Laterally excited bulk wave resonators (**XBARs**) based on thin Lithium Niobate platelet for 5GHz and 13 GHz filters

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***Abstract*—In a free ZY-LiNbO3 400nm thick platelet, narrow electrodes (500nm wide) placed periodically with a pitch of few micrometers can eXcite standing Bulk Acoustic shear wave Resonances (XBARs), by means of lateral electric field parallel to crystalline Y- axis. The resonance frequency of around 4.8GHz and 13.6GHz are suitable for development of RF filters. The XBARs 3rd, 5th and even 9th harmonics were observed up to 38 GHz.**

***Keywords*—Lithium Niobate, bulk acoustic waves, FBARs, I.H.P, 5 GHz resonators, 5G phones, Q-factor, Lamb modes, MEMS, XBARs.**

I. Introduction

In current technology, the frequency bands are allocated for mobile phones in 3.3GHz-5.0GHz range and above 24GHz. For example, band 78 (3.30GHz-3.80GHz) is 500MHz wide, while GSM phones at 900MHz typically use only 35MHz wide frequency band. Modern mobile phones operate in many frequency bands and, correspondingly, demand a large number (20 and more) of frequency filters. Currently, for frequencies below 2.5GHz- 3GHz the filters are realized with Surface Acoustic Wave (SAW) devices or ladder filters based on thin Film Bulk Acoustic Wave Resonators (FBARs). The problems, however, arise if one tries to use the same approach for the 5GHz range. In SAW devices one then requires electrodes with less than 200nm width, which is inaccessible for currently standard optical photolithography used for SAW filter manufacturing. Although direct solution, using e-beam lithography, is possible and gives good results [1], it is hardly suitable for mass production. Moreover, the narrow and thin electrodes have higher resistive losses, lower power handling, etc. FBARs at 5GHz and higher frequency range also have some problems: they use AlN films with relatively small piezoelectric coupling coefficient sufficient for 3% relative bandwidth, while, for example, above mentioned band 78 is about 14% wide. The resistive and acoustic losses in metal electrodes become a significant problem for 5 GHz devices, both in SAW and FBARs. Therefore, a radically new solution is required which

a) would be based on optical lithography,

b) would allow much wider relative bandwidth.

Here we propose such a solution. It is inspired by Kadota's results [2], [3] on Lamb modes in thin $LiNbO_3$ layers, by Murata's I.H.P. technology [4] of SAW devices and by recent developments in MEMS [7]-[9].

II. Laterally excited bulk wave resonators (XBARs)

A. *Thin Lithium Niobate plate devices*

In their pioneering paper M. Kadota and co-authors [2], year 2010, proposed to use asymmetric A1 Lamb mode in thin lithium niobate suspended film for 5GHz resonators, exploiting high phase velocity and high piezo-coupling of this mode when the film thickness t is small compared to the wavelength λ ($t/\lambda \cong 0.2$ was used). The strong resonance with a ratio of resonance and antiresonance impedances of 52 and 38 dB and a wide band of 7.2% and 3.7% was experimentally demonstrated on a thin film produced using CVD technology and having complex polycrystalline structure. Probably due to which, relatively low Q-factors from 140 to 200 were obtained. In one of their next papers, M. Kadota and T. Ogami (2011, [3]) experimentally demonstrated a resonator based on 395 nm ZX-cut thin crystal lithium niobate plate exploiting asymmetric Lamb mode (A1). This mode is a type of half of wavelength thickness resonance, with shear displacements in 0X direction having opposite signs on the platelet edges. The resonator had a high resonance frequency (fr) of 5.44 GHz, a high antiresonance frequency (fa) of 6.09 GHz, a wide relative bandwidth of 12%, and a high impedance ratio of 62 dB at fr and fa [3]. The period of the electrode structure, including 2 electrodes was $2.63\mu m$, which means that the electrode width was about $0.66\mu m$. The device operates at 5 GHz and can be manufactured with optical lithography. However, Q-factor at resonance was only 70, which is not acceptable for low loss filter applications. The authors explain this low Q-factor at resonance by high resistivity of thin electrodes. However, the measured impedance at resonance is close to 1 Ohm.

