Program Digest, 2019 IEEE International Ultrasonics Symposium (IUS)
Glasgow, Scotland, October 6-9, 2019

Mitigation of High Frequency Spurious Responses in Rayleigh SAW Resonators on $LiNbO_3$ Substrate

Masakazu Mimura, Daisuke Ajima, and Chihiro Konoma
Murata Manufacturing Co., Ltd.
Nagaokakyo-shi, Kyoto, Japan
mmimura@murata.com

***Abstract*—This paper describes the behavior of a higher-order mode spurious response on the low acoustic velocity (LAV)-Rayleigh surface acoustic wave (SAW) structure, which realizes remarkable miniaturization of temperature compensated SAW (TC-SAW) devices. In multilayered SiO_2/$LiNbO_3$ (LN) TC-SAW structures including the LAV-Rayleigh SAW, it is well known that a higher-order mode propagating in the SiO_2 layer causes a spurious response above the frequency of the main response, and its suppression is highly required. First, we calculated impedance characteristics of several configurations of Pt electrode thickness and cut angle of LN since the LAV-Rayleigh SAW is different in them from the conventional Rayleigh SAW. The results showed that the LAV-Rayleigh SAW has the following advantages of higher-order mode; 1) larger frequency difference between the main and spurious responses, 2) smaller response size. Next, we made additional calculations of acoustic velocity, electromechanical coupling factor (K^2), and field distribution of the spurious mode. As a result, we validated that the first advantage is due to dependency of acoustic velocity of the modes on Pt thickness, and the second advantage is induced by both the decrease of K^2 and the increase of acoustic radiation with the variation of Pt thickness and cut angle. Finally, one port resonators were fabricated to confirm the validity of the calculation results, and the superiority of the LAV-Rayleigh SAW is demonstrated.**

Keywords*—*higher-order mode, low acoustic velocity Rayleigh SAW, spurious response, TC-SAW

I. Introduction

Temperature compensated surface acoustic wave (TC-SAW) technology has been developed for high performance filters and duplexers of mobile phones. Among them, Rayleigh SAW on 128° Y-X $LiNbO_3$ (LN) substrates with an SiO_2 overcoat on interdigital transducer (IDT) electrodes [1-8] is widely used. In the SiO_2/LN structure, a higher-order mode propagating in the SiO_2 layer is often excited when the SiO_2 layer becomes thicker to obtain better temperature coefficient of frequency (TCF) [5, 9, 10], and causes spurious responses in higher frequency than filter passband.

Recently, carrier aggregation (CA) is employed for 4th and 5th generation (4G and 5G) mobile communications, and many multiplexers are required. In multiplexer design, since out-of-band spurious responses deteriorate insertion loss of other bands, high performance SAW resonators with no spurious response have been highly demanded. In recent years, there are several reports on suppression of out-of-band spurious responses on layered structure consist of a thin single crystal piezoelectric film and a support substrate [11, 12], and further investigations are in progress. However, there has been only a few reports on SiO_2/LN structure TC-SAWs [9, 10].

The authors have developed the low acoustic velocity (LAV)-Rayleigh SAW technology in order to fulfill strong demand of size reduction of TC-SAW devices in addition to high performances such as low loss, steep skirts, and small TCF. This technology employs thicker Pt layers for IDT electrodes on 120° Y-X LN substrate to lower the acoustic velocity of the SAW and realizes 19 % size reduction compared to conventional Rayleigh SAW devices keeping high performances [13, 14]. Moreover, we revealed that shear horizontal (SH) type spurious response free resonators can be obtained using this technology [15]. Similarly to other SiO_2/LN TC-SAW structures, a higher-order mode is generated in this structure and suppression of this mode is also required.

