*** Author presenting Paper**

Session: U1-A
CONTRAST AGENTS - PERFUSION
Chair: F. Forsberg
Thomas Jefferson University

U1-A-1 510AC 1:30 p.m.

ULTRASOUND-INDUCED COALESCENCE OF CONTRAST AGENT MICROBUBBLES

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When big gas bubbles collide, the following stages of bubble coalescence have been reported: flattening of the opposing bubble surfaces prior to contact, drainage of the interposed liquid film toward a critical minimal thickness, rupture of the liquid film, and formation of a single bubble.

For ultrasound contrast agents this phenomenon has not yet been studied. During insonification, expanding contrast agent microbubbles may come into contact with adjacent bubbles, resulting in coalescence or bounce. In this study, we give a description of the coalescence mechanism of insonified microbubbles, based on high-speed photography and theoretical modeling.

Our experimental setup for photographing insonified contrast bubbles consisted of a 500 kHz single-element transducer mounted into a water-filled container, spherically focused at the focal plane of the optical system. The optical images were recorded through a microscope with a fast framing camera capturing 8 frames at a frame rate of 3 million frames per second. Contrast agent microbubbles with monolayer lipid shells were insonified by 10 cycles of 0.5 MHz ultrasound with high acoustic amplitudes, in the range 0.66–0.85 MPa.

The same stages of coalescence described for colliding bubbles could be distinctly observed with expanding contrast agent microbubbles. Flattening of the opposing bubble surfaces occurs if and only if the bubble system has a Weber number greater than 0.5. In our results, Weber numbers are relatively high because of the rapid bubble expansions, with a maximal radius increase at a rate of several m/s.

We investigated the influence of the lipid shell on the coalescence by computing the film drainage for immobile (rigid) bubble surfaces resulting in a laminar flow, and for mobile (free) bubbles surfaces resulting in a plug flow. The observed coalescence times appeared to be at least three times shorter than the

times produced by laminar flow. Although small perturbations on the bubble surface may grow tremendously, a phenomenon known as parametric instability, sufficiently large perturbations to bridge the liquid film cannot be formed within the times observed. For two bubbles with radii of 1.9 and 2.5 μm, we computed a coalescence time higher than 3.2 μs based on laminar flow, and of 0.48 μs based on plug flow. The latter computation is in full agreement with the observed coalescence time, which is between 0.33 and 0.66 μs. In conclusion, during expansion the lipid shell is so dilute that the contrast agent microbubble coalescence times are comparable to those of free gas bubbles.
This work has been supported by the Technology Foundation STW (RKG.5104).

U1-A-2 510AC 1:45 p.m.

PERFUSION ESTIMATION USING SUBHARMONIC CONTRAST MICROBUBBLE SIGNALS

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Contrast enhanced subharmonic imaging (SHI) can detect slow, small volume blood flow due to its excellent contrast to tissue signal to noise ratio. Hence, it may be possible to estimate quantifiable flow parameters such as perfusion from subharmonic signal intensities. A modified Logiq 9 scanner (GE Medical Systems, Milwaukee, WI) operating in grayscale SHI mode (transmitting/receiving at 4.4/2.2 MHz) was used to measure SHI time intensity curves in a flow phantom. Different concentrations (1 and 2 % by volume) of the contrast agent Optison (Amersham Health, Princeton, NJ) and flow rates (9.8 and 19.6 ml/min) were evaluated and the relative changes compared. In vivo, three dogs received intravenous contrast injections (dose: 0.1 ml/kg) and renal SHI was performed. Low perfusion states were induced by ligating surgically exposed segmental renal arteries. Following 3 contrast injections a microvascular staining technique based on stable (non-radioactive), isotope labeled microspheres (BioPhysics Assay Laboratory Inc, Worcester, MA) was employed to quantify the degree of perfusion in 8 sections of each kidney. Digital clips were transferred to a PC and SHI time intensity curves acquired in each section using Image-Pro Plus software (Media Cybernetics, Silver Spring, MD). SHI fractional blood volumes (FBVs) were calculated and the perfusion estimated from the initial slope of the FBV uptake (i.e., $d\text{FBV}/dt$). SHI perfusion data was compared to the gold standard using linear regression analysis. In vitro, SHI intensity increased approximately linearly with time as the bubbles flowed in. The slopes of the uptake curves were estimated to 0.0074, 0.016 and 0.015 s-1, respectively. The slope approximately doubled when either concentration or flow rate doubled. In vivo, 184 SHI time intensity curves were acquired. SHI perfusion estimates correlated significantly with microsphere results ($0.36 < r < 0.84$; $p < 0.02$). The best SHI perfusion estimates occurred for low perfusions states in the posterior

of the kidneys (r = 0.84; p = 0.0001). The corresponding root-mean-square-error was 1.2 % . In conclusion, SHI perfusion estimates have been obtained in vitro and in vivo. The perfusion estimates were in reasonable agreement with a microvascular staining technique.

The U.S. Army Medical Research Material Command under DAMD17-00-1-0464 supported this work.

U1-A-3 510AC 2:00 p.m.

ASSESSMENT OF TRANSIENT MYOCARDIAL PERFUSION DEFECTS IN INTACT MICE USING A MICROBUBBLE CONTRAST DESTRUCTION / REFILL APPROACH

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In modern cardiovascular research, the mouse provides an attractive model for human cardiovascular disease because this species is amenable to genetic manipulations that enable research into the genetic factors underlying cardiovascular disease. In particular, there is interest in noninvasive approaches for tracking anatomical and physiological changes resulting from myocardial infarction in the mouse heart. Last year, we assessed perfusion before, during and after an induced closed chest coronary ischemia using a contrast bolus injection approach. However, this technique has been largely superceded by an approach that uses a combination of high Mechanical Index (MI) bubble destruction image frames and low MI imaging frames to map the rate of refill of contrast agent [1]. Regions of interest (ROIs) affected by the ischemia are identified and an exponential refill curve is fitted to the mean gray scale value within this ROI. We have repeated our measurements using prototype Siemens Sequoia instrumentation and software. We used a destructive MI of 1.9 (system display value) and an imaging MI of approximately 0.22. Contrast imaging was performed using Contrast Pulse Sequences on the 15L8 linear array transducer [2]. (We have observed, and will show, that we can detect individual bubbles, or bubble clumps, circulating in the mouse myocardium with this approach.) As anticipated, a significantly reduced refill rate was observed during ischemia. The refill exponential rate constant was observed to decline by 35% in the region of myocardium affected by the induced ischemia. The destruction / refill approach provides a more reliable and repeatable measure of perfusion than the bolus approach which was highly operator-dependent and required considerable manual dexterity. Some of the challenges involved in making these measurements are discussed. These include the need to carefully optimize the contrast dilution and injection rate and the need to identify as accurately as possible the ROI to be analyzed. Conclusion: The destruction / refill approach for assessing perfusion in the mouse heart is preferred over the older bolus injection approach. The approach discussed here is one of very few available for making a very difficult, yet very important, measurement.

[1] K. Wei, A. Jayaweera, S. Firoozan, A. Linka, D. Skyba, and S. Kaul, "Quantification of Myocardial Blood Flow With Ultrasound-Induced Destruction of Microbubbles Administered as a Constant Venous Infusion," Circulation, vol. 97, pp. 473-483, 1998. [2] P. Phillips, "Contrast Pulse Sequences (CPS): Imaging non-linear microbubbles," Proceedings of the 2001 IEEE Ultrasonics Symposium, vol. 2, pp. 1739-1745, 2001
University of Virginia Cardiovascular Center Heart Partners Fund and NIH grant EB001826. Equipment and engineering support from Siemens Medical Solutions. A 15L8 transducer was loaned by Sanjiv Kaul MD and Jonathan Lindner MD. Contrast agent was provided by Alexander Klibanov PhD

U1-A-4 510AC 2:15 p.m.

IDENTIFICATION OF ULTRASOUND-CONTRAST-AGENT DILUTION SYSTEMS FOR CARDIAC QUANTIFICATION

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The injection of an Ultrasound Contrast Agent (UCA) bolus allows the echographic measurement of an Indicator Dilution Curve (IDC). Nowadays, IDCs are directly interpolated and interpreted by specific models. However, for low concentration, the contrast dilution system is linear and a system impulse response could be estimated and used to derive important clinical information. Therefore, this study proposes a new approach for UCA dilution curve analysis. A small UCA bolus is peripherally injected and detected by a trans-thoracic ultrasound transducer. Several IDCs are derived from the measured acoustic intensity in different sites in the central circulation. The ultrasound scanner is set in power modulation mode with low Mechanical Index (MI=0.1) to improve the contrast detection and reduce the bubble disruption. An adaptive Wiener deconvolution filter is implemented to estimate the impulse response between the selected sites. The choice for a least-square-error deconvolution algorithm is due to the small signal-to-noise ratios (SNRs) of UCA dilution curves. The Pulmonary Blood Volume (PBV) and the Left Ventricle (LV) Ejection Fraction (EF) can be assessed by analysis of the impulse response between specific sites. For PBV measurements, the dilution impulse response between the Right Ventricle and the Left Atrium (LA) is estimated and fitted by the Local Density Random Walk model. The contrast mean transit time between the RV and the LA is derived from the fitted model and multiplied times the cardiac output for the PBV estimate. The cardiac output can be measured by echo-Doppler time integration in the aorta. For EF measurements, two IDCs are measured in the LA and the LV. The LA acoustic intensity is compensated for the attenuation due to the contrast in the LV. The estimated impulse response corresponds to the LV IDC after a theoretical rapid injection of a contrast bolus in the LV, which is the procedure that allows a correct EF assessment. Since the impulse response of a mono-compartment system, such as the LV, is given by an exponential decay,

the EF is calculated on the exponential fit of the impulse response down-slope. The volume measurements are validated in-vitro. Four different volumes are measured with flow varying from 1L/min to 5L/min. The correlation coefficient is higher than 0.99 and the standard deviation is smaller than 2.7%. The system is also applied to patients with promising results. The EF measurement is tested in patients. A group of 20 patients with EF going from 10% to 70% is selected. EF dilution estimates are compared to EF measurements by echographic bi-plane method after UCA opacification. The correlation coefficient is 0.93. The Bland-Altman statistical analysis shows an average and a standard deviation equal to 1.6% and 8% respectively. In conclusion, the impulse response estimation of UCA dilution systems is feasible even for low SNR. It allows a minimally invasive measurement of several clinical parameters, such as PBV and EF. The results are promising and encourage further validation and investigation for new applications.
The authors like to thank the Department of Cardiology of the Catharina Hospital Eindhoven and in particular Annemieke Jansen for providing this research with the validation measurements in patients. The authors also thank the Operating Room staff of the Catharina Hospital Eindhoven and in particular Susan van den Elzen for her valuable support with the in-vitro experimentation.

U1-A-5 510AC 2:30 p.m.

QUANTITATIVE LASER DOPPLER ANEMOMETRY MEASUREMENTS OF THE SHEAR-STRESSES EXERTED ON ULTRASONIC MICROBUBBLES ATTACHED TO SURFACES UNDER PHYSIOLOGICAL FLOW CONDITIONS

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Ultrasonic contrast agents are currently being developed to target and attach to specific sites of interest within the body. An in-house microbubble capable of targeting areas of atherosclerotic plaque has been developed. The microbubble is echogenic and has been shown in vitro to remain attached under physiological flow volumes. However, the shear stresses experienced by the attached microbubbles are unknown and difficult to measure in vivo. To this end we have developed a novel flow chamber and have used laser Doppler anemometry (LDA) to estimate the shear stresses experienced by the attached microbubbles. LDA is a well established technique allowing non-intrusive, high resolution, 2D measurements of the velocities of liquids and gases.

Method: In order to simulate physiological flow similar to that experienced within the coronary arteries, a flow chamber has been developed of dimensions similar to those of a coronary artery. The microbubbles were attached to agar samples which were placed in wells in the flow chamber. The surface of the agar was flush with the base of the flow channel. The dimensions of the flow area were 6 mm x 1.5 mm. Water containing seeding particles was passed over the surface of the agar at a constant flow volume. A front lens with focal point of 160 mm was used to focus the laser, giving a probe volume of 45 x 45 x 200 micron. The LDA set up was optimised for this application and velocity data was collected from the surface of the agar through the flow volume to the top of the flow channel. The shear rate from the sample wall was then calculated allowing the shear stress at the wall to be calculated. The shear stresses on attached microbubbles were calculated for different flow volumes.

Results: The velocity profile from the base of the chamber to the top was found to be parabolic. The peak velocities were 19.20 $\pm$ 0.03 cm/s, 21.71 $\pm$ 0.03 cm/s and 22.97 $\pm$ 0.03cm/s for flow rates of 80 ml/min, 90 ml/min and 100 ml/min respectively. The shear stresses at the surface of the agar, calculated from these profiles were 2.86 $\pm$ 0.02 dynes/cm^2, 3.47 $\pm$ 0.02 dynes/cm^2 and 4.50 $\pm$ 0.02 dynes/cm^2.

Conclusions: LDA has been used to calculate the shear stresses experienced at the flow chamber walls under physiological flow conditions and at the surfaces of microbubbles attached to these walls.

U1-A-6 510AC 2:45 p.m.

PHYSICOCHEMICAL PROPERTIES OF THE MICROBUBBLE LIPID SHELL

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Lipid-stabilized microbubbles are currently used as ultrasound contrast agents in diagnostic imaging and are being developed to facilitate drug and gene delivery in conjunction with ultrasound for therapeutic applications. The monolayer shell is primarily composed of lipids with long, saturated acyl chains (i.e. below their main phase transition temperature under physiological and storage conditions) and often contains a poly(ethylene glycol)-grafted emulsifier to enhance production yield, shelf life and in vivo stability. The monolayer shell is typically represented as a uniform film, in which the components are fully miscible. Recent microscopy studies, however, have shown that the shell is indeed polycrystalline and exhibits lateral phase separation whereby the lipid forms crystalline domains surrounded by a less ordered emulsifier-rich region. Lipid composition and microbubble processing history dictate the size and shape of these lipid crystals. Large, equilibrium-shaped domains are observed on microbubbles that undergo slow cooling through the main phase transition temperature, whereas small, ramified domains are seen at high quench rates. Domain branching increases with lipid acyl chain length. Networks of aggregated domains that span the entire microbubble circumference can be formed through either induced convection in the surrounding medium or compression and subsequent expansion of the gas core. The polycrystalline nature of the shell has implications on bubble stability and dissolution behavior. The shell effectively eliminates surface tension and lends a significant impedance to gas permeation, with resistances ranging from 10^2 to 10^3 s/cm, as shown through bubble dissolution and electrochemical

experiments. Shedding of excess shell material during dissolution occurs in distinct cycles whereby the shell exhibits crumpling for several seconds to minutes, depending on the degree of under-saturation of the filling gas in the surrounding medium, followed by a spontaneous restoration of bubble sphericity in less than 0.02 s. We are currently investigating the implications of microstructure and lipid shedding behavior in ultrasound-assisted microbubble targeting.
Dr. Marjorie Longo, Dr. Paul Dayton, Gang Pu & Gabe Runner

Session: U2-A

TISSUE ELASTICITY I
Chair: S. Emelianov
University of Texas

U2-A-1 510BD 1:30 p.m.

TRANSIENT RADIATION FORCE ELASTOGRAPHY: MODELING OF THE SHEAR WAVE PROPAGATION IN HETEROGENEOUS TISSUE BY A PSEUDOSPECTRAL METHOD

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Acoustic radiation force imaging is a relatively new approach to characterize mechanical properties of soft tissue. By using radiation pressure, it is possible to create deeply a localized stress in biological tissue. We previously studied analytically the induced displacements, supposing that the tissue can be modeled as a linear isotropic solid. Considering a homogeneous solid, we have described the directivities of the compression and shear waves generated by this localized force using the elastodynamic Green function. At a particular point, the purely longitudinal wavefront arrives first, and a near field term ensures the continuity of the displacement until the purely transverse wavefront arriving time. This near field term is very important in transient radiation force elastography because the associated displacements are large and the duration of these displacements are long (in the ms range). If we now consider a heterogeneous solid, the Green function theory cannot be used. Then we have developed a numerical technique based on a 2D pseudospectral (PS) method, which solves the wave equation with a source term in an isotropic solid. This code, used by Wojcik et al.* in the case of acoustic wave propagation in liquids, is extended for viscoelastic solids. Perfectly matched layers (PML) are used on the sides of the numerical grid to avoid reflections. Moreover, the temporal evolution is done with an Adams-Bashforth method. In the case of a point source in a homogeneous elastic medium, numerical results are favorably compared (directivity patterns, displacement shape,) with analytical results computed with the Green function. To correctly estimate the displacements generated by a localized

radiation force, the experimental pressure beam generated by a focused transducer has been measured and used to calculate the experimental stress source which has been inserted in the numerical model as source term. So we predict precisely the displacement vectors, induced inside a solid by a localized stress source, in a plane in which we have included a small shear elasticity inclusion. The shear wavefront deformation, as well as the diffraction and reflection of the shear wave, can be calculated and analyzed. Moreover, viscosity is taken into account to correctly model the relaxation time of the waves. We note that in a viscous medium, the relaxation times (decreasing time of the time/displacement curves) are increased. Finally, in order to show the importance of the spatial and temporal profiles of the stress source, different ultrasound beam configurations are tested and discussed.

* G. Wojcik et al., "Pseudospectral methods for large-scale bioacoustic models", Proc. IEEE Ultrason. Symp., pp. 1501-1506, 1997.

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U2-A-2 510BD 1:45 p.m.

3D ULTRASOUND-BASED DYNAMIC ELASTOGRAPHY: FIRST IN VITRO RESULTS

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3D Magnetic Resonance (MR) Elastography is a well-established technique based on monochromatic mechanical excitations to study soft tissues mechanical properties. Observation of tissue response to mechanical excitations is performed using MR Imaging. The three components of the spatio-temporal displacements induced by the mechanical vibration are calculated in a 3D area and used in an inversion algorithm to calculate tissue viscoelastic properties. The technique has been validated in vivo for human breast, liver and prostate but is limited by the acquisition time (about ten minutes). In this work, we study the feasibility of performing 3D Dynamic Elastography using an ultrasound based imaging system. In addition of providing a low cost system, the ultrasound approach enables the reduction of the acquisition time by a factor 300 (about 2 seconds). In our experiment two ultrasonic array were perpendicularly fixed and controlled by a stepper-motor-control positioning system in order to acquire ultrasonic images in a given volume of interest. Mechanical excitation were induced by a 20mm square plate linked to external vibrator. Displacements induced by the vibrator were calculated from ultrasound images using a 2-dimensional estimator developed at the laboratory [Tanter et al., IEEE Trans. Ultrason., Ferroelec., Freq. Contr. 49 (10), pp 1363-1374, 2002]. Each ultrasonic array was able to calculate in plane (axial and lateral) displacements. Lateral displacements calculated from both arrays were the same and then were averaged. Such a configuration leads to the estimation of the three displacement components in a full 3D area. Imaging sequences for 3D displacements calculation were realized using our fully programmable ultrafast ultrasonic scanner. Experiments were conducted in an heterogeneous tissue mimicking phantom with two harder inclusions inside. 3D Elasticity, viscosity and anisotropy maps of the studied phantoms are presented and shows the feasibility of building a full ultrasound based system for 3D Dynamic Elastography providing a complete description of tissue mechanical properties in a few seconds.

U2-A-3 510BD 2:00 p.m.

OPTIMIZING MULTICOMPRESSION APPROACHES TO STRAIN IMAGING

H. DU*[1], J. LIU[1], C. PELLOT-BARAKAT[1,2], and M. F. INSANA[1], [1]University of California, Davis, [2]INSERM.
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Introduction: Multicompression techniques in strain imaging are often applied to maximize lesion contrast while reducing the decorrelation noise introduced by large tissue compressions. However, electronic and quantization noise accumulate when summing successive small compressions. Image quality may be optimized by understanding the trade-off between these noise sources. This paper investigates the relationship between displacement variance and the number and magnitude of applied compressions.

Methods: We know that ultrasonic cross correlation techniques are unbiased, efficient estimators of displacement for small deformations. Therefore the Cramér-Rao variance bound [J Acoust Soc Am 107:1421-34, 2000] predicts displacement errors observed for simple phantom experiments when the object and instrumentation parameters are known. Strain variance is derived from displacement variance by propagation of error. Predictions were verified experimentally using displacement measurements obtained from a Siemens Antares system with an ultrasound research interface that provides beamformed RF echo signals digitized at 40 Msamples/s. A homogenous tissue-mimicking phantom was compressed from above and scanned with a linear array at 6.67 MHz. Boundary conditions gave plane-strain deformation in the image plane.

Results: Displacement variance versus applied strain is observed to be constant up to 0.1% strain, increasing slowly up to 1% strain, and increasing rapidly to the upper variance bound beyond 1%. Consequently each applied strain should be between 0.1 and 1%. For a fixed total applied strain ranging from 1.5% to 7.5%, we find concave curves of displacement variance versus number of compressions with minima between 4 and 20 compressions. This corresponds to an optimal applied strain increment between 0.3% and 0.5%. Larger strain increments reduce echo coherence for the correlator thus increasing decorrelation noise. Smaller strain increments accumulate echo signal noise unnecessarily. Predicted displacement variances closely matched those measured in phantom experiments. For 2.7% total strain, a 78% reduction in displacement noise was obtained by accumulating 6 compressions with 0.45% strain increment as compared to a single 2.7% compression. For 6 compressions, we measured a displacement standard deviation of 0.203 $\pm 0.096\mu$m; the predicted value was 0.206μm.

