Packageless SAW Devices with Isolated Layer Acoustic Waves (ILAW) and Waveguiding Layer Acoustic Waves (WLAW)

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***Abstract*—We report on two novel layered structure concepts and their acoustic wave properties for efficient, mechanically isolated, temperature compensated, and technologically attractive packageless SAW device applications as RF filters and duplexers. The piezoelectric substrate is covered with a layer of SiO_2 or Pyrex that is in turn covered by a material of higher acoustical impedance creating an Isolated Layer Acoustic Wave (ILAW). Otherwise the wave inside a relatively low acoustic velocity waveguiding layer is confined by the higher velocity topmost layer made with high SAW velocity material thus ensuring the creation of Waveguiding Layer Acoustic Waves (WLAW). Modeling of acoustical properties of these waves (ILAW and WLAW) is confirmed by experimental results while useful figures of coupling, reflection and temperature stability are obtained. Extensive experiments with in-situ monitored depositions of multiple layers were performed and very good acoustical isolation of the waves was achieved.**

I. INTRODUCTION

Dimensions and price reduction together with performance improvement are continuously driving the innovation in SAW filter technology. Among variants to achieve these goals, packageless structures are becoming more attractive. Some variants make use of acoustic waves that are confined near internal interfaces in solids like classic Stonely [1], Sezawa [2], Maerfeld-Tournois [3] waves, and more recent boundary waves [4], [5], [6] and [7]. These waves have low displacement on both sides of a complex laminated substrate and this feature allows avoiding a cavity above the surface, while the use of the materials with low temperature coefficients of frequency (TCF) for internal layers helps to remarkably reduce the TCF of broadband devices.

In fact some of these "boundary" waves propagate in such a way, that there are at least two boundaries on both sides of a more or less marked region where the main part of acoustic energy is confined. In our approach at least two distinct concepts may be derived that differ by the principles of wave confinement. In the first concept, (Figure 1, left) the propagation media is based on piezoelectric substrate such as $LiTaO_3$ or $LiNbO_3$ covered with a relatively thick layer of SiO_2 or Pyrex that is in turn covered by a material with higher acoustical impedance. The corresponding acoustic velocity in this material is below than the velocity of the resulting wave. Such a combination gives rise to an Isolated Layer Acoustic Wave (ILAW) with greatly reduced amplitude of particle displacement on the top surface. The degree of isolation can be further enhanced by a combination of high acoustical impedance and low acoustical impedance layers forming a Bragg like mirror structure in vertical direction thus confining the acoustical wave to the SiO_2 layer and resulting in negligible displacement on the top surface. The Isolated Layer Acoustic Waves (ILAW) thus formed can be based either on SH type wave or on a wave with sagittal plane displacement. The high impedance layers may be formed with W, Pt, Au and other dense metals as well as with WO, Yb_2O_3, ZrO_2 and other dense dielectrics, while for the low density materials dielectrics and metals, such as, SiO_2, Al, etc can be used.

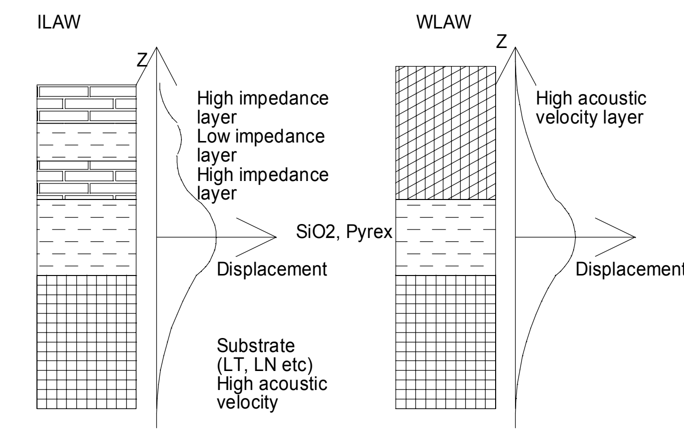

Figure 1. Illustration of layered structures for ILAW and WLAW concept

In the second concept, (Figure 1, right) the propagation of the wave inside the relatively low acoustic velocity waveguiding layer of SiO_2 or Pyrex is confined by the higher velocity substrate ($LiTaO_3$ or $LiNbO_3$) and by the topmost layer made with high acoustic velocity material (Al_2O_3, Si_3N_4 etc) thus ensuring the creation of Waveguiding Layer Acoustic Waves (WLAW) of either SH or sagittal plane polarization which has to some extent similar nature as the "boundary wave" described before [4], [5], [6], while using mainly different type of materials and technology.

