WEDNESDAY, AUGUST 25, 2004
POSTER SESSIONS: 3:00–6:30 p.m.

*** Author presenting Paper**

Session: P2FC-A

PHYSICAL SENSORS
Chair: R. Lucklam
University of Magdeburg

P2FC-A-1 O3

DEVELOPMENT OF SAW PRESSURE SENSOR USING ZNO/SI STRUCTURE

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Due to their high sensitivity to infinitesimal modifications of the propagation conditions surface acoustic wave (SAW) are very attractives for the design of miniature sensors combining good sensitivity, precision and selectivity. In the case of SAW pressure sensor, the pressure induces static stress and strain in the device. Due to non-linear coupling effect between the high frequency wave and the static bias, the wave velocity and therefore the frequency is modified. In most of the previous work, the pressure sensor is performed directly on piezoelectric materials such as quartz. In our work, the sensor was developed on silicon membrane. Due to the fact that silicon is not piezoelectric, it is necessary to add a piezoelectric layer such as zinc oxide (ZnO) or aluminum nitride (AlN) to generate the elastic wave. In addition to crystalline piezoelectric materials, silicon has gained interest as a substrate material for acoustic devices. Indeed acoustic devices implemented on silicon profit from the excellent properties of the silicon integrated circuit (IC) technology: high reliability, high reproducibility, small size and low cost. The monolithic integration of electronic circuitry and acoustic devices allows the development of highly reliable small size acoustic devices for sensor applications. The fabrication based on microelectronic technology makes such sensors very interesting objects for further investigations.

In this study the silicon membrane was realized using anisotropic etching and the crystaline wurtzite ZnO film was deposited by Magnetron sputtering. Using X-ray diffraction it was shown that the crystal are mostly oriented with c-axis perpendicular to the surface. The pressure sensitivities of Rayleigh mode as well as the Sezawa mode are studied as a function of normalized thickness ($kh=2\pi hZnO/\lambda$) and membrane thickness. The design of SAW pressure sensor on ZnO/Si structure take into account the opposite sign of zinc oxide and silicon contribution to the pressure sensitivitie [1]. To achieve a high pressure sensitivity, we can use a mode 0 with a kh $\geq$1.6. Another possibility is the use of mode 1 with kh $\leq$1.2. In this case the pressure sensitivities keep the same value and the ZnO contribution could be neglected. A theoritical approach based on perturbation method was develloped for the evaluation of pressure sensitivity for Sezawa mode. Experimental results obtained for ZnO/Si SAW sensor performed with kh=1.15 are in good agreement with calculation. Recomendations are made for optimal configuration of SAW sensor according to temperature effect

[1]: A. Talbi, F. Sarry, L. Le Brizoual, O. Elmazria and P. Alnot, Pressure sensitivity of Rayleigh and Sezawa wave in ZnO/Si(001) structures World Congress on Ultrasonics 2003 September 7-10, 2003 - Paris, FRANCE.

P2FC-A-2 O5

MEASUREMENT OF SILICONE RUBBER HARDNESS BY USE OF A QUARTZ-CRYSTAL TUNING-FORK TACTILE SENSOR

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Silicone rubber hardness has been investigated experimentally by use of a quartz-crystal tuning-fork tactile sensor. The quartz-crystal tuning-fork tactile sensor makes use of its impedance or frequency change at resonant vibration 32.48 kHz when its base gets brought into contact with an object. The quartz-crystal tactile sensor has many advantages. It is capable of distinguishing a wide variety of materials from soft to hard ones by use of the impedance change of the quartz-crystal tactile sensor. Their quality and surface roughness are also distinguished. The experiments were done for eight kinds of silicone rubbers (the values of rubber hardness tester are JIS85, 70, 65, 60, 50, 45, 40, and 35). Rubber hardens as the value of rubber hardness tester increases. The frequency of the quartz-crystal tuning-fork tactile sensor is increased in the order of several 100 mHz when its base is contacted to an object. The frequency increases according to the ratio E/ρ (E: Youngs modulus, ρ: density of an object) and the frequency characteristics is classified into two groups; one includes three kinds of silicone rubbers (rubber hardness JIS85, 70, and 50), and the other includes the rest of former three rubbers. The impedance change (ΔR) was calculated between the sensor in contact with an object and in no contact at room temperature. The impedance change increases according to the value of rubber hardness tester and the impedance change characteristics is classified into two groups described above. At the same time, the impedance change increases according to acoustic impedance ρC (ρ: density of an object, C: sound velocity of longitudinal acoustic wave in silicone rubber) and the impedance change characteristics is classified into two groups in the same manner. It is found that the impedance change is proportional to the transmitting energy resulting from the difference between silicone rubber and the base of the quartz-crystal tuning fork in acoustic impedance of the longitudinal plane wave. The reason for the appearance of two groups is that the magnitude of the viscosity against to the elasticity is different between these two groups because silicone rubber

is viscoelasticity. It is found that the impedance change correlates closely with the value of rubber hardness tester. It follows from the above findings that the impedance change of this sensor may be used as a rubber hardness tester.
This work was partly supported by a Grant-in-Aid for Scientific Research (C) from the Ministry of Education, Culture, Sports, Science and Technology.

P2FC-A-3 O7

EXPERIMENTAL STUDY OF QUARTZ CRYSTAL GYRO SENSOR USING DOUBLE-ENDED TUNING FORK RESONATOR

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We have conducted an experimental study to examine a flatly supported gyro sensor using a double-ended tuning fork quartz resonator set in parallel with the rotating plane. We verified experimentally that the double-ended tuning fork resonator functions as a gyro sensor. Conventional gyro sensors used for navigation systems are vertical type sensors, and their height is taller than other electrical parts on the circuit board. This requires a hole in the upper board because the distance between the boards is narrow. Therefore, the gyro sensor is located on the edge of the circuit board. The output signals of gyro sensors are easily affected by many types of noise because the distance from the sensor to the processing unit in the navigation system is great. The flatly supported gyro sensor avoids these problems as a consequence of the height of the gyro sensor. A solution to this problem is expected from navigation system makers. The flatly supported gyro sensor will likely be suited for use in navigation systems, vehicle stability control, and other apparatuses of digital video cameras, digital cameras, and cellular phones, for example. The double-ended tuning fork resonator has the advantages of flat form, high-precision vibration-characteristics and strong resistance to external shock. Moreover, fundamentally, the gyro sensor using this resonator is able to detect two-axial angular velocities. We herein clarify some of the features of the gyro sensor by discussing its advantages and disadvantages. The resonator is designed to have high efficiency in detection, applying the simulation using the finite element method, and is finely fabricated by photolithography and wet etching. As a result, the resonator is fabricated without the problems associated with the gyro sensor. In addition, we confirm experimentally that the prototype gyro sensor can detect the practical angular velocity. Consequently, we have clarified that the double-ended tuning fork quartz resonator could be practically used as a flatly supported type gyro sensor.

Session: P2FC-B
RESONATOR ANALYSIS AND MODE IMAGING
Chair: E. Eernisse
Quartzdyne Inc

P2FC-B-1 O2

VIBRATION MODES ANALYSIS BY X-RAY TOPOGRAPHY IN QUARTZ AND LANGASITE RESONATORS

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The previous studies of the mass-loading influence in thickness-shear quartz and langasite resonators, based on Ballatos transmission-line analogs, have shown that the harmonic dependence of resonator characteristics is influenced by the electrodes due to the coupling of thickness-shear with thickness-twist modes, as well as stresses at the interface between the electrodes and the piezoelectric substrate. Consequently, the vibration modes measured by X-ray topography, give us the information on the mass-loading effect in thickness-shear vibrating crystal resonators. This paper presents the results of the vibration modes measurements by X-ray topography in SC-cut quartz and Y-cut unpolished langasite resonators. A comparison of these results with X-ray diffraction topography images on AT-cut quartz resonators and Y-cut polished langasite resonators pointed out the behavior of mass-loading effect with plate orientation angle and with the surface state of the piezoelectric substrate. The results of the X-ray topography investigations are compared too with electrical measurements performed on the same resonators. 5MHz Sawyer plan parallel SC-cut quartz and Y-cut unpolished langasite resonators with 14mm plate diameter, 7mm electrode diameter and 100, 200, 300 nm electrode thicknesses were investigated by X-ray topography on fundamental, third and fifth overtones The measurements were performed by conventional transmission Laue setting using white beam synchrotron radiation at LURE/DCI, Orsay, France. The study by X-ray topography on SC-cut quartz resonators and Y-cut langasite resonators pointed out a good agreement with the results previously obtained on the same resonators by electrical measurements. Un important conclusion is that the SC-cut quartz resonator characteristics present a similarly harmonic dependence with those of the Y-cut langasite resonators. That reveals the stress-compensated feature of the Y-cut in langasite crystal.

P2FC-B-2 O4

AN ANALYSIS OF LATERAL FIELD EXCITATION CONVEX PIEZOELECTRIC RESONATORS OF THICKNESS-SHEAR VIBRATIONS

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Crystal resonators excited by lateral field at anharmonic modes have shown promising noise performance for precision sources of frequency. Design of such kind of resonators, with lateral-field excitation (LFE), is inherently asymmetric that, for the sake of accuracy, needs to be reflected in the vibration model. It has to be remarked that asymmetry does not allow using straightforward the well-developed linear symmetric theory related to both the piezoelectric plate and electrodes shapes.

In this paper, the vibration theory is developed for the LFE crystal resonator employing thickness-shear vibrations of the even anharmonic mode. The resonator is combined with a convex piezoelectric plate and two one-side placed electrodes of an arbitrary shape. Formulas are derived for the frequency spectrum, motional capacity, and static capacity. It is demonstrated how the electrodes shapes influence the frequency spectrum of a resonator. We show that this spectrum differs from that calculated for the traditional double-side placed symmetric electrodes. For the engineering purposes, the approximate relation is obtained for the frequency spectrum via the Airy functions. Graphical illustrations for the model performance calculated are also given.

P2FC-B-3 O6

IN-PLANE MODE SHAPE VISUALIZATION OF PIEZOELECTRIC RESONATORS USING STROBOSCOPIC LASER IRRADIATION

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A full-field view laser stroboscopic system has been developed that visualizes surface mode shapes in piezoelectric resonators. The system presented is based on the stroboscopic laser irradiation, the laser speckle and the two-dimensional correlation image processing. By employing a high-speed laser diode synchronized to the resonator motion, an in-plane vibrational distribution visualizer has been developed that is capable operation at over 100 MHz. The detection sensitivity of the proposed system is ten times better than that of the previous laser speckle system [1]. The measurement consists of two intervals corresponding to the frame rates of a CCD video. In the first interval, the laser is synchronously irradiates the device when the acoustic displacement is maximum positive. In

the next interval, the laser is synchronized to the maximum negative. The phase of the acoustic motion is estimated from the phase of the device driving voltage. Images are recorded in each measurement interval. By repeating the measurement, simple averaging is carried out to reduce noises in the speckle images. The averaged two images are processed by two-dimensional correlation function and then vibrational distribution maps are obtained. Results for thickness shear modes in HF and VHF AT-cut quartz resonators are presented. It is shown that the proposed system gives very clear mode shapes even if devices are driven by low power.

References [1] "Non-scanning measurements for determining in-plane mode shapes in piezoelectric devices with polished surfaces," Y. Watanabe, et al., Proc. of the 2003 IFCS.

P2FC-B-4 O8

A METHOD FOR THE FAST ANALYSIS OF VIBRATIONS OF MINDLIN FIRST-ORDER PLATES FOR RESONATOR DESIGN APPLICATIONS

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Mindlin plate equations are the foundation of quartz crystal resonator analysis, and tremendous efforts have been made to improve the equations and obtain efficient and accurate solutions in past decades. It is clear now that the simplified resonator model can usually be solved with Mindlin equations of chosen order with only one spatial variable, and this has been used for both theoretical studies and practical design work. As an improvement, many work have been done with the finite element implementation of the equations, and better solutions that can consider the actual configuration and electrodes have been obtained with intensive numerical computation. Of course, these solutions are not widely utilized due to the stringent requirement on the computing resources and less familiarity of Mindlin plate equations in general. On the other hand, we have found that the advances of the finite element method and computer software have made the precise solutions of the equations more affordable technically and financially. In this paper, we implement the well-known Mindlin first-order equations in Femlab environment, and find that the useful solutions can be quickly obtained to examine the mode shapes that are important in the design of quartz crystal resonators. These solutions are hard to obtain with traditional finite element method, thus offering a rare opportunity to use the complete solutions for product design, improvement, and optimization. We showed the applications of these equations to a simple resonator quartz strip model of AT- and SC-cut quartz crystal.

This research is supported by the Qian River Fellow Fund established by Ningbo University and Zhejiang Provincial Government and administered by Ningbo University.

P2FC-B-5 O9

OPTIMIZATION OF THE SAW FILTER DESIGN BY IMMUNE ALGORITHM

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It is effective to use the optimization program to design the IDT structure of the SAW device in order to aim at improvement in the characteristics and to shorten the lead time of the product design. In general, it is difficult to apply the gradient method such as Newton-Raphson's method because there are a lot of solutions in the allowable range of the design parameters. On such a problem, the heuristics procedure that can carry out multi-point search is useful. Genetic algorithm (GA) known well is one of the representation. In this paper, Immune algorithm (IA) which is one of the heuristics was applied. IA models the immunity mechanism and has the feature of being hard to reach a partial solution as compared with GA. The example of optimization of a SAW filter is shown. The calculation result which optimized a SAW filter using IA is shown.

Session: P2FC-C
CRYSTAL AND MICROWAVE RESONATORS
Chair: B. Oulmet
LCEP

P2FC-C-1 P2

PROPOSAL OF THE FREQUENCY MEASUREMENT METHOD FOR GHZ BAND CRYSTAL UNITS

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In this paper, the resonance frequency measurement reproducibility of the lead-less crystal unit for GHz band is described. This paper shows that the reflection method as a measurement method is examined and ppm grade accuracy has been realized as reproducibility of a crystal unit.

The measurement method shown in the next of the technique is expressed. As for basic measurement method, the technology of admittance circle technique by IEC 60444-5 and Mid-frequency Locus Method by Dr. Koga are applied.

The new measurement method is applied to lead-less crystal units that frequency range is 150MHz to 3GHz. As for crystal units, in this frequency range, the figure of merit (M) is M> 2 and/or M<=2. Admittance circle technique with IEC 60444-5 is applied at crystal unit of M>2. For crystal units with M<=2 is applied by Mid-frequency Locus Method that is not general measurement method. Therefore, the easy principle of Mid-frequency Locus Method is also shown.

On the other hand, explanation of the specification of test-fixture, an appearance figure, etc. is given. As for the initial calibration of a measurement system, automatic calibration equipment is applied, and the equipment is shown. The size error of a package of in 1GHz in frequency measurement reproducibility is about 10 ppm in 0.1mm. If the size error of a package is fixed in crystal units (600MHz, 1.8GHz, and 2.9GHz), frequency measurement reproducibility is about 1 ppm.

This research is the results from which QIAJ (Quartz Industrial Association in Japan) were obtained in cooperation with research of Nihon Dempa Kogyo Co., Ltd. A part of this research was reported by 2003 IEC TC49 London meeting. It will be scheduled to propose this result to IEC TC49 WG (Measurement Method), and to be examined as an international standard in the near future.

P2FC-C-2 P3

CAVITY DESIGNS FOR A SPACE HYDROGEN MASER

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Investigations have been performed to optimize parameters in a TE011 mode cavity resonator suitable for a space-borne H-maser. We report on designs that were explored to find a global maximum in the important design parameters for the microwave cavity used in a H-maser. The criteria sought in this exercise were both minimization of the total volume of the cavity as well as the maximization of the product of the z-component of the magnetic energy filling factor (η) and the cavity TE011 mode Q-factor (Q). The calculations were all performed with either a Method of Lines or Finite Element software from IRCOM, France. The investigations looked at different configurations: a sapphire tube in a copper cylinder, a sapphire tube in a copper cylinder with Bragg reflectors, and spherical copper cavities both empty and sapphire-lined on the inside surface.

We made it our goal for the sapphire tube in a copper cylinder to optimize the above parameters compared to the published design of Morikawa et al with unity aspect ratio. Hence we were restricted to volumes equal to or smaller than the latter. At 320 K, the simulations resulted an optimum product Q $\eta = 4.9$ x 104 at the same volume as Morikawa et als design. This represents a 54% improvement. The result can be attributed to a greater confinement away from the radial metallic walls.

The expected increase in the product Q η with the inclusion of Bragg reflectors to the sapphire tube was not achieved. Moreover the z-component of the magnetic filling factor was greatly reduced due to an increase in the radial H-field. This can be understood in terms of the fact that we are adding additional dielectric material to the region outside the inner tube, which has the effect of pulling the electric field energy away from the region inside the sapphire tube and hence also some of the magnetic energy with it.

The sapphire lined spherical cavity showed no better performance than an equivalent sized empty copper cavity. For the empty cavity the simulations resulted in the product Q $\eta = 4.4$ x 104. Though the empty spherical cavity resonator may not be suitable for the space-borne H-maser as the total volume in this case is 33% larger than the optimized sapphire tube resonator, it may well be an appropriate choice for ground based H-masers where volume and hence mass is not such a concern.

P2FC-C-3 P4

DUAL MODE CRYSTAL RESONATOR WITH LATERAL FIELD EXCITATION

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Oscillators with digital temperature compensation provide relatively high frequency stability at rather short setting time that makes it irreplaceable in a number of applications. As is known, a thermo compensated oscillators with dual-mode resonators have the best long-term stability and compensation accuracy. However, a problem of stable excitation of two modes in a wide range of temperatures is not finally solved yet. One of possible decisions of this problem consist of involving a method of quartz resonator excitation by lateral field. Under this method the developer has the additional freedom degree by choice of an azimuth of inter-electrode gap. Changing of this parameter allows get any required ratio of resistance of reference and temperature oscillation modes, down to full suppression of any oscillation.

Other variant of dual-mode excitation may be a resonator with two gaps (instead of one gape) with different azimuths. This theoretically enables an independent excitation of two modes by two separate oscillators. Thus the quartz resonator converts from a two-pole circuit to a two-port element, so the equivalent model such device is required. This work presents the calculations of doubly-rotated quartz resonators active mode resistance in a range of the first turn angle from 0 up to 60 degrees. At the same time the angles of the second turn is chosen to provide a minimal F-T curve deviation in standard ranges of temperatures. The calculation of electrode gap azimuths for obtaining of required ratio of mode resistance (in line of 1, 2, 3, 4, 5) is carried out. Although the calculation of azimuths providing the minimal resistance of the chosen mode (C or B) at a level of other mode suppression not less than 36 dB (on active resistance) is given.

The model of the "two-port" resonator with two electrode gaps, based on dependent sources (the IofV and VofV dependent sources modeling accordingly the direct and converse piezoelectric effects), realized as MicroCap program macromodel is offered. Parameters of model are value of static inter-electrodes capacity, frequencies, active resistances and Q-factors of two oscillation modes. The excitation circuit on a basis of two separate oscillators is offered. The numerical modeling of such system excitation by MicroCap program is performed. The modeling results show, that there is a significant mutual oscillators influence.

So some modification was made and "three-pole" variant of quartz resonator with partial electrode covering was offered. Numerical modeling of such circuit exhibit a steady independent excitation of two modes without any adjusting of oscillators circuits.

P2FC-C-4 P5

THERMAL TRANSIENT EFFECT OF Y-CUT LANGANITE AND LANGATATE

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Langasite and its isomorphs (LGX) have advanced as potential substitutes for quartz in certain frequency control applications, owing to their extremely high quality (Q) factors. In order for these materials to be realized as precision resonators, non-linear material properties need to be known in detail in addition to primary characteristics such as material constants and static temperature-frequency coefficients. We have reported some of the non-linear properties of the material: force-frequency effect and amplitude-frequency effect, and they show superior characteristics to quartz [1,2]. Now, also of interest is another property, due in part to non-linearity, namely a thermal transient effect.

In this paper, the thermal transient effect of a y-cut langanite (LGN) resonator and a y-cut langatate (LGT) resonator is reported, using a number of temperature-transient experiments with various temperature-time profiles such as linear ramp, exponential step (thermal shock), and sinusoidal cycle. The nominal frequency of the resonators is 2 MHz fundamental. The diameter of the crystal is 14 mm and the nominal thickness is 0.7 mm. The crystal finished with electrodes is vacuum-sealed in an HC-47 package. The resonator is installed in an oscillator circuit to enable rapid measurements of the resonant frequency using a frequency counter under temperature-transient conditions. Preliminary results with linear ramp and thermal shock testing show an improvement over AT-cut quartz resonators. We will report on the experimental values of the thermal transient coefficients of the LGX. This work leads to a search for possible SC-cuts in the LGX.

(1) Force frequency effect of y-cut langanite and y-cut langatate, Y. Kim and A. Ballato, IEEE Tr. Ultrason. Ferroelec. Freq. Contr., pp. 1678-1682, 2003.
(2) Amplitude-frequency effect of Y-cut langanite and langatate, Y. Kim, IEEE Tr. Ultrason. Ferroelec. Freq. Contr., pp. 1683-1688, 2003.

P2FC-C-5 P6

STUDY OF FREQUENCY-TEMPERATURE CHARACTERISTICS OF QUARTZ WITH VARIOUS CUT ANGLE AND METAL THICKNESS OF ELECTRODE

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Surface acoustic wave (SAW) resonators on quartz substrate are widely applied in oscillation circuits in the frequency range from hundreds of megahertz up to several gigahertz because they present excellent temperature characteristics and high quality factor, and possess a lower jitter and phase noise than overtone crystal resonators (bulk acoustic wave resonators). For oscillation circuits, temperature coefficient of frequency (TCF) and turnover temperature (TOT) are two key specifications. They are mainly determined by the temperature behavior of SAW resonators. In general, the TCF and TOT of SAW resonators depend on the cut angle of substrate, wave propagation direction and the metal thickness of electrode. Hence, it is crucial to choose a quartz substrate that results in a suitable temperature performance of SAW resonators with different metal thickness of electrode. Previous studies on thermal behavior of SAW devices were primarily focused on ST-X quartz with various wave propagation directions and metal thickness of electrode was less than 1%. However, in practical design of SAW resonators, in order to obtain an excellent temperature characteristics, substrates other than ST-X cut are often employed and metal thickness of electrode over 2% or more are required to create good reflection. Few published data provided useful information for SAW designers to select a suitable quartz substrate. In this work, the temperature characteristics of quartz substrates from Y32° -X to Y37° -X and ST-X were studied experimentally. Unlike previous experiments using a low-Q two-port delay line, more accurate data on measuring the resonant frequencies of high-Q one-port SAW resonators were obtained. The temperature varied from -40°C 100°C and metal thickness of electrode covered 1.8%, 3.6% and 5.4%, respectively. From the experimental results, TOT and TCF decrease linearly as substrate cut angle or metal thickness of electrode increases. The results of this work can be easily applied to determine substrate in design specific SAW devices with desirable frequency-temperature performance.

P2FC-C-6 P7

EXPERIMENTAL STUDY ON MODE-COUPLING STRENGTH IN AT-CUT QUARTZ RESONATORS WITH MULTI-STEPPED BI-MESA STRUCTURE

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To confirm mode-coupling strength between the fundamental thickness-shear (TS-1) and thickness-flexure (TF) modes in multi-stepped bi-mesa AT-cut quartz resonators, those frequency-temperature (f-T) characteristics have been experimentally studied. In the previous work[1], we calculated the multi-stepped resonators using two-dimensional finite element analysis in the X-Y region, and estimated the mode-coupling strength using the discrete Fourier transform. The results showed that the mode-coupling strength decreased as the mesa height increased, and that the resonators have plural mesa-height values giving minimal mode-coupling strength for any step shapes. At the minimal points, TF components (u_2) in the outer region of the mesa portions had nodes at the mesa edges, and had loops at the X edges. Because the mesa height changes the wavelength of the TF component in the outer region, the minimal points exist periodically. In practice, however, coupling between the face-shear in the X-Z plane and the TS-1 mode would be strengthened by increasing the mesa height exceedingly. In this paper, the bi-mesa resonators, which can be fabricated with very high mesa step height, were fabricated, and measured their f-T characteristics as an index of the mode-coupling strength. The resonance frequencies of the resonators are about 8.3MHz, the length-to-thickness ratio is 20.0 and the mesa step heights are chosen 0 to 50%. Because the mode-coupling affects the first-order temperature coefficient of the TS-1 mode, the f-T curve of pure TS-1 mode rotates clockwise depending on the mode-coupling strength. The experimental results showed that the rotation of the measured f-T data are in good agreement with the calculated mode-coupling strength in the range of mesa step height 0 to 25%. At the mesa step height 32%, where the coupling strength was very low in the calculation. In the measure, f-T curve is difference far from the curve of the pure TS-1 mode. This is because the face-share modes caused by the Z boundary are coupled with TS-1 mode and rotated the f-T characteristics. These results indicate that the validity of the mode-coupling strength between TS-1 and TF modes, and choosing the minimal points in low mesa step height offers less advantage.

[1] S. Goka, K. Tamura, H. Sekimoto, Y. Watanabe and T. Sato: *Proc. Int. Frequency Control Symp.* (2003) p.694.

P2FC-C-7 P1

EXPERIMENTAL STUDY OF TEMPERATURE EFFECTS IN VIBRATING BEAM AND THICKNESS-SHEAR RESONATORS OF GAPO4 MACHINED BY ULTRASOUND MILLING

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We report progress in modeling and measuring temperature effects in vibrating beam Gallium Orthophosphate (GaPO4) resonators. In addition to the well known thickness-shear AT-cut, temperature compensated cuts exist in GaPO4 for length extensional, flexural and torsional modes.

Analytical models of temperature-effects are compared with experimental measurements on beam resonator devices fabricated on AT (Y -16°) and Z-cut plates by ultrasound machining. Some prototypes of antimesa structures of AT thickness shear resonators have also been fabricated and tested.

As far as resonant frequencies and temperature effects are concerned, the agreement between theory and experiment is fairly good taking into account

that temperature coefficients of GaPO4 have been experimentally tested in the litterature only for a few thickness-shear resonators. A better determination of temperature compensated orientation of GaPO4 beam resonators is investigated.
This work is supported by the European Community under contract G5RD-CT-2002-00709

Session: P2FE-D

SINGLE CRYSTAL
Chair: S. Rhee
Fraunhofer - IBMT

P2FE-D-1 U10

GROWTH OF PB(IN1/2NB1/2)O3-PBTIO3 CRYSTALS BY THE SOLUTION BRIDGMAN METHOD

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In the ferroelectric field, much attention has been paid to relaxor-based piezoelectric single crystals such as Pb(Mg1/3Nb2/3)O3-PbTiO3 (PMNT) and Pb (Zn1/3Nb2/3)O3-PbTiO3 (PZNT) because of their supper piezoelectric and electro-optic properties and potential applications in medical ultrasonic devices, sonar transducers, solid state actuators and light switches. However, it is noted that the lower Curie temperature Tc (about 150° for PMNT and 170° for PZNT crystals) and lower coercive field are very unfavorable for device manufacture and practical application. Therefore, in the highlight are the piezoelectric crystals with excellent piezoelectric performance and higher Curie temperature. Though Pb(In1/2Nb1/2)O3-PbTiO3 (PINT) crystals have been grown by Yamashita et al using flux or solution Bridgman method, there are a lot of growth problems need resolving. For example, the as grown crystals were small and the compositional deviation was serious. Another kind of relaxor-based ferroelectric crystals Pb(Yb1/2Nb1/2)O3-PbTiO3 (PYNT) with high temperature and good piezoelectric properties seems more difficult to grow large according to the growth results of Zhang S. J. et al. and our group. In this paper, PINT crystals were chosen to grow by the solution Bridgman method in order to reveal more growth habits of these crystals and to obtain larger crystals. The charge composition of PINT was near the morphotropic phase boundary (MPB) of PIN-PT solid solution system and PbO and B2O3 were used as flux in the solution Bridgman growth. It was found that PINT crystals were more difficult to grow than PZNT crystals. The former needs higher growth temperature, which brings more serious erosion of Pt crucibles. In addition, the former grows more slowly than the latter. We have obtained PINT crystals after modifying growth art and growth parameters. The outcome consists of PINT crystallites, PbO and pyrochlore (occupying about 2 wt %). The PINT crystals are yellowish or dark, having various size and the largest reaching the size of 25mm $\times$ 10mm $\times$ 10mm (the largest PINT crystals reported up to present). They appear as irregular and cubic morphology. The yellowish crystals are transparent and almost single-phase

perovskite. The dark crystals have obvious deviation from the starting charge. Like PZNT crystals, the inclusions of PbO and pyrochlore frequently appear in the PINT crystals, which leading to the inhomogeneous color and transparence of crystal samples. It is proposed that some inclusions form during growth and others are related to the thermal decomposition of perovsite-phase PINT under high temperature. The compositional deviation and some electric properties of PINT crystals are being measured. Our experiments demonstrate that it is possible to obtain PINT crystals large enough to meet the needs of some practical application fields. It is underway to control spontaneous nucleation and grow larger PINT crystals with good piezoelectric properties and higher Curie temperature.
This work was supported by the National Natural Science Foundation of China (Grant No. 50072038) and the National 973 Project of China.

P2FE-D-2 U11

LOW SYMMETRY MONO-DOMAIN $PB[(ZN_{1/3}NB_{2/3})_{0.91}TI_{0.09}]O_3$ SINGLE CRYSTAL WITH GIANT ELECTROMECHANICAL COUPLING FACTOR OF K_{31} MODE

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Frequency responses of impedance up to 500 kHz in (100) $Pb[(Zn_{1/3}Nb_{2/3})_{0.91}Ti_{0.09}]O_3$ (PZNT91/09) single-crystal plates (13^Lx4^Wx0.36^T mm) were analyzed on the two kinds of the length extensional vibration modes of k_{31} (13^L mm) and k_{32} (4^W mm) when the DC poling direction is parallel to the thickness of the plate (0.36^T mm). It was found that there were two (low and high) frequency constants (fc), which corresponds to the half of the velocity of the longitudinal bulk wave to transmit in the crystal, of 470 kHz-m and 830 kHz-m on these modes. However, the fc on thickness vibration mode of k_t (0.36^T mm) was a constant of 2070 Hz-m and the electromechanical coupling factors of the thickness mode (k_t) were almost the same of 54 60%. The constant fc and k_t mean that the domain reorientation in thickness had been saturated after the poling. The response with the giant k_{31}[1,2] has only the low fc on k_{31} mode and the high fc on k_{32} mode, which are caused by the anisotropy of the crystal symmetry in the plate sample. The anisotropy on k_{31} and k_{32} modes can be explained by the reorientation for their frequency constants. From the relationship between the values of the k_{31} and the anisotropy of fc in PZNT91/09 single crystals, the k_{31} dependence of the crystal phases in PZNT91/09 could be explained by the anisotropy of the fc on k_{31} and k_{32} modes. In k_{31}=50 57%, there was the same high fc of 830 Hz-m on the k_{31} and k_{32} modes; this means that the crystal became tetragonal phase (a=b135c in length of the crystal axes; a, b and c correspond to the k_{31} , k_{32} and k_t modes). On the other hand, there were low fc (470 Hz-m) on the k_{31} mode and high fc (830 Hz-m)

on the k_{32} mode in the case of giant k_{31} over 80%; this means that the crystal changed into a new phase (a135b135c) such as monoclinic phase different from the rhombohedral and tetragonal phases. Therefore, the giant k_{31} appeared in the case of the phase with low crystal symmetry in comparison with tetragonal phase. Furthermore, this new phase can be realized the mono-domain structure in the single-crystal plates with giant $k_{31}>80\%$. 1) T. Ogawa, Y. Yamauchi, Y. Numamoto, M. Matsusita and Y. Tachi, Jpn. J. Appl. Phys., 41, L55-L57 (2002). 2) T. Ogawa and Y. Numamoto, Jpn. J. Appl. Phys., 41, 7108-12 (2002).
This work was partly supported by a Grant-in-Aid for Scientific Research (C) (No. 12650327) from the Ministry of Education, Culture, Sport, Science and Technology and the Murata Science Foundation. The authors would like to thank the Research Laboratory of Kawatetsu Mining Co., Ltd. for supplying the single-crystal plate samples.

P2FE-D-3 U12

TGS CRYSTALS WITH NON-UNIFORM DISTRIBUTION OF THE IMPURITY

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The stabilization of the domain structure for some applications of ferroelectric crystals is usually created by introduction of impurities into crystals in the process of crystal growth. The result of this is a unipolar state, which usually is connected with appearance of internal bias electric fields or/and mechanical stresses. In the work is shown that the unipolar state in crystals with an impurity to a large degree results from non-uniform distribution of impurities into the crystal. The fabrication of such crystals with a high unipolar state was illustrated on the example of ferroelectric crystals triglycine sulphate (TGS) with a tailored non-uniform distribution of the impurities of chromium ions. In the work the constructions and the work principle of devices for obtaining the crystals from solutions with smooth gradient and with periodical (layer-by-layer) changing of impurity concentration into the crystals volume is described. The modeling of growing processes of the crystals with programmed impurity distribution was carried out. The properties of TGS crystals with inhomogeneous distribution of the impurity of $Cr3+$ ions, grown at the temperatures higher and lower the Curie point, are investigated. The non-uniform TGS crystals of three types were grown: the first type- with the gradient of concentration of the impurity (the concentration of the impurity was changed smoothly along the length of the sample from a minimum up to the maximum), the second type - with a periodic change of concentration of the impurity (with the step variation of the impurities), the third type - with "sawtooth" change of impurity concentration. The crystals, grown in ferroelectric phase with the inhomogeneous distribution $Cr3+$ impurity, had a stable unipolar state and a high pyroelectric sensitivity over a wide temperature range in comparison with the crystals which grown up in paraelectric phase and with uniform crystals. This can be explained by the interaction of the defect structure and of the domain structure during of the crystal growth in ferroelectric phase.