Conclusion: A simple rationale for designing multicompression strain imaging techniques has been formulated from fundamental principles and verified experimentally. Strain increments between 0.3% and 0.5% give the lowest errors for applied deformations up to 7.5%. These finding have major implications for clinical imaging strategies and advanced techniques involving coded pulse excitation.

U2-A-4 510BD 2:15 p.m.

AUTOMATED THERMAL COAGULATION SEGMENTATION OF THREE-DIMENSIONAL ELASTOGRAPHIC IMAGING USING A COARSE-TO-FINE ACTIVE CONTOUR MODEL

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Delineation of RF-ablator induced coagulation (thermal lesion) boundaries is an important clinical problem not well addressed by conventional imaging modalities. Automation of this process is certainly desirable. Elastography that estimates and images the local strain corresponding to small, externally applied quasi-static compression can be used for visualization of thermal coagulation. Several studies have demonstrated that coagulation volumes computed from multiple planar slices through the region of interest are more accurate than volumes estimated assuming simple shapes and incorporating single or orthogonal diameter estimates. This paper presents an automated segmentation approach for thermal coagulations on three-dimensional elastographic data to obtain both area and volume information. This approach consists in a coarse-to-fine method for active contour initialization and gradient vector flow active contour model for deformable contour optimization with the help of prior knowledge of the geometry of general thermal coagulations. The performance of the proposed algorithm has been shown to be comparable to manual delineation by medical physicists (r = 0.97 for 38 RF-induced coagulations). Correlation coefficient of coagulation volume between auto-segmented elastography and manually delineated pathology is 0.91.

This work was supported in part by Whitaker Foundation grant RG-02-0457, start-up funds awarded to Dr. Varghese by the University of Wisconsin-Madison, and by NIH grant R21-EB002722

U2-A-5 510BD 2:30 p.m.

ESTIMATION OF DISPLACEMENT VECTORS AND STRAIN TENSORS IN ELASTOGRAPHY USING MULTIPLE ANGULAR INSONIFICATIONS

U. TECHAVIPOO*, Q. CHEN, T. VARGHESE, and J. A. ZAGZEBSKI, The University of Wisconsin-Madison.
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In current practice, only one out of three components of the tissue displacement vector and one of nine components of the strain tensor are estimated for ultrasound elastographic imaging. Other important elastic parameters, such as shear strains and the Poissons ratio, are not imaged due to the difficulty in obtaining this information. Moreover, reconstruction of the Youngs modulus would also be significantly improved if all the components of the strain tensor were estimated.

In this paper, we described a new method for estimating the components of the tissue displacement vector following a quasi-static compression. The method estimates displacements from radiofrequency (RF) echo-signals acquired along multiple insonification directions of the ultrasound beam. At a given spatial location in the compressed medium, the relationship between the orthogonal components of the tissue displacement vector and the displacements estimated from RF signals recorded along different insonification directions can be modeled using linear equations whose coefficients depend on the insonification angles. The actual displacement components are found by solving these linear equations using least squares solutions. Following displacement estimations, components of the corresponding normal and shear strain tensors are estimated. Poissons ratio images can be also obtained from the normal strain components under plane strain conditions.

The algorithm was applied to simulated RF echo-signal data from a cylindrical inclusion phantom and experimental RF data acquired from a thermal lesion in canine liver tissue. For simulations, the normal strain, shear strain, and Poissons ratio images computed by processing modeled echo data match well with the ideal images for single elastographic inclusions. For the experimental results, the outlines of the thermal lesions are clearly seen both on the normal and shear strain images. These results demonstrate the utility of this technique for the computation of the normal and shear strain tensors.

This work is supported in part by start-up funds provided to Dr. Varghese by the Department of Medical Physics, Medical School, and Graduate School at the University of Wisconsin-Madison, Whitaker Foundation grant RG-02-0457, and NIH grant 1 R21 EB002722.

U2-A-6 510BD 2:45 p.m.

ADAPTABLE CODED EXCITATION FOR ELASTICITY IMAGING

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We found that coded excitation significantly lowers decorrelation errors for strain estimation under several conditions, particularly those involving low echo signal-to-noise ratios (eSNR). To expand the utility of coded excitation to a broader range of experimental conditions, we examined two types of phase modulated (PM) codes – optimal and m-sequence – and two types of receive processing – matched filter and inverse filter. The goal was to discover codes and parameters that give the highest performance for lesion imaging.

Our study was limited to PM codes, which are the most straightforward to implement on laboratory and commercial imaging systems. Echo simulations allowed us to probe the large parameter space for coded excitation imaging to find promising approaches that were then verified experimentally with our lab scanner and phantoms. Lesion visibility was quantified for strain images using the signal-to-noise ratio for displacement (SNRd), contrast-to-noise ratio for strain (CNR), and local impulse response (LIR) for strain. Performance metrics were the basis for comparison in terms of lesion contrast, strain noise, and spatial resolution. Data were acquired using a 10 MHz, f/1.5 annular array transducer with 60% bandwidth and dynamic receive focusing.

Optimal codes give the flattest spectrum, which yields comparable performance for inverse and matched filter. These codes are optimal in the sense that they produce simultaneously the smallest range lobes and the least noise amplification. M-sequence codes with matched filter yield lower range lobes in limited situations, which are very important for strain imaging. Large time-bandwidth product (TBP) PM code performance was compared to that of conventional short pulse (TBP =1) imaging for a range of conditions: eSNR = 10-50dB; α = 0.1-0.9dB/cm/MHz; applied strain ϵ = 0.1%-1%. Matched filter outperforms inverse filter in noisy (eSNR$<$20dB) and highly attenuating ($\alpha>$0. 9dB/cm/MHz) environments. For larger deformations ($\epsilon>$0.7%) the inverse filter outperformed the matched filter because of lower range lobes. We found that SNRd could be increased as much as 20dB without a significant loss of spatial resolution by carefully selecting from known experimental parameters the code length, base sequence bandwidth, and receive processing.

Predictions were verified experimentally using a phantom with 2.5mm-diameter inclusions that mimic breast lesions. 15-bit optimal and m-sequence codes were transmitted using the lab system and f/1.5 array with limited depth of focus. Measured CNR for matched and inverse filter processing of the optimal code were 2.26 and 2.22, respectively, for 1% strain, but only 2.16 and 0.68 for the m-sequence.

Optimal codes from the radar literature and matched filter receivers can significantly lower strain image noise without reducing lesion contrast or spatial resolution. Phantom results clearly show increased depth of focus for fixed focus apertures and allow use of higher carrier frequencies for improved spatial resolution. Lesion detectability is best when many small deformations are accumulated.

Session: U3-A
NDE NON-CONTACT MEASUREMENT TECHNIQUES
Chair: R. Addison
Rockwell Scientific Company

U3-A-1 511AB 1:30 p.m.
(Invited)

LASER-ULTRASONICS: FROM BIRTH TO THE PRESENT DAY

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Generation of ultrasound goes back nearly to the invention of the laser. In 1963, the generation of stress pulses in a material was reported by using a ruby laser. Optical detection of ultrasound with a laser coupled to an interferometer has been on the other hand developing more slowly and was for many years limited to polished surfaces in a laboratory setting. The 80's and 90's have seen practical solutions to efficient detection from rough industrial surfaces as well as the use of very short pulses for very high ultrasonic frequencies. At present time several industrial applications have matured and there are several systems, although often in a limited number, operating in the aerospace, steel and microelectronic industry.

In this presentation, laser-ultrasonics will be presented from an historical perspective. The major developments, theoretical and experimental, including also the optical and laser advances that made them possible, will be outlined. Future perspectives, including possible solutions to overcome present limitations, and potential applications will be presented.

U3-A-2 511AB 2:00 p.m.

INLINE MEASUREMENTS OF TEXTURE AND RECRYSTALLIZATION ON ALUMINUM ALLOYS

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The recrystallization of hot-rolled aluminum sheets was measured in-situ in the laboratory and in-line after in-line annealing at Commonwealth Aluminum Corporation using laser-ultrasonics. The non-contact measurement is based on sensing ratios of compressional and shear sound velocities in the sheet thickness direction. Some of these ratios are insensitive to sheet thickness variations and vary with crystallographic texture and temperature. Therefore, recrystallization is sensed as a change of texture, from a rolled to an annealed texture. This scientific basis of the measurement was demonstrated in the laboratory and inline tests at CAC showed that the technology is well suited for inline measurements. The capabilities and limitations of the inline sensor will be discussed.

U3-A-3 511AB 2:15 p.m.

A NOVEL TECHNIQUE FOR ENHANCING THE SIGNAL TO NOISE RATIO OF LASER-BASED ULTRASONIC SYSTEMS

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Conventional laser ultrasonic systems use pulsed laser sources to generate broadband acoustic waves. The theoretical signal to noise ratio (SNR) of these systems, in the shot noise limit, is inversely proportional to the square root of the bandwidth of the detection system. Previous researchers have shown that improvements in the SNR can be made by generating narrowband acoustic signals using temporally and/or spatially modulated laser pulses and reducing the detection bandwidth accordingly. In this work, the generation of high frequency acoustic waves using an amplitude modulated continuous wave (CW) laser is demonstrated. The acoustic signals are detected using a path stabilized Michelson interferometer coupled to an RF lock-in amplifier. This system allows for the control of detection bandwidth, which can be reduced by many orders of magnitude below typical broadband laser ultrasonic systems. Experimental results showing CW generated acoustic waves in thin coatings, free-standing plates, and semi-infinite substrates are given. In these experiments, acoustic waves are generated with the CW modulated laser at discrete frequencies up to 200 MHz. The real and imaginary parts of the ultrasonic signals in the frequency domain are detected with the interferometer/lock-in amplifier system, and these data are in turn synthesized to reconstruct the time domain response. The use of narrowband generation/ detection combined with subsequent time domain reconstruction allows for a large increase in SNR without losing the ability to distinguish individual acoustic arrivals or multiple acoustic modes in the time domain.
This work is supported by the National Science Foundation under grant numbers : ECS - 0304446 and ECS - 0210752.

U3-A-4 511AB 2:30 p.m.

OPTICAL MEASUREMENT OF TRANSIENT ULTRASONIC SHOCK WAVES

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In order to measure acoustic shock waves generating pressures of some tens of MPa in water, an ideal sensor has to be calibrated, wide-band and sufficiently robust to support acoustic cavitation. We measure high intensity ultrasonic displacements and shock waves in water, using the phase modulation of an optical beam reflected from a thin immersed membrane materialising moving particles.

With a digital demodulation process, a 4.5-μm ultrasonic transient displacement (corresponding to a 21.5-MPa acoustic pressure in water) has been measured with a standard heterodyne interferometer. Results are in good agreement with those given by an hydrophone designed to measure high pressure waves. This sensitive optical method provides absolute measurements with a 50-μm lateral resolution, in a large bandwidth (from 20 kHz to 50 MHz). If the low cost membrane used in the experimental set-up is damaged by the acoustic cavitation, it can be replaced very easily. This operation does not change the calibration factor of the interferometer. The maximum measurable displacement is limited by the frequency bandwidth of the instrument. Since the photodetector cuts frequencies higher than 120 MHz, the interferometer is able to measure a 22-MPa peak acoustic pressure in water. This performance can be improved by increasing the Bragg cell frequency, to obtain a wider bandwidth. For measuring acoustic pressures up to 45 MPa, we have conceived an interferometer operating at a 140-MHz carrier frequency.

U3-A-5 511AB 2:45 p.m.

WITHDRAWN

Session: U4-A

OPTICAL INTERACTIONS
Chair: D. Hecht
DLH Laboratories

U4-A-1 513AB 1:30 p.m.

ACOUSTO-OPTIC PROPERTIES OF PHOTONIC CRYSTAL FIBERS

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Photonic crystal fibers is a new class of optical fibers. They basically consist of a single glass material such as pure silica. The guiding properties in this case are obtained by introducing several small air holes. Compared to standard optical fibers the photonic crystal fibers have a larger index of refraction contrast, and also more degrees of freedom of the geometric design parameters. This makes possible the fabrication of optical fibers with special and unique optical properties. It is the purpose of the presentation to complement previously known optical properties with acoustic properties and also to look into the interaction between acoustic and optical waves in this class of fiber.

The paper will review the optical properties of photonic crystal fibers with particular emphasis on unique properties of this new fiber class. We have investigated three types of fiber. In addition to a regular single-mode fiber included for reference, a photonic crystal fiber with an air core and one with a solid core have been investigated. The phase velocity of the lowest acoustic flexural mode has been measured and compared with theoretical predictions for the three fiber types. For the photonic crystal fibers the theory is limited to low frequency approximations. The agreement between theory and experiments is very good. We also report experiments on interaction between acoustic waves and optical modes in a photonic crystal fiber.
The support of The Research Council of Norway is acknowledged.

U4-A-2 513AB 1:45 p.m.

FDTD ANALYSIS OF WAVELENGTH-SELECTIVE SWITCHING IN WEIGHTED ACOUSTOOPTIC SWITCHES FOR WDM PHOTONIC ROUTERS

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Optical switches using collinear acoustooptic (AO) interaction have been attracting attention in the fields of WDM photonic networks and optical signal processing. Wavelength-selective switching or processing over wide wavelength range more than 100nm is performed with the collinear AO device in a simple structure. Multiple wavelengths can be switched by frequency multiplexed SAWs with a single integrated optic AO device. This function is attractive in wavelength-selective switching or routing of WDM optical signals, tunable wavelength filtering, optical cross connecting (OXC), and optical add-drop multiplexing (OADM). The authors have studied a collinear AO device consisting of directionally coupled optical waveguides and a SAW waveguide. An application to WDM photonic switching and routing systems has also been discussed. In most of applications in WDM systems, improvement of wavelength selectivity is indispensable because the filtering response in a regular AO device suffers from its large sidelobe at the level of -9.3dB. Several methods to suppress this sidelobe have been proposed, which employ weighting in AO coupling along the interaction region. The authors proposed two kinds of improve methods; one uses a tapered SAW waveguide and the other uses a slightly tilted SAW waveguide. The filtering characteristics in the weighted AO coupling were analyzed using the coupled mode theory. Since the coupled mode analysis is an approximate method, more detailed analysis in the device structure including all the constituent elements is required to evaluate the sidelobe structure in the filtering characteristics. Although experimental verification is also important, fabrication technique with high precision is required because a slight fabrication error effects sensitively the sidelobe level. In this report, FDTD method is used to analyze the filtering characteristics of the device which includes the interaction region and the input/output Y branches. The FDTD simulation results are compared with the coupled mode analysis. It is shown that sidelobe level as low as -20dB in filtering characteristcs is realized by using tapered SAW waveguides. It is found that the characteristics of the incident Y branching waveguides make the sidelobe characteristics complicated. Therefore, the careful designing of the incident branching waveguides are important to achieve expected low sidelobe level. A design of the tapered SAW waveguide is also discussed by using the scalar potential method. The SAW waveguide is made of dense-flint glass strip film. Suppression of the sidelobes under -20dB is realized, for example, by modifying the SAW waveguide with the width from 700 to 26 micro-meter. The required SAW power is 1.9 times larger than that for the regular device with constant width of 26 micro-meter. The thickness of the SAW waveguide strip film is accordingly varied from 0.4 to 1.0 micro-meter. The configuration of the proposed modified SAW waveguides is also convenient for efficient SAW coupling into the waveguide.

U4-A-3 513AB 2:00 p.m.

NEW ARCHITECTURE OF TUNABLE ACOUSTOOPTICAL ADD/DROP MULTIPLEXER FOR DYNAMIC DWDM WITH 25 GHZ ITU GRID

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The new architecture of compact reconfigure optical add/drop muliplexer (OADM) based on multi-reflector (MR) beam expanders and noncollinear acoustooptic tuning is presented. The advantage of this device is based on the use of the novel type of MR beam expander (see EP 1 318 418 A1) with the strong disperse properties that provides tunable filtering of optical radiation with the super-resolution. Wide range tuning (within total C-band or L-band) provides by Bragg diffraction of the guided optical waves by the surface acoustic wave in the planar optical waveguide. The proposed reconfigure OADM of one square centimeter size can have the 3dB optical bandwidth around 0.1 nm, good sidelobes suppression (-29 dB), moderate internal losses (-4 dB), small switching time (2 mks) and high temperature stability (0.01 nm/K), simultaneously. Simulated parameters of OADM multiply times exceeded the principal limitation of other types of acoustooptic devices. Given OADM at the wavelength of 1550 nm can handle up to 200 tunable wavelength channels spaced by 25 GHz. Presented results are very promising and may stimulate experimental investigation and development of the novel types of MR acoustooptic devices (see EP 1 316 839 A1) that can make the base of the future intelligent dense wavelength-division multiplexing (DWDM) fiber optical networks with 25 GHz and 12.5 GHz wavelength ITU grid.

U4-A-4 513AB 2:15 p.m.

HIGH FREQUENCY ULTRASOUND DETECTION USING FABRY-PEROT OPTICAL ETALON

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Optical methods for ultrasound detection have been investigated for at least several decades exploring wide variety of techniques. Optical detection of ultrasound provides a unique and appealing way of forming detector arrays (1D or 2D) using either raster beam scanning or simultaneous array detection exploiting wide area illumination. The etalon based optical techniques are of a particular interest, due to their relatively high sensitivities, which result from multiple optical reflections within the resonance etalon structure. Detector arrays formed by etalon based techniques are characterized by high element density and small element active area, therefore, enabling high resolution imaging at high ultrasonic frequencies (typically 10-50MHz). Yet, a number of technical difficulties still prevent the use of etalon based techniques in high-resolution medical imaging. Those include performance issues such as insufficient signal to noise ratio (SNR) and cost related issues arising from the complexity of the optical system required for scanning, tuning and stabilization. The difficulty in using complex optical scanning system is even more pronounced in minimally invasive medical imaging applications (e.g. intravascular imaging) where compact and robust design is essential. In this paper we present an application of optical etalon structure for very high frequency ultrasound detection (exceeding 100MHz). A thin polymer Fabry-Perot etalon (3.5 um thickness) has been fabricated using spin coating of SU-8 photoresist (epoxy based negative resist) on a glass substrate and using gold evaporation forming partially reflecting mirrors on both faces of the polymer layer. The choice of using SU-8 photoresist as an optical element was made due to its excellent optical properties and the flexibility in designing a patterned optical element using photolithography. The optical resonator formed by the etalon structure has a measured finesse (ratio of free spectral range to the resonator bandwidth) of about 10. The characteristic broadband response of the optical signal was demonstrated by insonifying the etalon using two different ultrasound transducers and recording the resulting intensity modulations of optical reflection from the etalon. A 5MHz (10mm area, flat, PZT) transducer was used for the low MHz frequency region and an 85MHz (2mm area, 4mm focal length, PVDF) transducer was used for studying the high frequency region. The optical reflection signal was compared to the pulse/echo signal detected by the same ultrasound transducers. The measured SNR of the optical detection system was 20 fold less than that of the pulse/echo signal in both low frequency and high frequency range. Ways of improving the SNR by modifying the etalon fabrication process, yielding etalon structures of higher quality, will be discussed. A scheme for wavelength encoding of individual array element signal is proposed, facilitating optical addressing of array elements as an alternative to mechanical beam scanning. This method of addressing different array elements is particularly suitable for realizing high-resolution intravascular imaging devices.

U4-A-5 513AB 2:30 p.m.

CHARACTERISTICS OF ACOUSTOOPTIC DEVICES FOR GENERATING SYMMETRIC DIFFRACTED SCANNING BEAMS

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This paper presents analysis and comparison of acoustooptic device types for generating symmetric diffracted scanning beams. This is a special mode of operation with applications such as dynamic beam tracking and control 1 and variable beam splitting. This mode differs from most acoustooptic device operation, typically based on Bragg single sideband mode. Configurations of interest include: Raman Nath (short interaction length -low Q or L/L0); phased array, and birefringent phase matched all in axial symmetric modes - where the input optical beam is normal to the main acoustic beam axis. Primary considerations are the acoustooptic bandshapes and diffraction efficiency per input power 2 . It is found that the axial birefringent diffraction modes and acoustic array beam steering modes provide higher diffraction efficiency for allowable bandshape ripple for comparable material constants. This is especially pronounced for small scanning fractional bandwidth compared to an octave

1. D. L. Hecht, S. Uma, R. Matusiak, R. Kowalski, E. Shrader Optical Beam Position Active Sensing and Control using Acoustooptic Satellite Beams. Proceedings IEEE Ultrasonics Symposim 2003, Honolulu, HI Oct. 7, 2003

2. D. L. Hecht. Characteristics of Acoustooptic Devices for Signal Proceedings. IEEE 1985 Ultrasonics Symposim, Oct. 16-18, 1985 San Francisco, CA, pp. 369-380.

U4-A-6 513AB 2:45 p.m.