In both concepts a number of modes exists with different properties and different velocities, thus obscuring the SAW device response, however most of them may be absorbed by topmost coatings and the layer content can be chosen in a way to move their velocities well apart from the working mode.

II. EXPERIMENTAL BACKGROUND

In order to obtain initial understanding of the waves that can propagate in layered structures we have used previously developed magnetron sputtering technique [8] with *in-situ* monitored resonator response. Synchronous resonators were patterned with 80 nm Au on 36º Y-cut of $LiTaO_3$, the gratings and IDT periods were 3.6, 3.8, 4.0 and 4.2 µm. A SiO_2 layer (about 1 µm) was deposited by CVD and the wire connections were made. The substrate was placed in a vacuum chamber and was connected to a network analyzer, so that the response was continuously monitored during the deposition and the data were registered against deposition time intervals.

A. ILAW concept verification

Several high acoustical impedance materials have been explored. Using dielectric coatings allows avoiding the procedure of electrical isolation of contact regions from deposited materials that is needed for metal coatings. For example Ytterbium oxide (Yb_2O_3) that forms by magnetron sputtering from Yb target in Ar + O_2 mixture gives a clear picture of involved modes.

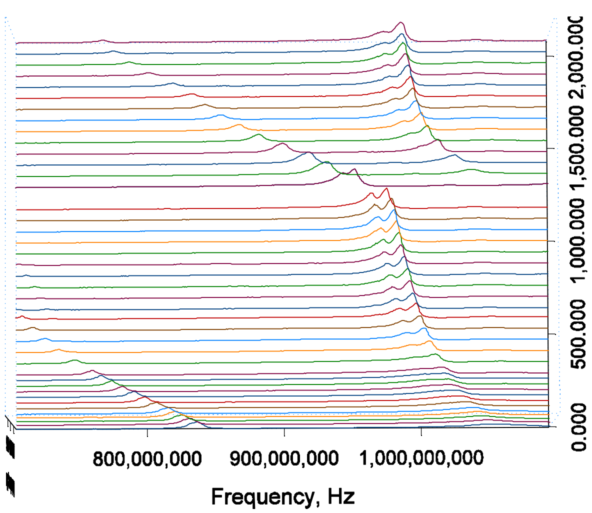

Figure 2. Result of Yb_2O_3 monitored deposition

Figure 2 shows gradual changes in the measured real part of resonator admittance (along Z-axis that is perpendicular to the view plane) after sputtering time intervals corresponding to thickness change of the growing Yb_2O_3 film during a 2000 seconds long deposition process (along Y-axis that is vertical in Figure 2). In fact the picture reflects the dispersion behavior of the modes existing in this system. The response in the low left corner can be attributed to the first mode of the modified Love wave that is initially already slowed down by Au electrodes and SiO_2 layer. The velocity and the coupling of this mode drop very fast with mass loading of the SiO_2 surface.

The mode that appears in the lower right corner of the graph can be attributed to a second mode of modified Love wave and its velocity and electro-mechanical coupling do not change significantly in a usefully large time interval between 300 and 1300 seconds, showing low sensitivity to gradually increasing mass loading. This means that in this range of related thickness the wave becomes more or less isolated from the influence of external coatings.

When the third mode of the modified Love wave appears (after 1500 seconds of deposition), the behavior of the second mode changes. The sensitivity to mass loading increases drastically.

B. WLAW concept verification

In Figure 3 the result of monitored deposition of Al_2O_3 is shown. As the sound velocity in Al_2O_3 is substantially higher than in the SiO_2 layer as well as in the substrate, the velocity of the first mode of the modified Love wave (lower left corner of the graph) increases while mass loading of the new born second mode (in the lower right corner) results in decreasing of its velocity. Finally after about 750 seconds of deposition all these modes tend to degenerate into one single mode of a waveguiding low velocity layer.

