Design of Piezoelectric Aluminum Nitride MEMS Resonator

Ravi Patni, Mohit Joshi, Sameer Mehra, and Akhilesh Mohan

Abstract— **The following work reports the design, numerical, analytical and simulation characterization of an Aluminum Nitride MEMS resonator. The paper offers a comparison of rectangular plate MEMS resonator (length extensional and width extensional mode shapes) and ring shape MEMS resonator. It also demonstrates the contour Eigen modes of resonators and their equivalent electric circuit model (BVD). Furthermore, an overview of a band pass filter that can be enabled by mechanical coupling of these counter mode resonators is briefly presented.**

***Keywords*— MEMS resonator, Contour mode, Electromechanical coupling, Aluminum Nitride, Tethers.**

I. Introduction

Microelectromechanical system or MEMS is a technology which aims at developing very small machines for the integrated circuit industry. Electrical components such as inductors and tuneable capacitors can be improved significantly compared to their integrated counterparts if they are made using MEMS and Nanotechnology. The use of MEMS devices reduces the power consumption and thereby preventing the losses. Their size varies between .001mm to 0.1mm. These devices consist of a central part which processes data along with a microprocessor and several other components which interact with the outside [1]. MEMS devices are used in communication, DNA amplification and identification, micromachined Scanning Tunneling Microscopes (STMs), pressure sensors to monitor blood pressure, the analysis of concentrations of O_2, CO_2, potassium and calcium in patient's blood and several other applications which necessitate the use of micro sized devices. The main advantage of this technology is the bulk production of MEMS devices on a single wafer which makes it cheap and easy to produce.

MEMS resonators are basically time based generators or references whose operating principle is similar to the mechanical tuning fork which is used to tune musical instruments. One of the most intriguing features of MEMS resonators is that in principal it can be tied to PLLs and oscillator circuits on the same silicon substrate which would allow the clock and timing generators together to occupy a single low profile semiconductor package.

Manuscript received July 16, 2011; Revised August 2, 2011.
This work was supported in part by the Indian Institute of Technology (IIT) Rajasthan.

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After the successful implementation of quartz in MEMS resonator [2], it was found that Aluminum Nitride is a possible substitute to quartz because of its low dielectric loss, high electric resistance, high breakdown voltage and ability to produce filters with relatively and sufficiently large bandwidths. Also, it doesn't have structural phase transition and it keeps piezoelectric properties in high temperature until 1200ºC.

This paper presents the design of different types of resonator having their fundamental frequency defined by in-plane dimensions and hence they are called contour mode resonators. Contour mode describes the vibration of a device whose displacements are in direction parallel to the major surfaces. This mode facilitates the batch fabrication of piezo electric microresonators having different frequencies on a single chip. The next sections will deal with the designing of piezoelectric resonators followed by comparing the theoretical and simulated results obtained by BVD Model or electrical equivalent circuit of Mechanical resonators.

II. Rectangular plate aluminum nitride resonator

The rectangular plate AlN vibrating contour mode resonator is made by slotting in a layer of AlN between a Pt electrode and an Al electrode. When a vertical electric field is applied across film thickness it excites the resonator which leads to vibration. The vibration can be in Length extensional mode or Width extensional mode or any other spurious mode. If the structure vibrates along its length is called as Length extensional mode of vibration and when it vibrates along its width, it is called Width extensional mode of vibration.

Fig. 1 shows the geometry of a rectangular plate resonator with tethers (of same materials) attached at $\lambda/4$ position which makes them quarter wave tether. The main purpose of using tether in the design of resonator is to make the mode shape more stable by countermanding spurious resonances and making the structure capable of withstanding higher power [3]. A more efficient way of building reflectors is to introduce a material mismatch between the mechanical structure and the anchors [4].

A lot of modes of vibration can be found in a rectangular plate resonator either by changing the thickness of electrodes or the thickness of AlN or by changing the mode number. A few of these modes can be electrically detected [5]. We will only consider the contour mode vibrations.