THE FORMATION OF TWO-BEAM TECHNOLOGICAL LASER WITH USE OF THE HIGH EFFICIENCY ACOUSTOOPTIC MODULATOR

S. ANTONOV[1], V. PROKLOV*[1], Y. REZVOV[2], L. CHESNOKOV[1], and V. CHESNOKOV[1], [1]Institute of Radio Endineering and Electronics RAS, [2]Novomoskovskii Institute of Russian Chemistry and Technology University.
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A numerous engraving laser systems based on the use of the amplitude modulated light beam from power technological lasers have a serious problems with making a facility to work with two different regimes- one beam output and two beam one under the same beam intensity with an appropriate modulation contrast. Unfortunately, the recently used used technique with implementation of the acoustooptic modulators (AOM) offers the only one beam regime [1], because of in accordance with the nonlinear AO theory [2] a simple use

of AOM in a case of two driving frequencies will be accompanied with the decrease of obtainable diffraction efficiency (below 33% in each beam) and the loss of modulation contrast due to remarkable growth of two side lobes related to two-tone third order intermodulations (up to 18% each of two). The present work investigates the possibility to overcome the mentioned problems of the AOM usage in the engraving laser systems by means of the adaptive AOM driving by the properly electronically corrected signals. There were developed the theoretical arguments for the possibility of the appropriate driving signals synthesis for the AOM operation with power technological lasers. The detailed experimental investigations with the widely used AOM based on TeO_2 crystals have shown a satisfactory agreement with corresponding theoretical considerations as well as demonstrated a rather good practical results. [1] S.N.Antonov, V.I.Mirgorodsky, Technical Physics, v.49, no.1, 2004, pp.83-86/ [2] D.L.Hecht, IEEE Trans., 1977, .SU-24, No. 1, pp. 7-17.
This work was supported by the Russian Basic Research Foundation, Project 03-02-16754.

Session: U5-A

SAW DEVICE MODELING
Chair: V. Plessky
GVR Trade SA

U5-A-1 512C-H 1:30 p.m.

PREDICTION OF THE P-MATRIX PARAMETERS DISPERSION USING PERIODIC FEM/BEM ANALYSIS

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A lot of work has been devoted to the simulation of electrical response of SAW devices. Even if some sophisticated models were developed during the last twenty years, most people still use simple COM or P-Matrix approach to design SAW components: it provides a fast and accurate simulation, which can be used in optimization loops. This representation is based on the knowledge of independent parameters, representative of the SAW emission and propagation under a grating of electrodes. Thus, to feed P-Matrix simulator, the electro-acoustic waves need to be accurately characterized in terms of phase velocity, reflection coefficient, coupling factor and propagation losses. Those P-Matrix parameters are usually estimated for one period, assuming a propagation under an infinite periodic grating of electrodes. They are extracted from the computation of the harmonic admittance and the dispersion curve [1]. Up to that day, all parameters are supposed frequency independent. This is a pretty good assumption for Rayleigh waves and IF filters, whose relative frequency bandwidths are small. But this is no more appropriate for RF applications, wide band devices or dispersive media. For instance, the phase velocity of leaky waves on Y+42° rotated lithium tantalate are known to be frequency dependent. The corresponding dispersion laws are usually fitted on experiments, but are valid only for a given material and cut, a given type of wave, and a given range of metallization height end ratio [2]. In this work, a general approach is proposed to predict the frequency dependence of the P-Matrix parameters. It is based on periodic FEM/BEM simulations and dispersion curve computations. Assuming a specific variation of the reflection coefficient with frequency, all dispersions laws are obtained in the neighborhood of the first stop band. The computed frequency dependences of P-Matrix parameters are reported and discussed for different types of substrate and wave. In addition, this technique is applied to well known leaky waves. An original variation of their losses is found and compared to experiments and already published material. Finally, the dispersion laws are introduced into P-Matrix formalism to simulate complete filters built on lithium tantalate and niobate. The corresponding simulations are compared to experiments and to finite transducer simulations, in which dispersion phenomena are naturally taken into account.

[1] P. Ventura, J. M. Hode, M. Solal, J. Desbois, J. Ribbe, Numerical Method for SAW propagation characterization, Proc. IEEE Ultrason. Symp. (1998), pp. 175-186.

[2] V. P. Plessky, D.P. Chen and C.S. Hartmann, Patch Improvements to COM Model for Leaky waves, Proc. IEEE Ultrason. Symp., pp 297-300 (1994).

U5-A-2 512C-H 1:45 p.m.

MODIFIED P-MATRIX MODEL AND IT'S IMPLEMENTATION FOR DESIGH OF SAW RESONATOR FILTERS

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Along with the equivalent circuit model and the Coupling-of-Modes model the P-matrix model is one of the most frequently used model for design of SAW low-loss filters. Classical P-matrix model stipulates that the P-matrixes of the simple basic cell like single electrod must be multiplied to get the P-matrix of the whole SAW element like grating or IDT. It requires a lot of computations for resonator filters that usually contain IDTs and gratings with large numbers of electrodes. There is a variant of the P-matrix model developed by Morgan [1] with simple design formulas for uniform grating. But that variant does not take into account propagation losses which is very important for many cases especially for LSAW and STW devices. The author has managed to take into account propagation losses in the Morgans variant of P-matrix model and to get relative simple design formulas for uniform grating and uniform IDT not depending on electrode number. That model was implemented for SAW resonator filter design software. By using that software the resonator filters on quartz [2], RF filters on 42LT[3] and the coupled resonator filters [4] were designed. In many cases the parasitic elements like the self- and mutual-inductance of bonding wires, the capacitance of package pads etc. strongly affect the resonator filter parameters. In some cases that influence can be useful for improving the filter parameters.

The easiest way to take that circumstance into design is to use standard electric circuit software. In this paper new variant P-matrix model is described in detail. Also a method showing how to combine SAW filter and electric circuit software is reported. All these materials are illustrated by results of several designs with experimental responses. [1] D.P. Morgan, "Reflective Array Modeling for SAW Transdusers", IEEE 1995 Ultrason. Symp. Proc., pp.215-220. [2] V.B. Chvets, V.S. Orlov, A.N. Rusakov, A.L. Schwarz, "Design of Narrow-Band Transversely Coupled and Balanced Bridge Resonator Filters Using Equivalent Circuit and P-Matrix Models", IEEE 2000 Ultrason. Symp. Proc., pp.79-82. [3] A.N. Rusakov, V.S. Orlov, "Application of Modified P-Matrix Model to the Simulation of Radio Frequency LSAW Filters", IEEE 2001 Ultrason. Symp. Proc., pp.7-11. [4] A.N. Rusakov, J.D. Dai, R.J. Kansy, "Design of Wide Band SAW Coupled Resonator Filters on Quartz", IEEE 2003 Ultrason. Symp. Proc., pp.513-517.

U5-A-3 512C-H 2:00 p.m.

WAVELETS CONSTRUCTED FROM SPECTRAL DOMAIN ASYMPTOTIC TAILS OF GREEN'S FUNCTIONS

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The boundary element method (BEM) is a powerful technique for obtaining approximate solutions in SAW devices. BEM discretizes the underlying integrals and generates a discrete version of the original problem. Generally speaking the impedance matrices arising in the BEM applications are dense. This property is a serious deficiency in most applications. Wavelets have been proposed to remedy this shortcoming. However, much remains to be achieved in constructing problem-specific wavelets, which would guarantee the desired degree of sparseness. This paper addresses a logical continuation of an earlier work presented three years ago at this conference. There, we demonstrated the existence and construction of a scaling function and the associated wavelet derived from the electrostatic Green's function in spectral domain. We showed that the resulting wavelet satisfies the axioms of the multiresolution analysis (MRA). On the hand, we showed that the application of our technique to general Green's functions merely produces shift-invariant bases, but fails to generate wavelets. In this work we generalize our previous ideas and construct scaling functions and wavelets based on the far-field asymptotic tails of the SAW and BAW Green's functions in spectral domain. In accordance with the Heisenberg uncertainty principle these asymptotic terms correspond to the quasi-static near-field expansion terms of the Green's functions. It will be demonstrated that the resulting wavelets being spline wavelets satisfy the criteria of the MRA upon construction. The most significant insight is the appearance of spline wavelets as the most natural analyzing functions for the field analysis of SAW and BAW devices. We apply

our results to field problems arising in SAW and BAW devices and discuss the properties of the resulting sparse matrices.
The Support provided by EPCOS, Munich, Germany is gratefully appreciated.

U5-A-4 512C-H 2:15 p.m.

QUASI-STATIC TRANSDUCTION IN MECHANICALLY-REFLECTIVE GRATINGS, WITH APPLICATION TO STW TRANSDUCERS

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Interdigital transducers for surface acoustic waves are often affected by internal electrode reflections arising from either mechanical or electrical loading. Mechanical loading is usually significant if the electrode thickness is more than about 1%, which is often the case. However, electrical loading usually has little effect if the substrate is weakly piezoelectric, as in the case of quartz for example. In this case the piezoelectric coupling can be analysed by making the assumption that it has no effect on the reflections. This implies that the transduction process can be handled by a quasi- static analysis, as done earlier [1]. This is essentially an electrostatic analysis which ignores electrode reflections. It can be illustrated by considering the reception of SAW's by a shorted transducer. If the transducer is non-reflective (e.g. the double-electrode type), each electrode generates a current which is directly related to the electrostatic element factor. If the transducer has internal reflections arising from mechanical effects, the same method can be applied but it is necessary to include contributions from the waves incident on the electrode from both sides. For a transducer with regular electrodes, the required element factor is a simple algebraic expression. For a launching transducer, the generation process can be deduced by reciprocity. This method is developed here to derive the COM parameters of a transducer. The short-circuit current gives the COM transduction parameter. For consistency with the COM equations, the reflection parameters for the open- and short-circuit cases differ by an amount depending on the transduction parameter. Consequently, the stop bands for the open- and short-circuit cases have different widths. For a surface wave on quartz, this method is similar to the earlier Reflective Array Model [2]. However, it can be applied more generally, including other waves such as layered Rayleigh waves, BGS waves and Love waves. This paper considers in particular STW's in quartz. The STW can be viewed as an infinite sum of Floquet components, each having an associated surface potential. For each component the above quasi-static method can be applied, thus giving the transduction parameter. This yields a new and convenient way of analysing transduction for STW's.

[1]. D.P. Morgan. "Surface-Wave Devices for Signal Processing". Elsevier, 1991 [2]. D.P. Morgan. "Reflective Array Modelling for Reflective and Directional SAW Transducers". IEEE Trans. UFFC, vol. 45, pp. 152-157 (1998)

U5-A-5 512C-H 2:30 p.m.

FAST CALCULATION OF GRADIENTS AND DIFFERENCE VECTORS OF IDT'S P MATRIX

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The transduction and reflection weighting coefficients of SPUDTs are usually determined by optimization methods. Some methods need gradients or the difference vectors of IDT's P matrix in order to calculate these quantities of the error function. The difference vector is defined by the change of the P matrix due to finitely large steps of the weighting coefficients. When a gradient component is calculated numerically, solely one weighting coefficient of solely one cell is changed. Nevertheless, the P matrices of all cells are calculated for the changed case. That required unneeded computing time. Shishkin [1] formulated differential equations by means of which the derivations of the P matrices can be attributed to the unchanged P matrices. This way is a differential approximation that is not applicable to finitely large changes of the weighting coefficients. The purpose of the proposed paper is to show that P matrix gradients can be attributed to the P matrix without differential approximation as well. Therefore, the method described is not only applicable for the calculation of gradients but also of difference vectors. The P matrix is transferred to stackable matrices and vectors. Solely the gradient component of the P matrix of the cell the weighting coefficients of which are changed is calculated analytically or numerically whereas the weighting coefficients of the remaining cells are not changed and therefore they have not to be calculated once more. By this way, the components of the difference vector can be obtained, too. The gradient or the difference vector of the entire transducer is obtained by cascading the gradient or difference vector component of the P matrix of the respective cell and the unchanged P matrices of the remaining cells. The calculation of the gradient or difference vector of the error function is based on the corresponding quantities of the transducers' P matrix. The computing time amounts 1/N of the time for the conventional numerical calculation only. N is the number of cells in the filter considered. The method suggested is applicable to all problems for which gradients or difference vectors of stack matrices play an important role, for instance for waveguides consisting of some regions of different phase velocity. [1] S. L. Shishkin, 2000 IEEE Ultrasonics Symposium Proceedings, pp. 149-153.

U5-A-6 512C-H 2:45 p.m.

ON THE POLYNOMIAL APPROXIMATION OF THE DISPERSIVE COM-PARAMETERS

B. V. SVESHNIKOV*[1], V. I. CHEREDNICK[1], and K. K. BHATTACHARJEE[2],
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In case of leaky surface acoustic waves (LSAWs) the key local characteristics (Coupling of Mode- or COM-parameters), describing the periods of infinite short-circuited regular grating and infinite interdigital transducer, acquire a dispersive nature. This dispersion appears, firstly, due to resonant scattering of the counter-propagating leaky waves into other acoustic modes on the short-circuited grating, and, secondly, because of the parasitic radiation of the bulk acoustic wave (BAW) modes by an interdigital transducer. Dispersion in COM-parameters may be evaluated with the help of a known extraction algorithm by proper analysis of the dispersion characteristics of an infinite regular grating and the admittance per period of an infinite interdigital transducer, found numerically by using the FEMSDA-like software [1]. Thus, all COM-parameters are influenced by frequency also, besides the grating input parameters (GIPs), such as, metallization ratio (w/p) and normalized thickness of rectangular fingers (h/p), where p = the grating pitch. Note, the form factor of the non-rectangular electrodes (trapezoidal, for example) may become a GIP too. Unfortunately, the dispersion portraits of COM-parameters have rather complex shapes. However, one favorable circumstance facilitates their approximation by polynomials. The estimation method, proposed in the present paper, assumes a sub-division of the frequency domain onto a set of intervals defined by the checking frequency points. These points possess a clear physical sense and depend on GIPs as a whole. Within each of these intervals the frequency dependence of every COM-parameter has a quite smooth form, allowing us to utilize a polynomial approximation of the required characteristics as functions of both GIPs and normalized frequency fn=f*p/Vn, where Vn = normalizing velocity. At this time, when looking into the reflection and dissipation coefficients per period of a shorted grating, the corresponding checking frequency points relate to the LSAW scattering on a grating into (i) Rayleigh mode, as well to (ii) slow shear (SS), (iii) fast shear (FS), and (iv) longitudinal (L) bulk wave modes. On the other hand, the checking points, being related to the dispersion properties of both the transduction and the total dissipation coefficients, which characterize the collective acoustic radiation of the leaky and bulk waves by an interdigital transducer under external voltage, are linked with the frequencies marking the onset of radiation into SS-, FS-, and L-BAW modes: fn(j)=V(j)/(2Vn), where V(j) = velocity of j-th BAW mode along a direction parallel to the substrate surface. The polynomial approximation of the COM-parameter dependences on both GIPs and frequency allows us to accelerate dramatically the simulation tools (based on the widely used COM-analysis or P-matrix modeling) needed to synthesize the modern LSAW-devices.

[1] B.V. Sveshnikov, A.P. Shitvov, and K.K. Bhattacharjee, Evaluation of Dispersion in COM Parameters, IEEE Ultrasonics Symposium Proceedings, 2003, pp. 715-719

Session: FE1-A

THIN FILM I
Chair: S. McKinstry
The Pennsylvania State University

FE1-A-1 513CD 1:30 p.m.

USING THE CANTILEVER CONTACT RESONANCE IN VOLTAGE-MODULATED FORCE MICROSCOPY TO STUDY THE ELECTROMECHANICAL PROPERTIES OF THIN FILMS

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Piezoresponse scanning force microscopy (PFM) has turned into an established technique for imaging ferroelectric domains in ferroelectric thin films. Since both the ferroelectric-electromechanical as well as the electrostatic interaction have been found to contribute to the electrically-induced cantilever vibration, the measurement technique may be named voltage modulated scanning force microscopy in contact mode.

It has been established that, at least for soft cantilevers, the piezoresponse signal is not only dependent on the elastic properties of the material under investigation but also on the elastic properties of the cantilever. Due to this dependency, the cantilever response and therefore the measured properties depend on the frequency of the small AC testing voltage. At the contact resonance the cantilever response is maximum and this increased sensitivity can be used to decrease the voltage applied to the sample. We will show that using the hysteretic ferroelectric switching, it is possible to separate the signal into its components (viz. electromechanical and electrostatic contributions).

Additionally, the measurement frequency can be tuned so that higher harmonics of the electromechanical response can be detected at the cantilever resonance, this providing information about the higher-order electromechanical coefficients.

Our results are of crucial importance in the study of ferroelectric and electromechanical nanostructures.

FE1-A-2 513CD 1:45 p.m.

SIMULATION AND MEASUREMENTS OF THE PIEZOELECTRIC PROPERTIES RESPONSE (D_{33}) OF PIEZOELECTRIC LAYERED THIN FILM STRUCTURES INFLUENCED BY THE TOP-ELECTRODE SIZE

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Layered thin film structures of tetragonal lead zirconate titanate (PZT) and platinum electrodes on silicon substrates are commonly used e.g. in piezoelectric actuator and sensor devices. Reduction of the effective piezoelectric coefficient $d_{33,eff}$ due to substrate clamping is already reported [1]. This work investigates the influence of varying elastic and geometrical properties of substrate, electrodes, and piezoelectric thin film on the effective piezoelectric small-signal coefficient $d_{33,eff}$ of the structure by means of finite element simulations. Beside the clamping effect under electrical operating conditions also a calculation of the influence of mechanical stresses induced by the last thermal processing step are included. Cooling down from an assumed stress free state during crystallization at 700°C down to room temperature will be investigated.

Additionally, significant decreasing piezoelectric properties have been observed with decreasing top electrode size. These results are obtained by measurements of the effective piezoelectric small-signal coefficient $d_{33,eff}$ and the piezoelectric large signal-strain S using a double-beam laser interferometer and are verified by finite element simulations too. Samples are investigated with squared top electrodes with dimensions of 5 mm down to 100 μm edge length. The loss of $d_{33,eff}$ is as high as 75 %, whereas the influence on the relative permittivity is only small. In combination with the simulations it therefore can be concluded that the source of the pad size effect on the measured piezoelectric properties can be attributed to the mechanics of the layered structure.

[1] A. Barzegar, D. Damjanovic, N. Ledermann, and P. Muralt, J. Appl. Phys. 93, 4756 (2003)

FE1-A-3 513CD 2:00 p.m.

APPLICATION OF PZT FILMS TO LARGE-STROKE, CONTINUOUS MEMBRANE DEFORMABLE MIRRORS

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Future ultra-large, ultra-lightweight space telescopes require large-area deformable mirrors (DMs) with thick (>10 μm) silicon membranes and a high-density actuator array [1]. Several micromachined DMs have been reported; however, they showed high-voltage operation (200-700V) [1-4], marginal surface quality [1,2], or high influence function [2,3]. In order to satisfy the requirements of future space telescopes, an actuator membrane for a DM must show > 4 μm stroke at 50 V and > 100 N/m stiffness. To achieve these goals, PZT films between 2 and 8 μm in thickness have been deposited on 4 wafers in our group, using a sol-gel process by spin-coating the precursor solution onto platinum coated device silicon substrates. After deposition of a single layer, the film is pyrolyzed to remove organics and heat-treated (typically at 700 °C) to crystallize the film. The resulting films typically show dielectric constants of about 1000, loss tangents of about 2-3%, remanent polarizations >20μC/cm^2, and effective transverse piezoelectric coefficients ($e_{31,f}$) of 5 to 7C/m^2. Using these PZT thick films, a series of actuators with metal/PZT/metal sandwich structures have been fabricated. Actuator deflection measurements show that a deflection of 5.4 μm has been successfully obtained at 50V for an actuator with a membrane diameter of 2.5mm and a electrode/membrane ratio of 60% together with a thickness of Si (15μm)/PZT(2μm). The resonant frequency of the membrane actuator was found to be 40 kHz, which far exceeds the bandwidth requirement of most deformable mirrors (1-3 kHz). From this resonant frequency, the stiffness of the actuator is determined to be 1600N/m, which is much larger than the requirement of 100 N/m. The performance of the actuator comfirms that the sol-gel derived PZT thick films can satisfy the requirements for large-area, continuous thick membrane deformable mirrors.

Reference: 1. T. Bifano et al., Continuous-Membrane Surface-Micromachined Silicon Deformable Mirror, Opt. Eng. 36 (5), p.1354 May 1997. 2. J. Mansell et al., Silicon Deformable Mirrors and CMOS-based Wavefront Sensors, SPIE International Conference, High-Resolution Wavefront Control, San Diego, USA, Aug., 2000, pp. 15-25. 3. G. Vdovin, Optimization-based Operation of Micromachined Deformable Mirrors, SPIE Conf. On Adaptive Optical System Technology, Kona, Hawaii, March 1998, pp. 902-909. 4. M. J. Mescher, A Novel High-Speed Piezoelectric Deformable Varifocal Mirror for Optical Applications, Proceedings of IEEE, Sensors, June, 2002, 1, pp.541-546.

FE1-A-4 513CD 2:15 p.m.