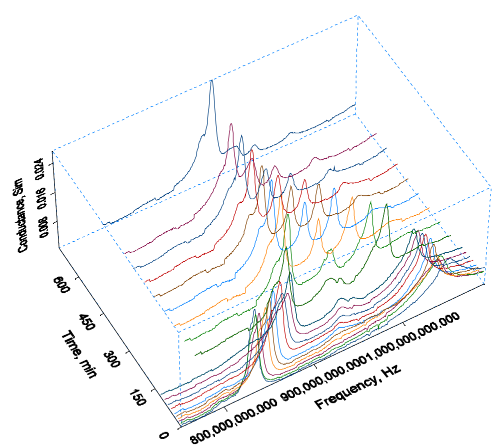

Figure 3. Result of Al_2O_3 monitored deposition

Remaining beatings on the right slope of the main peak after this deposition ended are related to modes that have a substantial displacement on the upper surface and their levels are reduced by placing an absorber on this surface, while the main peak level remains almost unchanged.

III. MODELING OF THE MODES IN LAYERD STRUCTURES

The algorithm is based on satisfying boundary conditions at each interface for solutions of equation system inside each material. Simplified software version that takes into account only shear-horizontal components of the mechanical displacement and of the piezoeffect may be applied to cases when SH component predominates in particle displacement of the wave. This approach is quite useful for calculation of wave velocity, electro-mechanical coupling, and for evaluating displacement profiles, but it is not valid for description of leaky loss.

A. ILAW structure modeling

This modeling example illustrates the concept of the wave isolation by choosing the second mode of the modified Love wave. The substrate is $LiTaO_3$ 42º YX cut and the layer of SiO_2 on top of it is quite thick (about half of the corresponding wavelength). The high impedance material used on top of the structure is W. The thickness of (uniform in this model) aluminum layer is 0.26μ, the thickness of SiO_2 is 2μ, and the thickness of W is 0.5μ. The frequency is 1.05 GHz. Horizontal lines in Figure 4 and in all the corresponding following figures mark the boundaries between the layers. The level "0" corresponds to the surface of $LiTaO_3$.

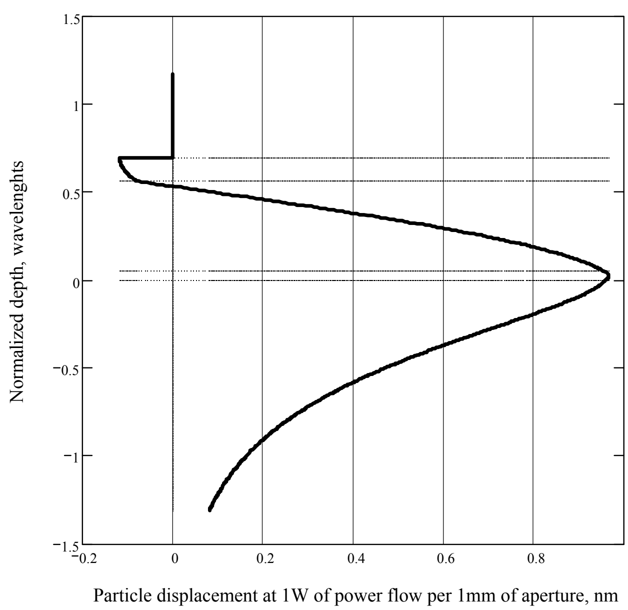

Figure 4. Modeling of ILAW concept.

This second mode has a large velocity (4096 m/s in this particular example and a low particle displacement on the upper surface (Figure 4). Main part of the energy of this wave propagates in the substrate, while a substantial part is located in the SiO_2 and in Al layers (Figure 5). This fact allows reducing the temperature coefficient of frequency (TCF) together with isolation of the wave from external mass loading. Meanwhile reasonably high electro-mechanical coupling remains in this system. The second mode of the modified Love wave may also exist without high acoustical impedance layer when the thickness of the SiO_2 layer exceeds half wavelength, but this wave has quite high particle displacement on the upper surface, so it is not an isolated wave.