Thin monocrystalline Lithium Niobate or Lithium Tantalate layers with micrometre thickness are used in Murata's Incredibly High Performance (I.H.P.) SAW technology [4], attached on a thick substrate. The device operation is based on wave guiding of quasi-shear waves in this thin layer on the "fast" substrate, inside which all existing bulk acoustic waves have higher velocities than the said guided wave. Using an SiO2 intermediate layer, TCF close to zero of total structure can be obtained. Low losses are achieved due to the absence of "leaky" bulk wave component (radiated into the bulk of the substrate) characteristic for quasi-shear waves in popular 42°rotated Y-cut of LiTaO3, and, incidentally, the cut also has low diffraction loss. In combination with relatively high piezo-coupling and low TCF "incredibly high performance" SAW devices are designed, with characteristics by far overcoming the "leaky" SAW devices and successfully competing with FBARs. In particular, resonator Q-factor of 4000 is achieved at 2 GHz and close to 2000 at 3.5 GHz, which is about 4 times higher than for the "leaky" wave SAW resonators. Nevertheless, the I.H.P technology still uses $\lambda/4$ wide electrodes and 5 GHz devices cannot be produced with optical lithography. Also, very low losses are demonstrated only for synchronous resonators, while devices having breaks in periodicity may have scattering from the waveguide and corresponding losses [5]. Excellent characteristics of I.H.P SAW are based on a new technology of transfer of thin monocrystalline LiNbO3 layer of desired orientation on different substrates [6].

Recently different devices exploiting Lamb mode in crystalline LiNbO3 platelets were described by S. Gong and co-authors [7], [8], [9] for MEMS structures. The Lamb A1 mode with high phase velocity was used [7] to develop MEMS resonator operating on 5GHz frequency with high Q-factor. The MEMS approach uses a few electrode structure on suspended micron-size lithium niobite platelet. These devices generally feature high level of spurious plate modes and have static capacitance of the order of tens of fF, corresponding to too high impedance at resonance despite excellent coupling K2 in many cases larger than 20%. These parameters render the devices not directly applicable for design of filters for mobile phone applications.

B. Geometry and simulation of XBARs

Here, we propose a device including periodic structure of 100nm thick and 500nm wide Al electrodes on suspended Lithium Niobate membrane 400nm thick with fixed edges as shown in Fig.1.

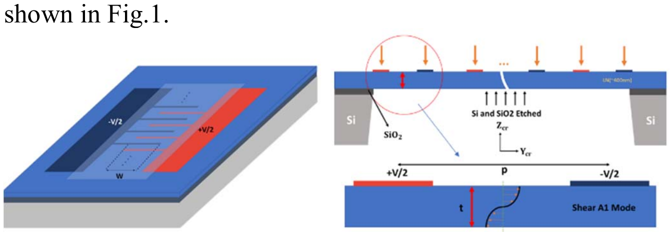

Fig. 1. Schematic of the device structure with crystalline Z axis perpendicular to the membrane surface, the electrodes are perpendicular to Y crystal axis (horizontal in this figure).

The ion-sliced monocrystalline Lithium Niobate layer on Si substrates, similar to that used in the I.H.P. technology [4], are now commercially available [6]. ZY orientation of LN for the membrane is suitable for lateral excitation of thickness vibrations with displacement in Y-direction due to strong e_{24} piezo-coefficient of LN and zero e_{26} responsible for shear horizontal (SH) modes generation. The electrodes with periodically changing polarity create in the platelet between them an electric field mainly directed horizontally. We use rather large pitch of 3μm (and 5 μm) in simulated and manufactured devices. The results of FEM simulation of two such structures are shown in Fig.2A and Fig.2B. The insets show horizontal component of displacement. The simulation was done using an approach similar to "hierarchical cascading"