If length is exchanged with the width and vice versa, we get a Width Extensional contour mode of vibrations. A certain aspect ratio between the length and the width is needed to be maintained [6] in order to maintain the desired contour modes and to reduce flexural vibrations.

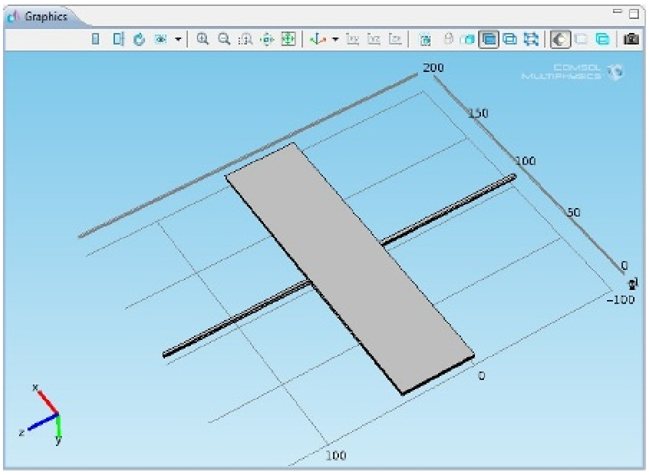

Fig. 1 Geometry of Rectangular plate resonator

Fig. 2 and Fig. 3 give the two possible phases for a Length Extensional contour mode vibrating resonator with Eigen frequency equal to 15.564MHz.

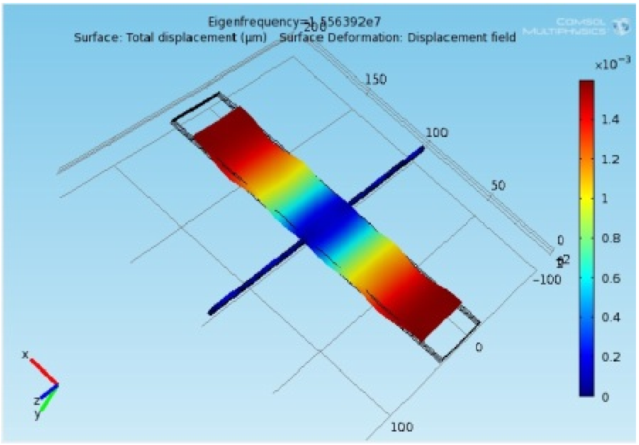

Fig. 2 Length Extensional contour mode (phase one)

We observed that as we keep on increasing the frequency we get the width extensional vibrating contour mode where the resonator vibrates across the width. Fig. 4 and Fig. 5 give the two possible phases for a Width Extensional contour mode vibrating resonator with Eigen frequency equal to 63.925MHz.

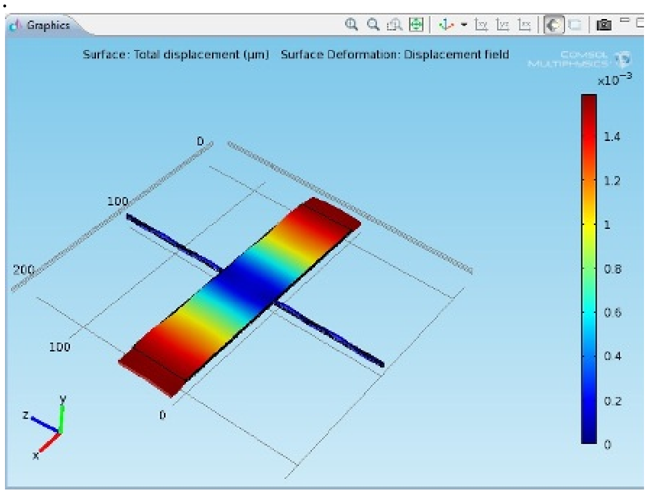

Fig. 3 Length Extensional contour mode (opposite phase)