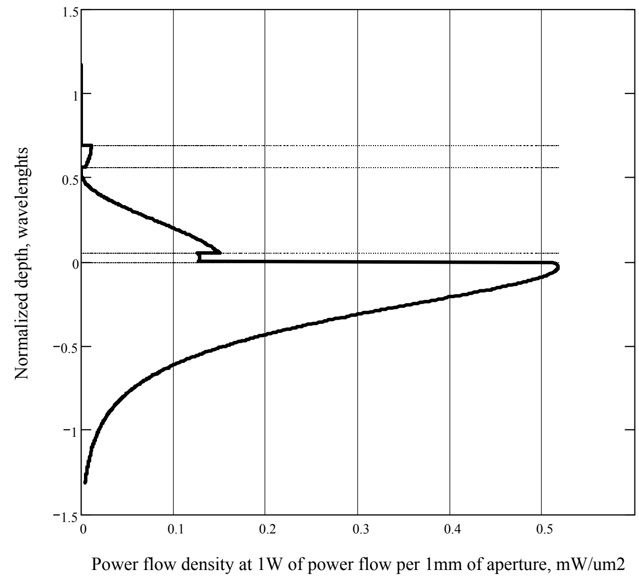

Figure 5. Power flow density profile for the previous example

Due to high impedance of the topmost layer together with low level of displacement at this interface the application of very low acoustical impedance materials like plastics on top of it prevents the acoustic energy from intensive leakage into the plastic material thus reducing it's influence on the attenuation and on the velocity of the selected mode to almost negligible value.

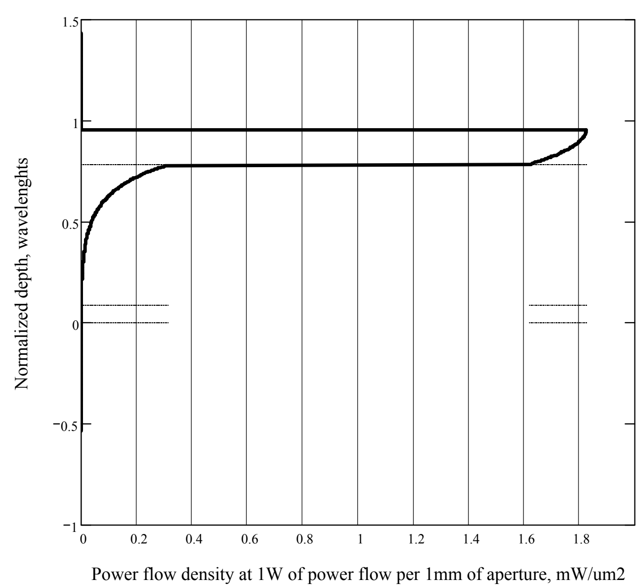

Figure 6. Power flow density in the first mode of the modified Love wave.

The first mode of the modified Love wave exists simultaneously with the second mode and it has low electro-mechanical coupling, high sensitivity to mass loading and low velocity 3046 m/s. Figure 6 shows the power flow profile in this mode. The latter ensures that this wave does not distort the signal related to the isolated mode, besides this wave is immediately attenuated by absorber or plastics on the top. Above 95% of this wave energy propagates inside the topmost layer, and it thus has the TCF and the velocity related to this layer. The displacement profile looks similar to the Love wave profile.

When the thickness of the topmost layer exceeds about one quarter of the wavelength the third mode is getting born, while the properties of the second mode begin to deteriorate - that means that in this layer combination simple increase of the thickness cannot be used to further improve the acoustical isolation, and additional structures have to be used for this purpose.

B. WLAW structure modeling

The approach is similar to the one described above. The main layer that supports the wave together with the substrate is SiO_2, the thickness of SiO_2 may vary from about the quarter to about 3 quarters of wavelength when higher order mode begins to appear. Depending on the thickness of the high velocity layer the displacement on the surface is gradually reduced.

