, for clock frequencies above 400 MHz, this problem can be solved by implementing low-noise SAW based microwave frequency clocks operating on the same supply voltage as the CMOS circuitry and driving ASIC core directly to eliminate level shifters and improve overall

system noise. This paper presents the design and performance of surface transverse wave (STW) based voltage controlled oscillators (VCSO) in the lower GHz frequency range, operating on very low supply and tuning voltages, and suitable for direct interfacing with the next generation CMOS circuits. The main goal in this design effort is to provide an oscillator whose output is switched between 0V and the supply voltage V_s and to maximize the output level for safe CMOS-circuit switching while keeping the RF/DC efficiency to a maximum for low DC power consumption. This is achieved by operating the active oscillator circuit in one of the switched nonlinear classes that are well known for their high power and efficiency, and low phase noise. The investigated 1.0 and 2.5 GHz VCSO are varactor tuned feedback-loop oscillators stabilized with two-port STW resonators. Each VCSO has a DC coupled high-impedance switched output to drive the CMOS circuit directly, and an additional sinusoidal 50 $\Omega\#$ output for other system applications. First preliminary results are summarized in the Table below. As shown by the 1 GHz data, by using an appropriate duty cycle and subsequent output matching to the sustaining amplifier, the switched VCSO output can provide a peak-to-peak level V_{opp} even higher than the supply voltage. This "buck-boost" effect, often used in dc-dc converters, was successfully applied in this study too to make a lower-voltage VCSO compatible with even higher-voltage CMOS circuitry. Phase noise levels as low as -115 dBc/Hz and -105 dBc/Hz at 1 KHz carrier offset have been achieved at 1 GHz and 2.5 GHz, respectively, when the varactors were replaced with fixed capacitors to eliminate varactor noise. These results were obtained at 2.5 V supply voltage and indicate the great potential for designing low-phase-noise STW oscillators operating on low supply voltages. Current optimization efforts are directed towards further phase noise and efficiency improvement in the 2.5 GHz VCSO at 1.2 and 1.8V. The final results will be presented in the full paper.

Performance of low-supply-voltage STW based VCSO

1 GHz VCSO / V_s	**1.2 V**	**1.8 V**	**2.5 V**	**3.3 V**
Output power (50 $\Omega\#$ load)	6 dBm	9.6 dBm	12.5 dBm	14.7 dBm
RF/DC efficiency	21.5%	25.3%	27.2%	29.3%
Phase noise (1 KHz carrier offset)	-103 dBc/Hz	-108 dBc/Hz	-112 dBc/Hz	-115 dBc/Hz
V_{opp}/V_s	1.05	1.06	1.06	1.04
Tuning range (0 ... $+V_s$)	165 ppm	230 ppm	280 ppm	300 ppm
2.5 GHz VCSO / V_s	**1.2 V**	**1.8 V**	**2.5 V**	**3.3 V**
Output power (50 Ω load)	2 dBm	4.7 dBm	8.3 dBm	11 dBm
Phase noise (1 KHz carrier offset)	-97 dBc/Hz	-95 dBc/Hz	-98 dBc/Hz	-102 dBc/Hz
Tuning range (0 ... $+V_s$)	100 ppm	145 ppm	200 ppm	240 ppm
V_{opp}/V_s	0.79	0.6	0.66	0.68
RF/DC efficiency	7.3%	11%	12%	12%

The author wishes to gratefully acknowledge George Maronich from Q-Tech Corporation and Tom Hardy from VC America for encouraging this work and for the most helpful discussions.

P1FC-A-5 N13

SMALL PACKAGED VCSO FOR 10[GBIT] ETHERNET APPLICATION

N. NOMURA*, M. ITAGAKI, and Y. AOYAGI, Toyo Communication Equipment Co., Ltd.
Corresponding e-mail: n-nomura@toyocom.co.jp

Information communication infrastructure has increased the needs for broadband. In order to meet those needs, the products for 10[Gbit] Ethernet application have been introduced to the market. The proliferation of Ethernet service, which offers lower cost and wider bandwidth in comparison with a leased line, enabled enormous amounts of high speed data. However, such kind of data transfers with large capacity and high speed demands tight specifications for an oscillator used as a frequency generator. In the case of 10[Gbit] Ethernet, the clock generator needs an oscillation frequency of 600MHz bandwidth. Also, the oscillator requires low jitter to transfer large capacity of information without errors. The jitter value is obtained by multiplying a frequency by the jitter. Therefore, as the frequency goes up, the requirements for jitter become all the more severe. In addition, frequency control range of the oscillator must synchronize with the received signal or another high-speed clock. To sum up, an important factor for the oscillator used for 10[Gbit] Ethernet application is high frequency, wide pulling range, and excellent jitter. A VCSO is an oscillator using SAW resonator. Since it has a wide pulling range and direct oscillation, it has excellent jitter performance at high frequency. Therefore, a VCSO is one of the products suitable as an oscillator for the 10[Gbit] Ethernet application. However, the VCSO that is currently available on the market is generally a delay line type using a SAW filter. Although such kind of delay line type VCSO offers a wide frequency control range, the linearity and short-term frequency stability are not very good in comparison with a VCXO. This is the problem, to use a VCSO for a 10[Gbit] Ethernet application. In order to solve this problem, we built a small packaged, 7x5mm, 622.08MHz VCSO with a SAW resonator using high density surface mount technology. As a result of our study, we confirmed that our VCSO could offer the same level of good linearity, wide pull range, and excellent short-term frequency stability as a VCXO, while providing excellent jitter performance.

P1FC-A-6 N12

NEW SUB ONE INCH ULTRA STABLE OSCILLATOR

L. COUTELEAU*, TEMEX.
Corresponding e-mail: laurent.couteleau@temex.fr

With its unique combination of : - small size - good stability in time domain (log term and short term) - good environmental sensitivities Ultra Stable Oscillator (USO) is one of the most important component in electronic communication

systems. TEMEX has developed a new generation of high stability and very compact OCXO (Package style 1 x 1 x 0.6)especially designed for CDMA and UMTS applications. Constant progress in thermal regulation have allowed us to overcome the heigh of 1 inch. The temperature of this tiny USO is stabilized by mounting the complete oscillator in a complex block that is temperature-controlled by a proportional heater achieving a thermal stability better than ± 1. 10-10 from 20°C to + 70°C. To achieve a high better than one inch the complete USO assembly is significantly smaller than an arrangement of separated packaged components. This assembly minimize the number of interfaces and connections. It can also offer premium performance due to the complete control of all critical components and integrating and matching functions. In particular control voltage can be access by standard numeric bus. Efficient linearization techniques provides linearity better than 5%. The major concern of synthesizer designers is the phase stability because an oscillators phase noise output may set the systems limits for dynamic range and reception sensitivity. By optimizing oscillator topology and component choice TEMEX USOs phase noise achieve limit performances of technology : - 80 dBc @ 0.1 Hz - 110dBc @ 1 Hz - 140dBc @ 10 Hz - 150dBc @ 100 Hz - 155dBc @ 1kHz The main characteristics at 10 MHz of this QEODO75 family and how to achieve them are discussed in this paper

P1FC-A-7 N11

A NEW SMALL-DIMENSIONS FULL PLL SYSTEM

Y. VOROKHOVSKY*, G. GIDON, and A. DOBROVOLSKY, Morion, Inc.
Corresponding e-mail: yakov@morion.com.ru

During last years super low-noise high-frequency oscillators have got more and more applications in a number of new systems such as high-resolutions radars, receivers, synthesizers and so on. This kind of HF OCXO usually has low temperature and long-term stability. Higher stability may be achieved in phase locked loop system (PLL) using low-frequency precision oscillator as a reference. Such system usually has big sizes and high power consumption. One of the ways to solve this problem is to use combined oven for both of OCXOs. But then some problems because of different temperature level and stability required for both OCXOs have appeared. One more problem is to save low noise floor of HF OCXO in close presence of another OCXO. During last year the design of such small size full PLL system including both OCXOs was made using a special calculation to minimize temperature gradients in a reference crystal in a presence of high-frequency crystal. The optimized topology in a planar-designed system allows saving a noise floor of HF OCXO.

The achieved main parameters of PLL OCXO model described above are:

Frequency	100 MHz
Noise floor	-165-170 dBc
Frequency stability vs.	
temperature range	40+70°C +5·10-10
Long-term stability	+5·10-8/year
Power consumption (steady state)	<2.5 W
Dimensions	50.8·50.8·16 mm

P1FC-A-8 N10

HIGH FACTOR FREQUENCY MULTIPLICATION IN 2.4 GHZ VCXO

D. V. BOGOMOLOV*, Valpey Fisher Corporation.
Corresponding e-mail: dbogomolov@valpeyfisher.com

The voltage control oscillators (VCO) with 2488.3 $\pm$0.25 MHz operating frequency band are intended to be used in SONET OC768 optical networks. 40 Gbps data rate allows to put into practice a new generation of digital data applications (video-on-demand, video conferencing and etc). The reference signals are needed for multi sequencing of the whole stream at 16 cannels with a slower rate. The frequency of VCO is synchronized with data rate in each channel by PLL. Low phase Jitter and low sub-harmonics level of the reference signals are the necessary conditions for the minimization of an bit error rate. Communication standards have the limits for those parameters: 4 ps for phase jitter and 45 dBc for sub-harmonics level . Large quantity of channels requires a minimization of the VCO price. The estimation shows that voltage control crystal oscillator (VCXO) with frequency multiplication technique meets the requirements of SONET OC768. Moreover, 2.4 GHz VCXO holds advantages in frequency temperature stability and calibration tolerance. The oscillator stage is Pierce circuit with A-cut 150200 MHz fundamental crystal. This source has the phase noise spectral density less than 95 dBc/Hz at 100 Hz offset. It is sufficient to obtain 70 dBc/Hz at 100 Hz value for 2.48GHz signal (equivalent to 4ps phase jitter), since phase noise degradation due to frequency multiplication is less than 22 dB. The regenerative amplifier is applied to realize a high factor frequency multiplication. The operation of BJT stage near to the stability threshold provides this sub-harmonic suppuration up to 17 dBc. That technique permits to avoid using expensive SAW filters. IC buffer fulfills enable/disable function and forms PECL output signals. The oscillator has frequency pullability of $\pm$100 ppm in the control voltage range of 1.65V $\pm$ 1.5V. The device is packaged in FR-5 based SMD 20 x 18.5 x 3.6 mm3 case.
Valpey Fisher Corp.

P1FC-A-9 N9

AN ANALYTIC APPROACH USED TO DESIGN A LOW POWER AND LOW PHASE NOISE CMOS LC OSCILLATOR

R. DEHGHANI*, Sharif University of Technology.
Corresponding e-mail: rasoul_dehghani@yahoo.com

An analytic method is presented to predict the oscillation amplitude and supply current values of a differential CMOS oscillator. This method enables a designer to get insight about main circuit parameters affecting amplitude and drawn supply current by which he or she can design an optimized CMOS LC oscillator in

terms of minimum phase noise and low power consumption. High frequency oscillators design procedure based on this approach is a systematic and timesaving one. The validity of method has been verified by designing an LC CMOS oscillator in a 0.25μm mixed-mode CMOS technology at the frequency of 2.5GHz. Ready-made on-chip inductors of TSMC process are used as inductors and RF NMOS transistors in strong inversion mode are exploited as varactors. The results obtained from analytical expression are in good agreement with simulation results over a rather wide range of supply voltage from 1.5 to 2.5V. In order to compare the performance of the designed oscillator with the recently reported results we adopt a figure of merit defined in [7] as follows:

$FOM = S_{SSB} + 10\log_{10}[(f_m/f_0)^2 P_{VCO}/m W]$

where S_{SSB} is the single side band phase noise, f_m and f_0 are offset and carrier frequencies, respectively, and P_{VCO} is the VCO power dissipation. In the following Table , some recently published VCOs are listed. As can be found, this work has the best performance due to the optimized design using the analytic relations for the oscillator amplitude and power consumption.

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Comparison of performance for different fully integrated VCOs

VCO	Tech. [μm]	Power [mW]	Phase Noise [dBc/Hz]@3MHz	Oscillation frequency [GHz]	FOM [dBc/Hz]
[8]	0.7	6	-130	1.8	-177.8
[9]	0.25	24	-132	1.8	-174.1
[10]	0.8	66	-132	1.24	-171.1
[11]	0.25	32.4	-141	1.8	-181.5
[7]	0.25	20	-143	1.8	-185.5
This work	0.25	5.8	-134.6	2.5	-186.5

Author would like to thank the IMRC for its financial support.

P1FC-A-10 M2

DUAL MODE SC-CUT CRYSTAL OSCILLATOR

T. OITA*, M. FUKUDA, A. NAKAMURA, T. ISHIKAWA, and K. ONO, Nihon Dempa Kogyo Co., Ltd.
Corresponding e-mail: oita@ndk.com

This paper present the dual mode oscillation circuit of the 5MHz 3rd overtone SC-cut Crystal eliminated seesaw effect. The oscillation circuit is combined with the wide frequency range phase linear crystal filters and differential amplifiers for each C and B-Mode signal filtering. These two filters input nodes are connected to the SC-cut Crystal directly, and the output nodes are connected to each differential pre-amplifier for the phase composition without any LC components. The phase variations of the oscillation circuits are less than three degrees at the range of ±10kHz from each mode's center frequency. This made the successful result to eliminate the influence for oscillation by the other mode signals to each other. It applies the wide temperature range dual mode oscillation from -40°C to +90°C without any seesaw effects by using smooth temperature coefficients of the B-mode. After the C-mode filter and amplified C-Mode signal, it is extracted not only for the frequency reference source to the outside, but also for the time reference of the frequency counter of the temperature controller. The beat frequency of the C and B-Mode is extracted from the common feed back loop line of the dual mode oscillator as the temperature information. This can eliminate the mixer circuit of the C and B mode signal additionally. The paper also describes the temperature control experiment's results. A PLD (Programmable Logic Device), an 8bit CPU, a PLL VCO, and an analog amplifier are used to regulate for the high-resolution temperature control. The random PWM (Pulse Width Modulation) algorithm is installed in the software for the temperature regulation to reduce the peaky noise, which equals as a 19bits D/A converter. A very thin disk type ceramic heater is used as the thermal source. The AlN sheet grew to get the high thermal conductivity attaches the disk heater to the SC-Cut crystal. The power transistor to drive the heater is thermally connected to the SC-cut crystal to reduce the power consumption. The oscillator PCB with the heater-assembly was packaged as the module construction. The module and the motherboard were assembled in two inches cubic metal package.

Over the temperature range of -20°C to +70°C, the temperature of the SC-cut crystal was locked within ±0.002°C converted from the beat frequency, and the power consumption at supply voltage of 12V, was less than 2.6W at 25°C in still air.

P1FC-A-11 M3

MINIATURISED OCXO: PROFESSIONAL COMPONENT FOR SPACE APPLICATIONS

P. GUILLEMOT*[1], A. MORIN[2], and G. RICHARD[2], [1]CNES (French Space Agency), [2]THALES Microeletronics.
Corresponding e-mail: philippe.guillemot@cnes.fr

For a few years, THALES and CNES have been developing new miniaturised OCXOs, a "micro-OCXO" and a "mini-OCXO Light Version" (respectively referenced EWOS 513 and EWOS 810), for space applications based on professional components instead of space qualified ones. Because standard space qualification rules cannot be used with such components, we have had to develop a new method to evaluate their ability to fulfil space missions. The method we

have retained derives from the "increased test", that is to say praticaly up to the breaking point. First EWOS 513 units using this process should fly with the ROSETTA mission now scheduled by February 2004 whereas last endurance tests under irradiations conditions are running on EWOS 810. This paper first describes the aggravated tests approach and how it has been applied to miniaturised OCXO. Then specifications and typical OCXOs performances are given, under conditions such as thermal vacuum, magnetic field or irradiations.

P1FC-A-12 M4

A NEW LOW PROFILE DOCXO

Y. VOROKHOVSKY*, S. ANASTASYEV, and A. VOLKOV, Morion, Inc.
Corresponding e-mail: yakov@morion.com.ru

Two years ago Morion, Inc. introduced its first DOCXO model. Since that time Morion have produced more than 15000 of such DOCXOs mainly for CDMA application. Now we introduce the new DOCXO design having much lower height.

Generally the height reduction of the oscillators case decreases thermal resistance between frequency depending components of the oscillator and ambient. This factor causes degradation of the frequency vs. temperature characteristics of the oscillator. In the new DOCXO temperature stability is achieved by increase of thermal gain of the two-stage oven, decrease of thermal gradients in outer ovens case, and use of some elements, which decrease the thermal link between inner and outer ovens. The major technical characteristics of this DOCXO are:

Standard frequencies

4.096; 5.0; 8.192; 10.0; 12.288; 15.0; 16.384; 20.0 MHz	
Frequency stability:	
vs. temperature range	40+70°C ± 1*10-10; ±2*10-10;
vs. supply voltage change	12V±10% ±5*10-11
vs. load change	50 Ohm ±10% ±1*10-10
vs. aging per day	±1*10-10
Allan variance for 1s	1*10-12
Output level	7±2 dBm
Power consumption	<3 W (steady state @25°C)
Dimensions	2*2*1
(50.8*50.8*25.4mm)	

P1FC-A-13 M5

PHASE NOISE REDUCTION IN MICROWAVE BIPOLAR TRANSISTOR AMPLIFIERS THROUGH ACTIVE FEEDBACK

M. J. LUCE* and E. S. FERRE-PIKAL, University of Wyoming.
Corresponding e-mail: mluce@uwyo.edu

In this paper, we document the effects of low-frequency active feedback on the phase noise of linear and compressed Si BJT and SiGe HBT amplifiers operating at 1GHz. Low noise, high frequency transistors manufactured by NEC were used in a common-emitter configuration and powered with DC batteries to insure low source noise. The feedback path consisted of a low noise op amp, the LT1028 connected as a voltage referenced difference amplifier.

The phase of the amplifier gain in BJT and HBT common-emitter amplifiers is a function of parameters that are dependent on DC current, such as transconductance, base-emitter capacitance, and others. Therefore, fluctuations in DC collector current will cause fluctuations in these parameters, and are then up-converted into phase noise around the carrier. Consequently, reductions in baseband collector current noise should reduce phase noise. There have been previous studies of phase noise reduction using active low frequency feedback in microwave MESFET and HFET amplifiers. However, the effect of active low frequency feedback on the phase noise performance of microwave bipolar amplifiers has not been documented. In this work, we will present results documenting phase noise reduction in HBT and BJT microwave amplifiers through active feedback. Different feedback configurations will be presented.

Preliminary measurements of amplifier phase noise were made using a two-channel measurement system with cross correlation. Each channel consists of a phase noise detector fed into a cross-correlation FFT analyzer. With active feedback, the measured base band collector current noise reduction in both cases agreed with the theoretical amount. The lowest phase noise achieved at 10Hz from carrier was L(f)= -144 dBc/Hz with the Si BJT in 4dB compression and L(f)= -141 dBc/Hz with the SiGe HBT in 4dB compression. These represent reductions of approximately 14dB and 10dB from the respective open loop configurations. In 4dB compression, the phase noise for both amplifiers was an additional 3dB below that achieved in the linear region of operation. The measured reductions are less than expected due to limiting factors which were not accounted for. These preliminary results are approaching the noise floor of this measurement system, so further improvement may be possible.

P1FC-A-14 M6

1/F NOISE IN CRYSTAL RESONATORS

V. F. KROUPA*, Institute of Radio Engineering and aelectronics Academy of Sciences of the Czech Republic.
Corresponding e-mail: Kroupa@ure.cas.cz

In the mid 20's of the last century, it was found by Johnson [1] that at very low frequencies the shot noise in electronic tubes lost the white noise character and the excess spectral density was frequency dependent. Schottky [2] introduced the name "flicker noise", the name still used.The same type of noise was observed with the India ink resistors, carbon microphones, and many other electronic and physical devices. In 1988 Van der Ziel summarized the state of the art 1/f noises [3]. The advent of atomic definition of the time unit brought about interest in precision frequency stability and in low noise crystal oscillators in particular as an intermediary procedure [4]. The first experience thought the greater the resonator Q the lower noise, as a consequence to decrease the carrier frequency fo , further it was found the noise is generated in the quartz resonator itself [5], and that the PSD (Power Spectral Density) of fractional frequency fluctuations is inversely proportional to the power of Q [6,7], and that the phase noise of quartz resonators is numerically close to the Qfo product [8]. In the present contribution we shall show that the losses connected with the current flow through the resonator generate frequency fluctuations which are changed into 1/f phase fluctuations due to the transportation delay. Further we shall prove that the magnitude of the corresponding Power Spectral Density (PSD) is independent of the resonator resonance frequency, fo, and that it is really function of the material constant Qfo. In addition, we will present a theoretical PSD model of the phase noise at the output of the resonator with a discussion on the $1/f^2$ and $1/f^3$ slopes [6, 7]. Finally, we shall investigate contribution of the white noise on the measurement and discuss the Allan variance for the resonator and an eventual crystal oscillator [9].

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This work has been supported by the Grant Agency of the Czech republic under the contract No. 102/00/0627.

P1FC-A-15 M7

NEAR-CARRIER PHASE-NOISE CHARACTERISTICS OF NARROW BAND COLPITTS OSCILLATORS

Y. WATANABE*[1], S. KOMINE[1], S. GOKA[1], T. SATO[1], H. SEKIMOTO[1], and T. UCHIDA[2], [1]Graduate School of Engineering, Tokyo Metropolitan University, [2]NDK Co., Ltd.
Corresponding e-mail: y.watanabe@ieee.org

A theoretical approach to estimate the near-carrier phase-noise level of narrow band transistor Colpitts quartz oscillators is described.

Improvement of near-carrier phase-noise characteristics of reference oscillators in mobile communication systems is always required. The authors proposed a narrow-band transistor Colpitts oscillator for 10 MHz SC-cut resonators in 1996 FCS [1]. This oscillator employed an AT-cut resonator as a band selection filter and we showed that the phase-noise level of the oscillator were improved over 5 dB compared to the conventional Colpitts oscillators.

This paper describes an analysis of the near-carrier $(1 / f^3)$ phase-noise characteristics of the narrow-band Colpitts oscillators with resonator filters. The open-loop impedance, that is, the series impedance of SC-cut resonator and active circuit, is calculated using a linear circuit theory with a non-linear transistor model. The loaded Q is derived from the reactance-frequency characteristics of the open-loop impedance. It is shown that the loaded Q can be improved by introducing the resonator filter. Based on the Leeson's formula, the near-carrier phase-noise level is estimated using the calculated Q values. The results corresponded well with the previous experiments [1]. The analysis also shows that the phase-noise of the 10 MHz oscillator can be improved, below 150 dBc/Hz at 10Hz offset, by using a high-Q filter and controlling the drive level of SC-cut resonator.

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P1FC-A-16 M8

FURTHER ENHANCEMENTS TO THE ANALYSIS OF SPECTRAL PURITY IN THE APPLICATION OF PRACTICAL DIRECT DIGITAL SYNTHESIS

J. R. JENSEN*, S. CHENG, and R. E. WALLIS, Johns Hopkins University Applied Physics Laboratory.
Corresponding e-mail: gregory.weaver@jhuapl.edu

In general the output of a direct digital synthesizer will inherently include spurious signals due to two effects: 1) not all of the phase accumulator bits are used to determine the output value; 2) the output value includes round-off errors. This paper will present an enhancement in the approach by which these spurious tones and their amplitudes can be determined in correspondence with changes in the control word of the accumulator.

The following conclusions may be drawn from the analysis to be presented:

For a given DDS implementation, the magnitude of the spurious tones is determined by the position of the least significant 1 in the accumulator control word.

The frequency associated with each spurious tone will change in a predictable way as the control word is varied such that the location of the least significant 1 remains the same.

The complete set of spurious tones obtained when the accumulator control word has its least significant 1 in the same position as the least significant bit of the output look-up table will determine the complete set of spurious tones obtained for any control word. The magnitude of the spurious tones in a reference spectrum is sufficient to predict the spurious when phase truncation occurs. The sign of the Fourier transform components is necessary to predict the spurious when not all the bits of the accumulator are used.

These conclusions and the equations presented in the paper will allow for the prediction of the spurious tones in a DDS output for one control word based on that observed by the spurious for any other word. This eliminates the need to empirically determine the spectrum of every control word of interest, but does require a reference measurement for all other predictions.

P1FC-A-17 M9

LOW FLICKER-NOISE AMPLIFIER FOR 50 Ω SOURCES

E. RUBIOLA*[1] and F. LARDET-VIEUDRIN[2], [1]Université Henri Poincaré - ESSTIN -LPMIA, [2]LPMO Dept, FEMTO-ST.
Corresponding e-mail: rubiola@esstin.uhp-nancy.fr

Low-noise preamplifiers are often needed in the general practice of phase and frequency metrology. We analyze the design of a low-noise preamplifier primarily intended as the post-detection front-end. In most practical cases the detector is a double balanced mixer that has nominal output impedance of 50 Ω. The near-DC output signal is measured in the frequency range between $10^{-2} - 10^{-1}$ Hz and $10^5 - 10^6$ Hz, or in a portion of this range. For reference, most commercial FFT analyzers accept a maximum input frequency of 10^5 Hz.

Low residual flicker is the main desired performance, and probably the most difficult to achieve. This feature can only be appreciated if white noise is sufficiently low, and if an appropriate design ensures DC stability. Thermal stability without need of temperature control, and of course without resorting to chopper-stabilization techniques, is also needed.

An optimal solution is proposed, in which the low-noise and DC stability features are achieved at a reasonable complexity. The input stage is a matched PNP differential pair terminated to 50 Ω at both inputs. The measured noise is $\sqrt{h_0}$=1.5 nV/$\sqrt{}$Hz (white) and $\sqrt{h_{-1}}$=1.1 nV/$\sqrt{}$Hz (flicker). The white noise exceeds by less than 20 % the thermal noise of the two 50 Ω input resistors. The corner frequency at which white and flicker noise are equal is f_c=0.5 Hz. Converting the flicker noise into two-sample (Allan) deviation, we get $\sigma_v(\tau)$=1.3 nV, independent of the measurement time τ.

The absolute value of the gain is accurate to 10^6 Hz. The phase of the gain is accurate to more than 10^5 Hz. This is relevant in correlation systems, where phase mismatch turns into measurement error.

Besides the primary application phase and frequency metrology, the proposed amplifier turns out to be a versatile general-purpose tool useful in experimental electronics and physics.

P1FC-A-18 M10

RECENT RESULTS ON QUARTZ CRYSTAL LD-CUTS OPERATING IN OSCILLATORS

S. GALLIOU*, F. STHAL, J. J. BOY, R. BOURQUIN, and M. MOUREY, LCEP, FEMTO-ST, UMR CNRS 6174.
Corresponding e-mail: serge.galliou@ens2m.fr

These last years, a new doubly-rotated cut of quartz crystal resonator [1] has been thought up at the LCEP (Laboratoire de Chronométrie Electronique et Piézoélectricité). This cut, named LD-cut for "Low isochronism Defect" cut, exhibits an amplitude-frequency effect one hundred times lower than the SC-cut one, that is to say a relative frequency change of about $1\times10^{-11}/\mu$W. This paper deals with the behaviour of such a crystal cut working in an oscillator. It is based on results from a batch of 10 MHz LD-cuts recently manufactured in a BVA process. Properties, advantages and drawbacks of the LD-cut are first reviewed. They have been tested in terms of noise and then built in oscillators. Experiments with various resonator drive levels have been performed. Measurements of their power spectral density of phase fluctuations are given and discussed.

[1] N. GUFFLET, F. STHAL, J.J. BOY, R. BOURQUIN, M. MOUREY "Doubly rotated quartz resonators with a low amplitude-frequency effect: The LD-cut". IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control, vol 48, no. 6, nov., pp. 1681-1685, (2001).

Session: P1U-B

CONTRAST AGENTS I
Chair: K. Ferrara
University of California

P1U-B-1 E7

THE SHORT-PULSE SUBHARMONIC RESPONSE OF MICROBUBBLES BASED ON A TWO-FREQUENCY APPROXIMATION

C.-Y. WU[1,2], M.-T. LO[1,2], J. TSAO*[1], D.-H. TSAI[2], Y.-C. CHANG[2], and D.-R. SU[2], [1]Graduate Institute of Communication Engineering, National Taiwan University, [2]Medical Group, Research Center, Micro-Star Int'l Co., Ltd.
Corresponding e-mail: drsu@msi.com.tw

The subharmonic response due to the nonlinear behavior of microbubble can be used to provide good discrimination between microbubble and surrounding tissue, especially in deep region. However, there is no proper analysis about the subharmonic response under short-pulse insonification. In this work, we extend the two-frequency approximated analytic solution of Newhouse et al. to derive the subharmonic response of microbubble under band-limited insonification. Based on Fourier theory, a band-limited signal can be synthesized by multiple sinusoids, with a two-frequency approximation being the simplest case. In this work, for a given bubble whose resonance frequency denoted as f_0, the transmission is modeled as the composition of two-frequency (f_1, f_2, and $f_1 > 2f_0 > f_2$) under the constraint condition at which the transmission has spectral continuity. Therefore, the bandwidth of the transmission can be approximated as the width of the spectral region spanned by theses two frequencies. Based on Ellers analytic solution of the amplitude of the subharmonics, we found that if f_1 and f_2 are away from $2f_0$ (i.e. the bandwidth of the transmission is increased), the amplitude of the subharmonics will decrease rapidly. Our theoretical analysis illustrates that the amplitude of the subharmonics decrease with the transmitted fractional bandwidth. Moreover, under an applied pressure of 0.1 MPa, it approaches zero when the fractional bandwidth is increased to 16 %. In other

words, this proves theoretically that only narrowband transmission can excite the microbubble to generate the subharmonics. Based on the nonlinear behavior of microbubble, in addition to the generation of subharmonics, we also derived that the resulting echo also contains difference response under two-frequency insonification. It is named as low-frequency response at the frequency, $f_L = f_1 - f_2$, in this work. It will reside nearby DC in spectrum if these two frequencies are close. Furthermore, the amplitude of low-frequency response can be derived to increase with the fractional bandwidth, which is different from that of subharmonics. The experimental data from the Levovist suspension were used to verify the theoretical predictions. It can be shown that the amplitude of the subharmonics decrease with the transmitted fractional bandwidth ranging from 2 % to 40 % when the emitted frequency is 2.75 MHz and the acoustic pressure is 0.8 MPa. On the contrary, the low-frequency response increases with the transmitted bandwidth. Consequently, both of range resolution and contrast to surrounding tissues can be achieved by using low-frequency response and subharmonics alternatively in imaging.
National science council in Taiwan

P1U-B-2 E8

USING THE CORRELATION PROPERTY OF SUBHARMONIC RESPONSE AS AN INDEX OF CAVITATION OF MICROBUBBLES

M.-T. LO[1,2], J. TSAO*[1], and S. LIN[2], [1]Graduate Institute of Communication Engineering, National Taiwan University, [2]Medical Group, Research Center, Micro-Star Int'l Co., Ltd.
Corresponding e-mail: drsu@msi.com.tw

Our previous research demonstrated when the subharmonic is significant, the correlation between two consecutive subharmonic signals denoted as $|R(1)/R(0)|$ is excessively weak. Our theory predicts the weak correlation is due to the reduced observation time for the subharmonics, since onset threshold is close to cavitation threshold. Therefore, if it can be proved the weak correlation is only related to the reduced observation time, the generation of the subharmonics could be used as a cavitation index. Our numerical results also illustrated under the insonified frequency fe, except for the bubble with resonance frequencies of 2fe and fe, the onset threshold increases with bubble size. Therefore, when bubble size is distributed, unlike the fundamental dominated by larger bubbles, the smaller bubbles have dominant influence on the subharmonics. The radiation force should have unnegligible effect on the reduced $|R(1)/R(0)|$, since it accelerates the smaller bubbles more. In this study we try to specify whether the reduced $|R(1)/R(0)|$ is related to the reduced observation time rather than the effect of radiation force. In this work, we demonstrate mean flow velocity (MFV) should be underestimated under the reduced observation time, since slower velocity components are weighted more heavily. In other works, the estimated MFV using the subharmonics is smaller than that using the fundamental. On the contrary, relative to the fundamental, the radiation force will increase

estimated MFV using the subharmonics when the bubble is away from the transducer. Therefore, only the value of |R(1)/R(0)| under the estimated MFV using the subharmonics is not larger than that using the fundamental can be used to specify whether the observation time is excessively reduced. It is demonstrated experimentally the ratio of averaged MFV using the subharmonics to that using the fundamental really increases from 0.9 to 1.5 when the applied pressure is increased from 0.4 to 1.6 Mpa due to the radiation force effect. Nevertheless, it is presented the estimated |R(1)/R(0)| using the subharmonics (i.e. 0.28) is still much smaller than that using the fundamental (i.e.0.89) under 0.4 Mpa. Note that under 0.4 Mpa, the subharmonics has SNR over 20 dB. Therefore, it can be concluded the weak |R(1)/R(0)| is related closely to the reduced observation time. In addition, the following experiment provides convincing evidence about the relation between the cavitation and the subharmonics. The suspension of Levovist was insonified by long sine-wave bursts at PRF 5KHz continuously. It can be observed the subharmonic decreased rapidly with insonified time (i.e. 10dB/48sec). However, there wasnt obvious decrement for the fundamental (i.e. 1dB/48sec). As theoretical expectation, the subharmonic and fundamental components are dominated by different categories of bubbles. Experimental results also proved most of the microbubbles which can produce subharmonics undergo cavitation while they move into the insonified region. Consequently, this work imply the substantial subharmonics can be used as cavitation index.

P1U-B-3 E9

ACOUSTICAL CHARACTERIZATION OF SUBMICRON PARTICLES OF PERFLUROCARBON IN SOLUTION

O. COUTURE*, E. CHERIN, and S. FOSTER, University of Toronto, Department of Medical Biophysics (Sunnybrook).
Corresponding e-mail: olicou@sten.sunnybrook.utoronto.ca

The combination of ultrasound biomicroscopy (UBM) and targeted contrast agents may become a very important tool for the assessment of various diseases in humans and for the tracking of biomarkers in animal models. Targeted submicron particles containing liquid perflurocarbon (PFC) have demonstrated significant acoustical enhancement both in-vitro and in-vivo at higher frequencies. To date there has been little effort aimed at understanding the physics and acoustic properties of submicron particle solutions. The purpose of this work is to explore the effect of varying the type of perflurocarbon, the concentration of surfactant, and peak ultrasound pressure on acoustic properties.

Submicron PFC droplets were produced by emulsifying a mixture of PFC (5%), fluorinated surfactant, and water at high pressure. We varied the concentration of surfactant (0.1% to 1.5%) in order to obtain particles with different size distributions. Three different types of perflurocarbon C_6F_{14}, $C_{10}F_{18}$, and C_7F_{16} were tested. The sizes of the particles were measured using a dynamic light scattering instrument (Malvern, Zetasizer Nano-S). We determined the attenuation of the diluted samples ($\sim$0.25% v/v PFC) with a substitution experiment in a range of frequencies covering 15 MHz to 50 MHz with narrowband and broadband pulses. We also measured the 90 degree scattering spectrum of the submicron particles at 20 MHz with a two transducer crossed beam experimental set-up. Finally, we assessed the harmonic generation caused by the propagation of the pulses through the samples. For the scattering and non-linear propagation experiments, we used pressures ranging from 0.5 to 2.7 MPa. Plastic microbeads and water were used as controls.

The attenuation values at 30MHz ranged from 0.28 to 0.48 dB/mm for the formulations and sizes tested. Both narrowband and wideband attenuation measurements were smoothly varying over the frequency range 15MHz to 50MHz. There was no evidence of any resonances that might be associated with non-linear interactions. The curves were fitted to a $\alpha = Af^n$ function where n varied between 1.3 and 1.7 and was PFC dependent. The relative attenuation measured at 30 MHz seemed to vary inversely with the average size of the particles. Harmonics created during propagation through the samples were 0.6 to 5 dB lower than through water, which could be due to frequency-dependent attenuation. Linear scattering increased with size, except for the particles made with $C_{10}F_{18}$. The interpretation of the non-linear scattering of the submicron particles was made difficult by low SNR and possible fluctuation of the PFC content. In contrast to commercially available microbubbles, submicron particles do not create strong coherent subharmonic or ultraharmonic at higher frequencies.
We would like to thank the Canadian Institute of Health Research and the National Cancer Institute of Canada for their funding support

P1U-B-4 E10

OPTICAL OBSERVATIONS OF MICROBUBBLE BEHAVIOR AT HIGH ULTRASOUND FREQUENCIES

D. E. GOERTZ*[1,2], C. T. CHIN[1], M. E. FRIJLINK[1], M. VERSLUIS[3], N. DE JONG[1,3], and A. F. W. VAN DER STEEN[1,2], [1]Erasmus MC, [2]Interuniversity Cardiac Inst. Netherlands, [3]Physics of Fluids, Univ. Twente.
Corresponding e-mail: d.goertz@erasmusmc.nl

There is growing interest in extending the use of microbubble contrast agents to increasingly higher ultrasound frequencies, using conventional ultrasound scanners (<15 MHz) as well as ultrasound biomicroscopy and intravascular systems (>15 MHz). While nonlinear microbubble imaging has recently been shown to be possible for transmit frequencies (f_{trans}) of up to 30 MHz, the mechanisms of nonlinear scattering and microbubble dynamics above 8-10 MHz remain relatively unexamined. In this study, we investigate microbubble behavior in response to 10-20 MHz ultrasound using high-speed optical imaging. The previously reported Brandaris 128 camera, which can acquire up to 128 images at a maximum frame rate of 25 mega-frames per second (MFPS), was employed. A broadband (19 MHz center frequency) focused (f# 1.6; aperture 8 mm) PVDF transducer was used at f_{trans} of 10, 15 and 20 MHz, pulse lengths from 10-40 cycles, and pressures ranging from 1 to 5 MPa. The frame rate limitation for examining high frequencies is overcome by implementing a stroboscopic approach which entails operating the camera at a frame rate that is offset by 1 to

2 MHz with respect to the transmit center frequency. At a transmit frequency of 20 MHz, for example, a frame rate of 19 MFPS was used, which resulted in fundamental frequency oscillations aliasing to 1 MHz, second harmonics to 2 MHz and subharmonics ($f_{trans}/2$) to 9 MHz. Experiments were carried out using the experimental lipid encapsulated agent BR14 (Bracco Research, Geneva). A number of nonlinear phenomena such as primary and secondary radiation forces, coalescence, disruption, and oscillation dynamics (e.g. fundamental and subharmonic) were observed. It is of particular interest to observe the size of bubbles participating in radial oscillations. At f_{trans}=10 MHz for example, fundamantal frequency oscillations are predominantly seen in bubbles on the order of 1-1.5 microns in diameter. Subharmonic radial oscillations are also observed, in many instances with a rapid onset. At f_{trans}=20 MHz subharmonics typically occur in bubbles in the range of 1-1.5 microns in diameter. Oscillations (fundamental and subharmonic) were also detected for bubbles below 1 micron in diameter, though quantitative analyses of dynamics were limited by optical resolution. This study has provided independent optical information of microbubble dynamics to complement recent acoustic observations of scattering at high frequencies.
This work was supported in part by STW and ICIN.