P2FE-D-4 U13

GROWTH OF SILVER LITHIUM NIOBATE SINGLE CRYSTALS AND THEIR PIEZOELECTRIC PROPERTIES

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Silver lithium niobate ($Ag_{1-x}Li_xNbO_3$, 0<x< 0.1) single crystals were grown by a slow cooling method without flux. The sizes of the grown crystals were almost 2mm cube, and the color of the crystals was changed from light green to yellow with increasing Li contents. These crystal structures were assigned to perovskite-type orthorhombic phase. The dielectric properties were measured from 20°C to 600°C. As a result, with increasing Li contents, the phase transition at around 60°C was shifted to lower temperatures below 20°C while the phase transition around 360°C was shifter to higher temperatures. The dielectric loss tangent of the crystals was always below 2 % from 20°C to 400°C. P-E hysteresis measurement revealed that pure silver niobate crystals were weak ferroelectric with Pr of 0.095 $\mu C/cm^2$ while $Ag_{0.9}Li_{0.1}NbO_3$ crystals were normal ferroelectrics with Pr of 10.68 $\mu C/cm^2$. Moreover, these piezoelectric properties were measured, and for $Ag_{0.9}Li_{0.1}NbO_3$ crystals, high electromechanical coupling factor were observed.

P2FE-D-5 V13

PYROELECTRIC PROPERTIES OF (1-X)PB($MG_{1/3}NB_{2/3}$)O-$_3$-XPBTIO$_3$ AND (1-X)PB($ZN_{1/3}NB_{2/3}$)O$_3$-XPBTIO-$_3$ SINGLE CRYSTALS MEASURED USING A DYNAMIC METHOD

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The pyroelectric coefficients of $0.72Pb(Mg_{1/3}Nb_{2/3}O_3$-$0.28PbTiO_3$ (PMN-28PT), $0.67Pb(Mg_{1/3}Nb_{2/3})O_3$-$0.33PbTiO_3$ (PMN-33PT) and $0.92Pb(Zn_{1/3}Nb_{2/3})O_3$-$0.08PbTiO_3$ (PZN-8PT) single crystals, oriented and poled along three different crystallographic directions, $[001]_C$, $[011]_C$ and $[111]_C$, have been measured using a dynamic method; the suffix C here indicates reference to the prototypic cubic coordinate system. Large coefficients of up to 1070 $\mu Cm^{-2}K^{-1}$ have been observed for the $[111]_C$ oriented, rhombohedral PMN-28PT and PMN-33PT samples, where the measurement direction corresponds to the polar axis of the crystal. For each composition and orientation two different poling procedures

are compared, a commonly used field cooling method and a low temperature poling protocol. It was found that in otherwise pseudoorthorhombic samples of PZN-8PT, a room temperature rhombohedral phase could be stabilized by application of a field along the $[111]_C$ direction while heating from $-70°$C.
The authors wish to acknowledge support from the Swiss National Science Foundation

P2FE-D-6 V12

PHASE TRANSFORMATIONS AFTER A PRIOR ELECTRIC FIELD POLING IN $PB(MG_{1/3}NB_{2/3})_{1-X}TI_XO_3$ CRYSTALS

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This report is to investigate what has affected thermal stability of phases in in $Pb(Mg_{1/3}Nb_{2/3})_{1-x}Ti_xO_3$ (PMNTx) crystals for a broad range of temperature after poling by an electric field, which is crucial for high piezoelectric applications. Dielectric properties and x-ray diffraction patterns have been measured as functions of Ti content (x=0.24, 0.26, 0.27, 0.28, 0.31, 0.35, and 0.39), strength of dc electric field, temperature, and crystallographic orientation. It was found that monoclinic phase plays an essential role in bridging higher symmetry phases (rhombohedral, tetragonal and orthorhombic) while phase transformations are taking place. Temperature-dependent domain structures (by using the polarizing microscope) and hysteresis loops of polarization vs. electric field have also been carried out for various compositions.
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P2FE-D-7 V11

PHASE TRANSITION BEHAVIOR FOR PMN-PT SINGLE CRYSTALS IN THE MORPHOTROPIC PHASE BOUNDARY REGION

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$Pb(Mg_{1/3}Nb_{2/3})O_3$-$PbTiO_3$ (PMN-PT) single crystals in the morphotropic phase boundary (MPB) region are known to have superior dielectric and piezoelectric properties when compared with conventional $PbZrO_3$- $PbTiO_3$ (PZT) ceramics. Dielectric constant and heat flow measurements are reported for phase transitions of PMN-PT crystals in the MPB region. We report the discovery of a new characteristic for the ferroelectric-to ferroelectric (FE-FE) transitions, for compositions furthest away from the MPB (but in the region), when compared with compositions closest to the MPB. Dielectric constant values up to 70000

were obtained in certain cases. DSC and dielectric constant measurements were used in a complimentary manner to define the transition temperatures for poled and unpoled crystals. It was found that poling had a significant effect on the temperature of the FE-FE phase transition for compositions closest to the MPB, indicating induced stability for the tetragonal phase, i.e., greater temperature range. The effect was minor for compositions away from the MPB (but still in the MPB region) and directly on the MPB. The effect of poling on dielectric and piezoelectric properties is discussed.

Session: P2FE-E
PIEZOELECTRIC MATERIALS AND DEVICES
Chair: E. Prasad
BM HiTech

P2FE-E-1 V1

DIELECTRIC PROPERTIES OF THE SFE (PB1-XLAX)(ZRYTI1-Y)1-X/4O3 CERAMICS UNDER HYDROSTATIC PRESSURES AND DC BIAS FIELD

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Lanthanum-modified lead zirconium titanium ceramic (Pb1-xLax)(ZryTi1-y)1-x/4O3 has properties of slim-loop-ferroelectric(SFE) materials, which are characterized by (i) very small value of remanent polarization, (ii) a nearly linear dependence of the electric displacement on the electric field, and, (iii) a large dielectric permittivity. Dielectric properties of the PLZT samples under different temperatures and different hydrostatic pressures are investigated, respectively. Dielectric property with dc bias field are also researched. Experiments reveal that dielectric frequency disperse increases with the temperature increasing and the phase transition temperature decreases with the pressure increasing. It is found the dc field has an significant influence on dielectric property, for example, the phase transition temperature Tc decrease.
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P2FE-E-2 V7

PHENOMENOLOGICAL AND STRUCTUAL STUDIES OF THE MORPHOTROPIC PHASE BOUNDARY IN LEAD ZINC NIOBATE (PZN)-LEAD TITANATE(PT)

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Many physical and electrical properties in perovskite materials may change markedly at or near the morphotropic phase boundary (MPB) with a solid solution with variation in composition but that is nearly independent of temperature. For example, in the perovskite family, the MPB is the result of rhombohedral and tetragonal phases; where as in the case of the tungsten bronze family, the MPB is a result of tetragonal and orthorhombic phases. The conventional Landau-Devonshire phenomenological thermodynamics has been used to explain successfully the phase transition, dielectric and piezoelectric properties. Just recently, a monoclinic phase in PZT has been discovered between tetragonal and rhombohedral phases below room temperature and subsequently in PMN-PT and PZN-PT. Such phases can not be explained by the conventional 6th power Landau-Devonshire model. Bell has proposed that the free energy of PZT might be expressed as an expansion in two polarization order parameter for the two end-member (PZ and PT). This has succeeded in predicting the appearance of a monoclinic phase at the MPB.(1) In this paper, we apply this model to PZN-PT and explain the monoclinic phase at the MPB and an abrupt change of dielectric and piezoelectric properties at the MPB.

1) Bell et al, Jpn. J. Appl. Phys. Vol.42 (2003) p.7418-7423

P2FE-E-3 V8

HARMONIC ANALYSIS OF THE POLARIZATION AND STRAIN RESPONSE IN LEAD ZIRCONATE TITANATE-BASED CERAMICS

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Lead zirconate titanate ceramic is an excellent piezoelectric material that suffers aging which cause its properties to change spontaneously with of time. In the past aging was mostly studied in terms of relative permittivity or distortion of polarization-field hysteresis loop. This study however used harmonic analysis to study aging of both doped and undoped PZTs. The results are compared to the classic works of Hardtl, Jonker and Takahashi and recent works of Pilgrim and his coworkers. It is shown that particular harmonics of strain and polarization signal are sensitive indications of aging behavior of PZTs.

P2FE-E-4 V9

THE ISOVALENT SUBSTITUTION AT B-SITE OF MODIFIED $BI_{0.5}NA_{0.5}TIO_3$ PIEZOELECTRICS

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The $Bi_{0.5}Na_{0.5}TiO_3$(BNT) piezoelectric ceramic was found as a good candidate for lead-free piezoelectric with the Curie temperature of 320 C. However, a huge

permittivity peak accompanied by an abnormal dielectric loss as a function of temperature and frequency limits the use of this material. The modified BNT compositions with 0.5 at% La could reduce the high dielectric loss and presented a piezoelectric coefficient d_{33} in a range of 90-100 pC/N, superior to modified $PbTiO_3$ (56 pC/N). To further improve the piezoelectric properties, the modified BNT with 0.5 at% La composition is now substituted with the Zr^{4+} ions at the Ti^{4+} (B) sites. The isovalent substitution with the Zr^{4+} ions could alter the crystal structure, leading to a change in piezoelectric properties. The BNT-based compositions are conventionaly mixed and cold-isostatic pressed (CIP) to prepare the specimens. The phase development and a change in lattice parameters are determined using the XRD technique. The modified BNT-based compositions are characterized in terms of microstructure, physical and piezoelectric properties.

P2FE-E-5 V10

PIEZOELECTRIC RELAXATION AND LARGE ANISOTROPY OF MODIFIED LEAD TITANATE CERAMICS

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The frequency and field dependence of piezoelectric coefficients is an important issue for better response control of high performance electromechanical devices. In ferroelectric materials the phenomena of hysteresis, creep and relaxation have been most commonly attributed to the presence of domain walls. Theoretical description of these phenomena is nontrivial as they manifest themselves in different ways even in the same family of ferroelectric materials. In this study we investigate piezoelectric relaxation in Sm-doped PbTiO3. The piezoelectric constants d33 and d31 were measured by a direct quasi-static method in the temperature range from 25 to 150 deg. C and frequency range from >0.01 Hz to 100 Hz. The results show presence of huge Cole-Davidson or Havriliak-Negami-type piezoelectric relaxation for both d33 and d31 piezoelectric coefficients, which change by factor of nearly two (d33) and four (d31) in the examined frequency range. It is interesting that while the state of bias and dynamic mechanical stress during the measurements of the longitudinal d33 and transverse d31 piezoelectric coefficients is different, they show qualitatively similar behavior as a function of frequency; however, the relaxation in d31 coefficient is more significant than in d33 coefficient. The piezoelectric anisotropy (d33/d31) of this material is found to be both temperature and frequency dependent. The maximum anisotropy is about 20 at room temperature and at100 Hz. It decreases as the temperature increases or frequency decreases and finally it approaches the value of PZT ceramic (about 3) at low frequencies. Possible origins of the reported behavior are discussed.

P2FE-E-6 X1

ENHANCED PIEZOELECTRIC PROPERTIES OF POTASSIUM NIOBATE SINGLE CRYSTALS BY DOMAIN ENGINEERING

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Potassium niobate ($KNbO_3$) single crystals were grown by a TSSG method. At first, single-domain treatment for $KNbO_3$ crystals was investigated. As a result, it was revealed that a combination between chemical etching and 2 step electric poling treatment was very effective to prepare the $KNbO_3$ single domain crystals. Using the crystals, all piezoelectric related parameters were determined using a resonance-antiresonance measurement. Most of piezoelectric parameters were consist with those reported by Zgonik et al. except for d_{32}. On the basis of the determined piezoelectric values, the crystallographic orientation dependence of the apparent d_{31}, d_{32} and d_{33} surfaces were calculated. In this study, the electric field was applied along [001] (monoclinic notification) direction of $KNbO_3$ crystals to induce the engineered domain configurations into $KNbO_3$ crystals. Prior to domain engineering, the piezoelectric properties of [001] oriented $KNbO_3$ single domain crystals were investigated, these measurement values were completely consisted with the calculated apparent d_{31}, d_{32} and d_{33}. Finally, the engineered domain configurations were induced into $KNbO_3$ crystals. As a result, piezoelectric properties increased with decreasing domain sizes of the engineered domain configuration.

P2FE-E-7 X2

(K,NA)NBO_3-$SRTIO_3$ LEAD-FREE RELAXORS

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Relaxor ferroelectrics with a high dielectric constant have many applications as for example capacitors, sensors and actuators. Typical relaxor materials are lead-based ceramics such as (Pb,La)(Zr,Ti)O_3 (PLZT), and $Pb(Mg_{1/3}Nb_{2/3})O_3$ (PMN), the relaxor behavior stemming from the cationic distribution disorder in the same crystallographic site. Due to environmetal concerns lead-free relaxors are currently investigated, as for example solid solutions based on bismuth or barium titanate. Sodium potassium niobate (K,Na)NbO_3 solid solution with the composition with K/Na 50/50 (further denoted as KNN) close to morphotropic phase boundary is a lead-free ferroelectric material with a moderate dielectric constant and piezoelectric response. KNN is an environment-friendly and biocompatible alternative to lead-based piezoelectrics such as Pb(Zr,Ti)O_3

(PZT). In this paper the dielectric properties of $K_{0.5}Na_{0.5}NbO_3SrTiO_3$ (KNN-STO) based materials as new lead-free relaxors are reported. The combination of these two perovskite phases has been chosen on the basis the similar ionic radii; the radius of Sr^{2+} (0.144 nm for CN12) is between those of Na^+ (0.139 nm for CN12) and K^+ (0.164 nm for CN12) and that of Ti^{4+} (0.061 nm for CN6) and Nb^{5+} (0.064 nm for CN6). The compositions (1-x) $K_{0.5}Na_{0.5}NbO_3$ $xSrTiO_3$ (KNN-STO) with x = 0.10, 0.15, 0.20, 0.25 and 0.33 were prepared by solid state synthesis and sintered in the temperature range from 1175°C for x = 0.10 up to 1250 °C for x = 0.25. According to X-ray diffraction and microstructural analysis the materials are single phase within the investigated range of compositions. Dielectric spectroscopy measurements revealed a typical relaxor-like behavior for the investigated materials a broad dispersive dielectric maximum and a Vogel-Fulcher temperature dependence of the characteristic relaxation frequency and the influence of the $SrTiO_3$ content on the dielectric response of the $K_{0.5}Na_{0.5}NbO_3SrTiO_3$. As relatively large values of the dielectric constant are almost independent of the frequency in the range of 100 Hz-1 MHz, $K_{0.5}Na_{0.5}NbO_3SrTiO_3$ relaxor system seems to be extremely promising for a variety of applications.

P2FE-E-8 X3

A HIGH-POWER PIEZOELECTRIC TRANSFORMER USING IN DC/DC CONVERTERS

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Recently, piezoelectric transformers (PTs) have viewed as an attractive solution to reduce size and weight of DC/DC converters. However, PTs poor ability to manage high power has limited the development of DC/DC converters greatly. Up to now, the reported maximum output power of these converters is less than 30 watts.

In this study, we developed a new type of piezoelectric transformer for DC/DC converters, which operates at the thickness shear vibration mode for the application of voltage step down and has a size of 120204 mm3. It has a very simple structure and a high output power. At the temperature rise less than 10 oC, the output power is over 60 watts with the voltage gain of 0.4 and efficiency about 88%. Also, the equivalent circuit for the PT operating at the thickness shear vibration mode was deduced and a DC/DC converter circuit was developed. The theoretical analysis for the converter was conducted and verified by the experiment results.

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P2FE-E-9 X4

DESIGNING A RADIAL MODE LAMINATED PIEZOELECTRIC TRANSFORMER FOR HIGH POWER APPLICATIONS

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In order to improve the piezoelectric transformers in terms of high density of transfer power, a laminated piezoelectric transformer with a radial extensional vibration mode was studied. Its structure consisted of uniformly poled piezoelectric ceramic plates at the input and output parts with an insulation layer between them. This type of transformer can provide higher power density with a simple structure as well as various output voltage levels. This research was aimed to develop a good understanding of the laminated piezoelectric transformer designs and their related properties, such as bonding materials, electrode materials and constructive parameters. We found that Stycast 1264 is a promising bonding material to improve transformer characteristics in terms of mechanical quality factor, and that the bonding layer thickness provides significant change in its properties, efficiency and output power. Size and shape of the piezoelectric element also affect the transformers performance. It showed that the power capablility of piezoelectric transformer can be increased when the disk-shape and bigger size of piezoelectric elements are used. From this study, the maximum output powers of approximately 7 and 36 W were obtained for 23.8 and 45.0 mm diameter piezoelectric transformers with the same total thickness, respectively. These laminated transformers exhibit approximately three times higher power density than a rectangular Rosen-type piezoelectric transformer with a similar volume.

P2FE-E-10 V2

DRIVING OF 35W (T5) FLUORESCENT LAMP BY THE ELECTRONIC BALLAST USING PIEZOELECTRIC TRANSFORMER

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Recently, 40W Fluorescent lamps with 32mm tube diameter are replaced with 32W one with 26 mm in diameter to conserve lamp materials and to increase luminance efficiency. Moreover, 35, 28 and 14 W fluorescent lamps with 16mm in diameter, T5, which are nowadays developed, also may replace 32 W lamps again. Application of slim lamps, however, requires small sized electronic ballast

to fulfill the design philosophy of miniaturizing. However, the traditional magnetic ballasts operated at 50-60Hz have been suffered from noticeable flicker, high loss, large crest factor and heavy weight. In this study, in order to solve these problems, a new type of electronic ballast which is composed of rectifier, active power corrector, series resonant half bridge inverter and piezoelectric transformer was proposed for driving T5 fluorescent lamp. Contour vibration-mode piezoelectric transformer with ring/dot electrode structure was fabricated to the size of 20202.5mm3 by cold isostatic pressing. Driving of piezoelectric transformer was carried out with input region for the ring electrode and output region for the dot electrode. A 35W (T5) fluorescent lamp was successfully driven by the fabricated ballast with piezoelectric transformer. After driving the lamp for 25 min using the proposed electronic ballast, input power factor of 0.95, efficiency of 90.7%, were shown, respectively, at operating frequency of 79kHz. And also, output power, efficiency and temperature rise of the piezoelectric transformer, 37.53W, 92 % and 25°, respectively.
This work was supported by KEPRI.

P2FE-E-11 V3

THE TRANSVERSE STRAIN RESPONSE OF ELECTROACTIVE POLYMER ACTUATORS

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Some electroactive polymers produce large electric-field-induced strains that can be used for electromechanical actuation. The measurement of the strain response, especially the dynamic response under high driving fields, is difficult. We have developed a transverse strain measurement system based on the Zygo laser Doppler interferometer. The system can measure transverse strain responses of polymer samples of different sizes over a wide displacement range and a frequency range from DC up to 100 Hz.

We have used this interferometric system to investigate the strain response of electroactive polymer actuators fabricated from silicone (Dow Corning HS III RTV) and thermoplastic polyurethane (Dow Pellethane 2103) films. The static and dynamic strain responses of the materials to a variety of driving electric fields such as step fields, AC fields and DC bias fields have been measured as functions of amplitude and frequency. The strain response has a quadratic relationship with the driving field and shows a strong dependence on the frequency of the applied field. Of the two kinds of polymers investigated, HS III silicone polymer shows higher strain and breakdown fields. High transverse strains of 3.25 % (static) and 2.08 % (dynamic at 1 Hz) for HS III silicone polymers have been obtained. The experimental data are interpreted in terms of measured material properties and small strain models for dielectric film actuators.

The effect of mechanical tensile load on the transverse strain has also been studied. We measured the electric-field-induced dynamic transverse strain responses of a HS III silicone polymer film as a function of static pre-strain due to

mechanical tensile load. The dynamic strain increases initially with the load then decreases after reaching a maximum. The maximum dynamic strain is about 50% higher than the load-free strain. When the pre-strain is beyond 40%, the dynamic strain becomes smaller than the load-free strain. The electric-field-induced dynamic strain vs. pre-strain data can be fitted very well by a second-order polynomial fitting. Although the dynamic transverse strain induced by a given electric field is strongly dependent on the pre-strain, it still depends linearly on the square of the excite electric field strength under a constant load. A quadratic relationship between strain and driving field is still valid, even under mechanical load.

P2FE-E-12 V4

ELECTROACTIVE POLYMER BASED MICROFLUID PUMP

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A polymer microfluidic pump has been developed using electrostrctive poly(vinylidene fluoride-trifluoroethylene) based electrostrictive polymer, which possesses a high electrostrictive strain ($>5\%$) and elastic energy density (~ 1 J/cm^3), as the driving microactuator. The microfluidic pump integrates the microactuator, which shows an actuation deflection of 80 μm for a pumping chamber size of 2.2mmx2.2mm, with a nozzle/diffuser fluidic mechanical-diode. The microfluidic pump exhibits a pumping rate of 25 μL/min with a back pressure of 350 Pa. The flow rate of this pump can be easily controlled by external electric field.

P2FE-E-13 V5

DEVELOPMENT OF BIMORPH VIBRATOR USING LEAD FREE BNT PIEZOELECTRIC FILM DEPOSITED BY HYDROTHERMAL METHOD

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PZT piezoelectric film deposited by hydrothermal method has been studied actively. The PZT films can be formed on the Ti substrate in the KOH solution with Pb ion, Ti ion and Zr ion under high temperature about 140 degrees centigrade and high pressure about 400kPa using hydrothermal method. We reported about a water immerse type ultrasound sensor with an acoustic radiation area of 10mm x 10mm and resonance frequency of 3MHz in 2003 IEEE International Ultrasonics Symposium in Honolulu. However, it is apprehended recently that

PZT affects on life and environment, because PZT is chemical compound including lead (Pb). Therefore, we tried to deposit lead free BNT piezoelectric film on titanium substrate by hydrothermal method. Bismuth oxide, sodium nitrate and potassium hydroxide were used as source material for lead free BNT piezoelectric film in this study. It was confirmed by SEM image, XRD (X-ray diffraction) pattern and EDS data that the deposited films on the titanium substrate were BNT multi-crystals with perovskit structure. We fabricated bimorph vibrators with size of 10mm x 20mm by depositing lead free BNT film with thickness of about 5 μm on titanium substrate with thickness of 40 μm by hydrothermal method. When the bimorph vibrators were clamped at their one end and driven by continuous sinusoidal voltage wave with amplitude of 2 V. Then, It was found by measurements with laser Doppler vibrometer that the bimorph vibrators vibrated at their free end with vibration velocity of about 2mm/s at resonant frequency of 108 kHz. This vibration velocities is about from one fifth to one tenth of vibration velocity of bimorph vibrator with PZT film deposited by hydrothermal method with same size. However, it could be confirmed that our lead free BNT films deposited by hydrothermal method have piezoelectricity.

P2FE-E-14 V6

COMPLEX RARE-EARTH SUBSTITUTED LEAD TITANATE PIEXOCERAMICS

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A rare earth element or pairs of rare earth elements have been often used in the last decades in the preparation of various materials for solid oxide fuel cell (SOFC), oxygen storage, supraconductors, microwave applications and ferroelectric random acces memories (FRAM). Rare-earth substituted piezoelectric ceramics with composition $Pb_{1-3x/2}$ Ln_xTi_{1-y} Mn_yO_3 (with Ln = La, Ce, Pr, Nd, Sm, Eu, Gd) have been investigated due to their high Curie temperature, high anisotropy in electromechanical properties (large k_t/k_p ratio) and good surface acoustic wave (SAW) properties. These materials can be employed in high frequency applications like linear array transducers, SAW filters etc. In this work we have investigated the properties of new compositions of Gd, Nd and a mixture of Gd+Nd -added $Pb(Ti,Mn)O_3$ ceramics, containing a few percent of Bi, to partially substitute lead. The samples have been prepared starting from high purity oxides by solid-state reaction of oxide powders, within the sintering range 1100-1220°C. Structural and morphological investigations were performed on poled samples. The use of X-ray diffraction together with microstructural examination by transmission electron microscopy has shown evidence for the formation of tetragonal perovskite phase. The domain structure and the lattice imperfection of the PT-type samples have been investigated by a high resolution transmission electron microscope (HRTEM). Samples with diameter 10mm and thickness 1mm have been employed for electrical characterization. Material coefficients have been investigated as a function of temperature. Dielectric permittivity and resistivity were measured with a four-wire probe also on unpoled samples in a wide temperature and frequency range. Surface acoustic wave properties have been also investigated.

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Session: P2FC-F

PIEZOELECTRIC MATERIALS
Chair: E. Eernisse
Quartzdyne Inc

P2FC-F-1 P8

PIEZOELECTRICITY IN POLED SILICA FILMS BY SUPER-LATTICE STRUCTURE WITH TETRAVALENT METAL DOPANTS

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Piezoelectricity of SiO_2 thin films with tetravalent-metal impurities was investigated. In spite of the amorphous character of the films, poling treatment produced piezoelectricity in these films. Poling treatment in germanium (Ge)-doped silica (Ge:SiO_2) glass films raises their of optical non-linearity and producers, among other things, the Pockels effect. We generated piezoelectricity in poled Ge:SiO_2 glass thin films[1]. Tetravalent-metal-doped SiO_2 (M^{4+}:SiO_2) films were prepared on Si substrates by RF magnetron sputtering. We used germanium, titanium (Ti), and tin (Sn) as doping materials. The piezoelectricity of the films was compared with the piezoelectricity of quartz. Piezoelectricity of the same order of magnitude as that in quartz was observed in the M^{4+}:SiO_2 films. However, less than a week later, the piezoelectricity disappeared almost completely in all the samples. To overcome the disappearance phenomenon, we proposed a super-lattice structure with three different M^{4+}:SiO_2 layers using Ge, Ti, and Sn[2]. Because the physical properties of Ge^{4+}, Ti^{4+}, and Sn^{4+} are different each other, the displaced doping ions across the layer boundaries through the poling may be trapped in the invaded layer. The super-lattice films were prepared by RF magnetron sputtering. Although the piezoelectric constant value was smaller than that of quartz, permanent piezoelectricity was obtained in the super-lattice films. The piezoelectric constant value was inversely proportional to the periodicity of the super-lattice. The piezoelectricity in the super-lattice structure thin films was produced not only poling but also thermal treatment without applied electric field at high temperature. These results suggest that the super-lattice structure of silicate glass is a useful way to develop new piezoelectric thin films. Because SiO_2 has excellent optical properties, the fabrication

piezoelectric SiO_2 films will pave the way for the development of many new acousto-optic devices. [1] T. Uno and S. Noge: Jpn. J. Appl. Phys., 41, (2002) 3431-3432 [2] S. Noge, M. Shiroishi, and T. Uno: Int. Conf. Electroceramics 2003, PS2-PZ-7,p208

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P2FC-F-2 P9

INFLUENCE ELECTRON AND γ-IRRADIATION ON PIEZOELECTRIC AND ELASTIC PROPERTIES OF LANGASITE CRYSTALS

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On the base of langasite family crystals various promising devices were designed: resonators with fQ factor exceeded ones for quartz [1,2], high temperature sensors which could be operated up to 1000 oC [3] and many others. In this regards sometimes it is important to know influence of various types of irradiation on electromechanical properties of langasite family crystals. The present deals with first results of experimental investigation of electromechanical properties of langasite family crystals irradiated with electron and γ-radiation. Irradiation with electrons and g-rays has been carried out by using experimental set-up of MT-25 FLNR JINR microtron. The samples were exposed at ambient conditions with 4 MeV electrons or bremsstrahlung gamma-radiation produced by 9.7 MeV electrons in wolfram target. The dose rate under g-irradiation was in the range 3–5 Gy/s. An average electron beam flux was 2–1011cm-2 s-1. Total absorbed dose and electron fluence were 105 Gy and 8–1013cm-2 , respectively. Crystals of several compounds from langasite family with dimensions 50 mm along z (growth direction), 25 along X and 30 along Y were grown by Chzochralsky method. Plates and rods from several compounds from langasite family crystals were used as samples. Spectra of elastic vibrations near fundamental modes and harmonics were measured before and after irradiation Dielectric constants also were measured before and after irradiation. From above data piezoelectric, elastic constants were derived. Most valuable changes ones can see for elastic constants and both dielectric and piezoelectric constants kept practically without variations. Possible mechanism of irradiation influence is discussed.

SILVER TANTALUM NIABOTE, $AG(TA_{0.5}NB_{0.5})O_3$, THIN FILMS ON $(111)PT/TI/SIO_2/(100)SI$ AND $(001)SRRUO_3$ $/(001)LAALO_3$ SUBSTRATES BY CHEMICAL SOLUTION DEPOSITION

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Next generation telecommunication applications such as radars and cell phones, require tunable filters and phase shifters working at higher frequencies, 1- 40 GHz. In order to miniaturize and decrease cost of the devices, there is a need for tunable thin film dielectric materials. $Ag(Ta_{0.5}Nb_{0.5})O_3$, (ATN), is one of candidate dielectric materials having temperature stable good dielectric properties. Thus, ATN thin films are explored via chemical solution deposition on $(111)Pt/Ti/SiO_2/(100)Si$ (Pt/Si) and $(001)SrRuO_3$ $/(001)LaAlO_3$ (SRO/LAO) substrates. A new chemical solution based on niobium ethoxide, tantalum ethoxide, silver nitrate, 2-methoxyethanol and pyridine precursors and solvents was synthesized. A chemical solution deposition route for ATN thin films was developed by using the synthesized solution. Based on X-ray diffraction data and transmission electron microscope study, ATN films developed two phase mixture a (200) oriented $Ag_2(Ta_{0.5}Nb_{0.5})_4O_{11}$, (ATNO), and a randomly oriented pseudocubic perovskite phases on Pt/Si substrates. The effects of processing parameters on formation of the unknown phase were investigated, and heating rate and the existence of the low temperature heat treatment steps were found to be critical in determining the extent of perovskite phase. Mixed phase 400 nm thick films had lower dielectric constants, ϵ_1, than bulk value of 415 and a decent loss, tanδ, at 10 kHz. Max ϵ_1 was 270 and observed for 600 °C O_2 crystallized film. The lowest tanδ was 0.002 and observed for 750 °C O_2 crystallized film. ATN films on SRO/LAO substrates developed (001) epitaxial perovskite phase without having any ATNO phase. However, a limited interfacial reaction between ATN and SRO/LAO substrate was anticipated based on X-ray diffraction study. (001) epitaxial ATN film had a higher dielectric constant, ϵ_1, and loss, tanδ than ATN films on Pt/Si substrates. ϵ_1 and tanδ of a 750 °C O_2 crystallized 330 nm thick film was 400 and 0.013 respectively at 40 kHz. The dielectric properties of the film had a little frequency dependence in the range of 1 Hz to 100 kHz. Its capacitance changed by 6.3 % at 55 °C and 12.7 % at 120 °C from its room temperature value at 100 kHz. The film had a breakdown strength of 210 kV/cm. DC field tunability was not hysteric but was limited to 5.6 % at 10 kHz with 150 kV/cm bias from its unbiased value at room temperature. When the measurement was repeated at the liquid nitrogen temperature, 77 K, DC field tunability became hysteric and complex.

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P2FC-F-4 P11

MEASUREMENTS OF THE VISCOSITY TENSOR COMPONENTS OF LANGATATE

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The quality factor of the perfectly designed piezoelectric resonators is governed by the acoustic losses in the material. This work is devoted to the study of the attenuation coefficients and the calculation from these data the viscosity tensor components in langatate. This material is one of the most promising new a quartz-like material. Two methods of the study were used. The first is microwave composite resonator spectroscopy. The composite resonator consists of a rather thick properly oriented LGT plate and thin ZnO film with electrodes providing electrical connection of the structure under study with external electrical circuit. Such a composite resonator is a multifrequency one. From the measurements of the bandwidth of the resonant peaks of the structure it is possible to find its quality factor and hence the attenuation. Such measurements were made on all principal directions of propagation and wave polarizations. In most cases the frequency dependence (0.5 3 GHz) of the attenuation coefficient was quadratic. It means that the physical nature of the losses was interaction of acoustic waves with thermal phonons. In order to find the whole set of the viscosity tensor components it was necessary to make measurements with modes propagating at 45° to the principal axes. The attenuation measurements for these directions were made using acoustooptic diffraction measurements (acoustic wave frequency 700 MHz). The data obtained for the principal directions by acoustooptic method coincide with the data obtained by resonant spectroscopy. As a result the full set of viscosity tensor was measured for the first time.

