The usage of SAW resonators as remote sensors is well known. Double resonator sensors for reducing disturbing influences from the radio channel as well as the separation of the sensor element from the SAW device into the matching network are already presented [1]. Here the change of the difference frequency is the sensor signal. Corrected matching was used to integrate the sensor function in the matching network [2], e.g. as a capacitive sensor. For passive wireless sensors it is very important to optimize the sensitivity and the resolution while keeping the energy conditions sufficient to be able to interrogate at longer distances. The system design for e.g. strain gauge sensors without sensitivity to the temperature demands to special properties of the used resonators. This paper shows a systematic calculation of the resonator behavior by using the PEC (parameters of equivalent circuit). The influence of the matching conditions and the connected SAW devices to different frequency detuning are calculated and compared to specified pairs of resonators. To extend the difference frequency shift by the sensor variation, resonators with obvious unequal Q factor have to be used. Also a certain derivation of the single resonator impedance results in different frequency dependencies from the detuning capacitor. This can be influenced during the design and fabrication process of the SAW devices. Typical values like the Q factor, the serial and parallel resonance frequency or the impedance of the SAW devices were taken to build the model of the double SAW resonator sensor. Finally the model is used to draw conclusions to the design parameters like reflection coefficient or aperture of the resonators to optimize the sensor behavior.


Session: P1M

RESONATORS
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P1M-1

DESIGN AND FABRICATION OF HIGH FREQUENCY BULK ACOUSTIC WAVE TRANSDUCERS USING INTERDIGITAL TRANSDUCERS

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The interdigital transducers (IDTs) deposited at an interface of piezoelectric crystal-liquid and powered by electrical signals of certain frequency can generate bulk acoustic waves (BAWs) only into the interior of liquid, and this phenomenon
can be applied in fabricating high-frequency BAW transducers. The imaginary part of the effective permittivity at the interface of piezoelectric crystal and liquid can be used to characterize the BAW generation with IDTs. The curves of effective permittivity versus orientation of piezoelectric crystal and interface slowness have been simulated. For a given piezoelectric crystal orientation, the appropriate interface slowness can be obtained, which corresponds to the case where IDTs generate BAWs only into liquid. According to the frequency of BAWs to be generated and the appropriate interface slowness, the space period of IDTs can be determined. Whereas IDTs contact liquid and generate BAWs into liquid directly, a layer of SiO2 is deposited at the surface of IDTs as a protective film to protect the electrodes of IDTs. Theoretical simulation results show that the thin film of SiO2 has less role for the BAW generation. The main advantage of this kind of transducer is that IDTs generate BAWs into liquid directly without the need of impedance matching. The transducer working frequency is only limited by the technics of surface acoustic wave devices. A BAW transducer using IDTs with a central frequency of 31.5MHz is designed and fabricated, and the experimental measurement results of frequency response are consistent with theoretical model.

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P1M-2

DESIGN OF COUPLED RESONATOR FILTERS USING ADMITTANCE AND SCATTERING MATRICES

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With the trend of increasing frequencies for wireless applications, new types of filters need to be explored to give alternative solutions to standard SAW ladder filters. A key technology appears to be Thin Film Bulk Acoustic Wave Resonators (FBAR) exploiting the fundamental thickness-extensional vibration mode of thin piezoelectric films. These resonators can be coupled electrically to form as well a ladder-type filter. An other way of achieving a filter response is to provide mechanical coupling between two or more resonators. This is best done by longitudinal coupling. Such structures are called Stacked Crystal Resonators (SCR) when two resonators are intimately coupled, or Coupled Resonator Filters (CRF) when coupling layers are inserted between them to reduce the coupling of the two resonators.

We use a numerical model that has already been described at last year’s symposium and has proven efficient to simulate single resonators. This model calculates the behaviour of electromechanical waves in multilayer structures. We have adapted it to calculate the electric response of SCR or CRF. This is obtained by applying successively a voltage at each port and calculating the
currents generated inside each electrode. This gives the admittance matrix of the device that can be easily converted into scattering parameters.

In this paper we briefly describe the numerical model and its adaptation to the case of CRF simulation. We use it to retrieve some design rules for such structures, by giving an example of filter design. Finally, we compare simulated responses to measures of devices.

P1M-3

RESONANT MODE CALCULATIONS OF CONTOURED DOUBLY-ROTATED QUARTZ CRYSTALS USING A VARIATIONAL APPROACH
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Results using published analytical approaches for calculation of fast shear (B) and extensional (A) modes of contoured, doubly-rotated quartz crystals have occasionally met with problems in our laboratories when compared with experimental data. Piezoelectric coupling can be off by more than a factor of two and well-trapped modes may appear experimentally when no trapping is predicted, and vice versa.

A technique has been developed using variational calculus which is similar to the perturbation approach developed by Dulmet a decade ago but derived directly here from the full Lagrangian of a piezoelectric material. Basis functions are of a form similar to past analytical solutions and can have displacements aligned with the plate axes or with the directions of the pure thickness mode solution. A computer program runs on a work station in a few minutes and gives all three mode families (A, B, and slow-shear C) up to the 7th overtone and anharmonic numbers up to 6.

Calculated frequencies for all three modes are consistent where applicable with results from analytical programs and with previously published results. One feature that should be noted is that the present variational model provides resonant frequencies and mode shapes for poorly trapped mode families where the analytical models do not. The model provides all three displacement components for use in calculating the mode shape and piezoelectric coupling. As an example, calculation of the piezoelectric coupling for the fundamental B mode of a 10 MHz, 3rd, contoured SC-cut crystal shows that the coupling is reduced by a mode distortion from a large accompanying orthogonal shear displacement component. The analytical models do not predict this effect. Experimental data for the dynamic capacitance supports the result.