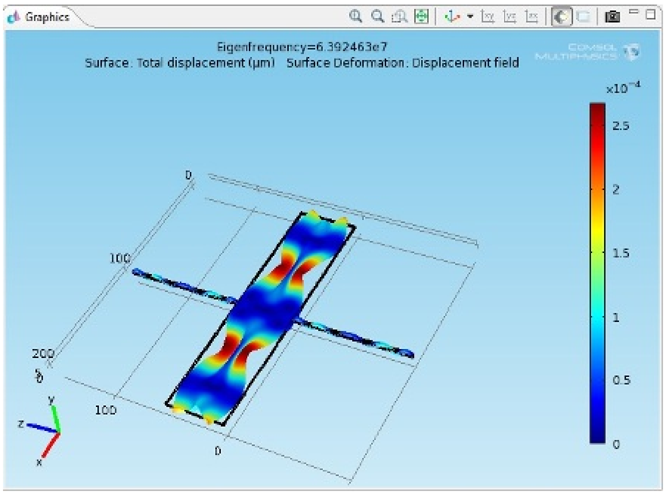

Fig. 4 Width Extensional contour mode (phase one)

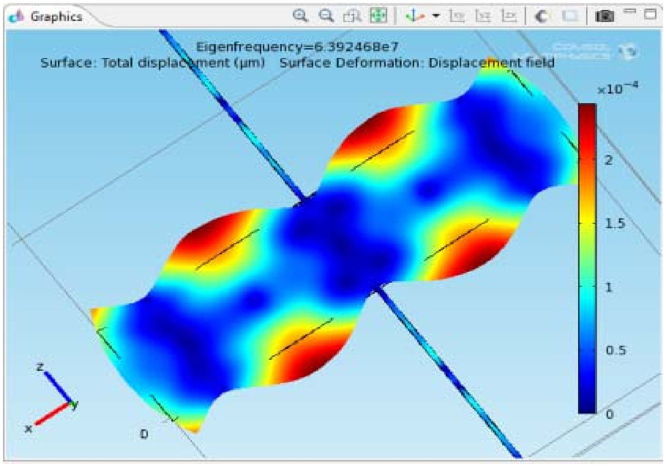

Fig. 5 Width Extensional contour mode (opposite phase)

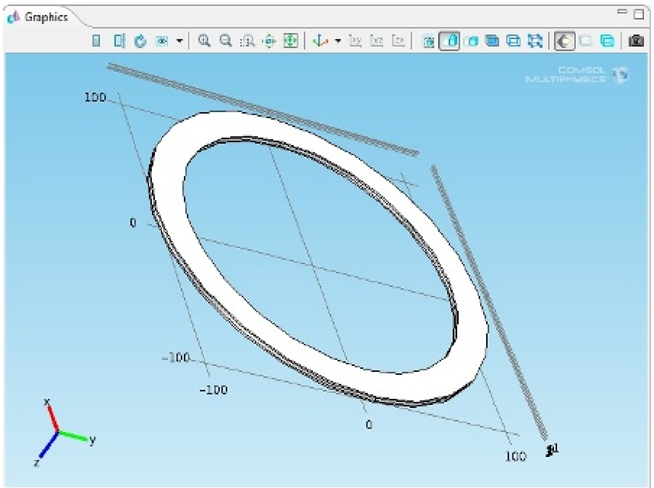

Fig. 6 Geometry of Ring shaped resonator (without tether)

III. RING SHAPED ALUMINUM NITRIDE RESONATOR

Analogous to the rectangular sheet, the Aluminum Nitride layer is slotted between an Aluminium electrode and a Platinum electrode. Here we have made an approximation

ISBN: 978-988-18210-9-6
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

that the average perimeter of the ring is much larger than its width.
The centre frequency of the resonator depends on the width of the ring.

A) Ring without tether

Fig.6 shows the geometry of Ring shaped resonator without tether. The contour mode detected in this model having an Eigen frequency of 100.99 MHz is shown in Fig. 8.