P1U-B-5 E11

AN ACOUSTIC STUDY OF DISRUPTION OF POLYMER SHELLED BUBBLES

P. D. BEVAN*[1,2], R. KARSHAFIAN[1,2], M. MATSUMURA[2], G. TICKNER[3], and P. N. BURNS[1,2], [1]University of Toronto, Department of Medical Biophysics, [2]Sunnybrook & Women's College Health Sciences Centre, [3]Point Biomedical.
Corresponding e-mail: peter.bevan@utoronto.ca

Clinically, disruption of ultrasound contrast agents is important both for perfusion imaging and for quantitation, with disruption-replenishment imaging techniques. For all of these applications, it is advantageous to have an agent with a sharp threshold for disruption which then disappears quickly. In this study, a series of agents were investigated that comprised air encapsulated within a polymer shell. The four agents shared the same bubble diameter (~4μm), contained the same gas (N_2) but had shell thicknesses that varied by a factor of 5. The goal of this experiment was to assess the threshold of disruption and the time-course of the subsequent acoustic response of these agents.

The time-course of the response was assessed by applying a series of pulses to a diluted suspension of these agents: a low amplitude pre-disruption detection pulse, a high amplitude disruption pulse, and then a sequence of seven detection pulses at 1, 10, 20, 30, 50, 100, and 200ms after disruption. The peak negative pressure of the disruption pulses was 0, 480kPa, 1.13MPa, and 1.95MPa at 2.0MHz. The detection pulses had a peak negative pressure of 30kPa. Separate transducers, placed such that their respective focal zones overlapped at a 90-degree angle, were used to transmit and receive. The same transducer was used to transmit both the detection and disruption pulses.

Measurements showed that the pre-disruption response of the agents decreased with increasing shell thickness. A higher threshold for disruption was observed for the thicker- shelled agents. Following disruption, all of the agents demonstrated a transient increase in scattered power. Above the disruption threshold for the agents, highly echogenic, nonlinear scatterers were observed and persisted for a mean half-life of about 12ms, which is consistent with the free diffusion of nitrogen in water. This suggests a picture wherein the shell is disrupted, releasing the gas contained within the bubble, generating free gas bubbles. This release is followed by diffusion of the gas into solution and resonant, high amplitude nonlinear scattering. As the shell thickness increased, ultrasound pulses with a peak negative pressure corresponding to the maximum used in diagnostic imaging became capable of disrupting a diminishing proportion of the bubble population. The optimum bubble tested thus combined a shell thickness which produced a well-defined disruption threshold within the diagnostic range and a gas which dissolved relatively rapidly, thus increasing the decorrelation signal obtainable for disruption imaging.
This work was supported by the National Cancer Institute of Canada, the Canadian Institutes of Health Research and a grant by Point Biomedical Inc.

P1U-B-6 E12

CONTROLLED GAS RELEASE FROM RIGID-SHELLED MICROBUBBLES

M. POSTEMA*[1,2], A. BOUAKAZ[1,2], and N. DE JONG[1,3], [1]Dept. of Experimental Echocardiography, Thoraxcentre, Erasmus MC, Rotterdam, The Netherlands, [2]Interuniversity Cardiology Institute of The Netherlands, Utrecht, The Netherlands, [3]Physics of Fluids, Dept. of Applied Physics, Faculty of Science and Technology, University of Twente, Enschede, The Netherlands.
Corresponding e-mail: postema@ieee.org

Sonic cracking is the ultrasound-induced release of gas from an encapsulated microbubble.

In this study, we visualize the release and the dissolution of air bubbles after sonic cracking. Furthermore, we compare simulations and optical observations of the dissolution of released air bubbles to previous measurements of acoustic decay times. This is the first study in which gas release from contrast bubbles is quantified.

We investigated two rigid-shelled ultrasound contrast agents, by subjecting them to high-amplitude ultrasound and simultaneously capturing high-speed photographs. Both agents consisted of rigid-shell encapsulated air bubbles. The contrast agent microbubbles were freely flowing through a capillary tube. For insonifying we used two spherically focused single-element transducers of 0.5 MHz and 1.7 MHz, typically transmitting 8 cycles at acoustic pressures that corresponded to mechanical indices above 0.8. The optical observations were recorded with two camera systems, one capturing 128 frames at 13 million frames per second, the other capturing 100 frames at 2000 frames per second. Our results are based on 588 experiments.

For both agents, the percentage of released gas bubbles is greater at 1.7 MHz than at 0.5 MHz insonification. We suggest that the occurrence of sonic cracking is determined by the proximity of the insonifying frequency to the resonance frequencies of the agents. The mean diameter of bubbles from which gas was released, agrees with the mean diameter in the bulk agent, but the free gas bubbles have equilibrium diameters smaller than the bubbles from which they have been released. The observations of gas left inside shell after cracking, may account for this difference. Most of the released gas bubbles have equilibrium diameters between 1.25 and 1.75 μm. We computed their disappearance to be within 15 ms. This disappearance was confirmed optically.

We conclude that controlled gas release from encapsulated microbubbles is feasible. The amount of bubbles released depends, among others, on the frequency transmitted. The rapid dissolution of released gas may be applied for the local delivery gaseous drugs, and for noninvasive pressure measurements.
This work has been supported by the Technology Foundation STW (RKG.5104).

P1U-B-7 E13

IN VITRO 40MHZ ULTRASONIC CHARACTERISATION OF IN-HOUSE LIPSOMAL MICROBUBBLE DISPERSIONS DEVELOPED FOR TARGETING ATHEROSCLEROTIC PLAQUE

C. M. MORAN*[1], J. ROSS[2], C. OLIVER[2], M. BUTLER[1], and W. N. MCDICKEN[1],
[1]Medical Physics, [2]Tissue Injury and Repair Group.
Corresponding e-mail: carmel.moran@ed.ac.uk

The size and composition of commercially available ultrasonic contrast microbubbles are such that when insonated at routinely used diagnostic frequencies (2-7MHz), the bubbles resonate and strongly scatter ultrasound. Recently there has been increasing interest in imaging and manipulating these microbubbles at higher frequencies (30-40MHz) for possible applications in targeting microbubble-encapsulated drugs to specific plaque sites in arteries and to image such sites using intravascular ultrasound.

Method: A baseline lipsomal dispersion (composed of cholesterol and a mixture of 3 phospholipids including phosphatidylethanolamine (PE)) was developed in-house and sized using a Malvern Mastersizer 2000. Using a ClearView Ultra system, a 40MHz Atlantis SR intravascular probe was inserted into each solution and one frame of unprocessed ultrasonic data was acquired to 8bits at 250Ms/sec. The data was downloaded onto a PC. A region-of-interest (ROI) of 128 data points and 9 ultrasonic lines was chosen at a series of depths. Over these ROIs, mean backscatter power was calculated and referenced to data collected from a water-air interface. Additional lipsomal dispersions were manufactured with incremental changes in the constituent composition and the size and mean backscatter power from these lipsomal dispersions were also measured and compared to commercially available agents Definity (Bristol-Myers Squibb) and Optison(Mallinckrodt). Sonication was also used to change the size distribution of the liposomes. Results: Mean number diameter of the baseline dispersion liposomes was 0.81±0.14 micron with a mean backscatter power of -32.4dB compared to water-air interface at 40MHz. An inverse relationship between percentage cholesterol content (5% to 35%) and mean diameter was observed (0.97micron to 0.81 micron) although there was no obvious relationship between mean backscatter and percentage cholesterol content. Increasing the percentage of PE in the liposome composition (15% to 80%), increased the size of the microbubbles with a corresponding increase in mean backscatter power (-32.4dB to 26dB). Sonication of up to 60 minutes also significantly reduced the diameter of the baseline liposomes (0.81microns to 0.42 microns). Incorporation of DPPE-biotin into the composition of the agent to facilitate the attachment of biotinylated antibodies via the strong streptavidin-biotin linkage did not significantly affect the size nor the mean backscatter power of the liposomal dispersion. Conclusion: A liposome microbubble dispersion has been developed for use at 40MHz. The agent can be targeted to specific cell-lines. Incremental changes in liposomal composition can change the size and mean backscatter of the liposome microbubbles.

Session: P1U-C

BEAMFORMING I
Chair: W. Walker
University of Virginia

P1U-C-1 F1

A HIGH VOLTAGE PULSER ASIC FOR DRIVING HIGH FREQUENCY ULTRASONIC ARRAYS

G. I. ATHANASOPOULOS*, S. J. CAREY, and J. V. HATFIELD, UMIST.
Corresponding e-mail: athanasopoulos@stud.umist.ac.uk

This paper describes the design and test of an Integrated Circuit (IC) that has been designed for connection to a hybrid PCB in close proximity to a PolyVinyldene Flouride (PVdF) transducer. The fabricated IC has 16 channels. For high resolution transducer arrays made from the polymer PVdF, the capacitance of individual elements is low (typically <2pF), but the pulsing electronics must still be designed to drive coaxial cables of impedance 50Ω or 75Ω. Hence, this circuit has to be specified more for the cable to which the transducer is attached, rather than the transducer itself. Pulser designs in discrete electronics typically occupy many square centimetres of printed circuit area and are unsuitable for incorporation within a scanning head. Ultrasonic transducers require a high voltage stress to force them into oscillation. A pulser should be able to sustain up to 100V and the high voltage output pulse should be able to be shortened down to possibly 25ns duration (20MHz frequency). This circuit was specified to be able to produce 15 repetitive pulses for Doppler imaging usage. The optimum rise time was experimentally obtained using a pulser made of discrete components and a PVdF transducer. This suggested a fall time of around

5ns, although anything less than 10ns was to be considered as acceptable. The simulated output pulse has short fall and rise times, typically 6.3ns and 13ns respectively, for a 680Ω resistor in parallel with a 2pF capacitor. Experimental results for the IC reveal fall and rise times of 12.5ns and 19.4ns respectively, with a load of 700Ω in parallel with approximately 5pF of capacitance. It is expected that the IC developed will meet fall/rise time requirements when integrated with the smaller load of a real transducer. Test results will be presented.

P1U-C-2 F2

PARALLEL BEAMFORMING USING SYNTHETIC TRANSMIT BEAMS

T. HERGUM*, T. BJÅSTAD, and H. TORP, Norwegian University of Science and Technology.
Corresponding e-mail: hergum@stud.fim.ntnu.no

When performing ultrasound imaging of moving structures such as the heart there is a demand to increase the rate of the image acquisition. This is particularly true for 3D imaging of the moving heart. A common way to increase the frame-rate of ultrasound imaging without compromising the number of scanlines is to use multiple beamformers. With this approach several parallel receive-beams from closely-spaced regions can be acquired simultaneously. However, due to the misalignment of the transmit- and receive-beams such a technique will cause image artifacts as we have considerable beam-to-beam variation across adjacent beams.

This paper presents a new method of parallel beamforming which eliminates this flaw. The underlying idea is to generate additional synthetic transmit beams through interpolation of the received, unfocused signal at each array element prior to beamforming. Now each of the parallel receive beams can be aligned perfectly with a transmit beam - synthetic or real - thus eliminating the distortion caused by misalignment.

By using an ideal interpolation filter this will yield identical results as using full transmit beam density when imaging a stationary object. However, the samples used as input to the filter are acquired sequentially, which for a moving object will cause motion-artifacts if the order of the filter is too large. Because of this linear interpolation was used in this study.

To investigate the performance of the technique a simulation study has been conducted with a spatial-frequency domain simulation. The results have been verified with a direct simulation using Field II (DTU, Jrgen Arendt Jensen). The simulations were done with parameters similar to a standard cardiac examination with two parallel receive beams and a transmit-line density corresponding to twice the Rayleigh criterion, λ F/2.

We used the skewness of the beam-profiles as a measure of the beam-to-beam variation of the imaging system. Without synthesizing additional transmit-beams, the first left and right sidelobes differed with 7dB. Knowing that adjacent beams are "mirror images" of each other this is a major source of beam-to-beam variation. After synthesizing additional transmit beams through linear

interpolation the right and left side-lobe level is found to differ with less than 0.5dB.
Priority program for medical technology, NTNU

P1U-C-3 F3

ALGORITHMS OF 3-DIMENSIONAL BEAM FORMING FOR SYNTHETIC APERTURE IMAGING SYSTEM USING PULSES CODED WITH WALSH FUNCTIONS

K. SATOH*[1], Y. TAMURA[1], M. MIURA[1], C. ISHIHARA[2], N. OKADA[3], and T. YAMASAKI[1], [1]Yamagata University, [2]Akishima Laboratories (MITSUI ZOSEN) Inc., [3]Honda Electronics Co., LTD.
Corresponding e-mail: tamra@yz.yamagata-u.ac.jp

An imaging system using coded transmission with Walsh functions has been developed by the authors for a high frame-rate 3D observation. This system enables us to observe a sequence of 3D images of moving objects for each transmission. Images of static phantoms and biological tissues were obtained successfully by using a small scale evaluating system which utilizes 32 transmitters and 32 or 128 receivers. The speed of computation is one of the most important subjects for practical applications. In this paper, two algorithms of the 3D beam forming are described for a synthetic aperture imaging system using transmitting pulses coded with Walsh functions. The system has been developed by the authors for dynamic ultrasound 3D imaging. The first algorithm utilizes fast Walsh transformation (FWT) and FFT for calculating cross-correlation functions between received waveforms and transmitted ones. All the cross-correlation functions are calculated first for all transmitting cycles. Next, calculation of the delay and sum is performed only once. All the transmitting and receiving beams are in focus with all depth. This algorithm is suitable for a stationary object, and the highest quality of image is obtained. It, however, is unsuitable for dynamic imaging when the objects are moving. The second algorithm consists of matched filters matched for the reference echo waveforms return from view directions. The echo waveforms for the reference are calculated in advance, and are stored in the memory as the coefficients of the filters. The matched filter operation is repeated for each transmitting cycle. For single transmission and reception, the calculation time of the first algorithm is short compared with the second algorithm, because of the less numbers of multiplies and additions. On the other hand, for multiple transmissions, the total calculation time by algorithm 1 increases in proportion to the number of transmissions, while the calculation time by algorithm 2 is almost constant to the number of transmissions. The second algorithm is suitable for implementations by hardware. Two algorithms were implemented in a personal computer using the C language in order to evaluate calculation times and the image qualities. A PC parallel cluster was constructed for a high speed computation and simulations for arrays with many elements. Implementation of algorithm 2 by FPGA are also examined.
This research has been partially supported by Grant-in-Aid for Scientific Research from the Japan Society for the Promotion of Science (JSPS).

HIGH VOLUME RATE 3-D ULTRASOUND IMAGING USING CROSS ARRAY BASED ON SYNTHETIC TRANSMIT FOCUSING

K.-S. KIM* and T.-K. SONG, Center for Medical Solutions Research, Dept. of EE, Sogang University.

Corresponding e-mail: kkim@sogang.ac.kr

3-D imaging methods using cross arrays based on conventional fixed focusing were proposed previously for fast volumetric scanning. In these methods, a 1-D transmit array(or a vertical array) placed along the elevation direction is used to project fan beams with a wide width in the transversal direction, of which the direction in the longitudinal direction is incremented in a succession of firings to scan a volume of interest. For each firing, the received signals at all elements of a 1-D receive array(or a horizontal array) that intersects the transmit array perpendicularly are sampled and recorded individually. These samples are then used to form all the scan lines on every transmit beam plane. However, this method suffers from low longitudinal resolution and low SNR since fixed focusing is employed in the longitudinal direction on transmit and both the transmit and receive arrays should have a very small width for wide view angles, respectively. To overcome these limitations, a new real-time ultrasound 3-D imaging method using a cross array based on synthetic focusing is proposed. In the proposed method, ultrasound wave is transmitted from each element of the 1-D transmit array and the resulting pulse echoes are received by all elements of the receive array. Using these received echo signals for all firings, all the scan lines within a volume of interest can be obtained by employing synthetic focusing and conventional receive dynamic focusing in the longitudinal and transversal directions, respectively. Consequently, ultrasound waves are focused in both directions at all imaging points, resulting in greatly improved resolution. This method can provide as many longitudinal scan planes as possible only with N transmit/receive events where N represents the number of transmit elements. We verified from experimental studies that ultra-fast volumetric imaging can be achieved with the proposed method in conjunction with a proper pixel-wise motion compensation even for fast moving targets. In terms of SNR, however, the proposed method is even worse than the conventional cross array method since only one element is fired at a time. Two methods will also be presented that can improve the SNR significantly. First, analytic and experimental studies showed that SNR improvement by more than 15dB can easily be achieved with coded excitation using orthogonal Golay codes or modified chirps. Secondly, it will be demonstrated that narrow fan beams can be synthesized using a synthetic transmit focusing method that fires all the transmit elements to transmit ultrasound waves with either spherical or linear wave front, which leads to additional SNR improvement by a factor of $\sqrt{N}$. Moreover, in case of synthetic transmit focusing using linear wave fronts, narrow longitudinal beam width is maintained over the large depth of field. Experimental results show that the

3dB logitudinal beam width not larger than 1.5mm is obtained over the depth of field of 200mm, only with 65 transmit/receive events, using a 65x255 cross array with the center frequency of 3.5MHz.

P1U-C-5 F5

DEVELOPMENT OF A LINEAR POWER AMPLIFIER FOR HIGH FRAME RATE IMAGING SYSTEM

J.-Y. LU* and J. L. WAUGAMAN, The University of Toledo.
Corresponding e-mail: jilu@eng.utoledo.edu

A prototype high frame rate imaging system for imaging of fast moving objects such as the heart has been designed and developed [1]. As a first step, the high frame rate imaging system was developed for use with 128 element one-dimensional (1D) array transducers for two-dimensional (2D) imaging. (A three-dimensional (3D) high frame rate imaging system with a 2D array transducer will be studied in the future.) To combine the high frame rate imaging method with coded excitation, harmonic imaging, and other medical ultrasound research projects, a linear power amplifier was developed. The specifications of the power amplifier are as follows: (1) wide bandwidth (from 50KHz to over 10MHz); (2) large output voltage at 75 Ohm load with an adjustable power supply voltage up to +/-144V (or a peak power of about 300W); and (3) the output changes linearly with a 12-bit D/A converter input without consuming a large static power. Since the number of power amplifiers for the high frame rate imaging system is relatively large and the maximum output voltage is high, a large temperature-dependent static current in the amplifier could result in a high static power. For example, with 100mA at +/-144V, each amplifier would consume about 28.8W, and thus 128 amplifiers will require a static power of about 3,686W in total. To avoid this problem, a circuit was designed to automatically minimize the output DC offset voltage and control the bias current of the amplifier to a specified low value through active feedback loops. The amplifiers have been manufactured and the test results of these amplifiers are very close to the specifications above. In this paper, we will report the design of the amplifiers that consume a smaller static power while meeting the specifications above and images constructed with the high frame rate imaging system.

REFERENCE: Jian-yu Lu, "2D and 3D high frame rate imaging with limited diffraction beams," IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, vol. 44, no. 4, pp. 839-856, July, 1997.

This work was supported in part by a grant HL 60301 from the National Institute of Health.

P1U-C-6 F6

HIGH FRAME RATE IMAGING USING PARALLEL TRANSMISSION OF CODED FOCUSED FIELDS

T. MISARIDIS*[1] and P. MUNK[2], [1]National Technical University of Athens, [2]SACLANT Undersea Research Centre.
Corresponding e-mail: thmi@iasa.gr

We have previously presented a numerical method for calculating the excitation signals on individual elements, in order to transmit multi-focused pulsed beams in parallel. The algorithm is based on a modified directivity spectrum method, where local fields are decomposed into plane waves, which are then back-propagated to the transducer elements. In order to form the received beams in parallel, the receiver is a matched filter-and-sum beamformer that uses the calculated transmitted pulses reversed in time. Such an architecture eliminates the need of delay calculations and apodization values on the beamformer, since both are incorporated in the filters. The beamformer is a correlator both in axial and lateral (beam) directions, and this can be used advantageously by generating correlation-based coded focused beams with no need for additional temporal-only compression filtering. This paper shows the design of FM-coded focused fields and how these fields can yield more strongly focused fields or higher frame rate. Simulated images show the implementation of the method using only 4 emissions. Neighboring beams to be formed in parallel use different codes with a cross-correlation of 20 dB. Such a cross-correlation would be insufficient using a conventional delay-and-sum beamformer. In the proposed system, the worst-case beam interference is at the order of 40 dB, making it possible to obtain images of similar resolution to conventional imaging at very high frame rates. Additionally, coding compensates for the SNR loss that is due to multi-focusing using only few emissions.
This work is supported by grants from the Greek Ministry of Development and Technology and GE Medical Systems Kretztechnik, Austria.

P1U-C-7 F7

AN EFFICIENT 3D BEAMFORMER IMPLEMENTATION FOR REAL-TIME 4D ULTRASOUND SYSTEMS DEPLOYING PLANAR ARRAY PROBES

A. DHANANTWARI*[1], S. STERGIOPOULOS[1], C. PARODI[2,3], F. BERTORA[3], P. PELLEGRETTI[3], and A. QUESTA[3], [1]CANAMET Inc., [2]Department of Biophysical and Electronic Engineering, University of Genoa, [3]Esaote S.p.A.
Corresponding e-mail: caterina.parodi@libero.it

The computational intensity of the standard beamforming process for 3D and 4D ultrasound imaging systems is a major limitation for achieving real-time system performances. Algorithms for 3D beamforming present high memory and processing power requirements, and are not inherently given to parallelization. The 3D beamforming algorithm here presented consists of an alternative and more efficient implementation with respect to the traditional approach. The proposed algorithm has been developed for 4D ultrasound systems, and assumes a 2D planar sensor aperture. The method is based on the decomposition of the 3D beamforming process for a regular two-dimensional array into two steps of simpler 2D beamforming. For example in the application considered, the calculations for the volume reconstruction, starting from the signals acquired by a planar phased array, are split up into two steps of standard linear phased array processing. The proposed decomposition of the 3D beamforming allows for the

parallelization of the required processing. This paper describes the components of a real-time 4D ultrasound system, including the transmission functionality, the efficient 3D beamforming implementation, and its mapping to a multi-computer platform. The platform consists of an 8-node cluster of commodity PCs. A planar phased array is used, and the inter-element transmission delays allow for a fully flexible energy focusing on space. Futhermore, multiple frequency regimes are coded, to allow for transmission focusing at multiple depths on a single firing. System results are presented, which have been obtained using 6x6 array elements on transmission, and 16x16 array elements on receiving. The acquisitions have been performed on a standard ultrasound phantom, and the reconstructed volumes are shown. The images obtained are compared to the corresponding reconstructions achieved by using standard 3D beamforming, along with measures of computation requirements. The presented results confirm the validity of the proposed methods both for coded phased array energy transmission, and for the efficient real-time 3D beamforming, as well as the feasibility of implementing the developed 3D beamforming algorithm on a parallel processing architecture.
The work presented is part of the European Commission project ADUMS (IST-2001-34088). The authors wish to thank the European Commission, and all the partners involved in the ADUMS project.

P1U-C-8 F8

SYNTHETIC APERTURE TECHNIQUE FOR ECHOGRAPHIC FOCUSING BASED ON PULSE COMPRESSION

E. BIAGI, L. MASOTTI, I. ROSSI, and M. SCABIA*, Ultrasound and Non Destructive Lab, University of Florence.
Corresponding e-mail: scabia@det.unifi.it

In the past years several mutual influences took place between acoustical and radar fields of study in the last decades: this is mainly due to the great similarities that exist between them, despite the different kind of waves involved. Such influences are, for example, the change of variables present in the so-called omega-k migration algorithm for focusing Synthetic Aperture Radar images that has been derived from geophysics or the use of phased array probes in ultrasound imaging systems that has followed the development of such arrays in radar applications. Moreover, many techniques have been proposed which use Synthetic Aperture approach for focusing ultrasound images; and, analogously to radar application, the use of coded signals and pulse compression has been studied also in ultrasound imaging. In this work we tackle the problem of applying to echographic imaging those Synthetic Aperture Focusing Techniques (SAFT) commonly used in the field of Synthetic Aperture Radars (SAR). The aim of this research is to improve echographic image resolution by using chirp transmit signals, and by performing pulse compression in both dimensions (depth and lateral). Due to the huge difference in physical quantities between the SAR and the echographic case, unfocused ultrasonic images present a different geometry and this is the

main obstacle to the direct application of SAR focusing algorithms to ultrasound. In this work we propose a remapping technique in the frequency domain that allows the application of SAR focusing algorithms to echographic images. We present the mathematical formulation of our algorithm called ICARUS (acronym for Imaging pulse Compression Algorithm through Remapping of UltraSound) and the results obtained by means of an off-line processing of simulated images. Simulated results make evident the advantages of ICARUS technique in terms of both improvement and uniformity of resolutions across the image on each dimension (depth and lateral). Thanks to the flexibility and the speed of FEMMINA platform (developed in the USCND Laboratory of Florence) in acquiring and processing RF signals, we have developed a real-time implementation of this algorithm (capable of handling full size images, 250 tracks, 4000 samples per track) and have started an experimentation using a modified commercial echographic machine. Some experimental results will be shown.

Session: P1U-D

MEDICAL SIGNAL PROCESSING

Chair: R. Chiao
Siemens Med Sols

P1U-D-1 F9

ICA BASED SOURCE SEPARATION IN TISSUE STRAIN WAVES

L. HUANG*[1,2], J. KUCEWICZ[1,2], and K. BEACH[1,3], [1]Center for Industrial and Medical Ultrasound, Applied Physics Laboratory, University of Washington, [2]Department of Bioengineering, University of Washington, [3]Department of Surgery, University of Washington.
Corresponding e-mail: huangly@u.washington.edu

Natural cyclic strain in tissue is caused by two sources: pulsation at the heart rate in arterioles due to cardiac activity and expansion of blood volume change in venules due to respiration. The pulsatile arteriolar filling is typically 0.1% by volume at around 1 Hz and the respiratory venular volume change is typically 0.5% by volume at around 0.2 Hz. The amplitude, phase and wave shape of the cardiac and respiration sources are expected to the reveal the state of the corresponding micro-vascular system. The cyclic tissue strain as a function of time could be useful in the diagnosis of diseases like ischemic stroke and tumor. We present a method to analyze the strain changes in tissue due to these different blood motion patterns in vessels.

The experimental system consisted of a Terason™ ultrasound system with RF acquisition capabilities, an ECG recorder, a photo-plethymography (PPG) sensor and a respiratory strain gauge to acquire synchronized frames of RF data from arm, ECG signal, PPG signal and strain-gauge respiratory signal across the chest respectively over 7.5 seconds. Using the RF data, strain images were generated for each frame with strain waves generated from a particular voxel across strain frames. PPG cardiac and strain gauge respiratory signals were used to validate the extracted source waveforms but not regarded as the sources directly.

We modeled the tissue strain wave as a linear mixture of three sources: 1) cardiac source, 2) respiratory source and 3) noise. These source waveforms were extracted from the estimated strain waves, estimated using the RF data. To extract the source waveforms, we used Independent Component Analysis (ICA). We also tested our source separation on simulated strain waves generated by mixing the PPG signal, respiratory strain gauge signal and band pass white noise with a SNR of 20db. Fifty strain waves were created through various linear mixtures of sources and then introduced into the ICA program. Correlation coefficient between the extracted sources and the original sources in simulation was greater than 0.98.

The ICA extracted cardiac and respiratory sources from the tissue strain waves generated from RF were compared to the PPG cardiac and strain-gauge respiratory signals. Cross-correlation was calculated between extracted source waveforms and PPG cardiac and strain-gauge respiratory signals respectively. The similarity in wave shape was found, but there was phase shift between them. The strain waves were reconstructed by the cardiac and respiratory source successively. The noise was rejected in reconstructed strain waves.

The author would like to thank Barbrina Dunmire and Matthew Bruce for reviewing the paper. The author would also like to thank Marla Paun for her help on ultrasound scanning.

P1U-D-2 F10

ESTIMATION OF TIME OF FLIGHT FOR ULTRASONIC REFLEX-TRANSMISSION TOMOGRAPHY WITH ACTIVE CONTOUR MODELS

M. ASHFAQ*, M. MIENKINA, and H. ERMERT, Institute of High Frequency Engineering.
Corresponding e-mail: mohammad.ashfaq@rub.de

The histological significance of acoustic speed, together with acoustic attenuation, in differentiating breast carcinomas from healthy tissue is well founded. A reflex-transmission system comprising a metallic reflector and a linear array (5.0HDPL, 5MHz center frequency) of a standard ultrasound system (Siemens Elegra with a research interface) was developed, the two fixtures being mounted in such a way that they can describe a whole revolution about the object to be imaged thus enabling a tomographic reconstruction, whose accuracy depends largely on that of the time of flight data estimated on the basis of the first arrival signals reflected from the metallic plate. The estimation is an extremely intricate task as multiple reflections, attenuation, refraction and speckle hamper the utility of conventional techniques like threshold detection and cross correlation. The ability of the active contour models to allow prior information to be formulated in the form of an energy functional to be minimized was exploited to circumvent the aforementioned problem and two different algorithms were successfully implemented, tested and compared to the conventional techniques.

The major priors used in this work are: (1) a markedly high amplitude and a steep rise of the reflector signal due to huge difference in the acoustic impedances of metal and water, (2) the approximate reflector position is easily estimable, (3) the lateral course of the reflector echo-signal is sufficiently smooth due to absence of any abrupt changes in the acoustic speed through breast tissue. In the first approach, based on the approximate position of the metallic plate, the snake is deformed to converge to the minimum of the energy functional. This amounts to a numerical solution of the Eulers equations. In the second approach a dynamic programming snake algorithm was implemented with the same prior information which has a substantial advantage over the first approach that it always converges and needs no start contour to be specified. The other advantage is that no matrix has to be inverted, as the minimization process can be viewed as a multi-level discrete decision making process, whereby starting from an arbitrary point, the following optimal points have to be found. The algorithms were tested on data acquired from measurements on several phantoms with known acoustic speed distributions for distances of 6 and 15 cm between the ultrasound array and the metallic reflector. For a measurement depth of 6 cm the mean error of estimation of the acoustic speed was 1m/s for Euler snake and 0.93 m/s for dynamic programming snake whereby the mean error for cross correlation was as big as 2.6 m/s. The real power of the snake algorithm was however revealed for the measurement depth of 15 cm, in which case the refraction shows the worst effects, the mean estimation error came out to be 1.6m/s and 1.8m/s for Euler and dynamic snake respectively and 4.9m/s for cross correlation.
A project of the Ruhr Center of Competence for Medical Engineering (KMR), funded by the German Federal Ministry of Education and Research (bmb+f grant No. 01EZ0206)

P1U-D-3 F11

A STUDY OF MORPHOLOGICAL EDGE ENHANCEMENT BY DOUBLE STRUCTURING ELEMENT FOR ULTRASOUND B-MODE IMAGES

M. TSUBAI*[1], T. NISHIMURA[1], A. SASAKI[1,2], T. MITAKE[2], and S.-I. UMEMURA[3], [1]Graduate School of Information, Production and Systems, Waseda University, [2]Hitachi Medical Corporation, [3]Hitachi Central Research Laboratory. Corresponding e-mail: tsubai@aoni.waseda.jp

We discuss a new adaptive morphological operations using double structuring elements (DSEs) and apply them to contrast enhancement of the ultrasound B-mode images. The important issues of the contrast enhancement for biomedical ultrasound images are follows. (a) Speckle noises are not emphasized while blurred tissue boundaries are sharpened well, and (b) important features of the original image are preserved, such as tissue boundary, detail structures and gray levels. However, conventional enhancement methods have following problems. (a) Noises are emphasized significantly while contrast of the boundary can be enhanced, and (b) overshoot and undershoot which are generated by high-pass filter distort the original image. Above problems are improved by our proposed method.

Generally, single structuring element (SSE) is used in the morphological operations. Opening operation and closing operation using SSE smooth the image components which do not fit a shape of the SSE, that is, smaller components than SSE are eliminated. On the other hand, the DSE is a couple of two structuring elements, which are not identical and are varying their geometric shape adaptively with the local characteristics of the processing image. The opening/closing with DSE can sharpen edges of the image components which fit a shape of the DSE and smooth the components which do not fit the DSE simultaneously. The DSE is adapted for local image so that homogeneous regions with speckle are smoothed and tissue boundaries are sharpened.

Tissue boundaries are enhanced and homogeneous speckle regions are preserved by adding correcting components to the original image. The correction is a difference of opening/closing with DSE from opening/closing with SSE. In our experiments, proposed method was applied to ultrasound breast tumor images with elliptic shape of the DSEs. The DSEs were determined so that DSEs do not fit the speckle at the every position of the image, reflecting the shape of speckle pattern and spatial resolutions in ultrasound B-mode system. The enhanced images by proposed method and by typical conventional methods based on spatial high-pass filtering were compared. In the former, blurred boundary has been sharpened without speckle emphasis, and details are preserved well without overshoot or undershoot. In the latter, noises were amplified significantly, or gray levels of the enhanced image differed from the original levels significantly because of overshoots and undershoots.

P1U-D-4 F12

REAL-TIME RESPIRATION PHASE MONITORING SYSTEM USING ULTRASONIC BI-PLANE IMAGE DATA FOR PROTON BEAM THERAPY

T. MOCHIZUKI*[1], M. KUNITA[1], Y. TOYAMA[2], S. MURAYAMA[3], and A. MARUHASHI[4], [1]Aloka Co., Ltd., [2]JRC Engineering Co., Ltd., [3]Shizuoka Cancer Center Hospital, [4]Kyoto University Research Reactor Institute.
Corresponding e-mail: moch1302@am.aloka.co.jp

Recently, conformal irradiation, which deposits a higher dose into a target, (i.e. a cancerous tumor) has proven essential in radiotherapy. In particular, the proton beam features a specific characteristic referred to as "Bragg peak", which enables us to take the offensive in a "pin-point-attack" on a tumor. The more precise the required treatment, the more important the positioning of the beam becomes. Maintaining this level of precision in irradiation treatment of a brain tumor, is comparatively easy, because the brain is a non-moving organ. On the other hand, a tumor in the abdominal region will move due to patient's respiration; it is thus very difficult to maintain the same degree of precision seen in the case of the brain tumor. Therefore, an irradiation technique has been

developed that is synchronized with the patient's respiration. This technique has minimized the dosage to the normal tissue surrounding the target and has reduced the risk of serious side effects. To monitor respiration using this technique, a laser beam or a strain gage has traditionally been employed. However, neither device can allow for the direct observation of the tumor's motion inside the body. In light of this problem, the objective of this study is to develop a method of directly detecting the periodic respiratory motion of the target in the body using ultrasound technology. The method proposed and explained below involves the application of what is referred to as TIMUP (3D TIssue Movement vector detected by Ultrasound bi-Plane) technology. First, in order to obtain image data, an ultrasonic beam is continuously scanned at high speed in both of bi-planes (the planes cross at right angles) using an ultrasonic two-dimensional (2D) array probe. Second, time-sequential data consisting of pairs of images on the same side of the bi-plane but in different phases are processed using a correlation method in order to calculate a vector for the tissue's movement. At the same time, the data on the other image of the bi-plane are processed in the same manner for the plane direction. Last, a three-dimensional vector for the tissue's movement is generated from the above vectors. To evaluate the accuracy of our method, a mimic phantom of living tissue was used. The phantom was set on a stage that was moved in a linear manner a distance of 30+/-0.01 mm by a stepping motor. Above the phantom, we fixed an ultrasonic 2D array probe, capable of detecting the phantoms motion. Twenty-eight measurement trials were carried out using this method. The resultant 95% interval estimation of the distance moved was from 28.7 to 30.4 mm. The accuracy yielded by this experiment was thus sufficient for radiotherapy. Based on these results, we attempted to evaluate the method on a human body. The motion of tissue in a volunteers body was monitored by this method. The result was in good accordance with the volunteers respiration. The developed system is expected to be very useful in reducing incidental damage to the normal tissue around a target in proton beam therapy.
This study has been supported by Grant-in-Aid for the Creation of Innovations through Business-Academic-Public Sector Cooperation in Japan.