EPITAXIAL THICK FILM HETEROSTRUCTURES OF $PB(MG_{1/3}NB_{2/3})O_3$-$PBTIO_3$ RELAXOR FERROELECTRIC FILMS ON SILICON FOR HIGH PERFORMANCE ELECTROMECHANICAL SYSTEMS

D. M. KIM*[1], C. B. EOM[1], J. OUYANG[2], V. NAGARAJAN[2], R. RAMESH[3], V. VAITHYANATHAN[4], D. G. SCHLOM[4], W. TIAN[5], and X. Q. PAN[5], [1]Department of Materials Science and Engineering, University of Wisconsin, [2]Department of Materials and Nuclear Engineering, University of Maryland, [3]Department of

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Relaxor ferroelectrics such as $Pb(Mg_{1/3}Nb_{2/3})O_3$-$PbTiO_3$ (PMN-PT) have attracted much attention because of their excellent piezoelectric and electromechanical properties. Major challenge is to fabricate epitaxial PMN-PT films between epitaxial metallic oxides and integrate them into microelectromechanical systems (MEMS) on Si wafer. We have studied the piezoelectric properties of epitaxial PMN-PT thick films grown by magnetron sputtering on the Si(001) substrates. The highest longitudinal piezoelectric coefficient was realized on silicon substrates by using epitaxial PMN-PT and nanostructuring it to reduce the substrate constraint. When subdivided into 1 μm^2 capacitors by focused ion beam processing, a 4 μm thick film shows a low-field d_{33} of 800 pm/V that increases to over 1200 pm/V under bias. These epitaxial heterostructures can be used for multilayered MEMS devices with high strain and low driving voltage for miniature devices, high frequency ultrasound transducer arrays for medical ultrasound imaging, tunable dielectrics, and capacitors for charge and energy storage. We will discuss the effect of substrate constraint and thermal strain mismatch on the piezoelectric responses in heteroepitaxial PMN-PT thick films on Si.

FE1-A-5 513CD 2:30 p.m. (Invited)

STRUCTURE AND FERROELECTRIC PROPERTIES OF SPUTTERED PMNT THIN FILMS

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Ferroelectric properties of thin film relaxor PMNT, (1-x) $PbMg_{1/3}Nb_{2/3}O_3xPbTiO_3$, will be different from those of bulk PMNT probably due to the presence of a stress. Thin films of PMNT with x=0 to 0.35, morphological phase boundary, MPB, at x$\sim$0.35 for bulk, were hetero-epitaxially grown on La-doped conductive (100) $SrTiO_3$ (ST) and Pt coated MgO, (100)Pt/(100)MgO, substrates by planar magnetron sputtering. The growth temperature was 500 to 650^{O}C. Typical film thickness was 100 to 2000 nm. Most of the sputtered PMNT thin films included pyrochlore and perovskite phase. The population of the pyrochlore phase increased with the increase of the film thickness. Pyrochlore free perovskite PMNT thin films were obtained at a narrow deposition condition on the ST substrates. At the substrate temperature 510^{O}C, single crystal PMNT thin films were epitaxially grown on the ST substrates with tetragonal structure of (001) orientation as a minor phase.The sputtered PMNT thin films showed bulk relaxor-like dielectric properties showing the frequency dispersion of permittivity with diffused temperature anomaly. However, the dielectric response of the sputtered PMNT thin films showed extremely broad temperature anomaly. The room temperature permittivity and their polarization were almost the same to bulk crystals. The maximum permittivity at Curie temperature was strongly reduced: For pyrochlore free single crystal PMN-35PT (x=0.35) thin films on ST substartes, the room temperature permittivity was 2700 and the maximum permittivity was 5000 at 100kHz with polarization $P_S=20\mu C/cm^2$. The piezoelectric coefficient of d_{33} and d_{31} for PMN-35PT films of 1800nm thick were 270 and 105 pC/N, respectively at ac applied voltage of 50V, which were lower than bulk values. The PMNT thin films with x=0 to 0.3 showed tetragonal structure at room temperature where bulk crystals showed rhombohedral structure. Sputtered PMNT thin films at bulk MPB condition also showed tetragonal structure. The highly mechanical constraints created a modified structural and ferroelectric properties.

Session: FC1-A

HISTORICAL OVERVIEWS
Chair: F. Hickernell
The University of Arizona

FC1-A-1 511CF 1:30 p.m.
(Invited)

DISRUPTIVE TECHNOLOGIES AND DEAD ENDS: TIME AND FREQUENCY STANDARDS IN THE 1930S

C. E. STEPHENS*, Smithsonian Institution.
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This historical presentation focuses on a set of unusual electromechanical time and frequency standards, developed in the late 1930s by Henry E. Warren of Ashland, Mass. Installed at Palomar and Lick astronomical observatories for driving the telescopes to follow the motions of celestial objects, Warren's standards were based on a wire that vibrated at a constant, but tunable rate, much like a violin string. Warren promoted his invention as an efficient and inexpensive alternative to his era's other frequency standards—high-end pendulum clocks, quartz resonators and metal tuning forks.

Warren's devices for the California observatories, replaced with electronic computers in the 1970s and now largely forgotten, are a fascinating technological dead end worthy of study for illuminating the competition among emerging frequency-control technologies in the 1930s and 1940s. Standard historical accounts sketch the triumphant rise of quartz standards, a "disruptive technology" in the terminology of Harvard's Clayton Christensen, that unseated mechanical time and frequency standards as the dominant method. Astronomical observatories around the world supposedly replaced their inferior mechanical time standards with quartz "clocks" in the 1930s and 1940s. But this paper will show that in the 1930s and 1940s, quartz was by no means the only method for establishing and keeping precise time and frequency, and actually very few observatories installed quartz standards.

Henry Warren (1872-1957) developed his observatory time standards toward the end of a career dedicated to solving problems related to frequency control. An MIT graduate with a degree in electrical engineering, Warren was simultaneously superintendent and chief engineer of the Lombard Governor Company of Ashland, Mass., from about 1905 onward. There he tackled the problems of controlling the frequency of electrical current generated from turbines at major electric power companies across the United States. In this context he invented a clock device in 1916 for detecting errors in frequency in the current emanating from power stations, and the device made it possible to regulate that frequency and standardize it to 60 cycles per second. A standard frequency permitted the linking of power stations in a common supply grid, and, coincidentally, enabled Warren to make his most enduring contribution to American life–the domestic electric clock. After successful experiments with small synchronous motors in the first decades of the 20th century, he secured capital from General Electric Corp. and developed the Warren Telechron Clock Co. to manufacture stylish timepieces that plugged right into house current.

Warren and his numerous inventions, especially the devices he developed for Palomar and Lick, are emblematic of the multiple paths—mechanical, electromechanical and electrical—inventors explored as they helped shape the transition from a mechanical to an electronic world. Sometimes the paths led to enduring technologies with broad impact, and other times the paths led nowhere.

FC1-A-2 511CF 2:00 p.m. (Invited)

BUILDING AN INDUSTRY FROM SCRATCH: THE QUARTZ CRYSTAL OSCILLATOR INDUSTRY OF WORLD WAR II

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Prior to World War II, the use of quartz crystal oscillators for frequency control took place primarily within the domains of the amateur (or ham) and the commercial radio broadcasters. The oscillator manufacturing industry, such as it was, was able to accommodate this small market through an artisan (i.e., making oscillators one at a time by hand) rather than a mass production approach. With the U.S. militarys switch to crystal control just prior to the war, the reality of crystal oscillator production changed dramatically. With the coming of war, the military suddenly needed millions of oscillators; a task far beyond the current industry which had never produced more than 100,000 units in a single year. Within a year, a truly mass-production industry was up and running, producing almost 6 million units in 1942 alone (and over two million units per month by the end of the war).

The development of this industry depended upon the efforts of three separate entities: the U.S. Army Signal Corps, the War Production Board and its attendant agencies, and the civilian manufacturers (both large and small). The work of these three groups was very interconnected. Breakthroughs in machinery and techniques for simultaneously grinding multiple quartz blanks were achieved both in Signal Corps research labs and in basement workshops. Increased knowledge of the electrical properties and the usable types of quartz crystals resulted from the work of WPB geologists and that of independent manufacturers. Wide-scale distribution of information was accomplished by the Signal Corps Quartz Crystal Section and through the network of subcontractors working for the Galvin Radio Corporation.

This episode in the history of frequency control, the genesis of a truly mass-production industry for crystal oscillators, presents a great deal of lessons in the development of a technology, the industrial engineering related to the manufacture of a high-precision electrical component, the response of a nation to a war-time technological and industrial crisis, and the successful interaction of federal, military, and civilian sectors of the country. Drawing on five years of research ranging from analysis of Signal Corps records to personal interviews and memoirs of participants, this talk will give an overview of the war-time development of this most important industry.

FC1-A-3 511CF 2:30 p.m.
(Invited)
HISTORICAL HIGHLIGHTS IN ULTRASONICS - 2

K. GRAFF*, Edison Welding Institute.
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A chronology of the history of ultrasonics is one of fascinating discoveries, inventions and uses of this high frequency "branch of acoustics." Behind this record of discovery lie equally fascinating tales of persons and personalities that have laid the groundwork for our still expanding field of science and technology. The "Highlights" presented here will dwell on some of the people and stories behind the scientific headlines of discovery. Ranging from the historically curious to the borders of scandal, the personalities of ultrasonics may prove as interesting as their inventions.

Biosketch

Dr. Karl F. Graff Edison Welding Institute 1250 Arthur E. Adams Drive, Columbus, OH 43221 Tel: 614-688-5269, Fx: 614-688-5001 e-mail. karl_graff@ ewi.org, also, kgraff2@columbus.rr.com

Dr. Graff received his Ph.D. from Cornell University and served on the faculty of The Ohio State University for many years, working in the field of vibrations, ultrasonics and wave propagation. He headed the effort to establish Edison Welding Institute. After retiring as Executive Director of EWI, a position he held from1987 to 2000, he has continued part time as a senior engineer at the institute, working in the area of ultrasonic welding. He continues consulting in ultrasonics, and teaching and advising at OSU.

Session: FC2-A

THIN FILM RESONATORS (FBAR)

Chair: A. Kong
Northrop Grumman Corporation

FC2-A-1 511DE 1:30 p.m.

MATERIALS PROPERTY DEPENDENCE OF THE EFFECTIVE ELECTROMECHANICAL COUPLING COEFFICIENT OF THIN FILM BULK ACOUSTIC WAVE RESONATORS

Q. CHEN*, F. LI, and Q.-M. WANG, University of Pittsburgh.
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The input electric impedance for a three-layer (electrode/piezoelectric film/electrode) thin film bulk acoustic wave resonator is derived by one-dimensional transfer matrix method to describe the thin film resonator behavior, especially the effect of electrode layer on resonator properties. Based on the impedance spectra, the effective coupling coefficient of thin film resonator can be evaluated with respect to the resonator structure and thin film properties. The results for both AlN and PZT thin film resonators reveal that the mechanical Q factor of the thin film piezoelectric material has a significant effect on the effective coupling coefficient of the device. The effective coupling coefficient decreases with the increase of the mechanical quality factor Q. It is also dependent on the thickness and material properties of the electrode layers. For a specific electrode material, a maximum value can be obtained at an appropriate thickness ratio of electrode/piezoelectric layers.
This research is supported by Pittsburgh Digital Greenhouse, a State funded consortium for system-on-a-chip (SOC) technology development.

FC2-A-2 511DE 1:45 p.m.

FABRICATION AND TESTING OF ALN FBARS WITH A SILICON ELECTRODE

L. A. CALLAGHAN*[1], M. V. REQUA[1], V. LUGHI[2], N. C. MACDONALD[1,2], K. L. TURNER[1], and D. R. CLARKE[1,2], [1]Mechanical & Enviromental Engineering Department, University of California - Santa Barbara, [2]Materials Department, University of California - Santa Barbara.
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Introduction Thin film bulk acoustic resonators (FBAR) have been examined for use in new generations of RF devices. A key novelty of the research presented here is that the aluminum nitride is deposited directly on the silicon substrate, which expands silicon integration possibilities. This abstract is a brief overview of the fabrication and testing of thickness-activated piezoelectric AlN membranes.

Fabrication The resonator is a circular shaped membrane with a diameter of 300 μm. It consists of the AlN piezoelectric layer sandwiched between a top metal electrode and a layer of silicon that acts as both an elastic support layer and an electrode. Below the silicon is the air cavity. The AlN films were sputtered directly on <100> silicon wafers. The AlN films were patterned with a chlorine-based plasma etch, using sputtered TiO_2 as the masking material. The air cavity is created by flipping the sample over and etching the silicon by switching between a SF_6 etch plasma and CF_4 protective polymere. The air cavities created had smooth sidewalls and floors, which are desirable to achieve a higher quality factor in an acoustic device.

Results The tested resonators were designed and fabricated to operate at acoustic wavelengths on the order of 1 micron. Resonance occurs when the wavelength, l, is an integer quotient of half of the device acoustic length, d. For a three-layered FBAR device with a single frequency source, the resonant frequencies become: $f_o = n/2(d_1/v_1 + d_2/v_2 + d_3/v_3)^{-1}$ where v is the acoustic velocity and the indexes 1,2,3 represent the top electrode, piezoelectric film and silicon membrane respectively. For material properties and dimensions of experimental devices (AlN 1.7 mm, Si 11 mm, Au 100 nm) the fundamental frequency (n=1) was calculated to be 325.6 MHz. Reflection coefficients for the resonators were measured using a HP VNA 8722D at atmospheric pressure. The over-moded resonances occurring at the 5th 9th harmonics can be observed from the scattering parameter data. The experimental primary mode frequency is 340.5 MHz. Discrepancies between theoretical and experimental resonators can be explained by fabrication variations in resonator thickness.

Conclusion Thickness actuated acoustic devices were fabricated using standard MEMS fabrication techniques. Silicon serves as both and acoustic transmission line and bottom electrode. These devices behave according to predictive acoustic model, which gives a platform to further analytically engineer device performance. Work is currently being done to reduce the noise and increase the quality of the devices along with incorporating substrate-decoupling structures.

Our thanks to Hongtao Xu for help with the network analyzer and RF probe station.

FC2-A-3 511DE 2:00 p.m.

ELECTRICALLY TUNABLE AND SWITCHABLE FILM BULK ACOUSTIC RESONATOR

W. PANG*[1], H. ZHANG[1], H. YU[1], and E. S. KIM[2], [1]University of Southern California, [2]University of Southern California.
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Phase noise of a voltage-controlled oscillator (VCO) based film bulk acoustic resonator (FBAR) and varactors is dominated by the relatively high 1/f noise of the varactors. A VCO can be formed without varactors, using the fact that FBAR frequency can be tuned by varying DC bias between the top electrode and the bottom electrode through piezoelectric stiffening effect in the piezoelectric film of an FBAR. But this approach offers typically only about tens of ppm/V.

Thus, electrically tunable FBAR with broader tuning range is desirable to create wideband VCOs with relatively low phase noise.

This paper describes an electrically tunable and switchable film bulk acoustic resonator (FBAR) that is formed by integrating FBAR with an electrostatic MEMS actuator. An air gap is formed with surface micromachining between the top electrode and piezoelectric ZnO film in FBAR so that a metal electrode bridge is suspended over FBAR. The fabrication process differs from that of a conventional FBAR bulk micromachining process only in steps associated with the top metal electrode construction. Xenon difluoride vapor is used to etch evaporated-silicon sacrificial layer (without attacking the metal and ZnO) and release the top metal bridge with sub-micron air gap. When DC voltage is applied between the floating metal bridge and the bottom electrode of FBAR, the air gap distance (and the series capacitance that the FBAR sees) can be electrostatically varied, and the FBAR resonant frequency can be electrically tuned. Around 0.8% tuning of the series resonant frequency (Δf 18MHz) at 2.3 GHz has been obtained with an electrostatic actuation voltage varying between 12.2 and 27.5V. The frequency tuning capability of 7,800ppm/15V is 6 times larger than what has been demonstrated through piezoelectric stiffening effect (1,220ppm/15V).

The metal bridge can also be operated as an ON/OFF MEMS switch to form a switchable FBAR. The FBAR shows a resonance with Q (quality) factor of more than 100 at 2.2 and 4.0 GHz when we apply DC voltage to pull the top metal bridge to touch the piezoelectric ZnO film, while at zero DC bias no resonance is observed. The resonance ON state is obtained with a DC voltage as low as 6V due to a low spring constant of the bridge and shallow air gap width of 0.4μm.

Moreover, we have come up with an idea to fabricate FBARs with various resonant frequencies on a chip without any additional processing complexity. The idea is to vary the mass density of a mass-loading layer (i.e. top electrode or an additional layer) through forming small holes by standard photolithography, in order to produce FBARs with various resonant frequencies on a single chip.

The electrically switchable FBARs (coupled with the idea of forming FBARs with various resonant frequencies on a chip) will be boon for a multi-standard mobile communication system that covers several different standards for wireless transceivers, and needs multiple banks of filters.

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

FC2-A-4 511DE 2:15 p.m.

A MEMS-BASED QUARTZ RESONATOR TECHNOLOGY FOR GHZ APPLICATIONS

F. STRATTON*, D. CHANG, D. KIRBY, R. JOYCE, T.-Y. HSU, and R. KUBENA, HRL Laboratories, LLC.
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We report on the development of a new quartz resonator technology that allows for the processing and integration of VHF to UHF high-Q oscillators and filters with high-speed silicon or III-V electronics. Current manufacturing technology for quartz resonators does not provide a straightforward method for reducing the size and thereby increasing the frequency of operation into the UHF range. Furthermore, integrating large arrays of precisely tuned structures with high-frequency RF electronics and vacuum packaging the resulting chip at wafer level are not possible with present techniques. This paper describes the successful demonstration of these new wafer bonding and dry plasma etching processes that make quartz-MEMS technology possible. In addition, we present impedance, Q, and temperature sensitivity data along with comparisons to 3-D harmonic and thermal analysis of our most recent VHF - UHF resonators. Our quartz-based MEMS process employs the bonding of a quartz wafer with top-side metalization to a silicon handle wafer for subsequent thinning. Conventional lapping and polishing followed by dry etching with SF_6 in an inductively-coupled high-density plasma has been developed for maintaining sub-nm surface roughness for quartz films thinned below 30 microns. A DRIE process with CF_4 chemistry and bottom-side metalization create the through-wafer vias and the resonator structures on the handle wafer. Vias are used to interconnect the top-side metalization to bottom-side bonding pads. Finally, Au-to-Au thermal compression bonding is used to attach (both electrically and mechanically) the resonators to a high-speed substrate followed by the removal of the handle wafer in either a wet or dry etch. A 2.4-μm-thick shear-mode resonator was tested using Cascade microprobes and an Agilent 4991A impedance analyzer. We obtained a fundamental frequency of 591 MHz and a Q value of 13,470 in air for this device. This yields an f x Q product of 8×10^{12} Hz, which is within a factor of two of the highest frequency-Q product reported to date for any quartz resonator. The motional resistance of this resonator was measured to be 40 Ω, thus providing good impedance matching to external transmission lines. For higher frequency applications, we have designed smaller single-side inverted mesa resonators for 2 GHz fundamental-mode operation that can be fabricated with our process. 3-D admittance analysis of these designs shows that one can maintain greater than 5 MHz separation from the fundamental mode to the nearest anharmonic mode, thus yielding nearly ideal susceptance versus conductance characteristics. For Q's of 5,000 at 2 GHz, the motional resistance is shown to be 25 ohms. Finally, we report on the use of focused-ion-beam (FIB) micromachining for post-process tuning. We show that frequency tuning with 100 ppb accuracy and short-term stability is possible with this technique. For small GHz resonators, FIB tuning is ideal due to its high spatial resolution and monolayer milling control.

The authors would like to thank Dr. John Vig for his valuable technical discussions and support. This project is being funded by DARPA's Microsystems Technology Office under contract DAAB07-02-C-P613.

Session: U1-B

DIRECTIONS IN ULTRASOUND IMAGING

Chair: T. van der Steen
Erasmus University

U1-B-1 510AC 3:30 p.m.
(Invited)

MY 50 YEARS OF MEDICAL IMAGING WITH ULTRASOUND

J. REID*, Drexel University.
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Medical applications of ultrasound to image soft tissues began in the U.S. in the late 1940s. This story follows efforts of the group in Minneapolis, MN to bring ultrasound diagnosis to clinical use in the 1950s, using vacuum tube and quartz crystal technology. The field has developed in concert with technological progress to the present day where digital techniques and semiconductors predominate. Mechanical scanning has been superseded by electronic arrays, although the early work clearly showed the way to the future. Some resistance to new imaging modalities was felt from the medical establishment, to be followed by claims of ownership. Then we turn to echocardiography after its introduction in Sweden, and to the development of Doppler techniques for monitoring blood flow, through this rather personal story of the interaction of engineering and medicine. Along the way the introduction of semiconductor technology and digital techniques revolutionized the field, and the effects are still developing.
My collaborators: John Wild, Herman Schwan. Claude Joyner, Robert Rushmer, Merrill Spencer, Barry Goldberg and many others.

U1-B-2 510AC 4:00 p.m.

