Transverse Mode Suppression in the AlN Lamb Wave Resonators by “Piston Mode”

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Abstract—Type I Lamb wave modes exhibit a strong affinity toward multimode behavior, especially the high-transduction-efficiency modes: \( S_0 \) and \( S_1 \) mode. Apodization, the standard technique to suppress the transverse modes for IDT-excited resonators, suffers from drawbacks such as additional loss and reduction of the effective coupling coefficient \( (k^2_{\text{eff}}) \). Most Lamb wave modes in AlN show a positive slope in the dispersion branch, so that a border region of lower eigenresonance frequency is required for spurious mode suppression. Based on dispersion calculations and finite element method (FEM) simulations, we demonstrate that by changing the transducer layout, the guiding can be improved and a “piston mode” can be obtained for the type I Lamb wave modes.

Keywords—Lamb wave resonator; transverse mode; \( S_0 \) mode; \( S_1 \) mode; piston mode; dispersion; aluminum nitride

I. INTRODUCTION

Piezoelectric microelectromechanical (MEMS) resonators offer fascinating prospects for frequency selection, control, and sensing applications thanks to its small size and low resonance impedance. Among various piezo-MEMS resonators, AlN Lamb wave resonators (LWRs) recently capture attention since they enjoy both advantages of surface acoustic wave (SAW) devices and film bulk acoustic resonators (FBARs): the multifrequency and CMOS-compatible ability [1]-[5]. For all Lamb wave modes propagating in an AlN plate, the \( S_0 \) and \( S_1 \) mode stand out for their excellent transduction efficiency [6]-[10].

In general, high quality factor \( (Q) \), large \( k^2_{\text{eff}} \), high frequency ability and spurious free are the 4 most desirable fundamental aspects for micro resonators to enable low-loss filters, stable oscillators and sensitive sensors. While the \( S_0 \) and \( S_1 \) Lamb wave resonators excellently address the former 3, they exhibit strong affinity toward multimode behavior along with their superior transduction efficiency. The presence of the strong transverse modes would hinder the accuracy and stability of oscillators and sensors, as well as hurt the performance of acoustic filters by creating severe passband ripples and potentially limiting the rejection [11]-[17].

Apodization as a standard solution for transverse modes in the IDT-excited devices by varying the resonance cavity length to smooth out the effect of transverse mode on the electrical response, its incomplete transduction from the electrical field to main mode resonance results in substantial drawbacks such as reduction of the transduction efficiency and additional losses for both SAW filters [11] and Lamb wave resonators [19]. A better solution can be borrowed from the SAW and FBAR devices: by creating a border region with different frequency from active region according to the mode dispersion characteristic, a “piston mode” can be obtained to cancel out the transverse wave vector in lateral direction without degrading the \( k^2_{\text{eff}} \) or \( Q \) [11]-[13].

II. DISPERSION CHARACTERISTICS OF LAMB WAVE MODES IN AlN

The dispersion characteristic of the first 4 Lamb wave modes is given in Fig. 1: the \( S_0 \) mode exhibits positive slope through all wave number range, meaning the positive group velocity \((v_g)\) and also corresponding to type I dispersion; the \( S_1 \) mode has a negative group velocity at \( h_{\text{AlN}}/\lambda < 0.3 \) while the type II dispersion happens and positive slope at \( h_{\text{AlN}}/\lambda > 0.3 \) in which case type I dispersion occurs.

To form “piston mode”, for resonances of type I dispersion, the frequency of the border region must be lower than that of the active area, which is the similar case for ZnO FBAR [12] and SAW filters (non-dispersive Rayleigh wave or SH wave has positive dispersion slope of \( 2\pi\nu_p \)). On the contrary, for resonances of type II dispersion, the frequency of the border region must be higher than that of the active area, which is the case for AlN FBAR [13].

However, for the LWR employing \( S_1 \) mode in the type II region, the transverse modes are not strongly excited, mostly...
below \( f_s \), and some other spurious modes, such as the interference from IDT fingers due to negative velocity, are much stronger and more of concern. As a result, the transverse modes and the design of "piston mode" for \( S_0 \) mode and type I \( S_1 \) mode are emphatically discussed herein.

III. TRANSVERSE MODES IN TYPE I LAMB WAVE MODES

Similar to FBAR and SAW resonators, the odd transverse modes are naturally cancelled in electrical response (as show in the left column of Fig. 5).

A. IDT Aperture

The IDT aperture and transverse mode order directly determine the wave number in lateral direction:

\[
\beta_x \approx \frac{\pi \cdot (n+1)}{w_a},
\]

where the \( w_a \) represents the active region width or aperture width and \( n \) stands for the transverse mode order. The wave number in propagation direction stays unchanged:

\[
\beta_y \approx \frac{2\pi}{\lambda}.
\]

Using orthogonal wave number vector superposition, the wave number value and frequency of each transverse mode can be estimated as:

\[
\beta_{x,\text{num}} \approx 2\pi \sqrt{\left(\frac{n+1}{2 \cdot w_a}\right)^2 + \left(\frac{1}{\lambda}\right)^2},
\]

\[
f_{x,\text{num}} = \frac{v_e}{\lambda} \sqrt{1 + \left(\frac{n+1}{2 \cdot w_a}/\lambda\right)^2}.
\]

Fig. 2 shows the theoretical curves from equation (4) and FEM simulated cases in dots. The longer the normalized active region \( w_a/\lambda \), the more transverse mode will be in passband, but with smaller amplitude because of inter energy dissipation. The FEM simulated frequencies are lower than theoretical because the inactive regions such as busbar and gap are taken into account. Longer aperture brings in more transverse modes and \( k_{\text{eff}}^2 \) will degrade for too-short aperture as \( f_s \) shifted to higher.