P1U-D-5 F13

DEVELOPMENT OF A DUAL-GATE AUTOMATIC EMBOLUS DETECTION SYSTEM

L. FAN[1], E. BONI[2], P. TORTOLI[2], and D. H EVANS*[1], [1]University of Leicester, [2]University of Florence.
Corresponding e-mail: dhe@le.ac.uk

Identification of micro-emboli in the cerebral circulation using transcranial Doppler ultrasound (TCD) provides valuable clinical information, but currently embolic signal detection and analysis are significantly limited because they rely mainly on costly off-line analysis by human experts. In this work, two new high-resolution real-time automated systems for the detection and archival of embolic signals are described, and preliminary results obtained with the first

presented. The first prototype consists of a commercial DSP board (utilizing an Analog Devices 21065L SHARC processor) coupled to a personal computer, and uses expert system theory to identify likely embolic events. The real-time features of the system include microembolic event detection, histogram display of detected events, and signal archival of approximately one-second of raw data for each detected event. The system can also be used to examine the signal during any 3-second time interval without interrupting the main real-time embolus detection task. The second prototype is being implemented on a more powerful DSP board built at the University of Florence, containing a Texas Instruments TMS320C6713 processor. The board is designed to include an onboard dual gate TCD unit in addition to all the real-time features previously implemented. The code for the SHARC processor has been translated for the TI processor and successfully implemented. Preliminary tests have been conducted with the SHARC board to evaluate the system's capability of differentiating embolic candidate events from background signals, artifacts, and other sources of interference, and to record the signals of these candidate events for further verification. Data from 10 carotid endarterectomy patients and 2 normal volunteers have been analysed. Using the widely accepted 7 dB threshold for human reliability, and a human expert majority decision gold standard, the system reached a sensitivity and specificity of 93.6% and 99.3% respectively, which were close to the results obtained by three human experts under ideal laboratory conditions. The new system has the potential to be used either as a bedside monitoring and signal acquisition device, or as a laboratory investigation station.
The authors gratefully acknowledge the financial support of the European Commission (UMEDS-QLG1-CT-2002-01518)

P1U-D-6 G13

EMBOLI SIZING IN BLOOD FLOW CIRCULATION USING PARAMETRIC MODELING

M. BIARD*, J.-M. GIRAULT, D. KOUAME, and F. PATAT, LUSSI CNRS FRE 2448.
Corresponding e-mail: biard_m@med.univ-tours.fr

Cerebral embolisms represent a major part of all ischemic strokes in occidental countries. It has been found that a good knowledge of emboli (detection, differentiation and sizing), which are foreign particles to blood normal cerebral circulation, remains a promising challenge. Their characterization can be used, in fact, as a diagnostic or therapeutic tool. An EBR (Embolus to Blood Ratio) parameter was introduced[1] as a discriminating criteria of solid emboli size estimation. It has been shown that this technique had some limitations due to experimental physical characteristics as nonuniformity of ultrasound beam, refraction angle, These features could yield a poor Doppler signal to noise ratio and result in high bias and variance in the estimated emboli size. The aim of this work was to improve this emboli sizing technique using autoregressive (AR) modeling. Initially introduced[2] to detect emboli, this technique was shown to outperform common approaches based on time-frequency distributions in terms of non-detection probability. Thus concerning emboli sizing, due to its intrinsic signal filtering and smoothing properties, this technique was expected to bring great improvements, in the estimation of the EBR and then emboli sizing. In order to evaluate these improvements, we use in vitro data. These data were acquired with a two frequencies 1.707 and 2.564 MHz emission PW Doppler apparatus. Experimental set-up consisted of a blood mimicking fluid, having blood acoustical properties, moving in a tygon tube simulating a cerebral artery thanks to a peristaltic pump. Solid emboli were simulated by acrylic particles of different sizes. As results, it has been found that Doppler power estimated by this parametric approach yield EBR values closer to expected theoritical ones than classical techniques. In a same size range, parametric EBR values present lesser bias and variance than other approaches.

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ATYS Médical French department of industry

P1U-D-7 G12

ADAPTIVE NOISE REDUCTION PROCESS BASED ON GRAY-LEVEL CONCENTRATIVE FILTER FOR CW DOPPLER SPECTROMETER

A. SASAKI*[1], T. AZUMA[2], H. KAMADA[1], T. HAYASHI[1], T. NISHIMURA[3], and S.-I. UMEMURA[2], [1]Hitachi Medical Corporation, [2]Hitachi Central Research Laboratory, [3]Graduate School of Information, Wasada University.
Corresponding e-mail: sasaki-a@kf.hitachi-medical.co.jp

It is well known that B-mode images are formed with speckles, whose typical patterns do not directly reflect the microscopic structures of tissues. Doppler spectra, on the other hand, are not formed with such speckles, but still have ripples due to the speckles formed by the interference between the point spread function of the beamformer and the scattering cross-sections of blood cells. In a gray-level concentrative filter, the pixel intensity is replaced with the local average when the intensity variance with adjacent pixels is below a certain level while it is not replaced when the gray level variance is above a certain level. A fast algorithm of such a gray-level concentrative filter was conceived and proven to be effective to reduce the speckles in B-mode images [1]. In this paper, the gray-level concentrative filter was tested to remove the ripples in the CW Doppler spectrogram of velocity versus time with the gray-level intensity modulated with the spectral intensity. It was tested for the Doppler signals of cardiac blood flow, obtained with a prototype diagnostic ultrasound scanner. The filter was proven to be effective not only to reduce the ripples in the spectrogram but also to separate the Doppler signal and the white noise in the intensity level of the spectra. Without the gray-level concentrative filter, the Doppler

signals and the white noise overlapped so much in the intensity level that it was virtually impossible to separate them from each other. However, they became separatable in the intensity histogram after filtration with the proposed filter. By adjusting the threshold to the valley between their peaks in the histogram of spectral intensity after the filtration, the maximum velocity of the blood flow was automatically traced with a simple algorithm in the gray-scale Doppler spectrogram. By adjusting the cut-off intensity to the peak of white noise also in the intensity histogram after the filtration, the background noise level in the displayed spectrogram was reduced by more than an order of magnitude while the spectral shape and structure of the cardiac blood flow were preserved. [1] A. Sasaki et al. Adaptive speckle reduction process enhancing structure and texture of B-mode image Proc. 2003 IEEE Ultrasonics Symp., pp. 1545-1548.
Authors thank to Mr. Toshihiko Kawano and Mr. Tsuyoshi Mitake for their supports in the implementation of this method to a prototype scanner.

P1U-D-8 G11

DETECTION AND ANALYSIS OF FETAL MOVEMENTS BY MULTI-SENSOR DOPPLER (THE ACTIFOETUS SYSTEM)

A. KRIBÈCHE*[1], S. BENDERBOUS[1], F. TRANQUART[1], D. KOUAMÉ[2], PH. VINCE[3], and L. POURCELOT[1], [1]INSERM U619, [2]LUSSI-GIP Ultrasons, [3]Ultrasons Technologies.
Corresponding e-mail: ali.kribeche@med.univ-tours.fr

Fetal Heart Rate (FHR) monitoring is a crucial part of fetal monitoring before and during labour. Its aim is to detect any abnormalities which might indicate **acute fetal distress** and need for rapid treatment to avoid death or serious sequellae, including cerebral handicap. The other monitoring parameters are fetal movement, fetal tone, Fetal Breathing Movement (FBM) and amniotic fluid volume. The first objective of our study is to automatically detect the global activity of the fetus (movements of the legs, the thorax and the heart) and to characterize those movements in quantitative terms (speed, amplitude, duration, rate). The second objective is to evaluate fetal behavior and well-being, for the long term follow-up of pregnancies. To enable the investigation of fetal movement we developed an special device called ACTIFOETUS which consists of a set of 12 miniature ultrasonic sensors which can be positioned in a flexible matrix of polymer placed on the maternal abdomen. Those captors are linked to a multi-gate (5 depth gates), multi-channel, pulsed Doppler system working at 2,25 MHz connected to a personal computer. Among the twelve Doppler captors, a group of four is aimed at the thorax and eight at the fetal limbs. The goal is to cover the major part of the fetal structures. Using the ACTIFOETUS System it is therefore possible to monitor and record the information needed to evaluate Fetal Heart Rate (FHR), Fetal Breathing Movement (FBM), limbs movements and global movements of the fetus. Movements of the mother are recorded in parallel using an accelerometer. Two different methods have been evaluated for the analysis of Doppler signals generated by the movements of fetal structures: Fast Fourier Transform (FFT) and Independent Component Analysis (ICA). Several parameters can be displayed over time in each of the 12 $\times$ 5 = 60 Doppler gates : power of reflected signals, real time Doppler signal analysis (velocity of reflecting structures in mm/s) and amplitude of structure displacements (in mm). Lastly, we used technique ICA in order to separate Doppler signal come from a particular source because the Doppler signals acquired by ACTIFOETUS System come from diverse sources : heart of the fetus, maternal hearts, limbs and trunk of the fetus. It is foreseen to monitor fetal activity over large periods of time, in the range of several hours, by sequential ultrasonic transmission/reception periods. From these data it is possible to compute several important information concerning fetal activity and fetal behavior: sleep/activity rate, synchronization of fetal activity with maternal activity, type of movements of the fetus (slow, harmonious, saccadic, . . .), response to stimuli (change in direction of gravity vector, acceleration, sound, . . .). Authors will present preliminary normal *in-vivo* results obtained in 15 pregnant women (32-35 weeks). Recording duration for each examination was between 15 and 20 minutes each.

We express great thanks to Philippe Vince and colleagues, Ultrasons Technologies company for their participation, particularly Fabrice, Laurent and Denis.

Session: P1U-E

CAVITATION IN THERAPY

Chair: K. Hynynen
Harvard University

P1U-E-1 G10

CORRELATION OF ENHANCED ACOUSTIC BACKSCATTER TO TISSUE DAMAGE PRODUCED BY CAVITATIONAL ULTRASOUND THERAPY

B. C. TRAN*, J. B. FOWLKES, and C. A. CAIN, University of Michigan.
Corresponding e-mail: tranbc@umich.edu

We hypothesize that tissue damage produced by cavitational ultrasound therapy requires the initiation and maintenance of highly dynamic gas bubble populations within the tissue. In this paper, we show that enhanced acoustic backscatter (EAB), indicative of gas bubble formation (cavitation), is predictive of tissue damage. *In vivo* experiments were conducted using an ultrasound transducer comprised of a central, 1.27 cm diameter, 5 MHz monitoring element and a surrounding, 6.25 cm diameter, 1.44 MHz therapy element. A total of 120 exposures were applied in 10 canine kidneys. Each exposure contained 10000 10 μs duration pulses at 10 kHz pulse repetition frequency with 2000 W/cm^2 to 3200 W/cm^2 spatial peak pulse averaged intensity. Generally, one of the two kidneys in each animal was treated without ultrasound contrast agent (UCA) and the other while Optison UCA was continually infused at 1 μL/kg/min. During the therapy exposures, acoustic backscatter received on the monitoring element was

captured with a digital storage oscilloscope for offline MATLAB analysis. An approach was developed to analyze the RF data to detect EAB from the therapy site. The approach utilizes the fact that the distribution of tissue level backscatter prior to the onset of cavitation is statistically separable from the distribution of enhanced backscatter levels after cavitation is initiated. Basis distributions were generated using 20 representative datasets and a threshold backscatter level corresponding to EAB, with greater than 99% confidence, was defined. Results of the RF analysis were compared to results of the tissue analysis, conducted independently. We found the absence/presence of EAB was highly correlated with the absence/presence of tissue damage regardless of exposure intensity or the presence of UCA. In 117 of the 120 exposures, EAB predicted the presence of tissue damage (chi-square test yielded $p << 0.001$). Furthermore, for all exposures with EAB and tissue damage, the onset of EAB was significantly earlier with UCA than without (t-test: mean 200 pulses vs. 2200 pulses; $p < 0.01$). This is consistent with our previous observations that cavitation occurs much earlier within the exposure with UCA and may explain why the maximum tissue damage cross sectional area with UCA for these exposures was 2-4 times greater than without (t-tests: all $p < 0.02$). Further experiments are needed to determine if specific characteristics of the backscattered RF are indicative of either damage extent or character. We believe that the variability in cavitational tissue damage is related to the stochastic nature of gas bubble formation and destruction. With active monitoring of EAB during the therapy exposure, it may be possible to control the gas bubble activity and make cavitational tissue damage more predictable and controllable.
This research is sponsored by NIH Grant RO1-RR14450.

P1U-E-2 G9

RESONANCE FREQUENCY OF MICROBUBBLES IN SMALL BLOOD VESSEL

E. SASSAROLI*[1,2] and K. HYNYNEN[1,2], [1]Brigham's and Women Hospital, [2]Harvard Medical School.
Corresponding e-mail: esassaro@bwh.harvard.edu

It is well established that ultrasound contrast agents used for diagnostic and therapeutic ultrasound introduce cavitation sites into blood vessels. The most favorable condition for the transfer of energy from an ultrasonic field to a contrast bubble occurs when the center frequency of the ultrasonic field equals the resonance frequency of the bubble. The resonance frequency of gas microbubbles has been determined in unbounded liquids, however when bubbles are confined in small regions, their resonance frequency is affected by the surrounding structures. We present here a parametric study on how the resonance frequency of microbubbles in the microvasculature is affected by the bubble radius, the radius and the length of the vessel as well as the bubble position in the vessel. The resonance frequency is determined by solving numerically the Laplace equation for the potential flow close to the bubble with the appropriate boundary conditions at the vessel wall, inlet and outlet. Numerical results indicate that the

resonant frequency of these bounded microbubbles is below standard therapeutic operating frequencies of 1 3 MHz. For example, the resonance frequency of a gas microbubble of radius 2 μm, containing octaflurопropane (Optison contrast agent), placed at the center of a capillary blood vessel of radius 4 μm is about 180 kHz. This work is expected to provide some useful insights into the mechanisms of energy absorption of a gas microbubble in small blood vessels as an aid for therapeutical focused ultrasound treatments.
NIH training grant

P1U-E-3 G8

INVOLVEMENT OF CAVITATION IN THE APPEARANCE OF HYPERECHOIC REGIONS IN ULTRASOUND IMAGE VISUALIZATION OF HIGH INTENSITY FOCUSED ULTRASOUND THERAPY: IN-VIVO RESULTS

B. A. RABKIN*[1,2], V. ZDERIC[1,2], and S. VAEZY[1,2], [1]Deptartment of Bioengineering, University of Washington, [2]Center for Industrial and Medical Ultrasound, Applied Physics Lab., University of Washington.
Corresponding e-mail: brabkin@u.washington.edu

High Intensity Focused Ultrasound (HIFU) treatment of soft tissues has been shown to result in a hyperechoic region in B-mode ultrasound (US) images. This is believed to result from bubble activity at the HIFU focus. Here we report our in-vivo results of detecting inertial and stable cavitation in correlation with the appearance of a hyperechoic region. **Methods:** The system consisted of a HIFU transducer, a cavitation detector transducer, and an US-imaging probe that were all co-focal and synchronized. Specifications are: (1) a single-element air-backed HIFU transducer (3.3 MHz) placed coaxially to (2) a broadband single element unfocused A-mode transducer, as the cavitation detector transducer, (bandwidth of 0.5-5.5 MHz) and coplanar with (3) a curved array imaging probe (bandwidth of 5-9 MHz). HIFU at in-situ intensities of 220, 490, 850, 1280 and 1710 W/cm^2 (80% duty cycle, 6.24 Hz pulse-repetition-frequency) was applied for 10 s to muscles of the mid-back and outer thigh of six pigs in-vivo at a depth of 2 cm. Active and passive cavitation detection (ACD and PCD, respectively) were performed. ACD consisted of measuring the changes in the peak-to-peak amplitude of the backscatter signal from the HIFU focal site, an indicator of bubble activity. PCD consisted of measuring the levels of broadband and subharmonic noise from the FFT of the collected RF signal, as indicators of inertial and stable cavitation, respectively. **Results:** Visualization of a hyperechoic region was achieved at intensities above 850 W/cm^2, with the probability of visualization increasing from 33% at 850 W/cm^2 to 100% at 1710 W/cm^2. ACD results show a linear correlation between the onset time of cavitation and the appearance of a hyperechoic region in the US image, with correlation coefficients greater then 0.84 and 0.87 for HIFU intensities of 1280 (n=19) and 1710 (n=18) W/cm^2, respectively. The PCD results show that inertial cavitation occurred typically within 0.5 s from the appearance of a hyperechoic region in the US image. The time difference between the onset of cavitation and the

appearance of a hyperechoic region decreased with increased in-situ HIFU intensity. The PCD results also show that the level of stable cavitation increased with the increase in HIFU intensity above 1280 W/cm^2 but stable cavitation was not present throughout the appearance of a hyperechoic region. **Discussion:** Cavitation activity, with good correlation, was detected during the formation of a hyperechoic region in a diagnostic US image, at the site of HIFU treatment. This correlation suggests a direct method of monitoring the therapy to avoid potentially-harmful effects of cavitation such as uncontrolled lesion formation in prolonged HIFU exposures, or utilizing the beneficial effects such as visualization of the HIFU focal spot, without causing coagulative necrosis, using short HIFU exposures.
Support by NIH, NSF and DoD USA.

P1U-E-4 G7

MICRO-CAPSULE DESTRUCTION USING ULTRASOUND FOR DRUG DELIVERY SYSTEM

D. KOYAMA*, K. WATARU, and Y. WATANABE, Faculty of Engineering, Doshisha University.
Corresponding e-mail: etc1102@mail4.doshisha.ac.jp

Micro-capsule destruction for drug delivery system (DDS) using ultrasound is discussed. In DDS using ultrasound, micro-capsules with an elastic thin shell release the inside drugs at the moment of their destruction. An optical observation of the capsule destruction using a high-speed video camera (FASTCAM, Photron, Japan) is carried out. In our experiments, micro-capsules (F-80ED, Matsumotoyushi, Japan) made of PVC (polyvinylden chlorideacrylonitrile) and whose average radius is 50 μm are used. The micro-capsule can be trapped at the anti-node of the acoustic standing wave at the frequency of 115 kHz. The micro-capsule in the resonance condition can be trapped by the lowest driving acoustic pressure. As the driving acoustic pressure of the standing wave is increased, the micro-capsules trapped at the anti-node show circling movements, and then they eventually collapse. The direction of the circling movements is irregular in the acoustic standing wave. The turning radii of the circling movements are approximately 1 to 3 times larger than the capsule radii, and the cycles of circling movements depend on the driving acoustic pressure, i.e., the cycles are becoming shorter and shorter with the increasing driving acoustic pressure. At the moment of destruction, it is found that the micro-capsules change their shapes and the internal gases jet out of the capsules instantly. The sound pressure threshold for capsule destruction depends on the radii of micro-capsules and is the lowest under the resonance condition. Applied in a clinical setting, achievement of local medication with low-energy is required. The capsule destruction by the pulse wave is also examined. The micro-capsules are trapped at the anti-node of the acoustic standing wave with the sound pressure of 25 kPa and are destroyed by the pulse wave. As the driving pulse duration is increased, the violent capsule destruction is appeared. In the driving condition of the pulse wave, the internal gas of the micro-capsule cannot be emitted completely toward

the surrounding media and a part of the internal gas remains inside the broken shell. After the capsule destruction, the emitted internal gases produce a new daughter bubble. The daughter bubble and the broken shell are attracted to each other due to secondary Bjerknes forces. The aggregation, the broken shell and the daughter bubble, cannot be trapped at the anti-node and moves beyond the camera view since the resonance frequency shifts to lower frequencies due to the shell rupture. It is confirmed that the sufficient pulse duration for the complete emission of the internal gas is necessary after the capsule destruction. Although the sound pressure threshold for the capsule destruction by the pulse wave shows data spread with decreasing the pulse duration, there is not so much of a difference between the threshold values by the pulse wave and by the continuous wave. It is considered that the capsule destructions by pulse wave mostly depend on the amplitude of the driving acoustic pressure rather than the driving pulse duration.

P1U-E-5 G6

TESTING THE ROLE OF SHEAR AND LONGITUDINAL WAVES IN KIDNEY STONE COMMINUTION BY A LITHOTRIPTER SHOCK PULSE

O. A. SAPOZHNIKOV*[1], R. O. CLEVELAND[2], M. R. BAILEY[3], and L. A. CRUM[3], [1]Faculty of Physics, Moscow State University, [2]Department of Aerospace and Mechanical Engineering, Boston University, [3]Center for Industrial and Medical Ultrasound, Applied Physics Laboratory, University of Washington.
Corresponding e-mail: oleg@acs366.phys.msu.ru

Shock wave lithotripsy has been in clinical use for many years but there is no consensus as to the main mechanism of kidney stone comminution. Experiments show that several mechanisms might be involved, including cavitation, spallation, and dynamic fatigue. Until recently little attention was paid to shear elasticity of the stone material, i.e. mechanical load was mainly attributed to the longitudinal waves. In a previous numerical study, we found that shear elasticity resulted in tremendous change in the stress pattern inside cylindrical stones. The numerical model has been extended to study elastic waves in cylindrical stones embedded into a layer of strongly absorbing or lower impedance medium. Strains and stresses in the stone are calculated based on the Lame equation for an isotropic elastic medium. Lithotripter shock waves of various temporal and spatial profiles were considered accordingly to several clinical models of lithotripters. Maximum compression, tensile and shear stresses are predicted depending on the side-surface condition in order to investigate the importance of the shock wave propagating in liquid near the side surface of the stone. The results of modeling are compared with the experimental observations of where cracks are formed. Shock waves were generated by a research electrohydraulic lithotripter modeled after the Dornier HM-3, and cylindrical stones were made from U-30 cement. The measurements and modeling show that both shear and

longitudinal waves play an important role in creating the regions of excess stress where cracks form.

Supported by ONRIFO, NIH-Fogarty, RFBR, NIH DK43881, and Whitaker Foundation.

P1U-E-6 G5

EX-VIVO STUDY OF CAVITATION-ENHANCED ULTRASOUND HEATING BY COMBINING LOW (40KHZ) AND HIGH (566KHZ) FREQUENCY ULTRASOUND

H.-L. LIU*[1], T.-C. SHIH[2], B.-Y. LU[1], W.-S. CHEN[3], and W.-L. LIN[2], [1]Department of Electronic Engineering, Tung-Nan Institute of Technology, Taipei, Taiwan, [2]Institute of Biomedical Engineering, National Taiwan University, Taipei, Taiwan, [3]Department of Rehabilitation, National Taiwan University Hospital, Taipei, Taiwan.
Corresponding e-mail: haoliliu@ntu.edu.tw

The objective of this study is to demonstrate the cavitation-enhanced ultrasound heating via combining low-frequency ultrasound during a thermal treatment. To perform this, *ex-vivo* fresh porcine muscle was used as the target of ultrasound ablation. Two ultrasound transducers were used: A 566-kHz spherical transducer (10 cm in diameter and 10-cm in radius) was used to generate the thermal lesion while another 40-kHz planar transducer (5 cm in diameter) was positioned orthogonally with its axis across the focus of the high-frequency one. The emission and backscattered signals from the bubble activity were also recorded during the heating process by a needle hydrophone. During each treatment, the tissue block was either exposed to the two transducers simultaneously, or pre-treated with the low frequency transducer 2 - 10 minutes prior to the use of the focused one. Compared to the lesion formed by exposure to the focused transducer only, its size enlarged up to 392% in the axial direction and up to 400% in its cross section. The enlarged lesion, rather than being in tadpole shape, symmetrically in the focal direction, which implied that the cavitation-enhanced lesions could be generated without losing its penetration ability. It was also found that the lesion enlargement effect depended both on the exposure time and intensity of the low-frequency ultrasound. This study demonstrates an easy and effective approach to enlarge the final size of a thermal lesion by applying low frequency ultrasound simultaneously, and would be important if a large-volume and deep-sited thermal lesion by ultrasound ablation was necessary.

P1U-E-7 G4

A GEL PHANTOM FOR MR CALIBRATION OF THERMAL THERAPIES

S. LOCHHEAD*, M. MCDONALD, R. CHOPRA, and M. J. BRONSKILL, Sunnybrook & Women's College Health Sciences Centre.
Corresponding e-mail: lochhead@sten.sunnybrook.utoronto.ca

Thermal therapy, the application of heat to coagulate tissue, is a rapidly developing therapeutic technique for soft tissue tumor treatment. Heating of tissue can be achieved with external, interstitial or intracavitary devices using a variety of energy sources including microwave; radiofrequency (RF); laser; and ultrasound. These treatments tend to be less invasive than conventional surgical resection and can sometimes offer an alternative when surgery is not feasible.

Cell death at the temperatures experienced during therapy is rapid, making accurate control and delivery of heating essential in order to reduce damage to surrounding normal tissues. Imaging technologies can play an important role in thermal therapy in the guidance, monitoring, and evaluation of a procedure. Magnetic resonance (MR) imaging is frequently used because of its ability to measure temperatures non-invasively during heat delivery, its superior soft tissue contrast for tumor visualization and device guidance, and its ability to differentiate after heating between regions of thermal damage and normal tissue.

A phantom material with tissue-mimicking thermal properties is essential for the development and characterization of thermal therapy devices, and for clinically related activities such as quality assurance, device comparisons, and treatment verification. Key requirements for such a material are (a) heat absorption and conduction properties similar to tissue; (b) stability over the range of temperatures experienced in thermal therapy (up to 100°C); (c) accurate delineation of the volume that is thermally coagulated; and (d) a coagulation temperature similar to that of tissue. To facilitate MR imaging of the coagulated volume, the thermal therapy phantom material should undergo a large, non-reversible change in MR parameters (T_1 or T_2) upon reaching a threshold temperature for thermal coagulation.

A tissue-mimicking phantom material has been developed for use with ultrasound thermal therapy devices and techniques, in conjunction with MR monitoring of heat deposition and thermal damage. Its heat absorption and conduction properties are similar to those of tissue with an acoustic attenuation coefficient of 0.52 ± 0.05 dB cm^{-1} MHz^{-1}, and a speed of sound of 1556 ± 4 m s^{-1}. The coagulation temperature of the phantom can be adjusted between 50°C and 60°C to simulate various tissues and it is stable at the higher temperatures experienced during thermal therapy. This material has MR properties that change upon thermal coagulation (i.e. the spin-spin relaxation time, T_2, decreases by approximately 60%), enabling its use for device characterization and treatment verification using simple T_2-weighted imaging techniques. A full three-dimensional set of MR images can be acquired within five minutes to outline the extent of the coagulated region with 1 mm spatial resolution. This material also has potential for use with other thermal therapy modalities (laser and RF).

Session: P1U-F

TISSUE ELASTOGRAPHY
Chair: P. Delachartre
Creatis

P1U-F-1 H1

DIAGNOSTIC RESULTS FOR BREAST DISEASE BY REAL-TIME ELASTICITY IMAGING SYSTEM

T. MATSUMURA*[1], S. TAMANO[1], R. SHINOMURA[1], T. MITAKE[1], M. YAMAKAWA[2], T. SHIINA[2], A. ITOH[3], and E. UENO[4], [1]Research & Development Center, Hitachi Medical Corporation, [2]Institute of Information Sciences & Electronics, University of Tsukuba, [3]Tsukuba University Hospital, University of Tsukuba, [4]Institute of Clinical Medicine, University of Tsukuba.
Corresponding e-mail: matsumura@rd.hitachi-medical.co.jp

It is known that the lesion, such as cancer, is changed to be harder as the disease becomes worse. Our group previously reported that our elasticity imaging system with 10 frame/s of real-time imaging capability was developed and clinically applied to the breast tissue diagnosis where cancers may be displayed as hard tissue. In this paper, we report the state of our intensive assessments on breast tissue diagnosis and discuss the clinical usefulness with our results so far. Our system is established with modified commercial ultrasound scanner with 7.5 MHz linear array probe, and PC with dual 2.8 GHz processors, where our algorithm called as Extended Combined Autocorrelation Method is implemented with highly optimized and 12 frame/s of frame rate is performed by the special task division for the dual processors. Through compressing the body by probe in free-hand, the echo signals are captured sequentially and using nearest-neighbor RF frames, differences of envelope peak and carrier phase shift are calculated to get tissue displacement in response to deformation. Then, tissue strain is color-coded according to its magnitude and translucently super-imposed on the conventional black & white 2D image for easy and fast comparison of local anatomical position between strain image and B-mode image. For the purpose of higher stability of imaging diagnosis, in addition, we tried to implement several post-processing techniques such as (1) frame-to-frame smoothing, (2) adaptive contrast optimization, (3) noise-frame rejection, and (4) noise-region reduction (i.e., tissue-region extraction). Those imaging procedures are processed with related for each other as is explained in paper. Our system was clinically assessed for 137 patients with breast diseases (benign 76 lesions, and malignant 61 lesions). Depended on the imaging pattern of strain-zero region inside and outside the lesion that is observed as low-echoic region in B-mode image, we introduced 5 grades of elasticity score ranging from 1 (no strain-zero region; benign) to 5 (broader strain-zero region; malignant). The scoring method was applied to all of the lesions, and its diagnosis capability was statistically evaluated as follows. (1) The statistical group of malignant lesions had the mean score of 4.26 (S.D.=±0.89) and significantly separated ($p<0.001$)

from the group of benign lesions, those mean score of 1.88 (S.D.=±0.99). (2) Elasticity scoring method provided a sensitivity of 86.9%, a specificity of 92.1%, and an accuracy of 89.8%. The details of elasticity scoring method will be discussed. In conclusion, due to the post-processing techniques aiming at stable imaging observation, reproducible elasticity imaging diagnosis has been realized. Furthermore, we confirmed that our preliminary clinical results derived from the elasticity scoring method provide promising feature for the diagnosis capability.

P1U-F-2 H2

HARDWARE IMPLEMENTATION FOR RECEIVE BEAMFORMING AND TRANSVERSE ELASTICITY IMAGING

P. DELACHARTRE*, H. LIEBGOTT, S. MICHELET, M. PERNOT, and D. VRAY, Creatis.
Corresponding e-mail: delachartre@creatis.insa-lyon.fr

A hardware implementation is presented in a context of receive beamforming for raw data derived from a commercial ultrasound scanner. The hardware is made of programmable components FPGA and microcontroller. This consists in a stand alone board completely configurable from a PC. The board is connected to a commercial ultrasound scanner. The present work is focussed on hardware implementation devoted to receive data beamforming for the transverse component estimation in elasticity imaging. The board is directly connected to the receive circuit of the ultrasound array before the beamformer of the commercial ultrasound scanner. The architecture includes 16 input channels with programmable filters, switch matrices for multiplexing the 16 input channels in a variable number of outputs, from 1 to 16, controlled by a FPGA (Xilinx Spartran II XC2S15), and 16 video amplifiers. The number of output can be changed by loading the new configuration in the FPGA memory using a microcontroller (PHILIPS P89C51RD2). The access to the microcontroller is achieved at any time through an USB connection from a PC. This architecture is flexible and has been designed in order to plug a digitization system with a single input or multiple channel inputs. The experimental board is plugged into a B-K medical 3535 ultrasound scanner equipped with a 8560 linear array. The 16 input channels are multiplexed in 4 outputs and digitized through a 4-channels 9374L Lecroy scope. The receive beamforming is achieved to produce a transverse oscillating Point Spread Function (PSF) leading to transverse RF signals for high resolution parameter estimation. The beamforming scheme consists in a dynamic focussing using a quadratic time delay and a dynamic double sinc aperture function. According to linear acoustic theory, the double sinc apodization produces a pressure field with oscillations in the transverse direction. The dynamic process maintains a constant lateral oscillations frequency with respect to the depth. Application to transverse elasticity imaging is shown. Experimental results of transverse displacement maps are found to be in good agreement with simulations performed with a Finite Element Method and a transient pressure

field calculation. The mean standard deviation of the transverse estimate is equal to 0.2 pixel. It can be compared to a mean standard deviation of the axial estimate of 0.14 pixel. The estimation results have good performances but show that the axial resolution is still better than the transverse one. The limitation is related to the transverse frequency which depends on the aperture size given by the active receive elements of the ultrasound array.

P1U-F-3 H3

SIGNAL PROCESSING FOR ULTRASOUND-BASED ARTERIAL PULSE WAVE VELOCITY ESTIMATION

R. T. HOCTOR*, A. M. DENTINGER, and K. E. THOMENIUS, GE Global Research.
Corresponding e-mail: hoctor@research.ge.com

Assessment of the arterial pulse wave velocity (PWV) using ultrasound has been an area of recent interest [1]. The signal processing methods associated with this problem have not proven sufficiently robust, however, especially in the presence of pulse wave reflections. Such reflections are always present throughout the arterial system and are a well-recognized source of error in PWV measurement. It is well-known that the apparent PWV, as measurements taken in the presence of reflections are called, can be strongly biased away from the true value. Accurate estimation of PWV in vivo is therefore an unsolved problem.

In the present work we propose a new signal processing technique for measuring PWV based on ultrasound measurements, which compensates for whatever pulse wave reflections are present in the observation. This estimator will be developed mathematically and the relationship between the new approach and signal processing approaches to a class of problems encountered in radar will be discussed in detail.

The new signal processing technique was tested on both simulated data with known PWV and reflection parameters as well as on in vivo data of human common carotid arteries. The simulation study compared the new algorithm to several existing techniques for PWV estimation including the commonly used foot-to-foot method applied to ultrasound measurements and the well-known Meinders approach [1]. All methods correctly estimated the simulated PWV for the case of no reflections. In the presence of a simulated reflection, the new signal processing technique correctly estimated the PWV independent of reflection parameters, while the other methods overestimated the PWV by 5-15% for a reflected coefficient of 0.1 and 10-40% for a reflection coefficient of 0.3.

The in vivo data was taken using a GE Vivid 7 ultrasound scanner with a 10 MHz linear probe positioned to acquire 8 beams spaced by 0.6 mm along the flow axis of the CCA. An initial data set was taken on several subjects before, during, and after isometric exercise. The signal processing technique produced average PWV estimates of 4.0-6.5 m/s in resting subjects with a 15-25% increase in the PWV during exercise. The other methods failed to produce average PWV estimates within realistic physiological limits (less than 15 m/s) for the in vivo data.

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P1U-F-4 H4

NONINVASIVE VASCULAR ELASTOGRAPHY BASED ON A NEW 2D STRAIN ESTIMATOR: SIMULATIONS RESULTS

C. SCHMITT*, R. L. MAURICE, J.-L. GENNISSON, and G. CLOUTIER, Laboratory of Biorheology and Medical Ultrasonics.
Corresponding e-mail: cedric.schmitt@umontreal.ca

Objectives: In vascular diseases, the detection of unstable plaques would be of high impact. This could be achieved by measuring the plaque geometry and elasticity. Recently, a new method was proposed to assess non-invasively vascular elastograms (NIVE). In this framework, the stress is generated intraluminally by the cardiac pulsatility and the RF images are acquired with an extra-corporal linear probe. In relation to this, we present an algorithm to assess the full 2D strain tensor. Originally used in medical image registration, this algorithm computes the affine transformation between two images, by considering a smoothness constraint on the intensity and strain tensor. To compensate for the intensity variation, local contrast and brightness parameters are incorporated to the model. To recover large deformations, a coarse-to-fine scheme is adopted. **Methods:** The algorithm robustness was explored using simulated RF. Axial compression and lateral dilatation (0-10%), axial shear (0-2.3°) and signal-to-noise ratio (SNR) (5-40 dB) were applied on homogeneous tissues. The three main causes of decorrelation noise were generated : "speckle motion artifact (SMA)"(induced by the PSF curvature and axial shear), out of plane motion (OPM) (during axial compression), and additive noise (SNR). Furthermore, homogenous and heterogeneous vessels were simulated. The first one similar to a healthy single-layer carotid artery was subjected to an intraluminal pressure ranging from 2 to 20 mmHg. The second one consisted in a diseased carotid artery with a hard plaque. The effect of plaque hardness and intraluminal pressure on the contrast estimation was investigated. The Von Mises (VM) elastograms were computed and compared to the theoretical forward problem simulations. **Results:** For the homogeneous tissue, the estimator was not sensitive to the SMA for axial compressions below 9%. For OPM (with an axial compression of 0%, 4% and 6% and a lateral dilatation ranging from 0% to 10%), the estimator was not biased and showed a low axial deformation error (SD = 0.45%). With an axial compression, the 2-D estimator measured a mean lateral dilatation close to the theoretical value. The variance was constant for a lateral deformation higher than 3%. Even in the presence of low SNR, the estimation was efficient. The homogenous vessel presented the lowest error on the

VM estimation for an intraluminal pressure of 11.5 mmHg. Contrasts obtained from the heterogeneous vessels did not depend on the applied pressure but was an exponential function of the elasticity ratio. **Conclusion:** The proposed algorithm showed a good robustness in the presence of artifacts. For the VM strain range investigated (up to 16%), theoretical and simulated results were in good agreement. This estimator is promising for *in vivo* application to characterize non-invasively the hard plaque evolution in carotid arteries.
This work was supported by grants from the Natural Sciences and Engineering Research Council of Canada (#138570-01) and Valorisation-Recherche Québec (structuring group program), and by a research scholarship award from the Fonds de la Recherche en Santé du Québec.