The example shown in Figure 7 is modeled for the thickness of aluminum layer of 0.26µ, the thickness of SiO_2 of 2µ, and the thickness of Al_2O_3 equal to 2.5µ. The frequency is again 1.05 GHz. The resulting WLAW velocity is 4076 m/s. We have taken the value of 140 GPa for alumina shear modulus and 3.9 g/cm^3 for the density. Depending on the choice of available materials with selected properties these concepts may require different layer thickness.

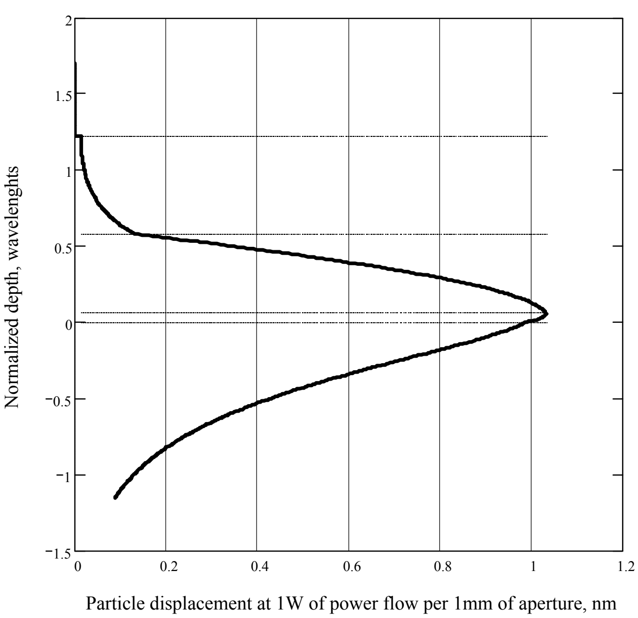

Figure 7. Modeling of isolation by a high velocity layer.

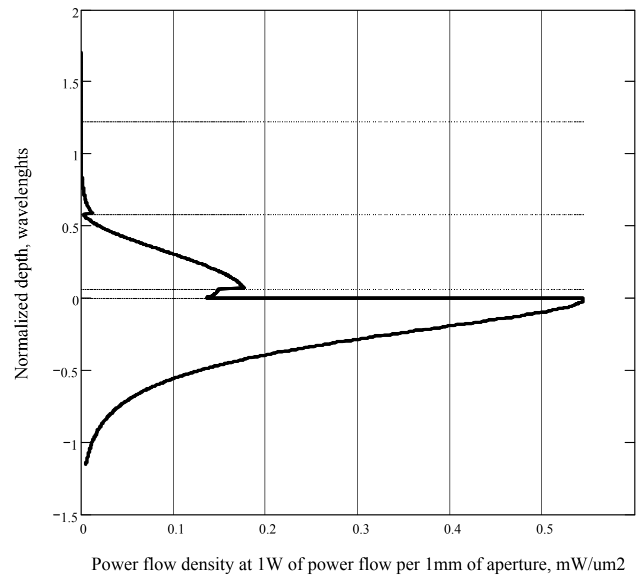

Figure 8. Power flow distribution in WLAW structure

The power flow density profile (Figure 8) in WLAW structure shows that a large part of the energy is located inside the substrate; a smaller part of it is related to the SiO_2 layer (and to Al layer) and only a very small portion goes in the high velocity Al_2O_3 layer. Thus the electromechanical coupling of this isolated wave may be up to two times lower than that of the initial SH wave on a corresponding cut of $LiTaO_3$ without SiO_2 layer. Simultaneously, the TCF is drastically improved and with material constants for fused silica it is predicted for some cases to be even positive +5 ppm/°C. These evaluations of wave properties are more or less valid for ILAW as well as for WLAW.

The modeling predicts flexibility of the WLAW concept with combinations of different materials it may give very high acoustical isolation of the wave and to serve as the basis of advanced packageless structures.

The experimental verification of isolation in WLAW structures (Figure 9) shows that the main wave properties are almost not affected by application of absorber (photoresist drop) on the top surface of the isolating Al_2O_3 layer, while the unwanted remaining modes get suppressed.