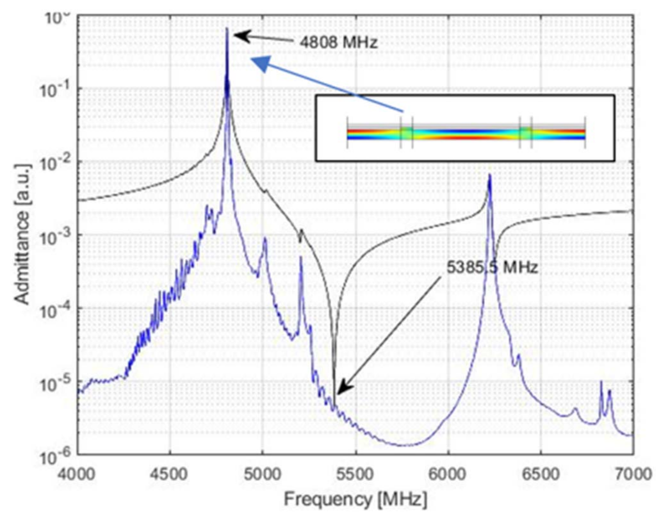

Fig. 2A. The XBAR structure with pitch p=3 μm, aperture W=20 μm, and number of electrodes Nt=51.

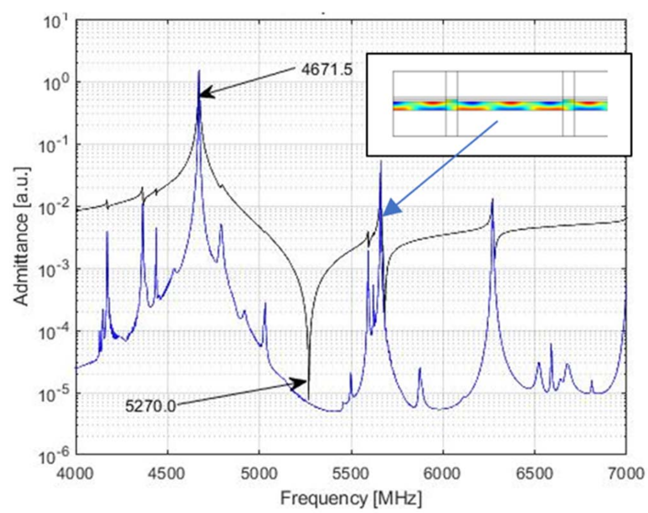

Fig.2B p=5 μm, W=40 μm, Nt=101. Al electrodes had 500nm width and 100nm thickness.

approach [10], which is very fast compared to COMSOL for 2D simulations, especially of structures with finite number of electrodes. COMSOL gives very close results.

The simulations show that the impedance at the resonance is of the order of 1 Ω, and imaginary impedance of the order of 50*j Ohms away from resonance – parameters required to design low loss filters for mobile phones - can be achieved. The relative Resonance-anti-Resonance (RaR) frequency distance which determines the low loss filter passband, is around 11% - 12%. These are huge values compared to 3% which are typical for AlN-based FBARs [11]. The simulations show excellent Q-factors at resonance and anti-resonance larger than 1000 at 5GHz, including electrode resistivity.

We treat the main resonance as shear bulk wave fundamental mode (when the membrane thickness $t \cong \lambda/2$, Fig.1), membrane resonates with displacements in horizontal crystalline Y-direction, as shown in Fig.1. The results of 3-dimentional (3D) simulations of periodic finite aperture structure illustrating the distribution of horizontal displacements on the membrane surface are shown in Fig 3. The main vibration mode is concentrated between electrodes where the electric field vector has large component in the direction perpendicular to the electrodes.

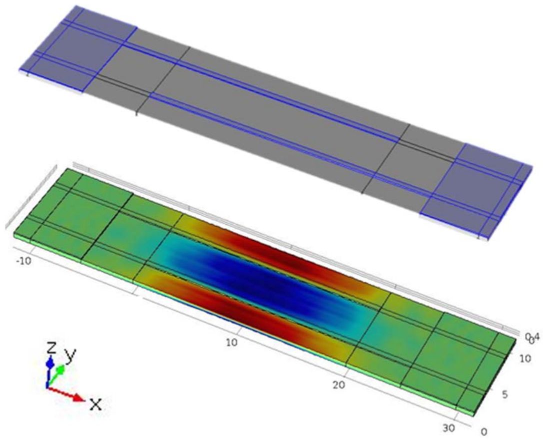

Fig.3 Distribution of displacement component in Y-direction (perpendicular to the electrodes) at resonance.