PORTABLE, LOW-COST MEDICAL ULTRASOUND DEVICE PROTOTYPE

M. FULLER*[1], K. RANGANATHAN[1], S. ZHOU[1], T. BLALOCK[2], J. HOSSACK[1], and W. WALKER[1,2], [1]Dept. of Biomedical Engineering, University of Virginia, [2]Dept. of Electrical and Computer Engineering, University of Virginia.
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We present test results of a prototype marking the first stage in development of a pocket-sized, sub-$1,000 medical ultrasound device. The ultimate goal is a device consisting of a fully-sampled 2D array, a single custom integrated circuit (IC) containing 1024 channels of receive circuitry, and a novel beamforming algorithm implemented on an inexpensive, off-the-shelf DSP chip. The prototype system consists of a fully-sampled 32x32 element 2D transducer array and a ten-layer, 11" X 11.5" printed circuit board (PCB) containing 16 custom integrated-circuit (IC) receive circuitry chips multiplexed into two bandpass filter stages. RF data is captured and digitized via a commercially available data acquisition

card and stored on a PC for subsequent analysis. The testing of this prototype allows for the characterization of transducer performance, circuit behavior, and anomalies such as cross-talk to facilitate refinement in transducer fabrication and chip design as well as verify assumptions made in the development of our beamforming algorithm and system architecture. The 2D transducer array is fabricated inexpensively by fixing PZT-5H ceramic material on a printed circuit board (PCB) and performing a dicing procedure that ultimately results in a 2D array whose 1024 elements are each electrically connected to dedicated receive channels on the custom ICs by way of surface mount connectors. Each receive circuitry chip contains 64 channels consisting of transmit protection circuitry, a preamplifier and an analog multiplexer. The chips were fabricated in a standard TSMC 0.35 micron CMOS process and each contains an active area of 1.9 mm X 0.9 mm. A watertank experiment was performed involving transmitting from a single-piston ultrasound probe (with 2.25 MHz center frequency) and receiving in the far-field with the prototype 2D array. This approximated the spatially broad transmit beam assumed in our system design and narrowband beamforming approach. Since the data acquisition card in the PC was only capable of receiving two channels simultaneously, 512 separate transmits were required to capture RF data from all 1024 channels and assertion of the multiplexing bits and trigger signals were performed by an on-board programmable logic device. The sampling rate of the acquisition card was 50 MHz and the PRF was 100 Hz. The transducer center frequency was measured with an impedance analyzer to be 3.25 MHz and the yield of active transducer elements was found to be 99%.
This work was supported in part by the Carilion Biomedical Institute and the NIH.

U1-B-3 510AC 4:15 p.m.

REAL TIME 3D IMAGING OF THE BRAIN

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We tested the feasibility of real time three dimensional ultrasound imaging in the brain. The 3D scanner uses a matrix phased array transducer of 512 transmit channels and 256 receive channels operating at 2.5 MHz with a 15 mm diameter footprint. The real time system scans a 65° pyramid producing up to 60 volumetric scans per second and features up to five image planes as well as 3D rendering, 3D pulsed wave and color Doppler. In a human subject, the real time 3D scans produced simultaneous transcranial horizontal (axial), coronal and saggital image planes and real time volume rendered images of the gross anatomy of the brain. In a transcranial sheep model we obtained real time 3D color flow Doppler scans of cerebral vessels as well as perfusion images using bolus injection of contrast agents into the internal carotid artery. Our long term goal includes phase aberration correction of the skull using the 2D array. Phase aberration measurements have been made from both polymer castings

of the temporal bone region and of a fixed human parietal bone. For the casting, average measurements have yielded an rms phase variation of 95 nsec, i.e. approximately $\lambda/4$ at 2.5MHz, with a correlation length of only 1.5 mm. The parietal bone sample had an rms phase variation of 55 nsec and a correlation length of 1.6mm. Such severe aberration data from the skull bone indicate a significant potential improvement in image quality yet to be realized in real time transcranial sonography. With our system we also have the ability to make rapid comparison of 3D beamplots from three independent sources: one instantaneous from our real time C-scan of a point target, one mechanical beamplot, as well as a numerical simulation using Field II. For example, comparisons of an unaberrated beamplot and a beamplot aberrated by the temporal bone show a loss of 9.2 dB and an increase of -6dB beamwidth of 80%.

U1-B-4 510AC 4:30 p.m.

3D CONTRAST HARMONIC ECHOCARDIOGRAPHY

M. M. VOORMOLEN*[1,2], A. BOUAKAZ[1,2], B. J. KRENNING[1], C. T. LANCÉE[1], W. B. VLETTER[1], F. J. TEN CATE[1], and N. DE JONG[1,2], [1]Thoraxcenter, Erasmus MC, [2]ICIN, Interuniversity Cardiology Institute of the Netherlands. Corresponding e-mail: m.voormolen@erasmusmc.nl

Background: Measurement of left ventricular (LV) volume and function is the most common clinical referral question in the echocardiography laboratory. A fast, practical and accurate method would facilitate access to this important diagnostic information. Currently, 2D-echo is employed to determine LV volumes with the use of geometric assumptions of its shape. 3D-echo allows for much more accurate calculation of LV parameters without the use of geometric assumptions. However, the analysis time of 3D-datasets is a limitation. Improved endocardial border delineation with the application of contrast agents should allow for less complex and faster tracing algorithms for LV volume analysis. We developed a fast rotating phased array transducer for 3D-imaging of the heart with harmonic capabilities making it highly suitable for contrast imaging. In this study the feasibility of 3D contrast harmonic imaging (CHI) is evaluated in-vitro and in-vivo.

Method: The array of the transducer contains 64 elements and has a center frequency of 3 MHz with a bandwidth of 85 % (-6 dB). The array is rotated continuously at a speed ranging from 240 to 480 rpm. The typical acquisition time for a 3D-dataset is less than 10 s, which has proven to be conveniently short during clinical application. In-vitro measurements were used to optimize the transmit and receive settings for 3D-CHI. In transmission frequencies ranging from 1.66 to 2.35 MHz and pulse lengths of 1.5, 2 and 2.5 cycles were explored. The receive settings were optimized in terms of center frequency and bandwidth of the receive filter. As contrast agent Sonovue was used at a dilution of 1 over 1000. Determination of the optimal transmit settings was based on the highest contrast to tissue ratio calculated from radio frequency data recorded with a General Electric / VingMed Vivid 5 system. Phantom recordings and reconstructions were made with and without contrast from which the extracted

volumes were compared with the real volumes. Finally the optimal settings were reproduced for patient recordings.

Results: An increase of more than 15 dB in the contrast to tissue ratio was found at the second harmonic compared to the fundamental level at an optimal transmit frequency of 1.74 MHz and a pulse length of 2.5 cycles. For these optimal transmit settings the receive filter was configured with a center frequency of 3.3 MHz and a bandwidth of 1 MHz giving the maximum harmonic amplitude. Using the optimized settings, volume measurements of a LV shaped phantom were performed. Without contrast the extracted volume data resulted in a volume error of 1 %, which was matched with the use of contrast. The results demonstrate the feasibility of accurate volume measurements with 3D-CHI. Ultimately 3D-CHI was used for clinical evaluation of patients. The results revealed improved delineation and successful 4D LV reconstructions.

Conclusions: 3D-CHI is feasible and results in improved border delineation when used in combination with harmonic imaging. Further investigations are required in a larger patient population to determine the improvement with 3D-CHI compared to other techniques like MRI.

This work has been supported by the Technology Foundation STW (RKG.5104).

U1-B-5 510AC 4:45 p.m.

INCREASING FRAME-RATE IN ULTRASOUND IMAGING BY TEMPORAL MORPHING USING TISSUE DOPPLER

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The diagnostic value of ultrasound B-mode sequences of the human heart seems to diminish when the frame rate is low. This often enforces the operator to use a limited size of the scan in order to retain frame rate. The problem becomes more evident when doing duplex Color flow and B-mode scanning, and increases even more in real-time 3D applications.

An obvious way to improve the visual quality of a low frame rate B-mode display is to interpolate between successive frames according to the actual screen update frequency.

In this work we used morphing based on velocity information to improve the quality of interpolated B-mode frames in sequences with low frame rate. Two different sources of information about tissue velocity were investigated: speckle tracking and Doppler signal processing. Based on a priori knowledge of the image, we calculated the velocity field in certain image locations throughout a cardiac cycle. Secondly, we extended the velocity information to the rest of each image frame to produce a velocity estimate for the entire data set. The velocity information was then used to create intermediate, morphed frames, were the frame rate could be chosen arbitrarily.

We applied this technique to data previously used in diagnosis. The quality of the morphed data was evaluated by removing frames from duplex B-mode and tissue Doppler recordings, then replacing the removed frames with morphed ones. The decimation factor was chosen so that the frame rate in the remaining sequence was between 12 and 18 frames per second. The decimated and morphed sequences were compared to the original ones, both frame by frame and as synchronized cine-loops running in true time or in slow motion.

Wall motion scoring is an evaluation of left ventricular wall motion based on the subjective impression of the endocardial echo inward motion towards the centre of the left ventricle and the degree of thickening of the myocardium. The wall motion score was performed on 16 segments of the myocardium for each patient, based on B-mode recordings from three standard cardiac views: apical 2-chamber, 4-chamber and long-axis.

We investigated data from 20 different patients, 10 healthy with normal ventricle and 10 with pathology (myocardial infarction). The 60 data sets were object to wall motion scoring two different times: First as part of the diagnosis, then scored blinded again two years later by the same operator, but the last time with morphed data. The feasibility of the two scorings were compared: With original data, 3.4% of the segments were not possible to score due to poor gray scale visibility, while for the morphed data, the same applied for 5.3%. We found that 92% of the segments had identical scorings in the two cases.

We conclude that the diagnostic value is retained in recordings with frame rates in the range 12 - 18 frames per second.

Session: U2-B
THERAPY: ADVANCED APPLICATIONS
Chair: C. Cain
University of Michigan

U2-B-1 510BD 3:30 p.m.

FINITE ELEMENT ANALYSIS OF TEMPERATURE RISE FROM AN INTEGRATED 3D INTRACARDIAC ECHO AND ULTRASOUND ABLATION TRANSDUCER

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We have previously reported on an integrated 3D intracardiac echo and ultrasound ablation transducer in the same 14 Fr catheter for the treatment of atrial fibrillation. Real-time 3D imaging was achieved with a forward-looking two-dimensional array built on a multi-layer flexible interconnect circuit. The ablation transducer was a ring of 10 MHz PZT-4 (4.5 mm outer diameter, 3.1 mm inner diameter) placed around the imaging array. Application of 5.9 W of electrical power to the ablation transducer produced $I_{SPTA} = 16.1\ W/cm^2$. It was used to heat tissue-mimicking rubber (polyvinyl alcohol cryogel and graphite) with absorption comparable to tissue. Thermocouples embedded in the rubber measured a temperature rise of 14 degrees Celsius after one minute. Recently,

we have used the finite element method to corroborate our experimental findings and to provide guidance in the design of new integrated catheter devices. We have used a procedure previously validated by one of us. The commercial software program LS-PREPOST (LSTC, Livermore, CA) was used to build a three-dimensional mesh with node spacing = 0.5 mm of one-quarter of the acoustic and thermal field. The relative acoustic intensity at each node in the mesh was calculated using Field II software running under Matlab. This relative acoustic intensity was linearly scaled to the experimentally measured value of I_{SPTA}. The commercially available finite element software package LS-DYNA (LSTC, Livermore, CA) was used to perform the thermal analysis. The acoustic intensity values were converted to heat loads and applied to the previously generated mesh. A sixty-second ablation was simulated, a process which took approximately 1.5 hours on a desktop computer with 3 GB RAM. Preliminary results show good agreement between the heat rise measured in our experiments and the heat rise simulated at the measured points. At the end of the simulation, the heat rise was 7 degrees Celsius. The simulation was performed with approximate thermal properties for the experimental rubber, (density = 1000 kg/m^3, heat capacity = 4.2x106 J/m^3 K, thermal conductivity = 0.6 W/m K) which likely resulted in the discrepancy from experiment. In the future we plan to simulate the temperature rise possible in fresh ovine myocardium, a material that is both well characterized acoustically and thermally and more clinically relevant. We plan to simulate a range of ablation transducer geometries and frequencies and compare the temperature patterns from each. This information will be of great use in the design of a new generation of integrated 3D intracardiac echo and ablation transducers.

U2-B-2 510BD 3:45 p.m.

FEASIBILITY OF NONINVASIVE TRANS-ESOPHAGEAL CARDIAC THERMAL ABLATION USING AN ULTRASOUND PHASED ARRAY

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Cardiac arrhythmias (heart rate disorders such as atrial fibrillation, tachycardia/bradycardia) are induced by cardiac electrical conduction system malfunction that triggers abnormal cardiac muscle contraction. Current endocardial arrhythmias treatments use radiofrequency catheter to ablate the malfunctioning cardiac muscle regions. Due to its proximity to heart, esophagus is an ideal ultrasound delivery window. This study proposes a noninvasive trans-esophageal cardiac thermal ablation technique using focused ultrasound. A section of simulated esophagus wall was approximated by adding small surface curvature variations (< 2 mm) onto a half cylindrical shell (65 mm long, 5.6 mm and 10 mm inner and outer radii of curvature). A planar phased array (1 MHz, 60 mm long, 10 mm wide, 0.525 mm element center-to-center distance, 2280 elements) was put

inside the esophagus, with transducer surface normal toward esophagus wall. Cardiac muscle filled outside of the esophagus wall. The transmitted ultrasound fields through the esophagus wall were simulated with a multilayer acoustic wave transmission model that considers refraction on curved tissue interfaces and attenuation in tissue layers. Using electronic beam steering, three groups of foci were defined in a radial plane perpendicular to the transducer surface at short, medium and long (20, 40 and 60 mm) radial ranges from transducer center axis (60 mm long axis). Each group consisted of five foci that were 15 mm apart and in a line parallel to transducer center axis, covering the 60 mm transducer length. The pressure field in a cardiac muscle tissue volume of $20\times20\times20$ mm^3 centered at each focus was calculated. The tissue temperature elevation caused by acoustic energy absorption in each volume during short, medium and long (1, 10 and 20 s) sonications was calculated using the bioheat equation. For the three sonication durations, the acoustic power ranges needed to achieve 60°C and 70°C maximal temperatures were 113 - 689, 32 - 120, 24 - 83 W and 162 - 989, 46 - 173, 35 - 120 W, respectively. The corresponding thermal dose ($>$ 240 min at 43°C) region lengths at these foci were 2 - 10, 5 - 12, 6 - 13 mm and 3 - 12, 9 - 15, 10 - 16 mm, respectively. The lesion widths at these foci were 2 - 7, 3 - 8, 4 - 9 mm and 3 - 9, 4 - 10, 5 - 11 mm, respectively. These simulation results show that the planar phased array is able to steer and focus its beam through esophagus wall into cardiac muscle in a wide range of field. By varying sonication duration and power, the array can produce thermal dose that is high enough to cause tissue coagulation. It is feasible to use a planar ultrasound phased array for trans-esophageal cardiac thermal ablation.

U2-B-3 510BD 4:00 p.m.

GENERATION OF A PSEUDO POINT SOURCE BY NONLINEAR BEAM-MIXING IN THE PRESENCE OF ULTRASOUND CONTRAST AGENT

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Aberration due to inhomogeneous intervening tissue is a significant problem in transcutaneous therapeutic ultrasound surgery. The ideal way to correct aberration is to have an acoustic point source at the target and to read the phase and amplitude received from each element of a therapeutic transducer array. In this paper, we explore a method for creating a virtual sound source through the nonlinear mixing of ultrasound beams from two small high frequency imaging transducers incident on an ultrasound contrast agent. This virtual source could then be used for the aberration correction of a large, low frequency therapeutic transducer. Experiments were conducted with 4MHz, 2.54cm diameter and 5MHz, 3.17cm diameter focused transducers generating a 1MHz difference frequency signal. The source transducers were aligned to intersect at the focal zone with 20° angle. The nonlinear mixing was expected to occur exclusively at the

intersection of the two focused fields. The size of this beam overlapping zone was measured by a 0.5mm diameter needle hydrophone. Two volume scattering objects were tested separately by placing them in the beam overlapping zone: a rubber phantom with 0.5% by weight ambolite particles and a thin latex bag containing degassed water (saturation $< 20\%$) with 1% dilution by volume of Optison ultrasound contrast agent. The reflected signal was collected by a 1 MHz unfocused transducer at 0° , 20° , 40° , and 60° angles with respect to the axis of intersection. The source transducers were dirven with 500kPa peak negative pressure over 100 cycles. For this excitation, the FWHM beam overlapping region, measured with the hydrophone, was an ellipsoid approximately 1.4 mm in diameter and less than 15 mm in length. It is expected the length will become smaller if a larger intersection angle is used. The maximum amplitude of the 1MHz signal was more than 40 dB lower than the source frequency components in plain degassed water. When the rubber phantom was placed in the beam overlapping zone, there was no detectable 1MHz reflection component. When the bag containing contrast agent was placed in the beam overlapping zone, the reflected 1MHz signal was measured to be approximately 10kPa peak negative pressure. The received amplitude of the difference signal was approximately the same for all placement angles of the 1MHz receiver. These results show a virtual acoustic source with potentially useful amplitude and directivity may be created by nonlinear beam-mixing with ultrasound contrast agent. Using this technique, a therapeutic array can measure the phase and amplitude of the virtual source signal at each element to correct for aberration.

U2-B-4 510BD 4:15 p.m.

A HIFU SYSTEM USING ANNULAR AND STRIP-ELECTRODE ARRAYS WITH A DIGITAL DIAGNOSTIC ARRAY SYSTEM

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A system for high-intensity focused ultrasound (HIFU) has been developed that integrates a digitally controlled diagnostic array system with a multichannel therapy system. Two types of HIFU arrays (5-MHz; 35-mm focal lengths; 32-mm diameters) have been tested and employed with the system. The first is a 5-element annular array used for adaptive focusing. The second is a 5-element strip-electrode array whose variable asymmetric (multilobed) beam is designed to induce lesions that are broad in one direction; this shape permits more efficient tissue treatment with close-packed lesion sites. Both HIFU arrays have central apertures housing a phased array (48 elements; 7.5 MHz center frequency) for tissue visualization. Digital RF echo acquisition is included for assays before, during, and after HIFU exposures. We have tested the system for two types of applications. For static targets (e.g., tumors), we have emphasized the strip-electrode array. We conducted simulation studies of asymmetric (paddle-shaped)

lesions using linear and non-linear propagation models. Results agreed well with lesion shapes produced in in-vitro tissue specimens (calf liver and chicken breast). For moving targets (e.g., the cardiac walls in ventricular tachycardia), we have emphasized the annular array. Simulations tested the ability of this array to induce lesions with repeated short pulses (0.2 0.4 sec.) designed to expose the heart during sequential periods near end-diastole when cardiac motion is minimal. We examined how lesion size varies with pulse duration, intensity, and total duration (number of cardiac cycles treated). We also examined effects of tissue motion during each HIFU pulse. We also examined the advantages of progressively altering the focal point location, starting at the rear segment of the wall and progressively moving it nearer on successive cardiac cycles. Again, linear and non-linear (KZK) propagation models were employed. Comparison with in-vitro lesions showed that the linear model is often sufficient and particularly useful since it permits rapid evaluations of alternate strategies which can then be examined in more detail with non-linear simulations. In-vitro studies used a variety of tissues including calf hearts. Open-chest canine experiments are now under way to determine the applicability of our findings under in-vivo conditions. While these studies focused lesion induction, the digital acquisition capabilities of the system are also being used to evaluate several techniques for positioning HIFU beams and monitoring lesion production. To specifically assist in the above experiments, we assessed the harmonic content of the incident HIFU beam by delivering a short pulse from the HIFU array and using the broad-band diagnostic array to digitally acquire received echo signals. Digital filtering was then used to examine in-situ harmonic energy as a function of incident intensity. Such information promises to help evaluate non-linear propagation effects on HIFU beams.

Portions of this research were supported by reserach grant CA84588 awarded by the National Cancer Institute and the National Heart, Lung and Blood Institute.

U2-B-5 510BD 4:30 p.m.

A NOVEL MULTI-FOCUS ACOUSTIC LENS TRANSDUCER SYSTEM FOR ULTRASOUND THERMAL THERAPY

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Introduction: Ultrasound thermal therapy is a promising technique for noninvasive treatment of solid tumours. The drawback with conventional therapeutic ultrasound applicators is that treatment times are excessively long because only small thermal lesions can be created by these systems. Therefore, hundreds of lesions are required to cover the entire tumour volume. The treatment time can be shortened if multi-focus applicators, *e.g.* phased arrays, are adopted because these applicators produce significantly larger thermal lesions. However, phased

arrays are difficult and expensive to manufacture. We report an alternative approach, which is to couple the conventional single-focus transducer to a specially designed acoustic lens, to produce a multi-focus field and thereby large thermal lesions. We also performed experiments and computer simulations to investigate whether overlying tissue layers could potentially degrade the incident beams, preventing the formation of this multi-focus field. **Methods**: A prototype of a 9-focus lens system was designed and constructed. The transducer (PZT4) had a diameter of 5cm, radius of curvature of 12cm and operating frequency of 2.0MHz. The lens (cross-linked polystyrene) consisted of approximately 500 elements. Thermal lesions were created in both transparent tissue-mimicking phantom and freshly excised porcine kidney tissue. The heating time for each exposure was 1 min at an acoustic power of approximately 70W. An acoustic-thermal model was developed using the finite element modeling technique, to calculate the temperature and thermal dose distributions created by this lens system. To study the effect of overlying tissue layers, intensity distributions of the lens system were measured with and without freshly excised porcine abdominal wall tissue placed between the applicator and the hydrophone. **Results**: In the tissue-mimicking phantom, the thermal lesions created using the transducer alone had cross-sectional area of only 3mm in diameter and length of 2.5cm; whereas lesions created using the lens system had cross-sectional area of 1cm$\times$1cm and length of 4cm. In porcine kidney tissues, the thermal lesions created by the lens system were slightly shorter in length compared to those created in the phantom. The 9-focus field of the lens system suffered negligible deformations after traveling through the intervening porcine tissue layers (skin-fat-muscle-fat-muscle) placed perpendicular to the beam axis. When the tissue layers were placed at an oblique angle relative to the beam axis, the entire 9-focus field was moved slightly off axis, but without distortion. Results of computer simulations agreed with these findings. **Conclusion**: This work indicates that the novel multi-focus lens transducer system may be a useful tool for ultrasound thermal therapy.
This work was supported by National Cancer Institute of Canada with funds from Canadian Cancer Society.