P1U-F-5 H5

TISSUE MIMICKING PHANTOM FOR ULTRASONIC ELASTOGRAPHY WITH FINELY ADJUSTABLE ELASTIC AND ECHOGRAPHIC PROPERTIES

K.-I. KAWABATA*[1], K. WAKI[2], T. MATSUMURA[3], and S.-I. UMEMURA[1],
[1]Central Research Laboratory, Hitachi, Ltd., [2]Development Design Depertment Ultrasound System Division, Hitachi Medical Corporation, [3]Research & Development Center, Hitachi Medical Corporation.
Corresponding e-mail: kk@crl.hitachi.co.jp

The determination of the elastic properties of soft biological tissues is of fundamental interest since these properties depend, in a significant manner, on the pathological status of the tissues. This tissue characterization is performed with a specific ultrasound imaging called elastography. This technique is based on evaluating the strain of the tissue under an applied axial stress. The strain is computed from the modifications in the ultrasound signals due to the compression. The elastography is expected to be a powerful diagnostic tool to distinguish malignant tissues from normal ones, especially in the areas of breast and prostate cancer.

As in other ultrasonic diagnostic methods such as echography, tissue-mimicking phantoms will be very useful in developing systems in elastography. Until now, several kinds of such phantoms are available utilizing hydrogels. Hydrogels are chemical systems consist of polymers and water bound to the polymers, and have acoustic parameters similar to tissues in bodies. Their elastic properties can be easily controlled by modifying the ratio of the polymers in gels. Polymers that show sol-gel transition by changing temperature such as agarose or gelatin are mainly used for phantoms in elastography because of the ease of handling. Simply heat-up and cool-down process is required. Despite the easiness in handling, there arise difficulties in predicting exact concentration of polymers when heat-up and cool-down process is involved. This also affects the uniform and reproducible distribution of ultrasound-scattering materials added in the phantom such as carbon particles to compute the degree of strains from ultrasound echographic data.

Using of thermally irreversible gels, which can be prepared from solutions of pieces of polymers (monomers) by adding polymerization initiators, is proposed

in this presentation. The procedure does not include heat-up and cool-down process thus virtually free from above problems with agarose and gelatin gels. The concentrations of the monomers in the gel suitable for hard, intermediate, and soft phantom were found to be around 20, 10, and 6 %, respectively. The phantoms were stable for more than one month. It was also found that fine adjustment of monomer concentration made it possible to obtain stealth phantom, which contain regions with the same echographic property and different elastic properties distinguishable with elastography.
Part of this work was funded by Japanese Ministry of Education, Culture, Sports, Science and Technology through Grant-in-Aid for the Creation of Innovations through Business-Academic-Public Sector Cooperation.

P1U-F-6 H6

CROSS-SECTIONAL ELASTICITY IMAGING OF ARTERIAL WALL IN SHORT-AXIS PLANE WITH ULTRASOUND

N. NAKAGAWA[1], H. HASEGAWA[1], H. KANAI*[1], M. ICHIKI[2], and F. TEZUKA[3],
[1]Graduate School of Engineering, Tohoku University, [2]Sendai Hospital of East Railway Company, [3]National Sendai Hospital.
Corresponding e-mail: hasegawa@us.ecei.tohoku.ac.jp

Background: We have developed the *phased tracking method* (PTM) [IEEE Trans. UFFC, 44, 1997] for measuring the minute change in thickness during one heartbeat and elasticity of the arterial wall with transcutaneous ultrasound. When this method is applied to a plane perpendicular to the axis of the artery (short-axis plane), only the ultrasonic beam which passes through the center of the artery, is coincides with the direction of the change in thickness. At other beam positions, the wall motion cannot be accurately tracked because the direction of wall expansion slips off the beam. **Methods:** To obtain the cross-sectional image of elasticity in the short-axis plane using transcutaneous ultrasound (10 MHz), in this paper, the directions of ultrasonic beams are designed so that each beam always passes through the center of the artery; thus, they always coincide with the direction of the wall expansion. Using the PTM, the minute change in thickness of the wall along each ultrasonic beam is measured. **Basic Exp.:** Using a silicone rubber tube, which was driven by pulsatile flow generated by an artificial heart, changes in thickness of both anterior and posterior wall were accurately measured by proposed method, in the region of $\pm$2.0 mm around the beam which passes through the center of the tube. The elastic moduli calculated from the maximum changes in thickness were homogeneously obtained and their average value (anterior wall: 5.7 MPa, posterior wall: 5.4 MPa) agreed well with that (5.8 MPa) obtained by the separate static experiment using a laser line gauge. **In vitro Exp.:** Using the same experimental setup as the basic experiment, the elastic modulus of an extracted human iliac artery was measured. By comparing with pathological images, the measured elastic moduli of collagen-rich region and the smooth-muscle-rich region were 2.7 $\pm$1.7 MPa and 0.47 $\pm$0.10 MPa. These values have similar tendency with

elastic moduli for the fibrous tissue of 0.91 ±0.23 MPa and the smooth muscle 0.51 ±0.22 MPa reported in the literature [*Circulation* 83, 1991]. **In vivo Exp.:** By the conventional linear scanning, the change in thickness was measured accurately only along 6 beams (width: 0.9 mm) around the beam which passes through the center of the artery. Using the proposed method, measured changes in thickness along all scan lines of carotid artery (number of beams: 30, width: 2.0 mm) had similar amplitudes (about 50 μm). From the change in the thickness along each beam, the cross-sectional elasticity image of anterior and posterior walls (0.35 ±0.25 MPa) was obtained within a sector-shape area of 38 degrees in the short-axis plane. Furthermore, the measured area was enlarged to 70 degree by measuring two different regions by rotating the probe along the neck. In these two elasticity images, the similar pattern was found within the region which was scanned by both measurements. **Conclusion:** This novel scanning method offers potential for transcutaneous elasticity imaging of atherosclerotic plaque in the short-axis plane.

P1U-F-7 H7

NONLINEARITY STUDIES IN SOFT TISSUES WITH THE SUPERSONIC SHEAR IMAGING SYSTEM

S. CATHELINE*, J.-L. GENNISSON, J. BERCOFF, C. BARRIÉRE, and M. FINK, Laboratoire Ondes et Acoustique.
Corresponding e-mail: stefan.catheline@espci.fr

The ultrafast scanner has shown to be a powerful tool to detect shear wave propagation within soft tissues in transient elastography experiments. More recently it was also used to generate shear waves thanks to the acoustic radiation pressure. This technique, the so called supersonic shear imaging, can easily be implemented in an acoustoelasticity experiment. Thus the association of static elastography with dynamic elastography, can reveal the nonlinear properties of soft materials. More over, using a new theoretical approach of the strain energy in soft solid [Hamilton, Ilinsky and Zabolotskaya, J. Acoust. Soc. Am., 114, 2436 (2003)], it is shown that the acoustoelasticity experiment can be greatly simplified. Instead of measuring shear wave speed for three different polarizations in order to completely determine the nonlinearity of standard solids, one is sufficient in soft solids to characterize the nonlinear shear elasticity.

P1U-F-8 H8

ASSESSMENT OF BONE FRACTURE AND BONE HEALING BY ULTRASOUND ASSISTED VIBRATIONAL METHOD

A. ALIZAD*, M. WALCH, J. F. GREENLEAF, and M. FATEMI, Mayo Clinic College of Medicine.
Corresponding e-mail: aza@mayo.edu

Bone fracture is a common and important clinical issue. Noninvasive evaluation of bone fracture and monitoring bone healing process is of significant interest. Structural characteristics of bone may be studied by vibration methods. The vibrational characteristics of any object are directly related to the physical properties of that object. A fracture in a bone results in the loss of mechanical stability of the bone. Alteration of the mechanical properties leads to changes the natural resonant frequency of the bone. The purpose of this research is to evaluate bone fracture and subsequent healing through the measurement of the natural frequencies of the bone before fracture, after fracture, and during healing. Resonance frequency analysis can be an effective tool in bone assessment. In this method, a vibrating force is applied to the bone and the resulting response is recorded and used to evaluate bone properties. Previously, investigators have utilized mechanical means to induce vibration in bone. Here, we present a vibration method based on the radiation force of ultrasound. An advantage of the proposed method is that it is remote and non-invasive. In this method, two continuous-wave ultrasound beams at slightly different frequencies are used. The beams are positioned to focus at the same spot on the bone. The interference of the two beams produces a small radiation force (normally in mN range) at the difference frequency (df) on the bone. This force vibrates the bone and the resulting motion (normally in nano-meter range) is detected either by a laser vibrometer or an acoustic hydrophone, and then recorded. Here, we use this method to monitor changes in bone structure introduced by a partial fracture. Experiments were performed on excised rat femurs. Each bone was secured in a fixture at one end while the other end was free. We placed the bone at the focal region of the ultrasound beam in a water tank. First, we determine the natural resonance frequency of an intact bone in the first bending mode by sweeping df from 0 to 10 kHz and recording the resulting motion of the bone. The resonance frequencies were found from the peaks of the recorded signal. Then, we simulated partial fracture by introducing a 1.5-mm deep and 300-micron wide transverse cut into the bone and measure the resonance frequency in the same manner. In the next experiment, we simulated bone healing by applying bone cement to bond at the cut and measured the resonance frequency again. The resulting resonance frequencies were typically 925 Hz, 850 Hz, and 947 Hz, for intact, fractured, and the bonded bone, respectively. The decrease in the resonance frequency of the fractured bone is due to a decrease in the effective stiffness of the bone. We also measured higher mode resonance frequencies with similar results. The above experiments demonstrate that the resonance frequency is an indicative of bone fracture and healing, and the radiation force method can be used as a remote and non-invasive tool for monitoring bone fracture and healing. Further studies are needed to apply this method in vivo.

P1U-F-9 H9

COMPUTATIONAL ASPECTS OF YOUNG'S MODULUS RECONSTRUCTION FROM ULTRASONIC FREEHAND SCANNING

J. JINGFENG*, T. J. HALL, and E. L. MADSEN, University of Wisconsin-Madison.
Corresponding e-mail: tjhall@wisc.edu

The onset of many cancers is accompanied by changes in tissue macrostructure and microstructure that result in an increase in tissue stiffness. Ultrasonic modulus imaging (UMI), derived from the relative displacement of echo signal sources between two echo fields, has the potential for detecting and characterizing tumors. More importantly, the elastic moduli provide absolute measures of inherent tissue properties that are otherwise unavailable during the pathological evolution of tumors. However, many previous methods are only capable of showing the relative modulus distribution. This limitation results in little advantage of UMI over ultrasonic strain imaging which can be performed in real-time and provides the very similar information. Furthermore, many existing UMI methods require complete knowledge of either natural or essential boundary conditions. Obviously, this is a difficult requirement if freehand scanning, the most common clinical scanning procedure, is employed. An additional challenge limiting the use of ultrasonic freehand scanning is that the natural coordinate system is referenced to the contact surface of the transducer, which is actually mobile, but a fixed coordinate with respect to the reaction force of deformation is needed to simplify the inverse solution.

The objective of this study was to develop a practical method for Youngs modulus reconstruction using ultrasonic freehand scanning. The abovementioned challenges may be met by modifying the Kallel-Bertrand (K-B) method (IEEE Trans. on Med. Imag. 15: 299-313) as follows. First, the original (K-B) formulation was recast in the presence of the acquiring surface pressures using a pressure sensor array mounted on the compression plate. As a result, the absolute modulus can be reconstructed, instead of the relative modulus distribution. However, a simple example demonstrates that the reconstructed Youngs modulus distribution may not be unique when only displacement boundary conditions are used. Second, a forward finite element analysis program (ANSYS Inc., Pittsburg PA) was used to systematically convert the surface pressure acquired from the integrated pressure sensor array on the top of the deformed object into the reaction forces on the bottom of the region of interest (ROI) where the displacements were known from a speckle tracking algorithm. Speckle tracking was also used to establish the boundary conditions around the ROI. Then, the estimated displacements within the ROI and the converted reaction forces were utilized to iteratively reconstruct the Youngs modulus distribution.

Data acquired from several tissue-mimicking phantoms with hard spherical or cylindrical inclusions embedded within soft backgrounds are used to test the proposed method. Our results match well with the known modulus distribution in phantoms. The performance of this approach and its limitations will be

discussed and compared with other approaches.
This work was supported, in part, by DAMD17-00-1-0596, NIH R01 EB000459, and the University of Wisconsin.

Session: P1U-G

SAW WIRELESS
Chair: R. Weigel
Erlangen University

P1U-G-1 K1

SAW ANTENNA DUPLEXER FOR TRUNKING COMMUNICATION

J. LIU* and S. HE, Institute of Acoustics, The Chinese Academy of Sciences.
Corresponding e-mail: heshitang@mail.ioa.ac.cn

The Trunking Communication System working in 300 400 MHz requires an antenna duplexer with low insertion loss, sharp-cutoff frequency characteristics, reactive characteristic in the mutual frequency bands and small size, which is not commercially available. We have proposed a SAW antenna duplexer to fulfill the requirements mentioned above. To satisfy the demand of reactive characteristic in the mutual frequency bands to reduce disturbing between the Rx and the Tx, we add a π-type high pass LC filter between the antenna and the Rx as phase shifter. In order to both get good stopband rejection and enhance the power endurance, we divide the Tx filter into two parts, one part before the power amplifier and the other coupling with antenna. The part before the power amplifier is composed of ladder-type SAW filter coupled with SAW bandstop filter with the insertion loss about 3.1dB and attenuation about 50dB in receiving frequency band (382 386MHz). The part coupling with antenna is composed of ladder-type SAW filter with the insertion loss about 0.6dB and attenuation about 20dB in receiving frequency band. The Rx filter is composed of ladder-type SAW filter coupled with longitudinally coupled resonator filter in the receiver with the insertion loss about 3.8dB and high attenuation about 60dB in transmitting frequency band (372 376MHz).

P1U-G-2 K2

ON THE DESIGN OF AN FBAR PCS DUPLEXER IN LTCC CHIP-SIZED PACKAGE

F. M. PITSCHI*, J. E. KIWITT, B. BADER, and K. CH. WAGNER, EPCOS AG.
Corresponding e-mail: maximilian.pitschi@epcos.com

Due to the specific advantages of surface acoustic wave (SAW) components in comparison to other RF filter technologies, SAW components have been a success story for years, in particular, regarding wireless applications. Besides their excellent performance and small size one of the most unique features of SAW components is their large flexibility allowing many solutions for different wireless applications based on SAW components. Frequently, both standardized off-the-shell as well as custom specific SAW components are offered. Coping with the steady request for new SAW components, the manufactures of SAW components have spent a lot in implementing and optimizing their own design processes. Reflecting their favored approach to the everyday design challenge, the design processes are based on experiment, simulation, or combinations thereof.

The paper reports about new results of a first-time attempt to utilize the existing design flow and methodology of SAW components to design film bulk acoustic resonator (FBAR) components. Due to the modular design of the computer aided design (CAD) environment, we could reuse many modules. In combination with new FBAR-specific modules, we obtained an FBAR-suitable CAD environment.

Designing an FBAR PCS duplexer comprising a low temperature co-fired ceramic (LTCC) chip-sized package with a quarter of a wave length line as well as the Rx- and Tx-filters we demonstrate the fitness for use of the new CAD environment. Starting from scratch the parts of the duplexer have been optimized with respect to each other. The latest experimental results of this one-shot design are presented indicating excellent performance especially regarding the Tx isolation. This most critical specification item has been over fulfilled with about 55 dB. Other specification items, such as, e.g., matching as well as pass band and stop band attenuation are also met. Measurement and simulation are in good agreement.

P1U-G-3 K3

OPTIMIZED TEST PCBS FOR SAW / FBAR RF FILTERS

H. BILZER[2], F. M. PITSCHI*[1], J. E. KIWITT[1], K. CH. WAGNER[1], and W. MENZEL[2], [1]EPCOS AG, [2]Microwave Techniques, University of Ulm.
Corresponding e-mail: maximilian.pitschi@epcos.com

Surface acoustic wave (SAW) as well as film bulk acoustic resonator (FBAR) radio frequency (RF) filters and duplexers have become very compact and complex components offering high performance and functionality. They are well established as indispensable key components in the microwave sections of mobile terminals.

Within these components electromagnetic (EM) effects appearing in, e.g., the die, the bonding structures, and the package, can have a significant impact on basically all electrical properties of SAW or FBAR filters and duplexers. Thus, the matching, the close-in and far-off selectivity as well as the Tx and Rx isolation being the specific electrical characteristic of SAW or FBAR duplexers can be changed considerably. As a matter of fact, the same holds true for EM effects appearing in the printed circuit board (PCB).

In contrast to the EM effects originating from within the component, EM effects that are due to the PCB cannot be considered reliable degrees of freedom

for the design of the respective component, since the PCB is not a well-defined, fixed part of the component. Being subject to change depending on who – component supplier or customer – measures the characteristic of the component for what purpose – unit or integration testing – just the opposite is true, as in general these measurements are performed in physically different environments, i.e., on PCBs with different layer stacks, trace widths, and so forth. Therefore, the PCBs should be optimized in order to show an electrically neutral behavior. In this context, neutral behavior means that the PCBs cause minimal reflections, minimal feed-through or cross-talk, and minimal losses.

The paper starts with the introduction of a suitable segmentation of test PCBs in their different functional parts. It offers a unique toolbox of tested building blocks as well as state-of-the-art design concepts and hints allowing to obtain optimized PCBs in a fast and efficient way. The building blocks have been theoretically and experimentally investigated and are described in detail. Then, the paper discusses how to apply both the toolbox and the design methodology on a couple of topical examples. Hereto, new designs of test PCBs for several up-to-date packages with standard footprints, such as, e.g., 2 mm x 1.6 mm and 2 mm x 1.4 mm, are proposed. Comparisons with simulations indicate excellent agreement.

P1U-G-4 K4

ANALYSIS OF PARASITIC EFFECTS OF GHZ-RANGE SAW MATCHED FILTERS FOR WIRELESS PULSE COMMUNICATION SYSTEMS

T. SATO*, T. SUGIURA, and H. NAGASAKA, Samsung Yokohama Research Institute.
Corresponding e-mail: tk-sato@ieee.org

Recently, wireless pulse communication systems operating in the GHz range, such as an ultra wide band (UWB) communication, have been actively developed. In the wireless pulse communication systems, the SAW matched filters can be used for high speed signal processing devices performing correlation of complex pulse waveforms. They are capable of realizing simplification of the circuits, miniaturization and low power consumption, compared to a digital correlator using semiconductor circuits. However, the correlation performance of the SAW matched filters in the GHz range will be degraded by parasitic effects due to an electro-magnetic coupling between input and output ports. The feed-through signals leaking directly between input and output generate a spurious response in the time domain, so that a ratio of desired correlation signal to unwanted signals (D/U ratio) after the demodulation is degraded. In this paper, we analyze the parasitic effects of the GHz- range SAW matched filter by combining a SAW simulator and an electro-magnetic wave simulator, to reduce the parasitic coupling and obtain good correlation performance. The device configuration with less feed-through is investigated by the full wave simulation. A new SAW matched filter at 4 GHz with high isolation is designed and fabricated on

42deg LT. The measured results show a good agreement with the simulations, and a good suppression of the feed-through. The correlation result using the SAW matched filter indicated that the correlation signal has a sufficient large D/U ratio.

P1U-G-5 K5

WITHDRAWN

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P1U-G-6 K6

A STATISTICAL MODEL OF PASSIVE REMOTE SAW SENSING EMPLOYING DIFFERENTIAL PHASE MEASUREMENT

Y. S. SHMALIY*, O. IBARRA-MANZANO, and R. ROJAS-LAGUNA, Guanajuato University.
Corresponding e-mail: shmaliy@salamanca.ugto.mx

Passive wireless surface acoustic wave (SAW) sensors are used to measure temperature, pressure and torque, identify the railway vehicle at high speed, etc. with a resolution of about 1%. Most frequently, the information bearer in such sensors is a time delay of the SAW estimated at the receiver. The basic principle utilized in such a technique combines advantages of the precise piezoelectric sensors, high SAW sensitivity to the environment, passive (without a power supplied) operation, and wireless communication between the sensor element and the interrogator.

In this report, we address a statistical noise model of an interrogating system of passive remote SAW sensing employing single differential phase measurement at ideal coherent receiver. An analysis is given of the limiting estimate errors of the time delay (phase difference) between two reflectors of the SAW sensor at the receiver detector where the estimation is provided in a sense of the maximum likelihood function in presence of Gaussian noise. Assuming the Gauss shape interrogating radio frequency (RF) pulse, we bring an important proof that the first time derivatives of its amplitude and phase do not affect the sensor phase (and phase difference) at the receiver. Rigorous and approximate relations for the mean error and mean square error (MSE) along with the probability for the estimate error to exceed a threshold are derived and studied in detail. The plots to evaluate the errors in a wide range of signal-to-noise ratios (SNRs) and thresholds are applied. Practical recommendations for designers of such systems are also given.

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P1U-G-7 K7

SIMULATION OF WIRELESS PASSIVE SAW ID-TAGS/SENSORS USING VHDL-AMS

Q. FU*, H. STAB, and W.-J. FISCHER, Semiconductor and Microsystems Technology Laboratory.
Corresponding e-mail: fu@ihm.et.tu-dresden.de

SAW devices can be used in a wide range because of their intriguing properties, such as their ability to store signal energy contained in acoustic waves for a relatively long time, their adaptability to semiconductor producing technology and so on. Since the last decade, SAW scientists show great interest to wirelessly readable identification(ID) tags, and sensors. Besides these general properties, SAW ID tags and sensors can work with no battery or wiring, withstand extreme temperatures and work reliably and maintenance-free over many decades even in harsh industrial environments. Since the flip chip technology became applicable to SAW devices, it was proposed to use this technology for bonding SAW devices onto a Silicon Application Specific Integrated Circuit(Si-ASIC). VHDL-AMS (VHSIC Hardware Description Language-Analog Mixed Digital) is an extension to VHDL ,which was used in ASIC design, to support the description and simulation of analog and mixed-signal circuits and systems. Any model valid in VHDL 1076 is valid in VHDL-AMS and yields the same simulation results. In this paper, a method to simulate SAW ID tags/sensors using VHDL-AMS was proposed. We have used VHDL-AMS simulator (ADVance Ms produced by Mentor Graphics) to simulate SAW ID tags and sensors produced on 128°YX lithium niobate substrates in radio frequency range.

Session: P1U-H
HIGH COUPLING SAW MATERIALS
Chair: J. Kosinski
US Army RCECOM

P1U-H-1 I7

THE CHARACTERISTICS OF LEAKY SURFACE ACOUSTIC WAVE OF PROTON-EXCHANGED LITHIUM TANTALITE

C.-J. CHUNG*[1], Y.-C. CHEN[1], K.-S. KAO[1], C.-L. WEI[1], and C.-C. CHENG[2], [1]Department of Electrical Engineering, National Sun Yat-Sen University, [2]Department of Electronic Engineering, De Lin Institute of Technology.
Corresponding e-mail: p923010002@student.nsysu.edu.tw

Proton exchange (PE) is an attractive method for the fabrication of optical and acoustic waveguides in lithium tantalite ($LiTaO_3$) substrate. Octanoic acid was used for the fabrication of PE $LiTaO_3$ waveguides. After the PE process, the resultant substrate showed a damage-free surface from observations by scanning electron microscopy (SEM). And X-ray diffraction (XRD) was adopted to identify the crystalline structure of $LiTaO_3$. From the X-ray diffraction (XRD) results, the reflection peak of (306) was shifted after PE process. The influences of the exchanging time on properties of leaky surface acoustic wave (LSAW) devices were discussed. The single electrode geometry of interdigital transducers (IDTs) was adopted to excite and receive the acoustic wave. The wavelength (λ) of the LSAW is 32μm. The frequency response of the LSAW is measured using an HP 8720ET network analyzer. The velocity of LSAW was decreased as the increase of PE time; nevertheless, the range of variation was quite small. Measurements of the temperature dependence of LSAW velocity were carried in the temperature range from 0° to 80°. The temperature coefficient of frequency (TCF) of LSAW devices was significantly increased by the increase of PE time. The PE process changed the characteristics of material and specific property can be obtained.
This research was supported by the National Science Council, (Taiwan, R. O. C.,) under contract no. NSC 91-2216-E-237-001.

P1U-H-2 I8

QUASI-LONGITUDINAL PSEUDO-SURFACE ACOUSTIC WAVES ON LITHIUM TANTALATE

V. I. CHEREDNICK*[1], M. YU. DVOESHERSTOV[1], and K. BHATTACHARJEE[2],
[1]State University, [2]Clarisay.
Corresponding e-mail: odissey@sandy.ru

Lithium Tantalate is one of the widely used materials for surface acoustic wave devices. In particular, orientations with Euler angles 90º, 90º, 112º and also 36ºYX and 42ºYX are well known. The first orientation corresponds to surface acoustic wave and the second and the third ones correspond to pseudo-surface acoustic waves with very small propagation attenuation. For high frequency devices in GHz range, orientations corresponding to high phase velocity are needed. From this point of view, pseudo-surface acoustic waves with phase velocities about 4 km/s are more preferable than surface acoustic waves (velocities about 3 km/s). But on Lithium Tantalate as on other crystals, waves with higher velocities exist. These are quasi-longitudinal pseudo-surface acoustic waves with velocities about 6 km/s and even higher. Some orientations for such waves on Lithium Tantalate are known, for example, orientations in X cut. In particular, calculated and experimental data for orientation 90º, 90º, 31º are published. In the present work, calculations of quasi-longitudinal pseudo-surface acoustic waves for all the Euler angles on Lithium Tantalate are performed. The first Euler angle was changed in range from 0º to 30º with 10º step, the second and the third angles were changed in range from 0º to 180º with 5º step. It was found, that quasi-longitudinal pseudo-surface acoustic waves exist in many ranges of Euler angles. All these ranges are shown in two-dimensional contour maps. It is shown, that in almost all these ranges propagation characteristics of these waves are not suitable for practical usage. In particular propagation attenuation is very large in almost all the Euler angles ranges - from 0.1 dB/λ to 2 dB/λ and even higher (λ is a wavelength). Only some separate orientation ranges correspond to propagation characteristics - those may be used in practical devices. In particular one of such region is in the vicinity of orientations 30°, 80° - 100°, 120° - 180° (or 90°, 80° - 100°, 0° - 60°). The phase velocity in this range is about 6 km/s, the propagation attenuation is 0.005 - 0.01 dB/λ, coupling coefficient changes from 0.5 % to 2.3 %, temperature coefficient of delay is 45 55 ppm/°C. Other such orientations were found near 0°, 145°, 45° (the phase velocity about 6 km/s, coupling coefficient about 0.17 %, propagation attenuation about 0.0002 dB/λ), and some additional ones. All the basic propagation characteristics of these orientations excepting velocity are worse than the characteristics of well known pseudo-surface acoustic wave orientations 36°YX and 42°YX propagation attenuation is larger and coupling coefficient is smaller. But, high velocity pseudo-surface acoustic waves on these orientations can be suitable for high frequency devices in GHz range, if the wave propagation path is not long, for example in resonator filters.

P1U-H-3 I9

PLATE AND GAP ACOUSTIC WAVES FOR HIGHLY SENSITIVE GAS AND LIQUID SENSORS

M. YU. DVOESHERSTOV[1], V. I. CHEREDNICK*[1], and K. BHATTACHARJEE[2],
[1]State University, [2]Clarisay.
Corresponding e-mail: odissey@sandy.ru

Surface acoustic waves on semi-infinite substrates are usually used for gas and liquid sensors. For more sensitivity of these sensors good propagation characteristics of the wave are needed. In particular, coupling coefficient must be as large as possible for maximal effective transformation of an electric signal into acoustic displacements and also a small value of a normal component of the displacement is desirable to minimize radiation loss in a liquid. Well known and widely used orientations in quartz, lithium tantalate, lithium niobate, lithium tetraborate, langasite, langanite, langatate and some other materials correspond to coupling coefficient from 0.12 % (ST-X quartz) to 5.4 % (138°YX $LiNbO_3$) for surface acoustic waves and about 8-12 % for pseudo-surface acoustic waves. Moreover, the normal component of the mechanical displacement in these waves is usually not small. Only in $KNbO_3$, surface acoustic waves with very large coupling coefficient (about 50 %) and with zero normal displacement exist. In this work, waves in thin plates (the thickness is comparable to wavelength λ) and in a gap between two thin plates are considered because propagation characteristics of these waves may be significantly better from point of view of coupling coefficient and normal component of the displacement. In particular, it was found that coupling coefficient in a single plate of XY-cut of $LiTaO_3$ (Euler angles 90°, 90°, 0°) is about 10 %, for XY-cut of $LiNbO_3$ - about 35 %, for YX-cut of PKN (Euler angles 0°, 90°, 0°) about 55 % and for YX-cut of $KNbO_3$ up to an

extremely high value 99 %. All these waves are SH waves without the normal component of a mechanical displacement, i.e. without radiation loss in a liquid. Thin plates with these waves may be used for highly sensitive gas and liquid sensors. Gap waves between two semi-infinite (or thick) substrates in all the cases correspond to very small coupling coefficients and therefore they cannot be effectively used in practical surface acoustic wave devices, including gas and liquid sensors. But a coupling coefficient of gap waves between two thin plates may be quit large. In particular, it was found, that for gap wave between two thin plates of XY-cut $LiNbO_3$ coupling coefficient may reach values about 5 %, 10 % and even 20 % for different wave modes. These modes are also SH waves without a normal component of a mechanical displacement. Thus, cuts in various piezoelectric crystals with plate SH waves and gap SH waves with very large coupling coefficients were found. These waves may be used for surface acoustic wave devices with very high efficiency of transformation of an electric signal into acoustic displacements, in particular for highly sensitive gas and liquid sensors. Absence of a normal component of a mechanical displacement in these waves provides an additional efficiency of such sensors because of absence of radiation loss in a liquid.

P1U-H-4 I10

ROUNDTRIPS OF SAW ALONG MULTIPLE ROUTES ON A SINGLE CRYSTAL $LINBO_3$ BALL

S. AKAO*[1], N. NAKASO[1], T. OHGI[1], and K. YAMANAKA[2], [1]Toppan printing Co., Ltd., [2]Department of Materials Processing, Tohoku University.
Corresponding e-mail: shingo.akao@toppan.co.jp

Recently, we excited a collimated, unidirectional Rayleigh wave on a sphere of an elastically isotropic material, and observed more than 20 roundtrips of surface acoustic waves (SAW) around the sphere [1]. In the next step, we found 4 specific routes on a single crystal quartz ball [2]. The roundtrips of SAW are not disturbed by addition or removal of structure or material in the area outside the routes of SAW. The long propagation distance of SAW on the sphere leads to super-narrow resonance and excellent sensitivity of its phase velocity measurements. Thus, it is extremely interesting to explore the possibility of fabricating a new type of SAW devices, such as ball SAW sensors. In this study, propagation of SAW was investigated on a single crystal $LiNbO_3$ (lithium niobate) ball, since $LiNb0_3$ has large electromechanical coupling constants. We found 10 specific routes, on which roundtrips of SAWs are observed, and one or more specific routes, on which multiple reflections of bulk waves are observed. The temperature coefficient of ten types of SAWa was about 80 ppm/$^\circ$C at 25 $^\circ$C, and it was different from that of the bulk wave, which was 50 ppm/$^\circ$C. By depositing various sensing films on a ball, we can produce protein chip, gas or smell sensor, and tactile sensor. In application to such sensors, many of the SAW routes can be used for sensing multiple quantities by coating various sensing films along each route. Here, one route without sensing film is used for temperature measurement in order to compensate the temperature dependency of SAW velocity on all other routes, since such route is not affected by the sensing quantities. In addition, when no sensing films are deposited on a ball, we can produce gyroscope and a pressure sensor working between atmospheric pressure and less than 1 Pa. In application to pressure sensor, SAW velocity on all routes is affected by pressure, so that no SAW route can be used for temperature measurement. But the bulk wave can be used for this purpose, since its velocity is hardly affected by the pressure. All above ball SAW devices can be driven by identical electronics circuit. One hundred balls with diameter of 1 mm can be built up in 1 cm^2 area as a multiple-ball sensor. And a technology for production of balls with smooth surface has previously been developed in the ball bearing industry. Therefore, we believe that ball SAW sensor on a single crystal $LiNbO_3$ ball will be major sensing devices in future generation. [1] K. Yamanaka, H. Cho and Y. Tsukahara: Appl. Phys. Lett. 76 (2000) 2797. [2] N. Nakaso, Y. Tsukahara, S. Ishikawa, K. Ymanaka: Proc. IEEE Ultrasonics Symposium (2002) p.47.

P1U-H-5 I11

TRANSVERSE ACOUSTIC ANISOTROPY OF OBLIQUELY PROPAGATING LSAW IN RESONATOR STRUCTURES ON $LITAO_3$ AND $LINBO_3$ SUBSTRATES

N. NAUMENKO*[1] and B. ABBOTT[2], [1]Moscow Steel and Alloys Institute, [2]Sawtek Inc.
Corresponding e-mail: nnaumenko@ieee.org

In this paper, the anisotropy of leaky surface acoustic wave (LSAW) characteristics is numerically analyzed in the planes of 42° -LT and 48° -LT cuts and some other substrates utilized in resonator filters. The analyzed waves propagate obliquely with respect to the longitudinal axis of the grating structure. The main LSAW characteristics - velocity, attenuation coefficient and power flow angle - are analyzed versus propagation angle. The resulting angular dependences are compared with similar dependences for uniformly metallized surface. This allows to predict the frequency intervals, for which maximum radiation of LSAW energy into bus bars is expected. Also some effects caused by transverse distribution of acoustic energy can be estimated, such as diffraction or coupling between parallel acoustic channels. In particular, it was found that in rotated Y-cuts of $LiTaO_3$ radiation of acoustic energy from the grating into bus bars is expected to decrease with increasing electrode thickness. Hence, for resonator structures with thicknesses optimized for minimum propagation loss (5% for 42° YX and 10% for 48° LT cuts), 48° LT cut is expected to provide lower radiation of acoustic energy into bus bars. The frequency intervals of weak and strong radiation predicted using numerical results for LSAW in 36° -LT and high-velocity LSAW in YZ-$LiNbO_3$ show good agreement with experimentally measured energy distribution recently reported by Koskela [1] and Knuuttila [2]. Using the simulated transverse acoustic anisotropy in these two orientations, the origin of transversal profile within the IDT aperture can be explained, and the number

of maxima of LSAW energy can be estimated at different frequencies, without rigorous 3D-analysis of resonator structure.

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P1U-H-6 I12

SAW PROPAGATION IN THE TWO DOMAIN STATES OF FERROELECTRIC LINBO3 CRYSTAL

J. NOSEK*, Technical University of Liberec.
Corresponding e-mail: jaroslav.nosek@vslib.cz

We propose a new geometry of ferroelectric LiNbO3 domain systems, which may be useful for SAW applications. Since two domain states of this material differ in elastic coefficients and in signs of piezoelectric constants, different domain geometries influencing the propagation of SAW can be considered. Here we wish to point out that even a simple system of two domains D1 and D2 can offer properties, which may be useful for SAW applications. The SAW propagates from the interdigital transducer IDT1 to IDT2. Each domain is provided with pair of electrodes A1, A2, so that electric fields perpendicular to the propagation direction of SAW can be applied. As shown before [2], it is possible to influence the group velocity of SAW in either of the domains by static or slowly changing electric field, and this can be achieved in each domain in a different way. The effect can be described simply by the change of elastic and piezoelectric coefficients: $c^*=c+aE$, $e^*=e+bE$, but more detailed tensor equations are derived in the paper. As a result, two time delay lines are produced on the substrate. On the domain wall considered here to be perpendicular to the signal propagation, significant reflection of the surface acoustic wave can occur [3]. Interference of the original and reflected SAW can be influenced by the electric field in domain D1. The whole system can be used for signal processing.

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This work was supported in part by the Grant of Ministry of Education of the Czech Republic under Contract Code MSM 242200002.

INFLUENCE OF THIN CONDUCTING LAYER ON LEAKY SH-SAW IN PIEZOELECTRIC CRYSTAL

B. ZAITSEV*, A. TEPLYKH, and I. KUZNETSOVA, Institute of Radio Engineering and Electronics of RAS, Saratov Department.
Corresponding e-mail: iren@ire.san.ru

In this paper the influence of thin conducting layer on leaky SH-SAW waves in 36Y-X LiNbO3 was first theoretically and experimentally investigated. Interest to this wave and structure was stimulated by results of preliminary calculations showing the possibility of anomalous resisto-acoustic effect. It meant that with increase of sheet conductance of layer wave velocity should increase, reach maximum and then decrease. The experiment was carried out when as thin conducting layer we used thin layers of aluminum which were deposited on the surface of operating delay line placed in vacuum chamber and connected up to the HF generator and vector voltmeter. Thus, in process of the slow depositing film we measured the change in wave velocity and attenuation as function of film thickness. Since the sheet conductance of thin aluminum film was uniquely defined by its thickness we actually measured the dependence of velocity and attenuation on film sheet conductance. Experiment showed the following. 1. From 16 studied samples only 4 ones displayed the anomalous resisto-acoustic effect but the positive change in velocity turned out to be less by order than theoretically predicted. 2. For significant film thickness when crystal surface may be considered as electrically shorted the change in wave attenuation did not vanish and had significant value. Another experiment allowed to estimate the wave penetration depth was carried out. For that we used the special precise arrangement allowing to make in crystal wave guide the groove on path of acoustic wave and to define its depth with accuracy 0.01 mm. The final groove depth was defined by decrease of output signal by e times. In this case the thickness of residual portion of wave guide corresponded to wave penetration depth. This experiment showed that for electrically open and electrically shorted surfaces the actual wave penetration depth turned out to be significantly less than theoretically predicted. In order to lead the theoretical results in accordance with experimental data we had formulated the choice rule of four partial waves from eight ones in standard method of analysis of surface acoustic waves. This choice was attributed by the best accordance theoretical and experimental data. In this case the increasing as well as diminishing partial waves were took into account because in all cases the phase velocity of SH-SAW was in the first transonic region. Such way allowed to lead in good agreement values of velocities and values of wave penetration depths, but did not predict anomalous resisto-acoustic effect. Then it was made the supposition about the appearance of the thin layer with disturbed structure and without piezoeffect in result of thermal, chemical, and mechanical treatment of crystal surface. The thickness of this layer could change from one sample to another. The calculation with consideration of this layer showed that for certain layer thickness the existence

of anomalous resisto-acoustic effect was possible with positive change in velocity corresponding to experimental data.
Thanks Prof. S.G.Joshi for useful discussion.