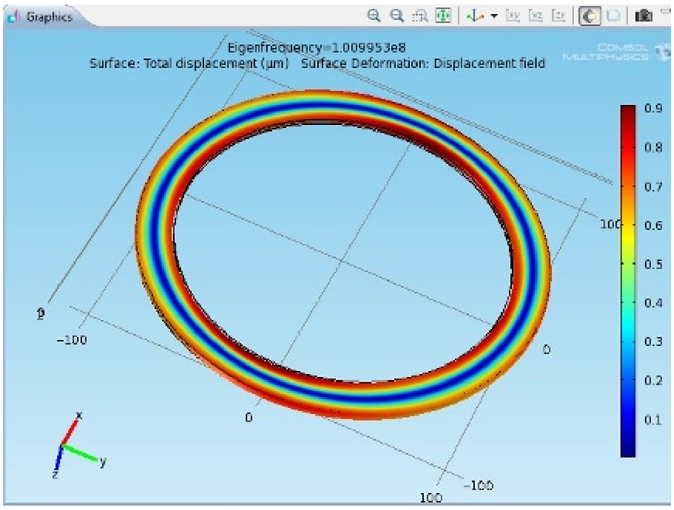

Fig. 8 Vibrating contour mode of ring (without tether)

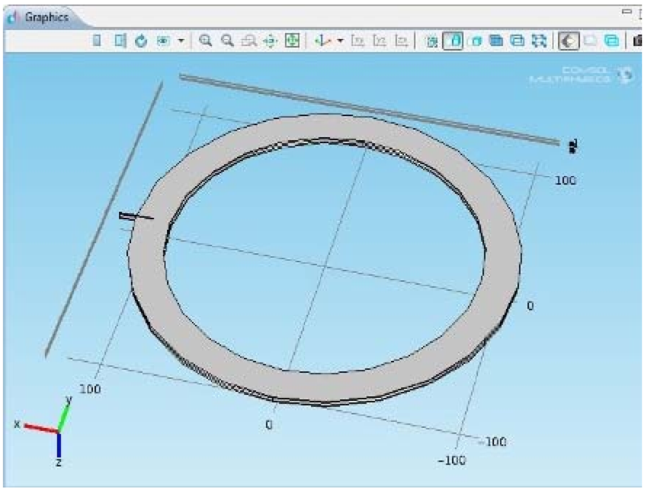

Fig. 7 Geometry of Ring shaped resonator (with tether)

B) Ring with tether

Fig. 7 shows the geometry of Ring shaped resonator with tether attached at λ/4 position for getting stable modes. The contour mode detected in this model having an Eigen frequency of 101.749 MHz is shown in Fig. 9.

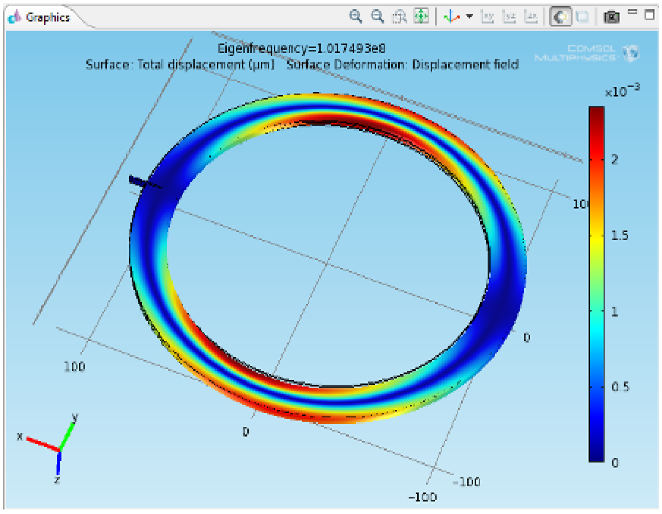

Fig. 9 Vibrating contour mode of ring (with tether)

Thus we can see that the use of tether doesn't have much impact on the vibrating frequency but shorter and thinner tethers do improve the Quality factor of the resonators. We have used quarter wave tether (λ/4 position) in both types of resonators but they do not play a substantial role in minimizing the energy loss. Some mechanical losses in the electrodes can be one of the main reasons for reduction in the Quality factor.