U2-B-6 510BD 4:45 p.m.

NON-INVASIVE MEASUREMENT OF IN SITU THERMAL DIFFUSIVITY AND LOCAL HEAT SOURCE USING BACKSCATTERED ULTRASOUND FOR THERMAL THERAPY PLANNING AND MONITORING

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PURPOSE Bioheat transfer equation (BHTE) based estimates of applied thermal dose during ultrasound thermal therapy typically use *a priori* knowledge or assume standard values for tissue properties that determine the thermal diffusivity (K) and the normalized local heat source (Q). The latter depends on local absorption as well as intervening insertion loss (due to tissue attenuation

and path inhomogenities) from the transducer to the focus. In reality, these tissue specific parameters are highly variable within a given tissue sample and across individuals. We have developed a new signal processing technique to *non-invasively* estimate these parameters *in situ* based on analysis of the raw RF data from two heat exposures, one at sub-ablative intensities to determine K, and another at therapeutic intensities to obtain Q. Both exposures are performed before the actual therapy session commences. **METHODS** Validation studies for this technique were performed using a nichrome heating wire embedded into the sample. 2-D RF data was acquired at 5 Hz frame rate during thermal energy delivery in samples of tissue mimicking alginate, agar and gelatin phantoms with mucilloid fiber added to provide adequate backscatter. Four thermocouples were placed in close vicinity of the heating wire. To estimate K, the maximum temperature rise was no more than 10C during the entire heating phase. 2-D local travel time change ($\Delta\tau$) maps (assumed directly proportional to temperature in this temperature range) were generated from the RF signals using correlation methods. Approximate analytic solutions of the heat diffusion equation were used to fit the $\Delta\tau$ values to estimate the unknown K at times corresponding to each RF frame acquisition and averaged to compute the mean value. Independent estimates of K derived from the thermocouple readings using the classic transient hot-wire analysis were used to validate the non-invasive measurements. To estimate Q, a passive acoustic sensor with sensitivity in the audible range was acoustically coupled to the sample to detect the onset of boiling. The time required to bring the sample to boiling was used to estimate Q by iteration of a numerical BHTE model. Thermocouples inserted adjacent to the heating wire under B-mode image guidance provided independent confirmation of temperatures achieved. **RESULTS** For each of the phantom types, the *non-invasive* estimate of K closely matched the ground truth measurements with a maximum error of less than 10%. Excellent correlation was observed between the time of occurrence of a rise in broad band energy on the passive acoustic sensor and the thermocouple reading near 100C, suggesting that this acoustic signature can be reliably used to detect the onset of boiling. Estimates of Q derived from iterated solutions of the BHTE were within 1% of the applied electric power. Temperature profiles computed using estimated K and Q at the thermocouple locations matched with a mean error of less than 1C.

This work was supported by DARPA / ONR (N00014-96-1-0630) U.S. Army MRMC/TATRC (DAMD 17-02-2-0014) Office of Naval Research (N00014-99-1-0982, N00014-01-G-0460)

Session: U3-B
NOVEL TRANSDUCER APPLICATIONS
Chair: Y. Takeuchi
Kagoshima University

U3-B-1 511AB 3:30 p.m.

PROTOTYPE DUAL FREQUENCY BILAMINAR ARRAY TRANSDUCER CAPABLE OF THERAPEUTIC EXPOSURE AT 500 KHZ AND DOPPLER MONITORING AT 2 MHZ

T. AZUMA*[1], S. UMEMURA[1], M. OGIHARA[2], J. KUBOTA[2], T. KOBAYASHI[2], M. IZUMI[2], A. SASAKI[2], M. NAKANO[3], J. SHIMIZU[3], T. ABE[4], and H. FURUHATA[3], [1]Central Research Laboratory, Hitachi Ltd., [2]Hitachi Medical Corporation, [3]ME Lab. Jikei Univ. School of Med., [4]Dept. of Neurosurgery Jikei Univ. School of Med.
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It is known that ultrasound can enhance thrombolysis with tissue plasminogen activator (tPA). An optimum control of the tPA injection and the therapeutic sonication requires simultaneous blood flow monitoring. The optimal frequency for ultrasound-enhanced thrombolysis and ultrasonic Doppler monitoring are different; typically 500 kHz and 2 MHz for the former and the latter, respectively. In order to use a temple for the acoustic window for transcranial ultrasound, the total aperture size for monitoring and therapy is very limited. In order to generate ultrasonic waves at two frequencies for imaging and therapy from the same aperture, we proposed a transducer consisting of a therapeutic array with an imaging array overlaid on it [1] and fabricated a prototype. Between these two arrays, a frequency selective isolation layer was inserted to ensure independent oscillatory motions of the two arrays. The function of this layer is to reflect the waves from the imaging array and allow the waves from the therapeutic array to pass through. Numerical simulation was performed using a finite element code, PZFlex. In the model, the imaging and therapeutic arrays used PZT ceramic with a center frequency of 2 MHz and 500 kHz, respectively. Several different thicknesses and materials of the frequency selective isolation layer were tested. The results showed that the isolation layer made of epoxy resin 50 micro-meters thick reduced the amplitude of the imaging pulse waves at 2 MHz reflected at the therapeutic array by 13 dB, while it reduced the amplitude of the therapeutic waves at 500 kHz only by 2 dB. A prototype sector array transducer was constructed based on this analysis. Both imaging array of 64 elements at 2 MHz and the therapeutic array of 16 elements at 500 kHz had a channel pitch of 0.4 wavelength at each frequency, respectively. B-mode and color flow images of human brains obtained with the prototype were comparable to those of conventional structure transducers with respect to sensitivity and resolution. Schlieren images showed that the sidelobe levels of the therapeutic beam were less than -20 dB when steering angle was limited to 45 degrees in

each direction. The efficacy of this therapeutic beam are now being tested in the in vitro experiments dissolving artificially made clots. [1] 2003 IEEE Ultrasonics Symposium Proceedings, pp.680-683

This work was supported in part by the Health and Labour Sciences Research Grants for Translational Research from the Japanese Ministry of Health, Labor and Welfare.

U3-B-2 511AB 3:45 p.m.

DESIGN OF A MULTI-LAYER TRANSDUCER FOR ACOUSTIC BLADDER VOLUME ASSESSMENT

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Background: In several clinical situations it is important to accurately measure bladder volume. Catheterization remains the golden standard for bladder volume assessment, but it is known to be invasive and introduces the risk of infections and traumas. Therefore, non-invasive bladder volume measurement methods are of high interest. In a preceding study we proposed a new technique to measure the bladder volume based on non-linear ultrasound wave distortion. Using available transducers it was shown that bladder volume correlates to the harmonic levels generated at the posterior bladder wall. **Objective:** A dedicated transducer is needed to verify and implement this approach. The transducer must be capable of both transmitting high-pressure waves at fundamental frequency and of receiving up to the third harmonic with sufficient sensitivity. **Methods:** We constructed an unfocused multi-layer transducer using a single element PZT transducer (2 MHz center frequency; 55% -6 dB BW) for transmission and a 52 μm thick PVDF film as top-layer for reception. The transducer has an active diameter of 29 mm. To ensure optimal performance, e.g. with respect to electrical matching and transmit waveform, a KLM-circuit model was used first. Results obtained from the model were compared to the measured electrical and acoustic impedances. Secondly, acoustic measurements were carried out in a water tank. We used a calibrated hydrophone to measure the generated pressures and a flat reflector to obtain the pulse-echo response. Finally, the transducer was used on bladder phantoms in pulse-echo mode to determine its usability for bladder volume assessment. Phantoms with volumes of 500 ml and 0 ml (tissue only) were used. Echoes originating from regions at a fixed depth (12 cm) were analyzed for their harmonic contents. **Results:** The KLM-circuit model sufficiently matched with the measured electrical and acoustic impedances. Hydrophone measurements showed that the PZT element, excited at a frequency of 2 MHz, could generate up to 0.51 MPa at the transducer surface. Next, pulse-echo measurements with a flat reflector at 90 mm revealed a generated second harmonic level at –8.0 dB and a third harmonic level at –23.4 dB relative to the fundamental. Also, phantom measurements showed that the PVDF film was 8.5 dB more sensitive in reception at second harmonic than the PZT element. Finally, measurements on the 500 ml phantom showed an increase of 10.8 dB in second harmonic generation with respect to measurements on the

tissue-only phantom. This confirms the correlation between bladder volume and harmonic contents. **Conclusions:** This study demonstrates the usability of the multi-layer PZT-PVDF transducer design for bladder volume assessment on the basis of non-linear wave distortion dependency.
Support was given by G. McMorrow from Diagnostic Ultrasound Corp. and H. Baartmans from Diagnostic Ultrasound Europe.

U3-B-3 511AB 4:00 p.m.

REAL-TIME 3D COLOR FLOW DOPPLER FOR GUIDANCE OF VIBRATING INTERVENTIONAL DEVICES

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The goal of this investigation is to examine the feasibility of guiding interventional devices using piezoelectric buzzers to create a velocity source which is imaged and tracked with real time 3D (RT3D) ultrasound and Color Flow Doppler. Interventional devices include pacemaker/defibrillator lead stylet, Brockenbrough needle for cardiac septal puncture, cardiac guide wire and radiofrequency ablation needles for cancer therapy. Each is mechanically coupled to piezoelectric buzzers capable of vibrating in the audible frequency range of 0.3 kHz to 8 kHz. The vibrating devices were imaged using our RT3D ultrasound system (Duke U./Volumetrics Medical Imaging) with a 2.5 MHz transducer, which scans a 65° pyramid at up to 60 volumes per second. The velocities created by the vibrating devices were detected using real time Color Flow Doppler and Pulse Wave Doppler modes. The scanner was modified to display thickened B-mode and C-mode planes with 3D Doppler. In vitro RT3D Doppler images acquired in a water tank, in tissue phantoms, excised liver with tumor target and in an excised sheep heart show strong vibration signals in both 3D Doppler modes, enabling real time tracking and guidance of all the devices in three dimensions over the entire 65° pyramid and a depth of 1 to 20 cm at a rate of one 3D Doppler image volume per second. In an open chest sheep model, the stylet was inserted into a pacemaker lead and introduced into the sheep from the jugular vein. *In vivo* tracking was performed in the jugular vein as well as the right atrium using RT3D Color Flow Doppler images. The vibrating RF ablation needles were guided through the liver toward tumor targets *in vivo* with RT3D Color Flow Doppler images in a closed sheep model. From these results, we believe that using a vibrating buzzer to create a velocity source may enable interventional device visualization and guidance in RT3D Color Flow images using Doppler methods.

U3-B-4 511AB 4:15 p.m.

FINITE ELEMENT MODELING OF ULTRASONIC SEPARATION AT THE MICROSCALE

M. K. ARAZ*[1], C.-H. LEE[2], and A. LAL[1], [1]SonicMEMS Laboratory, [2]Veeco Probes.
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Low power ultrasonic separation of different size of microparticles in a microfluidic device is shown in previous papers [1-2]. Device consists of a silica capillary attached to laser cut PZT plate. Separation and manipulation processes take place at low, CMOS compatible 5-10 Vpp drive. Separate force fields generated by transverse bending of the capillary and longitudinal acoustic pressure waves inside the capillary tend particles of different sizes to separate at the pressure nodes. With advantages such as, simple fabrication, low cost and low power CMOS compatibility; this device can be a good candidate for future chromatography assays for biological and non-biological applications. In terms of theoretical approach however, complicated structure of PZT plate, bonding material, impossibility of direct measuring pressure field inside the capillary and acoustic conditions of silica-fluid boundary make analytical understanding for principle of separation harder under these conditions.

Finite Element Modeling of the system, which consists of PZT, capillary, fluid medium and the bond material, gives better understanding of the working principle of the device. Especially for improvement in separation, details of separation process are needed. With the ANSYS software used for modeling, pressure field due to the longitudinal sound waves inside the capillary and inertial force field due to the transverse bending of the capillary can be obtained. Preliminary results of FE modeling are compared to frequency range of the experimental results with good agreement. In addition to analytical approach, instead of optimizing device by measuring results from devices fabricated in different dimensions, FEM modeling enables an easier approach for optimizing device dimensions and frequency sweeping for better results. Using the fields extracted from the FEM analysis, we computed the radiation and streaming forces numerically to predict the locations of particle concentration and particle motion.

In parallel to FEM analysis, analytical understanding of current device will lead to design and fabrication of new devices by silicon bulk micromachining techniques which will lead to smaller and more efficient devices. This may allow devices integrated into lab on a chip microfluidic systems for after separation processes.

[1] Lee, C., Lal, A., “Low-Voltage High-Speed Ultrasonic Chromatography For Microfluidic Assays”, Proc. of the Solid State Sen. Act. Workshop, Hilton Head Island, South Carolina, 2002, pp. 206-209

[2] Araz, M.K., Lee, C., Lal, A., Ultrasonic Separation In Microfluidic Capillaries, Proc. of Int. Ultrasonics Symp., Honolulu, Hawaii, 2003, pp. 1066-1069

This work was supported by DARPA-MTO under the BioFlip program, contract #F30602-00-2-0572 and Nanobiotechnology Center (NBTC) of Cornell University, an STC Program of the National Science Foundation under Agreement No. ECS-9876771.

U3-B-5 511AB 4:30 p.m.

TWO-DIMENSIONAL ULTRASOUND DETECTION WITH AN OPTICAL MULTILAYER HYDROPHONE USING SERIAL AND PARALLEL DATA ACQUISITION

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In spite of major improvements in transducer technology, two-dimensional arrays for ultrasound detection are still a matter of research. To achieve reasonable array sizes with small pixels, complicated micro-mechanical manufacturing processes are necessary and the large number of elements require sophisticated readout and data processing. Optical techniques offer alternative concepts incorporating inherent properties of optical signal processing like the possible small structure size for high spatial resolution, the high bandwidth and parallel data processing.

Two techniques for two-dimensional ultrasound measurement are presented which are based on a sensor concept using dielectric coatings on a flat glass substrate. The multilayer coating forms a micro-interferometer and the deformation by the ultrasound wave is detected by an optical reflectivity measurement system. In a serial scanning system a micro-mechanical mirror moves the focussed laser beam over the sensor and the reflectivity change, i. e. the ultrasound pressure is recorded point by point using a photodetector. Alternatively, parallel signal processing was achieved by illuminating the sensor area as a whole using short laser pulses and detecting the signal with a conventional CCD camera.

Both techniques were applied to various source transducers, and two-dimensional ultrasound pressure distributions in dependence on time are presented. It will be shown, that parallel signal processing takes less time to create a sound field image but suffers from a lower signal-to-noise ratio. The serial technique offers high sensitivity but requires synchronization between mirror movement and pulse repetition frequency. The methods presented are a milestone on the way constructing an optical ultrasound camera.

U3-B-6 511AB 4:45 p.m.

PIEZOELECTRIC TRANSDUCER SURFACE VIBRATION CHARACTERIZATION USING ACOUSTIC HOLOGRAPHY AND LASER VIBROMETRY

O. A. SAPOZHNIKOV*[1], A. V. MOROZOV[1], and D. CATHIGNOL[2], [1]Faculty of Physics, Moscow State University, [2]Unité 556, INSERM.
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Acoustic pressure radiated by a piezoelectric source can be predicted based on the normal velocity distribution along the transducer surface. However, up to now, there are no reliable direct methods of surface vibration measurement in liquids. The transducer vibration is frequently considered as being uniform

(thickness mode), which may be incorrect due to transducer structure (e.g. phased arrays) or due to excitation of Lamb waves in the piezoelectric plate in addition to the thickness vibration mode. In this work, a holographic method is developed and experimentally used that enables reconstruction of the radiator vibration pattern. The method includes a measurement of wave amplitude and phase in different points of a plane grid perpendicular to the acoustic axis at some distance from the source, theoretical time reversal of the waveform in each grid-point, and back propagation of the field to the source using the Rayleigh integral. In addition to the holographic approach, vibration of piezoelectric transducers was studied using laser vibrometry. A special experimental and theoretical study was performed in order to show that this well-developed method gives wrong results when the transducer is in contact with liquid, because of strong acousto-optic interaction in a condensed media. It is shown that although the acoustic holographic approach has limited spatial resolution (of order of a wavelength), it allows fairly exact prediction of the radiated field pattern.
Work supported by NIH-Fogarty, ONR IFO, and RFBR

Session: U4-B
BULK WAVE MATERIALS AND EFFECTS
Chair: E. Adler
McGill University

U4-B-1 513AB 3:30 p.m.

GROWTH OF ALN FILM ON MO/SIO$_2$/SI(111) FOR 5GHZ-BAND FBAR USING MOCVD

C.-M. YANG*, U. KENSEI, Y. AOTA, S.-K. KIM, S. KAMEDA, H. NAKASE, Y. ISOTA, and K. TSUBOUCHI, Research Institute of Electrical Communication, Tohoku University.
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We have developed a poly-crystalline c-axis oriented aluminum nitride (AlN) film on Molybdenum/SiO$_2$/Si(111) structures for film-bulk-acoustic resonator (FBAR) using metal-organic-chemical-vapor deposition (MOCVD). The FBAR filter is expected to be used as a 5GHz-band pass filter for a wireless local area network using the orthogonal frequency division multiplexing (OFDM). The Requirements of 5GHz band pass filter for IEEE802.11a are low insertion loss of less than 1.5dB and bandwidth of more than 100MHz. In order to fabricate the band pass filter, more than 6.0% of coupling constant (K^2) of piezoelectric film is required, which was evaluated from the Butterworth-Van Dyke (BVD) equivalent circuit model. According to the previous report from Naik et al, K^2 of more than 6% corresponds to full width at half maximum (FWHM) of less than 4°. Our target of FWHM of AlN piezoelectric thin film was determined as the value of less than 4°. Although (0002) AlN film with FWHM of less than 4° was grown by sputtering method, it is necessary to construct additional electrode layer structure such as Mo/Al-Cu/Si(111), which was reported by

Fujitsu Ltd. Furthermore, AlN growth rate was less than 0.3μm/h using sputtering method. We have already reported (0002) AlN film with FWHM of 2.98° on Mo/SiO_2/Si(100) at the AlN growth temperature of 1050°C. The growth rate of AlN film was 1μm/h. Membrane structure with Mo/AlN/Mo/SiO_2/Si was employed for our fabrication of FBAR. SiO_2 layer was formed on Si using thermal oxidization method in order to stop the Si etching. Mo electrode was deposited on SiO_2/Si using RF magnetron sputtering method. However, the Mo bottom electrode had a high resistivity of 8x$10^{-5}\Omega$cm after AlN deposition. For improvement of resistance of Mo bottom electrode, AlN films were grown on Mo/SiO_2/Si(100) and Mo/SiO_2/Si(111) with the substrate temperature of 950°C. Pressure in a reactor was 20torr. The V-III ratio was 25000. Before AlN deposition, hydrogen-annealing process was carried out with the temperature of 1100°C for 20minutes. In both case, c-axis oriented AlN films were grown. On Mo/SiO_2/Si(100), mean value of FVWM of (0002)AlN film is 8°. On the other hand, on Mo/SiO_2/Si(111), FWHM of (0002) AlN was found to be 3.8°. In addition, measured resistivity of Mo bottom electrode was 4x$10^{-5}\Omega$cm after AlN deposition. We have successfully grown highly c-axis oriented AlN film with low resistivity of Mo bottom electrode on Mo/SiO_2/Si(111). The deposited AlN film is satisfied with the rf band pass filter specification for 5GHz-band WLAN system.

This work was supported in part by the IT-program (RR2002) of MEXT, Japan.

U4-B-2 513AB 3:45 p.m.

RE-GROWTH OF C-AXIS ORIENTED ALN THIN FILMS: MICROSTRUCTURE AND PIEZOELECTRIC PROPERTIES

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Bulk acoustic wave (BAW) filters based on AlN thin films have emerged as promising components to compete with SAW products in rf filtering. BAW filters exhibit advantages with respect to fabrication, power limits, parasitics and size. Very important for future trends in packaging is the possibility to integrate BAW's into systems on chip or systems in package. For multi-channel operation and signal treatment purposes it would be desirable to dispose of several frequencies on the same substrate. The most economic way to deposit different thicknesses would be to interrupt growth, and to continue selectively there where BAW resonators of lower frequencies are needed. Such an approach requires screening and lift-off/etching procedures. In practice this means that after the first layer the waver is exposed to air, photoresist, developer and remover. In this work, re-growth of AlN thin films was studied. The first layer, and the total layer were characterized by means of x-ray diffraction, transmission electron microscopy (TEM), and atomic force microscopy, X-ray Photoelectron Spectroscopy (XPS), interferometry measurement of effective and residual stress measurement. The AlN thin films were grown by pulsed dc magnetron sputtering [1] on Pt(111) or Mo(110) electrodes. The investigated process showed an excellent of 5.1 pm/V, a small rocking curve width of 1.2 °, and a less than 100 MPa mechanical stress at a thickness of 1 μm, and when the film is grown on Pt(111) films . It could be shown that the properties improve with film thickness as long as the film is less than one micrometer thick [2]. We ascribe this effect to ion bombardment. TEM images showed nice columnar growth with fiber-like grains. We studied several types of interrupted growth. When growth is interrupted for some minutes while the wafer stays in vacuum, the film continued to grow in the same microstructure as before and no degradation of properties was observed. Interruption with air exposure lead to a substantial degradation. Treatment of the first layer by developer yielded a considerable roughening of surface and to a severe reduction of piezoelectric activity. In order to explain the large reduction, one must assume that the piezoelectric coefficient of the second layer is of opposite sign. TEM inspection revealed a complete change of the microstructure. The buried interface contained a very thin amorphous oxide layer. The nucleation of the second layer lead to multiple orientations. The c-axis orientation was dominating after a few tens of nanometers leading to the growth of huge grains. The negative effect of developer exposure could be cured to some extent by an etch-back with Ar ions. Potential solutions to the problem will be presented.