P2FC-F-5 P12

CHANGES IN DEFECTS UNDER EXTERNAL INFLUENCE IN LANGASITE

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In the growing process of multicomponent piezocrystalline langasite crystals (La3Ga5SiO14) even minor deflections from optimal growth conditions lead to changes in defect concentration and consequently to changes in properties of the whole crystal. Comprehensive study of crystalline lattice using X-ray structural analysis and optical spectroscopy shows the formation of point defects - vacancies for oxygen and lanthanum, substitution of gallium by silicon and vice

versa what corresponds with quasichemical reactions. In the spectrum of optical transmission the band 35000 cm-1 is connected with a lanthanum vacancy (VLa"'), bands 28500, 26000, 25000 cm-1 - with oxygen vacancies in three positions. Under γ-radiation to dose 200 kl/kg optical spectra are observed to increase absorbtion in the region 40000-30000 cm-1 which disappear at the annealing temperature of 300 oC. Also absorbtion is removed by ultra-violet radiation for 3-4 hours. An increase in transmission after annealing in vacuum at temperatures more than 1000 oC was noticed in all samples. The value of absorbtion at frequency 40000 cm-1 can be used for the primary crystal quality assessment.

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P2FC-F-6 P13

RADIATION INDUCED GLOW PEAKS IN GE-DOPED CULTURED QUARTZ CRYSTALS

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The impurity-related point defects present in the crystalline material of quartz have a major ramification as a device in frequency control appliances. Al is the most pervading impurity in quartz. In addition, Ge, Ti, Fe etc are some of the other substitutional impurities which can isomorphously replace silicon in quartz lattice. Radiation effects in quartz are complex and need further investigations. In all quartz, Al and Ge are always present in varying proportions. While Al 3+ in quartz acts as an acceptor atom and needs a charge compensation, Ge 4+ exists as a neutral atom. When exposed to ionizing radiation, the electrons and holes produced move through the crystal until they recombine or are trapped by these impurities present in the quartz material. While the electrons are trapped at Ge-sites the holes are captured by Al ions to form Al-hole centers. At room temperature, the alkali charge compensator M+ (Li+ or Na+) ion diffuses away and stabilizes the Ge-defect site forming [Ge(A)e-/M+]0 and [Ge(C)e-/M+]0. These centers are also designated as Ge (A)-Li and Ge (C)-Li, Ge (A)-Na and Ge (C)-Na. We have conducted thermoluminescence investigations on as-grown and irradiated Ge-doped quartz crystal having Ge and Al concentration 3000 and 100 ppm respectively. Irradiation was done at 300 K using 1.75 MeV electron beam from a Van de Graaff electrostatic accelerator The crystal was grown hydrothermally at Bell Laboratories, Murray Hill, NJ. Its near infrared absorption investigations and the irradiation effects have been studied earlier [1]. This crystal was examined for its TL glow peaks. Prominent peaks have been observed at 100°C, 200°C and 310°C. The irradiation at 300 K would allow the movement of both the alkali charge compensators at Al-sites as well as protons from the growth defect bands. Radiation doses of 2, 5 and 10 Mrad were used for this study. It has been observed that the 100 deg C peak shows a decay up to a dose of 5 Mrad; afterwards the peak intensity starts increasing a bit and by 10 Mrad of radiation dose, it was recovered to nearly 20% of its strength obtained after exposure to 5 Mrad.. The 310 deg C peak again shows a similar behaviour but saturates beyond 5 Mrad such that it attains nearly 15% of its original strength. This behaviour is analogous to the defect center responsible for production of 305 K anelastic relaxation [2]. The so far unreported 200 deg C peak which we attribute to the presence of Ge in quartz lattice shows the irradiation response that matches with the nature of production of 246 K anelastic relaxation representing a complex of Ge-Li and an electron [2]. After an initial small rise, the peak continues to decay with radiation dose such that at 10 Mrad, it reaches a value less than 20% of its initial value prior to irradiation.

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P2FC-F-7 Q13

POINT DEFECTS IN QUARTZ CRYSTALS AND THEIR RADIATION RESPONSE—A REVIEW

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Quartz oscillator crystals play an essential role in almost all the frequency control appliances. The impurity-related point defects present in the crystalline material of quartz have a major ramification with regard to the device operation. The defects and their contributions in the determination of resonance frequency of quartz oscillators have been studied for nearly half a century. Radiation effects in quartz crystals are complex and depend upon its previous history such as growth condition, impurity content and post growth treatment etc. The radiation effects become important to evaluate the contribution of these defects in frequency drift of quartz resonators in the satellite borne frequency standards.

In addition to the thickness and density, the resonance frequency of a quartz oscillator crystal depends primarily upon the elastic constants which represent the average of the interatomic forces. It thus becomes sensitive to the incorporation of impurities and their modification. When exposed to radiation, quartz oscillator crystals undergo both transient and steady state frequency shifts and Q losses. These effects primarily arise due to radiation-induced modification of impurity-related point defects. While the steady state frequency shifts arise due to migration of charge compensating alkali ions from the aluminum centers, the transient frequency offsets are believed to arise due to back diffusion of charge compensating protons to the aluminum centers. All quartz contains Al, Ge and H in varying proportions. A variety of spectroscopic techniques are available for monitoring the impurity-related point defects in quartz. These include e.g. acoustic loss measurements, near infrared absorption, electron spin resonance, thermoluminescence. Sweeping or high temperature electrolysis is another technique for replacement of charge compensator ions at the electron excess defects in quartz. Acoustic loss peaks at 53 K represents the Al-Na centers; peaks at 23 K, 100 K, and 135 K are associated with the production of Al-hole centers. Recently, the acoustic loss peak at 600 K has been traced to represent the Al-OH centers. In addition, Al-OH centers are monitored by near infrared absorption at 3367 and 3306 wave numbers. The Al-hole centers can also be monitored by optical absorption and electron paramagnetic resonance techniques. The mobility of charge compensators at aluminum centers can be monitored by irradiating at 300 K and 77 K. Upon irradiation at 77 K, only protons move away from the aluminum centers while at 300 K-irradiation, both protons as well as alkalis move. Thus, irradiation at 300 K breaks the Al-alkali centers into a mixture of Al-hole and Al-OH centers.

We present a comprehensive review of the point defects in crystalline quartz so that an accurate screening of the crystal prior to fabrication of devices reduces the fabrication cost as well as improves the reliability of quartz containing devices.

Session: P2FC-G
MANUFACTURING TECHNOLOGY
Chair: B. Tysinger
Agilent Technologies

P2FC-G-1 O10

QUARTZ RESONATOR OF PLANO-PLANO TYPE IN TWO-STEPS SHAPE

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A bio-sensor is a detection device to measure in a short time a specific protein, which is discharged from every virus and body cell, for example by utilizing a quartz resonator as the accurate balance to compare the change fundamentally due to allergen-reagin reaction. When the quartz resonator as the bio-sensor has two or more than two quartz blanks on one chip, this sensor can detect even only one initial cancer cell, which discharges the specific protein and discharge it into blood. If the quartz resonator has ultra-high accuracy as 10-18 (10 to the power -18)to detect the special kind of protein in blood or plasma from every different organ in a human body, this sensor can locate the diseased organ by measuring the protein even from only one cancer cell in a lever, stomach or lung for example. The accuracy as 10- 18(10 to the power -18) is extraordinary much stronger than 10-14(10 to the power -14) of the current technology of atomic clock with Cs atom.

Therefore we need the accurate quartz resonator, which has no spurious signal without any noises and monochromatic oscillation. Furthermore it is necessary for the quartz resonator to compensate the measuring various errors of the interested sample due to temperature and other environmental conditions by placing two or plural quartz blanks in series or parallel for the control sample on the same chip. As plural identical quartz resonators in a single- sided inverted mesa type or concavo-convex lens type were arranged on one chip in two-steps shape and their frequency conditions were identically same as well as the temperature, humidity, machining accuracy of quartz surface and others, here we report the measured results of the comparing the object to the control by utilizing two ultra accurate quartz resonators on the same chip.

P2FC-G-2 O11

MANUFACTURING METHOD AND ELECTRICAL CHARACTERISTICS OF SHOCK-TOLERANT GROOVED TYPE QUARTZ RESONATORS IN TWO-STEPS CONVEX-LENS SHAPE WITH BEND PHENOMENON

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In order to avoid the spurious modes near the primary resonance and to be used for the high frequency application and shock-tolerant, novel concave AT-cut quartz blanks of Single-Sided Grooved Type in two steps shape, whose vibrating parts is extremely thin, were manufactured by chemical etching processes on one side of quartz blanks.

The both-side of Single-Sided Grooved Type quartz blanks were polished with pressure from the upper and lower side by double-face polishing machine, and since the concave blanks were sandwiched between the upper and lower tables. When they were bended by the different polishing pressure, the convex lens shape quartz blanks transformed into a natural concavo-convex shape. The extremely thin devices were made by depositing electrodes on these quartz blanks in convex lens shape.

The electrical resonance frequency characteristics showed actually the excellent results without any spurious modes near the primary vibration. For examples, the following three resonators (a), (b) and (c) were made with different aperture rario as diameter d and thickness t (d/t), while the diameter of each grooved parts was same as 1.6 mm and the diameter of each vibrating parts was also 0.59 mm.

(a) The thickness was approximately 15.3 microns. (b) The thickness was 7.98 microns. (c) The thickness t was 6.53 microns.

When the electrical properties of three resonators were compared, the resonance frequency characteristics were found to be completely different. Since the resonating frequency was 108.9 MHz (Q value nearly equals 40,000) for (a), 209.1 MHz for (b) and 255.5 MHz for (c), no spurious modes of (a) which d/t was approximately 38 were observed within 7 MHz of the primary resonance in the ideal shape, and small spurious peaks were seen for (b) of d/t 74, while the spurious modes of (c) (d/t was about 90) were dominated by useless shape.

P2FC-G-3 O12

STATE-OF-THE-ART IN THE DESIGN AND MANUFACTURE OF LOW ACCELERATION SENSITIVITY RESONATORS

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Previously, a mounting structure called the QRM resonator was shown to yield excellent performance for low vibration sensitivity . The mount utilized a chemically etched lead-frame and a machined ceramic support base to provide the resonator with a compliant, in-plane support. Improvements in the design and manufacture of the QRM resonator have greatly simplified the overall construction and reduced the variation in the observed acceleration sensitivity.

The new QRM designs have resulted in a compact low profile construction that utilizes a low profile HC40 header, a ceramic base, a precisely aligned lead-frame structure, and an SC or MSC cut 10MHz 3rd OT crystal. The first design type uses polyimide construction and custom assembly fixturing to ensure tight tolerances on the positioning of the various QRM assembly components. Improvements of the design over the previous QRM design include a laser cut ceramic ring, lead-frame alignment holes, built in electrical connections on the lead-frame structure, and Kovar (CTE 5.87 ppm/°C) lead-frame material instead of the previously used machined ceramic base, hand aligned lead-frame, gold wire attachment, and $\frac{1}{2}$ hard Nickel Silver (CTE 16.4 ppm/°C) lead-frame material.

More recently, on-going work with Gold/Germanium eutectic solder attach has resulted in the second QRM design type. It uses similar components as the first type and is a combination of Gold/Germanium eutectic bonding and polyimide assembly. The lead-frame to ceramic attachment is made using custom fixturing with Au/Ge preforms in a high temperature vacuum reflow oven. The remaining assembly is done with polyimide.

In addition to the overall construction, improvement in the mechanical resonance behavior of the QRM resonator has been achieved. It was discovered that the QRM had a mechanical resonance in the range of 1.5 to 1.9kHz. Finite element modeling showed the mechanical resonance could be increased by increasing the thickness of the lead-frame. By increasing the lead-frame thickness from 0.004 to 0.006, the mechanical resonance of the QRM has been pushed far above 2 kHz.

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DEVELOPMENT OF THIN FILM GETTERS FOR ASSURING HIGH RELIABILITY AND LONG LIFETIME TO CRYSTAL OSCILLATORS

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The shrinkage of the size of crystal oscillators for mobile phones applications increases the surface to volume ratio of hermetic packages. The outgassing of the different parts of the packages of crystal oscillators is increasing the operating pressure of the crystal oscillators, causing a frequency shift during the life time of the oscillating system because of the influence of higher pressure on the vibration characteristics of the oscillators in form of the increased drag resistance and increased mass of the oscillators due to the stiction of gas molecules. Moreover, oxygen and moisture inside the hermetic packages might cause oxidation and corrosion respectively of metallised parts. Getters are a viable and technically proven way to keep vacuum in hermetically sealed packaged by chemically absorbing active gaseous molecules such as H_2 O, O_2, H_2, CO and CO_2. The getter material needs an activation process, consisting in a thermal process under vacuum or inert gasses, to be able to absorb gasses. The latest development of getter technology for crystal oscillators is a thin getter film, few micron thick of a special Zr based alloy, that can be easily patterned onto the lid of the hermetic package. The getter film morphology has been optimized to increase absorption capacities as well as to eliminate any particles. The activation of this getter film can be done during ordinary sealing processes such as anodic bonding or bonding with soldering paste. The getter film can be patterned onto different materials such as glass, quartz, metals and ceramic lids even in presence of the pre defined soldering paste. The pattern size of the getter film can vary from few hundreds of microns up to millimeter with every shapes. The getter film will absorb chemically all the active gasses inside the hermetic packages of crystal oscillators, assuring a constant low pressure during all the life of the device. In the case that a plate is used to seal many crystal oscillators at the same time, the getter film can be patterned with high accuracy on these plates in correspondence to the different base packages housing the crystal oscillators. In this particular case, the presence of a getter film at plate level can assure an homogeneous pressure inside all the oscillators hermetic packages together with the usual benefits of improving reliability and life time of the devices. At the same time, the presence of the getter film might shorten the process time to achieve a good vacuum because of conductance problems in the sealing equipment. The getter film is also the technical solution for absorbing active gasses such as moisture or hydrogen inside the noble gas filled crystal oscillators hermetic packages. Finally, the getter film can take care of active gasses released from the package materials in presence of high temperature changes.

NOVEL DESIGN METHOD OF HIGH-FREQUENCY QUARTZ CRYSTAL RESONATORS IN GROOVED-TYPE AND CONCAVO CONVEX SHAPE

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The objective of our research is to manufacture quartz resonators that can oscillate elastic waves with a single wavelength and a high directionality. This objective has been the dream of many researchers since the discovery of the piezo-electric effect of quartz in 1880 by the brothers Pierre & Jacques Curie, who brought into being the development of the ultrasonic and electromagnetic oscillation of solid elastic vibration. Up to now, we separately produced the concavo lens shape and the convex lens shape by using two steps processing methods in order to make the concavo-convex lens shape quartz objects. Because of that, there existed a defect that two central axes of the convex lens shape axis and the concavo lens shape axis didnt become identical by themselves, which has been unable to succeed in resonating a single wavelength. The key to our success in resonating a single wavelength and directional high frequency elastic wave in quartz crystal resonators is the discovery of the design method of simultaneous machining the convex surface and the concave rear surface in order to make a concavo-convex lens shape by using the bending phenomenon and dynamic pressure force. We propose that this design procedure enables the simultaneous shaping of central machining axes both for convex lens and concave lens. As a result, the two central axes become completely identical by themselves. Furthermore, we propose the design method for making those two axes precisely identical to the quartz optical or rotational or AT-cut main surfaces axes. Based on these designs, quartz resonators whose three axis lines comprised of two central axes and an optical or rotational axis or AT- cut main surfaces are exactly overlapped and finished up as a resonating part of the single-sided, grooved-type quartz crystal resonator in a two-step shape with an extremely small concavo-convex lens.

Session: P2U-H

CONTRAST AGENTS II
Chair: N. De Jong
Erasmus University

P2U-H-1 E7

GAUSSIAN INTEGRATION TECHNIQUE TO PREDICT BACKSCATTER CHARACTERISTICS FROM MULTIPLE MICROBUBBLES WITH WIDE SIZE DISTRIBUTION USING A MODIFIED RAYLEIGH-PLESSET MODEL

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Recently, many new ultrasound imaging modalities have emerged that take advantage of the non-linear characteristics of contrast microbubbles, including second harmonic and subharmonic detection techniques. These modalities typically provide higher appreciation of blood flow than tissue since harmonic or subharmonic signals from the contrast agents are stronger than those from the surrounding tissue. Further development of these imaging modalities requires continuing understanding of harmonic and sub-harmonic backscatter physics; in this regard, both experimental and numerical modeling techniques have been explored in the past. In the numerical arena, the single-bubble modified Rayleigh-Plesset equation has been the mainstay for exploring bubble backscatter. However, extrapolating results from a single-bubble model to the real situation where multiple bubbles are present may be of limited use. Conversely, numerical models incorporating the full complexity of multiple bubbles and potential bubble interactions may be too computationally unwieldy for backscatter predictions. We have recently developed a Gaussian-Integration method based on a modified RayleighPlesset equation for predicting the backscattered signals from a group of microbubbles with wide size distribution. The method employs a weighting scheme based on the histogram of bubble size distribution to determine the cumulative backscatter. This method is capable of predicting the occurrence and relative amplitude of subharmonics, ultraharmonics, and super-harmonics from bubble groups. The numerical predictions were validated using experimental data reported in the literature for two types of commercially available bubbles: Levovist, as reported by Shi et al (Ultrasound Med Biol, 1999); and Optison, as reported by the same group (Shi et al, Ultrasound Med Biol, 2000). Good agreement between these experimental results and our numerical results were found, including precise prediction of the three stages (occurrence, grown and saturation) of subharmonic emission from Levovist, and the full spectrum of backscatter from multiple bubbles of Optison under varying pressure amplitudes. This computationally inexpensive method should be useful for predicting backscatter spectra from multiple microbubbles with varying size distribution.

Moreover, the technique can be used as an inverse model to determine bubble characteristics from experimental data, or to determine ideal backscatter characteristics for particular imaging applications. Experimental work to further validate this method is ongoing.
This work is supported by NSF (EECS-0225405) and NIH (HL72738 & 67393).

P2U-H-2 E8

MULTIPLE SCATTERING OF ULTRASOUND IN SUSPENSIONS OF CONTRAST AGENT PARTICLES: SIMULATIONS AND EXPERIMENTAL RESULTS

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Existing models for the behaviour of ultrasound contrast agents consider single, isolated contrast agent particles (CAPs) suspended in infinite media.[1,2] The behaviour of a CAP population is predicted by summing the results for single CAPs weighted according to their size distribution and ignoring multiple scattering effects. It is known, however, that the effectiveness of contrast agents is due to the fact that CAPs are strong scatterers of ultrasound. It would therefore seem reasonable to suppose that at certain concentrations and frequencies there may in fact be interactions between CAPs which affect the overall response of the population. This supposition is supported by a number of studies which report discrepancies between experimental measurements and the predictions from single CAP theories at the concentrations and frequencies used in ultrasound examinations.[3,4]

If contrast agent design is to be improved, or indeed if reliable experimental measurements of CAP properties are to be made, it is essential to identify the conditions under which CAP multiple scattering becomes significant. In this investigation, existing linear scattering models[5,6] are modified for use with CAPs and used to determine approximately the conditions for multiple scattering. These predictions are compared with new experimental measurements of attenuation in CAP suspensions at various concentrations and frequencies in order to determine their accuracy. The results of both these studies are then used in the development of new model for non-linear multiple scattering in CAP populations. Finally the potential applications of this model for improving CAP design are discussed.

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P2U-H-3 E9

ULTRASOUND SIGNALS AND IMAGES SIMULATION OF PHANTOMS WITH CONTRAST AGENT

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The aim of this paper is to introduce a Simulator of Echo Contrast Imaging (SECI) which simulates the entire process of echographic imaging with contrast agent. It gives the possibility, through a GUI, to choose simulation parameters such as the contrast agent, the probe (size, geometry, central frequency,), the imaging modality, the echoscanner tunning The aim of SECI is to simulate the image, considering a particular configuration.

First the transmitted field of the defined probe is simulated using Field II. For each point of the slice to be scanned, the pressure over time is available. Then the scattered response of the tissue is modeled as a spatial uniform distribution of Dirac. The Morgan's model is used to simulate the bubble's response. Note that bubbles destruction is not modeled and the interactions between bubbles are neglected (Born approximation, non multi-diffusion). Along the ultrasound propagation the attenuation of both the tissue and the bubble cloud is taken into account. This leads to an ultrasound Radio Frequency (RF) signal simulation.

SECI offers the possibility to simulate all kind of phantoms with contrast agent. Modalities, such as B mode images, second harmonic images, pulse inversion, time variant images, or others, may be computed from the RF signals.

This simulator was validated using two sets of in-vitro experiments. First a tissue mimicking phantom (ATS Lab) and a solution of Sonovue® (Bracco Research). From there, concentrations and Mechanical Index (MI) were the varying parameters. Second, it is a flow phantom consisting of a 8 mm diameter tube in which water and Sonovue® are flowing, in this case MI and pulse length were the varying parameters. In both the experimental and simulated data, two Regions Of Interest (ROI) at the same depth were selected, one inside the bubbles cloud the other in the tissue. Then the Agent to Tissue Ratio (ATR) were calculated in those ROI. The ratio was computed using first the gray level of the image and then the power over a particular frequency window of the RF signal.

A full set of MI (6 values from 0.1 to 0.36), and concentrations (6 values from 1 000 and 50 000 micro-bubbles per mL) is used. The results show the simulator is working accurately for MI between 0.1 and 0.3 and for concentrations between

1 000 and 5 000 micro-bubbles per mL. Both the experiment and the simulation show similar ATR evolutions, an increase of 10 dB per decade of the ATR versus the concentration, and no change of ATR versus MI (within the proper range of MI). So SECI can provide simulation of both RF signals and final images.

P2U-H-4 E10

CONTRAST AGENT DETECTION THROUGH LOW FREQUENCY MANIPULATION OF HIGH FREQUENCY SCATTERING PROPERTIES

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In medical ultrasound imaging, contrast agents in the form of encapsulated gas bubbles are intravenously injected to enhance the scattered blood signal which is weak compared to the scattered tissue signal. Obtaining information about blood flow in small vessels, i.e. in the microvasculature, is from a medical diagnostic point of view very helpful. Due to the masking effect of the strong linearly back-scattered tissue signal, contrast imaging today utilizes the strong nonlinear scattering properties of the added gas bubbles. These harmonic contrast techniques typically have important limitations with respect to sensitivity, and/or specificity, and image range resolution. In addition, nonlinear contrast signals scattered in the forward propagation direction will add in phase with the transmit pulse and hence accumulate in the forward direction. These nonlinear contrast components may then be linearly back-scattered from tissue and interpreted as tissue signal. A new contrast detection technique is proposed, applying the total scattered contrast signal, and in particular the linear component, for image reconstruction. A high frequency imaging pulse and a low frequency contrast-manipulating pumping pulse are simultaneously transmitted so that the contrast bubbles are interrogated by the high frequency pulse while being manipulated by the low frequency pulse. In the new method, contrast signals and tissue signals are differentiated applying a simple two-pulse subtraction technique which cancels or significantly reduces the scattered tissue signal, whereas the scattered contrast signal, due to the transmitted low frequency pulses altering the acoustic scattering properties of the contrast agent, is preserved in the process. The main mechanism through which this imaging technique selects the contrast agent signal is the linear resonant properties of the contrast bubbles and the new method is thus mainly a linear contrast agent detection technique.

P2U-H-5 E11

DESIGN AND IMPLEMENTATION OF FM-CODED HARMONICS

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Coded harmonics for tissue harmonic imaging (THI) can solve the two main limitations of THI: a) the 10-20 dB SNR loss compared to conventional (fundamental) imaging, and b) the trade-off between fundamental frequency suppression and axial resolution, or in the case of pulse inversion the trade-off between fundamental frequency suppression and frame rate. Implementing coded harmonics with bi-phase codes is a challenge, since the code phases are not maintained in the harmonic domain. Frequency coding has several advantages and combined with the concept of matched filtering can be used with no need of pulse inversion. This paper presents design strategies for such an implementation. The harmonic field of an FM signal is also an FM signal with double the bandwidth, and therefore improved axial resolution. A small frequency band can be swept at the fundamental frequency, thereby eliminating bandwidth overlap between harmonics, while at the same time, axial resolution is restored. However, axial sidelobes are introduced, and an asymmetry in the harmonic bandwidth. It is shown how those issues can be treated by unilateral weighting of the transmitted chirp based on the available bandwidth, and by unilateral mismatched filtering of the 2nd harmonic. A cost-effective design using bipolar pseudo chirps has been implemented on the GE Voluson 730, modified for this purpose. The degradation of this low-cost approximation is evaluated with a non-linear version of the simulation program Field II. Clinical images are also shown and compared with the pulse inversion method implemented using the same imaging parameters. It is shown how coding increases the 2nd harmonic generation yielding an improvement in SNR of 8 dB, while lateral beam profiles are very similar.
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P2U-H-6 E12

CONTRAST ENHANCED FLOW IMAGING WITH PHASE-CODED PULSE SEQUENCES

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Contrast agents have improved flow imaging, mainly because of increased signal intensities. Pulse inversion Doppler (PID) tackles the problem of overlapping spectra in the Doppler frequency domain by separating the spectral components of the 2nd harmonic spectrum generated by microbubbles from the fundamental spectrum of echoes reflected from tissue. Two problems still need to be solved: Firstly, the above mentioned separation is limited to low acoustic intensities, where 2nd harmonics arising from nonlinear propagation effects are at a negligible level, but where 2nd harmonic levels from microbubbles are also not very high. Bubbles behave much more nonlinearly at higher power levels; however, the assumption that tissue is a linear medium does no longer hold and 2nd harmonic components from both media overlap. Secondly, linear scattering

from microbubbles is stronger than nonlinear scattering, at least at low power levels. Hence, neglecting the fundamental component reduces the SNR. Newer approaches aim at combining the flow information from the fundamental and 2^{nd} harmonic components after flow processing. We have developed a signal processing method that considers the fact that for each of the two media, i.e. tissue and microbubbles, the fundamental component and the 2^{nd} harmonic component in an echo signal have the same origin so that their amplitudes and phases have a constant relationship throughout the Doppler Sequence. Consequently, we implemented least square estimators that decompose a Doppler signal, i.e. base-band echo signals of a Doppler Sequence sampled at constant depth, into two complex signals, where the two signals are (modulated) harmonics signals developed in a 2^{nd} order Taylor series. If both media exhibit a 2^{nd} harmonic component and have similar velocities, the decomposition would fail. Therefore, it is necessary to distinguish between nonlinear propagation and nonlinear scattering. This can be achieved by a phase-coded sequence that repeats four carrier phases: 0°, 90°, 180°, 270°, 0°, 90° etc. This sequence can be interpreted as an interleaving of two pulse inversion sequences with 0°, 180° and 90°, 270° pulses, respectively. Microbubbles respond differently to the two pulse inversion sequences while tissue does not so that the decomposition can be achieved. Once preliminary estimates for the flow velocities of tissue and microbubbles have been calculated, the estimates can further be improved by sampling the echo signals along trajectories that correspond to the axial flow velocities. Along the trajectory that e.g. describes the velocity of microbubbles, their signal components should be stationary so that the phase-coding allows a complete cancellation. In an iterative process, the two velocity estimates are then optimized with respect to the signal cancellation. We have performed in vitro measurements to test the algorithms. The results were compared to standard Doppler and PID processing. For flow velocities of 10 cm/s and below, the proposed processing reduced the standard deviation of velocity measurements by about 6 dB compared to the other approaches.
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P2U-H-7 E13

REMOVING LOCAL MOTION FROM ULTRASONIC IMAGES USING NON-AFFINE REGISTRATION FOR CONTRAST QUANTIFICATION

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When imaging the liver, the motion due to patient breathing causes local motion in the images. This adversely affects the quantitative assessment of wash-in and wash-out characteristics of contrast agents in the liver, such as the computation of the time-intensity curves (TIC), and measurements such as the rise time and the arrival time and curve fit parameters such as the exponential wash-in rate parameter, β.

We present a method to remove the local motion from the liver images so that contrast quantification can be effectively performed in real imaging situations, where breathing-induced motion artifacts are the norm.

Clinical contrast images were acquired using contrast pulse sequences (CPS). Frame-to-frame local motion vectors are then estimated using local speckle correlation and minimizing the sum of the absolute difference of image data. A motion vector is excluded if the underlying area of the image does not contain sufficient pixel data to support using the motion in any further calculation. The remaining motion vectors are then used to estimate the motion for the entire image. Motion of each pixel over the entire movie clip is then tracked using accumulated frame-to-frame motion and bilinear interpolation. The warping was affine within a given quadrangle defined by four corner pixels. This resulted in a new clip where the motion due to breathing is removed.

The affect of automatic registration using the above method was quantified by repeatedly analyzing a contrast wash-in sequence fitted with the function, I(t) = I(0) + A*(1-exp(-βt)). β calculated when automatic registration was used was compared to when no alignment was used and when each frame was aligned manually. Manual alignment and region of interest placement were repeated six times on the sequence with the ROI containing the same anatomic features in each repetition. The mean β using automatic alignment was 1.08 $\pm$ 0.22 s^{-1} compared to a mean of 0.92 $\pm$ 0.07 s^{-1} manually aligning the images and 1.46 $\pm$ 0.10 s^{-1} when no alignment was used. These data indicate that automatic alignment was not statistically different to a 90% confidence level than the β value produced with manual alignment. Furthermore, the removal of the local motion resulted in a new movie clip where it was easier to visually appreciate the wash-in and wash-out characteristics of the contrast agent.

Session: P2U-I

BEAMFORMING II
Chair: J. Hossack
University of Virginia

P2U-I-1 F1

VERY SMALL SIZE BEAMFORMER WITH 1.5BIT ADCS FOR HAND-HELD ULTRASOUND IMAGING SYSTEMS

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Conventional multi-bit delay-sum beamformers require an 8- or 10- bit ADC and an interpolation filter for each channel in addition to two-port memories, delay calculators, and complicated control logics. Therefore, such conventional beamformers are not suitable for hand-held scanners. In this paper, we propose

a novel 1.5-bit beamforming algorithm and its architecture for very small and cheap scanners. In the proposed 1.5-bit beamformer, the received RF signals are quantized into 3 levels, -1, 0, +1(actually log2(3) = 1.59bit) and the 1.5-bit samples from all active elements are aggregated taking into account dynamic focusing delays. It is obvious that the 1.5-bit quantizer is greatly simpler than conventional multi-bit ADCs. In addition, hardware complexity of the interpolation filter can be dramatically reduced since all the multipliers can be replaced with simple adders. Moreover, the interpolation filters can be completely eliminated by acquiring the 1.5-bit samples at a rate higher than 16fo. Consequently, the proposed 1.5-bit beamformer is much superior to conventional multi-bit beamformers in hardware complexity. Since reducing one bit in quantization drops the SQNR by 6dB, the 1.5-bit beamforming method must suffer from low SNR problems. To improve the SNR of the 1.5-bit beamformer, we add dithering noises to the received signals prior to quantization, perform quantization at a rate higher than the signal Nyquist rate to eleminate more quantization noise using lowpass or bandpass filters, and adjust decision levels to obtain the similar effects as B-mode gain and dynamic range controls. We verified experimentally that the dithering technique can improve the SQNR by about 12 dB. Though not used in the proposed beamformer, it is worth noting that adopting a simple sigma-delta modulation in the quantization process should improve the SQNR further. The experimental results with in-vivo data show that a 64 channel 1.5-bit beamformer provides 5 MHz linear array images that might be acceptable for hand-held applications when the quantized sample rate is 80 MHz. To further improve the image quality, 5- and 7- level quantization and beamforming schemes are being studied, of which the results will also be presented at the meeting.