In this paper, we investigate the behavior of the higher-order mode on the LAV-Rayleigh SAW comparing to conventional Rayleigh SAW. First, we perform finite element method (FEM) calculations of impedance characteristics, and show the new structure has two advantages. Next, additional simulations are carried out to obtain frequency of the main Rayleigh mode and the higher-order mode, electromechanical coupling factor (K^2), and field distribution of the spurious mode, and reveal the origin of the advantages. Finally, we evaluate measured impedance characteristics of the LAV and conventional Rayleigh SAWs to confirm the validity of the calculation results. From these results, high applicability of the LAV-Rayleigh SAW to next generation mobile communication systems is demonstrated.

II. Calculation Results

A. Impedance of LAV and conventional Rayleigh SAW

Fig. 1 shows the basic structure of this study. We employed multi layered electrodes of Pt and Al [13]. Fig. 2 shows calculated impedance characteristics including the higher-order mode spurious response of several configurations of Pt electrode thickness H_{Pt} and cut angle θ of LN listed in Table I. Type A and D are the configurations of conventional Rayleigh SAW and LAV-Rayleigh SAW respectively, and type B and C are intermediate ones. SiO_2 thickness H_{SiO2} is set at 0.4λ in all configurations, where λ is wavelength of SAW. The horizontal axes are normalized by resonant frequency of each

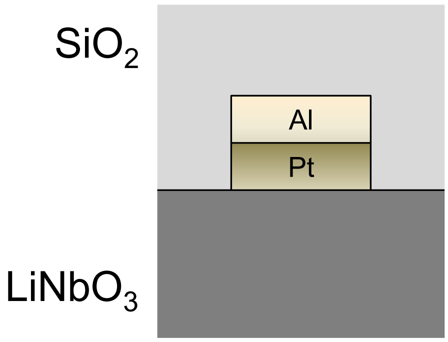
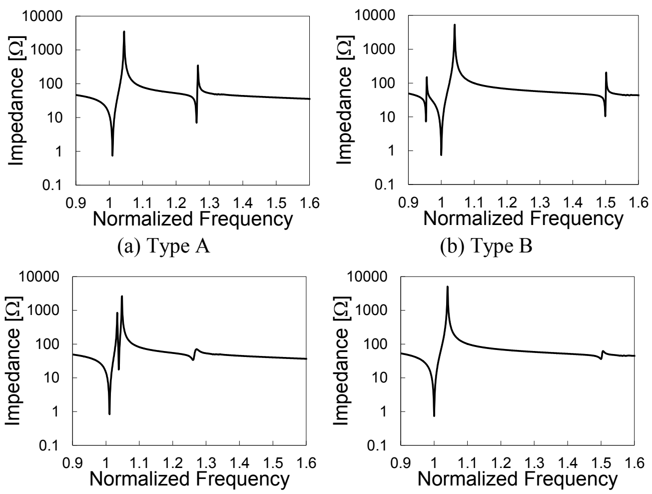


Fig. 1. Basic structure of this work which consists of LN substrate, layered IDT electrode of Pt and Al, and SiO_2 overcoat.



(a) Type A (b) Type B (c) Type C (d) Type D

Fig. 2. Calculated impedance characteristics of the configurations shown in Table I.

TABLE I. Calculated configurations.

Type	Pt thickness H_{Pt}/λ	Cut angle θ	Note
A	0.026	128°	Conventional Rayleigh SAW
B	0.089	128°	Intermediate
C	0.026	120°	
D	0.089	120°	LAV-Rayleigh SAW

characteristics. It is clearly seen that the frequency differences between the main and spurious responses of type B and D are larger than those of type A and C, and that impedance ratios of the spurious response of type C and D are smaller than those of type A and B. It should be noted that the SH type spurious response appears near the resonant frequencies in type B and D because θ is not optimized to minimize K^2 of the SH mode. Generally, it is more desirable for device design that out-of-band spurious responses are small and far from the main response. Therefore, it is indicated that the LAV-Rayleigh SAW has two advantages in higher-order mode characteristics compared with the conventional Rayleigh SAW; 1) larger frequency difference between the main and spurious responses, 2) smaller response size. In order to validate the origin of these advantages, we made additional simulations.