1. M.-A. Dubois and P. Muralt, J.Appl.Phys. 89, 6389-6395 (2001) 2. F. Martin, P. Muralt, M.-A. Dubois, and A. Pezous, J.Vac.Sci.Techn. A 22, 361-365 (2004)

European 5th framework programs and Swiss Office for Education and Science (MARTINA project)

U4-B-3 513AB 4:00 p.m.

PZT MATERIAL PROPERTIES AT UHF AND MICROWAVE FREQUENCIES DERIVED FROM FBAR RESONATOR MEASUREMENTS

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Lead Zirconate Titanate (PZT) is a high dielectric constant, high coupling coefficient piezoelectric material with possible application to Film Bulk Acoustic Resonator (FBAR) based devices at UHF and microwave frequencies. Although this material is widely used for applications at audio and low MHz range frequencies, there is a concern that excessively high acoustical attenuation would preclude its usage at microwave frequencies. Likewise, the bulk dielectric/piezoelectric/elastic (DPE) properties are well known at low frequencies, but have not been as well measured at UHF and microwave frequencies for thin film samples. The goal of this paper is to report the measured thin film material properties of selected PZT compositions, at high frequencies. To acquire these data, we have fabricated FBAR resonators from thin film PZT samples and

measured the acousto-electric coupling kt**2, the acoustic attenuation, Q, and some of the DPE properties. We gathered samples of PZT thin films that were deposited by metalorganic chemical vapor deposition (MOCVD), sol gel, or RF sputtering methods. PZT films in the 0.1 micron to 3 micron thickness range were deposited on thin ($\sim$0.1 um) platinum or iridium bottom electrodes. Samples with composition near the morphotropic phase boundary (Zr/Ti = 52/48) or within the tetragonal phase (Zr/Ti = 30/70) were examined. To measure the material properties, air backed FBAR resonators were chosen as a test vehicle. They were fabricated by depositing a gold, platinum, or iridium electrode layer on top of the PZT film, then defining a small (50 micron diameter) contact and opening a window to the bottom electrode, both by photolithographic/dry etching techniques. The resonators were freed from the silicon substrate by a deep silicon etching technique to form an air backed resonator, with Q limited mainly by the PZT material and slightly by the electrode materials. Electrical measurements were made with an Agilent 8722C swept frequency network analyzer to obtain the scattering parameter S11 vs. frequency. From the Mason model, the salient DPE coefficients were extracted from these data. The devices exhibited dielectric constants in the range 200 to 400, coupling constants kt**2 in the range 12 to 38%, and acoustic attenuation of the order 500 to 1000 dB/cm at 1 GHz. In the presentation, we will more fully describe these results, and show that it is feasible to build FBAR resonators and filters at UHF/microwave frequencies.
S.M. Bilodeau, B.C. Hendrix, J.F. Roeder of ATMI Corp. for CVD deposited PZT thin films. S. Hoen, T. Verhoeven, K. Williams, D. Ritchey & V. Tumangan for processing help.

U4-B-4 513AB 4:15 p.m.

FREQUENCY SENSITIVE REFLECTION, REFRACTION, AND TRANSMISSION OF BULK AND SHEAR WAVES IN FUNCTIONALLY GRADED MATERIALS (FGM)

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Functionally Graded Materials (FGMs) are defined as materials featuring engineered gradual spatial transitions in microstructure and/or composition thus having gradually varying mechanical properties. So far the development of such material systems is driven by the demand to produce objects which are hard and wear resistant at the surface but have a ductile and tough body - like cutting tools - to give an example. Ceramically coated turbine blades might be mentioned as another application where FGMs are used in order to reduce thermally induced mechanical stress concentrations at the ceramic / body interface.

A rarely treated topic is the elastodynamic wave propagation in FGMs. It is of particular interest since the reflection, refraction, and transmission of mechanical waves is frequency dependent provided that the spatial area in which the material properties vary is in the order of the mechanical wave lengths to be distinguished. This opens a wide field of potential engineering applications like micromechanical frequency filters, spectrum analyzers, or acoustic isolation layers.

Frequency sensitive elastodynamic wave propagation phenomena are demonstrated based on two dimensional numerical simulations and on a series of short-pulse-laser-acoustic experiments. There the frequency dependent reflection and transmission behavior caused by intermetallic interface layers of 10 to 20 nm thickness has been demonstrated which corresponds to a micromechanical filter operating in the frequency range of 0.5 THz.

Future directions of the on-going research project are presented.

U4-B-5 513AB 4:30 p.m.
(Invited)

ACOUSTOELECTRONICS: NEW IDEAS FOR A NEW ERA

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The application of high frequency acoustic devices to enhance electronics saw an extraordinary growth in eastern and western countries in the sixties and seventies. A major impetus for these developments was the tension existing between the eastern Soviet Bloc countries and the western allies. Government military spending on both sides provided funding to explore new acoustoelectronic concepts in universities, institutes, and major defense companies. Direct exchange of visits between scientists and engineers of east and west was limited until the 1980's when travel restrictions were lifted on both sides, and author names in the open literature became face to face contacts and exchanges at conferences of mutual interest. This paper explores the major acoustoelectronic developments of the sixties and seventies from an east and west perspective. This resulted in a new era of cooperative work between east and west and a large number of device applications now seen in electronic systems around the world today.

Session: U5-B

FROM SAW TO THIN FILMS
Chair: W. Hunt
Georgia Tech

U5-B-1 512C-H 3:30 p.m.

STUDY OF LAYERED SAW DEVICES OPERATING AT DIFFERENT MODES FOR GAS SENSING APPLICATIONS

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Properties of different propagation modes for a novel layered ZnO/XY $LiNbO_3$ Surface Acoustic Wave (SAW) device have been investigated both theoretically and experimentally. Additionally, gas sensing performance of two propagating modes of this structure have been studied. Propagation properties of blank XY $LiNbO_3$ and ZnO/XY $LiNbO_3$ were theoretically compared using the multi-layered spectral Green's function. It was observed that before ZnO thin film deposition the major propagation modes are leaky SAWs and Rayleigh waves. After the thin film deposition the leaky mode attenuation is reduced. Additionally, it transforms to a generalized SAW with a significant normal particle displacement component. This mode had a higher electromechanical coupling coefficient than the Rayleigh mode. For experimental measurements a SAW structure with a 24 μm periodicity was patterned onto a XY $LiNbO_3$ substrate with a ZnO thickness of 1 μm. A 20 nm layer of InO_x thin film has been deposited as the gas selective layer. Responses of the two different propagation modes to NO_2 gas have been investigated by locking the oscillation frequencies onto different propagation modes. It was observed that frequency shift of the device to 1 ppm NO_2 gas in synthetic air is 2.5 kHz when locked into the generalized SAW mode (operational frequency of 144 MHz) but the Rayleigh mode (operational frequency of 136 MHz) showed a 45 kHz frequency shift. This demonstrates that despite the higher electromechanical coupling of the generalized mode for this structure, the Rayleigh wave has 18 times higher sensitivity to surface conductivity changes than the generalized mode.
The authors would like to thank CRC for Microtechnology, Australia, for its financial support.

U5-B-2 512C-H 3:45 p.m.

HIGH COUPLING AND HIGH VELOCITY SURFACE ACOUSTIC WAVES USING A THREE-LAYER STRUCTURE ZNO/ALN/DIAMOND

M. EL HAKIKI[1,3], O. ELMAZRIA*[1,3], M. B. ASSOUAR[1,3], V. MORTET[2], A. TALBI[1,3], and F. SARRY[1,3], [1]LPMIA UMR 7040 Université H. Poincaré - Nancy I, [2]IMO Limburgs Universitair Centrum, [3]Laboratoire Européen de Recherche Universitaire: Saarland -lorraine (LERUSL).
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Layered structures based on diamond are an attractive solution for high velocity surface acoustic waves (SAW) and show a promising solution for the development of GHz-band SAW devices. However these structures have the trade-off relationship between the acoustic phase velocity (Vj) and the electromechanical coupling coefficient (K^2). According to the theoretical calculations, the best compromise obtained for ZnO/diamond structure is K^2=1.2%, V=11.612km/s and for the structure AlN/diamond is K^2=1.36, V=12.120km/s. Even if a better compromise is expected for LiNbO $_3$/diamond structures, the deposition of highly oriented LiNbO $_3$ film on diamond seems to presents serious difficulties to date.

In this work, we propose the use of a three-layer structure ZnO/AlN/diamond that combine the advantages of both piezoelectric materials: high K^2 of ZnO and high velocity of AlN. Theoretical study based on Campbell and Jones model was performed to calculate the phase velocity and K^2 dispersion curves of the Rayleigh mode as well as the higher modes. Both configuration ZnO/IDT/AlN/diamond and IDT/ZnO/AlN/diamond were calculated considering various thickness of ZnO and AlN layers. Both high values of K^2 ($>$4%) and acoustic velocities higher than 15km/s for the propagation mode 3 are expected on this new structure according to the theoretical results.

In order to confirm the simulation results, SAW filters was processed on ZnO/AlN/diamond structure. Highly oriented c-axis AlN and ZnO films were deposited on nucleation side of freestanding CVD diamond by reactive magnetron sputtering process. Technological process as well as the optimisation of deposition parameters were published in previous works [1,2]. First experimental results are in accordance with the theoretical results and confirm the high potentiality of the new ZnO/AlN/diamond structure for the processing of high performances and high frequencies SAW filters.

[1] O. Elmazria, V. Mortet, M. El Hakiki, M. Nesladek and P. Alnot, IEEE Trans. Ultras. Ferro. Freq. Contr. Vol. 50 No. 6, 710-715 (2003); [2] M. B. Assouar, M. El Hakiki, O. Elmazria, P. Alnot, C. Tiusan; Diamond and Related Materials, In press;

We would like to thank L. Bouvot and J-F Pautex for their precious technical help.

U5-B-3 512C-H 4:00 p.m. (Invited)

TWO BITS OF HISTORY: THERMOELASTIC WAVE GENERATION AND SAW TRANSDUCTION

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This invited talk will review two developments in which I was involved - analysis and application of the thermoelastic generation of bulk acoustic waves, and the early transduction of surface acoustic waves with interdigitated electrodes on piezoelectric crystals. It is interesting to note that the energy sources for the thermoelastic effect can be optical pulses, RF waves, resistive heating, or impact by ions or electrons, and the medium involved can be a solid or a liquid. Our SAW work, made possible by a move to the University of California at Berkeley, was carried out in collaboration with talented students using the newly constructed microfabrication facility there.

U5-B-4 512C-H 4:30 p.m.

DIAMOND-BASED SAW OSCILLATOR AT 1GHZ

U. PRECHTEL[1], V. ZIEGLER[1], S. KOLODZIK[1], B. PLEHN[2], H. DOWNAR[3], J. HAERING[3], R. KUNZE[4], G. MARTIN[4], H. SCHMIDT[4], and M. WEIHNACHT*[4], [1]EADS Corporate Research Center, [2]EADS Deutschland GmbH, [3]Dornier GmbH, [4]Leibniz Institute for Solid State and Materials Research Dresden.
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Diamond with ZnO thin films appears as an appropriate material system for high power gigahertz SAW devices. For the purpose of oscillator applications with extremely low phase noise, a resonator on this material base has been developed. According to the requirements of resonator design the extraction of parameters like dispersion curve of SAW velocity, coupling factor, reflection coefficient, propagation loss, capacity per finger pair was accomplished using test structures and in interplaying manner with the improvement of material properties by technological variations. The first Sezawa mode was selected for our device application. The geometric parameters were 900 nm for the ZnO thickness, 100 nm for the Al electrodes, and 9.43 μm for the IDT period. For the enhancement of the resonator quality factor, different loss contributions have been analyzed including the ZnO dielectric and ohmic losses, the leakage into the silicon substrate below diamond, and the effective reduction of quality factor by laterally inhomogeneous SAW properties. A longitudinally coupled resonator with 61 finger IDTs and an aperture of 42 wavelengths was used to build an oscillator loop containing a phase shifter, a SiGe amplifier, and a 10dB coupler. The oscillator frequency was 1.008 GHz, the tuning range 2 MHz, the power consumption 0.48 W, the noise floor was -171 dBc at 1MHz offset from the carrier (extrapolated from phase noise measurements down to 150dBc, due to measurement set-up limitations). The loading power for the SAW resonator was 24 dBm.

U5-B-5 512C-H 4:45 p.m.

FABRICATION OF 5-GHZ-BAND SAW FILTER WITH ATOMICALLY-FLAT-SURFACE ALN ON SAPPHIRE

K. UEHARA*[1], C. -M. YANG[1], T. SHIBATA[2], S. -K. KIM[1], S. KAMEDA[1], H. NAKASE[1], Y. ISOTA[1], and K. TSUBOUCHI[1], [1]Research Institute of Electrical Communication, Tohoku University, [2]NGK Insulators, Ltd.
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5-GHz-band surface acoustic wave (SAW) filters were fabricated on atomically-flat-surface (0001) aluminum nitride (AlN) on (0001) sapphire substrate for wireless local area network (WLAN) system. (0001) AlN on (0001) sapphire structure has advantages to 5-GHz-band SAW filter as follows (1) easy-fabrication due to wide width of line and space determined by high SAW velocity of 5,700 m/sec, (2) moderate electromechanical coupling coefficient of 0.75% and (3)

zero-temperature coefficient of delay (TCD) with control of AlN film thickness, which was found by authors group. Atomically-flat-surface AlN with mean roughness of 0.2 nm was developed in order to improve SAW propagation loss. Inter-digital transducer (IDT) was designed based on crossed field model. Line and space of single electrode was about 0.275 μm. Wavelength (λ) was 1.1 μm. Number of finger-pair was 136. Length of aperture was 90 λ. Distance of center-to-center between input and output IDT was 272 λ. Electrode was aluminum deposited using radio frequency magnetron sputtering. The thickness of aluminum was 350 nm. SAW filters were fabricated using electron-beam lithography and lift-off method. Directions of SAW propagation were vertical axis to a-axis of sapphire substrate because the direction of SAW propagation is parallel to the direction of zero-power-flow angle on sapphire substrate. Scattering parameters of transmission and reflection characteristics of the fabricated SAW filters were measured using network analyzer and probe station with thermal micro chamber. Center frequency of the fabricated SAW filters was measured to be 5.18 GHz. SAW velocity was calculated to be 5,688 m/sec at normalized thickness by wave number (kH) of 11.4, where k is wave number and H is AlN thickness, respectively. The SAW velocity in atomically-flat-surface (0001) AlN was found to be higher than SAW velocity in conventional (0001) AlN of 5,607 m/sec, which was determined by calculated fitting curve. Propagation loss was evaluated to be 0.0053 dB/λ at 5.18 GHz. The propagation loss was less than that of AlN on poly-diamond structure at 5 GHz-band. Measured TCD was found to be excellent coefficient of 9 ppm/°C at kH of 11.4, which is exceedingly less than typical piezoelectric substrate such as lithium niobate. These results indicate SAW filter using atomically-flat-surface (0001) AlN on (0001) sapphire structure has features of low insertion loss and excellent temperature stability. Atomically-flat-surface (0001) AlN on (0001) sapphire structure is expected to use for 5-GHz-band SAW filter for WLAN system.

The authors would like to thank Dr. Meguro of Laboratory for Electronic Intelligent System, Research Institute of Electrical Communication at Tohoku University for many discussions and cooperation of electron-beam lithography. This work was supported in part by the IT-program (RR2002) of MEXT, Japan.

Session: FE1-B

TUNABLE AND RF MATERIALS

Chair: M. Lanagan
The Pennsylvania State University

FE1-B-1 513CD 3:30 p.m.

LOW-LOSS CAPACITOR REALIZATION AND ITS MODELING WITH CUBIC PYROCHLORE BISMUTH ZINC NIOBATE (BZN) THIN FILM

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Thousands of modern electrical applications require miniaturized and low-loss components such as phase shifters, tunable filters, and electro-optic modulators using ferroelectric Barium Strontium Titanium (BST) thin film and etc. And the demands on these components have stimulated researchers to find higher dielectric constant and lower-loss materials such as Bismuth Zinc Niobate (BZN) that is introduced in this paper. One of the representative candidates so far is BST thin film, which is known to have high permittivity and low dielectric loss. However, strong function of thin film thickness is its permittivity, which is 20 50 times lower than that of bulk, and other factors such as polarization effect and film non-stoichiometry affect characteristics of BST film. BZN thin film can be the alternative candidate having low loss and high permittivity, which is less affected by stoichiometry and film thickness. The electric-field dependent capacitance is also its attractive feature for applications such as voltage-controlled oscillator and can be estimated with the percentage tunability defined as $(C_{max}C_{min})/C_{max}$x100%. In this paper, BZN thin film is implemented in metal-insulator-metal (MIM) capacitor realization for low loss microwave frequency applications. BZN film is prepared by RF magnetron sputtering system after a bottom electrode (Ti/Pt, 250/2000(4000)) is deposited by electron beam evaporation technique. Ex-situ annealing, then, is done at 750°C with air ambient for 5 minutes for crystallization. With this temperature and film thickness, the relative permittivity of BZN thin film approximately gives 200. Lift-off process of top electrode (Au, 5000) is accompanied. The rapid thermal annealing (RTA) at 700°C for 30 seconds is followed, and the evaporation of thick metal for probe measurement contact (Au, 1μm) completes the process. Q factor at 1 GHz is around 230, and remains higher than 100 up to 4.5 GHz for $360\mu m^2$ capacitor and shows 30% tunability for maximum 8.82×10^5 V/cm electric field. The Q factor is extracted from S parameter measurement up to 40 GHz. And its modeling is carried out along microwave frequency range for investigating dielectric properties of BZN thin film. Resultant Q factor and capacitance of BZN thin film at microwave frequency regime shows that the Q factor of BZN thin film is above 600 and capacitance changes less than 3% up to around X-band ($\sim$13 GHz), which imply that extremely low loss passive microwave circuits can be realized with BZN thin film in microwave ranges. The effects on different substrate such as Al_2O_3 and MgO need to be investigated for optimized microwave range performance.

FE1-B-2 513CD 3:45 p.m.

CO-FIRED BST THICK FILMS ON ALUMINA SUBSTRATES FOR RF/MICROWAVE PHASE SHIFTER APPLICATIONS

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We have deposited BaxSr1-xTiO3 (x=0.5 and 0.6) thick films on alumina substrates, with thickness ranging from ~5-50 μm, by the MicroPenTM direct-write technique, which were then co-fired in air at 1300-1350 oC. Analyses by SEM have revealed that the sintering of crack-free films is strongly thickness dependent, and increased with decreasing film thickness. BST films with thickness <10 μm showed good densification at 1300 oC, while higher sintering temperatures resulted in abnormal grain growth, and excessive film-substrate reactions. We measured the strain in the films by X-ray diffractometry using the $\mathrm{Sin}^2\Psi$; technique, and analyzed the evolution of strain as a function of film thickness and sintering conditions. We provide an in-depth discussion on the effects of MicroPenTM deposition parameters, sintering conditions, films thickness, film composition, and especially strain on the dielectric properties (permittivity and loss) as well as tenability in the range 1-20 GHz.
The authors gratefully acknowledge the funding provided by the New Jersey Commission on Science and Technology, and the Howatt Foundation

FE1-B-3 513CD 4:00 p.m.

A HIGHLY TUNABLE RADIO FREQUENCY (RF) FILTER USING DENSE BULK FERROELECTRIC MATERIALS

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The desirable attribute of software defined radios (SDR) implies that RF front-ends must be multi-band and frequency agile. Wideband SDRs need a lower size, light weight, and reduced power (SWAP) tunable filter technology to meet the militarys current and future communications needs. This is essential for the SDR operating in a battery powered environment such as man-portable Joint Tactical Radios (JTRS). The current method for building a tunable filter is to use discrete semiconductor varactors at each section of the filter. These devices are nonlinear and their low third order intercept points make them highly susceptible to intermodulation which severely limits their dynamic range.

In this paper we will present a new approach to construction of tunable RF filters using low loss highly dense ceramics of high dielectric constant perovskite and tungsten bronze dense ceramics. These ceramic compositions with good features of both crystal and thin film exhibit large change in dielectric constant with applied electric field. This approach allows the use of a simpler structure replacing numerous RF interconnects in a conventional agile filter. A prototype tunable filter has been built using these materials exhibiting a 3:1 permittivity tunability. We will present a lumped circuit filter design for 30-450 MHz, and a distributed combline filter for 700 2000 MHz using these ferroelectric capacitors. The circuit design, electromagnetic simulation, and the experimental results along with the achievement of 2:1 frequency tunability of these filters will be shown. An insertion loss of 4 dB in the 30 - 450 MHz range along with a third order intercept point exceeding 50 dBm was achieved. The tunable combline filter operating in 700-2000 MHz range exhibited lower loss. This presentation will also include material fabrication, RF characterization and system applications.