IV. Equivalent Electric Circuit - BVD Model

The mechanical parameters can be replaced by suitable electrical parameters which are described by BVD Model or Butterworth Van Dyke Model. Fig. 10 shows the BVD model for rectangular plate resonator simulated in ADS software.

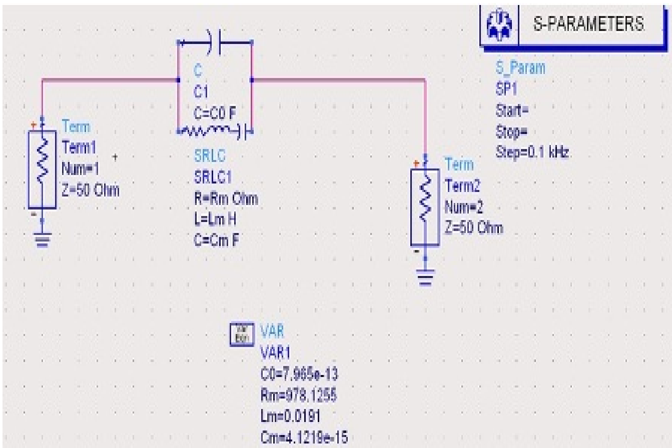

Fig. 10 BVD Model for a Rectangular plate resonator

The top branch also called as the Static branch and only contains capacitances represents the quartz capacitance and external connection capacitances. It gives a current component 90º out of phase with an applied voltage.

The bottom branch also **c**alled as the Motional branch represents the acoustic resonances in the quartz and its load. At series resonance the L_m and C_m reactances cancel each other, leaving only R_m which represents the losses in the

ISBN: 978-988-18210-9-6
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

quartz and its load. It gives a current in-phase with an applied voltage. When R_m is large, this in-phase current is small. The current from the static branch is no longer negligible and will distort the zero phase frequency to give errors in the resonant frequency. The effect of C_0 must be eliminated or compensated to ensure that the resonant frequency is not distorted.

The parameters for rectangular plate can be obtained by the following formulae:

$$C_m = \frac{8}{\pi^2}\frac{WL\,d_{31}^2}{T}E_P \qquad L_m = \frac{TL\,\rho}{8Wd_{31}^2\,E_P^2}$$

$$R_m = \frac{T\,\rho^{0.5}}{Wd_{31}^2\,Q\,E_P^{1.5}}\frac{\pi}{8} \qquad C_0 = \frac{WL\,\epsilon_{33}\,\epsilon_0}{T}$$

where W is width of resonator, L its length and E_P and T, the equivalent Young's modulus for AlN and the thickness of resonator.

We can see that motional resistance R_m is inversely proportional to the Quality factor Q. Here ρ and d_{31} represents the density and piezoelectric coefficient.

Similarly the BVD model for ring shaped resonator is shown in Fig. 11

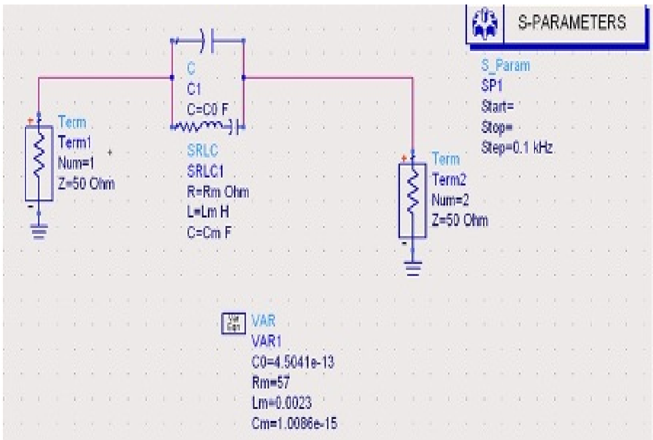

Fig. 11 BVD Model for a Ring shaped resonator

To get the required parameters for ring shaped resonator Length L is replaced by $2\pi R_{AVG}$, where R_{AVG} is the average radius of the ring.