In comparison to WLAW concept, the ILAW concept misleadingly appears to be less robust. There is no improvement in isolation if the high impedance layer thickness is gradually increased after some optimum value because higher order modes begin to appear, while the isolated mode becomes again very sensitive to additional surface loading. In the case of WLAW one can interpret the thickness increase of topmost layer as a repeated application of this isolating technique to an already isolated structure for isolation improvement. In the case of ILAW the method of isolation improvement by repeated application of ILAW-type isolating technique also exists. The analogy with solidly mounted resonators (SMR) gives hope that alternating layers with high and low acoustical impedance may result in isolation improvement.

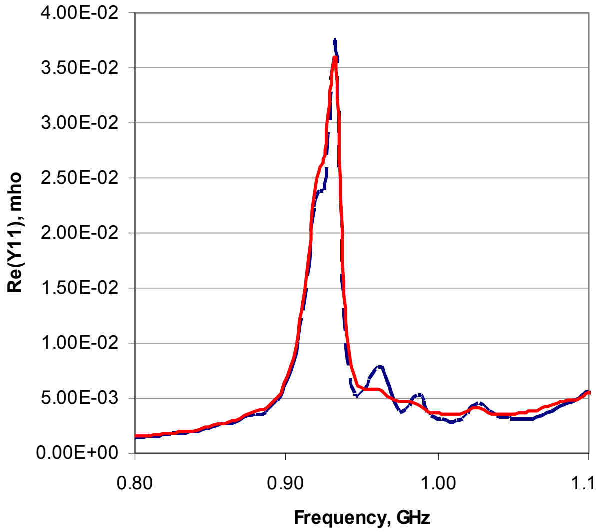

Figure 9. Application of photoresist on the top surface of a test sample with Al_2O_3 isolating coating. Dashed line before and solid line after application.

IV. BRAGG TYPE MIRROR-LIKE ISOLATING STRUCTURES IN ILAW

The example of modeling in Figure 10 shows the result of deposition of two additional layers with low and high acoustical impedance. In addition to the layers used for modeling in Figure 4, in this case we have used a layer of Al of 1μ and a second layer of W of 0.5μ. More layers can be added in case of need.

The resulting wave velocity in this example is 4096 m/s, and it is almost the same, as without new layers. The displacement on the top surface has decreased about 3 times more (about 5% of that at the LT interface). And the power flow density is already very low near the top surface. Experimental verification of this concept with different dielectric and metal coating has shown that the acoustical isolation improves with each consequent couple of layers with different impedance. It was confirmed that the higher is the impedance of the main isolating layer (the layer that is placed directly on SiO_2 layer), the better is the isolation. However the latter depends a lot on the choice of the thickness for all layers and this subject probably requires optimization in modeling as well as in experimental structures. The coupling is slightly worse in metallic structures due to increase in the static capacitance of the IDT but mainly due to increase of parasitic capacitance between bus-bars, for this reason the metal coating on the bus-bars should be avoided.

As somewhat higher amount of energy in ILAW concept may be located in the high impedance layer than in WLAW concept in the high velocity layer the TCF of SAW resonators may be affected by the properties of the first high impedance layer. For this reasons the choice of the properties of such layers and their thickness have to be made quite carefully. Our experience shows measured TCF values ranging from about 15 to about 60 ppm/°C depending on choice of materials for isolating structure and on the thicknesses of the layers.