If the plate surface would be completely free, without electrodes, one could say that these vibrations correspond to anti-symmetric Lamb mode of the 1st order, A1, with velocity 15,000 m/s (for p=3 μm) or 25,000 m/s (for p=5 μm). Such fast velocity is a geometric effect – the wave fronts of a shear wave reflected up and down propagate almost vertically. The high phase velocity corresponds to almost zero group velocity: vertically reflected waves do not carry energy horizontally. In case of finite structure, simulations show no wave propagating outside electrode array.

C. Resonance at 13 GHz

In this device, except discussed main resonance, other resonating modes are present. Fig.4 shows the 3rd harmonics.

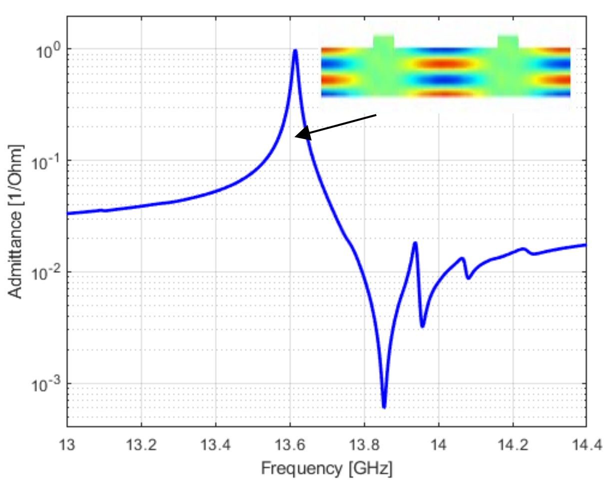

Fig.4 Simulated 3rd harmonics; pitch p=5um, electrode width a=0.4 um, number of electrodes Nt=401 and aperture W=20um, with the same LN platelet.

The 3rd, 5th, 7th, … "vertical" harmonics at frequency 3x, 5x, 7x… times higher can be simulated and were observed experimentally (see below). These modes correspond to the situation when the plate thickness t = n*λ /2 (n=3, 5, 7, …), where the wavelength λ is that of vertically propagating shear wave with displacements perpendicular to the electrodes. One can say that anti-symmetric Lamb modes A3, A5, A7, … are exited.

The 3rd harmonic resonance (Fig. 4) at least theoretically, shows parameters close to what is needed for applications. The simulated admittance for selected geometry (different from that in Fig.2) at the resonance is of the order of 1 Ohm, far from resonance it is around j*50 Ohms with coupling coefficient K2 ≈ 3.3%. The simulated Bode-Q factor is about 1000 for resonance and even higher at the anti-resonance. It is essential to stress that the device has CD = 0.5 um and can be produced with optical lithography. Evidently the device frequency is determined mainly by Lithium Niobate platelet thickness and will be sensitive (inversely proportional) to it. Thickness non-uniformity across the device will result in reduction of Q-factor.

D. Asymmetric Lamb mode A1 or just platelet resonance?

The presence of the rather thick electrodes (1/8th of λ) changes the system and its eigen modes. We have fixed wavelength in Ycr direction for all frequencies around the main resonance – antiresonance region. Moreover, we can see horizontal harmonics with 3, 5, 7 … with changes of polarity of vibrations between the electrodes, see inset in Fig.2b wherein the 3rd and 5th harmonics are strongly pronounced. They always correspond to A1 Lamb mode, half-wavelength standing wave in vertical direction, having higher frequency and about 3, 5… times smaller phase velocity in horizontal direction. It remains to be confirmed how close the observed resonances follow the Lamb mode A1 dispersion curve.

E. Other parasitic modes

Numerous, but weak, parasitic modes can be generated in the structure by the main horizontal component of the electric field, through e_{21} and e_{22} components of piezo coefficient exciting the compressional plate modes (see Fig.2A, B and experimental curve in Fig.5). Other sources of excitation of parasitic modes are vertical and shear component of the electric fields, strong immediately under electrodes and near the electrode tips. These modes are propagating along the structure, are reflected by the electrodes, and at some frequencies their amplitudes increase resonantly. Because they carry energy away from the resonator, their presence is not desirable. Many of these modes can probably be suppressed changing the electrode geometry.