B. IDT gap

Fig. 3 shows the slowness curves of the transducer region, gap region, and busbar region of the \( S_0 \) mode for the \( h_{\text{AlN}}/\lambda=0.1 \) case as an example. The \( \theta \) monotonically increases with frequency for the transducer, busbar, and gap regions, meaning that the \( S_0 \) Lamb wave exhibits convex slowness curve feature in all regions.

Usually for a wave with a convex slowness curve to be trapped, a faster region is required at the lateral end to guide the wave [19]. For TCASAW resonators on SiO\(_2\)/LiNbO\(_3\), the faster gap region helps trapping energy, and for Quartz resonators the faster busbar region does the guiding job [11]. However for the \( S_0 \) mode here, the gap region exhibits too high phase velocity to make the wave guiding right at the transducer/gap interface. Also as the busbar region has phase velocity close to the transducer region, the wave guiding is actually close to the busbar/gap interface. As a result, by
modifying the gap region width \( w_g \) the energy trapping would not be impact much. Unlike the TCSAW who has a larger \( Q \) for wider gap, the energy loss of \( S_0 \) Lamb wave resonator is not dependent on the gap width; rather, the gap width has direct impact on the transverse mode amplitude.

Fig. 4 depicts the simulated conductance of \( S_0 \) resonators with different gap widths using PML-based FEM. When \( w_g / \lambda \) is 2, the transverse mode level becomes minimized. For slightly larger \( w_g \), the effective active region got stretched a little bit so that each transverse mode got smaller \( Q \) and lower frequency especially the first two modes \( 2^{th} \) and \( 4^{th} \). When the gap becomes too large, the increase in the \( k_{eff}^{2} \) will overcome the \( Q \) decrease, resulting in larger amplitude.

IV. PISTON MODE DESIGN FOR TYPE I LAMB WAVE MODES

A. Piston mode design for Type I Lamb wave modes

For the type I modes, by adding a small border region with a slow velocity on the edge of the acoustic aperture, a propagating mode has a zero transverse wave vector in the active aperture. The transverse wave vector is real in the border region and imaginary on the gap region. One simple implementation of the border region consists in using larger metal coverage ratio electrode – the “hammer head” in the border region. The proposed IDT is shown in Fig. 5 (b).

Fig. 5 also compares the displacement profiles \( u_{x,n} \) of the \( n^{th} \) transverse mode in a traditional resonator and \( u_{x,n} \) of the resonator employing “piston mode”. For the traditional resonator, approximately an extra half wave lengths fits to the active region for all even modes leading to non-vanishing coupling, while for the “piston mode”, the even order modes which have a multiple of full wave lengths in the active region, do not couple to electrical domain.

B. FEM simulation demonstration

Figs. 6 and 7 show the FEM simulated frequency response for the \( S_0 \) mode and type I \( S_1 \) mode employing regular IDT and two types of hammer-head IDT forming the “piston mode”. By carefully designing the metal ratio which corresponds to the reduction in phase velocity together with the border width \( w_b \), the amplitude of the transverse modes in \( S_0 \) mode and type I \( S_1 \) mode can be effectively reduced, or even eliminated in electrical response.

Assuming the phase velocity difference between the gap

![Plot](image)
region $\nu_{pg}$ and active region $\nu_{pa}$ invariant, the desired optimum normalized border width $w_b/\lambda$ is simply proportional to the normalized velocity difference between the border region and active region, independent from aperture length $w_a$ [11]:

$$\frac{w_b}{\lambda} \propto \frac{\nu_{pa} - \nu_{pb}}{\nu_{pa}}. \quad (5)$$

Fig. 8 shows the admittance of a $S_0$ mode resonator when the width of the border region is too large. In this case, the “hammer head” no longer just works as the wave field modification region, but as the transducer itself. Thus, another resonance is excited by the “hammer head” at frequency slightly lower than the main mode due to the larger duty factor, making the response split into two resonance peaks. As shown in the inset of Fig. 8, the resonance displacement of the first peak happens right at the hammer head region and for the main mode the effective active region is reduced to $(w_a-2w_h)$.

V. CONCLUSIONS

For Lamb wave devices on AlN, the transverse modes are strong in the large-$k_{eff}^2$ type I modes. The dispersion characteristics for the first four Lamb wave modes are calculated: except for partial of the $S_1$ mode, most Lamb wave modes exhibit positive group velocity and type I dispersion. By wave vector superposition, the active region width $w_a$ is found to determine the transverse mode frequency directly. The slowness curve indicates that the gap region width $w_g$ in $S_0$ LWRs does not play an essential role in wave guiding and energy trapping, rather impact a bit on transverse mode strength. The “piston mode” for type I Lamb wave modes created by adding a slow border region at the edge of the active aperture can eliminate the transverse modes and yet not introduce degradations. The FEM simulated AlN $S_0$ and type I $S_1$ mode LWRs using simply “hammer head” enabling the “piston mode” exhibit spurious free operation. These spurious free, high $Q$, and large $k_{eff}^2$ LWRs enable the construction of single-chip filters, oscillators and sensors with superior characteristics.

REFERENCES