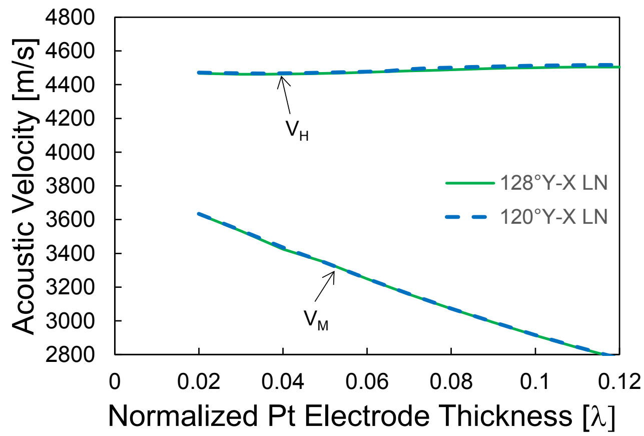


Fig. 3. Dependency of acoustic velocities of Rayleigh and higher-order mode (V_M and V_H respectively) on Pt electrode thickness.

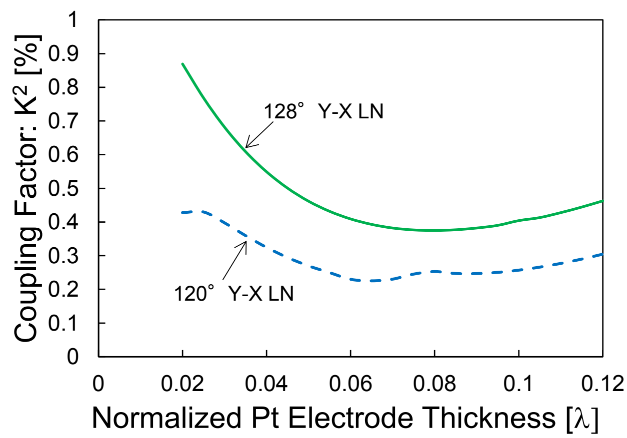


Fig. 4. Calculated K^2 of higher-order mode as a function of Pt electrode thickness.

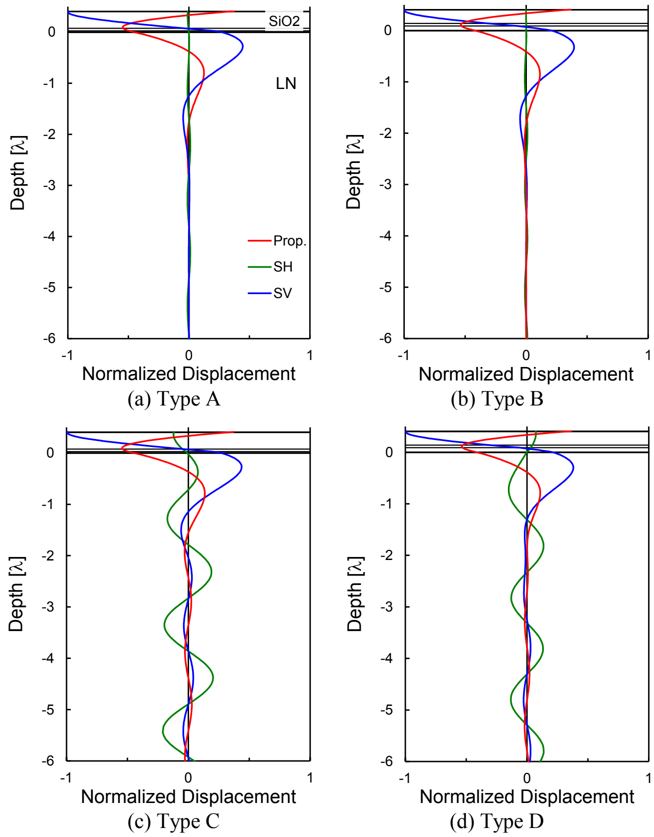
B. *Frequency of main and higher-order modes*