Session: P1FC-I
TIME TRANSFER AND CHARACTERIZATION
Chair: R. Wang
JPL

P1FC-I-1 N1

A PHASE LOCKED MECHANISM FOR TIME SCALING FREQUENCY CONTROL SYSTEM

S.-Y. LIN*, Telecommunication Laboratories.
Corresponding e-mail: sylin@cht.com.tw

A new mechanism was developed for a time scaling frequency control system. We use an ensemble with 7 cesium clocks to generate a paper clock and try to synchronize two hydrogen masers with this paper clock via the new mechanism. The aim of this work is to synchronize these two hydrogen masers with the paper clock in 1 nano second without any prediction algorithm. The simplest way to synchronize an oscillator with a reference frequency source may be the phase locked loop; we can just use a phase comparator and feedback voltage control to let an oscillator follow a reference frequency. If there exists a mechanism which simulates a phase locked loop process, we can use it to lock the hydrogen maser with the paper clock we generated. In the mechanism we developed, two micro steppers are used for replacing the voltage control part of the phase locked loop, and the frequency reference input of each micro phase stepper comes from two different hydrogen masers. Since the paper clock has no physical output, we calculate the time scale of the paper clock every hour and compare the phase difference between the paper clock and these two micro phase steppers every several hours. We adjust the frequency offset of micro phase steppers with a fixed and small amount if the phase output of these two micro phase steppers was advanced or retardative with the paper clock. Through this mechanism, we expect the paper clock and the two micro phase steppers can be synchronized together and the frequency output of these two micro phase steppers can present the virtual frequency output of this paper clock. In out experiment, we checked their phase differences from every hour to every 24 hours and changed the frequency-offset from 1E-16 to 1E-14. A primary result showed the output of micro phase stepper would have better accuracy if we checked the phase difference every hour and better stability if we checked the phase difference every 24 hours. Here we make an eclectic choice that we check the phase difference every 4 hours, and the amount of frequency-offset change is set to be about 2E-15. For this setting, the phase difference between two micro phase steppers and paper clock both were kept in 1 ns and the related Alan deviation was about 6E-14 (tau = 600sec). Here the Allan deviation between two hydrogen masers

is about 4E-14 in our measurement system. That is, its possible we synchronize more than one hydrogen masers with a single paper clock and need no prediction algorithm. Our mechanism is also helpful if we set up a backup time scaling system, the primary and backup system will be kept in phase without any extra artificial adjustment.

P1FC-I-2 N2

THE THREE CORNERED HAT METHOD: AN ATTEMPT TO IDENTIFY SOME CLOCK CORRELATIONS

F. VERNOTTE*[1], J. DELPORTE[2], and M. BRUNET[2], [1]Observatoire de Besançon, [2]Centre National d'Études Spatiales.
Corresponding e-mail: francois.vernotte@obs-besancon.fr

The three cornered hat is a well known method for estimating the instabilities of each clock in a set of three clocks. The first assumption lies in the hypothesis of total uncorrelation between the clocks [1]. A revisited method has been proposed which no longer assumes the uncorrelation hypothesis, but yields a more realistic approach estimating the covariance matrix by ensuring suitable properties such as positive variances [2]. Finally, we propose a new method which goes further by assuming a power law model for the spectral density of frequency deviation of each clock, and hence, of the clock differences. In this case, negative noise levels may be directly interpreted as the effects of some correlations between certain clocks. The originality of this method lies in the estimation of the noise levels by using the multivariance method [3] which provides an assessment of the uncertainties on these levels. Dependending on their confidence interval, negative noise levels may be discarded as measurement artefacts or taken into account as correlation effects.

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P1FC-I-3 N3

A STUDY ON GPS COMMON-VIEW OBSERVATION DATA WITH MULTISCALE KALMAN FILTER ALGORITHM

X. OU, X. HAN, H. WANG*, H. ZHOU, and W. ZHOU, Xidian University.
Corresponding e-mail: wzhou@xidian.edu.cn

GPS common-view time transfer in near real-time may be implemented by processing observation data with high speed and high precision. However, normal smoothing and filtering method is not satisfied with near real-time case. Based on the data from GPS common-view, traditional Kalman filtering algorithm can solve the problem, but how to get the initial filtering parameter is often a puzzle. The usual method is by experience estimation. If one can get the optimal initial parameter, the accuracy will be higher than it is used to be. Recently, a filter bank design based on orthonormal wavelets and equipped with a multiscale Kalman filter was proposed for signal restoration of fractal signals corrupted by external noise. In this paper, Fractional Brownian Motion is presented to demonstrate the clock difference data from GPS common-view, and multiscale Kalman filter is used to process the data. Then, the clock difference at remote different places can be obtained. Comparisons between Kalman filter and multiscale Kalman filter are given. The latter gives us more accurate estimation. Typical computer simulation results demonstrate its feasibility and effectiveness.

P1FC-I-4 N4

SOME PROBLEMS AND THEIR SOLUTIONS IN QUASI-PARALLEL MTIE ASSESSMENT

A. DOBROGOWSKI* and M. KASZNIA, Poznan University of Technology, Institute of Electronics and Telecommunications.
Corresponding e-mail: mkasznia@et.put.poznan.pl

Maximum Time Interval Error (MTIE) is one of the parameters describing the quality of timing signal of the telecommunications networks. The MTIE is usually computed for a series of observation intervals starting from some τ_{min} until some τ_{max} using a sequence of time error samples. The time of the parameter's calculation is rather long, because of the number of data needed and the complexity of the parameter's estimator. Therefore several different time effective methods of MTIE calculation enabling rather fast evaluation of the timing signal were proposed and widely described in the literature. Some methods were proposed by authors of this paper. One of these methods (called extreme fix with sequential data reducing, EFSDR) exploits very specific mechanism of the sequential reducing data volume. The search of the MTIE estimate value for the first (shortest) observation interval is performed for the whole time error data series using the extreme fix (EF) method. The MTIE search for the next longer observation intervals is performed using reduced data sequence, containing only previously found extreme samples. The data reduction causes that the calculation process runs very fast, especially for longer observation intervals. Therefore, this method was adopted for real-time quasi-parallel MTIE assessment performed during time error measurement. Unfortunately, the incorrect MTIE estimates may happen, when the EFSDR method is used. Because of data reduction some sample values, which affect the MTIE value, may be omitted for specific arrangement of samples and windows' (observation intervals) lengths. As result, the MTIE value is underestimated until greater value is found for some longer observation interval. In the paper the mechanism of the error appearance for the EFSDR method is described. Then the error free solutions oriented at the quasi-parallel MTIE computation are proposed. The first solution consists in changing the extremes searching rules. Instead of EF method based on fixing the extreme samples' positions for current window's location and shifting the window to the position of the first extreme, the direct method is proposed. The one-sample shifts of a window are performed in this case, and the extreme samples for each window's location are found. As a result none extreme sample affecting the MTIE estimate is omitted in data reduction process. The direct method proved to be time effective for short observation intervals (having, let say, less than 10 samples), but in the case of sequential data reduction it can be time effective also for longer observation intervals. Such solution can be used for the real-time MTIE assessment as well as for the off-line calculation. The second solution is dedicated especially for the real-time MTIE assessment. We suggest performing parallel calculations for each observation interval independently using time effective EF method without the data reduction process. In the paper both algorithms are described. The results of MTIE calculation for several types of time error series are presented and compared.

P1FC-I-5 N5

INSTANTANEOUS FREQUENCY ESTIMATION THROUGH THE APPLICATION OF WARBLET TRANSFORM AND OPTIMAL SAMPLING STRATEGIES

L. ANGRISANI[1], M. D'ARCO[2], R. SCHIANO LO MORIELLO*[2], and M. VADURSI[2], [1]Università di Napoli Federico II, Dipartimento di Informatica e Sistemistica, [2]Università di Napoli Federico II, Dipartimento di Ingegneria Elettrica. Corresponding e-mail: mvadursi@unina.it

As well known, instantaneous frequency (IF) estimation is a very helpful analysis and diagnostic tool in a wide range of research and industrial fields, from seismic and oceanic investigations to biomedical applications, from telecommunication and microwave apparatuses test and measurement to power system quality assessment. The authors have recently presented in [1] a digital signal-processing method, based on the use of a modified version of the chirplet transform, for accurately estimating the IF trajectories both of monocomponent and multicomponent signals (i.e. signals consisting of more than one component, each of which is characterized by its own instantaneous frequency). Good accuracy (within 1%), along with remarkable resolving capability in IF trajectory reconstruction, have been exhibited in the analysis of signals whose IF trajectories evolve versus time according to a roughly polynomial law. The paper pays attention to the different and large class of monocomponent and multicomponent signals whose IF trajectories reveal a periodic nature. A new measurement method, based on warblet transform (WT) [2] is proposed capable of granting such good accuracy and resolving capability in IF estimation as those achieved in the past experience. Moreover, an original procedure allowing WT parameters to be properly fixed according to the spectral content of the analyzed signal IF trajectory is

presented, too. The proposed method has been applied on several emulated and actual monocomponent and multicomponent signals. Specifically, natural signals, radar signals, as well as frequency-modulated telecommunication signals have been taken into consideration. Furthermore, to gain the highest possible frequency resolution in the analysis of the latter, an optimal sampling strategy and a related algorithm are also presented, based on some theoretical results on alias-free sampling of band-pass signals [3-4]. In particular, given signals bandwidth, carrier frequency and desired normalized central frequency, the algorithm finds out the lowest alias-free sampling frequency, thus guaranteeing the maximum theoretical frequency resolution without any analog downconversion.

P1FC-I-6 N6

ADAPTIVE OCXO DRIFT CORRECTION ALGORITHM

C. W. T. NICHOLLS* and G. C. CARLETON, Nortel Networks.
Corresponding e-mail: cnicholl@nortelnetworks.com

An algorithm is presented which provides a 5 fold reduction in the stability requirement of the CDMA base station time reference oscillator necessary to maintain synchronization of the base station to the network for 24 hours without an external time reference. The algorithm adaptively extracts the frequency drift characteristics of the CDMA base station time reference OCXO with respect to a noisy 1pps time reference received via satellite. The resultant OCXO model generated by the algorithm is used in the event of loss of satellite service to provide time correction of the base station reference oscillator. The algorithm has been implemented in a CDMA cellular radio system to enable a 5 fold reduction in the frequency stability requirement of timing module reference oscillator.

The novelty of the algorithm is in the use of two parallel Kalman filters to adaptively model the temperature and aging dependent frequency stability of the OCXO. The algorithm extracts the stability dependencies of the OCXO which are of the order of 0.4ppb/75C and 0.05ppb/24hours from the stability measured with respect to the 1pps satellite time reference which has a 1 sigma jitter of 50ppb/s. Adaptive training of the Kalman filter models occurs up to the time satellite visibility is lost which ensures the algorithm is cognizant of changes in the OCXO frequency stability characteristics over the product lifetime. In holdover the Kalman filters operate as predictive state machines which generate a correction signal for the base station OCXO time reference based on the trained coefficients of the adaptive models.

The correction algorithm has been trialed in a CDMA base station network and demonstrated to maintain the 10MHz timing module reference oscillator to within 1.5us of the CDMA System time over a holdover period of 24hours, this is well within the 3GPP2 CDMA standard cumulative time error specification of 10us over an 8hr holdover period. Simulations indicate the feasibility of the algorithm to compensate for a further 10 fold reduction in reference oscillator stability whilst still meeting the 8 hour holdover specification.

The author wishes to acknowledge the technical support of G.C.Carleton who provided invaluable insight into the operation of the Kalman filter, to D.Sychaleun for collection of the measurement data and to Phillip Wu for the implementation of the Matlab code into the Nios processor.

P1FC-I-7 N7

A NEW REALIZATION STRATEGY FOR THE TIME SCALE UTC(PTB)

A. BAUCH*, D. PIESTER, and E. STALIUNIENE, Physikalisch-Technische Bundesanstalt, Germany.
Corresponding e-mail: andreas.bauch@ptb.de

The time scale UTC(PTB) shall be realized with an active hydrogen maser steered in frequency in a way that the maser's short-term frequency instability is preserved, the medium-term instability is provided by PTB's primary time references and UTC(PTB) is in the long term steered to UTC. Based on past data we analyzed the possible ways of achieving this, searching for the best combination of data from two hydrogen masers, the primary reference clocks CS1, CS2, and CSF1, and optimum frequency prediction. Differences between UTC and a fictive time scale UTCp(PTB) were calculated for various combinations, and these time differences were analyzed in terms of their time variance (TVAR) and their forward predictability for 45 days. It turned out that the properties of UTCp(PTB) could be made superior to that of UTC(PTB) as it was realized up to now only if CSF1 serves as the steering reference with an attack time on the maser of 1 to 2 days. We discuss the properties of UTC(PTB) now and in the future in view of its potential use as an intermediate reference for steering the system time GST of the European satellite navigation system Galileo towards TAI.

P1FC-I-8 N8

THE ESTABLISHMENT OF A SADC TIME NETWORK

E. L. MARAIS*, CSIR - National Metrology Laboratory.
Corresponding e-mail: elmarais@csir.co.za

South Africa is at present the only member of the Southern African Development Community (SADC) that is a signatory of the Metre Convention. Very few of the member countries (South Africa, Lesotho, Swaziland, Namibia, Botswana, Mozambique, Angola, Zimbabwe, Zambia, Malawi, Democratic Republic of Congo, Seychelles, Mauritius and Tanzania) have an established metrology structure, apart from those measurements required for trade, such as mass and volume. As a first step in developing the metrology structure in the region, we propose the establishment of a time network for SADC.

The proposed network will consist of a time center in each of the member countries. Coordination will be done (for the present) from the South African National Metrology Institute, the CSIR - National Metrology Laboratory.

The time stations to be deployed in the countries mentioned above will consist of a dual redundant system, containing two timing components. Each component will contain a GPS synchronized Rubidium clock, an NTP server, a Telephone Time server (similar in function to ACTS) and a common view GPS receiver. The unit will also contain the necessary control for switching out any of the components in the event of a failure, so providing redundancy. Relevant data will be sent to the coordinating station. The system will also contain an uninterruptible power supply.

The proposed network will be established within the next three to five years, depending on the availability of funding for the project.

P1FC-I-9 O1

HIGHLY-ACCURATE REAL-TIME SYTONIZATION USING A GPS SINGLE-FREQUENCY RECEIVER WITH AN INTELLIGENT ATMOSPHERE FORECASTING MODEL

C.-L. CHENG*[1], F.-R. CHANG[1], L.-S. WANG[2], and K.-Y. TU[3], [1]Dept. of Electrical Engineering, National Taiwan University, [2]Inst. of Applied Mechanics, National Taiwan University, [3]NSTF Lab., TL, Chunghwa Telecom. Co., Ltd., Taiwan.
Corresponding e-mail: randy7@ms36.hinet.net

The purpose of this paper is to develop a low-cost, highly-accurate and real-time syntonization system composed of a single-frequency receiver with GPS carrier phase. The scheme could achieve the traceability of frequency dissemination. The GPS receiver was modified in order to estimate the real-time average frequency deviation of the steered Oven-Controlled Crystal Oscillator (OCXO) with respect to the GPS system time by performing the time-difference, all-satellites-in-view average and atmospheric correction. The neural network MPC (Model Predictive Controller) was employed to implement the syntonization system. The steered clock was then syntonized with the GPS system time by way of the D/A converters. For averaging time of one day under the configuration, our experimental results showed that the accuracy of the steered oscillator could be improved from about two parts per billion to about three parts per one hundred trillion, and the stability of the disciplined oscillator could be improved from about four parts per ten billion to about three parts per one hundred trillion. Three improvements and advantages in our methodology were given. First, we developed a forecasting model with recurrent neural networks (RNNs) to correct atmospheric errors in real time. The model was more accurate than the existed ionosphere model and troposphere model for a single GPS receiver. Furthermore, it was available simply and anticipative day-to-day partially, irrelevant to user locations. Second, the low-cost clock could be automatically steered to obtain the very high frequency accuracy and stability in the short term as well as in the long term. Experimental results showed the stability of per second was about five parts per trillion. Compared with the commercial GPS Disciplined

Oscillator (GPSDO), the short term stability (1s) was improved from about ten to fifteen times. Moreover, the suddenly-increased instability of the GPSDOs in the medium term (about at from 100s to 10000s observation interval) due to atmosphere effect was also improved. Third, the frequency performance of the syntonization system by use of low-cost GPS engines, inexpensive clocks and less communication effects was as good as the commercial atomic clock. So, the frame of syntonization was sound, reliable and cost-effective

We gratefully acknowledge the NSTF Lab., TL, Chunghwa Telecom. Co., Ltd., Taiwan, R.O.C. for experiment supporting of this paper.

Session: P1FC-J

CHEMICAL SENSORS
Chair: R. Lucklum
Otto-Von-Guericke University

P1FC-J-1 Q1

SAW SENSOR FOR LIQUID CHROMATOGRAPHY USING SH-SAW RESONATOR

T. NOMURA*[1], A. SAITOH[1], and S. FURUKAWA[2], [1]Shibaura Instotute of Technology, [2]Kyushu Institute of Technology.
Corresponding e-mail: nomurat@sic.shibaura-it.ac.jp

New liquid sensor system using SAW resonator is presented. Surface acoustic wave (SAW) devices offer many attractive features for applications as many sensors. A shear horizontal mode surface acoustic wave (SH-SAW) has only shear horizontal displacement. Therefore the SH-SAW sensor is very useful devices to sensing the liquid properties. In this paper, a new liquid chromatography using the SAW resonator has been developed for sensing the properties of liquid. The surface acoustic wave with the shear horizontal displacement (SH-SAW) are excited on a 36 degree rotated Y cut X propagated LiTaO3 (36 YX LiTaO3) substrate. A two-port SH-SAW resonator was constructed on the substrate and a liquid flow cell having a very small channel was set on this resonator. The flow of sample liquids was interacted with the SH-SAW only on the area between the IDT electrodes of the resonator in very small volume. The resonator was used as a liquid conductivity sensor. A liquid chromatograph column was used to separate the species in complex mixture. The SH-SAW resonator was connected in the feedback circuit of an amplifier, resulting in SAW oscillator. The frequency changes of the SAW oscillator were detected as the sensor response and the time responses to the flow of the sample liquid were measured. The experiments were carried out using complex solution (LiCl, NaCl, NH4Cl, and KCl). Results showed that the SAW oscillator frequency varied with the conductivity of the ionic solution and the chromatogram were obtained due to the ions (Li, Na, NH4, and K) in the complex solution. Moreover, it clearly shows that the SH-SAW resonator having the small flow cell is very suitable to detect the complex solution in very small volume liquid. The liquid chromatography system using the SH-SAW resonator sensor can provide identification and quantification of many species in complex solution.

P1FC-J-2 Q2

ZERO TCF ZNO/QUARTZ SAW STRUCTURE FOR CO_2 SENSING APPLICATIONS

A. TALBI, F. SARRY*, M. EL HAKIKI, O. ELMAZRIA, F. MOREIRA, and L. LE BRIZOUAL, LPMIA-UMR7040 CNRS-Universite Henri Poincare.
Corresponding e-mail: frederic.sarry@lpmi.uhp-nancy.fr

SAW devices have been shown suitable not only for signal processing but also for sensor applications. Due to there small size, they can react very fast to the changes in the environmental conditions. This implies also to get a signal even if a small amount of the material under investigation is available. Numerous physical effects affect the elastic constants of the substrate leading to a shift of the oscillation frequency corresponding to a modification of the phase velocity. Furthermore, the frequency can be resolved over several orders of magnitudes and this results in a high sensitivity and a high accuracy. In order to avoid parasitic phenomena such as temperature, SAW devices with zero TCF are required. It is well known that ST-X cut of quartz shows a high stability in temperature. However, this cut exhibits a weak electromechanical coupling coefficient (K^2=0.16%). The aim of this work is to investigate the potentiality of the structure ZnO/quartz with higher K^2 and zero TCF value to be used in gas sensor applications. Due to its negative TCF value, zinc oxide (ZnO) thin film was deposited by reactive magnetron on quartz substrate with specific cut or propagating direction to obtain zero TCF ZnO/ quartz structure. The ZnO guiding layer is also employed to increase the K^2 value and to provide the selectivity toward detected gas. The considered structure has the advantage of confining the acoustic wave energy at the surface of the device, which increases the sensitivity of the device. Both quartz cuts ST-35X and Y-X were investigated. Our calculations based on Campbell and Jones model show that zero TFC is reached with ZnO normalized thickness values of kh_{ZnO} of 0.78 and 3 for ST-35 X and Y-X respectively. With these thickness, the K^2 values were also improved: K^2=1.1% for ST-35 X and K^2=1.17% for Y-X cut. Experimentally, the compensation was obtained with normalized thickness of 0.8 for ST-35 X and 2.7 for Y-X. Finally, the zero TCF structures were investigated as gas sensors for carbon dioxide detection. Sensor's responses are analyzed in terms of response time, and response magnitude as a function of CO_2 concentrations in air at different operating temperatures. Experimental results show a high sensitivity and reproducibility of the sensor in time and in temperature. Furthermore, the CO_2 interaction with the ZnO selective layer is briefly described.

P1FC-J-3 Q3

AMMONIA SENSING PROBE USING SHEAR HORIZONTAL SURFACE ACOUSTIC WAVE TECHNIQUE

C.-Y. SHEN*, C.-P. HUANG, Y.-T. SHEN*, K.-C. HSU, and J.-S. JENG, Department of Electrical Engineering, I-Shou University.
Corresponding e-mail: cyshen@isu.edu.tw

Modern biosensors developed with further microfabrication and signal processing techniques are becoming inexpensive, accurate, reliable, and miniature. The surface acoustic wave (SAW) devices can satisfy the previous requirements. The advantages of SAW sensors include real-time measurement, competitive price, high sensitivity and accuracy, and intrinsically reliability. Ammonia is an important species for the refrigeration and fertilizer industries. Ammonia's widespread use and toxic nature introduce a need to monitor it quantitatively at its very low concentration. Recently, the concentration monitoring for ammonia in ppb level can be used in clinical diagnosis. The purpose of this work is to investigate the advanced properties of an improved SAW gas sensor for detecting ammonia in ppb level. The Coupling of Modes (COM) theory was used in SAW device design and simulation. 36° YX-LiTaO3 was applied as the substrate and two-port resonator was as the device. L-glutamic acid hydrochloride was the chemical interface for ammonia detection. The length of delay line should be enough to deposit the chemical interface. The long length of delay line results in multimode in 3 dB pass band, and it frequently occurs mode hopping during ammonia detection. Then the inaccurate data can be obtained. This study solved the problem of mode hopping by COM simulation. The SAW sensor based on L-glutamic acid hydrochloride presented excellent reversibility, sensitivity, and repeatability when ammonia was in ppb level. This SAW sensor could easily detect 31.8ppb ammonia at 50°C. According to the signal to noise ratio of two, the limit of detection (LOD) of the SAW sensor to ammonia at 50°C was 1.2ppb.

P1FC-J-4 Q4

3-D FINITE-ELEMENT SIMULATION MODEL OF SAW PALLADIUM THIN FILM HYDROGEN SENSOR

M. ATASHBAR*, B. BAZUIN, M. SIMPEH, D. BANERJI, and S. KRISHNAMURTHY, Department of Electrical and Computer Engineering, Western Michigan University.
Corresponding e-mail: massood.atashbar@wmich.edu

Metallic thin films have gained much interest for fabricating conductive gas sensors and have been widely used to fabricate sensitive and selective sensors. Integrating these thin films with Surface Acoustic Wave (SAW) devices enhances the speed, efficiency and reliability of the sensor. Hydrogen sensors have many applications in the fields of space launch vehicles, industrial leak detection, and automobile fuel additives. For a sensor to be effective for detecting hydrogen

the baseline detection limit should be below the explosive limit of hydrogen (4% in air). Many of the group VIII transition metals like nickel, palladium, and platinum absorb hydrogen spontaneously. This absorption alters the electrical and optical properties of these metals. In this work a bi-layered thin film of palladium and copper phthalocyanine (CuPc) on an XY Lithium Niobate substrate with a two-port delay line SAW structure was analyzed. A 3-dimensional simulation finite-element (3D-FE) approach of this device was investigated. Deformation caused by the SAW was examined in addition to the particle displacement profile in various depths at different operating frequencies. In addition the frequency response of the multi-layered structure with various boundary conditions were simulated in order to show the performance of the device with modeled interaction between hydrogen and palladium thin films The result was compared with the experimental and theoretical data to confirm the accuracy of the model. This model will help optimizing the SAW gas sensor design without having to perform the actual fabrication.
This material is based upon work supported by the National Science Foundation under Grant No. 0225427.

P1FC-J-5 Q5

COMPUTATIONAL SIMULATION OF VIBRATION DISPLACEMENT ON PIEZOELECTRIC QUARTZ CRYSTAL USING FINITE ELEMENT METHOD

C. KUROSAWA*[1,2], S. KUROSAWA*[1], H. AIZAWA[1,3], and T. HORIBE[2], [1]National Institute of Advanced Industrial Science and Technology (AIST), [2]Ibaraki University, [3]New Energy and Industrial Technology Development Organization (NEDO).
Corresponding e-mail: shigeru-kurosawa@aist.go.jp

Recently, piezoelectric quartz crystal has found widely applications in chemical- and biosensor. The quartz crystal microbalance (QCM) is well-known technique of mass sensing using mass-loading transduction property for frequency shift. The behavior of vibration displacement of electrodes surface on QCM for various applied voltage is important problem to understand the physical property of QCM, but it is very difficult to detect the displacement. In this paper, the effects of resonant frequency of QCM caused by the variation of the applied voltage are studied by using the finite element method (FEM) software. The ANSYS 6.1 program was used to calculate vibration displacement of 9 MHz QCM (AT-cut) under several boundary conditions. The hexahedral element was used to crystal and electrodes models for the calculation. The vertical (Z-axis) elements for thickness of crystal part were settled 16, and that of 3 of each for thickness of electrode parts was used. The horizontal elements were automatically settled. The displacements of two nodes in the center of the thickness of the crystal were fixed. The distribution of vibration displacement of electrode surface on QCM was calculated at resonant condition in air. The resonant frequency for QCM varied from 8.9 to 9.1 MHz at selected voltage, and several displacements of QCM was computed by frequency response analysis. Damping ratio was used

at 0.1 and 0.01. A vibration displacement of electrode was concentrated on the central part, and it was greatly attenuated around electrode. The maximum vibration displacement on QCM for various applied voltage is calculated from ref. [1]. According to the calculated results, the vibration displacement (0.05 to 100 nm) of central electrode point of QCM is proportional to applied voltage on electrodes from 0.5 V to 1,000 V. It is consistent with the theoretically calculated values for QCM. More detail simulation results and discussion will be reported at 2004 IEEE Conference. References [1] T. Kojima, J. Med. Ultrasonics, 30, 2 (2003) J171-J190. $\Delta l = 0.1$ V at 9MHz QCM. Δl is vibration displacement (nm), and V is applied voltage (V).

Session: P1U-K

SENSORS
Chair: J. Vetelino
University of Maine

P1U-K-1 J1

LAYERED CYLINDRICAL VISCOSITY SENSORS

P. KIELCZYNSKI*, W. PAJEWSKI, and M. SZALEWSKI, Institue of Fundamental Technological Research.
Corresponding e-mail: pkielczy

In the laboratory and industrial practice piezoceramic viscosity sensors must often operate in liquids which can be chemically aggressive. In this case, a direct contact of the piezoelectric ceramics and liquid is not recommended. To overcome this disadvantage the authors designed a new type of a layered piezoelectric cylindrical viscosity sensor. The sensor is composed of one (active) inner piezoceramic cylinder connected with the outer (passive) metallic cylinder. In this case only the outer metallic cylindrical surface is in contact with an investigated liquid. Theoretical analysis of the shear vibrations of this layered cylindrical system was performed. First, using a continuum electromechanical model the impedance **Z** matrix (3x3) has been established for a piezoceramic cylindrical resonator vibrating in a shear mode. Electrodes are deposited on the inner and outer cylindrical surfaces. Polarization is along the vertical z axis. The impedance matrix of a metallic (passive) cylinder is a (2x2) submatrix of the mentioned above (3x3) impedance **Z** matrix. Second, knowing the elements of the impedance matrix **Z**, an input impedance (admittance) of the layered system: piezoceramic cylindrical resonator+metallic cylinder loaded with a viscoelastic liquid on the outer metallic cylindrical surface was derived. Numerical calculations of the admittance diagrams were performed for a layered structure: PZT-4 (Valpey-Fisher) cylinder + aluminium cylinder+viscoelastic liquid. Motor oil, gear oil and epoxy resins were used as a viscoelastic liquid. The preliminary experimental investigations performed by the authors are in conformity with the results of numerical and theoretical investigations. The established above method can be extended to the case of multi-layer piezoelectric

and non-piezoelectric cylindrical structures. The results obtained in this paper are original and have not been reported in the literature. The analysis performed in this work can constitute the basis for the design and construction of resonators, accelerometers and viscosity sensors.

P1U-K-2 J2

APODIZATION AND ASYMMETRY OF THE ACTIVE AREA OF ACOUSTIC HYDROPHONE AND IT'S IMPLICATIONS ON ULTRASOUND EXPOSURE

V. DEVARAJU*, Drexel.
Corresponding e-mail: dv@drexel.edu

Abstract The objective of this work was to determine the effective diameter of ultrasonic hydrophones by measuring the angular response of several PVDF membrane hydrophones of different kinds, various geometrical spot size and different thickness of PVDF film in two rotational axes perpendicular to each other and discuss the cause and effect of apodized behavior and asymmetry of the sensitive region of the hydrophones. If the size of the sensing element of the hydrophone is large compared to the beamwidth of ultrasound, spatial averaging will take place resulting in substantial underestimation of the true acoustic pressure during measurements. In view of the non-availability of hydrophones with smaller spot size to measure the acoustic output from transducers operating at higher frequencies, the precise value of the effective diameter of the hydrophone probe is to be known in order to determine the acoustic pressure radiated by the ultrasound transducer accurately.

The effective diameter of the hydrophone was determined from the measurement of its directivity pattern. The directivity pattern was obtained by rotating the hydrophone in the far field of the transducers plane wave and by measuring the response at some angle of rotation. The measurements were carried out in two rotational axes and studied the variations in effective diameter.

It was seen that the effective diameter decreased with increasing frequency. The directivity measurements on two orthogonal axes revealed that there was a marked asymmetry in the effective diameter of the hydrophone. The effective diameter measured along the line collinear with the electrical lead was greater than the other diameter measured and it varied significantly with frequency and with reference to axis of rotation. The effective diameter values obtained from the measurements at two perpendicular axes varied by more than $\pm 10\%$ of the maximum value. It was also demonstrated as to how the presence of Lamb wave affects the main lobe at higher frequencies and also in hydrophones with larger spot size. For the larger physical spot size, the effect of the fringing field was comparatively smaller than the hydrophone with smaller spot size.

The results emphasized the need to perform the directional response measurements as a function of frequencies covering the entire bandwidth of the hydrophone and also at two perpendicular axes in order to determine the effective diameter of the hydrophone accurately. The precise determination of the effective diameter is essential while evaluating the newly developed ultrasound

equipment in view of the usage of transducers with enhanced upper bound of the fundamental and harmonics frequencies. The measured acoustic output using such hydrophone is the basis in deciding the potential bioeffects due to exposure to diagnostic ultrasound.

The author would like to thank Dr. Mark E. Schafer for his help and support and Perceptron, Inc., where the author performed the measurements.

P1U-K-3 J3

PULSED INTERROGATION OF THE SAW TORQUE SENSOR FOR ELECTRICAL POWER ASSISTED STEERING

V. KALININ*, G. BOWN, J. BECKLEY, and R. LOHR, Transense Technologies plc.
Corresponding e-mail: victor.kalinin@transense.co.uk

A contactless SAW torque sensor for electrical power assisted steering (EPAS) working in the 430-437 MHz frequency range is presented in this paper. It contains four one-port SAW resonators on quartz substrates connected to a single rotational coupler. Two of them are attached to one side of the steering shaft and two others are attached to the opposite side in order to compensate an effect of shaft bending on the sensor output. The mechanical part of the sensor is designed in such a way that the torque sensitivity of the difference between two SAW resonant frequencies is approximately 14 kHz/Nm. As a result we simultaneously achieve an acceptable overload protection and accuracy of torque measurement. Temperature compensation technique is also discussed in the paper.

A single stationary interrogation unit is used to measure resonant frequencies of all four SAW resonators attached to the rotating shaft. The interrogation method is based on a pulsed excitation of the natural oscillations of the resonators and their subsequent spectral analysis. The accuracy of the frequency measurement is mainly limited by the phase noise of the clock generator and the frequency synthesisers of the interrogator. The standard deviation of the measured frequency is approximately 600 Hz. It is sufficient to satisfy requirements for the EPAS torque sensor. Unlike a previously used interrogator based on continuous tracking frequency control loop, the pulsed interrogator is more cost-effective because it allows increasing the number of the SAW resonators in the sensor without complicating the interrogator's circuitry. It achieves a 1 ms or shorter torque update period that complies with the EPAS torque sensor specification.

P1U-K-4 J4

THIN FILM BULK ACOUSTIC WAVE RESONATOR (TFBAR) GAS SENSOR

M. BENETTI[1], D. CANNATÀ[1], A. D'AMICO[2], F. DI PIETRANTONIO[1], V. FOGLIETTI[3], and E. VERONA*[1], [1]Istituto di Acustica O.M. Corbino, CNR, [2]Dipartimento di Elettronica, Università di Roma Tor Vergata, [3]Istituto di Fotonica e Nanotecnologie, CNR.
Corresponding e-mail: verona@idac.rm.cnr.it

Electroacoustic devices exploiting the propagation of both bulk (BAW) and surface acoustic waves (SAW) have shown to be a powerful tool to measure physical parameters, like force, pressure, acceleration or chemical and biochemical values, like concentrations of gases, vapors or ions in both gaseous and liquid environments. The most simple acoustic wave based chemical sensor is the quartz micro-balance (QMB), consisting of a piezoelectric resonator, usually made of a quartz platelet, covered by a proper chemically interactive membrane (CIM). The performances of the QMB, whose operation frequency is limited to 30 $\div$ 40 MHz, can be improved by use of SAW devices (delay line oscillators or resonators) whose higher frequencies of operation increase the sensor output signals, making thus possible an improvement of the device sensitivity. In this paper we present a chemical sensor based on a TFBAR structure. The device has been implemented on (001) Si, using a Si_3N_4 or SiO_2 membrane covered by an AlN piezoelectric layer. The membrane was obtained by anysotropic chemical etching of Si from the back side, followed by CIM deposition. Sensor tests have been performed by using a thin Pd film as CIM, deposited by thermal evaporation, and exposing the device to different concentrations of hydrogen in nitrogen. The sensor response is reversible and H_2 desorption take place when exposed to dry air. Time response upon different cycles of hydrogen adsorption/desorption are reported together with the calibration curves vs. H_2 concentration. Measurements of the time stability, repeatability, sensitivity, etc. have been performed and are reported. The high operation frequency of the device, in the GHz range, allows to obtain very high sensor responses (frequency shifts); moreover the device is robust in construction and miniaturized in size. The technologies involved in its implementation are compatible with those of Si integrated circuits, so that a monolithic integration of arrays of these sensors with the oscillator amplifiers and electronic conditioning circuits is possible.

P1U-K-5 J5

ULTRASONIC ATTENUATION IN ACOUSTIC TOUCH PANELS

M. TAKEUCHI*[1], T. GOTSU[1], and J. KENT[2], [1]Faculty of Engineering, Tamagawa University, [2]Elo TouchSystems, Inc.
Corresponding e-mail: takeuchi@eng.tamagawa.ac.jp

Acoustic touch panels are increasingly used in commercial display monitors as a user-friendly touch sensitive input device. Water droplets can produce false touch signals on conventional touch panels which use Rayleigh waves on glass. Substituting horizontally polarized shear waves such as Love waves avoids this defect. At the 2000 Symposium, Kent et al. reported on experiments with Love waves on trilayered substrate consisting of glass microsheet bonded to a glass plate via a thin polymer layer. In this paper, the attenuation of the Rayleigh wave and the Love wave due to finger touches or the drop of water is investigated theoretically and experimentally for the development of the touch panel which is no sensitivity in the droplet though there is sensitivity in the touch of the finger. In the theoretical analysis, the finger is assumed to be a visco-elastic solid. Moreover, the influence of water droplet is analyzed using the leaky wave model. According to the analysis in case of the Rayleigh wave, attenuation with the finger touch is considerably larger than attenuation with the water droplet. Attenuation of the Love wave on trilayered substrate with finger touches is less than the attenuation of the Rayleigh wave. Experimental data at 5.6 MHz will be presented. The results obtained here are useful for the design of excellent acoustic touch panels.