P1M-4

FOCUSING NONDIFFRACTING BAW TRANSDUCER
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We present a detailed piezoelectric interdigital type transducer for quartz (wafer cut with c axis along surface normal) that can be used to produce a localized nondiffracting beam within the depth of a crystal [1]. The transducer is analogous with optical diffractive elements but the presence of anisotropy and several acoustic modes leads to a much more complicated design, and numerical modeling is required for the optimization of the local transducer structure. The transducer proposed is suited for the detection of the wave pattern on the opposite face of the crystal at a distance of 500 μm, so as to verify the formation of the nondiffracting wave. The wave can be measured, for instance, with the use of interferometric scanning on the back face of the crystal [2].

The transducer focuses the acoustic energy onto the propagation axis inside the bulk crystal where the characteristic properties of nondiffracting waves are revealed. If the crystal features nonlinear behavior, it should only take place in the regions of high amplitude; nondiffracting waves would therefore allow the study of nonlinear acoustic effects, such as harmonic generation or soliton formation, that only occur in a limited region inside the crystal. They may also be conceived of being useful for studying novel effects in piezoelectric crystals, such as acoustic memory [3] or dispersively backward propagating waves [4]. A very high acoustic power may even cause irreversible structural changes to occur on the propagation axis. Similarly, acousto-optic coupling is also enhanced where the acoustic amplitude is high, thus allowing the optical detection of effects arising near the focal line.


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P1M-5

ANALYSIS OF THICKNESS-EXTENSIONAL WAVES PROPAGATING IN THE LATERAL DIRECTION OF SOLIDLY MOUNTED PIEZOELECTRIC THIN FILM RESONATORS

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As an acoustic wave device for a super-high-frequency range over 1GHz, the solidly mounted piezoelectric thin film resonator (SMR) using λ/4 layers attracts increasing attention recently. In such a structure, acoustic waves generally propagate not only in the thickness direction but also in the lateral direction. In this
paper, we analyze the acoustic waves in the SMR-type piezoelectric thin film resonator and derive the dispersion relation between the lateral wave number and frequency, considering wave propagation in the lateral direction. Specifically, we consider a thickness-extensional wave in the multi-layer structure consisting of ZnO, SiO_2, Mo, and Si as the piezoelectric film, the low impedance layer, the high impedance layer, and the substrate, respectively. From the numerical calculations, it is shown that the lateral wave number generally turns into a complex number due to the leak of the acoustic energy to the substrate. This phenomenon is notable especially near the cutoff frequency of the wave, so that the cutoff frequency cannot be a real but a complex. It is also shown that the Q value can be calculated from the complex cutoff frequency and it becomes high with increasing the number of quarter-wave layers. Using the calculated dispersion relation, the solidly mounted resonator with a finite electrode width is analyzed considering the boundary conditions at the edge of the electrode, thereby yielding the resonance frequency spectrum and the resonance modes, that is the particle displacement distribution.

P1M-6

SPECTRUM OF PARAMETRICALLY EXITED BULK ACOUSTIC WAVE COMPOSITE RESONATOR
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The possibility of bulk acoustic wave generation and amplification in composite resonator due to parametric interaction in piezoelectric semiconductor layer placed in alternating uniform electric field is analyzed. A BAW resonator consisting of two piezoelectric layers is considered. The first layer (the electric input of the structure) is connected with the source of signal frequency . The second one is a piezoelectric semiconductor parametric layer placed in an alternating uniform electric field of frequency . The acoustic wave propagation in this layer is accompanied by the electron density wave of frequency . In the external electric field along with oscillations with main frequency the electron waves with combined frequency are excited. These oscillations result in acoustic oscillations on combined frequency. It was shown that input electric impedance of the acoustic composite resonator depends on frequency and amplitude of the external electric load. If pumping frequency is closed to double value of one of the composite resonator eigenmode frequency, parametric resonance may occur. The change in applied voltage amplitude governs the rearrangement of the resonator spectrum. At threshold voltage parametric amplification of the acoustic waves takes place. In this case the real part of electric impedance changes its sign. Numerical calculations of the structures composed of ZnO as a transducer and InSb as parametric medium confirmed the possibility of parametric amplification and wave generation. Small deviations of pumping frequency from double frequency of main resonance practically do not change the threshold values, but they change the frequency of the amplified peak and its amplitude.
The nucleation of ice by power ultrasound at elevated temperatures (compared to control experiments) has been well documented for the past four decades, however there is a limited understanding of the influence, if any of cavitation bubbles. This work reports high-speed observations of the crystallisation of ice in the presence of acoustic cavitation.

The experimental system allowed a small sample of pure water to be cooled rapidly to sub-zero temperatures. Ultrasound could then be applied at the desired frequency and amplitude and a single acoustic bubble could, if required be levitated in the liquid. The observations were made using a high-speed camera capable of 1100 f.p.s. and a microsecond flash unit.

Three main experiments were performed. The first results show that the presence of bubbles in the absence of an ultrasonic field have no effect on the nucleation temperature. The second set of results shows that ice cannot be nucleated at a higher temperature in the presence of an ultrasound field, and absence of a cavitation bubble. In both these cases, nucleation occurs at similar temperatures to ice crystallisation under control conditions, and the ice is initiated at the liquid container surface. These results confirm that acoustic cavitation is essential for the sonocrystallisation of ice.

The third set of experiments shows that ice is nucleated at elevated temperatures in the presence of a single levitated bubble. There appears to be a driving pressure amplitude threshold, above which the ice can be nucleated. In this case, the ice is initiated in the immediate vicinity of the acoustic bubble. The bubble apparently does not undergo the rapid collapse phase that is often associated with the mechanism of ice crystallisation and which is typically found for sonoluminescing or chemically active bubbles. Instead, the levitated bubble