The resonant frequency is expressed as –

$$f_o = \frac{1}{2L}\sqrt{\left\{\frac{Ep}{\rho(1-\sigma^2)}\right\}}$$

where, σ is the in-plane Poisson's ratio.

Table 1 shows the comparison between the theoretical and simulated results that we obtained for the length extensional, width extensional and the ring shaped resonator.

TABLE I
PARAMETERS OF RECTANGULAR PLATE AND CIRCULAR RING TYPE RESONATOR

Resonator variables	Length-Ext. Plate		Width-Ext. plate		Circular Ring	
	TH.	SIM.	TH.	SIM.	TH.	SIM.
f_0[MHz]	17.944	15.564	71.774	63.925	103.4	100.99
C_0[pF]	0.796	0.796	0.796	0.796	0.80	0.80
L_m[μH]	19100	19100	1200	1200	2300	2300
C_m[fF]	4.121	4.121	4.121	4.121	1.008	1.008
R_m[Ω]	978	978	244	244	57	57
Q Factor	-----	2200	-----	2200	-----	2800

The following values were used: E_P =170GPa, ρ= 3300kg/m^3,
d_{31} = -1.72953 pC/N, ϵ_{33}= 9, L= 200μm, W= 50μm, T= 1μm. For the ring shaped resonator, R_{AVG}= 90μm, W= 20 μm, T= 2 μm.

By carrying out the Finite Element Analysis (FEA) and defining different types of damping in COMSOL software, the Quality Factor of the rectangular sheet is determined to be 2200 and for the ring shaped resonator the Quality factor is equal to 2800.

Fig. 12, Fig. 13 and Fig. 14 shows the admittance plots for the Length Extensional, Width Extensional and Ring shaped resonator on ADS corresponding to the BVD model described before.

Fig. 12 Admittance plot for Length Extensional Mode

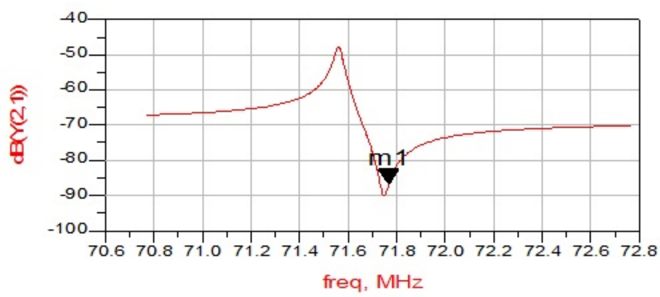

Fig. 13 Admittance plot for Width Extensional Mode

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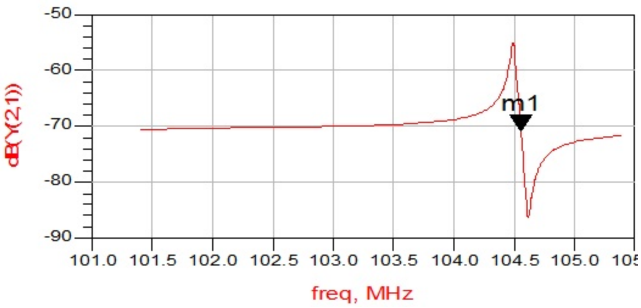

Fig. 14 Admittance plot for Width Extensional Mode

V. COUPLING OF RESONATOR

This section deals with the coupling of rectangular sheet resonator with the help of quarter wave tether i.e. the two similar sheets of rectangular plates with AlN sandwiched between Al and Pt electrodes. Fig. 15 and Fig. 16 shows the Odd and Even mode respectively of Length extensional contour mode. The Eigen frequency obtained is 15.56 MHz and Fig. 17 and Fig. 18 shows the Odd & Even mode of Width Extensional contour mode respectively. The Eigen frequency obtained is approximately 63.9 MHz.