P1U-K-6 J6

MEASUREMENT OF DRAUGHT USING ULTRASONIC AIR TRANSDUCERS

G. P. P. GUNARATHNE*, The Robert Gordon University.
Corresponding e-mail: g.gunarathne@rgu.ac.uk

Draught currents in buildings and houses in cold weather are a common problem that is often caused by poor insulation of windows and walls. The extent of draught is mainly dependent on the temperature gradient between inside and outside of the building and the thermal resistance of that part of the building exposed to the outside atmosphere. While the qualitative effect of draught currents can often be felt by the cooling effect, it cannot give a quantitative assessment of the effectiveness of room insulation. However, significant draught currents are still very slow, which causes problems in measurement.

Although, various conventional ultrasound techniques such as time-of flight and Doppler methods are widely used to determine flow velocities, such methods are not suitable for the measurement of very slow convection currents such as draught, since the effect they produce are masked by parametric fluctuations of measurement. In this paper, work carried out in developing an ultrasonic sensory system capable of measuring low air flow velocity in the range of 1 cm /s presented.

The principle of operation is based on measurement of phase change of ultrasound due to the movement of the medium in comparison to a reference channel. In this regard an uncertainty analysis has been carried out and the major contributory factors masking the required effect have been isolated and appropriate signal processing stratergies were formulated.

Based on the above principle, a prototype model was then built and tested. It was found that the system operated as expected. It was also noted that further improvement could be made by controlling the temperature of the environment in which the signal acquisition hardware is placed. Work in progress includes further refinements to acquisition hardware and software for improving the accuracy and reliability of measurement.

The dedicated contribution made by a number of engineering stdudents within the school during various stages of development as part of their studies and the support extended by the technical staff are kindly acknowledged.

P1U-K-7 J7

RECIPROCITY CALIBRATION OF HYDROPHONES AT VARIOUS TEMPERATURES IN THE MHZ FREQUENCY RANGE

C. LABUDA, J. L. RAYMOND*, and C. C. CHURCH, National Center for Physical Acoustics, University of Mississippi.
Corresponding e-mail: jraymond@olemiss.edu

Hydrophone calibration data are typically specified over a range of frequencies but usually at only one temperature. In this study, the influence of temperature on a passive PVDF needle type hydrophone was determined over the range 3 deg C-37 deg C using a reciprocity technique. Calibration of an Imotec 300/24/62 bilaminar PVDF needle hydrophone over the frequency range 1-12 MHz was conducted using a two-transducer reciprocity method. This method makes use of pairs of unfocused reciprocal transducers (send/receive) to provide redundant measurements and simplicity. This technique has the advantage that none of the sensitivities of the transducers involved in the calibration need to be known a priori. The method was tested by calibrating a hydrophone for which the manufacturers calibration data were available (Sonora Medical S4-155 membrane hydrophone). Our results showed that there is a marked decrease in sensitivity for a passive PVDF probe (Imotec) as the temperature decreased from 22 deg C (i.e., room temperature) to 3 deg C. An increase in EOC sensitivity is observed as temperature rises from 22 deg C to 37 deg C, although the sensitivity remains about the same order of magnitude.

P1U-K-8 J8

A LOCALIZED ACOUSTIC FIELD FORMED IN THE VICINITY OF A BENDING-VIBRATOR END AND ITS APPLICATION TO PIEZOELECTRIC SENSORS

K. YAMADA*, D. YAMAZAKI, and K. NAKAMURA, Graduate School of Engineering, Tohoku University.
Corresponding e-mail: k.yamada@ecei.tohoku.ac.jp

The velocity of a flexural wave (the lowest order anti-symmetric mode of Lamb waves) propagating in a thin plate can be lower than that in the surrounding medium (air or gas) if the product of the frequency and plate thickness is smaller than a threshold value. In this case, evanescent acoustic fields which decay exponentially from the plate's surfaces are formed in its close vicinity. In a plate having a finite lateral size, the plate end vibrating in bending modes can be regarded as an acoustic dipole because two pressure sources having opposite polarities are supposed to exist near the upper and lower edges separated each other by a small distance. Therefore, a kind of evanescent acoustic field localized at the end of the plate will be created. When an object is brought into the evanescent field formed by a piezoelectric bending vibrator, the electric admittance of the vibrator varies depending on the vibrator-to-object distance d. The authors' group has been interested in this non-radiant wave, and has studied it with a view to applying it as a proximity sensor. It has been found in the studies so far that, when an object is brought into close proximity with the plate end, an unexpected phenomenon occurs such that the Q-factor, which once decreased as the object approached the plate, starts to increase in a small range of d. In this study, this unique phenomenon is examined in detail by experiments. Some new facts are clarified with respect to the variation of the vibrator characteristics such that the Q-factor and the resonance frequency vary in a complicated manner as an object approaches the vibrator end. Theoretical explanations are given to conjecture the mechanism of this phenomenon by introducing a simple model. The possibility for using this bending vibrator for a proximity sensor and/or a pressure sensor is discussed.

P1U-K-9 J9

CLAMP-ON SHEAR TRANSDUCERS SIMPLIFY GUIDED TORSIONAL AND/OR EXTENSIONAL INVESTIGATIONS

L. C. LYNNWORTH*, Lynnworth Engineering.
Corresponding e-mail: larry@kynosoura.com

Dry coupling of shear waves at normal incidence between unpolished elastic specimens in the past has utilized high coupling pressure, 10 to 100 MPa ($\sim$1500 to 15,000 psig), implying high coupling force if the coupled area exceeds about 1 cm^2. However, if the area of contact is small, e.g. a line contact, then adequate coupling pressure can be achieved merely by finger-tightening a pair of opposed plastic thumbscrews. T. H. Nguyen (unpubl.) several years ago appears to have originated the use of a clamp-on NDT shear transducer pair operated as a couple in a plane perpendicular to the axis of a waveguide to generate and detect torsional guided waves. With respect to some guided wave studies, particularly where temporary coupling suffices or is advantageous, the clamp-on shear stress method appears to be faster and easier to use than previous methods for launching and detecting guided torsional and/or extensional waves in metals and nonmetals. The method avoids bonding and couplants. Developments on sensors having cross sectional dimensions on the order of one cm may provide physical robustness but are opposite today's emphasis on nanoscale devices. With suitable clamping fixtures, standard NDT-style shear contact transducers are now easily and quickly (< one minute) clamped against various elastic waveguides, solid or tubular. The nominal operating frequency of the transducers used in these tests was 2.25 MHz. But the echoes observed were typically downshifted in frequency by a factor of approximately twenty, to 0.1 MHz, depending somewhat on waveguide diameter. In the tests described, at the transducer sites, most waveguides were 6.4 to 12.7 mm diameter. Starting with waveguides in this diameter range, sensor segments may be fabricated at one or more locations along the waveguide by conventional machining operations. Sensors may be characterized by, or created by, their smaller diameter, conical transitions, or special geometric shapes such as a diamond. The diamond is known to be a preferred shape in which the torsional speed is reduced by mass loading of an adjacent fluid [2]. For this reason it was used previously for density and liquid level determinations. In the present study, waveguide lengths were 0.3 to 2 m, including sensor segments as short as 25 mm. Measurands considered in this paper include fluid density and temperature.

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[2] J. O Kim and H. H. Bau, *J. Acous Soc Am*, Vol. 85 (No. 1), pp. 432-439 (Jan. 1989).

This work was conducted with the assistance of T. H. Nguyen when the author was at GE Panametrics. GE's support of the work is acknowledged.

Session: P1U-L

PHYSICAL ACOUSTICS IV
Chair: K. Liang
Schlumberger-Doll Research

P1U-L-1 J10

SECOND-HARMONIC GENERATION OF LAMB WAVES IN A SOLID LAYER ON A HALF SPACE

M. DENG*[1], P. WANG[2], and X. LV[2], [1]Department of Physics, Logistics Engineering University, China, [2]College of Automation, Chongqing University of Posts and Telecommunications.
Corresponding e-mail: hgwldmx@cta.cq.cn

This work develops an effective approach for studying the generation of second harmonics of Lamb waves in the composite structure consisting of a solid layer on a half space. Using a second-order perturbation approximation and a modal expansion analysis approach for waveguide excitation, an effective theoretical model has been established. The nonlinearity in the elastic wave motion process can result in the generation of second harmonics when a primary Lamb wave propagates in the composite structure. And this nonlinearity can be treated as

a second-order perturbation of the elastic response of the primary Lamb wave propagation. There are second-order bulk and surface/interface driving sources in the composite structure wherever a primary Lamb wave propagates. These driving sources can be thought of as the forcing functions of a finite series of normal Double Frequency Lamb Waves (DFLWs) in terms of the approach of modal expansion analysis for waveguide excitation. The fields of second harmonics of a primary Lamb waves can be regarded as superpositions of the fields of a finite series of DFLWs. Despite the strongly dispersive nature of Lamb waves, it can be found that the DFLW component can grow with the propagation distance down the composite structure when the DFLW phase velocity equals that of the primary Lamb wave. The formal solutions for the second harmonics of a primary Lamb wave have been obtained. The numerical simulations have been performed to understand the physical process of the generation of second harmonics of a primary Lamb mode. The present results show that the complicated problems of the generation of second harmonics of the primary Lamb wave propagation in a solid layer on a half space can be exactly solved within a second-order perturbation approximation.
This work was supported by the National Natural Science Foundation of China under Grant No. 10004016.

P1U-L-2 J12

PRINCIPLES OF ULTRASONIC VELOCIMETRY BY MEANS OF NONLINEAR INTERACTION OF PHASE CONJUGATE WAVES

Y. PYLNOV*[1,2], O. BOU MATAR[1], V. PREOBRAZHENSKY[1,3], and P. PERNOD[1], [1]Institut d'Electronique, de Microélectronique et de Nanotechnologie (IEMN DOAE UMR CNRS 8520) Ecole Centrale de Lille, [2]Moscow Institute of Radioengineering, Electronics and Automation, [3]Wave Research Center of General Physics Institute RAS.
Corresponding e-mail: pylnov@yandex.ru

Development of the supercritical parametric technique of acoustic wave phase conjugation (WPC), notable for giant amplification of phase conjugate wave (PCW), stimulated the beginning of investigations in the field of nonlinear wave front reversal acoustics [1]. Recently it was found that the wave of low frequency ($\Delta\omega = \omega_1 - \omega_2$) emitted by the local nonlinear interaction of phase conjugate beams (of frequencies ω_1 and ω_2) near the scattering object has abnormal sensitivity of phase to the object position [2]. Displacement of the object leads to the phase shift of the emitted wave proportional to the high frequency $\Omega_+ >> \Delta\omega$, were $2\omega_1 < \Omega_+ < 2\omega_2$. In the present paper we demonstrate possibility to apply this phenomenon for high resolution measurements of velocity of moving objects immersed in a medium. In the experiments we used the focused acoustic wave of 11MHz interacted with the PCW of 10MHz scattered by object moving in a homogeneous liquid. The measurements of the velocity were carried out at the frequency 1MHz and show the improvement of the resolution of equipment due to super sensitivity of phase of low frequency emission (LFE). This improvement

is expected to be used for ultrasound velocimetry in medical ultrasound diagnostics and NDT. Principles of application of LFE for measurements of current velocity of liquids in Doppler ultrasonography are discussed. [1] A. Brysev, L. Krutiansky, V. Preobrazhensky //BRAS Phys. Supp: Phys.Vib. v.9, (2001), 52 [2] Yu. Pylnov, Ph. Pernod, V. Preobrazhensky, //Acta Acoustica united with Acoustica, v.89, (2003), 942-947
The research described in this publication was made possible in part by Awards No. RP-2367-MO-02 of the U.S. (CRDF) and No VZ-010-0 of the U.S. (BRHE), PICS program CNRS-RAS N5008, Ecole Centrale de Lille, French Embassy in Moscow (MAE), Interrag IIIa.

P1U-L-3 J13

NUMERICAL ANALYSIS OF NONLINEAR AXISYMMETRICAL ACOUSTIC RESONATORS

C. VANHILLE*[1] and C. CAMPOS-POZUELO[2], [1]ESCET, [2]Instituto de Acùstica.
Corresponding e-mail: c.vanhille@escet.urjc.es

High-power ultrasonic applications in industrial processing are based on nonlinear effects produced by finite-amplitude pressure variations. The knowledge of the nonlinear pressure distribution inside resonant cavities is essential for the development of practical applications. Some one-dimensional numerical models exist, which have shown the important dependence of pressure values and distribution, first, on the nonlinear distorsion and nonlinear attenuation, and second, on the geometry of the resonator. In this framework, we propose a finite-difference algorithm able to simulate linear standing waves and strongly nonlinear quasi-standing waves inside axisymmetrical rigid-walled resonators for homogeneous absorbing fluid. A fully nonlinear 3-D wave equation valid for axisymmetrical systems is written in Lagrangian coordinates, considering only bulk attenuation via an ad-hoc parameter. All calculations are performed in the time domain, giving all the harmonic components of the wave by only one resolution step, and allowing the possibility of using any time function excitation signal.
This work has been supported by the MCYT DPI2002-03409 and URJC PPR-2003-46 Projects.

P1U-L-4 K13

NON PERIODIC ACOUSTIC DEVICES RADIATING IN SEMI-INFINITE SOLIDS SIMULATED BY A COMBINATION OF FINITE ELEMENT ANALYSIS AND A BOUNDARY ELEMENT METHOD

M. WILM*, S. BALLANDRAS, and V. LAUDE, Institut FEMTO-ST, Dept LPMO.
Corresponding e-mail: ballandr@lpmo.edu

The combination of boundary integral methods (BIM) and finite element analysis (FEA) has demonstrated its efficiency for modeling infinite periodic and finite non periodic surface acoustic wave transducers. Recently, we have shown that the use of a boundary element method (BEM) for the simulation of radiation

conditions in periodic FEA offers more adaptability without any loss of precision for many kind of problems, such as inhomogeneous acoustic wave guides, passivated surface acoustic wave devices, piezocomposite transducers and even micro-machined ultrasonic transducers. In this work, we investigate the possibility to applied this approach to the simulation of finite non periodic devices with radiation boundary conditions. Actually, most of the vibrating devices implemented in acoustics are clamped to or built on a massive body in which electro-acoustic energy is radiated. The classical approach simply consisting in the simulation of isolated vibrators or rigidly clamped devices (for which displacements are set to zero in the embedment region) is revealed improper to rigorously predict their resonant behavior. We then propose to implement a computation code able to mix FEA and a BEM for the simulation of finite non-periodic structures with reasonable computation delays. In the case of radiation in semi-infinite fluids, the problem is simplified by the knowledge of the exact analytic form of the Green's function used to compute the boundary element contributions. However, this situation does not occur for semi-infinite solids which still requires some efforts in that pursuit. It is then necessary to compute the spatial Green's function relating the surface stresses to the displacements thanks to its spectral form (accessible analytically) by Fourier transform. In that matter, it is shown how to compute the Green's function asymptotic behavior along the wave number (or the slowness) for isotropic solid and to integrate the resulting contributions in the BEM. The contribution of the shear wave to the Green's function is also identified analytically. A generalization of these results to anisotropic solids is regarded. Finally, the boundary element computation consists in a combination of analytic and numerical integration. Fit procedures are finally developed to improve the convergence and to reduce the computation time of numerical integrations.
The authors thank Th. Pastureaud and R. Lardat for fruitfull discussions on the subject

P1U-L-5 K12

TRANSIENT CAVITATION INDUCED BY PERIODIC SEQUENCE OF TONE BURSTS

V. ANDREEV* and V. ALEYNIKOV, Acoustics Dept., Faculty of Physics Moscow State University.
Corresponding e-mail: andreev@acs366.phys.msu.ru

Time of ultrasonic cavitation development in liquids is defined by initial bubble concentration. The concentration of bubbles and their size distribution can be varied in experiments when periodic sequence of tone bursts is employed for cavitation inducing. The shorter the pause between the successive pulses the more residual gas bubbles can be remained inside sonicated water volume. Theoretical model was developed for analyzing of bubble concentration evolution and bubble size distribution in the pauses between successive pulses. Dissolving of small gas bubbles, floating of large bubbles, bubbles fusion were taken into account in the modeling. Results of theoretical calculations were compared with data obtained from digital photos of cavitation zone just after ultrasound burst

termination. It was demonstrated that an equilibrium bubble concentration similar to initial one in undisturbed water was settled up after 60 sec. Acoustic cavitation in water was induced by 4-kW magnetostrictive transducer with 18 kHz resonant frequency. Continuous ultrasound and 0.4-s tone bursts with 1 - 20 s repetition intervals were employed for cavitation excitation. Cavitation noise was detected by a piezoelectric spherical hydrophone with 230 kHz resonance frequency. The realizations of cavitation noise were acquired during 0.1 sec just after beginning of radiator vibration both in undisturbed liquid and after radiation of some set of bursts. Time of steady-state cavitation development was evaluated from comparison of noise pressure harmonics obtained in liquid after 5-sec continuous sonication and in liquid with transient cavitation. It was found that time of steady-state cavitation development in undisturbed liquid was about 40-50 ms for our experimental conditions. Development of cavitation when infrequent pulses were used was similar to cavitation progress in the undisturbed water. For the case of small pause between bursts (1 2 sec) the development of cavitation was performed two times faster compared with undisturbed water. Results of time of the steady-state cavitation development in dependence of pulse duration and number of pulses are also included in the paper. To explain experimental results a theoretical approach based on Nolting-Neppiras equation with additional term depending on bubble concentration was employed. Phenomenological model for a temporal dependence of cavitating bubbles in liquids was proposed. It was found that the growth of bubble concentration resulted in significant reduction in maximum radius and time of its collapse.

P1U-L-6   K11

2D NUMERICAL SIMULATION OF SUPERCRITICAL PHASE CONJUGATION OF ULTRASOUND IN ACTIVE SOLID MEDIA

O. BOU MATAR*[1], V. PREOBRAZHENSKY[1,2], and P. PERNOD[1], [1]Institut dElectronique, de Micro-électronique et de Nanotechnologie (IEMN-DOAE UMR CNRS 8520), [2]Wave Research Center of General Physics Institute (RAS).
Corresponding e-mail: olivier.boumatar@iemn.univ-lille1.fr

Parametric wave phase conjugation (WPC) of sound using supercritical electromagnetic pumping in solids is of great interest for various applications in nondestructive testing, medical imaging and power ultrasonics [1]. It provides in particular automatic retro- focusing of acoustic beams in inhomogeneous media. The problem of supercritical WPC has no analytical solution for geometry and operation conditions of real conjugators. Recently, numerical studies of WPC supercritical dynamics were made for the linear [2] and nonlinear [3] pumping modes, in a one-dimensional configuration. To study the influence of reverberations and multiple mode conversions inside the active element of the conjugator on the parametric WPC processus, simulations have to be extended in 2D or 3D. In the present study a 2D axisymmetric numerical model is developed for cylindrical magneto-ceramic active element of finite length emitting phase conjugate wave into a liquid. Pseudospectral time domain algorithm (PSTD) is used due to its efficiency to model large-scale problems. PSTD solves elastic wave equation in time dependent heterogeneous isotropic and axisymmetric anisotropic solids using FFTs for high order approximation of the spatial differential operator on staggered grid, and a 4th order Adams Bashforth time integrator. Absorbing boundary condition, to truncate the computational domain, is introduced with complex frequency shifted perfectly matched layers (CFS-PML), found to be highly effective at absorbing evanescent waves and signals of long time-signature. The free-surface of the active ceramic rod is introduced through a method of images. A systematic study of the influence of lateral limitation of the active medium on parametric WPC of sound has been made. It is shown, that retro-focusing of the incident pulse take place even in the case of mode conversion inside the active zone. Nevertheless, amplitude and form of the obtained conjugate pulse depend on the simulated configuration. Numerical simulation correctly describes the parametric amplification and retro-focusing of ultrasound observed in experiments, when the conjugator is loaded at one end by water, and is free on the opposite one.

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The research described in this publication was made within the CNRS-RAS PICS program n° 5008, Interreg IIIa n° 56, and in part by support of the french embassy in Moscow (MAE), Award No. RP-2367-MO-02 of the U.S. Civilian Research & Development Foundation for the Independent States of the Former Soviet Union (CRDF), grant 02-02-16916 from RFBR, and grant 1553.2003.2 of the president of RF.

P1U-L-7 K10

EFFECT OF COMBINED STACKS AS A HEAT PUMP ON THE THERMOACOUSTIC COOLING SYSTEM

S. SAKAMOTO*, T. TSUJIMOTO, and Y. WATANABE, Faculty of Engineering, Doshisha University.
Corresponding e-mail: etc1103@mail4.doshisha.ac.jp

The cooling effect of the stack as a heat pump on the thermoacoustic cooling system was experimentally investigated by combining stacks of channel-diameter, to induce the effective heat interactions between the channel walls of stacks and working fluid, and to decrease more effectively the temperature at the cooling point. A loop-tube was employed as a thermoacoustic cooling system. The total length of the loop-tube was 3.2m. The working fluid was air at atmospheric pressure. Two stacks, stack 1 and 2, sandwiched between heat exchangers, were placed in the tube. A stack, honeycomb ceramic, was 50 mm in length. For the

stack 2, three kinds of stacks of different channel-diameter were used: 1.1 mm, 0.9 mm and 0.7 mm on a side. The number of the cells per inch-square of each stack was 600, 900 and 1200, respectively. Stack 1 was employed as a prime mover and stack 2 as a heat pump. The heat exchanger A (TH) on the stack 1 was an electric heater. In the heat exchangers B (TR), one under the stack 1 and the other on the stack 2, water was circulating in order to maintain the reference temperature (TR), 18 degrees C. These heat exchangers created the temperature gradient in the stacks. The temperature variations at the cooling point under the stack 2 were measured at the center axis of the tube with a K-type thermocouple. While after the heat supply was started, the self-sustained sound was spontaneously generated by the thermoacoustic effect. Just after the self-sustained sound was generated, the temperature at the cooling point was decreased. For the stack 1, one 900-cell stack was used. For the stack 2, one or plural stacks were used. Plural stacks were in combination to the series with those of same channel-diameter or those of different channel-diameter. When one stack was used, more temperature decrease was confirmed with a stack of smaller channel-diameter. When two stacks of same channel-diameter were combined, the temperature decrease of 140% was observed, in comparison with the observation with one stack. When two stacks of different channel-diameter were combined, the remarkable results were found. When a 600-cell stack on the side of the reference temperature and a 1200-cell stack on the side of the cooling point were combined, the temperature was decreased by 17.2 degrees C. The rate of decrease was 130%, in comparison with the observation with two 600-cell stacks combined. When a 1200-cell stack on the side of the reference temperature and a 600-cell stack on the side of the cooling point were combined, the temperature was decreased by 15.7 degrees C. From these results, it was found that it is effective to combine the stack of smaller channel-diameter on the side of the cooling point than that on the side of the reference temperature. The maximum temperature decrease of 18 degrees C was observed when a 900-cell stack on the side of the reference temperature and a 1200-cell stack on the side of the cooling point were combined. Consequently, combined plural stacks as a heat pump of different channel-diameter have a good effect on the thermoacoustic cooling system.

P1U-L-8 K9

BASIC STUDY ON EFFECTS OF ACOUSTIC INTENSITY AND SOUND PRESSURE ON SURFACE MODIFICATION AND DISPERSION OF DIAMOND PARTICLES

T. UCHIDA*, A. HAMANO, N. KAWASHIMA, and S. TAKEUCHI, Toin University of Yokohama.
Corresponding e-mail: shin1@cc.toin.ac.jp

Diamond particles dispersed sufficiently should be used for polishing electronics devices such as hard disk substance. Many types of dispersants were developed

to improve the dispersion property of the materials for ultra precision polishing. However, such dispersants not always improve the surface properties of the polishing materials, so that the treated polishing materials cohere again. The purpose of this study is to disperse diamond particles into the diamond slurry by disaggregation and surface modification of diamond particles using ultrasound exposure and acoustic cavitation. Improvement of the dispersion property of diamond particles by ultrasound at 155kHz was reported in 2002 IEEE Ultrasonic Symposium in Munich. We reported that the aggregated cluster diamond with size of a few microns could be disaggregated to the particles with sizes of about 100nm and zeta potential of the sonicated diamond particles increased about 10mV from those of unsonicated diamond particles in the symposium 2002. Effects of acoustic intensity and sound pressure by ultrasound exposure at 155kHz on diamond particles were considered in this paper. Hydrophone was used to measure the sound pressure. The stainless steel vibrating disk was attached on the bottom of the water tank with a cross section of 70 mm 70 mm, height of 150 mm in the ultrasound exposure system. Diamond slurry was prepared by suspending 30mg of cluster diamond particles in 500mL of distilled water and stirred fully. An output signal of a function generator (HP 8116A) is amplified using a power amplifier (ENI 2100L) with a gain of 50 dB. The amplified signal is applied to the Langevin type transducer equipped on the vibrating disk. Ultrasound was exposed from bottom of the water tank. Sound pressure was controlled by adjusting output voltage of transmitter. Average acoustic intensity was calculated from measurement values of sound pressure. The zeta potential is used as a reference of surface modification. When diamond slurry was exposed to ultrasound with average acoustic intensity less than 14w/m2 (maximum sound pressure 20kPa), the zeta potential of diamond particles did not change before and after ultrasound exposure. When exposed to ultrasound with average acoustic intensity more than 35w/m2 (maximum sound pressure 40kPa), absolute values of the zeta potential on sonicated diamond particles increased. It is found that threshold of average acoustic intensity for modification of diamond particles lies between 14w/m2 and 35w/m2.

P1U-L-9 K8

ACOUSTOELECTRIC TRANSIENT SPECTROSCOPY OF MICROWAVE TREATED GAAS-BASED STRUCTURES

O. Y. OLIKH*, Kyiv Taras Shevchenko National University.
Corresponding e-mail: olikh@class.semicond.kiev.ua

The microwave irradiation influence on the electron capture cross section and the energy level of centers in the forbidden gap of n-GaAs monocrystal and n-GaAs-based epitaxial structures has been investigated for the first time. It is found that the deep level parameters are modified, and the character of changes is different for monocrystals and epitaxial structures. The observed changes are likely to be due to defects gettering in the material surface layer and internal stress relaxation, induced by the microwave treatment applied. The three types of samples were investigated: 1) The monocrystal GaAs wafer, 300 μm thick, Sn-doped (electron concentration was 10^{16} and 10^{18}cm^{-3}; 2) The GaAs epitaxial n-n$^+$ structures (GaAs:Te epitaxial layer, carrier concentration was 35x10^{15}cm^{-3}, grown on monocrystal GaAs substrate Te-doped with concentration 10^{18}); thickness of layer and substrate were 6 and 300 μm, respectively; 3) The GaAs:Te epitaxial n-n$^+$ structures with two buffer layers: 1 μm thick (n=8x10^{16}cm^{-3}), and 2 μm thick (n=7x10^{15}cm^{-3}), - grown consistently on (100) GaAs substrate (n=2x10^{18}cm^{-3}). Samples were irradiated in free space at a room temperature using magnetron emission (microwave frequency 2.45 GHz, power density 1.5 W/cm^2, treatment time 20-60 seconds). The electron capture cross section and the energy depth of the electronic trap level at near-surface region have been determined both before and after the microwave treatment. The method of acoustoelectric transient spectroscopy was used [1]. Results: 1) irradiation influence on the carrier trapping cross section is considerably stronger than the influence on the energy level position; 2) irradiation dose for a substantial center parameters changing for the epitaxial structures is higher than for monocrystalline samples; 3) character of changes is different for monocrystals and for structures; 4) microwave stimulated changes degree depend on the free carrier concentration. On our opinion, the changes of the deep level parameters are related to the structural-impurity alteration of a semiconductor near-surface region, caused by microwave treatment. Such alteration is earlier found out in [2]. Namely, defects are gettered in a material surface layer after irradiation. The charged defects concentration increase must result in the electric field strength increase at this region. Simultaneously, the capture cross section is known to decrease when the electric field increase. If the free carrier concentration is higher, than the charged defects screening is more effective and, consequently, the change is less significant.

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The author would like to thank prof. Konakova R.V. for helpful discussions.

P1U-L-10 J11

INVESTIGATING ULTRA-THIN LUBRICANT LAYERS USING RESONANT FRICTION FORCE MICROSCOPY

W. ARNOLD*[1], M. REINSTAEDTLER[1], U. RABE[1], A. GOLDADE[2], and B. BHUSHAN[2], [1]Fraunhofer Institute for Non-Destructive Testing (IZFP), [2]Nanotribology Laboratory for Information Storage and MEMS/NEMS.
Corresponding e-mail: arnold@izfp.fhg.de

The ultrasonic friction mode of an atomic force microscope is a scanning probe technique allowing one to analyze the load and velocity dependence of friction. The technique is based on evaluation of the resonance behavior of an AFM cantilever when in contact with a vibrating sample surface. The effect of load and lateral displacement of the sample surface on the shape of the torsional resonance spectra of the AFM cantilever is evaluated under dry and lubricated sliding conditions. A characteristic flattening of the torsional resonance curve has been observed at large surface displacements, resulting from the onset of sliding friction in the AFM cantilever-sample surface contact. An analytical model describing torsional cantilever vibrations in Hertzian contact with a sample surface is presented and numerical simulations have been carried out in order to confirm that the flattening of the resonance curve occurs with the onset of the sliding friction in the contact.

Session: P1U-M

UNDERWATER TRANSDUCERS
Chair: V. Varadan
The Pennsylvania State University

P1U-M-1 E1

MINIATURE FLEXTENSIONAL PIEZOELECTRIC TRANSDUCERS WITH RECTANGLULAR GEOMETRY FOR IMPROVED IN-WATER ACOUSTIC BANDWIDTH AND POWER

D. C. MARKLEY*[1,2], R. J. MEYER, JR.[1], R. E. NEWNHAM[2], and A.-C. HLADKY-HENNION[3], [1]Applied Research Laboratory, [2]Materials Research Laboratory, [3]IEMN, ISEN.
Corresponding e-mail: dcm13@psu.edu

Over the last several years, our research group has developed a broad family of miniaturized flextensional piezoelectric transducers. Cymbal transducers are small, thin, and inexpensive Class V flextensional transducers. A single cymbal consists of a piezoelectric disk sandwiched between two metal cymbal-shaped endcaps that serve as mechanical transformers, converting the small extensional motion of the ceramic into large flextensional motion of the endcap. Transmission bandwidth and transduction efficiency are critical variables for characterizing sonar acoustic transducers. In the cymbal design, the cap and disk have their respective fundamental resonance frequencies an order of magnitude apart. This was not an efficient use of the ceramic motion for projector applications. Recent studies demonstrated that by starting with a rectangular shaped ceramic driver, the ceramic length and width resonance modes could be brought closer to the frequency of the fletensional modes of the caps. The interaction of these various modes allowed the device to produce a more broadband higher power acoustic response. Finite element analysis, using the ATILA program developed by ISEN, provided guidance for improvements in bandwidth, power, and efficiency. Model and measurement results will be presented.
The authors gratefully acknowledge the support of the Office of Naval Research under contract #N00014-01-1-0872

P1U-M-2 E2

COMPARISON OF THEORETICAL PREDICTION AND EXPERIMENTAL PERFORMANCE USING FEM FOR MARINE TRANSDUCERS

J. LAN*, R. H. TANCRELL, and S. G. BOUCHER, Airmar Technology Corporation.
Corresponding e-mail: jlan@airmar.com

This paper describes a theoretical model for transducer performance, based on FEM which yields full description of the transducer. These parameters are transmit voltage response, receive voltage response, impedance, figure of merit (insertion loss), directivity pattern – all as a function of frequency around the resonance frequency. The model for water loading on the transducer face treats the water as a 'force' on the transducer proportional to the localized displacements across the transducer's face, with a small dependence on the shape of the transducer surface (flat or cylindrical, for example). This model simplifies the calculation since FEM is confined to determining displacements within the transducer body, and propagation in the water can be calculated using classical analytic techniques, based on these transducer displacements. The purpose of this paper is to demonstrate that excellent agreement can be obtained between theory and experiment with a relatively simple model, which does not require extending FEM into the propagating medium (water).

In almost all cases, the transducer motion is not piston-like. Rather, displacement varies across the transducer face, and this variation significantly affects beamwidth, sidelobe levels, and TVR. These parameters, in particular, are shown to be accurately predicted by the model when compared to measured values.

Several illustrative transducer designs are presented, based on a large variety of transducers that have been designed in recent years. Center frequencies range from 3kHz to 500kHz for the various designs illustrated here. One transducer is a Tonpilz design with an acoustic matching layer where a large operating bandwidth was obtained extending from 15 to 43kHz. As predicted by the theory, this large bandwidth could only be obtained by water loading the edges of the matching layer – in contrast, with the pressure-release material along the matching layer's edges (as in the customary design), bandwidth was about 50% smaller both theoretically and experimentally. Full frequency curves are presented in the paper.

Other examples are flexural transducer designs where the effects of water vs. air loading are clearly predicted by shift in center frequency, increase in bandwidth, and overall change in beam shape and impedance. Another example is one where a portion of the transducer's interior is liquid filled, a design often used for in-hull transducers and for transducers intended for pressure compensation at deep depths. In this case, FEM is used for the whole transducer with the liquid region having a Poisson ratio approaching 0.5.

This paper demonstrates that proposed transducer designs for marine applications can be analyzed with a reasonable number of FEM nodes yielding results that are adequate for engineering purposes. Typically, center frequency is within

5%, TVR is within 2 dB, beamwidth is within 2 degrees, and impedance is within 20%.

P1U-M-3 E3

PIEZOCOMPOSITE TRANSDUCERS FOR OPERATION IN 15–25 KHZ RANGE

A. ABRAR*[1], A. SKEA[1], S. COCHRAN[1], K. J. KIRK[1], D. CHOI[2], and M. P. WALSH[2], [1]Microscale Sensors Group, University of Paisley, [2]Piezo Composite Transducers Ltd.
Corresponding e-mail: aneela.abrar@paisley.ac.uk

The demands on transducer performance for underwater applications have increased considerably with broadband and high source level now being expected at low frequencies. With these high expectations comes the challenge of designing innovative transducers in relation to material, composition and geometry. Initial FE studies for a 3-1 piezocomposite multilayer transducer of unusual geometry exhibits promising results around an operating frequency of 20 kHz. Testing has demonstrated experimental comparability with FE results. The measurements have been taken both in air and underwater at high excitation signal levels. Key results are presented to demonstrate the TVR, RVS and beam pattern of the prototype device. Previous work on optimisation of multilayer designs using stochastic techniques [1] suggest that the new design may be further improved by varying the properties of individual layers. We discuss the relevance of the optimisation process and indicate potential changes to the transducer geometry to achieve improved results based on -3dB bandwidth. Bondlines are particularly important in multilayer devices and their effects are carefully considered.
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P1U-M-4 E4

MONOLITHIC MULTIMODE TRANSDUCERS PROTOTYPED USING EXTRUSION AND FUSED DEPOSITION OF CERAMICS (FDC) TECHNIQUES

D. C. MARKLEY*[1,4], R. E. NEWNHAM[1], A.-C. HLADKY-HENNION[2], J. K. COCHRAN, JR.[3], R. J. MEYER, JR.[4], A. SAFARI[5], and M. ALLAHVERDI[5], [1]Materials Research Institute, [2]IEMN, ISEN, [3]Materials Science and Engineering Department, [4]Applied Research Laboratory, [5]Department of Ceramic and Materials Engineering.
Corresponding e-mail: dcm13@psu.edu

Prototypes for a family of small, inexpensive flextensional piezoelectric transducers have been fabricated utilizing ceramic extrusion and Fused Deposition

of Ceramics (FDC) techniques. These processes allow for fabrication of devices based on classical flextensional geometries, but with the metallic shells replaced by poled piezoelectric ceramics. Several initial geometries have been tested including Class I (concave and convex), Class IV and Class VII types, as well as other more novel designs. In-air testing results will be presented along with comparison to in-air and water FEA modeling studies. Designs such as the Class IV flextensionals, with fixed cross-sections, can be made in large quantity very inexpensively by extrusion. The convex and concave varieties could be made by inexpensive injection molding methods. The current prototypes made by fused deposition are being used to verify the effectiveness of FEA modeling for various transducer topologies, cross-sections and symetries. Multimode operation and broad bandwidth are possible with extruded transducers of complex cross-section. Shell diameters can range from one millimeter to 10 cm providing resonant frequencies from above 1 MHZ to below 10 kHz. Lengths can be as long as a meter or more. Vibration modes, resonant frequencies, and radiation patterns are controlled through the symmetry of the transducer material, its external shape, and the poling pattern.
The authors gratefully acknowledge the support of the Office of Naval Research under contract # N00014-01-1-0872

Session: P1U-N
TRANSDUCER ARRAY MODELING
Chair: H. Kunkel
Philips Ultrasound

P1U-N-1 I1

EFFECT OF A CURVED DOME ON THE EFFECTIVE FOCUS OF AN ANNULAR ARRAY – NUMERICAL SIMULATIONS AND EXPERIMENTAL MEASUREMENTS

S. P. NÄSHOLM*, T. F. JOHANSEN, and B. A. J. ANGELSEN, Inst. comp: Department of Circulation and Imaging, Norwegian University of Science and Technology.
Corresponding e-mail: peter.nasholm@medisin.ntnu.no

Many ultrasound imaging systems have the transducer array enclosed by a curved fluid filled plastic dome. Examples of this are mechanically steered annular array probes and tilted linear array probes for 3D imaging.

As the dome itself and the fluid have sound velocities that differ from the tissue it is applied to, the dome and fluid work as a lens which make the effective transducer array differ from the true transducer array. This fact both moves the effective focus position of a pre focused array and changes the effective aperture of the array elements.

The study takes into account geometrically pre focused annular arrays, both when each array element (ring) has the same focal point and when the focal points of the rings vary within the transducer array.