FE1-B-4 513CD 4:15 p.m.

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

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

FE1-B-5 513CD 4:30 p.m. (Invited)

TUNABILITY AND LOSS OF THE FERROELECTRIC-DIELECTRIC COMPOSITES

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The properties of composites of linear dielectric materials have been studied since long time, but those of composites containing non linear dielectrics have attracted much less attention. This paper addresses the modeling of the dielectric-dielectric composites, consisting of an electrically tunable (nonlinear) dielectric with a linear, low loss dielectric. We propose a new method of calculation of tunability and loss of composites as a function of the concentration of the linear dielectric. We reformulate the Bruggeman concept of effective medium approximation in terms of the energy of the electric field stored and dissipated

in the composite. This modification allows analytical modeling of the tunability and the loss tangent of the composites, where the dielectric permittivity of the tunable component is weakly field dependent $(\epsilon_0 - \epsilon_E)/\epsilon_0 << 1$ (ϵ_0 and ϵ_E are the dielectric permittivities of the nonlinear component at zero and at non-zero electric fields, respectively). The finite element method (FEM) is used to evaluate the tunability of the composites in case of strong nonlinearities. Existing theories are used to model the electrical properties of composites in which a tunable ferroelectric is mixed with a linear dielectric, the dielectric permittivity and loss tangent of the linear dielectric being much smaller than those of the ferroelectric. It is shown that in this case the addition of small amounts of the linear dielectric into the tunable ferroelectrics leads to a small increase of the tunability of the mixture. Namely, it is possible to reduce significantly the permittivity of the composite, while keeping the initial level of the tunability or even increasing it slightly. At the same time, the loss tangent of the composite is virtually unaffected by the addition of the low-loss dielectrics. Thus, it is theoretically shown that the tunable performance of ferroelectrics can be slightly improved by mixing them with linear dielectrics and that, contrary to the general intuitive belief, the origin of this improvement is due to a slight increase of tunability rather than due to a decrease of the loss tangent. The possibility to reduce the dielectric permittivity keeping the tunability makes ferroelectric-dielectric composites attractive for applications where tunable materials with a reduced dielectric permittivity are needed.

This work was supported by the Swiss National Science Foundation and Swiss Office of Science and Education (EC program "Melody")

Session: FC1-B

SINGLE CRYSTAL PIEZOELECTRIC MATERIALS

Chair: V. Klipov

Sawyer Research Products

FC1-B-1 511CF 3:30 p.m. (Invited)

HISTORY OF THE INDUSTRIAL PRODUCTION AND TECHNICAL DEVELOPMENT OF SINGLE CRYSTAL CULTURED QUARTZ

G. R. JOHNSON*, Sawyer Research Products, Inc.
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Quartz is an important part of the history of the frequency control industry over the last fifty years. Today, single crystal cultured quartz is the most widely used material in frequency control and ranks second only to silicon in the quantity of single crystal materials produced for all electronic applications.

The first commercial process for quartz growth was developed in The United States in 1956. Since then the growth and improved performance of frequency control components has related closely to the technical and commercial development of quartz.

Quartz crystal production is concentrated in Japan, The United States, China and Russia. These geographic sectors have followed diverse paths to significantly different industry structures and technical focus.

Miniaturization, improved performance, and lower cost are the main economic and technical factors influencing all stages of the electronics industry from material production to equipment distribution. The techical and commercial history of quartz is guided by these same drivers, resulting in advances to improve purity, lower inclusion density, and improve structural perfection, while lowering cost and expanding availabiity. These developments in the quartz growth industry have enabled frequency control component manufacturers to produce smaller, less expensive components, in huge volume, with improved performance.

FC1-B-2 511CF 4:00 p.m.

DISTRIBUTION OF AL AND OH IMPURITIES IN SYNTHETIC QUARTZ CROWN FROM CYLINDRICAL SEEDS

P. L. GUZZO[1], A. H. SHINOHARA*[1], C. V. D. CABRAL[1], A. E. S. SANTOS[1], A. A. RASLAN[2], and T. KAGAMI[3], [1]Federal University of Pernambuco, Department of Mechanical Engineering, [2]Federal University of Uberlandia, Faculty of Mechanical Engineering, [3]Nihon Dempa Kogyo Co., Ltd.
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In the industrialized mass production of synthetic quartz, Y-bar and rectangular Z-plate seeds with a long Y direction are usually adopted as seed-crystals. As a result, the characterization of structural defects in synthetic quartz has been constrained to growth sectors appearing around the Y direction, i.e., Z-, S-, +X- and X-sectors. Until now, there are only few works considering the distribution of structural defects in sectors grown from seed-crystals with unconventional orientations. In the present study, the distribution of substitutional Al and OH species were investigated in the growth sectors formed around X, Y and Z directions. For this purpose, cylindrical bars with 18 mm diameter and 20 mm length were extracted from a synthetic quartz block by ultrasonic machining and were further used as seed-crystals. Cylindrical geometry was selected because its permits indistinctly the growth of all sectors around a given crystal axis. The hydrothermal growth was carried out in a commercial autoclave at Nihon Dempa Kogyo Company (Japan) under NaOH solution during 50 days. Prismatic habit crystals with m-, R-, r-, and x- faces grew from cylindrical seeds. From these crystals, plates perpendicular to the direction of the cylindrical seed were sectioned, lapped and polished. The growth sectors formed around each crystallographic direction were identified by the darkening grade produced by gamma irradiation. The specimens were exposed to a dose of 50 kGy at room temperature using a Co-60 source. Optical spectroscopy performed in as-grown and irradiated plates was adopted to evaluate the formation of Al-hole centers. Infrared spectroscopy was used to evaluate the intensity of as-grown OH, Al-OH and Li-OH centers. Compared to the growth sectors appearing around the Y

direction, a different distribution of Al-related centers was found in +X- and X-growth sectors appearing around the Z direction. Mayor (R) and minor (r) rhombohedral sectors appearing around the X direction were distinctly affected by gamma-irradiation. Al-Li centers were mainly converted into Al-OH and Al-hole centers in R- and r- growth sectors, respectively. The distributions of substitutional Al and OH species are discussed in relation to the growth rate anisotropy of the crystal faces.
CNPq, CAPES, IFM/CNPq, CTPETRO/FINEP, CHESF/ANEEL

FC1-B-3 511CF 4:15 p.m.

PHASE TRANSITIONS IN LANGASITE FAMILY CRYSTALS

B. V. MILL*[1], B. A. MAXIMOV[2], YU. V. PISAREVSKY[2], A. PAVLOVSKA[3], S. WERNER[3], J. SCHNEIDER[3], and N. P. DANILOVA[1], [1]Moscow State University, [2]Institute of Crystallography RAS, [3]Universitat Muenchen, Institut fuer Kristallographie und Angewandte Mineralogie.
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From the beginning, it is considered that langasite family crystals grown by the Czochralski method have no phase transitions below Tm, which is regarded as a significant advantage for piezoelectric applications. At once, some crystal properties (i.g. dielectric permeability, acoustic wave velocities) have anomalous temperature behaviour indicating that not all is so simple. Among 140 compounds with Ca3Ga2Ge4O14 structure, three compositions, namely La3SbZn3Si2O14, La3SbZn3Ge2O14, and SrLa2Ga4Si2O14, have distorted trigonal crystal lattice. Based on above, we have started a special program on search for phase transitions and their manifestation in crystal structure in langasite family crystals. Possible structural changes described by the group–subgroup relationships in the Ca3Ga2Ge4O14-type structure (sp. gr. P321) were considered. The most probable phase transitions seemed to be those with lowering of the symmetry to the maximal non-isomorphic subgroups P3 and C2. It was shown that only destructive phase transitions with the symmetry rise up to the minimal non-isomorphic supergroups can take place for the given structure type. The change of the trigonal symmetry to monoclinic is revealed in La3SbZn3Ge2O14, whose crystal structure is refined within the sp. gr. A2 (C2) as derivative of the Ca3Ga2Ge4O14-type structure. At 250oC, La3SbZn3Ge2O14 undergoes a reversible phase transition with symmetry rise, A2 <-> P321. Similar phase transitions, P321<-> A2, were also observed in La3Nb0.5Ga5.5O14 and La3Ta0.5Ga5.5O14 under the hydrostatic pressures 12.4(3) and 11.7(3) GPa, respectively. The mechanisms of phase transitions are based on the anisotropic compressibility of a layered structure. With the attainment of the critical stress level in the structure, the increased compressibility in the ab-plane gives rise to a phase transition accompanied by the loss of the threefold axis. The search for low-temperature phase transitions has not revealed them in a number of representatives of the langasite family. We can state now that at least some crystals of langasite family possess phase transitions under heat and pressure treatment.

Considering a great variety in composition and properties, other ways of phase transitions may be found.

Session: FC2-B

COLD ATOM CLOCKS
Chair: A. Bauch
PTB

FC2-B-1 511DE 3:30 p.m.

RECENT IMPROVEMENTS IN NIST-F1 AND RESULTING ACCURACIES OF $< 7X10^{-16}$

T. P. HEAVNER*, S. R. JEFFERTS, E. A. DONLEY, J. H. SHIRLEY, and T. E. PARKER, NIST Time and Frequency Division.
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Since our last detailed publication [1] describing the accuracy budget for NIST-F1 (a laser-cooled Cs fountain primary frequency standard) we have made many improvements resulting in nearly a factor of 2 reduction in the uncertainty in the realization of the SI second and greater reliability. We now routinely produce frequency evaluations of NIST-F1 with combined standard uncertainties below $1x10^{-15}$ and we recently reported a combined standard uncertainty of $0.67x10^{-15}$ consisting of a type A uncertainty of 0.50×10^{-15} and a type B uncertainty of 0.44×10^{-15}. We discuss improvements in the physics package and fountain operation which has resulted in greater reliability and run time.

A review of the error budget in [1] shows the three major contributors to the final systematic type B uncertainties were the spin-exchange shift, the second-order Zeeman shift and the Blackbody shift. While the uncertainties due to these three have decreased, most notably the spin-exchange shift, they are still dominant. However, other shifts, once considered minor, are now significant contributors to the error budget. We will reconsider systematic shifts previously determined to be less than $1x10^{-16}$ and thus ignored in earlier evaluations.

Improvements to NIST-F1 we discuss include the laser system, detection system, atom number control, C-field uniformity and mapping, physics package temperature monitoring and control software.

The implementation of a diode-pumped Titanium:Sapphire ring laser system with higher power allows for larger diameter horizontal cooling beams. Thus our optical molasses is physically larger and we operate with a lower spin-exchange shift than reported in [1] using the same atom number for stability. Additionally, this laser system is very reliable. Consequently, this has reduced the statistical uncertainty (Type A) due to total measurement time as well as reduced the dead time in the comparison with our hydrogen maser reference. Improvements in the detection system have resulted in a quantum projection noise limit at 500 atoms. The detection light power is also now servo controlled which has reduced AM noise in the laser light and reduced long term drift. New monitor and alarm systems allow us to quickly detect problems and bring the fountain back on line thus increasing fractional run time. Improved magnetic field uniformity and new mapping techniques have reduced the second-order Zeeman shift. The blackbody shift uncertainty has been reduced slightly by the addition of more accurate temperature sensing instrumentation within the drift tube region of the physics package. References

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FC2-B-2 511DE 3:45 p.m.

DEVELOPMENT OF COMPACT COLD ATOM FREQUENCY STANDARDS: FROM MICROWAVE TO CPT INTERROGATIONS

S. TRÉMINE, T. ZANON, S. GUÉRANDEL, E. DE CLERCQ, D. HOLLEVILLE, A. CLAIRON, and N. DIMARCQ*, BNM-SYRTE, CNRS UMR8630.
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Laser cooling techniques can be applied to design either ultra high performance frequency standards or atomic clocks combining compactness and high frequency performance atomic clocks. The frequency stability target of such compact clocks is better than 5. 10^{-13} $t^{-1/2}$. Low velocities are suitable to reach a frequency accuracy much better than 10^{-14}.

Two compact cesium clock projects are currently developed at BNM-SYRTE. The first clock project, called HORACE, is the simplest cold atom clock where the cesium atoms are successively cooled, interrogated and detected at the same place, inside an optically polished microwave cavity. This original cooling configuration without collimated laser beams has been demonstrated to lead to noticeable cold atom numbers (a few 10^8) with sub-Doppler temperatures (a few microKelvins). As all interactions take place in the microwave cavity, it is possible to use almost the same cold atoms at each operation cycle. For an operation on Earth, the operation cycle is limited by the free fall under gravity of the atoms inside the cavity. Cycle periods as fast as 50 ms with an interrogation time limited to a few 10 ms can be obtained : this should give a clock fringe less than 100 Hz wide, much narrower than the thermal beam clocks. Experiments with Rabi and Ramsey microwave interrogations will be presented and discussed. The influence of the clock cycle parameters will be detailed in order to determine the reachable frequency performances.

The second clock project aims at utilizing Coherent Population Trapping (CPT) techniques in a cold atom clock. In a CPT clock, the microwave interrogation is replaced by optical interactions with copropagating laser beams

which induce Raman resonant transitions. Atomic clocks based on CPT are interesting because of the narrow linewidths achievable with simple and compact design. The linewidth of a CPT resonance mainly depends on the following effects : transit time in the laser beams, coherence relaxation, first order Doppler effect and saturation of the optical transitions. The interest of using cold atoms in a CPT clock will be pointed out. To drive the dark resonance in cesium, two coherent laser beams with 9.2 GHz frequency offset have been generated using two phase-locked Extended Cavity Laser Diodes (ECLD) emitting at 894 nm. Different CPT interaction configurations have been studied on thermal atoms in a vapour cell filled with N2 as buffer gas. Results of theoretical and experimental studies will be presented.
The authors are grateful to CNRS, CNES, DGA and BNM for their financial support.

FC2-B-3 511DE 4:00 p.m.

THE CESIUM PHYSICS PACKAGE DESIGN FOR THE PARCS PROJECT

E. BURT*[1], W. M. KLIPSTEIN[1], and S. R. JEFFERTS[2], [1]Jet Propulsion Laboratory, California Institute of Technology, [2]National Institute for Standards and Technology.
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The Primary Atomic Reference Clock in Space (PARCS) is a collaboration between the National Institute of Standards and Technology (NIST), the Jet Propulsion Laboratory (JPL) and the University of Colorado to build a laser-cooled cesium-beam atomic clock as a science payload for the International Space Station (ISS). The three primary goals of the PARCS experiment are (1) to demonstrate laser cooling of atoms in space, (2) to use laser cooling to build the most accurate space clock, and (3) to use the clock to test fundamental assumptions and predictions of relativity theory. Aspects of the cesium physics package subsystem design addressing magnetic, microwave and vacuum requirements as well as operational scenarios will be presented.

Part of the research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Part of the research described in this paper is work of the United States government, not subject to US copyright.

FC2-B-4 511DE 4:15 p.m.

PROGRESS TOWARDS AN OPERATIONAL RB FOUNTAIN

S. CRANE*, S. PEIL, T. SWANSON, and C. EKSTROM, U. S. Naval Observatory.
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The U.S. Naval Observatory's (USNO) newest atomic fountains are using rubidium in order to exploit the small cold-collision frequency shift. These clocks are being constructed for incorporation into the clock ensemble and have been designed for operational use.

We report on several subsystems, including our erbium- doped, frequency-doubled fiber laser, the four-layer magnetic shield set, and the vacuum system. We also expect to report our initial frequency stability measurements and comparisons with the USNO timing ensemble.

FC2-B-5 511DE 4:30 p.m.

MICROWAVE CAVITIES WITH SMALL PHASE GRADIENTS

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We have theoretically analyzed the phase gradients in a microwave cavity. We specifically consider a cylindrical TE_{011} cavity which is widely used in atomic clocks. Our analytic treatment of a cylindrical cavity with no endcap holes leads to clear physical models on how to minimize phase gradients for atomic clocks. The effects of holes in the endcap are analyzed using a variety of finite element methods. We will show new cavity designs that have phase gradients that are an order of magnitude smaller at the cavity midsection, and orders of magnitude smaller at the endcaps holes, than the phase gradients of cavities that are currently used in primary standards. In our analytic treatment, we solve the wave equation including losses from the cavity sidewalls and endcaps. The results are noteworthy as they produce simple expressions and show a significant phase gradient term that has been omitted in two dimensional analyses of cavities[1,2]. Previous two dimensional analyses suggested that phase shifts at the cavity midsection should vary as $\cos(m\phi)$ where m is the number of cavity feeds[2]. Further, the two dimensional analyses suggest that phase gradients are minimized for cavities with large diameters. We show that the endcap losses produce an azimuthally symmetric (m=0) quadratic phase variation at the cavity midsection. This term dominates for large cavity diameters when m>2. For a cavity radius of 3 cm, the phase gradients from the m=0 term are a factor of 10 larger than those from a two dimensional calculation for 4 feeds[2]. Our analysis shows that tall cavities with radii quite close to cut-off have order of magnitude smaller phase gradients near the center of the cavity. The cavities need to have holes in the cavity endcaps to allow the atoms to enter and exit and these produce local phase gradients that are very large. The fields near the endcap holes were studied both analytically and with finite element methods. We have previously shown that the microwave magnetic field near the corner is as large as the field at the center of the cavity[3,4]. Our analytic results show that the field diverges as $r^{-1/3}$ when r, the distance from the corner, is much larger than the skin depth. Within a few skin depths of the corner, we have used a finite element method that couples the real and imaginary parts of the

fields. We use our analytic models as a guide to consider different geometries using finite element methods. We can eliminate the large phase gradients due to the endcap holes by using large and small cut-off waveguide sections[3]. We will present new cavity designs that have much smaller phase gradients.

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We acknowledge financial support from NASA and the ONR.

FC2-B-6 511DE 4:45 p.m.

AN OPTICAL MOLASSES LOADED FROM A LOW-VELOCITY INTENSE SOURCE OF ATOMS

E. A. DONLEY*, T. P. HEAVNER, and S. R. JEFFERTS, NIST Time & Frequency Division.
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For a number of reasons it is desirable to boost the load rate of an optical molasses for an atomic fountain. For one, the dead time could be reduced, thereby improving the fountain stability by reducing both the cycle time and signal degradation from the Dick effect. A higher load rate would also allow for the implementation of the multiple velocity fountain technique [1], which could be used to reduce the size of the cold collision frequency shift. The initial demonstration of the method [2] was limited by the low fill rate of the optical molasses. We have demonstrated an improvement of the molasses fill rate by over a factor of 20 by loading the molasses with a low-velocity intense source of atoms (LVIS) [3], which is an atomic beam created from a hole drilled into one of the retroreflectors in an otherwise ordinary magneto-optical trap.

Our typical LVIS flux was 10^{10} atoms/s. The atoms in the highly collimated beam had a longitudinal velocity of 11 m/s and a transverse velocity of 5 cm/s. The asymptotic value for the number of atoms captured in the optical molasses was $1.1(1)\times10^9$ atoms and the fill time constant was $\tau = 290(30)$ ms. The fill rate at short times gives the relevant fill rate of $R_{t=0}=3.8\times10^6$ atoms/ms. At this rate, it would require 24 ms to capture and launch 10^7 state-selected atoms.

The fill rate at short times indicates that 38% of the LVIS atoms were being captured in the optical molasses. The current apparatus has suffered from vacuum leaks, and with those fixed, it is likely that the load rate will be twice as large as what we have demonstrated, taking the capture rate to nearly 100%.

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TUESDAY, AUGUST 24, 2004
POSTER SESSIONS: 5:00–6:30 p.m.

*** Author presenting Paper**

Session: PS1
STUDENT PAPER FINALISTS

PS1-1 510AC

BUBBLE-BASED ACOUSTIC RADIATION FORCE FOR MONITORING INTRAOCULAR LENS ELASTICITY

T. N. ERPELDING*[1], K. W. HOLLMAN[1], T. JUHASZ[1,2], and M. O'DONNELL[1],
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Previously, we demonstrated ultrasonic methods to monitor overall changes in the elastic properties of laser manipulated intraocular lenses. We also presented results using acoustic radiation force on laser-generated bubbles to measure viscoelastic properties of collagen gel phantoms. In the current study, we test the hypothesis that acoustic radiation force applied to laser-generated bubbles can monitor local changes of intraocular lens elasticity during a potential presbyopia treatment. Presbyopia is an age-related condition resulting from increased stiffness of the lens, reducing its ability to accommodate. Laser-induced optical breakdown (LIOB) treatment can increase compliance by applying a loose grid of photodisruption sites within the lens. A real-time elasticity monitoring system is needed to study the outcomes and guide this potential treatment. Optical breakdown occurs when sufficiently high threshold fluence is attained at the focus of femtosecond pulsed lasers, inducing plasma formation and bubble generation. The small transient gas bubbles can be used as targets for acoustic radiation force measurements prior to their ultimate collapse. While ultrasonic speckle is extremely limited within the lens, LIOB bubbles provide strong ultrasound backscatter to measure lens elastic properties. In this investigation, explanted porcine lenses are embedded within a gelatin phantom (5 w/w%) prior to laser treatment. An integrated optical-acoustical system has been constructed enabling simultaneous bubble creation and radiation force experiments. Femtosecond laser pulses (800 fs) are focused into the lens media to form bubbles using variable pulse number (1-3000) and peak powers. A two-element confocal ultrasonic transducer generates acoustic radiation force with the 1.5 MHz outer element while monitoring the bubble displacement within the lens using the 7.44 MHz inner element. The timing of acoustic radiation force application relative