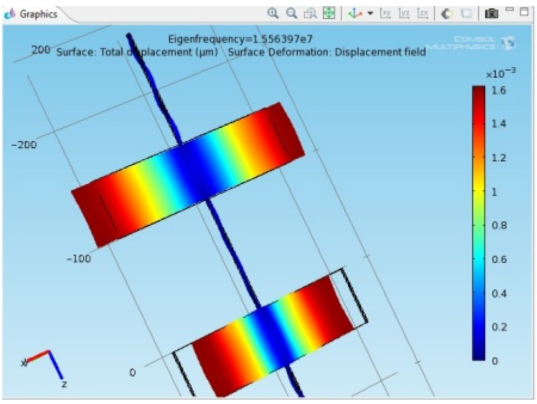

Fig. 15 Odd Mode of Length Extensional contour mode

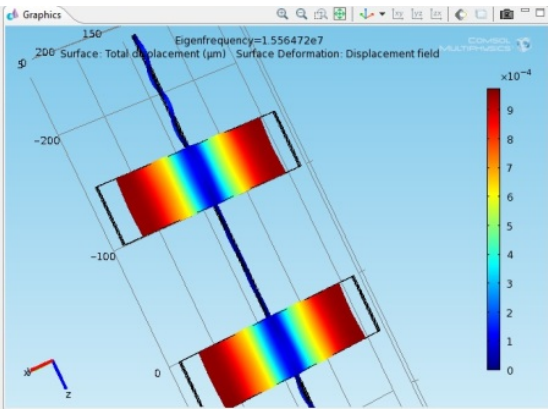

Fig. 16 Even Mode of Length Extensional contour mode

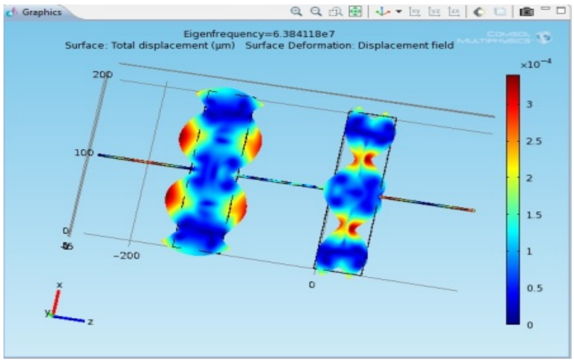

Fig. 17 Odd mode of Width Extensional contour mode

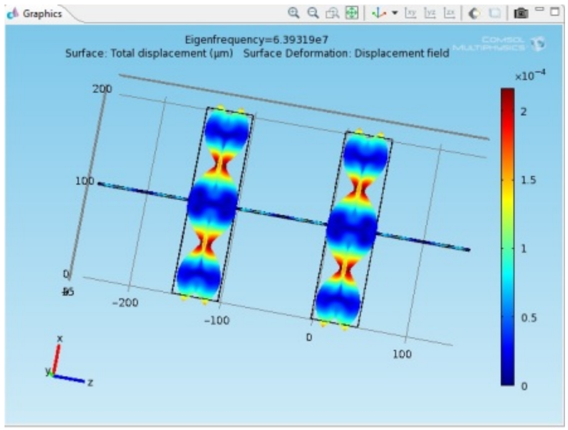

Fig. 18 Even mode of Width Extensional contour mode

VI. CONCLUSION

Aluminum nitride piezoelectric contour mode resonators have been demonstrated up to 105 MHz frequency. On a same substrate multiple devices at arbitrary centre frequency can be fabricated by using contour mode resonators. Ring shape resonator shows higher Quality Factor, lesser motional resistance at higher centre frequency in comparison to rectangular plate resonator. In contrast to band pass filter, increase in number of resonators will provide desired multi pole filter response and lowers the pass band ripples. Ongoing future research is focusing on demonstrating equivalent electric circuit model for band pass filter and finding a novel design of resonators to reduce motional resistance and improve the Quality factor.

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ISBN: 978-988-18210-9-6
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)