Two different methods for prediction of the effective array geometry are developed:

1. A model which is based on calculations of propagation times through the fluid-dome-water system using ray tracing.

2. A simple model using ideal lens equations. This model is useful only for prediction of the effective focus points.

The models are verified by experimental hydrophone measurements of the sound fields in a water tank. From these, the effective element apertures and focii are determined.

The transducer array used has a total aperture diameter of 15 mm. The elements are geometrically pre focused to points at distances below 50 mm along the central axis, measured from the center of the array. The emitted pulse has a center frequency of 12.5 MHz and consists of a 3 half period vibration. The curved dome is 1 mm thick and has a radius of curvature of 14 mm.

The main source of error is the difficulty to predict the sound velocities of the dome and the fluid as they are strongly temperature dependent.

Accurate information about the effective array geometry is important for precise electronic focusing of the sound beam.

The model based on ideal lens equations is accurate within the domain of small apertures compared to the dome dimension, but diverges from the ray tracing model for large apertures since it requires small incident angles where the sound crosses the dome surfaces.

The ray tracing based prediction model is found to fit well to the experimental results within the error tolerance considering the characterization of the sound velocities and dimensions of the dome and the fluid. It is useful for array design and focusing fine tuning.

P1U-N-2 I2

EFFECT OF ACOUSTICAL PROPERTIES OF A LENS ON THE PULSE ELECTROACOUSTIC RESPONSE OF A SINGLE ELEMENT TRANSDUCER AT DIFFERENT LOCATIONS IN THE RADIATED FIELD

P. MARECHAL[1], F. LEVASSORT[1], L.-P. TRAN-HUU-HUE[1], N. FELIX[2], and M. LETHIECQ*[1], [1]GIP ULTRASONS/LUSSI, [2]VERMON SA.
Corresponding e-mail: lethiecq@univ-tours.fr

For medical imaging, the classical trade-off between lateral resolution and depth of field is usually obtained with a f-number around 2 or 3. In the case of single-element circular transducer, this condition leads to a highly curved spherical lens. The objective of this work is to determine the limits of classical one-dimension models compared to axisymmetric 2D models, such as finite element analysis (FEA). The 2D models allow to take into account both the thickness and other vibration modes, such as radial vibration mode, as well as the specific non-planar shape of the lens.

In the first (theoretical) part, the results obtained using FEA (ATILA software) are compared to those of a specially developed method based on the superposition of several elementary ring-shaped transducers having a front layer of given thickness, each of them being modeled by a 1D KLM circuit. The different front layer thicknesses are chosen to fit the lens curvature. Initially, a slightly focused single element transducer is modeled both with the modified-1D and with the axisymmetric 2D models. It is shown that the results are similar in such a case. Then, in the highly focused case, pressure differences are highlighted at the lens surface. Thanks to a propagation code, the fields generated around the focal zone are calculated. The two sets of results are quantified, compared and discussed.

In the second (experimental) part, several transducers are fabricated with a center frequency around 10 MHz. The transducer backing and matching layer(s) are previously dimensioned and optimized on the base of a lead titanate ceramic (PT) piezoelectric element. Various materials are tested for the acoustic lens, with acoustical impedance between 2 and 3.5 MRa. The transducer characteristics are measured and compared to the theoretical results previously described. The electrical input impedance and pulse-echo response at different locations around the focal point are determined. In particular, the influence of the acoustical properties of the lens on the pulse electroacoustic response are discussed.

This study shows that a 1D approach is sufficient for lightly to moderately focused transducers (f-number around 2 or over). However, the radius of curvature of the lens is found to be an important parameter. When a small radius is considered (i.e. for a given f-number when the wave velocity in the lens is close to that of the propagation media) a 2D model is necessary. Finally, an optimization procedure for transducer design is proposed, taking into account the acoustical properties and geometry of the lens.

The authors thank Mr. Dominique Dinet of VERMON S.A. for transducer manufacturing.

P1U-N-3 I3

CROSS-COUPLING IN A 1-3 PIEZOELECTRIC COMPOSITE: SIMULATION AND EXPERIMENT

M. WILM*[1], O. BURAT[2], J.-F. GELLY[3], F. LANTÉRI[3], and S. BALLANDRAS[1], [1]Institut FEMTO-ST, Département LPMO, CNRS UMR 6174, [2]Framatome-ANP, Technical Center, [3]GE Parallel Design SAS.
Corresponding e-mail: mikael.wilm@lpmo.edu

Ultrasound devices for medical imaging applications and non-destructive evaluation are mainly based on multi-periodic transducer arrays like piezoelectric PZT-based composites. Due to their periodicities, these structures can exhibit strong cross-talks, which are particularly undesirable, especially in phased arrays. Many works have been dealt with in order to estimate cross-talk effects and their influence on radiation patterns, and to reduce them by modifying the geometry of the array (for instance by adding undercuts) or the materials of such complex transducers. However, the electrical boundary conditions applied to the array, when measuring cross-talks, may change significantly the measurement results, since the cells neighboring the excited one can be either short- or open-circuited. Moreover, no rigorous theory has been clearly addressed to calculate cross-talk levels in periodic transducers. Whatever the experimental conditions adopted for these cross-talk measurements, they must be reliable and simple enough to allow for an efficient theoretical description, with a model able to predict any contribution of the vibrating structure to the electrical response of the device. In this paper we present a theoretical approach well-known in the surface-acoustic-wave domain, that introduces the concept of harmonic and mutual admittances. This approach is combined with a multi-periodic finite-element method to compute cross-talk levels in ultrasound transducers. This approach is preferred to alternative methods based for instance on equivalent homogenized material derivation for different reasons. First, the use of a periodic finite-element analysis (FEA) was found appropriate to accurately describe all the modes excited in the structure, and more particularly those specifically due to the periodic nature of the substrate. Second, the capability to derive an operator relating all the voltages and the currents of the array to each other allows for handling almost any electrical boundary conditions, assuming the array is large enough to get rid of mechanical edge conditions. Computations are performed for a 1-3 connectivity piezoelectric composite and compared to measurements.

P1U-N-4 I4

MEDICAL TRANSDUCER ARRAYS USING COMPOSITE MATERIALS FOR ACOUSTIC MATCHING LAYERS –FABRICATION AND EXPERIMENT–

T. KONDO*[1], T. KITATUJI[1], and M. IZUMI[2], [1]Tokushima Bunri University, [2]Hitachi Medical Corporation.
Corresponding e-mail: tkondo@fe.bunri-u.ac.jp

The use of quarter-wave matching layers as acoustic impedance transformers has been standard practice, and is applied for modern commercial transducers. We proposed new composite materials and structure for matching layers and showed the significant improvements of sensitivity and reduction of mechanical coupling between array elements using the finite element analysis. Our analysis showed that low value of Poissons ratio of the matching layers gives a great affect on the sensitivity and the mechanical coupling between the adjacent elements. We proposed carbon fiber-epoxy with W powder and highly crystalline polyethylene fiber-polyurethane unidirectional composites as the materials with optimum acoustic impedance for the matching layers. The composites allow the realization of the materials with Poissons ratio below 0.1 and the satisfactory results have been obtained by the computer simulations based on the data [1]. To verify this analysis, we have tried to fabricate the transducer arrays and examined the properties of them. Manufacturing process to form the composite materials without heterogeneity of acoustical properties are described. Various kinds of carbon fiber and Dyneema to make composite materials were commercially available. The Poissons ratio of unidirectional composite plies depends on the anisotropy of it and the Youngs modulus of the carbon fibers used in the experiment covers 230 Gpa-650 GPa. Dyneema is a trademark of Toyobo in Japan, which is a highly crystalline polyethylene fiber (crystallinity of about 80 %) and has ultra high molecular weight and ultra molecular chain orientation. Acoustical properties of unidirectional composite plies are evaluated theoretically using Bettis reciprocal law, and experimentally using the Sing-Around method. The agreement between theoretical and experimental acoustic properties is fairly good. The optical heterodyne interferometer was newly developed for the experiment and the vibration modes of prototype transducer arrays were observed by using the instrument. The two dimensional displacement on a vibrating element and its adjacent elements of the transducers was measured and the improvements in sensitivity and cross coupling between the elements were verified by the experiment. [1] T. Kondo and H. Fujimoto, Proc. 2003 IEEE Ultrasonics Symp., p. 1318

P1U-N-5 I5

OPTIMUM CHOICE OF ACOUSTIC PROPERTIES OF FILLING MATERIALS BY OPTICAL MEASUREMENT

F. P. BRANCA[1], F. BINI[1], F. MARINOZZI[1], and A. GRANDONI*[2], [1]University of Rome La Sapienza", [2]Transducer Manufacturing Engineer, Industrial Engineering Group ESAOTE S.p.A.
Corresponding e-mail: franco.marinozzi@uniroma1.it

The filling material inserted between the elements of an acoustic imaging array gives mechanical robustness to the array, but acts as a path of interaction, transmitting, between the elements, shear and lateral compressional forces. Practically, it is difficult to simulate the behavior of a filling material because its actual acoustic properties often depends on several unpredictable factors such as the doping and/or the curing processes, during the manufacturing of the probe. This work started for a quantitative evaluation of these scarcely documented coupling phenomena. In order to assess the best filling material among various candidates an extensive experimental investigation was made by manufacturing several linear array probes. The measurement of the cross-coupling between adjacent element has been done in previous works by sensing the potential generated across the electrodes of the neighboring element while exciting the central one. This kind of measurements have fixed the misleading opinion that the inter-element cross talk is roughly -30dB. This value could be probably correct if considering only the electrical effects due to the pattern of the equipotential lines across the array. Probably the success of these “commonly accepted” values could be ascribed to a fundamental early paper by Kino (1979), which stated -30dB as a satisfactory crosstalk level for a “well designed” array transducer. Moreover, the influence on the whole cross-coupling due to the presence of the filler has been poorly outlined in the past. Since the filler is a non-piezoelectric material, the transmission of the perturbation from the excited element to the neighboring ones occurs by means of a direct mechanical coupling. Kino rightly considered in his model only the conversion of energy via the lateral modes of the piezoelement, since no filling material was included. The presence of filler allows for the transmission also of shear modes because a transverse wave can be supported across the filler from a piezoelement to another. This circumstance definitely contribute to rise the cross-coupling from -30dB (the "golden standard") to a more realistic -10dB value. In fact, Kino outlined the undesired effects due to the presence of the filling material, declaring that the ideal filler should be made of "hard air" (some kind of foam). However, some measurements performed on air filled prototypes demonstrate that also the air filled array, suffers of a conspicuous amount of crosstalk. This probably was due to the presence of the acoustic lens which couples the excited element to the neighboring. Since the actual ultrasound field is generated by the mechanical oscillation of the array elements, a reliable evaluation of the cross-coupling should be done by a direct measurement of such mechanical displacement amplitude. Measurements carried out by means of a laser interferometer (LDV) clearly outlined typical interelement crosstalk of roughly -10dB, well above the electrically induced crosstalk.

P1U-N-6 I6

3D FINITE ELEMENT MODELING OF OBLIQUELY ORIENTED PIEZOCOMPOSITE MATERIALS AND TRANSDUCER ARRAYS

W. LI*, J. M. GILMORE, and F. J. BENNETT, SonoSite, Inc.
Corresponding e-mail: gli@SonoSite.com

Piezocomposite transducers have proven to provide high acoustic efficiency and broad frequency band. Compared with a conventional 2-2 composite transducer with parallel or orthogonal orientation of the transducer array dicing cuts, obliquely oriented piezocomposite transducer array is formed of a 2-2 composite material in which the pattern of the composite material is oriented at an oblique angle to the elevation axis of the transducer array elements. Such obliquely oriented piezocomposite, as stated in US Patent 6,104,126, offers additional benefits such as easier in-process dimension registration, increasing element-to-element uniformity, mechanical flexibility for curved array conformation, and performance improvement by strongly suppressing the lateral resonance modes. Due to the unsymmetrical nature of such composite pattern and array element orientation and configuration, a 3D model is necessary to study such composite material and facilitate the transducer array design. In this paper, a 3D Finite Element Analysis (FEA) model using PZFlex package has been developed to simulate and optimize the obliquely oriented piezocomposite material and transducer array designs. Experimental data from different obliquely oriented piezocomposite materials and transducer arrays have been taken and compared with the model. The 3D FEA modeling results showed very good agreement with the experimental data.

Session: P1U-O

COMPOSITE TRANSDUCERS

Chair: H. Kunkel

Philips Ultrasound

P1U-O-1 L1

A NEW LOW FREQUENCY PIEZOELECTRIC COMPOSITE TRANSDUCER

D. ROBERTSON*, G. HAYWARD, and A. GACHAGAN, Centre for Ultrasonic Engineering, Department of Electronic and Electrical Engineering.
Corresponding e-mail: d.robertson@ultra.eee.strath.ac.uk

Piezoelectric composite transducers have many recognised advantages for medium frequency (0.2 MHz-20 MHz) ultrasound applications. However, the extension to lower frequency bands has not been straightforward, especially with regard to active (i.e. transmission) behaviour. Manufacture from single ceramic blocks is problematic, due to polarisation limitations and inevitably, the low capacitance compromises transmit sensitivity. Alternative configurations, based on multi-layered stacks can overcome most of these problems but introduce additional complexities with device manufacture and operational robustness. This paper presents a different method for manufacture of low frequency composites, utilising the fundamental symmetric Lamb mode (S0) in a conventional thickness drive piezoelectric plate. A composite plate, with electrodes positioned on the major faces, is driven at the fundamental frequency corresponding to the plate length dimension. This is shown to correspond exactly with the S0 mode and demonstrates low loss, longitudinal wave propagation, with extremely uniform surface displacement at the end faces that are normal to the direction of wave travel. A combination of experiment and finite element modelling using PZFlex is used to demonstrate the validity of this approach for low frequency (10 kHz-100kHz) 1-3 and 2-2 piezoelectric composite arrays. Measured coupling coefficients of approximately 0.55 for pzt5h ceramic and 0.8 for single crystal pmn-pt are shown to provide good agreement with theory, as do laser scans of the radiating surface profile. The measured TVR is shown to be comparable with stacked configurations of a similar frequency.
The authors would like to thank the EPSRC for funding this research under programme GR/R42542/01

P1U-O-2 L2

FABRICATION AND MODELING OF BROADBAND GRADED TRANSDUCERS USING PIEZOELECTRIC PARTIAL COMPOSITES

H. K. GUO*, J. CANNATA, Q. F. ZHOU, and K. K. SHUNG, Department of Biomedical Engineering, University of Southern California.
Corresponding e-mail: hkguo@usc.edu

Ultrasonic transducers have been widely used in various fields such as nondestructive evaluation and medical imaging. In many applications, broadband ultrasonic transducers with high resolution are strongly needed. Graded piezoelectric material is one of methods to achieve broadband transducer. In previous reported works, the piezoelectric ceramics were graded by triangular V-grooves. Because the V-grooves result in a complex vibration of the piezoelectric materials and the shape of the V-grooves affect directions of the transmitting acoustic field, finite element modeling (FEM) showed the conventional graded transducers with V-grooves couldnt give a satisfied pulse-echo performance. In this study, rectangular kerfs (grooves) were diced on a surface of $PbTiO_3$ ceramics with depth that is less than half of the ceramics total thickness. A kerf filler was applied to the kerfs, the resultant active transducer material consisted of one half of 2-2 or 1-3 composite and one half of monolithic ceramic to produce a partial 2-2 or 1-3 composite. These partial composites offer the advantages of lower acoustic impedance and higher coupling coefficient than monolithic ceramics, greater power and better handling capability than traditional composites. The transducer developed for this study used silver powder/epoxy as the kerf filler of the 2-2 composite layer and first matching layer. Parylene and a lossy conductive epoxy backing were used as the second matching layer and backing layer. The designed center frequency of this device was 15MHz. Electrical impedance measurements showed several resonant peaks instead of only one resonant frequency peak for regular transducers. Pulse-echo measurements demonstrated that a broadband ultrasonic transducer, which is 94% bandwidth in this study, can be achieved. The experimental results were consistent with the FEM results.

P1U-O-3 L3

FINITE ELEMENT ANALYSIS OF THE THICKNESS MODE RESONANCE OF PIEZOELECTRIC 1-3 FIBRE COMPOSITES

R. STEINHAUSEN, C. PIENTSCHKE, W. SEIFERT, and H. BEIGE*, Martin-Luther-University Halle-Wittenberg.
Corresponding e-mail: steinhausen@physik.uni-halle.de

Piezoelectric composites with embedded ceramic fibres are suitable for ultrasonic applications due to the absence of spurious lateral resonances. These lateral resonances were caused in conventional 1-3 polymer-ceramic-composites by the periodical arrangement of the piezoelectric active component (rods or cylinders). The Finite Element Analysis is a commonly used tool for modeling of the dynamic behaviour of ultrasonic transducers. Commercial software like ANSYS allows the accurate calculation of resonance modes and frequencies as well as impedance spectra. However, it is impossible to model the whole composite with its internal structure because of the limitation of memory and computing time. Therefore, a unit cell is used for modelling, representing the recurrent part of composite consisting ceramic rods and polymer matrix. In composite materials there are

the fibers unregular distributed in the matrix. Thus, the creation of a unit cell is impossible. Here, we propose a method for modeling of the impedance spectra of such a non-periodical composite. First, a representative cell containing 6 randomly distributed fibers was created. It turned out that spurious resonances occur in the impedance spectra in addition to the thickness resonance. The frequencies of these resonances strongly depend on the position of the fibres in the cell. 20 cells with different fiber positions were built (fibers were positioned by a random generator) and the their spectra were modelled. We consider the cells as electrically connected in a parallel circuit and the spectra were added respectively. The mechanical coupling between the cells were neglected. This results in a impedance spectra with a sharp thickness mode resonance and without spurious lateral resonances. Addionally, the influence of the variation of the diameter of fibres on the spectra was investigated. For this purpose, a unit cell with 9 regular arranged fibres with different diameters was used for the modeling. It was shown, that the variation of the diameter also results in a shift and an attenuation of the spurious resonance modes.

P1U-O-4 L4

NET SHAPE CERAMIC PROCESSING AS A ROUTE TO ULTRAFINE SCALE 1-3 CONNECTIVITY PIEZOELECTRIC CERAMIC-POLYMER COMPOSITE TRANSDUCERS

S. COCHRAN*[1], D. ZHANG[2], N. PORCH[3], B. SU[3], A. ABRAR[1], and K. KIRK[1], [1]Microscale Sensors, [2]Functional Materials Group, [3]Applied Functional Materials Ltd.
Corresponding e-mail: nicola.porch@afm-ltd.com

Piezoelectric-polymer composite materials are now widely used in underwater sonar, biomedical imaging and non-destructive evaluation. Piezo-composites suitable for frequencies from below 30 kHz up to approximately 30 MHz have conventionally been manufactured with the dominant dice-and-fill technique. However, the best method to extend the upper frequency limit still higher is unclear because of the processing demands of the ultrafine scale of the ceramic components. In this paper, we briefly review potential piezo-composite fabrication methods including injection moulding, mechanical dicing, and laser machining. We report of a new net shape processing method to fabricate ultrafine scale 1-3 ceramic structures. The modified "lost mould" method utilises Viscous Polymer Processing (VPP) to obtain a lead zirconate titanate (PZT) paste with high solid loading, which is then formed into polymer moulds. PZT bristle-blocks with feature sizes of 50-100 μm and height-to-width ratios of the order of 5-10 have been successfully fabricated. Experimental bristle-blocks have been backfilled with a low viscosity epoxy and lapped to thickness to form complete 1-3 piezo-composite transducer elements. We report of their electrical impedance and pulse-echo behaviour and show that it corresponds well with

computer modelling. We conclude that the processing route has the potential to extend the frequency range of piezo-composite material beyond existing limits.

P1U-O-5 L5

3-3 CONNECTIVITY MULTILAYERED PIEZOELECTRIC COMPOSITES

R. L. O'LEARY*, M. KIJOWSKI, and G. HAYWARD, Centre for Ultrasonic Engineering.
Corresponding e-mail: r.oleary@eee.strath.ac.uk

Multilayered piezoelectric devices have been proposed for high frequency operation for biomedical imaging as a result of their improved sensitivity. Harmonic imaging applications have also been investigated through differential drive and reception to attain frequency agility from a single device. However, multilayered piezoelectric composite devices prove difficult to manufacture; for example where the 1-3 connectivity is employed the continuity of the surface electrodes is not retained and as such each layer must be manufactured individually and then bonded together. This introduces the further complication of attaining alignment of the microstructure in the thickness dimension and attaining thin bond lines. Multilayered devices also have the potential to generate even and odd harmonics of the fundamental through the use of non-uniform layer thickness, leading to multi frequency and wideband devices.

This paper describes the theoretical investigation of 3-3 connectivity multilayered piezoelectric composite that can be manufactured using the dice and fill technique; the dicing operation is undertaken such that the continuity of the surface electrode is maintained on the inner layer. The PZFlex finite element modelling package is used to investigate the resonant behaviour of a three layer design with a fundamental thickness mode of 1MHz. Comparison is made between devices comprising uniform and non-uniform layer thickness; not all of the non-uniform layer designs that were investigated generate both the even and odd harmonics of the fundamental. Designs possessing three layers of 0.214mm, 0.428mm and 0.857mm or 0.428mm, 0.214mm and 0.857mm in thickness exhibited a strong second harmonic in theoretical pressure output of the transducer. This was found to be at the expense of a reduced output at the fundamental. A selection of experimental devices, and a technique to minimise the inter layer bond thickness by the deposition of a controlled wet film thickness of the adhesive layer, are described.

Session: P1U-P

BULK ACOUSTIC WAVES
Chair: J. Larson
Agilent

P1U-P-1 L7

COMPARISON OF ULTRASOUND AND γ-RADIATION INFLUENCE ON ELECTROPHYSICAL PROPERTIES OF MNHGTE

J. M. OLIKH*[1], M. D. TYMOCHKO[1], and V. I. KHIVRYCH[2], [1]Lashkarov's Institute of Semiconductor Physics NAS Ukraine, [2]Institute of Nuclear Researches NASU.
Corresponding e-mail: olikh@class.semicond.kiev.ua

Semiconductor MnHgTe crystals have been used as an alternative to application of CdHgTe in infrared photo electronics. These crystals have better crystalline structure and stable surface properties. It allows creating surface heterostructures of better quality for the protection of crystal and to improve the photoelectric properties of the devices created on their base. This work is concerned with the clarification of the efficiency of the defects formation processes in MnHgTe samples under an action of external factors (US-treatment, 5-17 MHz, W=0.5 Wcm^{-2} , and γ-radiation Co^{60} , $D=10^9$ rad) and determination of γ-radiation influence on a composition, width of a band gap, concentration of donors and acceptors of the investigated samples. The Mn_x Hg_{1-x} Te monocrystals were grown by the modified zone melting method (x=0.1 in the synthesis). As a result of experimental and theoretical investigations of temperature dependences (77-300-) of the Hall coefficient and a conductivity of the samples before and after treatments it was established, that: 1)-radiation influence results in the increase of carrier concentration in p-type samples and decrease in n-type samples and in the increase of their mobility (both for n- and p-type) in high temperature region and in the decrease in the low temperature region, respectively; the ultrasound influence have qualitatively similar character. 2)Main changes of electro physical parameters in the case of γ-radiation are related to the origin at the surface region of "shunt" volume conductivity of layers; in the case of p-type conductivity it is decreased, and in p-type samples it is increased. 3)Mechanism of γ-radiation action results in the intensive knocking of the mercury atoms out from the knots of crystal lattice with their subsequent migration to the sample surface; in that case there is the increase of concentration of mercury atoms on the sample surface and the vacancies in the sample volume. 4)Small changes of the carrier concentration and mobility under the γ-radiation influence confirm of high radiation stability of MnHgTe materials. Comparison of electrophysical properties of ultrasound treated and irradiated samples shows some analogy between two kinds of external action effects, allows to carry out an acoustic annealing of radiation defects and in some cases to use ultrasound for modeling radiation induced processes in MnHgTe.

P1U-P-2 L8

A 3.8 MM X 3.8 MM X 1.37 MM HERMETIC CELL-BAND FBAR DUPLEXER FOR HANDSETS

P. BRADLEY*[1], K. GRANNEN[1], D. CLARK[1], B. YU[1], and R. RUBY[1], [1]Wireless Semiconductor Division/Agilent Technologies, [2]Personal Systems Division.
Corresponding e-mail: paul_bradley@agilent.com

We will describe the design and measured performance of a 3.8 mm x 3.8 mm x 1.37 mm duplexer based on Film Bulk Acoustic Resonators (FBARs) for the 850 MHz cell-band cellular phone market. Typical Tx insertion loss is <1.25 dB and Rx insertion loss is <2.0 dB dB. Typical rejection is >57 dB in the Tx band and >47 dB in the Rx band. Typical isolation is >60 dB in the Tx band and > 50 dB in the Rx band.

P1U-P-3 L9

INVESTIGATION OF SPURIOUS RESONANCES IN THIN FILM BULK ACOUSTIC WAVE RESONATORS

A. REINHARDT*[1,2], V. LAUDE[1], M. SOLAL[2], S. BALLANDRAS[1], and W. STEICHEN[2], [1]FEMTO-ST, LPMO Department, [2]TEMEX Microsonics.
Corresponding e-mail: alexandre.reinhardt

With the maturation of Thin Film Bulk Acoustic Wave Resonators (FBAR) technology, a key in filter design becomes now not only the determination of thicknesses of layers, but also the ability to provide a very pure spectral response. Whatever the type of resonators considered, either membrane based or solidly mounted atop an acoustic Bragg mirror, spurii in the electric response arise from the generation of waves within the thin piezoelectric layer, either Lamb-like waves in membranes, or Love-like ones in Solidly Mounted Resonators (SMR).

We use a specific finite-element code to simulate FBAR structures. This enables us to simulate finite structure in a classical way. We also use a coupled Finite Element Analysis / Boundary Integral Method (FEA/BIM) in order to acurately simulate a radiation medium, like a Bragg mirror underneath a resonator, without having to mesh it entirely. Finally, by applying periodicity conditions at the edges of a meshed structure, we are able to simulate infinite structures quite acurately. All these features are used to investigate the generation of spurious modes within the structure and to understand their behaviour.

In a first part of this paper, we briefly describe the models used to achieve these simulations. We then analyse the generation mechanisms of spurious modes, by studying the Lamb or Love-like modes in stacked structures. Finally, we compare the two resonator types and investigate the geometry effects.

P1U-P-4 L10

PROPERTIES OF ALN FILMS GROWN BY TWO-STEP DEPOSITION AND CHARACTERISTICS OF ALN-FBAR DEVICES

D.-H. CHO*, D.-Y. KIM, B.-H. KIM, J.-B. LEE, J.-P. JUNG, and J.-S. PARK, Dept. of Electrical Engineering, Hanyang University.
Corresponding e-mail: rhlwwk@ihanyang.ac.kr

Practical film bulk acoustic resonators (FBARs) consist of a piezoelectric thin film sandwiched between top and bottom electrodes onto which an electrical field is then applied. The top and bottom electrodes often use the Mo metal since it has small acoustic wave attenuation and possesses the temperature coefficient similar to that of AlN films. Thin film AlN is considered to be the promising piezoelectric material for FBAR devices operating at high frequency in wireless communication technology due to its high thermal conductivity, excellent piezoelectricity, and high acoustic velocity. The most critical factor that determines the characteristics of the FBAR is the property of piezoelectric AlN film, which is directly related to the c-axis preferred growth along (002)-orientation, the crystal quality, and the surface roughness. In this study, we propose a two-step deposition method which enables to achieve AlN films having desirable properties for FBAR application, such as the enhanced c-axis preferred orientation and the reduced surface roughness, without deteriorating the crystal quality. AlN films are deposited on Mo/Si (111) substrate using an RF magnetron sputtering method. The process conditions for each step of the proposed method for AlN deposition are controlled to aim at the following goals; the 1st-step for reducing the surface roughness and the 2nd-step deposition for achieving the highly c-axis crystal orientation. The x-ray diffraction (XRD) spectra are monitored to estimate the texture coefficient and the full-width at half maximum for (002)-orientation peak. The surface morphology and roughness are also measured by using field-emission scanning electron microscopy (FE-SEM) and atomic force microscopy (AFM), respectively. Other process parameters, such as RF power, working pressure, and Ar/N_2 ratio, have also been varied to examine their impacts on the resulting crystal orientations, surface morphologies, and roughness of the AlN films deposited. The results obtained in this study obviously show that the AlN films grown by two-step deposition method possess the enhanced (002)-TC value as well as the reduced surface roughness, compared with the films prepared by conventional one-step deposition method. For the fabrication of FBAR devices, the top electrode with the resonance area of 200 ㎛^{2} is formed with Al by using a lift-off method. The frequency response characteristics (S_{11}) of FBAR devices fabricated are measured using a network analyzer (HP 8720C) connected to probe station (G-S-G type). It is also presented that the FBARs using the AlN films grown by two-step deposition reveal the superior device parameters including return loss and coupling coefficient, which is attributed mainly due to the positive effect of two-step deposition on the material property of AlN.

This work was performed by the technical support from the center for Electronic Materials and Components (EM&C) of Hanyang University at Ansan campus.

Session: P1FE-Q

THIN FILMS
Chair: J. P. Maria
North Carolina State University

P1FE-Q-1 Y5

THERMODYNAMICS OF PHASE STABILITY AND ELASTO-DIELECTRIC PROPERTIES OF PARAELECTRIC BST THIN FILMS UNDER 3D STATE OF STRAIN

E. K. AKDOGAN*, W. K. SIMON, and A. SAFARI, Dept. of Ceramic and Materials Eng'g, Rutgers University.
Corresponding e-mail: eka@rci.rutgers.edu

A heteroepitaxial paraelectric thin film under anisotropic plane stress conditions that gives rise to a 3D state of strain is considered. We develop a Landau-Ginzburg-Devonshire type free energy functional that includes 3D state of strain in a self-consistent manner; and determine its effects on the paraelectric phase stability, i.e. the change in m3m-4mm phase transition temperature. We also analyze the effect of the said state of strain on the linear and nonlinear permittivity, as well as the tunability. We also compare our analysis with our recent experimental work, where we have analyzed <110> fiber textured BST 60/40 thin films on <100> NdGaO3, and provide a justification for our approach. The phenomenological free energy formalism presented herein described the effects of the state of strain in its most general form, and as such, it is of universal use.
The authors gratefully acknowledge the funding provided by the Howatt Foundation.

P1FE-Q-2 Z6

OPTICAL MICRO-SCANNER FABRICATED ON STAINLESS STEEL BY AEROSOL DEPOSITION METHOD

M. LEBEDEV* and J. AKEDO, National Institute of Advanced Industrial Science and Technology.
Corresponding e-mail: maxim-lebedev@aist.go.jp

Recently Aerosol Deposition Method (ADM) [1] has become very attractive for deposition of piezoceramics thick films on different kinds of substrates. Having very high deposition rate as compare with conventional techniques and relatively low process temperature less than 600 °C , ADM is applicable for micro electro mechanical systems (MEMS) pplications as well. Particular feature of ADM is simple and fine patterning of piezoelectric films in deposition process and deposition on delicate structures. The density of deposited film is close to that of theoretical density. The films thickness is varied from less than 1 μm up to 500μm that gives flexibility in optimization of piezoelectric layers thickness for microactuator application. The breakdown electrical voltage of piezoelectric

films is very high and is more than 700 kV/cm for films thinner than 4 μm. A performance of a new type of optical 1-D micro-scanner for a raster scanning laser display was investigated. In our previous work [2], the Si-based structure of scanner was used. In present study, the piezoelectric (lead zirconate titanate PZT) actuators were directly deposited using ADM on the stainless steel based scanning device. We realized high resonance frequency of 25.4 kHz and scan angle (peak to peak value) of more than 10 degree.

1. J. Akedo M. Lebedev Aerosol Deposition Method (ADM): A novel method of PZT thick film producing for microactuators. Recent Research and. Development in Materials Science, 2, Research Signpost publisher, ISBN: 81-7736-045-0, pp. 51-77, 2001 2. N. Asai, R. Matsuda, M. Watanabe, H. Takayma, S. Yamada, A. Mase, M. Shikida, K. Sato, M. Lebedev, J. Akedo. Proc. IEEE 16th Annual Int. Conf. Micro Electro Mechanical Systems (MEMS) Kyoto, Japan, 2003, pp.247-250, 2003

This research was partially supported by the NEDO Project Nano Structure Forming for Advanced Ceramic Integration Technology in Japan Nanotechnology Program of Japan.

P1FE-Q-3 D5

SOL-GEL DERIVED PB(ZR,TI)O_3 THIN FILMS: RESIDUAL STRESS, ORIENTATION, AND ELECTRICAL PROPERTIES

R. J. ONG*[1], T. A. BERFIELD[2], N. R. SOTTOS[2], and D. A. PAYNE[1], [1]Department of Materials Science and Engineering and Frederick Seitz Materials Research Laboratory, University of Illinois at Urbana-Champaign, [2]Department of Theoretical and Applied Mechanics, University of Illinois at Urbana-Champaign, [3]Department of Materials Science and Engineering and Frederick Seitz Materials Research Laboratory, [4]Department of Theoretical and Applied Mechanics.
Corresponding e-mail: r-ong@uiuc.edu

Pb(Zr,Ti)O_3 compositions have been under investigation as potential integrated ferroelectric, piezoelectric and capacitor thin films for some time. Sol-gel synthesis and spin-coating are popular routes to the formation of high-quality, dense, crack-free, insulating films. However, electrical properties measured in thin film form can be different than those observed in bulk specimens of the same composition. Pb(Zr,Ti)O_3 films with a nominal composition at the MPB (53/47) were deposited from a 2-methoxyethanol based sol-gel system onto Pt/Ti/SiO_2//Si substrates via spin-casting. Multiple layers were sequentially deposited and heat-treated to 650C with the use of a PbO overcoat to ensure complete formation of the perovskite phase. Films with a final thickness varying from $<0.2\mu$m to $>0.5\mu$m were fabricated and studied by analytical techniques, including, electron microscopy, XRD, wafer curvature and electrical measurements to relate functional properties with the film?s macroscopic state (phase, stress, orientation). Electron microscopy allowed for the study of phase assemblage and morphology in thin films of various thicknesses. X-ray diffraction studies were used to interrogate not only phase purity in the film, but also film orientation with respect

to the substrate. *Ex-situ* wafer curvature measurements allowed for the determination of residual stresses in the Pb(Zr,Ti)O_3 films and the Pt/Ti/SiO_2//Si substrates. Final properties of interest such as dielectric constant, dielectric loss, remanent polarization, and coercive field were measured for films of various thicknesses and residual stress states. These measurements were employed as a whole in an attempt to separate the potential causes of property variations in a model Pb(Zr,Ti)O_3 thin film system when compared with their ceramic bulk counterparts. While, dielectric constant values of $\sim$1200, loss tangents of $\sim$2%, remanent polarizations of $\sim 18\mu C/cm^2$ and coercive field strengths on the order of 4 MV/m were measured for the thickest films, significant variations were observed as film thickness decreased (and the measured stress increased).
Authors would like to thank National Science Foundation for its support through grant CMS 00-8206. This material is based upon work supported by the U.S. Department of Energy, Division of Materials Sciences under Award No. DEFG02-91ER45439, through the Frederick Seitz Materials Research Laboratory at the University of Illinois at Urbana-Champaign. Research for this publication was carried out in the Center for Microanalysis of Materials, University of Illinois at Urbana-Champaign, which is partially supported by the U.S. Department of Energy under Award No. DEFG02-91-ER45439.

P1FE-Q-4 Z8

DEPOSITION OF PZT THIN FILMS BY HYBRID PROCESS COMPRISING SOL-GEL METHOD AND LASER ABLATION FOR MICROSCANNERS

Z. WANG*[1], H. KOKAWA[1], J. TSAUR[2], and R. MAEDA[2], [1]Department of Materials Processing, Graduate School of Engineering, Tohoku University, [2]National Institute of Advanced Industrial Science and Technology.
Corresponding e-mail: wangzj@matarial.tohoku.ac.jp

Lead zirconate titanate (Pb(ZrxTi1-x)O3: PZT) thin films have received much attention, because of their excellent ferroelectric, pyroelectric and piezoelectric properties. A large number of potential applications in micro-electromechanical systems (MEMS) have been reported recently, for example, atomic force microscopy (AFM) cantilevers and microscanning mirror devices. For use in these AFM cantilevers and microscanning mirror devices, high-quality 3-μm-thick PZT films on electrodes/substrates are desirable. Many fabrication techniques, such as the sol-gel method, laser ablation and jet print deposition, have been used to fabricate PZT films for microactuators. However, it is not easy to obtain thick PZT films with good electrical properties by any of the fabrication techniques. In this work, we attempt to deposit PZT films using hybrid process: sol-gel method and laser ablation. Namely, we deposited (100)- or (111)-oriented 0.15-μm-thick PZT layer on Pt/Ti/SiO2/Si substrates using sol-gel method firstly, and then deposited 1.5-μm-thick PZT films using laser ablation. The 1.65-μm-thick PZT films with well-crystallized perovskite phase and the (100) or (111)-preferred orientation were obtained using the hybrid process in a short time. The remnant polarization and the coercive field of this film were 28.6 μC/cm2 and 58.0 kV/cm, while the dielectric constant and loss values measured at 1 kHz were approximately 1050 and 0.045, respectively. The devices of micro mirrors were successfully fabricated through the PZT film deposition, lithography cyclotron resonance (ECR), reactive ion etching (RIE) and inductively coupled plasma (ICP) releasing processes. We could show that piezoelectric PZT thin films deposited by the hybrid process (sol-gel method and laser ablation) have sufficient actuation capability for MEMS application.