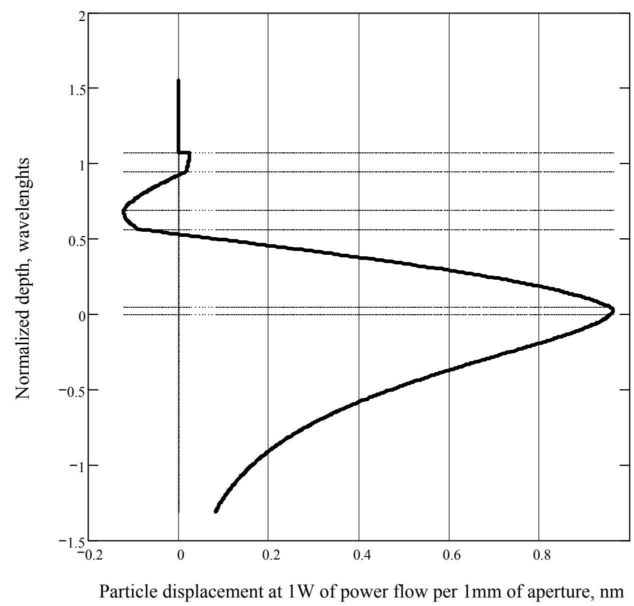

Figure 10. Example of ILAW isolation improvement by a mirror-like structure

Another important feature is that using thick Al electrodes (about 10% of wavelength) influences the response and it changes drastically with subsequent layer depositions. The problems with the change in reflection magnitude and sign often distort the response already after the deposition of SiO_2 films. This was shown in [9]. That is why in our proof of concept test samples we have manly used thin Au electrodes (80 nm).

V. MATERIAL CHOICES

Among materials for the waveguiding or for the isolated layer, SiO_2 based films are preferred. The well known property of temperature effect compensation by these films [10], [11] on $LiTaO_3$ and on $LiNbO_3$ substrates makes such films very attractive. One of such materials is Pyrex (Simax and other trade names exist for similar products) that has been extensively studied in [12]. We have tested both materials and so far we did not make any definitive choice besides the availability for immediate production. Other materials with good temperature related properties and with relatively low acoustical impedance and sound velocity may probably be used, as confirmed by our modeling. The experimental verification of such combinations is still required.

As high velocity materials in WLAW concept Al_2O_3 films may well be replaced by a number of other relatively low density rigid materials.

The choice of high impedance materials for ILAW concept is rather wide. We have experimentally confirmed the possibility to use W that gives almost the best acoustical isolation, and of Yb2O3, of WO_2 and HfO_2 (the HfO_2 monitored deposition is illustrated in Figure 11) that all the three dielectrics give better coupling and better TCF.

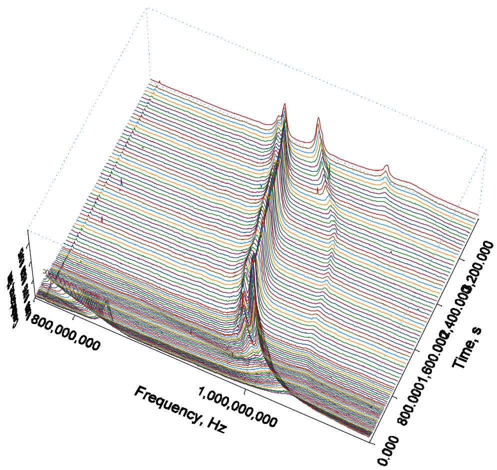

Figure 11. Monitored deposition of HfO_2 on a SiO_2 covered resonator on LT36.

As shown in Figure 11 the small imprint of the additional mode is observed at earlier stages of HfO_2 deposition and it gradually grows with thickness increase. This feature restricts the thickness of the isolating layer of this material. Bragg mirror structures are achievable with all these dielectrics. So far we have tested it for HfO_2/SiO_2 laminates.

The choice of materials is also relatively wide for layers with low acoustical impedance that alternate with high impedance layers. SiO_2 or Pyrex that can serve as the first layer in the stack, they are also fine in following layers. As Al also has quite low acoustical impedance, in metal mirror stacks it combines well with W. Al layers reduce internal stress at the interfaces that is often characteristic to W deposition.

VI. Discussion

The levels of acoustical isolation achievable in WLAW and Bragg mirror-type ILAW structures have both useful values at reasonable film thickness for RF resonators and filters. Practically sufficient deposition rates are achievable by CVD and by sputtering in order to make the processing economically viable. The deposition of plastics or liquids on the top surface imitating molded plastics shows that the level of isolation may be sufficient for packageless integration of such elements into modules with common enclosures.

VII. Conclusion

Both the WLAW concept and the ILAW concept (the latter improved by introduction of multiple layers of impedance alternating materials) show sufficient potential for packageless applications. The coupling factors have useful values while the TCF of the resonators and filters is greatly improved.

Acknowledgment

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