P2U-I-2 F2

A METHOD FOR SIMULTANEOUS MULTI-ZONE FOCUSING ALONG MULTIPLE SCAN LINES USING ORTHOGONAL CODES AND ITS APPLICATION TO MULTI-DIMENSIONAL ARRAY IMAGING

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We present a novel method for achieving simultaneous transmit multi-zone (STMZ) focusing along multiple scan lines using orthogonal codes. In the proposed method, M mutually orthogonal Golay sets are simultaneously transmitted along M respective directions to obtain M scan lines, where each Golay set consists of M complementary sequences, $[a_{i1}(n),...,a_{iM}(n)](1 \leq i \leq M)$. Moreover, each complementary code is convolved with a signal obtained by aggregating L approximately orthogonal chirps with proper delays so that they are focused at L different depths. The L chirps are designed to occupy different frequency bands according to the corresponding focal depths, where some overlap between adjacent bands is allowed. Consequently, the proposed method requires M T/R events to obtain M scan lines with L transmit foci each, whereas ML T/R events are required in conventional pulse echo imaging. The M transmit waveforms, which should be transmitted sequentially, are represented as $g_j(t)=[a_{1j}(t)+...+a_{Mj}(t)]*[c_1(t-t_1)+...+c_L(t-t_L)]$, $1 \leq j \leq M$, where * denotes convolution and $a_{ij}(t)$ represents the impulse modulated version of the j-th complementary sequence of the ith code of a set of M mutually orthogonal Golay codes, i.e., $a_{ij}(t)=\Sigma_{n=1}^{N} a_{ij}(n)\delta(t-nT)$, where T is a chip interval. The summation over i in the above equation implies that M orthogonal codes are transmitted simultaneously. $c_l(t-t_l)$ $(1 \leq l \leq L)$ represents the l-th chirp with focusing delays t_l for the l-th transmit focus along each scan line. After M firings, the M orthogonal Golay codes are compressed separately using their orthogonal and complementary property. Next, the compressed Golay signals are individually correlated with L respective chirps to separately compress the L chirps. Finally, the L compressed chirp signals undergo receive dynamic focusing and are combined to produce narrow beams along M scan lines, each with multi-zone transmit foci. To demonstrate the performance of the proposed method, we performed experiments using a 192-elements linear array transducer with center frequency of 7.5MHz, 6dB bandwidth of 60% and element pitch of 0.2mm. We used Golay codes of length 8 (M=2, N=8) and two chirp signals with frequency bands, [3.5MHz 8.2MHz] and [11.5MHz 6.8MHz], with different focusing delays for two transmit foci at 3cm and 6cm. The experimental results showed that the reflected signals from a point target are successfully separated into two compressed signals, each with 6dB pulse width of 0.3us and sidelobe levels smaller than -40dB. We also observed that the proposed method provides almost the same lateral resolution compared to the conventional multi-zone pulse echo imaging, but with higher frame rate and SNR. Computer simulation study also showed that multi-zone focusing in the elevation direction on transmission can be achieved without sacrificing frame rate, which contributes greatly to improving the efficacy of multi-dimensional arrays.

P2U-I-3 F3

OPTIMIZED FILTERS FOR DYNAMIC RF ECHO BLENDING IN MULTIPLE FOCAL ZONE IMAGING

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For several practical and technical reasons related to e.g. computational cost, hardware complexity, sensitivity to motion artifacts, frame rate and SNR, most medical ultrasound machines use a fixed focus on transmit and dynamic focusing and filtering on receive. To further improve image resolution, multiple focal zones may be used. Given that the number of foci is *N*, the system acquires

N echoes per beam line, one per transmit focus. The resulting A-lines are superimposed (blended) after envelope detection by means of depth dependent weighting. Due to this incoherent superposition, the spatial resolution of the resulting image can only reach the resolution of the N images that were superimposed. To overcome the shortcomings of incoherent superposition, we have developed a technique for coherent blending of the N echoes. The N echoes are passed through N different, depth dependent (dynamic) filters. The filtered echoes are then summed together in the RF domain to form an A-line after envelope detection. The depth dependent transfer functions of the filters are designed to improve especially the lateral resolution. The filter design follows an approach that our group has developed to optimize contrast agent imaging: W. Wilkening, B. Brendel, H. Jiang, J. Lazenby, H. Ermert, "Optimized Receive Filters and Phase-Coded Pulse Sequences for Contrast Agent and Nonlinear Imaging," Proceedings of the IEEE Ultrasonics Symposium, 2001, 1F-4. In the original approach, the N echoes per beam line resulted form different transmit pulses instead of different apertures and foci. The filters were designed to maximize the contrast between echoes from microbubbles and tissue. The present goal is to maximize contrast between the core region of the point spread function (PSF), which defines the spatial resolution, and the surrounding, where the side and range lobes occur. To calculate the impulse responses of the filters, training data is needed. To acquire the training data, we used a Siemens Sonoline Antares System equipped with an Ultrasound Research Interface (URI) for RF data acquisition. Point (line) spread functions were measured with a 3.5 MHz curved array (C5-2) in water at 4 cm, 6 cm, 8 cm and 10 cm. Four transmit foci were set to the same depths. We then designed optimized filters for these depths. The core regions were chosen to be slightly smaller than the measured width of the PSF in axial direction, but significantly (50%) smaller than the measured width of the PSF in lateral direction. The actual filter design is based on the solution of an Eigenvalue problem and is described in the aforementioned publication. The reconstructed image showed that the 6 dB-width of the PSF did not change, but that the width in lateral direction was reduced by almost a factor of 2 for all four depths. Only very slight increase of the side lobe level of a few dB could be seen. The dynamic filters were then tested on different tissue mimicking phantoms to confirm the findings under more realistic conditions.
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P2U-I-4 F4

ARBITRARY WAVEFORM CODED EXCITATION USING BIPOLAR SQUARE WAVE PULSERS

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This paper presents a new coded excitation scheme with which codes of arbitrary waveforms can be efficiently synthesized using a bipolar square wave pulser. In addition to synthesis of arbitrary codes, the scheme is also employed to design predistorted chirps (Tukey-windowed) such that pulse compression can be efficiently implemented to achieve an optimal tradeoff among the signal-to-noise ratio (SNR), axial resolution and the peak range sidelobe level (PSL). Coded excitation has been used in medical ultrasound. Although the transmit pulse length is increased to improve the SNR, a wide transmit bandwidth is still maintained and thus the axial resolution can be preserved after pulse compression. Performance of pulse compression is directly related to the code spectrum and is generally characterized by the mainlobe width, the sidelobe level and the SNR improvement. Ideally, a flat spectrum over the entire transducer bandwidth is desired such that the compression filter can be designed using inverse of the spectrum. Several approaches have been proposed in the past to take advantage of the flat code spectrum. However, either an expensive arbitrary waveform transmitter is required or performance is degraded. In this study, we propose a method that preserves the low-cost advantage of a bipolar pulser while achieving good compression performance at the receiver end. The main idea of the proposed method is to convert a non-binary code into a binary code by code translation and code tuning. The code translation is done by sending the non-binary code into a virtual one-bit delta-sigma analog-to-digital converter. The code tuning is to minimize the root-mean-squared error between the resultant binary code and the original non-binary code by sequential and iterative tuning, with the transducer response taken into account. We converted predistorted chirps with different durations (16, 20, and 24 microseconds) and all with a taper ratio of 0.15, a center frequency of 2.5 MHz, and a bandwidth of 1.5 MHz into binary predistorted chirps. The compression performance is then compared with that of the corresponding pseudochirp (i.e., binary version of a linear FM chirp) over the same bandwidth. The bit rate was 40 MHz. The compressed mainlobe width was set to 2.5 microseconds in all cases and the PSL was set to 40 dB to 61 dB with a step of 3 dB. Simulations show that a binary predistorted chirp can achieve a 20% reduction in code duration than a pseudochirp. If the code duration and the SNR improvement are the same, on the other hand, the binary predistorted chirp can achieve an at least 6 dB lower PSL than a pseudochirp. Experimental results under the same settings are in good agreement with the simulations. Thus, efficacy of the new coded excitation scheme is successfully demonstrated and the proposed scheme only requires bipolar pulsers. Formulation of the scheme, simulations and experimental data will be presented and discussed.

P2U-I-5 F5

A NEW PERFORMANCE ANALYSIS METRIC FOR MEDICAL ULTRASOUND

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The characterization of imaging performance of ultrasound systems is a critical part of the system development process. Imaging resolution is usually assessed using the full width at half maximum (FWHM) criterion from beamplots. However, Vilkomerson et al [1] demonstrated that the FWHM criterion sometimes provides misleading information about system performance. Contrast detail studies are another method commonly used to analyze performance; however, they do not provide a way to theoretically assess the performance of different hypothetical imaging systems. A general metric is therefore needed to theoretically quantify the performance of an ultrasound imaging system. Vilkomerson et al [1] proposed the concept of cystic resolution in which performance was quantified as the size of the void that produced a given contrast. The analysis, while novel and useful, was limited to narrowband circular apertures. It ignored the axial dimension and also the effects of speckle.

We have extended the concept of cystic resolution by developing a general metric for 3D broadband analyses of arbitrary systems. We define a spherical void in a speckle generating medium and express the pulse-echo signal as a function of the pulse-echo point spread function (psf) and the scattering function (which includes a mask that specifies the void). We then derive an expression for the contrast of the void by computing the ratio of the rms power of the received signal with the void to the rms power of the received signal with only the background. The contrast is expressed in terms of only the psf and the mask. We can therefore quantify imaging performance as the radius of the void that produces a specified contrast. Since our metric requires only the psf, we can perform 3D comparisons of arbitrary ultrasound systems in a straightforward manner.

We performed an example simulation, comparing the performance of a 128 element 1D array with a pitch of 160 um to a 32 x 32 element 2D array with a pitch of 635 um. The focus was placed at 2.5 cm. We used 1D and 2D Hann windows to apodize the 1D and 2D arrays respectively. We defined a void of radius 0.5 mm and computed the void contrast for both systems. We determined the contrast using the 2D array to be 45% better than the contrast obtained using the 1D array. The radius of the void required with the 1D array to generate a contrast similar to that obtained using the 2D array (with a 0.5 mm radius void) was approximately 1.2 mm. However, note that due to computational complexity in calculating the psfs, our psf window was not large enough to account for grating lobes. We can perform similar analyses (with sufficiently large psf windows) to compare arbitrary systems. We present examples of application in which we compare the performance of different array types (1D and 2D) and different beamforming algorithms. We also demonstrate the effects of quantization and element crosstalk on imaging performance.

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P2U-I-6 F6

TRANSCRANIAL ULTRASOUND FOCUS RECONSTRUCTION WITH AMPLITUDE CORRECTION

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Non-invasive therapeutic and diagnostic ultrasound procedures performed through the skull require a reliable method for maintaining acoustic focus integrity after transmission through the bone due to the refracting, attenuating, and scattering effects of the inhomogeneous bone structures. It has been previously demonstrated that adaptive phase correction with a multi-element focused transducer array yields a significant correction to an acoustic field that has been distorted by the heterogeneities of the skull bone [Clement *et al.*, PMB, 45(4) 1071-83 2000]. This study investigates the use of amplitude correction in combination with established methods of phase correction with multi-element phased transducer arrays to reconstruct ultrasound focuses through the human skull. The additional introduction of amplitude correction, in which acoustic intensities from each individual array element are adjusted to be normalized at the focus, has demonstrated minor improvements in acoustic side lobe suppression and spatially tighter focus profiles. For a series of sonications performed on three locations for each of four *ex vivo* human calvaria, the side lobe intensity, in direct comparison with the peak intensity, was reduced by an average of 1.2%. The same tests yielded a lowering of the full-width-at-half-maximum by 2% on average. Yet these improvements come at the expense of significant ultrasound intensity loss at the focus since the amplitude normalization method requires that, at constant power, a larger proportion of the energy must be transmitted through regions of the skull with higher attenuation. In fact, each of the 12 cases yielded an acoustic intensity loss at the focus giving an average reduction of 16.7%. These results indicate that although a nominal improvement does exist for the normalization method of amplitude correction, the reduced acoustic amplitude at the focus may be a factor that would outweigh its utility as a transcranial ultrasound optimization technique.

P2U-I-7 F7

BEAM STEERING IN PULSED DOPPLER ULTRASOUND VELOCITY ESTIMATION

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Many clinicians use pulsed Doppler ultrasound to measure the maximum blood velocity in a variety of situations and make use of the results for diagnosis. When

using linear phased array transducers with electronic beam steering, they generally assume that the estimation of maximum velocity is accurate. However, as first demonstrated by Daigle et al. [1] serious maximum velocity overestimation errors can occur in linear array Doppler ultrasound transducers. Using a string-phantom to produce a pulsatile signal they reported both intra- and intermachine errors as well as discrepancies between unsteered and steered Doppler beams, with errors ranging from -3% up to 61%. For the most part, the effect of electronic beam steering and its contribution to the maximum velocity error has been ignored. We have used a pulsatile flow phantom model and Doppler computer simulation model to investigate the possible contribution of beam steering to the maximum velocity error. First, to gain an understanding of the effect of beam steering, we used our Doppler ultrasound simulation model to study the characteristics of sample volumes. The variables simulated were steering angle, sample volume depth, aperture size and axial length. We found that the beam-steered sample volume does not significantly differ from the corresponding non-steered sample volume. Second, pulsatile flow experiments were performed using a tissue mimicking phantom and a waveform similar to that in the carotid artery. Measurements were made using linear array transducers held in a holder with accurate control of three degrees of freedom and relative angles. For clinically realistic beam-to-flow angles, we determined that additional errors arising from beam steering were not significant. These findings are in agreement with those previously reported for steady flow [2]. Our experimental results, along with the beam steered sample volume simulations, will be presented.

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P2U-I-8 F8

AN ALTERNATIVE FREQUENCY DOMAIN BEAMFORMING

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Ultrasound Imaging (UI) has been introduced in medical diagnostic in the late '70s as an alternative scanning modality. In spite of its recent development it has gained a meaningful position on behalf of diagnostic procedures. In analysing the history of UI it appears that the hardware development of scanners hasn't yet been followed by an equivalent improvement nor in beam-forming neither in processing techniques. Nevertheless, the present lowering of electronic costs makes new and more sophisticated solutions very attractive for UI. Particularly, new frequency domain beam-forming of the type presented in this paper are suitable and reliable alternatives to the usual scan approach. The proposed

beam-forming is based on the "seismic migration" algorithm originally developed for geological prospecting. With respect to the trivial frequency approach, consisting of a direct transposition of the time domain beam-forming, it is very efficient and the resulting computational load is in the range of performances ensured by present high-speed processing architectures (e.g., ARM). Specifically, it consists in solving the scalar wave equation, and in propagating the echo field measured by the probe in reverse time towards deep tissues. This approach allows to reconstruct an image from each tissue insonification, thus resulting in a significant improvement in the maximum frame-rate achievable with respect to the usual scan technique. In its simplest implementation, suitable both for linear and convex transducers, it foresees the emission of an unfocused wave. Therefore a relevant saving can be obtained as no specific focalisation hardware is required. The extension to phased and curved geometry probes has also been studied. Here specific focalisation hardware is required to provide cylindrical wave insonification for ensuring a suitable field-of-view. Using linear and phased probes also gives the further advantage of not requiring specific scan conversion hardware, being the reconstructed data already in cartesian coordinates. Promising results are presented both on phantom and on live tissues. Data to be processed have been acquired with a prototype ultrasound machine allowing collection of received radio-frequency echoes whereas the off-line images reconstruction had been carried out using a Matlab software running on an external PC. At present, a dedicated hardware platform to accomplish a real-time processing is under development.
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P2U-I-9 F9

PRE-AMPLIFIER ARRAYS FOR INTRA-ORAL ULTRASOUND PROBE RECEIVING ELECTRONICS

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High rates of oral cancer have been reported in recent years that could be linked to high risk factors such as smoking, poor eating and drinking habits. This has led to the search for a reliable diagnostic system for such cancers. An efficient means of early oral cancer cell detection by ultrasound imaging system is being investigated utilising a centre ultrasonic frequency of 20MHz, which has been proven to be effective in the imaging of skin and cutaneous malignancy. As no intra-oral ultrasound probe with operating frequency of 20MHz can be readily found in the market, the above-mentioned will be designed and the pre-amplifiers array that form part of the receiving electronics will be presented here. The intra-oral probe is required to be small enough for manoeuvring in the human mouth; hence, for the receiving circuitries to be housed in the probe, they have to be implemented with integrated electronics. The pre-amplifier performs the main task of buffering the echo signals. This design is a two-stage

operational transconductance amplifier that is low noise, capable of proving adequate gain with sufficient stability for further stages, whilst at the same time, providing high bandwidth. The pre-amplifier chip is fabricated using AMS 0.35μm CMOS Technology and contains a 16-channel array of amplifiers. Due to the high impedance nature of the PVDF transducers used in the probe (unlike conventional PZT ceramic transducers), the array of amplifiers will closely couple to the transducers (to reduce the interconnect capacitance). The pitch of the amplifiers matches the requirement of the transducers, which is set at 250μm. Several of these arrays can be combined in series for channels that are more than 16 in number, without affecting the pitch requirement Special attention were given to the minimisation of crosstalk between adjacent channels through good layout technique. This is an important issue, as the close proximity of adjacent channels can lead to unacceptable noise and cross- coupling. The resultant ASIC measures 5mm x 2mm in size and operates on +/- 2.5V rails. The amplifier has a gain of 12dB and simulations show that the amplifier is capable of operating up to a - 3dB bandwidth of 30MHz whilst driving a load equivalent to a high impedance coaxial cable. Under zero load condition, the amplifier has a bandwidth of up to 50MHz. The noise level and crosstalk will be less than 10nV/ (root Hertz) and - 16dB respectively at 20MHz.

Session: P2U-J
TISSUE CHARACTERIZATION: VESSELS
Chair: K. Thomenius
GE R&D

P2U-J-1 F10

ULTRASONIC MEASUREMENT OF CHANGE IN ELASTICITY OF BRACHIAL ARTERY DUE TO FLOW-MEDIATED DILATATION FOR EVALUATION OF ENDOTHELIAL FUNCTION

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Background: Endothelial dysfunction is considered to be an initial step of arteriosclerosis. For assessment of the endothelium function, brachial artery Flow-Mediated Dilatation (FMD) has been evaluated with ultrasound. In conventional methods, the change in artery diameter caused by FMD is measured. Although the arterial wall has the layered structure (intima, media, and adventitia), such a structure is not taken into account because the change in diameter reflects the characteristic of the entire circumference. In this study, to make use of such a layered structure, we divide the wall of the brachial artery into two layers with the same thickness (the intima-media and adventitial sides), and the elasticity of each layer was obtained. **Method**: Blood flow of brachial artery was shut with a cuff at a pressure of 250 mmHg for 5 minutes. After release

of the cuff, nitric oxide (NO) generated by the endothelium in response to the shear stress caused by increased blood flow makes the smooth muscle relax. We measure the change in elasticity due to FMD for 2 minutes for 5 subjects with a 10 MHz linear-type probe. We divide the wall into two layers for the intima-media and adventitial sides by setting equally-spaced three points along an ultrasonic beam. For the elasticity estimation, the change in thickness of each layer was obtained by measuring displacements of these three points using the phased tracking method [H. Kanai, IEEE Trans. UFFC, 43, 1996]. The change in thickness was obtained by subtracting displacements of neighboring two points. **Experimental Results**: In the case of 30-year-old male, after the cuff was released (t=0 s: release), the change in elasticity of the intima-media side was found (t=11 s: 669 kPa → t=44 s: 578 kPa → t= 56 s: 537 kPa → t=67 s: 601 kPa → t=102 s: 618 kPa). The decrease in elasticity of the intima-media side was also found in the case of 23-year-old male (t=0 s: 544 kPa → t=25 s: 321 kPa → t=50 s: 262 kPa → t=111 s: 356 kPa). The ratio of the change in elasticity of 23-year-old male (35.2%) to elasticity before release of the cuff was larger than that of 30-year-old male (17.4 %). On the other hand, the elasticity of the layer on the adventitial side did not change so much (8.7 %) (t=0 s: 402 kPa → t=50 s: 451 kPa → t=111 s: 452 kPa). For other 3 healthy subjects, similar results were obtained. We also obtain the elasticity by measuring the change in diameter as well as conventional methods. The ratio of the change in elasticity was 10.4% (original: 1091 kPa, minimum: 978 kPa). **Conclusion**: It is supposed that only the layer on the intima-media side, which includes almost all of the smooth muscle in the media, responded to NO. In conventional methods, the mechanical property of the adventitial side, which was not changed by FMD, is included because the change in diameter is employed. Therefore, the proposed method has potential for improving sensitivity in evaluation of the endothelium function by measuring the change in elasticity only in the intima-media region.

P2U-J-2 F11

BLOOD COAGULATION AND CLOT FORMATION STUDIES USING HIGH FREQUENCY ULTRASOUNDS

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This study applied high frequency ultrasounds, up to 50 MHz, for better detecting the process of blood coagulation (BC) and clot formation (CF) using only a 5 ml minimal volume of blood sample. Measurements were carried out using various focused ultrasonic transducers of central frequencies ranged from 5 to 50 MHz. Different hematocrits between 25 and 55% of the porcine blood were restituted from the separated plasma and red cells. A 2.5 ml calcium chloride was added into the blood sample for inducing clot formation. Per each measurement, backscattered signals of the blood digitized at a 500 MHz sampling

frequency were collected for 30 minutes at a 1 A-line per second temporal resolution. Thus it allowed direct observation of changes of backscattered signals associated with process of BC and CF by both backscattered strengths and M-mode image. Results indicated that the backscattered strength was decreased initially corresponding to the addition of calcium chloride. The backscattered strength was increased gradually as more blood coagulated and was then saturated when the clot was finally formed. The rising time indicating the early stage of blood coagulation was found ranged from 212 to 35 seconds corresponding to the applied ultrasound frequencies from 5 to 50 MHz, respectively, meaning that high frequency ultrasound has a better sensitivity than that of the low frequency ultrasound. This discrepancy might be directly interpreted due to that ultrasonic backscattering is significantly dependent on the ultrasound frequency. It moreover suggests that high frequency ultrasound is capable of sensitively examining the variation of the blood clinically.
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P2U-J-3 F12

CLASSIFICATION OF VENOUS THROMBOSIS COMBINING ULTRASOUND ELASTOGRAPHY AND TISSUE CHARACTERIZATION

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Introduction: Treatment of deep venous thrombosis (DVT) succeeds only during the first 7 days. Therefore, an exact age determination of DVT is of high importance for an appropriate treatment of the patient. The accuracy of available methods including CT, MRI and conventional B-mode imaging is often not sufficient. Thus alternative approaches for staging thrombosis are desirable. Blood clots leading to venous thrombosis undergo an organization process, which results in a hardening with increasing age. In a previous work, we demonstrated results of ultrasound elastography for staging DVT. Although larger variations in strain estimates of one age could be observed, clear age dependence in average strain, in particular an increase in stiffness between day 6 and day 12, was found. In this work, strain estimates obtained using elastography are combined with ultrasonic tissue characterizing parameters from spatial and spectral domain. Parameters are fed into a classifier to differentiate between thrombi of age $\leq$ 6 days and age $>$ 6 days. **Experiments and Data Acquisition:** 22 Thrombi of defined age (1, 3, 6, 9, 12 and 15 days) were induced in pigs. Resected thrombosed vessel segments were embedded in cold soluble gelatin with additional 1% silica gel. Ultrasound echo signals were acquired using a Siemens Omnia diagnostic ultrasound system (9.0 MHz linear array transducer) equipped with a custom designed RF-interface. Data was acquired at 3 different cross sections of each specimen. RF data was digitized using a 50 MHz,

12-bit PCI A/D converter (GaGe 1250). For elastographic measurements external compression was applied using a stepper motor. **Methods:** In B-mode images, a region of interest was defined comprising of the vascular cross section. ROIs were transferred automatically to the parameter images. For the ROIs the mean value of each parameter was calculated. Besides elastography first order statistics as well as spectral analysis using Fourier transform and autoregressive modeling were applied to extract spatial and spectral parameters. Datasets were subdivided into two classes, age $\leq$ 6 days and age $>$ 6 days, respectively. Total cross validation was performed using a Euclidian classifier. **Results and Conclusion:** More than 80 % of the samples could be classified correctly using Euclidian distance. Therefore we conclude that combining elastography and tissue characterizing parameters can be useful to discriminate young thrombi (age $\leq$ 6 days) from older thrombi (age $>$ 6) and thus facilitate to choose an appropriate treatment for DVT.
This work is an activity of the Ruhr Center of Competence for Medical Engineering (KMR), Bochum, funded by the German Ministry of Education and Research (BMBF), grant no. 13N8079.

P2U-J-4 F13

SEGMENTATION OF THREE-DIMENSIONAL INTRAVASCULAR ULTRASOUND IMAGES USING SPECTRAL ANALYSIS AND A DUAL ACTIVE SURFACE MODEL

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Background: Intravascular ultrasound (IVUS) imaging provides detailed assessment of coronary anatomy and can be used as a quantitative tool for tracking the progression of atherosclerotic disease. The geometric information also provides evaluation of positive remodeling, a phenomenon linked to the likelihood of plaque rupture. To provide this valuable information, luminal and medial-adventitial borders must be identified in the sequence of IVUS images, a problem traditionally approached using gray-scale intensity based algorithms. However, by acquiring the radiofrequency (RF) IVUS data, the frequency information that is typically ignored can be used to improve segmentation algorithms. **Methods**: 25 clinical RF pullbacks were acquired using a custom designed hardware and software platform that streams ECG-gated RF images to a PC in real-time. 545 regions-of-interest (ROIs) were selected from these 25 data sets and 9 spectral parameters were calculated from each ROI. The average spectra from these regions were normalized using the system transfer function computed using blind deconvolution. 75% of the ROIs were used as training data to build a classification tree (CT) and the remaining 25% were used to test the sensitivity and specificity of the CT, which was incorporated into the 3D segmentation algorithm. A dual active surface algorithm, which utilized a priori information about the shape and relationship of the 2 borders within the image frame and

between image frames, is being developed. The external energy used to drive the surfaces is derived from a classified image created using the CT for spectral analysis and the gray-scale echo intensity gradient information. **Results**: The test set for the CT that was used to help guide the active surface algorithm included 138 ROIs not included in the training data set. 73 of these ROIs were from blood, 37 were from plaque, and 28 were from plaque with shadow behind it. The sensitivities of the CT for the training data were 88.9% for blood, 88.0% for plaque, and 90.4% for plaque with shadow behind it. The specificities for the training data were 93.7% for blood, 90.6% for plaque, and 98.5% for plaque with shadow. In the test data, which was not used to build the CT, the sensitivities were 87.7% for blood, 70.3% for plaque, and 82.1% for plaque with shadow. The specificities for the test data were 83.1% for blood, 87.1% for plaque, and 99.1% for plaque with shadow. **Conclusions**: Spectral analysis of RF data aids in distinguishing blood and plaque. The CTs were built based on 9 parameters calculated from the spectra of the RF data. Using a classified image as an external force for a dual active surface model provides a more powerful approach to border detection than more traditional techniques only including gray-scale echo amplitude and gradient information. These preliminary data demonstrate that spectral analysis in combination with a dual active surface model can potentially provide automated luminal and medial-adventitial border detection in IVUS pullback images.

P2U-J-5 G13

DEVELOPMENT OF BONE-MIMICKING PHANTOM AND MEASUREMENT OF ITS ACOUSTIC IMPEDANCE BY INTERFERENCE METHOD

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We have developed a bone-mimicking phantom dispersing calcium in oil jelly (plasticizing material contains oil and resin) and measured its acoustic impedance by the interference method. Since osteoporosis is related with the decrease of calcium and mineral content, the acoustic impedance is also related with the disease, because of the fact that the acoustic impedance is given by the product of velocity and density of the ultrasound propagating media. In order to assess the change in acoustic impedance due to the contents of Calcium, we have developed a bone-mimicking phantom. The phantoms were dispersed with 60%, 66% and 71% of Calcium in weight percent in oil jelly. The impedance of the samples was measured by the interference method [1]. The experiment was conducted at 3.5 MHz. The phantom was placed in distilled water, and the transmission line made of acrylic bar was used for the interference measurement. The impedance of the phantoms were 2.0, 2.2 and 2.6 x 106[kg/m^2 ·s] respectively. Impedance measurement was also conducted by measuring the speed of sound and the density of the phantoms. These values were coincided with an error of around 10 %. The speeds of sound of the phantoms were 148E+3, 1.54E+3 and 1.55E+3 [m/s] respectively. In conclusion, the phantom can be used as a bone mimicking phantom, and the interference measurement method can be used for non-invasive method for the impedance measurement of the bone. [1] R. Hatakeyama, M. Yoshizawa and T. Moriya, A Method for the Measurement of Acoustic Impedance and Speed of Sound in a Small Region of Bone using a Fused Quartz Rod as a Transmission Line, Jpn. J. App. Phys. 39.(2000) pp.6449-6454.

P2U-J-6 G12

GENERATION OF REGIONAL STRAIN INSIDE OBJECT USING ACOUSTIC RADIATION FORCES

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Background: Recently, there are some reports on assessment of the mechanical properties of tissue by measuring its displacement induced by two ultrasonics of slightly different frequencies. That is, one transducer irradiates an ultrasound with frequency of f_0 Hz, and another irradiates an ultrasound with frequency of ($f_0+\Delta f$) Hz. However, to accurately measure the regional viscoelasticly of inhomogeneous tissue, it is necessary to expand and compress regional tissue to generate local strain. For this purpose, in this paper, two ultrasonic transducers irradiate two low-frequency acoustic radiation forces which are driven in the inverse phase to generate the regional strain. **Method:** One transducer was driven by the sum of signals at frequencies of f_1 Hz and ($f_1+\Delta f$) Hz, and another was driven by the sum of f_2 Hz and ($f_2+\Delta f$) Hz. These two transducers irradiate two acoustic radiation forces at the same difference frequency of Δf Hz but with the inverse phase. The target can be expanded and compressed locally by applying these two acoustic radiation forces at the top and the bottom of the target. The resulting displacement at each depth along an ultrasonic beam inside the target was simultaneously measured by the ultrasonic phased tracking method [H. Kanai, IEEE Trans. UFFC, 43, 1996] using another ultrasonic probe. To avoid the mutual interference of these ultrasonics for measurement and actuation, we controlled the irradiation timing using the electronic switch circuit [K. Michishita, Jpn. J. Appl. Phys., 42, 2003] **Experiments:** In basic experiments using a silicon rubber as a target, we simultaneously measured displacements inside the target caused by the acoustic radiation force. A gel (static elastic modulus: 25.5 kPa, sound velocity: 1472 m/s), which is made from polyurethane, was placed in a water tank. The sound pressure exerted on the top and the bottom of the object were 154 kPa (5 MHz+(5 M+10) Hz) and 199 kPa (3 MHz+(3 M+10) Hz), respectively, at the difference frequency of 10 Hz. These two ultrasound waves exert acoustic radiation forces of 2.7 Pa at the top and 4.6 Pa at the bottom, respectively. We measured displacements at two points A around the top and B around the bottom along an ultrasonic

beam (distance between A and B: 3.6 mm). **Results:** We found that both points were vibrated at the difference frequency of 10 Hz in the inverse phase. Amplitudes of displacements at A and B were 0.4 μm and 1.5 μm, respectively. The elastic modulus of the gel was determined as 17.8 kPa from acoustic radiation forces calculated by sound pressure of ultrasonics and the strain (0.5%) obtained by subtracting two displacements. It was found that the elastic modulus measured with ultrasound was similar to that obtained by static experiments (25.5 kPa). **Conclusions:** We measured resultant displacements in micrometer order induced by two acoustic radiation forces, and the phases of displacements at the top and the bottom of the object were different by 180° . These results show that the proposed method is effective to generate local strain inside the object.

P2U-J-7 G11

MECHANICAL CHARACTERIZATION OF THE VITREOUS BODY WITH ACOUSTIC RADIATION FORCE

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Several studies have shown that changes in the mechanical properties of tissues are correlated with the presence of disease. In the eye for example, the vitreous body goes through mechanical changes with age which may eventually lead to the formation of several vitreoretinal disorders, including retinal detachment. While the changes in the mechanical properties of the vitreous are clearly important in the development of retinal detachment, there are currently no viable methods to monitor vitreous mechanical properties and boundary conditions. We are developing a method to quantify these mechanical changes using a non-invasive technique called KAVE (Kinetic Acoustic Vitreoretinal Examination). KAVE uses acoustic radiation force as a means to produce small, localized displacements within the tissues. Returning echoes are processed using ultrasonic motion tracking so that the response of the tissue to the induced force can be evaluated. By repeating this process at a number of locations, images depicting viscoelastic properties of tissues can be formed. In this paper we present results obtained by applying KAVE on human eyes both in vivo and in vitro. Experiments were conducted using a Philips SONOS 5500 imaging system employing a 6 MHz linear probe. Within the current FDA ophthalmology limits of 68 mW/cm2, we observe in vivo displacements of approximately 35 microns. Through the combination of appropriate mechanical modeling and signal processing, we are able to generate images of viscoelastic parameters. This imaging method has the potential to offer new insight into the formation of retinal detachment. In addition, it has tremendous potential to improve diagnosis of retinal detachment by identifying those patients at high risk before a retinal detachment forms.

We acknowledge the support from the Whitaker Foundation.

Session: P2U-K

ULTRASOUND THERAPY
Chair: L. Crum
University of Washington

P2U-K-1 G3

AUTOMATED HIFU TREATMENT PLANNING AND EXECUTION BASED ON 3D MODELING OF THE PROSTATE, URETHRA, AND RECTAL WALL

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Current treatment planning with the Sonablate®500 image-guided high-intensity focused ultrasound (HIFU) device (Focus Surgery, Inc.) used for the treatment of prostate cancer consists of defining treatment zones on up to 15 ultrasound images that span the entire prostate. While effective, this process may be time-consuming in the case of large prostates or if multiple treatments are required. For this reason, a method has been developed to quickly model the prostate, urethra, and rectal wall from 2D ultrasound images to allow for completely automated treatment planning for HIFU treatments of prostate cancer. It is based on the identification of boundaries and prostate structures in 4 to 6 orthographic ultrasound images prior to treatment. The boundaries and structures can be defined either through operator tracing, pointing, or automated detection, and form the input to structure-specific 3D models. All structures are modeled as deformable parametric surfaces that are then processed by the automated treatment planning module. Early results show that the developed models are robust, flexible, generate good closed surfaces even in the absence of full imaging data, and within 5 mm correctly model the wide variation encountered in tracing and pointing skills, human prostates, urethras, and rectal wall shapes. Such model accuracy has shown to be sufficient for planning these HIFU treatments. The entire treatment planning process will be presented, highlighting the usefulness of the developed 3D models. Specific model details for the prostate, urethra, and the rectal wall will also be shown. Finally, results using *in-vivo* animal and human data as model inputs and envisioned treatment planner outputs will also be shown, together with the initial integration activities into the Sonablate500®HIFU device.
This work was supported by SBIR NIH Grant 2R44DK059664-02.