P1FE-Q-5 Z9

THE ELECTRICAL CHARACTERISTICS OF THE $(BA_{0.7}SR_{0.3})$ $(TI_{0.9}ZR_{0.1})O_3$ THIN FILM USING OXYGEN PLASMA SURFACE TREATMENT

K.-H. CHEN*, Y.-C. CHEN*, C.-H. CHANG, and C.-J. WANG, Department of Electrical Engineering.
Corresponding e-mail: d9131802@student.nsysu.edu.tw

The ferroelectric materials have been widely used for various applications such as memory cell, tunable microwave devices and optical waveguide devices. For memory and capacitor applications of next generation, the continuous increase of storage capacitance and high dielectric constant of material are necessary in the future. In this study, the optimized deposition parameters of the $(Ba_{0.7}Sr_{0.3})$ $(Ti_{0.9}Zr_{0.1})O_3$ (BSTZ) thin films using the sputtering technology have been obtained to be the sputtering power of 160 W, the oxygen concentration of 25%, the substrate temperature of 580 °C and the chamber pressure of 15 20 mtorr. The growth rate of the films was calculated to be about 15 nm/min from the measurement of SEM cross sectional morphology and the averaged surface roughness obtained from the AFM measurement was about 1.75 nm. The dielectric constant and leakage current density of the films obtained from the measurements of capacitance-voltage (C-V) and leakage current density-electric field (J-E) were about 130 and 5×10^{-7} A/cm^2 under the electrical field of 0.1 MV/cm. In addition, we attempt to investigate the effect of plasma surface treatment using oxygen plasma gas on the dielectric and leakage current characteristics of the thin films. The results showed that the surface roughness and thickness of the BSTZ films would be linearly decreased as the duration of oxygen plasma treatment increased. The dielectric constant and leakage current density of the film with oxygen plasma surface treatment were about 300 and 10^{-8} A/cm^2 under 0.1 MV/cm, respectively. These results indicated that the electrical characteristics were improved by the oxygen plasma surface treatment. Finally, the simulation results calculated from the measurement of leakage current versus electrical filed (J-E) for film with oxygen plasma surface treatment demonstrated the electrical field enhanced thermionic excitation of oxygen trapped in the thin films into the conduction band of the thin films, that is the Poole-Frankel conduction mechanism.

P1FE-Q-6 Z10

PREPARATION AND CHARACTERIZATION OF $PB(ZN_{1/3}NB_{2/3}O_3$-$PBTIO_3$ THIN FILMS

H. MAIWA*[1] and N. ICHINOSE[2], [1]Shonan Institute of Technology, [2]Waseda University.
Corresponding e-mail: maiwa@mate.shonan-it.ac.jp

Piezoelectric microelectromechanical systems (MEMS) employing ferroelectric thin films have been extensively studied. Of these thin films, PZT has been most widely studied. Single crystal $Pb(Zn_{1/3}Nb_{2/3}O_3$-$PbTiO_3$ (PZN-PT) has been reported to exhibit a larger field-induced strains, compared to PZT. So far, however, reports on PZN-PT thin films have been limited, most probably due to difficulty in obtaining single perovskite films. In thin reports, PZN-PT films were prepared by chemical solution deposition. By using PT nucleation layer, PZN-PT films annealed at 650°C and 700°C do not contain pyrochlore phase. These films exhibited ferroelectric hysteresis loops with remanent polarization of $5\mu C/cm^2$. Temperature dependence of electrical and electromechanical properties of the films will be reported.

P1FE-Q-7 Z11

EVALUATION OF BA0.5SR0.5TIO3 AS A BUFFER LAYER FOR PB0.3SR0.7TIO3 THIN FILMS

B. NI, D. PENG, W. WU, and Z. MENG*, School of Materials Science and Engineering, Shanghai University.
Corresponding e-mail: zymeng@guomai.sh.cn

Lead strontium titanate (PbxSr1-xTiO3, PST) thin films are considered to be a new promising material for applications of tunable microwave devices. But the dissipation factor of these materials is relatively high and it will limit the films to be used in microwave devices. It is well known that the interface between the film and substrate plays an important role in characteristics of PST films. In recent years, there has been a wide interest to control the structure like film/substrate interfaces by using buffer layer and improve dielectric properties. In this paper, Pb0.3Sr0.7TiO3 films with very thin Ba0.5Sr0.5TiO3 buffer layer inserted between the film and Pt/Ti/SiO2/Si(100) substrate were fabricated by sol-gel technique. The buffer layer was obtained from a highly dilute spin-coat 0.05mol/l Ba0.5Sr0.5TiO3 solution, and the upper Pb0.3Sr0.7TiO3 layer was achieved by 0.4mol/l solutions using a multiplayer spin-coating approach. The thin films were characterized by X-ray diffraction technique (XRD), field emission electron microscope (FE-SEM) and dielectric measurements. It was found that Ba0.5Sr0.5TiO3 buffer layer yield Pb0.3Sr0.7TiO3 films with dense, homogeneous microstructure. The upper Pb0.3Sr0.7TiO3 films were (111) preferential oriented and the surface morphology was uniform, smooth and crack free. The dielectric properties were measured in the frequency ranging from 100KHz to

100MHz at room temperature by using a precision impendence analyzer. The results show that use of Ba0.5Sr0.5TiO3 buffer layer yields Pb0.3Sr0.7TiO3 films with good dielectric properties. The dielectric constant of the multiplayer increased by 30% and the loss tangent decreased by 40% respectively. All these improvement of properties attributed to the more perfect crystallization and the Ba0.5Sr0.5TiO3 layer act as a sink of oxygen vacancies, suppress interface reactions between the film and the substrate and prevented the interdiffusion of Pb and Si elements, which directly result in the decreasing of defect densities and the leakage current.
This Project received support from Chinese National Natural Science Foundation (Grant No. 50332030)

P1FE-Q-8 Z12

INFLUENCE OF CA CONTENT ON DIELECTRIC PROPERTIES OF (BA1-X-YSRXCAY)TIO3 THIN FILMS

D. PENG, W. WU, and Z. MENG*, School of Materials Science and Engineering, Shanghai University.
Corresponding e-mail: zymeng@guomai.sh.cn

A strong DC electric field dependence of dielectric constant makes Ba1-xSrxTiO3 ferroelectric thin film to be promising materials for tunable microwave devices. However, the high inherent dielectric loss and constant of the films have hampered its further applications. It is well known that the dielectric properties ferroelectric films can be controlled by the ions at A-sites of ABO3. In this paper, the A-sites of BST ferroelectric were replaced in part by Ca ions, and the effects on the intrinsic dielectric property were discussed. The different compositions of (Ba1-x-ySrxCay)TiO3 (1-x-y=0.4, x=0.1, 0.2, 0.3, 0.4, BSCT) films were prepared on Pt/Ti/SiO2/Si (100) substrates sol-gel methods layer-by layer. And, the deposited films were annealed at 750 oC for 1.5 h in air. Films were characterized by XRD, FE-SEM, and dielectric measurements. XRD patterns revealed the films were well perovskite polycrystalline structure, and there is no existence of an anomalous phase after post-deposition annealing. The Ca contents dependence of dissipation factor was investigated. The results indicated both the dielectric constant and the dissipation factor decreased dramatically with increasing Ca ration, and Ba0.4Sr0.2Ca0.4TiO3 thin films have a dissipation factor of 0.015 at 1 MHz. When the Ca content exceeds 0.4, the dissipation factor would be increased dramatically. The paraelectric-ferroelectric phase translation was proposed to understand these phenomena.
This project received support from Chinese National Natural Science Foundation (Grant No. 50332030)

P1FE-Q-9 Z13

THE SIMULATION OF FERROELECTRIC THIN FILM GROWTH BY KINETIC MONTE CARLO METHOD

G. YU, J. ZHU*, W. LU, P. YU, and D. XIAO, Department of Materials Science, Sichuan University, Chengdu 610064, China.
Corresponding e-mail: yuguanglong@163.net

At present, simulation has become one of important tools of researching materials besides theory and experiment method, which can be applied widely in every aspect. Now, most of the simulations of thin film growth are about two dimensional and the object of simulation is only one kind of atom, such as Cu, Al, or Si thin film growth on different substrate. However, it is very important for understanding the growth kinetics of ferroelectric thin films, which were used as smart materials and functional materials. A new model for simulation of ferroelectric thin film growth basing on kinetic Monte Carlo method has been developed. This model is a three-dimensional model of ferroelectric thin film growth and the object is the multiple oxide ferroelectric thin film PbTiO3. In this paper, the model is described in detailed and some characteristics of the film growth of PbTiO3 are also discussed.

P1FE-Q-10 Y6

PREPARATION AND CHARACTERIZATION OF PZT(80/20)/PT FERROELECTRIC MULTILAYER THIN FILMS PREPARED BY SOL-GEL METHOD

X. YUAN, D. XIAO, G. YU, Y. FANG, and J. ZHU*, Sichuan University Material Science Department.
Corresponding e-mail: yxw711@163.com

Ferroelectric lead zirconate titanate/lead titanate (PZT/PT) multilayer thin films were fabricated by the sol-gel multiple coating process on Pt-coated Si(100) substrates. All PZT/PT multilayer thin films showed a uniform grain structure without the presence of rosette structure. The dielectric constants of PZT/PT thin films increased with increasing PZT film thickness. XRD patterns show that PT layers can decrease the crystallization temperature of PZT films. No pyrochlore phase was detected in PZT/PT films. It can be assumed that the PT layers played the role of a nucleation site or a seeding layer for the formation of the PZT layer. The relationship between the thickness and electrical properties of PZT/PT thin films was investigated. PZT/PT multilayer thin films exhibit good electrical characteristics compared with PZT films directly deposited on Pt-coated Si substrate. The pyroelectric characteristics of PZT/PT multilayer thin films have been examined and discussed. The domain structure of these films was also observed by Pieroresponse Force Microscopy (PFM).

P1FE-Q-11 Y7

THE EFFECT OF THERMAL TREATMENT ON PLD-DERIVED $BA_{0.8}SR_{0.2}TIO_3$ THIN FILM CAPACITOR

C. LIN*, S. XING, and Z. SONG, Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences.
Corresponding e-mail: cllin@simgui.com.cn

$Ba_{0.8}Sr_{0.2}TiO_3$ (BST) thin films have been known as one of promising candidate capacitor dielectrics for applications of next generation ultra-high density DRAM. The electrical property of BST film has a close relationship with deposition technique, including deposition process and thermal treatment process. In this paper,the BST thin films were deposited on platinized Si substrates by pulse laser deposition (PLD) under different O_2 residual pressure, and the effect of prolonged thermal treatment on the films was investigated. It was found that both surface roughness and oxygen vacancy affect the conductance of the capacitor. The prolonged thermal treatment does not change surface roughness of 10 Pa deposited film much, leading to a decrease of leakage current by eliminating oxygen vacancy; whereas strongly increases surface roughness of 20 Pa deposited film, resulting in a slight rise of leakage current in contrast. The BST thin flm capacitor with good dielectric and electric properties for device application was achieved by prolonged annealing of 10 Pa deposited film with forward leakage current of 2.42×10^{-8} A/cm^2 and reverse leakage current of 2.51×10^{-9}A/cm^2 under 1.5 V bias.
This work is supported by the National Nature Science Foundation of China under award No. 90101012

P1FE-Q-12 Y8

FABRICATION AND CHARACTERIZATION OF DOPED (BA,SR)TIO3 THIN FILMS BY AN IMPROVED SOL-GEL METHOD

Y. FANG, D. XIAO, X. YUAN, G. YU, W. LU, and J. ZHU*, Department of Material Science,Sichuan University.
Corresponding e-mail: nic0400@scu.edu.cn

Ferroelectric thin films of barium strontium titanate (BST) and Mg-doped BST, Bi-doped BST have been deposited on Pt/Ti/SiO2/Si substrate by a modified sol-gel method. Crystallized films were obtained by post deposition annealing at a temperature of 750°. X-ray diffraction (XRD) scanning electron microscopy (SEM) and atomic force microscopy (AFM) studies have been carried out to access the crystallinity, phase formation and grain growth pattern. The dielectric properties of the BST thin films were strongly depended with doped atoms. Electrical characterization of the films such as resistivity, C-V property, pyroelectric property in metal-ferroelectrics-semiconductor (MFS) configuration

have been carried. The domain structure of these films have been also observed by Pieroresponse Force Microscopy (PFM).
Jianguo Zhu:Corresponding author*

P1FE-Q-13 Y9

THE INFLUENCES OF VARIED SPUTTERING CONDITIONS ON THE PIEZOELECTRIC COEFFICIENTS OF ALN THIN FILMS

K.-S. KAO*[1], T.-F. OU[1], Y.-C. CHEN[1], and T.-K. SHING[2], [1]Department of Electrical Engineering, National Sun Yat-Sen University, [2]Microsensor Laboratory, Industrial Technology Research Institute.
Corresponding e-mail: d8831802@student.nsysu.edu.tw

Piezoelectric thin films have been used for decades as high frequency surface and bulk acoustic wave devices. Aluminum nitride (AlN) has been considered as an attractive thin film piezoelectric material for the applications of acousto-optic, acousto-electronic, and sensor interactions. In this study, the c-axis-oriented AlN films were deposited on piezoelectric substrate, lithium niobate ($LiNbO_3$), and non-piezoelectric substrate, silicon (Si), by reactive rf magnetron sputtering. The sputtering parameters were varied with the $N_2/Ar+N_2$ concentration of 20–80%, the chamber pressure of 1–15 mTorr, the rf power of 200–450 W and the substrate temperature of 100–400 °C. The correlations between growth parameters and piezoelectric coefficients are investigated. The measurement of piezoelectric coefficients of thin film is different from that of bulk material. The clamping effect and the constraint between thin film and substrate are the chief considerations. For the reasons, the piezoelectric coefficients (d_{33}) of AlN thin films were measured using the method of periodic compression force. A piezoelectric transducer connected with a metallic rod is submitted close and in contact with the sample surface. The d_{33} measurements for AlN thin films were performed on AlN/Si and AlN/$LiNbO_3$ multilayer structures. The experimental results showed that the value of d_{33} is larger as the intensity of X-ray diffraction is stronger. It can also be concluded that the smaller the FWHM angle is, the larger the value of d_{33} will be. The values of d_{33} are influenced by the uniformity of AlN thin films. The piezoelectric properties of thin film were much varied by the microstructures depending on the processing parameters. For the AlN/$LiNbO_3$ structure, the d_{33} value of 35 pC/N was obtained at the sputtering pressure of 3 mTorr, rf power of 290 W, N_2 concentration of 80% and substrate temperature of 400°C. For the AlN/Si structure, the d_{33} value of 7.1 pC/N was obtained under the sputtering pressure of 3 mTorr, rf power of 450 W, N_2 concentration of 80% and substrate temperature of 400 °C.
This research was supported by the National Science Council, (Taiwan, R. O. C.,) under contract no. NSC 92-2216-E-110-023 and NSC 92-2216-E-237-001. The authors wish to acknowledge C. J. Ho at the Industrial Technology Research Institute for the piezoelectric measurement.

P1FE-Q-14 Y10

MICROSTRUCTURAL AND X-RAY DIFFRACTION INVESTIGATIONS OF NANOSTRUCTURED THIN FILMS OF ZNO

H. BAHADUR*[1], A. K. SRIVASTAVA[1], R. KISHORE[1], and S. CHANDRA[2],
[1]National Physical Laboratory, [2]Center for Applied Research in Electronics, Indian Institute of Tecchnology.
Corresponding e-mail: hbahadur@yahoo.com

Characterization of piezoelectric thin films of ZnO forms an important part of our project of integrating such films into MEMS based acoustic sensors. Also, thin films of nano-grained ZnO have driven much potential for gas sensors as well. It thus becomes important to investigate the crystalline features of these films for any preferred orientation during growth. We report our measurements on the polycrystalline thin films of ZnO prepared by using two different routes of sol-gel process. Primarily, we present our XRD, electron diffraction, transmission and scanning electron microscopy data. Optical absorption peak at 372 nm was used to calculate the band gap. Refractive index calculated by ellipsometric and optical absorption methods were in close agreement. Thin films of the order of 1-2 u thickness were deposited on the Si wafer and quartz substrates employing a spinner. The sol was prepared using two different routes. The first route involved dissolving zinc nitrate [Zn(NO3)2. 6H2O] in ethylene glycol monomethyl ether [CH3O-CH2-CH2OH] to make a 10% solution. The other consists of using zinc acetate [Zn(CH3COO)2. 2H2O) and dissolving in boiling isopropyl alcohol. Multiple spin coatings were done to obtain the workable thickness of the film using both the routes of sol preparation. Optical constants (n 1.9), band gap (3.3 eV) and microanalysis confirmed that the films consisted of mainly ZnO. Work is continued in this direction to obtain high quality films for use in MEMS based acoustic sensor. X-ray diffraction measurements done in grazing incidence geometry on a Bruker -AXS (Model D8 Advance) using CuK" radiation showed the formation of hexagonal ZnO with (100), (002), (101), (102), (110), (103), (200), (112) and (201) planes resolved clearly. The lattice parameters calculated were a = 0.32 nm and c = 0.52 nm. SEM topography showed dendritic growth with agglomerations in some areas for film grown by zinc nitrate. However, the film grown by using the zinc acetate showed a much smoother surface with uniformly spread needle shaped particles at very high magnifications. For investigations of nano-structure of the deposited ZnO films, we operated the TEM at 200 kV and were able to resolve the fine grains with the size of 20-60 nm with clear surface boundaries. Individual grains have shown contrast at different facets with sharp edges. The non-spherical shape and faceted morphology of these grains shows a preferred crystallographic growth during deposition. A selected area electron diffraction pattern recorded on such films show the presence of three planes of hexagonal structure (100, 101 and 202) as rings in the reciprocal space. It demonstrate that the film is polycrystalline in nature. However, the absence of certain important reflections of hexagonal ZnO in the electron diffraction patterns elucidates that the film has certain texture

with the preferred growth direction. The films prepared by the zinc acetate precursor have shown still finer nano-grains in the bright field micrographs.

P1FE-Q-15 Y11

PROCESSING AND PROPERTY STUDIES OF HIGH ASPECT RATIO FERROELECTRIC NANOSTRUCTURES

B. SROWTHI*[1], N. SALDHANA[2], M. LI[2], T. MAYER[2], V. GOPALAN[1], and S. TROLIER MCKINSTRY[1], [1]Materials Science and Engineering and Materials Research Institute, [2]Electrical Engineering Department.
Corresponding e-mail: bss11@psu.edu

High aspect ratio ($\geq$50:1) ferroelectric nanostructures are potentially applicable in areas such as tunable photonic devices and bio sensors. For these applications, fundamental understanding of the electrical and optical properties is required. In this presentation, we report processing details of large area arrays of high aspect ratio nanostructures of Pb(Zrx,Ti1-x)O3, and LaNiO3/Pb(Zrx,Ti1-x)O3/LaNiO3 trilayers. The structures were prepared by vacuum infiltration using mesoporous Si, alumina, and SU-8 photoresist templates. A two step pyrolysis process was used to prevent cracking of these structures. Initial pyrolysis was done at 150 oC for 2 min. followed by high temperature pyrolysis at 300 oC for 3 min. and crystallized at 650 oC for 1 min. using rapid thermal annealing procedure. Appropriate wet/dry etching techniques, and chemical mechanical polishing techniques were employed to release the structures from the templates. Possible electrical integration issues of ferroelectric nano structure ensembles and dielectric, electrical and photonic properties will be presented.
Authors would like to acknowledge Dr. Fred Roozeboom (Philips Research Lab, Netherlands) for supplying meso porous Si substrates.

P1FE-Q-16 Y12

THICKNESS EFFECT OF LANIO3 INTERLAYER ON ELECTRIC PROPERTIES OF PB(ZR,TI)O3 WITH METAL SUBSTRATES

L. HE, P. ZHENG, J. CHENG, and Z. MENG*, School of Material Science and Engineering, Shanghai University.
Corresponding e-mail: zymeng@guomai.sh.cn

Lead zirconate titanate (PZT) thin films deposited on metal subtrates had received much attention for applications of embedded capacitors, sensors and actuators in micro-electron mechanical system (MEMS). To enhance the electric properties of the PZT films, perovskite-type LaNiO3(LNO) were introduced as buffer layers.In this work, the influence of different thickness of LNO films on electric properties of PZT films was investigated. PZT thin films were deposited by sol-gel method on Nickel-Chromium(NC) and Titanium (Ti) substrates, which were coated by LNO films varying from 50nm to 250nm.The

samples were characterized by XRD, FE-SEM and TEM, the dielectric and ferroelectric properties of PZT films were measured by HP4294A impedance analyzer and RT6000HVS ferroeletric measurement system. It was observed that the electric properties of PZT films on Ti substrates were superior to that of PZT films on NC substrates. This may be attributed to the worse interfacial condition and larger residual stress between PZT films and NC substrates. It was noted that the change of dielectric constants and dielectric dissipation as a function of frequency become more flat with increasing thickness of LNO films. The ferroelectric properties and fatigue behavior were remarkably improved of PZT films with 250nm LNO films, which were attributed to the alleviation of diffusion and mismatch between PZT films and substrates when LNO films were used as buffer layers. Oxygen vacancy accumulation was also decreased at the ferroelectric-electrode interface by LNO buffer layer. With increasing thickness of LNO films, dielectric constants descended and leakage current increased in the PZT films. It was suggested that LNO film with 150nm was more suitable to be the buffer layer for PZT films prepared on metal substrates.
This project received support from Chinese National Natural Science Foundation (Grant No. 50302006)

P1FE-Q-17 Y13

180° DOMAIN STRUCTURE IN EPITAXIAL PBTIO$_3$ FERROELECTRIC FILMS

S.K. STREIFFER*[1], G.B. STEPHENSON[1], D.D. FONG[1], J.A. EASTMAN[1], C. THOMPSON[1,2], O. AUCIELLO[1], and P.H. FUOSS[1], [1]Materials Science Division, Argonne National Laboratory, Argonne, IL 60439, USA, [2]Dept. of Physics, Northern Illinois University, DeKalb, IL 60115, USA.
Corresponding e-mail: streiffer@anl.gov

Ferroelectric film behavior is a very sensitive function of the electrical and mechanical boundary conditions experienced by a sample. For example, it is known that coherent, epitaxial $PbTiO_3$ films deposited onto insulating $SrTiO_3$ substrates assume a film-thickness-dependent, equilibrium 180° domain pattern to minimize the electric field energy resulting from uncompensated polarization. These domain patterns can be used as a probe of ferroelectric phase transition physics, and are sufficiently well ordered that they also yield information on 180° domain wall structure. Here we will describe our work utilizing synchrotron x-ray scattering to explore phase transition behavior and 180° domain structure in epitaxial $PbTiO_3$ films grown on $SrTiO_3$ as a function of film thickness, using an apparatus for *in situ* studies of metalorganic vapor phase epitaxy located at BESSRC beamline 12-ID-D of the Advanced Photon Source. Our measurements indicate an upper bound on the 180° domain wall width of 1.5nm at approximately 100°C below TC. Furthermore, the phase transition temperature dependence on film thickness combined with the evolution of domain period and wall structure with temperature yields insight into the degree of compensation of the polarization at the film/atmosphere and film/substrate interfaces. This is an important and unresolved issue for ferroelectric thin films, even though the

effects of size and of incomplete charge compensation of the polarization have been studied for many years. Data will be presented for three sets of electrical boundary conditions under constant mechanical constraint (thin films coherently lattice matched to (001) $SrTiO_3$): $PbTiO_3$ directly on $SrTiO_3$ (ferroelectric on insulator); $PbTiO_3$ on epitaxial $SrRuO_3$ on $SrTiO_3$ (ferroelectric on conductor); and Pt-capped $PbTiO_3$ on $SrTiO_3$ (ferroelectric on insulator with better defined electrical boundary condition at top interface). Variations in behavior for these different cases will be summarized, and related back to the outlook for relevant device structures.
We gratefully acknowledge experimental assistance from the BESSRC beamline staff, and from L. Thompson, P. Baldo, and J. Pearson. We thank Prof. C.-B. Eom and his group for providing the $SrRuO_3$ films used in this work, and M. Zurbuchen and M. Biegalski for assistance measuring some films described here. Work was supported by the U.S. Department of Energy, BES-DMS under contract W- 31-109-ENG-38.

P1FE-Q-18 X13

ELECTRON BACKSCATTER DIFFRACTION MICRO-TEXTURE ANALYSIS OF PT AND PZT THIN FILMS FOR FRAM

G. FOX*[1], T. MAITLAND[2], X. HAN[2], and M. VAUDIN[3], [1]Ramtron International Corp., Colorado Springs, CO 80921, [2]HKL Technology Inc., Danbury, CT 06810, [3]NIST, Gaithersburg, MD 20899.
Corresponding e-mail: Glen.Fox@Ramtron.com

One of the primary questions concerning the scaling of FRAM for high density (greater than 1Mb) and small feature size (less than 0.35 μm transistor gate length) CMOS processes is whether the ferroelectric capacitor area can be reduced without increasing the capacitor-to-capacitor variability of the switchable polarization, P_{sw}. For polycrystalline PZT films, upon which production FRAM is based, the P_{sw} of a data storage capacitor is fundamentally determined by the crystallographic orientation of the grains composing the PZT. The capacitor P_{sw} can be no more than the vector sum of the P_{sw} of the individual grains and this vector sum is determined by the localized crystallographic texture of the PZT grain assemblage. Factors such as non-stoichiometric interfaces and domain pinning can only reduce the observed P_{sw} from the limits imposed by the local crystallographic texture. In order to understand the capacitor-to- capacitor variability introduced solely by the crystallographic texture, a method for measuring the local PZT texture within a capacitor is required. Local texture measurements of both PZT and Pt bottom electrode thin films were obtained in this study by using high resolution electron backscatter diffraction (EBSD). The Pt bottom electrode acts as a template for textured PZT growth. An automated EBSD system was combined with a field emission scanning electron microscope, FESEM, which provided for EBSD resolution of approximately 5 nm. A series of Kikuchi type EBSD patterns were collected by stepping through an array of measurement points separated by a step size of either 5 or 10 nm, depending on the sample, and using a sampling rate of 30 - 50 points/s. Band contrast images produced by associating a pixel gray scale value with each EBSD pattern provide microstructure images similar to those collected by secondary electron imaging. All indexable EBSD patterns are combined to produce an orientation map that reveals the in-plane (X, Y) orientation and normal (Z) orientation of individual grains comprising the thin film. Z-orientation maps of Pt films reveal a {111} fiber texture of greater than 99grains as small as 10 nm can be detected. Clustering of in-plane grain orientations can be observed in the X- and Y-orientation maps. Orientation maps of a PZT thin film 2.00 μm^2 area shows that 93% of the grains exhibit a {111} orientation perpendicular to the substrate normal. The remaining fraction of misoriented grains consists of a mixture of {100} and other random orientations. With the EBSD technique demonstrated on Pt and PZT samples it is possible to map the local crystallographic texture of thin films comprising FRAM ferroelectric capacitors. This quantitative, spatially resolved texture mapping provides the necessary tool for determining texture imposed limits of the capacitor-to-capacitor variability of P_{sw}. A correlation between EBSD texture measurements and capacitor P_{sw} properties wil be presented.

P1FE-Q-19 Z5

FERROELECTRIC THIN FILMS FOR EMBEDDED CAPACITOR APPLICATIONS

J.-P. MARIA*[1], J. IHLEFELD[1], B. LAUGHLIN[1], L. JIMISON[1], M. LOSEGO[1], and W. BORLAND[2], [1]North Carolina State University, Department of Materials Science and Engineering, Raleigh, NC 27695-7919, [2]Dupont iTechnologies, Durham, NC.

Embedding decoupling and power capacitors within the layers of printed wiring boards (PWB) offers the ability to free surface space, to increase board reliability, and to reduce electromagnetic interference and inductance losses. The challenges associated with this application stem largely from the incompatibility between high permittivity ceramic dielectrics and the polymer layers of standard printed wiring boards.

In this poster presentation we discuss recent efforts at NCSU to achieve high capacitance density embedded passive layers using the "portable" substrate approach. In this case, ferroelectric thin films are processes on thin metal foils, and the entire film/foil stack is laminated into the high density interconnect layers. The materials challenges associated with this work are centered upon achieving process compatibility between ferroelectric oxides and inexpensive base metal foils. The dielectric compositions used belong to the PZT and BST solid solution families and are produced by chemical solution or physical deposition. For PZT films, as processed materials exhibit loss tangent values between 0.01 and 0.02 from 1 kHz to 1 MHz while capacitance densities range between 300 and 400 pF/cm2 over the same frequency spectrum. BST films exhibit loss tangent values between 0.01 and 0.02 while capacitance densities range between 3 and 5 F/cm2 Data will be shown detailing the microstructure-process-property relationships for these capacitor devices, and how processing conditions are tailored to minimize dielectric/foil interactions during high temperature processing steps.

Session: P1FC-R
THIN FILM BULK ACOUSTIC RESONATORS
Chair: E. Eernisse
Quartz Dyne Inc.

P1FC-R-1 Q6

SELF-ALIGNED LATERAL FIELD EXCITATION FILM ACOUSTIC RESONATOR WITH VERY LARGE ELECTROMECHANICAL COUPLING

W. PANG*[1], H. YU[1], G. FENG[1], H. ZHANG[1], and E. S. KIM[1], [1]University of Southern California, [2]University of Southern California.
Corresponding e-mail: weipang@usc.edu

This paper describes a self-aligned lateral-field excitation (LFE) film bulk acoustic resonator (FBAR) that exhibits an electromechanical coupling coefficient (K^2) of 10% at 4.1 GHz, albeit a relatively low Q of 35. The unique features of this resonator include (1) improved energy trapping structure that does not require an electrode gap close to micron and (2) a simple two-mask self-aligned fabrication process that eliminates misalignment between the piezoelectric ZnO and the metal electrode. The quality factor is expected to increase greatly when we narrow the electrode gap down to less than 10μm from our current gap dimension of 35μm. The electromechanical coupling coefficient of 10% at 4.1 GHz is very large, considering that the theoretical limits of ZnO thin film are 8.5% for pure thickness-field excited (TE) FBAR and 12.5% for pure shear mode FBAR.

Lateral electric field applied in a direction that is not parallel to the *c*-axis of ZnO generates shear wave. Shear-wave electromechanical coupling constant is a function of the angle between the electric field and the *c*-axis, and at some specific angles the electromechanical coupling of shear wave is much higher than that of pure longitudinal wave [1]. This is due to the fact that the stiffening correction term in the full-stiffened *Christoffel* matrix involves vectors corresponding to the orientation of the acoustically generated electric field (related to the wave propagation direction) with respect to the applied electric field.

The effect of electrode gap size has been investigated, and proven to be very important for the device performance when all the electrodes are on the top surface of ZnO film. As the gap size increases, less laterally excited acoustic energy is confined in the electrode region. If the gap is too small, the strengths of the shear wave and longitudinal wave may be about the same, canceling out each other. In the new energy-trapped LFE FBAR structure, the electrode (having the thickness about same as that of the piezoelectric layer) is self-aligned with the piezoelectric layer, and produces a uniform lateral field in the piezoelectric film across a relatively large gap ($\sim$35μm wide) that requires no expensive high-resolution mask. This self-aligned fabrication process is described as follows. After depositing aluminum (followed by parylene) on a sapphire substrate, we delineate the aluminum with the parylene as an etch mask. Then

we deposit ZnO onto the sapphire and parylene so that poor adhesion between ZnO and parylene allows the ZnO on the parylene surface to be lifted off. In this self-aligned process, no more masking step is needed to pattern ZnO, and we can avoid the misalignment as well as a large lateral undercut that commonly happens during a wet ZnO etching. Details of device design and experimental results will be discussed.

[1] L. I. Maissel et al., handbook of thin film technology, McGraw-Hill Book Company, 1970.

This material is based upon work supported by Defense Advanced Research Projects Agency (DARPA) under CSAC (Chip-Scale Atomic Clock) program, contract # N66001-02-1-8918.

P1FC-R-2 Q7

BIAS-ENHANCED DEPOSITION OF ALN FILMS AND CHARACTERIZATION OF ALN-BASED FILM BULK ACOUSTIC RESONATORS

D.-H. CHO*, D.-Y. KIM, B.-H. KIM, J.-B. LEE, J.-P. JUNG, and J.-S. PARK,
Dept. of Electrical Engineering, Hanyang University.
Corresponding e-mail: rhlwwk@ihanyang.ac.kr

A film bulk acoustic resonator (FBAR) has become one of the most promising components for the realization of microwave monolithic integrated circuits (MMICs) in high performance frequency control devices of a few GHz-band wireless communication systems since it shows smaller size and possesses much lower insertion loss than other devices. Practical FBAR devices require the piezoelectric materials to possess the material properties such as excellent c-axis orientation, high crystal quality, and small surface roughness. Polycrystalline AlN can be one of the promising piezoelectric materials for FBAR devices due to its high thermal conductivity and acoustic velocity. However, the piezoelectric properties of AlN films may vary with deposition techniques and process conditions used. This research has been purposed to examine the influence of dc bias application during AlN deposition on the material properties of AlN films deposited as well as on the frequency response characteristics of FBAR devices using these AlN films. The AlN thin films are deposited at room temperature employing an rf magnetron sputtering method by varying dc bias voltages from 200 V to + 200 V. To compare the material properties of the AlN films deposited under the bias-enhanced situation with those of the films prepared with no bias, c-axis preferred orientation, crystal quality, surface morphology, and roughness are measured by x-ray diffraction (XRD) spectroscopy, field-emission scanning electron microscopy (FE-SEM), and atomic force microscopy (AFM), respectively. In addition, FBAR devices with sandwich-type configuration of Mo(top)-AlN-Mo(bottom)/Si have been fabricated using a lift-off method. The frequency response characteristics (S_{11} parameter) of the FBAR devices fabricated are measured by a network analyzer (HP 8720C) connected to probe station. To find any optimal dc-bias condition, all the data regarding to the material properties of AlN films and the device characteristics of AlN-FBARs

are characterized in terms of the dc-bias applied. At the optimal dc-bias condition, the AlN film possesses the enhanced properties and the FBAR fabricated adopting the AlN film reveals much superior device characteristics. The quantitative data regarding to the material properties of AlN films including texture coefficient for (002)-orientation and surface roughness as well as the device parameters of AlN-FBARs such as return loss and coupling coefficient are presented in more detail. It should also be noted that the excessive dc bias may deteriorate the material properties and the frequency response characteristics.
This work was performed by the technical support from the center for Electronic Materials and Components (EM&C) of Hanyang University at Ansan campus.

P1FC-R-3 Q8

THE METHOD FOR INTEGRATING FBAR WITH CIRCUITRY ON CMOS CHIP

S. PO HSUN*[1], C. YUNG CHUNG[2], F. CHI MING[3], C. PEI YEN[4], and C. PEI ZEN[3], [1]ERSO,Industrial Technology Research Institute, [2]Institute of Electronic Engineering,Chung Yuan Christian University, [3]Institute of Applied Mecahnicas, National Taiwan University, [4]Chung-Shan Institute of Science and Technology. Corresponding e-mail: phsung@itri.org.tw

For the development of the wireless communication, FBAR (Film Bulk Acoustic Resonator) has the potential to integrate with a CMOS circuit. In the IC design flow, the accurate device model verified by the IC foundry is crucial for designers. For the realization of integrating FBAR on the CMOS chip, this paper describes an accurate equivalent circuit model of FBAR which can be implanted in IC design software. In order to simulate the composite multilayer structure of FBAR, the theoretical model is constructed by cascading the Mason model of each layer and incorporating the attenuation effect of electrical and acoustic losses in material. Using network analysis method, the behavior of FBAR can be simulated by a Matlab program. In this paper, the integration of FBAR filter and LNA (Low Noise Amplifier) will be demonstrated. In order to design a ladder type filter which is composed of the serial and parallel FBARs, the image parameter method can be adopted. First, the simplest one by one filter is designed by choosing the image impedances of the both ends as the 50Ω transmission line at the central frequency of the filter. Next, the stop band rejection of the filter can be increased by cascading the simplest one by one filter imaginarily. Finally, the ratio of the areas of the serial and parallel FBARs can be determined by the bandwidth of the filter, using a numerical simulation procedure. Afterwards, the proposed FBAR model can be taken as the building block for the FBAR filter design. The complete theoretical model has been verified with the measurement result of the FBAR filter on wafer. With including the parasitic effect and substrate loss on the CMOS chip, the FBAR filter theoretical model can be treated as a functional block for use. Besides, the matching network components on the both ends of each device must be considered for having better performance. The circuit model of low noise amplifier (LNA) developed for the TSMC 0.18um 1p6M CMOS process is combined with the FBAR filter block. A two by one

ladder type filter (sized as 340μm x 550 μm) centered at 1.96 GHz has been integrated on chip by a post-CMOS MEMS process. This process divided into pre layout step and post surface micromaching step will be described in detail. In the first step, the top metal layer of CMOS structure is taken as a sacrificial layer. And, the passivation layer is used to define the whole layout of FBAR filter. In the second step, the thin film of bottom electrode is deposited onto the top metal layer. A well-oriented piezoelectric layer is sputtered on the patterned bottom electrode. A top electrode layer and a loading layer are deposited in order. After defining the etching holes, the suspending structure of FBAR filter can be released by wet etching the sacrificial layer. Finally, a resonant frequency trimming method is adopted to tune the FBAR filter with 1.96 GHz center frequency. To sum up, the integration of FBAR filter with LNA on CMOS chip has been designed, manufactured and demonstrated. This method is promising that FBAR has the capability to integrate with other circuitry by post-CMOS MEMS process.

This work thanks the Taiwan Chip Implementation Center(CIC)