III. First Experiments

The first experimental devices were manufactured. Fig.5 shows measured admittance of device having pitch p=3 μm, aperture 20 μm and 51 electrodes. Its geometry corresponds to the simulated device presented in Fig.2A. The insert in Fig.5 shows a microscope image of one of manufactured devices. The Si wafer with 2μm of SiO2 and LiNbO3 layer of about 400nm thickness produced by NanoLN [6] was grinded down to 250μm thickness and diced in chips of 10x13 mm^2. The LiNbO3 membrane was first released by etching the Si and

SiO2 from the bottom. This was followed by e-beam lithography, evaporation of metal and liftoff technology for Al electrode fabrication.

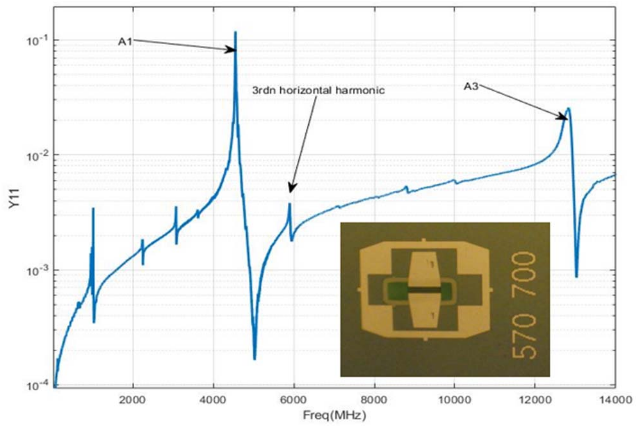

Fig.5 Manufactured device performance; In the insert is the photo of this device: bright areas are Al contacts, green area is LiNbO3 membrane, the electrodes look black

IV. Discussion

The first measurements show good qualitative agreement with the simulations. Detailed quantitative comparison of simulation with experiment will be presented elsewhere when we have more experimental samples with better known parameters and repeatable measurement data.

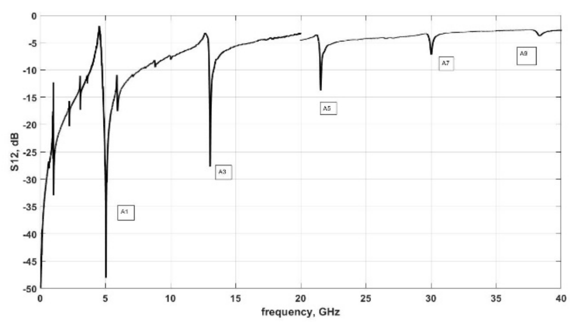

Fig.6 Measured transmission response: 3rd, 5th, 7th and 9th harmonics can be seen

Apart from the main shear plate resonance at about 4.5 GHz, we also see strong 3rd harmonic at triple the frequency of around 13 GHz. Measured as 2-port device (see insert in Fig.5), S12 data show the plate resonances up to 38GHz (Fig.6). The measured relative frequency gap between the resonance and the anti-resonance for the main 4.6 GHz resonance is about 10% corresponding to the piezoelectric coupling coefficient K2 $\cong$ 24%, the numbers are close to those predicted by simulation, Fig.2A.

With these parameters, the device is readily suitable for design of the ladder filters for mobile phones at 4GHz -6 GHz frequencies. The potential merits of this device include:

- CD >0.5 μm at 5GHz frequency range. The devices can be manufactured with standard optical lithography
- Potentially extremely high Q-factors can be obtained due to use of shear waves, and absence of metal in areas with high stresses
- Addition of SiO_2 layer between electrodes can be used for temperature stabilization and for control of resonance frequency and coupling. Uniquely strong coupling and, correspondingly, wide relative bandwidth of filters can be achieved
- The solid $LiNbO_3$ membrane attached from all sides is mechanically stable and provides better heat dissipation than if suspended in a few points such as anchors in MEMS devices.
- The device 3rd harmonic looks reasonable for trials of design of a filter operating at 10GHz- 15GHz frequency range, manufactured with optical lithography.

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