P2U-K-2 G4

INTRAVASCULAR ULTRASOUND ABLATION CATHETER FOR TREATING ATRIAL FIBRILLATION

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Atrial fibrillation (AF) affects 1% of the population and can cause stroke and death. Circumferential pulmonary vein ablation can isolate abnormal foci which are the genesis of AF in up to 30% of cases. Currently, RF electrodes are used to treat AF. Since mechanically steering a long catheter under poor fluoroscopic guidance is difficult, treatments can take over 7 hrs and have a 70% success rate. RF burns often have discontinuities, so electrical pathways are still intact to trigger AF. Though balloon catheters have been suggested for continuous circumferential burns, they are unsuccessful because the anatomy of the pulmonary vein ostia is highly variable in size and shape, which makes continuous contact difficult.

Intravascular ultrasound can be precisely electronically focused and steered. Also, the same array can image the region to correctly position a burn; this will make continuous precisely placed ablations possible.

While external ultrasound has been used to ablate cardiac tissue, air in the lungs around the heart deflects much of the ultrasound. We propose an intravascular linear ultrasound array on a 7 French catheter for ablation and have performed simulations and a preliminary experiments to show its feasibility.

Using Ultrasim (Univ. of Oslo), we simulated a 20mm X 2mm, 32 element array with electronic focusing in the long axis and a lens focusing in the short axis. Focusing to 5mm at 10 MHz, we produced an elliptical spot (100 μm by 1mm), a burn depth of 0.6mm, and a power density of 867 W/cm^2. Since previous work has shown that application of 150-1000 W/cm^2 for 10 seconds produces burns, these simulations show a small ultrasound array is feasible.

For proof of concept, we used a single element transducer the same total size as the array (20mm X 2mm) and a spherical reflector (25mm diameter, 10mm focus) to focus the beam. We positioned the meat (5mm X 5mm X 2mm) to produce an on axis burn at the reflector's focus. Using an AR Kalmus linear amplifier, we applied $10\frac{W}{cm^2}$ to the transducer at 8.6MHz for 10 sec. The temperature rose to 60C in meat submerged in a still water bath (21C). To further model the movement of blood, we pumped water slowly over the tissue, which resulted in a temperature rise to 45C. Since cell necrosis occurs at 43C, this temperature change is enough for ablation.

We should expect better results from the ultrasound array since the reflector causes more beam spreading. This is because the focal length of the reflector (10mm) is longer than our array focal length (5mm) and spherical reflector focuses to an arc, not an ellipsoid. Also, the tissue was small, so the temperature rise was dominated by convection to the water bath. However, in the heart, convective heat loss is limited to one side of the tissue in contact with moving blood. In addition, the larger mass and density of heart tissue decreases conductive losses.

We are currently building an ablation system for a 32 element array. When built, the system will have computer control of focusing and steering.

The authors would like to thank John Pauly for his thoughtful ideas, time, and support.

P2U-K-3 G5

B-SCAN IMAGING AND THERMAL LESION MONITORING USING MINIATURIZED IMAGE-TREAT ULTRASOUND ARRAYS

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A key potential advantage for ultrasound therapy is the ability to treat and image tissue using the same device. Recent development of miniaturized dual-functionality (image and treat) probes, capable of both high power ($>$80 W/cm^2 at 3.1 MHz) and broad bandwidth (50% centered at 3.5 MHz), has allowed real-time imaging and monitoring of thermal lesioning with complete co-registration of image and treatment regions of interest. Using arrays with 32 elements spanning an aperture of 2.3 $\times$ 48 mm and center frequencies of about 3.5 MHz, high-quality B-scan images and useful monitoring information can be obtained during therapy planning and treatment.

B-scan image quality is quantitatively comparable to current transabdominal ultrasound arrays (azimuthal point resolution 3 mm, axial point resolution 2 mm, contrast resolution 3 dB). Challenges associated with limited probe dimensions and channel count are met using interpolation, filtering, and reverberation reduction methods that improve image definition and contrast. Tissue boundaries and critical structures are shown to be clearly delineated in phantoms and *in vivo*.

Monitoring of thermal lesioning by these arrays can be performed simultaneously using the same array elements. In addition to real-time B-scan visualization, techniques employed include quantification of tissue backscatter and attenuation changes, and analysis of echo waveform changes to detect boiling and tissue modification. Gas activity, associated with gross B-scan changes as well as large waveform and attenuation changes, consistently implies tissue ablation for the exposure conditions studied here. However, preliminary experience suggests that absence of large echo changes does not consistently predict absence of ablation, and that the magnitude of echo changes shows limited correlation with the severity of ablation.

P2U-K-4 G6

ULTRASOUND THERAPY SYSTEM AND ABLATION RESULTS UTILIZING MINIATURE IMAGING/THERAPY ARRAYS

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Array-based imaging and therapy systems have several advantages over single element approaches, and it was shown that the imaging and therapy functionality may be combined into dual-mode arrays [1]. In this work, minimally invasive, miniature (2.2 mm X 50 mm aperture, 3.3 mm diameter) dual-mode linear arrays have been developed into probes with high acoustic power output (120 W/cm^2 at the source), high transmit efficiency (>65% typical), and good imaging performance (3.5 MHz center frequency, 50% fractional bandwidth, >100 mm deep field of view). These therapy/imaging probes have been integrated into a flexible intense ultrasound surgery platform which also includes conventional diagnostic imaging probes. A system architecture has been developed which includes a 64-channel therapy driver with software selection of array aperture and phasing (1/16th wavelength), frequency (0.5 - 8 MHz), drive amplitude (5 W/channel, nominal), mechanical rotational steering ($\pm$80 degrees), and temporal sequencing/switching of imaging/therapy/monitoring modes. The array-based imaging/therapy system has produced encouraging results in preclinical studies of bulk tissue ablation and imaging of liver in vitro and in vivo, examples of which will be presented. [1] P.G.Barthe, M.H.Slayton, Efficient wideband linear arrays for imaging and therapy, Proc. IEEE Ultrasonics Symp., pp. 1249-1252, 1999.

P2U-K-5 G7

EXTERNAL ULTRASONIC VALVULOPLASTY FOR THE TREATMENT OF SUPERFICIAL VENOUS INSUFFICIENCY : A FEASIBILITY STUDY

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Deformations on the valvular tissues of the saphenous vein can cause an abnormal reflux of blood. This reflux is the main cause of Superficial Venous Insufficiency (SVI) and varicose veins. Since High Intensity Focused Ultrasound (HIFU) induces a strong rise in the temperature of biological tissue, and collagen in veins deforms when exposed to a high temperature, we conducted a study to demonstrate the feasibility of using HIFU to induce shrinkage of the collagen

of the saphenous vein near the valvular tissue. This shrinkage should restore normal function of the valve. An experimental protocol was carried out where several in vitro segments of human saphenous vein were sonicated with HIFU. In order to better recreate in vivo conditions, the segment was inserted in porcine muscle. The segment of vein and the porcine muscle sample were placed into a PVC cylinder. After being degassed, the sample was inserted in a recipient filled with degassed-saline solution and sonicated with a real-time imaging HIFU probe. The probe has a focal length of 45 mm, a diameter of 52.5 mm and operates at 3 MHz. Ultrasonic imaging, obtained by an 8MHz 128-element linear array placed in the center of the HIFU probe, was used to spot the focal zone on the wall of the vein. Individual sonications of the vein wall were performed for acoustic power values ranging between 8.75 and 35 W at a constant sonication duration of 5 s. Different sonication durations ranging between 3 and 7 s at constant power were also tested. Results showed that shrinkage of the vein wall was observed by echographic and macroscopic analysis for the cases of high-power sonication. Histological analysis showed that collagen of the vein wall was indeed altered for all cases of sonications but no signs of perforation were found. However, a macroscopic ablation was observed in the surrounding muscle. The observed shrinkage of the vein wall suggests that dysfunctional valves of the saphenous vein could be treated with HIFU since a significant shrinkage of collagen could restore competence of the abnormal valve.
The first author expresses his gratitude for a graduate fellowship from the Consejo Nacional de Ciencia y Tecnología (CONACYT) of Mexico.

P2U-K-6 G8

ACCURACY OF THE RESONANCE ULTRASOUND METHOD IN DETERMINATION OF THE ACOUSTIC PHASE SHIFTS IN PLASTIC PLATES AT OBLIQUE ANGLES OF INCIDENCE

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The accuracy of resonance ultrasound method is determined when used towards resolving the acoustic phase shifts in single-layer and three-layer plastic plates at oblique angles. Oblique angles of incidence are encountered if resonance method is applied in determining the phase shifts in the skull bone with a hemisphere trans-skull therapy array. At first, the investigation is conducted with a single, broad band transducer at frequency range from 0.45 to 1.45 MHz while the angle of incidence of the sound beam is varied by rotating the studied plate by 0-15°. After that, when rotations greater than 10° are used, a second transducer operating in the same frequency band is used to receive the reflected sound beam. Acoustic phase shifts are calculated using the resonance frequencies of the plates resolved from the reflected spectrum, and phase shifts are compared

to those calculated from hydrophone signals in through-transmission measurements. Materials include 20 pieces of PMMA and 6 pieces of polycarbonate (PC) plastic, of which 10 PMMA and 3 PC plates are bent to model on the shape of human skull. PMMA and PC plates are used to form three-layer plastic skull bone phantoms. Results show that with the flat single-layer plates, 70% of the measured phase shifts (of altogether 416) deviate by less than 30° from those measured with the hydrophone, after bending the similar performance is about 65% (of 208) and about 55% (of 192) with the flat three-layer phantoms. Further, an average of three measurements in each plate show deviation of higher than 90° between the methods. The increase in the discrepancy is due to the destruction of the resonance pattern at higher angles of incidence as sound beam is reflected away from the transducer and uncertainty in resolving the resonance frequencies increases. After implementing the second transducer the resonance patterns can be reconstructed and the discrepancy between the methods decreased. This kind of geometry could be easily implemented into the trans-skull focused ultrasound therapy array. It is hypothesized that the phase shifts in the skull bone could be resolved with the resonance ultrasound method using a multi-element trans-skull phased array and be used towards reconstructing the focus non-invasively inside the human brain.
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P2U-K-7 G9

EVALUATION OF ULTRASONIC TEXTURE AND SPECTRAL PARAMETERS FOR COAGULATED TISSUE CHARACTERIZATION

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Introduction: Thermal ablation is well accepted for the treatment of tumors in cases where established therapeutic methods like surgical resection are either inapplicable or ineffective. However, the ablation process monitoring as well as the detection of the coagulated tissue volume is still challenging. Conventional B-mode imaging is often not sufficient due to the formation of gas bubbles during the ablation process and low contrast between coagulated and healthy tissue after the ablation process. Therefore we propose to apply tissue characterizing parameters from spatial and spectral domain to characterize coagulated tissue. The aim of this work is to evaluate the potential of various parameters. The calculated parameters are first and second order texture parameters, estimates of attenuation coefficient, spectral parameters (slope, intercept and midband value) and coefficients of autoregressive spectral estimates. **Experiments and Data Acquisition:** Measurements were performed on porcine and bovine liver samples in vitro. Coagulation was induced using an RF-ablation device. For the acquisition of radiofrequency data a Siemens Omnia diagnostic ultrasound system (3.5 MHz curved array transducer) equipped with a custom designed RF-interface was used. RF data was digitized using a 25 MHz, 12-bit PCI A/D converter (GaGe 1250) for offline processing. Afterwards the liver samples were sliced along the imaging plane and photographs of the coagulated zone were taken to serve as a reference. **Methods:** Temporal windowing of the rf data was performed in order to allow a spatially resolved calculation of parameters. The size of the window was set to 128 samples (3.9 mm) axially and 16 lines (4 degrees) laterally. B-mode and parameter images were calculated offline. According to the photographs boundaries of the coagulated zone were delineated in the B-mode images. The boundaries were transferred accordingly to the parameter images. Thus two classes (coagulated and not coagulated) were defined based on the reference. For each parameter sensitivity and specificity and hence the receiver operating characteristics (ROC) curve was determined. As a measure of selectivity of each parameter the area under the ROC curve AROC was utilized. **Results and conclusion:** First order texture parameters as well as autoregressive parameters reached values of AROC > 0.8 and performed better than attenuation estimates with AROC < 0.75. The best performing parameters can be used to be fed into a classification system.

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Session: P2U-L

BIOEFFECTS
Chair: W. O'Brien
University of Illinois

P2U-L-1 E1

THE EFFECT OF TISSUE TYPE AND EXPOSURE PARAMETERS ON CONTROLLED ULTRASOUND TISSUE EROSION

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The ability to differentially damage tissue may extend the capabilities of ultrasonic surgery. Controlled ultrasound tissue erosion has the unique ability to erode away tissue in the focus with limited peripheral damage. The effect of tissue type, tissue Youngs Modulus (YM), acoustic intensity and gas content of the liquid on the erosion rate was explored. The tissues used were porcine lung, liver, intestinal muscle, uterine muscle, pericardium, kidney and thoracic aorta. A 750 kHz, 18-element split aperture annular array transducer with an aperture of 16 cm and an f-number of 1.5 was used to treat the tissue. A PD of 3 cycles was used with a PRF of 18 kHz at I_{SPPA} values of 1800 to 15000 W/cm^2 and

gas saturations of 40%, 50%, 70% and 90%. To determine the erosion rate, a 15 MHz transducer was placed confocally with the 18-element array. Before and after the exposure, the thickness was measured using pulse-echo recordings. The erosion rate was defined as the difference in thickness divided by the time of ultrasound exposure (um/sec). The YM was measured using a microelastometer. In these preliminary studies, for gas saturations of 50-90%, there was a characteristic curve for erosion rate vs. YM that changed in magnitude, but not shape, with changes in I_{SPPA}. For 50% and 70% gas saturations, there are 2 erosion maxima at YM values of 2kPa and 18kPa. Above YM = 130 kPa, there is no erosion for any gas content or I_{SPPA}. For 90% gas saturation, the shape of the curve was the same as that for 50% and 70% gas saturations, but only 3 tissues were eroded, yielding erosion maxima at 7 kPa and 23 kPa. At 40% gas saturation, the two-maxima structure was not seen. With I_{SPPA} values below 10000 W/cm^2, the erosion rates for tissues with YM$<$ 2 kPa were very small and there was only one peak in erosion rate at YM = 6 kPa, after which the erosion rate decreased with increasing YM. Above 15000 W/cm^2, the erosion rate simply increased with decreasing YM. For the intestine and the uterus, there was a tissue-specific effect uncorrelated with the YM. For the intestine, at gas saturations of 50% and above, for all I_{SPPA} values tested, there was swelling, not erosion. When examined histologically, this swelling is an infiltration of fluid into the area in which the tissue is exposed that causes minimal acute damage to the cells in the tissue. For the uterine muscle, a similar effect is seen for all I_{SPPA} values tested, but only at 90% gas saturation. This effect may protect the tissue from further damage after swelling has occurred. The effects observed show that there is tissue specificity and great dependence on gas saturation for erosion rate. Specifically, there is a correlation between the YM and the erosion rate of the tissue. There also appears to be a property of smooth muscle that may protect it from erosion for specific exposure conditions and indicates a potential method for fluid transport. Based on the effects observed, this research potentially leads to the ability of a given exposure to differentially treat tissue.
This research has been funded by grants from the NIH R01 RR14450.

P2U-L-2 E2

MICROBUBBLE POTENTIATED CHANGES IN CELL PERMEABILITY AND VIABILITY

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The combination of ultrasound and microbubbles has opened new possibilities for the noninvasive delivery of drugs and genes into the cells of a target. Cell membrane permeability can increase reversibly following their exposure to ultrasound, a process known as sonophoresis or sonoporation. The physical mechanisms by which this occurs have yet to be elucidated. However, physical sequellae to bubble disruption (such as formation of microjets and shockwaves) and to stable oscillation (such as acoustic microstreaming) in ultrasonic fields are almost certainly implicated. In this study, we use a suspension of cells and calibrated ultrasound beams and flow cytometry to investigate the effect of combinations of microbubbles and ultrasonic exposure parameters on changes of cell membrane permeability. Fluorescent labelled markers and flow cytometry are used to identify and quantify cell permeability and viability following exposure. Cell suspensions of KHT-C (a murine fibrosarcoma cell line) were exposed to ultrasound in the presence and absence of microbubbles (15 cycle tone burst, 2.0 kHz pulse repetition frequency) at various acoustic settings. The parameters investigated were peak negative pressure (MI = 0.1-0.9), frequency (1.0-3.5 MHz), exposure time (10 sec to 5 min), and microbubble concentration (Optison, 0 to 10%). The number of cells permeabilised (stained with FITC-dextran) and viable (not stained with propidium iodide) were measured using flow-cytometry. FITC-dextran (77 kDa) was used as a model of a high molecular impermeable drug. Sonoporation in KHT-C tumour cells was possible. The uptake of FITC-dextran increased with peak negative pressure and exposure time, and decreased with frequency. The addition of microbubbles induced an approximately four-fold increase in uptake; this effect was strongly dependent on bubble concentration. Cell death was induced by ultrasound alone and enhanced by the addition of microbubbles, especially at lower frequencies. The ratio of cells in which reversible permeability was induced to nonviable cells was calculated as an analogy to a therapeutic index. Though the number of cells permeabilised at 1 MHz is greater than at 3.5 MHz, so is the number of nonviable cells. At 3.5 MHz, bubbles had the effect of increasing sonoporation with less impact on the number of cells killed. Surprisingly, then, higher frequencies may therefore be preferred for sonoporation. Future work will continue to characterize the effect of different exposure parameters and bubble combinations; in-vitro and in-vivo model of drug uptake will follow.

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P2U-L-3 E3

CORRELATION OF THE EXPOSED-CELL MORTALITY WITH THE TRANSIENT CAVITATION NOISE IN VITRO

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The cavitation noise is a suitable and accurate indicator of the cavitation activity induced in a liquid. Frohly (J. Acoust. Soc. Am. 2000) proposed a quantitative indicator of the transient cavitation calculated as a cavitation spectrum integration in a logarithmic scale and called CNP cavitation noise power indicator. This work studied the relation between CNP and the exposed-cell mortality in the following conditions. The cell suspension to be insonified (prostatic cells AT2 at 2.5 10^6 cells/mL) is placed in a medium sample tray (12 wells/tray, 2

mL/well, well diameter: 20 mm). This tray is submerged at mid-depth in degassed water and positioned 5 mm above the face of a flat ultrasonic transducer (diameter 22 mm, frequency: 445.5 kHz; intensity: 0.08-1.09 W/cm2, exposure time: 30 sec-4 min). This technical configuration was admitted to be conducive to standing-wave generation through reflection at the air/medium interface in the well thus enhancing the cavitation phenomenon. Laterally to the transducer, a home-made hydrophone (PVDF film of 10 mm diameter molded in araldite AY103) was oriented to receive the acoustical signal from the bubbles. From this spectral signal (0.1 to 7.1 MHz bandwidth) recorded every 3 sec on a computer during the exposure condition, CNP was calculated. Its mean value was compared to the cell mortality measured just after ultrasound exposure with a flow cytometer (FACScan) by counting 10 000 events. This was accomplished by adding 7AAD solution (Via-Probe kit). 10 exposure conditions were chosen. Two of them corresponded to the experimental limits: - no effects on cells (i.e. 0.08 W/cm^2; 4 min) complete destruction of cells (i.e. 1.09 W/cm^2; 30 sec). 3 to 8 measures were realized for each exposure condition. The mortality due to cavitation effect varied from 0.1 % to 85.5 % and was compared to CNP mean given in relative value (from 3.8 % to 97.5 %). A simply linear relation between this parameters was given by *Mortality(%)=1.08xCNP(%)+0.36* with a correlation coefficient of r^2=0.81. This correlation coefficient came better when exposed times were considered (for 1 min r^2=0.82 and for 2 min r^2=0.95). These results show that CNP is a good indicator of the effect induced by the cavitation phenomena in cell culture medium *in vitro*.
This work was supported by the Association Franaise contre les Myopathies

P2U-L-4 E4

A STUDY ON PREMATURE VENTRICULAR CONTRACTIONS CAUSED BY ULTRASOUND EXPOSURE WITH MICROBUBBLES USING CULTURED CARDIAC MYOCYTES

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It has been shown in a study using a human volunteers that diagnostic ultrasound examination using a contrast agent can cause premature ventricular contractions (PVCs). In this study, we investigated the generation of PVCs using cultured cardiac myocytes. Cultured cardiac myocytes of neonatal rats start autonomous pulsation several days after isolation. In this study, cardiac myocytes isolated from neonatal rats were cultured on a cover glass. After incubation for one week, autonomous pulsation of myocytes was confirmed. The cover glass was attached to the top of an observation chamber with the cultured myocytes facing down, and a suspension of microbubbles was injected into the observation chamber so that the rising microbubbles made contact with the cells. The observation chamber was then exposed to pulsed ultrasound of 1 MHz in center frequency. The pressure amplitude was set at five steps of 0.28, 0.55, 0.73,

0.92, and 1.1 MPa in negative peak pressure. Pulsations of cardiac myocytes were observed using an inverted-type microscope, and images were recorded on a VCR. Plastic-shelled microbubbles of about 3 microns in diameter were used in the experiments. In the experiments, eight samples of cardiac myocytes were exposed to ultrasound pulses with microbubbles, and eleven samples were exposed to ultrasound pulses without microbubbles as controls. In the control group, slight irregular pulsation was found in only one sample at the pressure of 0.73 MPa, and the rate of PVC generation was smaller than 50% even at the maximum pressure amplitude of 1.1 MPa in peak negative pressure. In the case of plastic- shelled microbubbles, changes in contraction rhythm were observed to start at the lowest pressure amplitude of 0.28 MPa, and the rate of PVC exceeded 50% at the second- lowest amplitude of 0.55 MPa. At the maximum pressure of 1.1 MPa, pulsation was stopped by ultrasound irradiation for about 10 s, which is much longer than that in previous experiments without bubbles. From these results, it was confirmed also *in vitro* that PVC production is strongly dependent on the presence of microbubbles, and it was concluded that this *in vitro* experiment system is useful to study the mechanisms of PVC caused by ultrasound contrast agents.

P2U-L-5 E5

EFFECTS OF LOW INTENSITY ULTRASOUND ON THE CONDUCTION PROPERTY OF NEURAL TISSUES

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Previous studies in literatures demonstrated that the administration of high intensity or low intensity ultrasounds could either inhibit the signal conduction or accelerate the regeneration of neural tissues, respectively. To better investigate the effects of low intensity ultrasound on neural tissues, a 5 MHz transducer was employed to generate different energy, including 200, 500, and 700 mW, and duty cycles, ranged from 25 to 100% of a 2 KHz pulse repetition frequency, of ultrasounds were administrated to the excised sciatic nerve suspended in the Ringers solution in conjunction with electrical stimulations. The conduction properties of an excised nerve were assessed by the magnitude of compound action potential (CAP) and conduction velocity (CV). Results showed that both CAP and CV of the sciatic nerve tended to increase or decrease associated with ultrasonic stimulations of all applied energy at a duty cycle of 100% or that of without ultrasonic stimulation, respectively. The prominent effect was found corresponding to the stimulation using a 500 mW ultrasound that moreover brought changes of CAP and CV to be 41.3% and 3.8%, respectively. The variation of temperature was within 0.5°C throughout each measurement. Consistent results were also acquired from a series of studies that applied a 500 mW ultrasound of different duty cycles ranged from 25% to 75% to stimulate the sciatic nerve for 5 minutes. Both the magnitude of CAP and CV were increased

exponentially during the ultrasonic stimulation and were decreased as the stimulation was removed. These results validate an apparent dynamic effect for the low intensity ultrasound capable of activating the conduction of neural tissues.
This work was supported by the National Science Council of Taiwan, ROC, of the grant: NSC 92-2218-E-033-003.

P2U-L-6 E6

QUANTIFICATION OF ACOUSTIC EXPOSURE DURING CATARACT SURGERY

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Over the last 15 years, ultrasonic surgical devices have become the preferred instruments for cataract surgery within the ophthalmologic community. This approach, called phacoemulsification, uses needle tips which vibrate longitudinally at frequencies between 28 and 50 kHz (depending upon the manufacturer). Mechanical impact and inertial cavitation at the tip both act to erode and liquefy the lens material, which is then aspirated out through the needle core. This study attempted to determine the total acoustic exposure of the eye during a typical cataract removal procedure. This presentation will review the methods of determining the acoustic exposure from phaco devices, provide a clinical example, and demonstrate the utility of providing this information to the surgeon. A series of nearly 200 surgeries were performed by a single surgeon, using either of two different phacoemulsification systems. Each cataract was graded for relative density and hardness. After each surgery, system settings and surgical times were recorded. The acoustic energy radiated into the eye was calculated assuming a monopole model, consistent with IEC Standard 61847, with inputs of frequency, tip excursion, tip dimensions, and exposure time. Power was determined as $(\rho_0 ck^2 Q_s{}^2)/8\pi$, where Q_s is the source strength (radiating area times the normal surface velocity). Simplifying assumptions were made to account for factors such as excursion ramp up, ramp down, and pulsing sequences. One of the two systems used a unique microburst ultrasound pulsing scheme using bursts as short as 6 milliseconds; each system had a different mechanism for ramping power up and down (one changed excursion with a fixed duty cycle, and the other had fixed excursion with a variable duty cycle). The system printout documentation of control settings and cumulative output was very manufacturer specific, and required considerable effort to standardize in a form suitable for analysis. The results indicated that the total acoustic energy ranged from 0.01 Joules for a grade 1 cataract to up to 0.3 Joules for a Grade 5 cataract, with an exponential increase in ultrasound exposure with cataract grade (e.g. $y = 0.0033e^{0.66x}$, $R^2 = 0.974$). Further, after an initial run of experiments, the surgeon was able to modify the system control settings to reduce the patient exposure by 20 percent without compromising clinical effectiveness. The conclusions from this work are: 1) the novel pulsing approach using very short bursts appears to significantly reduce the total acoustic exposure; 2) if surgeons are

given dosimetric information, they can reduce exposure without reducing clinical effectiveness; 3) the data currently available from manufacturers are very difficult for clinicians to interpret and compare between devices; 4) based on the latter two conclusions, manufacturers are encouraged to provide on-screen labeling of acoustic output.
The authors acknowledge the cooperation of Advanced Medical Optics and Alcon, Inc.

Session: P2U-M
DEVICES AND TOMOGRAPHY
Chair: M. Kolios
University of Toronto

P2U-M-1 I1

ULTRASOUND RESEARCH PLATFORM

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Recent advances in the research and development tools at MathWorks and Xilinx have provided a coherent path from designing ultrasound experi-ments in the Matlab environment to implementing the experiments in a real time scanner in custom hardware. At WinProbe, we have implemented a medical ultrasonic scanner based on boards with 32 analog channels (pulsers, receivers and analog to digital converters) closely attached and control-led by a multi-million gate filed programmable gate array (FPGA). Multiple boards may be assembled to make state of the art systems. An example system implementing all the usual functions of a upper end ultra-sonic scanner and the implementation is supplied to researchers as working machine code and its source code. The source code written in VHDL is compartmentalized into Boxes any of which may be replaced by a custom implementation designed by the researcher in the researchers field of interest. All aspects of the acoustic transmission and reception are programmable. The main building blocks are the transmitter waveform code and focus, the recept-ion aperture, apodization, and dynamic focus, the acoustic line sequence, the types of acoustic line (direction, narrow bandwidth, wide bandwidth), the summation of the RF data into acoustic beams, the feature detection, the scanconversion and image presentation. Most functions are performed at the clock speed of the analog to digital converters, which is 40 MHz, and up. When a function requires more time than the clock period a latch is inserted and a pipeline delay is implemented. Correlation and normalizations sometimes require hundreds of pipeline delays but the throughput is not compro-mised. The advent of the Simulink-System Generator tools allow the researcher who is fami-liar with MatLab to design hardware in a simple graphical environment. Simulink is a multidomain modeling and simulation environment that lets you accurately describe, evaluate, and refine a systems behavior. System Generator builds the machine code from the Simulink output that can be down loaded into the hardware in seconds effectively making the scanner re-configurable on the

fly. The tools are used in new areas of ultrasound where ultra-fast ultrasound and very intensive computational processes are needed such as elastography, 3-D Flow and Opto-acoustics. In Opto-acoustics an entire frame is acquired in less than 100 microseconds and the computational power of beamforming the flash of data into acoustic lines is the usual limiting resource. In elastography the FPGAs capacity to implement multiple cross-correlators all working in real time is paramount. A large memory buffer between the analog to digital converters and the FPGA is currently being constructed to store thousands of acoustic frames before beamforming in order to visualize the passage of a shear wave. A method by which the researcher can encrypt his or her process and license it for use in other research laboratories or commercially is being developed.

P2U-M-2 I2

SUPERRESOLUTION ULTRASOUND FOR IMAGING AND MICROSCOPY

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An ultrasound technique for imaging objects significantly smaller than the source wavelength is investigated. This preliminary research is designed to evaluate the feasibility of the method in a controlled setting. The physical foundation for the approach is based on the fact that high spatial frequencies introduced by the object affect the lower frequency, propagating spatial frequencies of the signal. First, a planar projection method is used to back-propagate an acoustic image to an object plane. A nonlinear image recovery filtering algorithm is then used to analyze the spatial frequency spectrum along a single dimension in an attempt to deduce what object caused distortions in the image. Our technique achieves this by using a priori measurements of the ultrasound focus, which gives full spectral information about the image source. A guess is then made regarding the size and location of the object that distorted the field, and this is convoluted with the a priori measurement, thus creating a candidate image. A large number of candidates are generated and the one whose spectrum best matches the uncorrected image is accepted. Effects of random signal noise on selection ability are considered. The method is demonstrated using 0. 34 mm and 0.60 mm wires with a focused 1.05 MHz ultrasound signal and then a human hair ($\sim$0.03 mm) with a 4.7 MHz signal. Using a wavelength at least five times larger than the object, both numerical simulation and experimental results successfully identified an objects location and size in 5 out of 6 initial trials. These preliminary results suggest the method, once generalized to 3-dimensions could potentially have application in complementing the wide range of areas where very high frequency ultrasound is presently being investigated.

P2U-M-3 I3

RADIAL RADON TRANSFORM FOR ELECTRODE LOCALIZATION IN BIOLOGICAL TISSUE

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Utilization of micro-tools as needles, electrodes or micro probes in biological tissues meets a large developpement in diagnostic or surgery and are difficult to detect and localize. Low cost, simplicity, non invasive approach and real-time 3D data processing make ultrasound imaging one of the best imaging modality. Here, tissues are scanned by an ultrasound probe in order to determine the position of the inserted needle. Classical approaches perform a reconstruction of the volume, and apply then signal processing tools. We propose a method which processes directly the ultrasound radio frequency (RF) signal and avoids image reconstruction. It is then independant from the probe used, linear or sectorial, and decreases data interpolation. This offers an original solution for 3D data processing, as volume acquisitions are performed sphericaly or cylindricaly. The Radial Radon Transform (RRT) method is based on a new implementation of the Radon transform that preserves its robustness towards the noise, but reduces the number of interpolations. In a classical Radon transform, volumes are reconstructed and then projected on the Radons plane, which resolution has an impact on the precision of the method. These orperations implie successives low pass filterings and losses of accuracy. Here, radial RF lines are directly projected on the Radons plane. This projection plane performs the required but single low pass filtering. Having transformed the RF signal, the coordinates of the maximum in the Radon space is located. For this purpose, a multi-resolution approach was used to speed this procedure up. Finally, from the knowledge of the maximum in the Radon space, the analytical equation of the line segment is determined. The implemented algorithm was tested on RF signals acquired on a dedicated RF scanner by imaging a cryogel phantom crossed by a metal electrode of 150 mm diameter. The experiments showed that the RRT allows line-segment detection from RF signal. From the experiments we conclude that this technique, in comparison to other methods, gives robust results even in the case of noisy data with a lower computational cost. Further research will focus on more complex shapes localisation where the Radon transform fails.

P2U-M-4 I4

FOCUSED ARRAY TRANSDUCER FOR OPTOACOUSTIC TOMOGRAPHY

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Optoacoustic (OA) imaging is based on the generation of thermoelastic stress waves by heating an object in an optically heterogeneous medium with a short laser pulse. The stress waves contain information on the distribution of structures with preferential optical absorption that can be used for early cancer diagnostics. In this work a new design of array transducer allowing to enhance imaging resolution is proposed and developed. The array consists of 32 focused piezo-elements made of PVDF slabs imposed on a cylindrical surface. Theoretical and experimental investigations of a single element response to an OA signal coming from arbitrarily located point source have been performed. In experimental studies a diode-pumped Q-switched Nd:YAG laser has been employed for thermo-optical excitation of the OA transients. Experimental data confirm the numerical calculations. The results are employed for investigation of spatial sensitivity of a single element. Spatial sensitivity maps for elements with aperture angles 30° and 60° are presented and discussed; the resolution in direction perpendicular to the imaging plane is determined from these maps. Point spread function of the whole array has been calculated using experimentally obtained signals from the sources located at different distances from the array. For reconstruction of the images back projection algorithm has been employed.
The work is supported by RFBR grant #02-02-08008.

P2U-M-5 I5

TOMOGRAPHIC RECONSTRUCTION OF SOUND VELOCITY DISTRIBUTION IN THE BREAST USING LINEAR ARRAYS: EXPERIMENTAL RESULTS

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An approach based on limited-angle transmission tomography for reconstruction of the sound velocity distribution in the breast using linear arrays was proposed last year. The imaging setup allows acoustic data acquisition for simultaneous B-mode image formation and the tomographic sound velocity reconstruction. The time-of-flight data are acquired by a linear array positioned at the top of a compressed breast and a metal plate is placed at the bottom as a reflector. A reconstruction algorithm based on a convex programming formulation was successfully developed. Simulation results based on a 5 MHz linear array showed that the sound velocity error generally ranged from 1-3 m/s with a maximum at 5.8 m/s. It was demonstrated that the approach can be used to complement conventional B-mode imaging to enhance the detection of breast cancer. In this study, we investigate performance of the approach using experimental data. The experimental setup consisted of a 5 MHz, 0.3-mm-pitch, 128-channel linear array (Acuson L-5, Mountain View, California), a programmable digital array system (DiPhAS, Fraunhofer Institutes, St. Ingbert, Germany) that was used to acquire radio frequency channel data, a custom made tissue-mimicking phantom (Professor Ernest Madsen, Department of Medical Physics, University of Wisconsin-Madison), and a personal computer for central control. The digital

array system was used to collect channel data for simultaneous B-mode image formation and the limited-angle tomographic sound velocity reconstruction. The phantom was made of materials mimicking different tissues in the breast. The sound velocities in these tissue mimicking regions are 1522 (glandular tissue), 1464 (fat), 1570 (cyst), 1547 (highly attenuating tumor), and 1553 m/s (irregular tumor), respectively. The distance between the array and the metal plate was 37 mm. A total of 9 different cases were scanned for objects with different sizes, shapes, image positions and sound velocities. The background was glandular tissue. The estimation errors were below 1 m/s in the background in all cases. The estimation errors in the fat regions (radius from 2 mm to 6 mm) ranged from 4.3 m/s to 4.8 m/s. The estimation errors for the tumor, on the other hand, were 10.5 m/s (highly attenuating tumor, 4mm, center) and 11.5 m/s (irregular tumor, irregular shape, center), respectively. Thus, results show that obtaining the sound velocity distribution is feasible with the proposed reconstruction algorithm under current B-mode imaging setup with linear arrays. Details of the reconstruction algorithm and the experimental results will be presented. Issues regarding the application of the reconstructed sound velocity distribution to phase aberration correction will also be discussed.

P2U-M-6 I6

A NEW APPROACH TOWARDS ULTRASONIC TRANSMISSION TOMOGRAPHY WITH A STANDARD ULTRASOUND SYSTEM

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Capability of ultrasound transmission tomography to reconstruct acoustic parameters of proven histological relevance like acoustic speed and attenuation has been established over the past few decades by several researchers. The approach taken so far was a fully custom designed transmission tomography system which is a considerably multifaceted venture rendering it to be adequate enough to demonstrate its feasibility but failed to find its way into the clinical environment due to inadequate spatial resolution and reconstruction accuracy. In a novel approach a commercially available ultrasound system is supplemented with an add-on module thus taking full advantage of the former and enabling it to collect transmission mode data. A Siemens Omnia system equipped with a custom designed interface that allows real-time acquisition of trigger information as well as the RF data over an external PC via a 14 bits, 50 MHz, A/D converter board (Gage CS1450) was used. Two identical transducers of type 7.5L70 with a center frequency of 7.5 MHz are used. One of the transducers is connected to the ultrasound system driven in B-mode, whilst short pulses of the same center frequency are sent from the other using an external wave generator synchronized with the shot trigger of the ultrasound system over a custom designed trigger interface. The acquired B-mode RF data thus contains the transmitted data as well. The delay between the shot trigger of the two transducers is selected in

such a way that the transmitted pulse appears in the B-mode image in an echo poor region. The two transducers are fixed to a ring looking into each other in such a way that the object to be imaged hangs in a water bath between the two transducers which are driven about the object along a helical trajectory with precise servo drives. Data was acquired with an angular resolution of 1 degree and a pitch of 2 mm. A reference measurement through water makes it possible to reconstruct both the acoustic parameters tomographically. Since the data acquisition leans on the concept of helical CT, it is possible to reconstruct both the acoustic speed and attenuation through the object in any plane parallel to the B-mode imaging planes thus enabling a three dimensional registration. Agar and cryo gel Phantoms with known acoustic speed and attenuation distributions were used to quantify the reconstruction accuracy and the spatial resolution of the system. The system could be demonstrated to be capable of reconstructing acoustic speed contrasts as good as 1 m/s with a spatial resolution of less than 2.5 mm and the attenuation contrast of 0.1 dB/mm with a spatial resolution of less than 3 mm. The achieved accuracy is much better than hitherto reported in literature. Results of in vitro imaging will also be presented. The use of a standard ultrasound system makes the acquisition of transmission as well as echo data of the whole object possible, the later allows a further processing for 3D rendering of the B-mode image, compounding and TC. In vivo experiments on female breast will be presented in future.
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P2U-M-7 I7

COMPARISON OF WAVEFRONT DISTORTION IN THE BREAST BETWEEN OPTOACOUSTIC IMAGING AND ULTRASONIC IMAGING

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The detection of breast cancer using optoacoustic (OA) imaging has emerged as an attractive modality recently as it combines the merits of the optical contrast with the spatial resolution of ultrasound. In conventional ultrasound, it has been widely recognized that wavefront distortion caused by acoustic inhomogeneities is a major cause prohibiting breast ultrasound from obtaining the diffraction-limited resolution. It is the primary purpose of this study to investigate wavefront distortion in OA imaging and to compare with that in conventional ultrasound. In addition, an adaptive OA imaging method is proposed to compensate for the degradation caused by breast tissue inhomogeneities. Both OA and ultrasound wave propagation were simulated using a finite difference time-domain method. The underlying tissue map was based on a measured two-dimensional breast model that included acoustic scatterers with a distribution of optical absorption coefficient. A disk-like tumor with a radius of 1mm was placed in the center of the simulated breast. The optical absorption coefficient of the tumor was set

to be 3 times that of the background tissue. Uniform optical irradiation was assumed. Point ultrasound receivers were placed on a circle around the breast at an interval of 0.25 degree (i.e., a total of 1440 receivers) to detect the OA signals. The radii of the breast model and the circle of OA detection were 5 cm and 6 cm, respectively. The pulse-echo ultrasound data was also simulated assuming a 5.4 cm linear array placed 1 cm from the breast wall with a focus at the tumor center. A time domain reconstruction algorithm was adopted to form the OA image. The proposed OA image correction method adaptively adjusted the sound speed at each image pixel in order to maximize an absorption-based image quality factor. Similar to the in vivo ultrasonic measurements reported in the literature, the spatial coherence of the ultrasound data agrees with the van Cittert-Zernicke theorem and it decreases as the acoustic inhomogeneities increase. For the OA signals, on the other hand, relatively small time fluctuations (root-mean-square value = 60 ns) and waveform distortion (waveform similarity factor = 0.965) were observed. In other words, the OA signals exhibit higher spatial coherence under the same conditions. Results also showed that the proposed correction algorithm can greatly enhance the OA image quality. The root-mean-square error between an undistorted OA image and the corresponding distorted image was reduced by 82% after applying the correction algorithm. Possible reasons of the high spatial coherence of OA wavefronts and efficacy of the proposed correction algorithm are discussed. It is concluded that breast OA imaging is less affected by the wavefront distortion and can be more effectively corrected as compared to conventional breast ultrasonography.

P2U-M-8 I8

SIMULATIONS OF OPTOACOUSTIC WAVE PROPAGATION IN LIGHT-ABSORBING MEDIA USING THE FINITE DIFFERENCE TIME-DOMAIN METHOD

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Optoacoustic (OA) imaging is an emerging technology that combines the high contrast of tissue optical properties and the high spatial resolution of ultrasound. In order to take full advantage of the imaging scheme, a better understanding of the OA wave propagation in light-absorbing media is necessary. Current simulation methods are mainly based on simplified conditions such as thermal confinement, negligible viscosity and homogeneous acoustic properties throughout the image object. In this study we propose a new numerical approach based on the finite difference time-domain (FDTD) method to solve the general OA equations, including the continuity equation, the Navier-Stokes equation, and the heat conduction equation. We adopted a MacCormack-type splitting scheme that is forth-order accurate in space and second-order accurate in time for modeling OA wave propagation in a light-absorbing medium with heterogeneous acoustic properties. The FDTD code was validated using a benchmark

problem that has an approximate analytical solution. OA experiments were also conducted. Nd:YAG laser pulses at 532nm were employed to induce OA signals in a light-absorbing phantom made of gelatin mixed with commercially available black pigments. A broadband hydrophone (-3dB cut-off frequencies at 0.2 and 40 MHz) with high sensitivity (28 nV/Pa) was used to record the OA signals in a backward mode in which laser irradiation and ultrasound detection take place on the same side of the image object. Experimental data were in good agreements with those predicted by the FDTD method. Numerical results also show qualitative agreement with reported data of OA signals in the forward mode and the sideward mode. Characteristics of simulated OA waveforms and OA images will be discussed, with emphasis laid upon the effects caused by acoustic heterogeneities in practical imaging conditions. The proposed FDTD code can be used to aid in OA imaging system design, visualization of OA wave propagation in biological tissues, and development of advanced image reconstruction algorithms.

Session: P2FC-N

FREQUENCY STANDARDS

Chair: R. Wang

JPL

P2FC-N-1 R1

A HIGH-RESOLUTION FREQUENCY STANDARD COMPARATOR BASED ON A SPECIAL PHASE COMPARISON APPROACH

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Along with the accuracy enhancement of atomic frequency standards, the higher frequency standard comparison resolution is necessary. Based on the concept of the greatest common factor frequency and a common frequency source, utilizing phase coincidence detection approach the high-resolution phase comparison between frequency standards can be completed. The resolution of a simple instrument is better than 10 ps, and the resolution of theoretical analysis is much higher than it. In the long-term frequency standard comparison higher than 1×10^{-14}/hour accuracy can be obtained and for one day comparison the measuring precision can be 10^{-16}. This method can also be used in the measurement of short-term frequency stability or as a terminal display device of frequency standard comparator, and $10^{-13}/\tau$ stability resolution can be obtained. In the practical device the phase coincidences between a high-stability common crystal oscillator signal f_c and two compared frequency standard signals f_1 and f_2 are detected respectively, with the phase coincidence between f_c and f_1 as a start signal and with the phase coincidence between f_c and f_2 as a stop signal to build a gate time. This gate is synchronized by the multiple periods of the f_c, and

± 1 count error can be eliminated when using f_c as the counting signal. The frequency of f_c or its frequency division has a small frequency difference with f_1 and f_2, for example 100 Hz or 1kHz. With this way, sampling the phase difference and measuring it highly accurately are combined together, higher resolution and low cost are easily obtained. In ordinary phase comparison of two frequency signals with the same nominal frequency, every period the phase is compared. However, based on the new approach and common oscillator to compare the phase the phase comparison period is equal to the least common multiple period between f_c and f_1 or f_2. From the theoretical analysis the resolution of the phase comparison is equal to the quantized phase variation resolution ΔT between f_c and f_1 or f_2. When the common oscillator is locked by f_1 or f_2 , the calculation equation of the phase difference is $\Phi = N_c \Delta T$. N_c is the counted cycle of f_c in the gate time.

P2FC-N-2 R2

FREQUENCY STANDARDS AND TIME METROLOGY IN ROMANIA

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The present paper describes the practical realization and characteristics of new atomic frequency standards realized in Romania by the National Institute for Laser, Plasma and Radiation. Our work in the field of atomic frequency standards started in 1974 with an intensive program of development of hydrogen masers. Between 1974 and 1987, nine hydrogen masers were built for the National Institute of Metrology, University of Bucharest, Astronomical Institute of the Romanian Academy, and one for our own purposes. Following that program, a new initiative was started in the early 90's, in the field of atom laser cooling with the goal of implementing a primary frequency and time standard. In the field of hydrogen masers our research work was concentrated on: the characterization of the atomic hydrogen source (400 MHz excitation) and optimization of its parameters; studies of the dependence of the maser output power as a function of the various maser parameters (hydrogen beam intensity, discharge intensity, power of the discharge, etc.); theoretical computation of the relaxation times and their experimental determination [1], [2]. The program of present interest concerns the study and the realization of an atomic fountain using cold Cs atoms. The main goal of the program is to provide the country with a primary standard of time for the implementation of the SI second and to contribute to TAI at the same level as the metrological international community. At present, time and frequency metrology in the country relies on a commercial unit HP5071A. The main emphasis of our work on the fountain until now has been on the following subjects : characterization of the intensity noise and line broadening of the lasers diodes used in the system; stabilization of the laser

diodes used in the cooling of the Cs atoms; design and manufacturing of an extended cavity for the laser diodes; design and realization of a magneto-optical trap for the cesium atoms; theoretical studies concerning the dependence of the cold cesium atoms cloud size on the trapping parameters; theoretical studies concerning the dependence of the number of atoms on the trapping parameters. We have completed the construction of the cesium magneto-optical trap and we will report on its characteristics. [1]. O. Gheorgiu, C.Mandache, C.R.Acad. .Sci. Paris, t.295, p.131-134 (1982) [2]. C. Mandache, Rev. Roum. Phys. 30, 4, p.303-306 (1985)

P2FC-N-3 R3

FREQUENCY-LOCKED LOOP BETWEEN A H-MASER AND A CS CLOCK

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The time and frequency reference in Besançon is based on Cesium clocks for absolute accuracy and long-term stability, on a H-maser for medium and long term stability, and on a liquid-He whispering gallery sapphire oscillator for best spectral purity an short-term stability. These standards are located in three different buildings. In order to obtain the full accuracy and stability at least at one site, we combine these references using a frequency locked loop.

The traditional method consists of locking a VCO to a reference. The short-term stability of the VCO and the long term performance of the reference are therefore combined in the output signal, provided the cut-of frequency of the control be properly chosen. Yet, in our case we have to lock the VCO to two references, the H-maser in the medium term and the SC clock in the long term.

The control system consists of two mixers that compare the references to a quartz oscillator (VCO), and of a recursive digital filter. The H-maser and the Cs clock are not controlled. At the present state, the liquid-He whispering gallery oscillator can not be included in the loop because any attempt to control it would impair the spectral purity. Therefore the measurement based on this reference can only be corrected a-posteriori by comparison to the locked VCO.

This paper analyzes the method for choosing a suitable control algorithm, and presents the results based on simulated data.

P2FC-N-4 R4

RECENT EXPERIMENTAL ASPECTS OF RUSSIAN CAESIUM FOUNTAIN

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The feasibility of a laser cooled Cs fountain clock has been demonstrated more 10 years ago. Presently, by using laser-cooled atoms at μK temperatures, it may possible to improve the accuracy and stability of Cs fountain up to the level of 10^{-16} [1]. We started our Cs fountain project in 1999, minding to get an uncertainty up to one order magnitude, compared with classical Cs-beam primary frequency standard. At the present time a prototype of the fountain has been designed and manufactured. Although our fountain is not intended to operate as a primary frequency standard in its present form, this system has been operated now to provide optimal regime and evaluate setup that will contribute to the design of the primary frequency standard of Russian Federation. The design of the physical parts, both laser and optical systems are described in details elsewhere [2,3]. The present paper is a summary of the latest experimental results obtained at IMVP VNIIFTRI. They are in following: 1. We have proposed the novel optical scheme for the distribution of cooling and repumping laser beams in the horizontal and vertical plane. 2. We have made detailed temperature measurements, exploring a wide range of laser intensity and detuning. The lowest measured temperature about of 1.2 μK for molasses is reached 3. Ramsey fringes have been observed for the first time and some causes of frequency shifts are investigated.

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P2FC-N-5 R5

NIM4# CESIUM ATOMIC FOUNTAIN PRIMARY FREQUENCY STANDARD: PERFORMANCE AND EVALUATION

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The NIM4# laser cooling - Cs atomic fountain clock has been operating stably and sub-continually since August 2003 and a first run evaluation for its systematic frequency shifts was performed during 9-12, 2003. Following the configuration of BNM LPTF (France) fountain clock FO1[1], NIM4# captured about 2E8 atoms in 0.6s in a X-Y-Z MOT, then the magnetic field was turned off, the atoms further cooled to below (3-5)μK and launched up to 56cm (16cm above the Ramsey cavity) in the OM. The atoms interacted twice with the 9.19GHz microwave in their upward and downward movements and were then detected generating a Ramsey pattern with FWHM width of about 1.4Hz. A

PC servo-locked the 9.19GHz microwave frequency, from a synthesizer synchronized by a H-maser H1, to the central frequency of the Ramsey central fringe by the squarewave modulation - digital servo to produce the frequency comparison between NIM4# and H1. Experiments showed that the frequency stability of NIM4# was (4-6)E-15 (τ>15000s) and reproducibility about 5E-15. Table 1 showed the results of the first run evaluation. Confined by the design of NIM4# for the first time and as early as in 1997, also limited by devices and technology available at that time in this country the combined evaluation uncertainty was about 8.5E-15. The C-field was mapped using the low frequency transition technique[2] and turned out to be with distributed difference of about 23nT in the 16cm region above the Ramsey cavity mainly attributable to the bigger bottom end hole of the magnetic shields so a Majorana frequency shift was induced. In order to restrain the Majorana effect a bigger 512.6nT C-field was used and the residual Majorana shift was quantified by experiments with uncertainty of 6.3E-15. Another term with bigger error was the collision frequency shift. The atomic MOT cloud of NIM4# was an oblate ball with height of 5mm and horizontal diameter of 7mm. Bigger volume of the cloud reduced the density of atoms and the collision shift. But the evaluating uncertainty of collision shift was limited on NIM4# by the experimental frequency repeatability and this was in turn, to a relatively larger extent, attributed to the performance of H1 during the experiments. We have started to build our second fountain clock NIM5#. NIM5# is been designed based on the experiences and lessons of NIM4# and consulting the new developments of the atomic fountains worldwide, and will be moved to the NIM second base which is under construction to be as the next new primary time and frequency standard of this country.
[References] [1] A.Clairon, P.Laurent, G.Santarelli et al, A Cesium fountain frequency standard: preliminary results, IEEE Trans. IM44N2p128-131 (1995). [2] G.Costanzo, D.Meekhof, S.Jefferts et al, An old method for magnetic field mapping applied in a new way in a Cs fountain frequency standard, Prog. 14th EFTF2000 p494-497, Torino (2000).

Frequency shift evaluation of NIM4# during 9-12,2003

	Physical Effect Physical Effect	Bias Value (E-15)	Uncertainty (E-15)	
1	Second order Zeeman:	1222	1.4	Hc=512.6nT
	H(L)135H(l):	20	0.2	
2	Cold atom collision:	-3.1	5.5	
3	Microwave power:	0.0	0.2	
4	Blackbody:	-16	0.5	Cavity temperature: 23°C
5	Gravitation:	3.8	0.1	Height above sea level: 35m
6	Majorana effect:	94.0	6.3	
7	Light shift:	0.0	0.1	
8	Cavity pulling:	0.0	0.1	Detuning 0.7MHz, Qc=5400
9	Cavity phase difference:	0.0	0.1	Phase difference: 4μradian
	Combined:	1320.7	8.5	

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Session: P2U-O

TRANSDUCER AND TRANSDUCER MATERIALS

Chair: B. Sinha

Schlumberger-Doll Research

P2U-O-1 I9

TEMPERATURE-COMPENSATION FACTOR FOR MEASUREMENT OF CONCENTRATION IN SOLUTION USING ULTRASONIC LIGHT DIFFRACTION EFFECT

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This paper describes the workings of a temperature-compensation factor for measuring concentration in solutions using an acousto-optic effect over a range of ultrasonic frequencies (fa) (9-30 MHz) on which Raman-Nath diffraction occurs. We analyzed the temperature-compensation factor VcF on which the temperature-compensation circuit is designed, in order to eliminate the strong temperature dependence of sound velocity in liquids. By using a Taylor series expansion of the equation for sound velocity, which is a function of concentration and temperature centered on a reference concentration and reference temperature, we obtained a new empirical equation for the sound velocity of NaCl solution that covered a concentration range of 0.0 to 20.0% and a temperature range of 15 to 45 degrees Centigrade. Performing a least-squares fit to experimental values measured using the phase-locked loop method yields the coefficients for the polynomials of the Taylor series expansion. The value of VcF, calculated by the empirical equation of the sound velocity for NaCl solution within the concentration range of 0.0 - 1.0%, is 9.49 mV/degrees Centigrade for the temperature range of 25 degrees Centigrade plus minus 2degrees Centigrade. Its value is reasonably consistent with the experimental value 9.65mV. A proportional coefficient for NaCl solutions for VcF over the temperature range of 20 to 30degrees Centigrade and ultrasonic frequency range of 9 to 30 MHz is 0.318 mV/degrees Centigrade MHz . Its value over the temperature range of 30 to 40degrees Centigrade is 0.230 mV/degrees Centigrade MHz. Furthermore we describe measured values of sound velocity using an acousto-optic effect. We obtained the ultrasonic velocity of sN=10.0, 20.0% which is the concentration of NaCl solutions v=1615.1, 1714.5 m/s at fa=29.398 MHz. For the concentration of sucrose solutions sSA=10.0, 20.0% v=1538.6, 1572.8 m/s are obtained at fa=22.298 MHz.

P2U-O-2 I10

NON-DESTRUCTIVE EVALUATION OF THIN ZNO SHEAR WAVE TRANSDUCER BY BRILLOUIN SCATTERING

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Elastic properties of thin ZnO shear wave transducers have been investigated. These transducer films were fabricated by magnetron sputtering. They are almost composed of unidirectionally ZnO crystallites, which were confirmed by X ray diffraction measurements. The elastic properties of the film seem difficult to obtain by conventional mechanical measurements. We have then applied a Brillouin scattering technique to the film. This technique enables the measurement of the hypersonic wave velocity in the GHz range. In addition, by using an adequate optical geometry, we can select adequate phonon wave vector for the measurement. The ZnO film, however, are very thin and not perfectly transparent. We have then tried the precise measurement of velocity by data analysis. The estimated error of velocity measurements was 0.5%, which was sufficiently small to evaluate the film. For the Brillouin measurements, we have adopted the θA optical geometry technique. In this technique, we can obtain the θA scattering, which selects the phonons propagating in the ZnO film plane. The velocity of these phonons are calculated by the equation,

$v_{\theta A}=f_{\theta A}\lambda_0 /(2\sin(\theta/2))$,

where θ is the angle between the incident and scattered lights. In this study, θ was set to 90 degrees. $f_{\theta A}$ is the measured frequency by Brillouin scattering and λ_0 is the vacuum wavelength of argon ion laser used (514.5 nm). First, in order to investigate the elastic anisotropy of the film, we have measured the dependence of wave velocity on the angle from the direction of aligned crystallites. The full width at the half maximum intensity of focused laser beam was approximately 50μm. The obtained results suggested clear anisotropy of wave velocities, showing maximum value in the aligning direction of crystallites. The tendency of velocities is similar to that of the theoretically estimated longitudinal wave velocities in the single crystal ZnO films. The velocity values, however, were a little lower, which reflected the small polycrystalline structure of the film. Next, the velocity distribution of the film was investigated using a microscopic Brillouin technique. The full width at the half maximum intensity of focused laser beam was approximately 5μm. In the aligning direction of crystallites, velocities of θA scattering showed clear dispersion due to the measuring point. The difference between the maximum and minimum values of wave velocities reached 300 m/s. Considering the microscopic structure and thickness distribution of the films, the anisotropy of the film seems to change gradually. From θA scattering measurements, we could also observe very small Brillouin peak, showing velocity values of around 2800 m/s. This does not conflict with the shear wave behavior. With the polarization analysis of the scattered light, the polarization of this small peak was different from longitudinal mode, indicating the possibility of simultaneous measurements of shear and longitudinal waves.

P2U-O-3 I11

CYLINDER-SPHERE 3-DOF ULTRASONIC MOTOR AND ITS CONTROL

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A three degree-of-freedom (DOF) ultrasonic motor (USM) with cylinder-shaped stator and a spherical rotor was developed using one first order longitudinal and two second order bending nature vibration modes of the cylinder. Control strategies for two DOF trajectory following are studied and applied to the prototype USM. The control strategies of this type USM include phase-difference control, frequency control, and vibration amplitude control. This paper concentrated on vibration amplitude control. Our first strategy is the step-motor-wise interpolation with two bending vibration exciting voltage regulators as speed servo loops and the longitudinal exciting voltage was a constant. Basically, this is an on-off vibration control with variable vibration amplitude. The second strategy is vector control, where the stator bending vibration vector is regulated to following the tangent vector of the trajectory at each micro segment with the two bending vibration exciting voltages as control parameters and the longitudinal exciting voltage was a constant. This paper presents three pulse width modulation (PWM) methods for the control of the voltages. These three methods were compared and experimentally verified through several typical trajectories following experiment. The key is to keep the phase differences of the three vibrations constant and small exciting voltage distortion while changes the exciting voltages for simplify the control process and obtain good control characteristics. The vector control method takes several advantages, such as small trajectory following error, smooth moving and hence low noise.
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P2U-O-4 I12

2-D NUMERICAL SIMULATION OF ACOUSTIC WAVE PHASE CONJUGATION IN ACTIVE MEDIUM

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The effect of parametric wave phase conjugation (WPC) in application to ultrasound acoustic waves in magnetostrictive solids has been addressed numerically in [1] using 1-D unsteady formulation. Here we apply the numerical method

presented in [2] to the analysis of probable 2-D effects by practical implementation of WPC. The model describes universally elastic solids and liquids. A source term is included in the model similar to [2] to describe coupling between deformation of magnetostrictive material and external periodic magnetic field. Supplementary to the 1-D simulations, the present model involves longitudinal/transversal mode conversion at the sample boundaries and separate magnetic field coupling with dilatation and shear stress. The influence of those factors in a 2-D geometry on the potential output of a magneto-elastic wave phase conjugator is analyzed in this paper. The process under study includes propagation of a wave burst of a given frequency from a point source in a liquid into the active solid, amplification of the waves due to parametric resonance and formation of time-reversed waves, their radiation into liquid and focusing.

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Session: P2U-P

THIN FILMS AND DEVICES
Chair: D. Malocha
University of Central Florida

P2U-P-1 J1

OBSERVATION OF THE WAVE PROPAGATING INTO SUBSTRATE

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In accordance with the size-shrinkage of the SAW device, the radiating wave from an active resonator might affect to the neighboring resonators by re-coupling and cause the deterioration of the device performances. We have already developed visualizing technique for the SH type SAW distribution, and found the existence of the leakage wave1),2). However, not only the surface wave but also the wave propagating into substrate should be observed to examine the influence of the leakage wave to the neighboring resonators. For that purpose, the previous observing technique has been improved to be able to observe the wave distributions propagating into substrate. The improved technique utilizes the simple principle that the interaction between the laser light and the acoustic wave is detected only when the spot size of the laser is smaller than half of the wavelength. Therefore, once the laser focus point is moved into the substrate, the sectional wave distribution at that depth is observable. The wave distributions in the substrate were observed at various depths and frequencies by employing this technique. At resonant frequency (502MHz), the wave distribution was hardly

observed at about 30mm (4γ) deep. On the contrary, non-negligible amount of the acoustic wave was detected above the anti-resonant frequency. Also, spreading wave from IDT area was observed at various frequencies. They could reach to the neighboring resonators. This improved observation technique enables the direct observation of the acoustic wave distribution at the surface and in the substrate. Consequently, the total behavior of the acoustic wave could be understood including the interference between the neighboring resonators. Therefore, this technique will contribute to the improvement of the SAW device performances. 1) A. Miyamoto, et al., IEEE 2002 Ultrasonics Symposium P2D-6. 2) S.Wakana et al., IEEE 2002 Ultrasonics Symposium P2D-6.

P2U-P-2 J2

A MODEL FOR THE ACCURATE DETERMINATION OF THE ELECTROMECHANICAL COUPLING FACTOR OF THIN FILM SAW DEVICES ON NON-INSULATING SUBSTRATES

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Many acoustic wave devices and MEMS use piezoelectric thin films (AlN, ZnO) as actuating elements. The fabrication of these devices on conventional silicon wafers is becoming ever more common, since it offers the possibility of integrating them into mature silicon technologies. In that case, the assessment of the morphological properties of the films (composition, crystal quality) is straightforward. However, in order to determine their piezoelectric properties (electromechanical coupling factor k^2, propagation velocity v_s), it is necessary to measure specific devices (SAW filters) whose electrical response can be dramatically affected by several parasitic effects. These include the conductive character of the silicon substrate, which is the source of electromagnetic feedthrough (EMF) between the interdigital transducers (IDTs), the capacitive coupling between the IDTs and the substrate, the series resistance of the electrodes, etc. Conventional methods to derive k^2 based on the measurement of the real or imaginary part of the input or transfer admittance are directly affected by these parasitic effects, which are inextricably embedded in the device. Another method is based on the measurement of the shift of the resonance frequency when a metallic layer is deposited between the two IDTs. In this case, parasitic effects may change the resonance frequency and reduce the accuracy of the method. In this communication we propose a circuital model that takes into account the parasitic elements present in a thin film SAW fabricated on a non-insulating substrate; it allows to obtain accurate values of the magnitudes of interest (k^2 and v_s). The model includes the effects of the substrate, airborne coupling and mounting. The values of the different parasitic elements are deduced by fitting the out-of-band response of experimental SAW measurements over a wide range of frequencies. Once the stray discrete elements are obtained, the values of k^2 and v_s are derived by refitting the SAW response around the resonance frequency. This procedure has been applied to SAW delay lines made on AlN thin films of different qualities on several substrates ((100) and (111) silicon with various resistivities between 0.1 Ω·cm and 2000 Ω·cm and metal-covered silicon). The c-axis oriented AlN films were deposited by RF reactive sputtering of an Al target in Ar and N_2 admixtures. The electric response S_{ij} of SAW filters with acoustic wavelengths of 40 μm and 20 μm was measured with a network analyzer and fitted as described previously. The values of the different parasitic elements depend on the SAW geometry and on the substrate resistivity. The values deduced for k^2 ranged from 1% to 2.2% depending on the crystal quality of the AlN film. If parasitic effects are not considered, the values of k^2 are underestimated by up to 20 times.

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P2U-P-3 J3

VELOCITY DISPERSION OF NANO-, POLY-, AND AMORPHOUS-SILICON THIN FILMS

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Thin films of amorphous, polycrystalline and nanostructured silicon are of great importance in micro- and nano-technology applications. Therefore, they received a great deal of interest in the investigation of their electronic, magnetic, and optical properties but only very little work is reported on their elastic properties. In this context, we first deduce their SAW velocities longitudinal, VL, transverse, VT and Rayleigh, VR. It is found that these velocities change according to grain dimensions, atomic structure and defect densities characterizing each Si type; with the highest values corresponding to crystalline Si followed by those of poly-Si, then a-Si, and finally the smallest values were obtained for nano-Si. Moreover, in order to establish dispersion curves, we calculate the acoustic material signatures, via Sheppard and Wilson formula that describes the output response as a function of the defocusing distance in acoustic microscopy configuration. Such signatures are determined for different film thickness of all the above Si types deposited on crystalline Si substrates. Their spectral analysis led to the determination of the propagating wave velocities which were plotted in terms of normalized thickness. It is found that the general trend of the curves is dispersive: with increasing normalized thickness, the surface wave velocity decreases from the value of the substrate velocity to that of the deposited film. However, for very thin films of poly Si, we noticed an anomalous behavior consisting of a small initial increase followed by the usual velocity decreases.

P2U-P-4 J4

TEMPERATURE EFFECT ON THE CHARACTERISTICS OF SURFACE ACOUSTIC WAVE ON SiO_2 THIN FILMS

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In selecting a suitable substrate for surface acoustic wave (SAW) devices, the temperature coefficient of frequency (TCF) is one of the important factors to be considered. It reveals that the SAW device on the Lithium niobate exhibits large negative TCF. To improve the temperature stability, thin film SiO_2 is introduced as compensation layer for its positive TCF property. The reactive rf sputtering method is adopted for the growth of SiO_2 thin films. By the control of deposition time, different thickness of SiO_2 thin film could be obtained. SOPRA spectroscopic ellipsometer was used to evaluate the refractive index and thickness of thin film. The measurements were carried out in the wavelength range of 270 to 870 nm with 5nm step and angle of incidence. Analysis and calculation of indices used advanced material mixing laws (Bruggeman, Alloy) based on numerous physical models. The refractive index of tested thin film was accorded with the N&K database of standard SiO_2. The TCF of SAW devices on Lithium niobate ($LiNbO_3$) substrate were obtained. The measurement was performed by the Hewlett-Packard (HP) 8720ET network analyzer for the temperature range from 0 to 80 $^\circ$ C. The results of $SiO_2/LiNbO_3$ based structure showed that the magnitude of TCF was significantly decreased due to the positive TCF of SiO_2 thin film deposited on $LiNbO_3$ substrate. The TCF of SAW on $SiO_2/LiNbO_3$ device was measured to be about -51 ppm/$^\circ$ C at $h/\lambda=0.12$, where h was the thickness of SiO_2 film and λ was the wavelength of SAW. It revealed that the SiO_2 thin film deposited on $LiNbO_3$ substrate could improve the temperature stability, as compared with that of SAW on $LiNbO_3$ of about -73 ppm/$^\circ$ C. In addition, the phase velocity (V_p) of SAW on $SiO_2/LiNbO_3$ substrate was not changed by the increase of SiO_2 thickness (h/λ).
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P2U-P-5 J5

APPROACH TO ON-WAFER CONTROLLABLE TRIMMING OF SAW FILTERS

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We have developed the concept and the processing details of SAW filters trimming by thin film deposition having in mind the applicability of such process

to controllable on-wafer trimming. Our goal was to find proper means for individual trimming of wafer regions by programmable mask movement based on frequency deviation map for each patterned wafer obtained from prior measurements. An elegant suggestion of using thin layers of gold for SAW resonators trimming has been presented in [1]. Even a very thin non-conducting gold layer decreases the SAW velocity sufficiently for trimming a resonator on quartz. Fast and repeatable deposition is the key element for individual processing of multiple wafer regions.

We discussed the following options: deposition of platinum (or other metals) instead of gold and deposition of selected dielectrics instead of metals. These possibilities are experimentally compared with resonators and filters on lithium tantalate. We have obtained trimming ranges of about 0.1% with negligible loss increase and little distortion in response and we discuss the requirements for filter design to ensure increased trimming range.

We compare experimental results obtained with different dielectrics, notably with alumina and ytterbium oxide. We show that the latter is a promising candidate for trimming due to high density and low stiffness while the former does not prove to be too useful. Technological details and material properties relevant to possible ageing or power handling characteristics are also discussed.

1. S.M. Wang et ales, Proc.IEEE Ultrason. Symp. 2003, p.1730

This works was supported by Clarisay Inc., the free software by K. Hashimoto was used for velocity estimates.

P2U-P-6 J6

BONDING METHOD OF SEMICONDUCTOR DEVICES ON PIEZOELECTRIC SUBSTRATE USING LASER ENHANCED FLIP-CHIP TECHNOLOGY

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Surface acoustic wave - semiconductor coupled devices, in which highly functional semiconductor devices are integrated on piezoelectriic substrates with high coupling coefficients, are very attractive for signal processing devices used in mobile communication and optical fiber communication system. We have proposed film bonding technology and fabricated a convolver and SAW amplifer[1]. In order to improve reliability of these devices, in this paper, we report new flip-chip bonding technology with leaser enhanced, in which, semiconductor film devices cab be bonded on the on piezoelectric substrate with small size solder bump. We used LiNbO3, quartz, LiTaO3 as piezoelectric substrates, and GaAs, Si as semiconductor film devices. The low melting solder is used as bond electrode material. In experiment, we formed solder electrode on semiconductor film devices and piezoelectric substrate, we used laser to locally heat solder electrode and bonded semiconductor film devices on piezoelectric substrates. We investigated bonded processes conditions such as laser power, heating time, thickness of solder electrode etc. The experimental results indicated that possibility of

the new bonding technology. We also investigated the temperature characteristics of this bonding technology. Based on the results, we fabricate functional device that semiconductor diode array and SAW delay line are integrated on the LiNbO3 substrate and show the basic characteristics of the devices. [1] K. Hohkawa, T. Suda, Y. Aoki, C. Hong, C. Kaneshiro and K. Koh, "Design on Semiconductor Coupled SAW Convolver", IEEE Trans. U.F.F.C., Vol. 49 No.4 pp.466-474 (2002)

P2U-P-7 J7

FABRICATION OF SAW DEVICES BASED ON SEM-BASED EB LITHOGRAPHY FOR LAB USE

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This paper introduces micro-fabrication process developed for the daily research work on SAW devices in the authors' laboratory. Combination of SEM-based electron-beam (EB) lithography and lift-off process is shown to be suitable for producing well-defined IDT finger patterns with upto 180 nm line width at high yield without special clean facility. Since it takes only 10 minutes for writing each field (0.5x0.5 mm^2), test SAW devices can be fabricated and evaluated within a half day after completing device layout design. For large devices, the writing area can be extended effectively using a precision XY-stage driven by an ultrasonic motor. When EBs are applied to insulating materials such as piezoelectric ones, charge accumulation may occurs on a resist layer resulting in EB diffraction. In order to avoid this, a very thin organic anti-static layer (Showa Denko Espacer 300Z) is coated on the EB resist layer (Nihon Zeon ZEP-520) in our process. The layer scarcely influences achievable resolution of EB lithography. Note that the anti-static layer can simply be removed by distilled water after the EB exposure. Currently two types of EB lithography system are being operated in parallel. One is based on a low cost W-filament-type SEM (JEOL JSM-5310), and the other is based on a relatively expensive field-emission-type SEM (Hitachi S-4300E). These systems were used for the fabrication of SAW devices with various configurations including SHF resonators and SPUDT filters, and detailed discussions will be laid upon the impact of their performance.

Session: P2U-Q

SAW FILTERS
Chair: D. Malocha
University of Central Florida

P2U-Q-1 J8

GENETIC OPTIMIZATION ALGORITHMS IN THE DESIGN OF LONGITUDINALLY COUPLED SAW FILTERS

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High demands are set on the optimization methods employed in the design process of modern SAW devices. In some devices, e.g., longitudinally coupled resonator filters (CRFs) with several transducers (IDTs), the number of the simultaneously optimized parameters easily exceeds ten, and may be more than twenty if several tracks are connected together. The object function may contain several minimums. The gradient-based methods traditionally employed in the optimization tend to be time-consuming and computationally heavy. Moreover, the quality of the final solution may strongly depend on the initial guess for the parameters. There is no simple way of knowing whether the solution is near a global minimum of the object function. Stochastic optimization methods, such as the genetic algorithms studied here, are based on randomly selecting initial parameter sequences over the whole parameter space [1]. Only the value of the object function is evaluated in each iteration. Since no gradients or Hessians are calculated, these methods can be computationally less demanding. Stochastic methods can be used to search for the global minimum of the object function. They are also well-suited for IDT structures in which the electrode polarities are not known in advance, such as SPUDT filters. In hybrid methods, several optimization methods are used in one problem; for example, the solution found with the genetic algorithm is passed on to gradient optimization. Genetic algorithms have previously been applied to optimization of SPUDT filters [2]. Randomly generated parameter sets, or individuals, are selected for recombination, based on their object function value, or fitness. A typical method for recombination is to cut the bit strings of both parents at a randomly selected position and exchange the left parts between the parents [1]. A modified version of this cut-and-paste method is employed in [2]. We have applied a genetic algorithm in the design of multi-transducer CRFs. In recombination, the parameter values of the parents are used as the upper and lower limits for the offsprings corresponding parameter values. We present a detailed analysis of the method and its applicability to the CRF optimization problem, and compare the results with those given by the cut-and-paste method. Several combinations of the optimization settings, such as the size of a generation, are studied. The first results indicate that the method is suited for the design of CRFs. The fitness of the best individual reaches its limiting value after 5-10 generations. For a population of 2000 individuals with 20% recombination for each new generation this means 4000-6000 function evaluations. For such a set of parameters, the final solution found using the genetic algorithm is extremely close to the converged optimum in the subsequent gradient optimization.

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P2U-Q-2 J9

DESIGN OF HIGH SELECTIVITY LOW-LOSS LADDER FILTERS

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Ladder resonator (LDR) filters provide the lowest insertion loss compared to other types of LSAW filters, for example, longitudinally coupled resonators filters. The drawback of LDR filters is non-sufficient attenuation in the stop band (typically about 40-45 dB). Besides, sometimes it is difficult to match conventional ladder filters with balanced or differential loads. In the present paper we describe modified symmetric π-type and T-type ladder sections, which allow to use ladder filters in different regimes of operating modes: single/single, single/balanced, balanced/balanced. The frequency responses of modified symmetric ladder sections and different ladder filter structures were analyzed in wide frequency range. In particular, it was found that attenuation in the stop band grows with frequency for symmetric π-type sections, and reduces with frequency for symmetric T-type sections. Thus, combining of symmetric sections and half-sections of different types in one filter structure allows to provide ultimate rejection UR=65-70 dB within wide frequency range, with typical insertion loss IL=1.8-3.0 dB. The problem of matching between different sections within one filter was investigated to optimize center frequencies of element resonators and therefore provide VSWR $<$ 1.3-1.5 in the filter. It was shown that prevailing number of π-type sections in the filter results in improved low-frequency slope of the amplitude response $|S21|$, while prevailing number of T-type sections improves high-frequency slope. This can be used in the design of Rx / Tx filters for Duplexer Modules, which have non-symmetric $|S21|$ response in the stop band. The results of simulations are confirmed by measured performance of RF filters with frequencies 600 MHz (BW3=6 MHz, IL=1.6 dB, UR>65 dB); 650 MHz (BW3=12 MHz, IL=4 dB, UR=70 dB); 1217 MHz (BW3=14 MHz, IL=2.0 dB, UR>68 dB); 1220 MHz for TV tuner (BW3=20 MHz, IL=2.0 dB, UR=60 dB); Tx 455 MHz and Rx 465 MHz filters for CDMA Duplexer module.

P2U-Q-3 J10

BALANCED WIDEBAND THREE-TRANSDUCER LOW-LOSS SAW FILTERS USING TAPERED IDTS WITH IMPEDANCE CONVERSION

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The tapered SPUDTs are widely used in the SAW filters for obtaining the fractional bandwidth over 10 % and reducing an insertion loss[1]. But sufficiently large insertion loss of 8-10 dB and narrow $\lambda/8$ or $\lambda/6$ width electrodes limit the application of these filters. In this connection the use of a three-transducer structure containing the conventional tapered input IDT and two output IDTs placed symmetrically around the input IDT is very perspective[2]. Theoretically an insertion loss of the three-transducer structure with full matching is 3 dB. Because this structure has the conventional $\lambda/4$ width electrodes it may be used readily in the frequency range up to 1 GHz. A passband ripple of the tapered three-transducer structure is controlled by an inclination of the output IDTs and may be about 1 dB[2]. In this structure a symmetrical connection of the tapered input and output IDTs to the loads is possible. Moreover this structure allows to increase the output impedance in sufficiently large limits by a series connection of the output tapered IDTs. Consequently, the tapered three-transducer SAW filter can be the balanced/unbalanced structure with an impedance conversion in the wide frequency range. This paper presents the balanced three-transducer SAW filters using tapered IDTs on YZ $LiNbO_3$ with impedance conversion as 1:5 from an input to output in a wide fractional bandwidth of 5 40 %. The filters have shown an insertion loss of about 5-6 dB, passband ripple around 1 dB, shape factor of 1.2, stopband attenuation over 40 dB in a frequency range of 30 600 MHz. Matching filters with the loads was provided by LC-elements. Withdrawal weighting is used in both tapered input IDT and output IDTs in order to improve the filter selectivity. An optimization of the filter topologies was provided with a computer simulation using a mixed matrix model. The samples were presented for 374, 450 MHz WLAN filters. The filters have shown an insertion loss of about 6 dB, 3-dB bandwidth of 20-24 MHz, stopband attenuation over 45 dB. The samples were housed in the 551.8 mm SMD packages and could operate in the balanced/unbalanced 50 250-Ω systems. [1]L.Solie. Proc. IEEE Ultrason. Symp., 1998, pp. 27-37. [2]M.Tsukamoto. J.Appl. Phys., v.50, No. 5, 1979, pp. 3146-3152.

P2U-Q-4 J11

EXTENDED P-MATRIX MODEL TO CALCULATE IMBALANCE CHARACTERISTICS OF CRF FILTERS

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Front-stage SAW filters with balanced-unbalanced output-input configuration find a large variety of applications in mobile communication systems. To satisfy passband and stopband specifications the coupled resonator filters are usually consisted of some parts of non-periodic electrode sequences with different electrode polarities. Additionally to suppress in-phase interference signals the strict limitations are imposed to the phase and amplitude imbalance characteristics. The imbalance effect is due to nonsymmetrical distribution of transduction efficiency and static capacitance in the filter structure [1,2]. In the present report the extended P-matrix model is introduced that includes additional electrical ports to take into account particular electrode polarities. The transduction efficiency and static capacitance of any particular electrode are calculated using the model of reflecting grating and electrostatic charge distribution in the total electrode structure. The electrostatic charge distribution is calculated taking into account singularities at electrode ends and using Chebyshev polynomials up to fifth order. The extended P-matrix model is consistent with widely used P-matrices based on coupling of modes theory, and the filter frequency response can be calculated as a combination of such P-matrices for periodic sections of transducers or reflectors and extended P-matrices for end electrodes and non-periodic electrode sequences. The calculated imbalance characteristics for 3 IDT test filters on 42^o-rot. YX cut of lithium tantalate with widen end electrodes as metallic spacers agree well with measured data. [1] M.Koshino, H.Kanasaki, T.Yamashita, S.Mitobe, M.Kawase, Y.Uroda, and Y.Ebata, "Simulation modelling and correction method for balance performance of RF SAW filters", in Proc. of the 2002 Ultrasonics Symposium, pp. 291-295. [2] G.Kovacs, "A generalised P-matrix for SAW filters", in Proc. of the 2003 Ultrasonics Symposium.

P2U-Q-5 J12

MODELING OF ELECTROMAGNETIC AND ACOUSTICAL PROPERTIES OF RF SAW FILTERS FROM ON-CHIP LAYOUT INCLUDING ALL ELECTRODES AND COMPARISON WITH EXPERIMENTAL DATA

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Modeling of electromagnetic properties of packages has proven to be very important in SAW filters design procedure. More recently, modeling of on chip properties became a necessity in various design teams. However, in all the reported approaches the electrodes in the transducers and reflection gratings are omitted, as the current CAD software tools are usually unable to handle problems of such enormous size. Static field evaluation has successfully been used in [1] to describe on-chip structures.

In this contribution, we describe for the first time, to the best of our knowledge, a successful approach to modeling of the full RF filter layout including all electrodes of interdigital transducers and gratings with a commercial microwave software. We use IE3D, a MOM based software by Zeland, to model the layout imported from AutoCAD (by AutoDesk) and we use COM method to describe acoustic properties of the elements. We make use of unique meshing capabilities of IE3D in order to obtain reasonable size of the problems in order to be solved with ordinary PC in reasonable time. We take special care to properly define ports for combining acoustic responses obtained from carefully fitted experimental COM parameters.

We are able to automatically predict with this procedure some very important features of electromagnetic interactions within electrodes used for acoustical excitation, such as, coupling between transducers in DMS structures. In this paper we describe an example of a two-port resonator with detailed comparison of all experimental and modeled responses.

This work opens the way to further reduction of uncertainty in RF filter design.

1. J.J.Caron and S.Malocha, Electrical Parasitic Modeling in SAW RF Filters. UFFC Symposium Proceedings, pp.348-351, 2002.

The use of evaluation version of IE3D by Zeland Inc. is gratefully acknowledged, the support of Clarisay is acknowledged.

P2U-Q-6 J13

21 CHANNEL SAW CHANNELIZER FILTER BANK

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SAW channelizer filter bank is a key component in the channelized receiver. It must have both wide bandwidth and the number of channel as many as possible in order to satisfy the demand of wide band, high frequency resolution and small size of the receiver. We have developed a 21 channels SAW channelizer filter bank. In order to decrease the insertion loss, the individual filters used for bank consisted of multistrip coupler and two apodized EWC-SPUDT. The experimental devices are fabricated on Y128° -LiNbO3, which center frequency are 251.25 445MHz with 6 dB bandwidth 7.5, 10, 15MHz respectively, the minimal IL about 9 14dB respectively, out-of-band rejection more than 40dB and shape factor less than 1.6. To reduce the insertion loss of input interconnection network, a modified and thus optimized series-parallel combination of the individual SAW filter is used. The experimental filter bank result in bandwidth of 200 MHz, insertion loss of less than 20dB and stopband rejection of more than 40 dB.

P2U-Q-7 K13

ULTRA WIDE BANDWIDTH SAW MATCHED FILTER WITH CHIRP SIGNAL CHIPS

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In this paper, we propose an ultra wide bandwidth SAW matched filter useful for sensors and short link communication systems. The device has features to perform real time analog signal processing and to be simply co-integrated with CMOS devices using a simple flip chip bonding fabrication process. This enables a rapid acquisition and synchronization in connecting link and a relatively clean communication with small cross interferences between neighboring communication channels. This would effectively increase system performances. The filter consists of phase-coded transducer having chirp characteristics in each chip. Any sequence having a steep auto-correlation and a small side lobe characteristics such as, Barker, Hadamard and M-sequence, would be useful as the phase code. We discuss performance of the device and discuss design trade off of the length of code sequence and chip time duration and bandwidth. It is clarified that the side-lobe suppression more than 50dB, by using Golay complementary sequence, as up and down chirp signal for each complementary pair. We also clarify that the cross interference signal levels, caused by another communication channel, are suppressed by using specially coded pairs in each communication channel. We present experimental results and discuss performance of the filter. We also discuss system applications of the device, such as multi-channel high speed LAN, and multi-channel motion sensor.

Session: P2U-R
HIGH FREQUENCY APPLICATIONS
Chair: Q. Zhang
The Pennsylvania State University

P2U-R-1 K1

HIGH FREQUENCY ULTRASONIC NEEDLE TRANSDUCERS FOR RETINAL DOPPLER

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High frequency ultrasonic needle transducers in the frequency range of 40 MHz through 70 MHz have been fabricated. Nine micron P(VDF-TRFE) piezoelectric material was used as the active element. The copolymer was boned to the backing material (E-Solder 3022) using Epotek 301. A lathe was used to machine the aperture size to 0.9 mm. The element was fitted inside a polyimide tube for electrical isolation from the ground plane (18 gauge stainless steel needle) and active element. The pulse echo response and impedance was measured. The center frequency was 45 MHz with 48% bandwidth. The impedance was 489 ohms (magnitude) and -86 degrees (phase). In order to improve device sensitivity an inductor in series was used. However, the bandwidth was reduced to 25%. The intended use of this device was in-vivo retinal doppler for measuring the blood flow of the microcirculation.
National Institutes of Health (NIH) Technology Resource Grant (# P41-RR11795)

P2U-R-2 K4

PVDF ARRAY CHARACTERISATION FOR HIGH FREQUENCY ULTRASONIC IMAGING

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Polyvinylidenefluoride (PVdF) has been utilised for a number of years within ultrasonic hydrophones. However, polymeric materials have rarely been incorporated into medical imaging phased arrays due to lower emitted power levels (relative to PZT transducers), and higher transducer element impedance. PVdFs advantages as a transducer material lie in its inherent wide bandwidth and the potential to create high-resolution images whilst maintaining low transducer manufacturing costs. Here we report the fabrication and test of PVdF linear arrays with 28μm PVdF film with elements on a 250μm pitch. These arrays are connected to equipment that has been developed to perform transmit beamforming to a variable focal point, and receive echoes from single transducer elements that are close-coupled to a 48-channel array of amplifiers. A-line data can then be post processed to perform dynamic receive beamforming. Utilising this equipment, measurements of pressure field distributions are presented, and compared with simulations, to determine the optimum number of pulsed elements. Using the arrays in pulse-echo mode, imaging quality is assessed with biological tissue samples and ultrasound phantoms. A prototype transducer, operated to produce ultrasound with 20MHz centre frequency, realised spatial resolution of <0.4mm laterally and 0.1mm axially, at a distance of 15mm from the transducer.

P2U-R-3 K5

$LINBO_3$ ULTRASONIC TRANSDUCERS WITH AN INVERTED-DOMAIN LAYER FOR RADIATION INTO A SOLID MEDIUM

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Ultrasonic transducers have been extensively used for medical application, acousto-optic devices, and various other applications. In many applications, broadband ultrasonic transducers are often required. Ordinary high frequency longitudinal wave transducers use a thickness-extensional mode of a uniform piezoelectric plate. Nakamura and his co-authors found that domain inversion in a lithium niobate ($LiNbO_3$) plate was induced by heat treatment at temperatures higher than 1070°C, and thereby a ferroelectric inversion layer

was formed. In such a piezoelectric plate with an inversion layer, even-order thickness-extensional modes, as well as odd-order modes, can be excited piezoelectrically. The ultrasonic transducer using such a piezoelectric plate can operate over a wide frequency range. The broadband characteristics of the transducer with an inversion layer for radiation into water have been demonstrated [1]. In this paper, it is theoretically and experimentally shown that broadband ultrasonic transducers for radiation into a solid medium can be obtained when the inversion layer faces on the acoustic load and its thickness ratio to plate thickness is around 0.3. A 50-110 MHz high frequency transducer was fabricated using a 36° rotated Y-cut $LiNbO_3$ plate with an inversion layer formed by heat treatment. The $LiNbO_3$ plate was bonded to a thick plate of fused silica by Au diffusion bonding via interfacial Au layers at a relatively low temperature (150-200°C) under application of a compressive force in vacuum. In the measured electrical admittance characteristics of this transducer, many peaks of thickness-extensional overtone modes standing over the whole thickness of the bonded structure were observed. This suggests the high bonding-quality. The conversion loss of the transducer was calculated from the admittance characteristics. The transducer had low conversion loss in the range from the fundamental resonance frequency (55 MHz) to the second harmonic frequency (110 MHz). The 3-dB specific bandwidth was about 74%. The minimum conversion loss was as low as about 2 dB. This transducer would be promising as a high frequency and broadband transducer. [1] K. Nakamura, K. Fukazawa, K. Yamada and S. Saito, IEEE Trans. Ultrason. Ferroelectr. Freq. Control, 50, pp.1558-1562 (2003)

P2U-R-4 K6

A LINEAR SYSTEMS MODEL OF THE THICKNESS MODE PIEZOELECTRIC TRANSDUCER CONTAINING DUAL PIEZOELECTRIC ZONES

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The 'inversion layer' transducer (ILT), incorporating oppositely polarised piezoelectric zones across the thickness, has attracted recent interest. Such devices offer interesting properties, particularly with regard to harmonic generation and the potential for wideband behaviour. The electrical and mechanical interactions that occur are complex and analysis has involved a combination of experiment and computer modelling, mostly using finite element methods. This paper attempts to investigate the fundamental physical mechanisms that take place, through the creation of a 1-D, linear systems model of the thickness mode ILT that incorporates two, oppositely polarised zones of piezoelectric polarisation. Closed form solutions are obtained for the operational impedance, in addition to the transmission and reception transfer functions when the device is interfaced

to an arbitrary electrical load. By representing device behaviour in a block diagram, systems feedback format, cause and effect relationships are readily identified and the underlying differences between the ILT and conventional thickness mode transducer are demonstrated clearly. Examples are provided for a range of operating configurations, materials and external load parameters.

P2U-R-5 K7

10 MHZ ULTRASOUND LINEAR ARRAY CATHETER FOR ENDOBRONCHIAL IMAGING

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This paper presents the acoustical design, manufacture and evaluation of an ultrasound catheter array for endobronchial imaging. In order to be used in an existing bronchofiberscope, the 64 elements transducer is included in a 7 Fr (2.4 mm Outer Diameter) catheter, using a ribbon-based cabling technology. The ultrasound array has a 200 μm pitch, a 1.5 mm elevation, and operates at 10 MHz center frequency. The piezoelectric material is based on 1-3 piezocomposite technology and the front layer (optimised multilayer stack of passive materials) is selected to act both as a matching and barrier layer. The probe is integrated into the 7 Fr catheter and interfaced to a commercial ultrasound system. Besides the manufacturing process of the whole transducer, the paper reviews electro-acoustical characteristics including sensitivity, frequency, bandwidth and homogeneity performances. The aim of this probe is the detection of epithelial abnormalities, transparietal extension of lesions and detection of lymph nodes related to local cancer. Finally, *in vivo* images realised through a bronchofiberscope are presented and discussed from a clinical perspective.

P2U-R-6 K8

200 MHZ SELF-FOCUSED ZNO MEMS ULTRASONIC TRANSDUCERS FOR BIOMEDICAL IMAGING

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A dome-shaped diaphragm-transducer (DSDT) was fabricated using MEMS silicon bulk micromachining. The IC-compatible fabrication process will allow for the DSDTs controlling electronics and amplifiers to be placed directly adjacent to the transducer, minimizing noise. With MEMS micromachining techniques, the design can be easily modified to create a 200 MHz array. The cost-effective

batch process for fabrication makes this device an attractive choice for cellular microstucture imaging, skin cancer detection and pathology, and acoustic property measurement of biomolecules.

The active element of the transducer was a self-focused, 14 μm ZnO thin film with a center resonant frequency above 200 MHz. The element was suspended on a membrane in a 2.5 mm aperture hole etched in the (100) silicon. Self-focusing was achieved using a wax molding of a 5mm sphere to obtain an f-number of 1. The DSDT incorporates a one-quarter wavelength, conformally vapor-deposited parylene matching layer. The transducer membrane is structurally supported by its backing layer, 1 cm thick lossy conductive epoxy. Impedance characteristics measured with a HP4291B impedance analyzer showed a phase peak at 210 MHz. The DSDT was pulse-echo tested with a 400 MHz broadband Panametrics pulser/receiver and a 1 GHz LeCroy oscilloscope. An echo signal from a quartz target was obtained with little noise at 210 MHz and about 20% bandwidth. Experimental results are in good agreement with those predicted by the KLM model.

P2U-R-7 K9

FABRICATION OF DOME-SHAPED-DIAPHRAGM-TRANSDUCER ARRAY FOR HIGH FREQUENCY BIOMEDICAL IMAGE APPLICATION

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This paper presents the microfabrication technique for a Dome-Shaped-Diaphragm-Transducer (DSDT) array for 200 MHz cellular microstructure imaging. The DSDT uses piezoelectric ZnO film (around 13 μm thick) to generate acoustic waves, and is fabricated with an IC-compatible process on a silicon substrate. The fabricated DSDTs have been tested with a pulse echo method with a quartz target, and shown to produce a signal at 200 MHz with 20% bandwidth.

The DSDT fabrication uses spherical balls (with surface roughness less than 0.2 μm from Bal-tec, Inc.) to precisely shape desired wax molds, on which parylene is deposited as a support layer for DSDT. The wax molds are removed by toluene to release parylene dome diaphragms. The whole fabrication process is done at below 50 degree C so that thermally induced stress in the parylene could be avoided [1]. We have fabricated a two-dimensional array of large dome-shaped (ranging from 2,500 to 6,000 μm in diameter) and thin (about 13 μm) piezoelectrically active diaphragms (composed of Aluminum/ZnO/Aluminum) on a 3 silicon wafer. Piezoelectric ZnO film is sputter-deposited on the parylene dome diaphragm with its C-axis oriented perpendicular to the dome surface. Quarter wavelength thick (about 3 μm) parylene is deposited on the front side of the wafer for acoustic matching. After depositing the parylene acoustic matching layer, we remove the parylene support layer with oxygen plasma from the wafer backside. To make the DSDT water immersible for the pulse echo measurement, e-solder silver epoxy is used as the backing material.

The fabrication technique for the DSDT array is meant for low-cost mass production of the array for high frequency biomedical image applications. Moreover, the technique allows a precise control the radius and curvature of the dome-shaped diaphragm through adjusting the size of the front-to-backside thru holes and/or the radius of the spherical balls.

[1] G.H. Feng and E.S. Kim, "Universal Concept for Fabricating Micron to Millimeter Sized 3-D Parylene Structures on Rigid and Flexible Substrates," IEEE MEMS2003, Kyoto, Japan, January 19-23, 2003, pp. 594-597

P2U-R-8 K10

HIGH PERFORMANCE PIEZOELECTRIC FILMS FOR HIGH FREQUENCY MEMS ULTRASONIC TRANSDUCERS

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There has been an increasing interest in the applications of piezoelectric films to high frequency microelectromechanical (MEMS) ultrasonic transducers. To increase the sensitivity of high frequency transducers, developing newer materials with improved piezoelectric properties compared to PZT has been the goal of many investigaters. Recently, very large piezoelectric responses have been reported in relaxor ferroelectric PbTiO3 single crystals. Among them, (1-x) Pb[Yb1/2Nb1/2]O3 xPbTiO3] has the highest transition temperature, which reduces property temperature dependence. In this work, (1-x) Pb[Yb1/2Nb1/2]O3 xPbTiO3] (PYbN-PT, x=0.5) (001)-oriented and epitaxial thin films were deposited onto (111) Pt/Ti/SiO2/Si and (001) CaRuO3/(001) MgO substrates by sol-gel process, respectively. The dielectric permittivity and loss of the films were measured. Compared with PZT thin films, PYN-PT films showed better ferroelectric and piezoelectric properties. The remanent polarization was over 35 μC/cm2; the effective transverse piezoelectric e31,f coefficient was about -12.2 C/m2 for the epitaxial film. Finally, following PiezoCAD modeling, the PYbN-PT film high frequency transducer was designed and fabricated with MEMS technology.

P2U-R-9 K11

FABRICATION OF SOL-GEL MODIFIED PIEZOELECTRIC THICK FILMS FOR HIGH FREQUENCY ULTRASONIC APPLICATIONS

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The high frequency ultrasound transducers have been studied intensively in order to improve the imaging resolution. These transducers are gaining acceptance as clinical tool for the examination of the anteriror segement of the eye, skin and intravascular imaging. Their developments have pushed the limits of ultrasonic imaging technology to give diagnostic quality information on microscopic structure in living tissue. One of the technical challenges for high frequency of ultrasound is fabrication of piezoelectric elements with a thickness of only a few tens of micrometers. It is very difficult to lap down thinner ceramic and dice very small element to fabricate high frequency single element transducer and array. Piezoelectric thick-film technology is an alternative solution at low manufacture cost. In this work, a fabrication process of high performance piezoelectric PZT thick films up to 60 μm deposited on silicon and aluminum substrates is reported. Crystalline spherical modified PZT powder about 0.3 μm in diameter was used as filler. PZT polymeric precursor produced by Chemat Inc was used as matrix materials. Spinning films was annealed at 700 ° C for half hour in air. Comparing with previous piezoelectric PZT composite films, the modified piezoelectric thick films exhibit very good piezoelectric properties. The dielectric constant is over 750 and dielectric loss is 0.03. Electromechanical thickness coupling factor is over 0.35. Using KLM model, the high frequency transducer can be obtained. The characteristic of transducer will also be presented.
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P2U-R-10 K2

ULTRA-FINE PIEZOELECTRIC COMPOSITE FOR HIGH FREQUENCY ULTRASONIC TRANSDUCERS

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Interdigital Pair Bonding (IPB) is a well-understood technique for fabricating 2-2 composite materials. Typically this dicing saw technique is used in an effort to increase the bandwidth of ceramic ultrasonic transducers and can also be used for making linear array ceramic structures where the pitch of the array can be considered for use at frequencies $>$ 20 MHz. The IPB approach is

generally limited to creating structures with a pitch that is larger than the blade thickness. In this paper, the authors present a new technique called interdigital phase bonding (IPHB). Interdigital phase bonding involves a second dicing step in which two original IPB composites are spatially shifted by a fraction of the intended pitch. The result is a 2-2 composite structure with a pitch that it is less than the blade thickness. An ultra-fine scale composite with 15mm wide PZT ceramic strips (CTS 3203HD) embedded in an epoxy matrix (EPOTEK 301) with a pitch of 24.5mm, giving a volume ratio of 61 percent, is presented. The composite was fabricated using a conventional dicing saw (Disco DAD-2H/6TM) and a 50mm thick blade. Based on the linear array element criteria of a width:height ratio of < 0.6, this structure is suitable for the fabrication of ultrasonic arrays with central frequencies of up to 85 MHz. A single element transducer working at central frequency of 55MHz has been made with this ultra-fine scale composite. The Impedance spectrum and pulse echo response have been taken to characterize the transducer performance. Measurements show that the longitudinal electromechanical coupling coefficient is greater than 0.6 and that there are no significantly noticeable lateral resonances in the frequency range of 55 150 MHz. The measured results are compared with theoretical predictions based on velocity dispersion curves calculated from 2-dimensional general Lamb modes and shows good agreement.

P2U-R-11 K3

A 20-40 MHZ ULTRASOUND TRANSDUCER FOR INTRAVASCULAR HARMONIC IMAGING

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Initial studies have suggested the feasibility of conducting tissue harmonic imaging in the context of intravascular ultrasound imaging. However, little work has been done on the transducer design and fabrication, in which the main drawbacks are the small element size (<1mm) and wideband frequency sensitivity. The goal of this study is the modeling, design and prototyping of a wideband intravascular ultrasonic transducer, suitable for mounting on a fast-rotating catheter tip.

As a basis for the transducer design we used the KLM model, extended with material losses. To evaluate different designs and piezoelectric materials, and to find the optimal values for layer properties such as thicknesses and acoustic impedances, a Harmonic Imaging Capacity (HIC) number is defined. The generation of a second harmonic pressure field is approximately proportional to the square of the local acoustic pressure. Therefore, we define the HIC number as the product of the squared voltage-to-pressure transfer function at the fundamental frequency (20MHz) and the signal-to-noise ratio at the second harmonic frequency (40MHz). The signal-to-noise ratio is assumed to depend on the transducer Johnson thermal noise, the pre-amplifier noise and the pressure-to-voltage transfer function at the frequency of the second harmonic.

In an iterative process of simulation, construction and testing, we developed a 0.9 mm diameter, single element transducer with an optimized HIC number. Fine grain Stettner PPK22 PZT is used as the active piezo layer, which was chosen for its appropriate dielectric constant and good mechanical robustness at small thickness. An aluminum layer and a conductive ink layer are added to optimize the bandwidth and the acoustic impedance matching to the medium. A - lambda mismatching layer between the piezo-electric layer and the backing optimizes the efficiency of the transducer.

In water-tank hydrophone experiments, the transducer prototype produces an on-axis maximum output pressure of 1.3 MPa at 20 MHz with an input pulse of 25 % fractional bandwidth and 90 Vpp. The pulse-echo frequency response displays peaks at 22 and 40 MHz and a 14 dB trough in between, the 40 MHz peak is 11 dB lower than the fundamental peak. The 6 dB fractional bandwidths are 25% at 22 MHz and 20% at 40 MHz. These results, which are in good agreement with theoretical predictions, indicate that the transducer is suitable for intravascular harmonic imaging.

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Session: P2FC-S

OSCILLATORS, SYNTHESIZERS AND NOISE

Chair: M. Driscoll

Northrop Grumman Corporation

P2FC-S-1 R6

THE NOISE CONVERSION METHOD FOR OSCILLATORY SYSTEMS

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In this report, we discuss the method for calculating the amplitude and phase noise power spectral density (psd) functions of an oscillatory system (resonator, oscillator, filter, selective circuit, etc) via the psds of its intrinsic noise sources and relevant transformation coefficients. A systematic description of the method is given for the scalar and vector noises. As a noble illustration, the noise model is considered of a piezoelectric series branch with the fluctuating motional inductance, capacity, and losses. Based upon we clarify the rules regarding the shaping of the amplitude and phase psd functions.

General relationships are derived to transform the intrinsic noise of the BAW and SAW resonators to fluctuations of its amplitude and phase. It is shown that the generic relations are valid for the arbitrary excitation frequency of a crystal resonator. An extensive analysis is provided for the Butler, Colpitts, and 'low-noisy' operation modes with the assumption of full and zero inter noise

correlation. Several examples are given as an illustration of a good agreement of the measured data with the prediction curves.

A one-port steady-state noise model of a crystal oscillator is discussed. Employing the method, we translate the thermal additive and flicker noises of both the resonator and amplifier into the oscillator amplitude and phase. The generic noise transformation coefficients are derived based upon we provide in a detailed analysis of the oscillator phase psd for the Butler and Colpitts operation modes. Consistency with the Leeson model is shown.

The importance of this method resides in the fact that it enables us to study particular finite ranges of the phase psd function, such as those predicted by Leeson and postulated by the IEEE Standard SRD 1139-1988.

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P2FC-S-2 T2

EXPERIMENTAL INVESTIGATION OF PHASE NOISE IN HIGH-EFFICIENCY CLASS-E AMPLIFIERS

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In mobile and satellite communications the power amplifier (PA) in the transmitting module can consume up to 50% [1] of total system power. Increasing the PA's efficiency is therefore desirable, helping to reduce heat output (consequently relaxing sinking requirements) and conserve battery power in portable units. In response to this need of higher efficiency in generating RF power, class E and F switching-mode amplifiers have been extensively investigated up to the micro- and millimeter wave range [2] yielding very promising results. Typical Class-E power-added efficiencies are of the order of 50% compared to linear (class A) amplifier efficiencies of 30% at microwave frequencies. This increase in efficiency reduces heat-sinking by about a factor of 2 and increases battery lifetime by about the same factor. The high efficiency of class E amplifiers results from the use of the active device as a switch, arranging it to have smooth transitions between on and off, so that the duration of the simultaneous presence of both bias current and voltage is minimized, thus reducing power dissipation within the transistor[3]. Because of this highly non-linear operation, given a certain active device with known noise characteristics, it is unclear what the noise performance of the Class E amplifier will be. Moreover, the relationship between the noise performance and bias conditions for Class E amplifiers is unknown, while the efficiency and harmonic content of the amplifier is critically dependent on these bias conditions. We will present for the first time some of the tradeoffs between noise performance (both wideband and close-to-carrier) and efficiency in Class E amplifiers. A class-E amplifier has been built with a Fujitsu FLK027WG GaAs MESFET capable of 250mW of output power. Preliminary measurements of the 4.6GHz class-E amplifier indicate a power-added efficiency of about 42% at 250mW. At full power, this particular class-E circuit is operating in a sub-optimal class-E mode. A more efficient mode can be obtained by operating at a lower output power level. These measurements are still in progress, as are measurements of the phase noise of the class-E amplifier.

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P2FC-S-3 T3

THÊO1 CONFIDENCE INTERVALS

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An important challenge of characterizing oscillators is accurately determining frequency stability at long-term averaging times. For a given data run of length T, the Allan deviation (Adev) can only estimate frequency stability up to averaging times of $T/2$ and at that value with minimal confidence. Theoretical variance #1 (Thêo1) has been developed at NIST to improve the estimation of long-term frequency stability. Its square-root (Thêo1-dev) has two significant improvements over Adev in estimating long-term frequency stability in that (1) it can evaluate frequency stability at averaging times 50% longer than those of Adev and (2) it can estimate frequency stability with greater confidence than any other estimator. To determine confidence for Thêo1, we use simulation studies to establish the distribution function of Thêo1 for each noise type. From the distribution function we provide expressions for computing confidence intervals for Thêo1 at averaging times up to and beyond the $T/2$ limit of Adev. In addition, we discuss a method for determining the exact confidence intervals of Thêo1, particularly for small sample sizes, using analytic techniques.

APPLICATION OF DUAL-MIXER TIME-DIFFERENCE MULTIPLICATION IN ACCURATE TIME-DELAY MEASUREMENT

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The dual-mixer time difference (DMTD) multiplication system [1] provides a very low noise floor which makes it possible to easily measure the frequency stability of a pair of quasi-synchronous high-performance oscillators, even at relatively low RF frequencies such as 5 MHz. In order to allow high-precision short-term frequency/phase stability measurement, IREE decided to develop its own DMTD multiplier whose first version achieved the short-term background stability ADEV($\tau = 1$ s) = 4.210 (-14) at 5 MHz and low-pass cutoff frequency fc = 100 Hz [2]. Through optimization, also based on the experience and the know-how of BNM-SYRTE in this area, a significant improvement has been achieved. Currently the second version shows ADEV($\tau = 1$ s) = 6.910 (-15) at 5 MHz and fc = 16 Hz. The corresponding time deviation is TDEV ($\tau = 0.2$ s) = 3.5 fs and the flicker phase floor shows TDEV(τ) = 2 fs from $\tau = 1.6$ s to a few tens of seconds [3]. Because of its extremely low noise it is appealing to use the DMTD multiplier also for accurate measurement of short time delays. Obviously, if a component (connector, cable etc.) is inserted in one of the channels, the corresponding time-delay multiplied by N will be added to the measurement result. The resolution of this measurement is only limited to a few femtoseconds by the TDEV noise floor, but the accuracy of the result is severely degraded by the mismatches at the ends of the line which may cause errors up to $\pm$500 ps for usual mismatches at 5 MHz. Nevertheless, the mismatch impact on the accuracy can be substantially reduced since its contribution depends on frequency. The dependence can be found by using two low-noise synthesizers instead of the fixed-frequency test oscillator and the common oscillator. This allows varying both frequencies while maintaining the same multiplication factor. Then by fitting the result to the theoretical formula, we can correct for the mismatch error. In a first simple approach, we assume that the mismatches do not vary in the frequency range of interest. The expected inaccuracy is of the order of 1ps for cable lengths from a few cm to several tens of meters. Theoretical and experimental results will be presented at the Conference. [1] D.W. Allan, H. Daams. Picosecond time difference measurement system, Proc. 29th Annu. Symp. Frequency Contr., Atlantic City, USA, pp. 404-411, (1975). [2] L. Sojdr, J. Cermak, G. Brida. Comparison of high-precision frequency-stability measurement systems, Proc. IEEE International Frequency Control Symposium and 17th European Frequency and Time Forum, Tampa, USA, pp. 317-325, (2003). [3] L. Sojdr, J. Cermak, R. Barillet. Optimization of dual-mixer time-difference multiplier, 18th European Frequency and Time Forum, Guildford, UK, (2004) (accepted for oral presentation).

MODELING PHASE AND AMPLITUDE NOISE IN HETEROJUNCTION BIPOLAR TRANSISTOR AMPLIFIERS

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Understanding the origin of 1/f phase modulation (PM) noise in microwave amplifiers is an important topic as the phase noise in microwave oscillators is limited by the loop amplifier 1/f phase noise. In [1] it was shown that 1/f noise in dc currents and voltages result in PM and amplitude modulation (AM) noise about the carrier frequency in bipolar junction transistor (BJT) amplifiers. In this paper we present an expanded noise model and use it to predict the 1/f PM and AM noise in linear microwave heterojunction bipolar transistor (HBT) amplifiers. In this model we include dependences of transistor parameters on dc bias conditions such as the collector current. Once the magnitude (|G|) and the phase (θ) of the gain of the amplifier are found, the PM and AM noise due to baseband current noise can be obtained using the following expressions:

AM sensitivity to current noise $= .25\ (\mathrm{I}\times \mathrm{d}/\mathrm{dI}[|\mathrm{G}|]\div|\mathrm{G}|)^2$

PM sensitivity to current noise $= .25(\mathrm{I}\times \mathrm{d}/\mathrm{dI}(\theta))^2$

The results from the above expressions can then be used to find the dependences of PM and AM noise due to current noise on carrier frequency and other operating conditions. The model is used to investigate the noise of a linear HBT common-emitter amplifier with grounded emitter. The model predicts that at carrier frequencies much smaller than the amplifiers 3-dB frequency, the AM sensitivity to current noise is independent of carrier frequency, but at higher frequencies the AM sensitivity decreases with increasing carrier frequency. In addition, the AM sensitivity decreases with increasing current. AM sensitivity measurements made at 500 MHz and 1 GHz at different dc currents agreed with the predicted trends. The model also predicts that at low currents the PM sensitivity increases with dc current, it then reaches a maximum and then decreases with dc current. This general trend was verified by preliminary measurements made at 500 MHz and 1 GHz, and in most cases the measured sensitivities were within 4 dB of the ones predicted by the model. We will present theoretical results from the model on dependences of PM and AM sensitivities on carrier frequency, dc bias, and circuit elements. We will then compare the theoretical results to experimental sensitivities at carrier frequencies of 500MHz, 1 GHz, and 2 GHz.

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P2FC-S-6 T6

DOUBLE TEMPERATURE COMPENSATED CRYSTAL OSCILLATOR

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In the temperature compensated crystals oscillators, the frequency–temperature stability of ordinary analogue temperature compensation crystal oscillator TCXO is not high. The microcomputer compensated crystal oscillator based on AT cut crystal can show a better compensation performance, but the demand to components and control accuracy is also very high. This paper introduces a double temperature compensated TCXO which combines the two different compensation techniques. The crystal oscillator is compensated with analogue approach firstly, then compensated secondly with digital approach based on an improved frequency–temperature performance. There are many different integrated VCTCXO and with a very small size $\pm$ 1 2 $\times$ 10^{-6} frequency–temperature stability can be obtained in a wide temperature range. According to the frequency–temperature characteristics of VCTCXO a microprocessor generates the secondary compensation voltage after processing. With the voltage as the control voltage to VCTCXO, the frequency–temperature stability of the crystal oscillator can be compensated into $\pm$ 2 3 $\times$ 10^{-7} in –55 to 90 degree temperature range. Utilizing this way, the request to the secondary compensation is decreased obviously and the structure can be very simple. For example one can use a very simple microprocessor (PIC12C509) and a width-regulated pulse from it as the control voltage, and the temperature sensor is also simple. The temperature compensated crystal oscillator based on the double compensations is of low cost and can show less influence from power supply stability and better reliability. Compared with ordinary DTCXO and MCXO based on AT cut crystals it is easier to be produced.

P2FC-S-7

WITHDRAWN

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P2FC-S-8 T8

OPTIMIZATION OF DRIVE-LEVEL IN HIGH STABILITY LOW-NOISE OCXOS

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Choosing optimal value of driving current through a crystal resonator in OCXOs is an actual problem for the designer striving for simultaneous fulfillment of high

long-term stability and low phase noise requirements. A goal of the present work was search for maximum level of the driving current that still doesn't influence noticeably aging rate of OCXOs using SC-cut 3d overtone resonators. While the experiments a bunch of 24 pcs of 10 MHz 3d overtone SC-cut resonators packaged inside the TO-8 vacuum holders was exited by the current varied steps by step from 0.5 to 3 mA during the tests. Each the step was followed by stabilization of the frequency at about (1-2)E-10/day drift rate. During the tests we observed no essential degradation of the aging at raise of the drive level up to at least 1.8 mA. At higher levels we noticed increase of the aging rate for some of the tested OCXOs however even at 3.0 mA excitation essential portion of the units remained insensitive to the current raise showing about 1E-10/day drift after a few days stabilization. Having returned the drive level down to 0.5 mA the aging rate of 1-2 E-10/day restored for almost all the crystals. We also compared discussed above aging of the crystals under gradual rise of the drive level with aging of similar crystals tested at different drive levels sustained constant through the whole test while. The paper discusses obtained results. On the carried out researches we've come to following conclusions: 1. Drive level below 2.0 mA doesn't perturbs noticeably long-test stability of the SC-cut resonators at drift rate of at least 2E-10/day that provides possibility for reduction of floor phase-noise level of the OCXOs to at least -165 dBc/Hz. 2. Essential portion of the SC-cut resonators remains insensible to the drive level up to 3 mA that allows designing the OCXOs combining extremely low-noise level with high long-term stability on using such units.

P2FC-S-9 T9

COLPITTS-TYPE OSCILLATOR FOR HIGH FREQUENCY APPLICATION

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In recent years, as band expansion of the fiber optic network has materialized, the transmission speed for optical transmission equipment is approaching 2.4[Gbps](OC-48)/10[Gbps], with 40[Gbps] under study. This kind of high-speed optical transmission system needs to send the proper signal on the optical cable and to send it back as an electrical signal. The oscillator for the system requires high stability, high frequency and low jitter. To make a high frequency oscillator, a PLL or multiplying method is commonly used. However, since the oscillator used in these circuits has spurious oscillations in the fundamental mode, the jitter characteristics deteriorate. Although the best method to achieve good jitter characteristic is to operate in the fundamental mode using a crystal or a SAW resonator, it is difficult to get sufficient negative resistance with the Colpitts-type oscillator, which is used. Therefore, we propose a new Colpitts-type oscillator using multiple transistors, which create sufficient negative resistance in the high frequency range. In this paper, our design is shown. We connect the emitter of the Colpitts-type circuit to the base of the next emitter follower circuit and the output terminal of the emitter follower circuit is then connected to the collector of the Colpitts-type circuit. We have confirmed that this design can achieve enough negative resistance in the [GHz] base band. The result is that the negative resistance of the high frequency Colpitts-type circuit is determined by the phase shift of the transistor's capacitance between the base and the collector and the coupling capacitor between the output terminal of the emitter follower circuit and the collector of the Colpitts-type circuit. Furthermore, we have shown that the high frequency Colpitts-type circuit we proposed could oscillate even by the mirror capacitance of the transistor used in the oscillator circuit. Finally, we built a 622.08[MHz] VCSO and studied it. As the result, we have confirmed: (a) We can achieve frequency stability versus temperature of +/-70ppm maximum for -40 to +85degree C. (b) At control voltage from 0V to 3.3V, frequency control range is at least +/-240ppm. (c) Excellent phase noise is achieved.

P2FC-S-10 R7

A NEW OSCILLATOR CIRCUIT EFFECTIVE IN FREQUENCY RANGE 100MHZ TO 1GHZ

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The importance of a stable oscillator has been increasing in the frequency range from 100MHz to 1GHz, as the key device of a synchronous optical network, wireless LAN, ultra wide band communication system, etc. As the stable oscillator in this frequency range, the SAW oscillator and the crystal oscillator with a frequency multiplier have been developed. A colpitts oscillator is widely used as the oscillator circuit for these oscillators. The characteristics of the oscillator circuit is expressed by the series circuit of negative resistance and equivalent capacitance. In the frequency range between 100MHz and 1GHz, the negative resistance of colpitts oscillator decreases rapidly and sufficient negative resistance can not be obtained. The capacitance used in the oscillation loop becomes extremely small to obtain sufficient negative resistance. Recently, Prof. Sekine's group of Nihon university proposed a new crystal oscillator circuit for the use in this frequency range. This oscillator circuit is the colpitts oscillator with feedback by collector-common amplifier. Its negative resistance improves compared to the usual colpitts crystal oscillator. This circuit is effective and useful but its design flexibility is small.

In this paper, we have proposed the new oscillator circuit for the use in the frequency range from 100MHz to 1GHz. The proposed oscillator circuit is composed of a colpitts oscillator and an emitter-common amplifier for enhancement of the negative resistance. The output signal of colpitts oscillator is amplified and fed back to the oscillator with adequate phase shift via emitter-common amplifier. We have designed the proposed oscillator circuit at 300 MHz and evaluated its performance by simulation. The small-signal negative resistance is about seven times bigger than that of the usual colpitts oscillator. The output

voltage above 2.0 Vpp has been obtained. The second harmonic of the output voltage is less than -14 dB. The duty of the output voltage is 56 percent. The phase noise is slightly degraded from the usual colpitts oscillator but is sufficient for practical use. The DC current consumption of the proposed circuit is a little bigger than that of the colpitts oscillator but is sufficiently small for the use in optical synchronous system.

The relation between the circuit parameters and the frequency characteristics of the negative resistance has been examined in detail. The outline of design procedure has been given by these data. The oscillator circuits have been designed at 600MHz, 900MHz, and 1.2GHz, too. The sufficiently large small-signal negative resistance has been obtained at each frequency. The equivalent capacitance of the oscillator can be made bigger in the proposed circuit than in the usual colpitts oscillator. Therefore, the variable frequency range can be widened compared to the usual colpitts oscillator.

From these results, we have thought that the proposed circuit is useful for the application in the frequency range from 100MHz to 1.2GHz. The measurement is now under way for the confirmation of the simulated results.

P2FC-S-11 R8

SYMBOLIC ANALYSIS OF QUARTZ CRYSTAL OSCILLATORS

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Symbolic analysis is the computation of the behavior of a circuit in terms of symbolic and numerical parameters, in contrast to numerical analysis that only provides numerical results. Symbolic simulators can express explicitly which circuit parameters determines the circuit behavior. They offer more advantages than numerical simulators in many applications such as parameter optimization. Despite of its potential, it has not been widely used by analog circuit designers.

We claim in this paper that symbolic analysis can be very useful in the particular field of quartz crystal oscillator simulation. In this domain, it has the capability to provide insight into the circuit behavior impossible to obtain with numerical simulation. This paper presents a symbolic simulator that takes into account all the equations of semiconductor devices. Every parameter of each component of the circuit can be considered a symbol or given a numerical value.

Of course, there is no hope to obtain a closed-form solution of the system of non-linear differential equations representing the oscillator behavior. The designer must choose some components or parameters he wants to study the influence on the oscillation. All the other parameters are then substituted by their numerical values. Finally, The system is solved by a perturbation method. The solution of the system gives the designers the influence of the selected components or parameters on the most relevant features of the oscillation.

PROGRESS ON 10 KELVIN CRYO-COOLED SAPPHIRE OSCILLATOR

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We present recent progress on the 10 Kelvin Cryocooled Sapphire Oscillator (10K CSO). Included are incorporation of a new pulse tube cryocooler, cryocooler vibration comparisons, phase noise, and frequency stability tests. The 10K CSO was built to support the Cassini Ka-band Radio Science experiment and is designed to operate continuously for periods of a year or more[1]. Currently three CSOs are operational: one in NASA's deep space network (DSN) and two at the JPL test laboratory. Short term stability has been routinely verified at $2x10^{-14}$ at one second measuring time, and $2x10^{-15}$ at 1000 seconds, with drift of approximately $1x10^{-14}$ per day. The first generation of 10K CSO incorporated a Gifford-McMahon type of cryocooler which has a life time of one year before maintenance. With a pulse tube cooler, the anticipated minimal continuous operation period is three years. The new generation of pulse tube cryocoolers allows cold-head operation at temperatures down to 4.2K with reduced vibration at the coldhead. One significant advantage is no moving parts at coldhead which gives no preset service period allowing much longer continue operation. This increased reliability is a major requirement for DSN. We will present long term operation data on coldhead temperature, vibration, and reliability. We will also report on a single stage pulse tube that was integrated in another (40K) Cryocooled Sapphire Oscillator [2] 10K CSO is designed with an externally compensated resonator that uses paramagnetic chromium impurities in a thermally attached ruby element to provide a compensation that can be adjusted to lie in the relatively narrow temperature band between that which can be realistically achieved with available cryocooler cooling (7-8K) and the point at which the Q is degraded (10K). Sapphire resonators have been tested which show quality factors of $Q{\sim}10^9$ at temperatures up to 10K. However, stable operation can only be achieved near a preferred turnover temperature which is typically too low (1.5K-6K) to reach with by cryocooler, and which varies from resonator to resonator depending on the concentration of incidental (1 PPM) paramagnetic impurities. The range of measured turnover temperature is 7.2 to 8.8K compares well to a calculated value of 7.3K. The mode excited is $WGE_{14,1,1}$ at 10.395 GHz. Performance targets are a frequency stability of $3x10^{-15}$ (1 second $\leq$ tau $\leq$ 100 seconds) and a phase noise of -73dB/Hz 1Hz measured at 34 GHz.

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P2FC-S-13 R10

ROTATING MICHELSON-MORLEY EXPERIMENT BASED ON A DUAL CAVITY CRYOGENIC SAPPHIRE OSCILLATOR

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Recent experiments based on cryogenic microwave oscillators [1,2] have tested the isotropy of the speed of light (Michelson-Morley experiment) at a sensitivity of order of a part in 10^{15}, which is a similar sensitivity to other best tests [3,4]. Further improvements of the accuracy in this type of experiment are not expected due to the already long data set and the systematic error limit [2].

Currently, we are constructing a new Michelson-Morley experiment on a rotating platform. The experiment consists of two cylindrical cryogenic sapphire resonators placed perpendicular to the normal to the Earths surface and orientated in orthogonal directions. Resonators are excited in whispering gallery modes $WGH_{8,0,0}$ near 10 GHz from two separate oscillators, which are, in turn, tightly frequency locked to the corresponding resonance. The temperature of the dual cavity is controlled at approximately 8 K where the beat frequency between two oscillators is independent on temperature. The dual oscillator is rotated on a platform with a period between ten to one hundred seconds, and the beat frequency is counted. Improvement of several orders of magnitude in the sensitivity of light speed isotropy measurements is expected, as the relevant time variations will now be at the rotation frequency (= 0.01 - 0.1 Hz), where the frequency stability of the cryogenic oscillators is the best.

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P2FC-S-14 R11

WHISPERING GALLERY TRAVELING WAVE INTERFEROMETER FOR LOW PHASE NOISE APPLICATIONS

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Modern ultra-low phase noise microwave oscillators use widely ferrite circulators to separate a wave reflected with a standing wave whispering gallery resonator (WGR). Intrinsic circulator noise limits in many cases an oscillator noise floor.

The only way to overcome radically this drawback is to replace a ferrite circulator with a noiseless reciprocal network [1]. A traveling wave (TW) sapphire resonator excited at whispering gallery modes (SWGR) is a good candidate for that replacement. The published realization of such an interferometer declares using of microstrip lines to couple a TW SWGR [2]. It can be shown, however, this design is not able to provide the desired characteristics due to bad electromagnetic field matching between a microstrip line and the SWGR. Contrary to that our paper examines in detail a classical approach of a traveling wave sapphire disk WGR coupled with a dielectric waveguide (DW).

The TW SWGR design is obtained by means of electrodynamic 3D finite element (FE) analysis. As found by numerous simulations, the TW regime in SWGR is very sensitive to excitation line features and coupling parameters. This fact was practically ignored in the TW WGR approaches proposed previously that led to strong disagreements in those designs. Even in the investigated classic TW WGR case the variation of a distance between SWGR and DW is revealed to be unacceptable for coupling coefficient adjustment. When the distance is unequal to its definite optimal value the strong structure performance degradation occurs. Along with that it was proved that coupling adjustment can be arranged via changing a DW material permittivity value.

Our analysis revealed that the investigated TW WGR structure possesses appropriate parameters for efficient noiseless FD interferometer implementation. The evaluated scattering parameters show that magnitude and phase frequency responses of a TW WGR transmission coefficient are the same as for a bridge-type circuit which is commonly used in reflected wave interferometers. The relatively low (-10 dB or even less) input reflection coefficient can be achieved in a TW regime. It is interesting that despite the reflection coefficient low magnitude its frequency responses permit to implement a reflection type oscillator with an additional phase noise suppression loop.

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P2FC-S-15 R12

LOW-POWER, LOW-JITTER DIRECT DIGITAL SYNTHESIZER WITH ANALOG INTERPOLATION

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1. Introduction A low-power direct digital synthesizer (DDS) with analog interpolation is described. In modern processors, several unrelated frequencies are required for digital signal processing and sampled analog sub-systems. One solution is to use accumulators to generate desired clock frequencies from one

high-frequency PLL clock generator. This solution, however, produces high jitter, spurious sidebands, and consumes large power consumption.

One way to reduce the jitter produced by accumulators is to use analog phase interpolation on the output signal [1], [2]. Previous attempts, however, rely on absolute reference levels and are prone to system offset mismatches. In this paper, a fully differential topology and a replica feedback controlled circuit are used to produce the required output frequency accurately across all process and temperature corners with low power consumption.

2. MNA Counter

The operation of an MNA counter is best illustrated through an example. A 3-bit (N=8) modulo counter is assumed with an input of M=3. This means that the input frequency, FCLK, is divided by 3/8. The average period of this output is 8/(3*Fclk). Due to limited accumulator bitwidth, the worst case cycle-to-cycle jitter is 1/(8*Fclk). In general, for an n-bit delay generator, the cycle-to-cycle jitter will be $1/(2^n)$/Fclk.

A delay generator produces accurate delays that are fractions of the input clock signal. Delay is generated by charging and discharging current (proportional to the accumulator contents) across a bank of capacitors. Stability of the delay generator across process and temperature is guaranteed by the used of a current locked loop (ILL). The input clock signal is delayed by half a cycle and compared to the output of the delay generator. The analog delay generator is programmed to produce a delay of one-half a period. The delay generator used in the ILL is identical to the one used in the MNA counter, therefore, the current produced tracks process and temperature.

3. Results

Table 1 compares the proposed technique to others. In the proposed technique, differential circuit techniques allow the reduction of the unit size of the capacitor in the analog interpolation circuitry, resulting in less active power is consumed and less area. Furthermore, the ILL is turned on only 1 or 2 cycles before it is needed. This technique alone reduces the power consumption by ten fold. The figure of merit used is proportional to the ratio of power consumption to the amount of jitter reduced (larger is worse).

[1] T. Nakagawa et. al., A Direct Digital Synthesizer with Interpolation Circuits, IEEE JSSC, May 1997, pp. 766-770. [2] A. Yamagishi, et. al., A Phase-Interpolation Direct Digital Synthesizer with an Adaptive Integrator, IEEE Transactions on Microwave Theory & Techniques, June 2000, pp. 905-909.

Comparison of proposed scheme with state-of-the-art

	Proposed	[1]	[2]
Area	0.12mm^2	N/A	12mm^2
Spur Reduction	30dB	40dB	40dB
Power (mW/MHz)	0.0262	5.63	0.3125
Digital Bitwidth	6-bit	8-bit	8-bit
FOM (normalized)	1	40.29	2.23

DIRECT DIGITAL SYNTHESIZER CLOCK FREQUENCY VERSUS TEMPERATURE DEPENDENCY COMPENSATION USING TWO LOOK-UP TABLES

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The paper describes a new approach of the direct digital synthesizer (DDS) clock frequency versus temperature (f-T) dependency compensation. Here we present a digital compensation module, which works efficiently with the most reconfigurable devices available today and which may be implemented to improve f-T stability of already existing systems. The crystal self-temperature-sensing method based on dual-mode crystal oscillator (DMXO) has been used. The DMXO excites fundamental frequency f_1 and 3rd overtone frequency f_3 of the crystal. Processing of both frequencies enables prediction of their shifts due to ambient temperature changes. The frequency f_3 forms the clock of the system. The clock f-T dependency is compensated periodically. The clock frequency is divided by three and then subtracted from the fundamental frequency f_1 using a digital mixer. During a given compensation period, which depends on the difference frequency f_1-$f_3/3$ at the digital mixer output, the clock pulses are accumulated in the digital counter. The amount of the clock pulses N represents an actual temperature of the crystal in the DMXO. Eight most significant bits of N (i.e. N_0) indicate a location of the two appropriate compensation coefficients C_0 and C_1 in the two look-up tables. Eight least significant bits of N (i.e. N_1) are multiplied with C_1. An initial DDS frequency tuning word W is set according to the required output signal carrier frequency considering a nominal frequency of the clock. Compensated DDS frequency tuning word $M=W+C_0+N_1\times C_1$ is calculated automatically at the end of each compensation period and forms an output of the compensation module. Utilizing the compensation module we have obtained residuals below ±0.03ppm in the temperature range between -35°C and +85°C. The compensation principles, the compensation coefficients computation and mapping to the look-up tables are discussed in the paper. The results we have obtained are also compared with the ones published in [1].

References: [1] Stofanik, V., Balaz, I., Minarik M., Digitally Temperature-Compensated DDS, Proceedings of the 2001 IEEE/EIA International Frequency Control Symposium, pp. 816-819.

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ANALYSIS OF MULTIFREQUENCY CRYSTAL OSCILLATOR STABILITY AREA BY COMPUTER SPICE SIMULATION

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The perspective way of crystal oscillator (XO) temperature stability improving is digital temperature compensation. Temperature compensated oscillator (TCXO) must have a sensor of piezo-plate temperature. For temperature sensor an additional oscillation mode of a reference resonator may be used. This realizes "self-temperature-sensing" regime with very high static and dynamic measuring characteristics. The accuracy of such sensor is adequate to TCXO temperature stability of 1-3 ppb, which allows creation of a new class of reference sources. The main obstacle to wide application of this technique is low stability of multifrequency oscillation regime in an oscillator circuit.

The multifrequency mode is possible only in relative narrow area of internal (elements values) and external (temperature) parameters of oscillation circuit - an area of stability. Any parameter moving out of this area results in failure of the multifrequency mode (suppression by one fluctuation of all others). Thus, for multifrequency XO designing the information of multifrequency mode stability area is the most important. At the same time, at the present there are no other ways for obtaining the information of stability area except for long experiments. Lack of the information about multifrequency XO behavior complicate their designing greatly, and make significant demands to intuition and skill of the designer.

In [1] the authors offer the method of quartz oscillator computer simulation, realized by means of standard EDA (SPICE or MicroCAP) and mathematical (MathCAD) programs. The method is build on combining of numerical and analytical analysis methods on basis of XO model described at two hierarchical levels. In the given work the further development of the method mentioned above for multifrequency XO simulation and calculation of multifrequency mode stability areas is submitted.

Diagram of stability area in coordinates of resonator resistances on oscillation modes is offered as the most informative parameter showing capability of oscillator circuit sustain the multifrequency mode and allowing to compare the efficiency of various circuit decisions. This diagram allows to determine parameters of resonators excited by oscillator circuit in multifrequency mode, estimate multifrequency mode stability at resonator resistance temperature drift, study influence of nominal variation of circuit elements and various circuit decisions on stability area limits.

In this paper the method of two-frequency XO stability area calculation by means of standard commercial EDA and mathematical software is presented. For the first time the stability areas for some dual-mode XO circuits are calculated and analyzed. The recommendations providing two-frequency mode stability increasing are given.

[1] A.A. Gubarev, A.V. Kosykh, S.A. Zavjalov, A.N. Lepetaev SPICE simulation of high-Q crystal oscillators: single and dual-mode oscillator analysis - Proc. of the 2003 joint meeting IEEE IFCS and 17th EFTF, рp. 606-614.