The frequency difference between the main and higher-order modes depends on the acoustic velocity of the two modes. Thus, we calculated acoustic velocities at resonant frequencies of the main and higher-order modes, V_M and V_H respectively, as a function of H_{Pt}. The results are shown in Fig. 3. Although V_M drastically decreases when H_{Pt} is increased, variation of V_H is very small. Namely, frequency difference of the two modes becomes large with the increase of H_{Pt}. In Fig. 3, velocities V_M and V_H in the case of 128° and 120° of θ are also shown, and it is found that the velocities are almost the same. Therefore, the first advantage, i. e. large frequency difference, is caused by thick Pt layer.

C. *K^2 and field distribution of the higher-order mode*

Since the higher-order mode is strongly excited when its K^2 and quality (Q) factor are large, we also calculated K^2 and field distribution of the higher-order mode. The latter represents acoustic radiation into the piezoelectric substrate, and is thought to have an impact on Q factor.

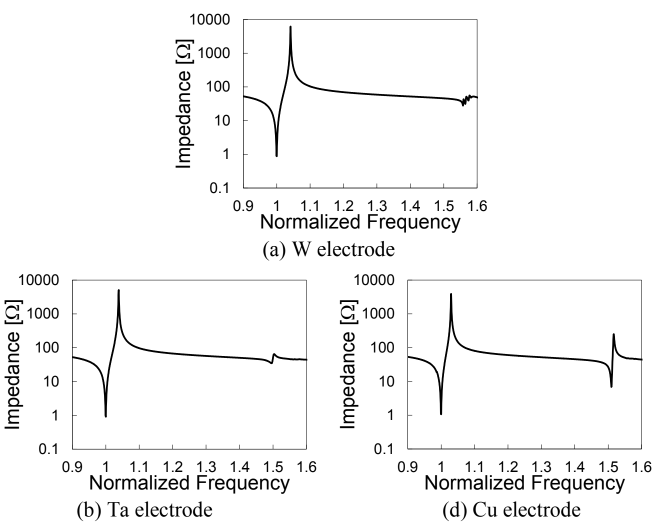
Fig. 4 shows calculated dependency of K^2 of the higher-order mode on H_{Pt} and θ. It is confirmed that K^2 becomes smaller with the increase of H_{Pt} and the decrease of θ. This K^2 decrease is thought to have a certain effect on the suppression of the



(a) Type A (b) Type B

(c) Type C (d) Type D

Fig. 5.Calculated field distribution of higher-order modes.



(a) W electrode

(b) Ta electrode (d) Cu electrode

Fig. 6. Calculated impedance characteristics of various electrode materials.

spurious response. However, the spurious response of Fig. 2(b) is larger than that of Fig. 2(c) whereas K^2 of type B and C in Fig. 4 are nearly equal. Hence, intensity of the spurious response in Fig. 2 cannot be completely explained by K^2.

Fig. 5 shows calculated cross-sectional field distributions of the higher-order mode in the configurations shown in Table I. Apparently, significant acoustic radiations, especially SH component, are seen in the cases of type C and D, and the radiations in type A and B are small. In other words, the acoustic radiation occurs strongly when θ is 120° and rarely when θ is 128°, and this radiation is not changed with the variation of H_{Pt}. From the calculation results of K^2 and field distributions, both the decrease of K^2 and the increase of acoustic radiation according to H_{Pt} and θ are thought to be the origins of the second advantage, small spurious response.

D. Impedance characteristics of other electrode materials

We also carried out several calculations using other electrode materials in addition to Pt. Fig. 6 shows impedance characteristics of the structures with electrode materials of W, Ta, and Cu. In all cases, θ and H_{SiO2} are 120° and 0.4λ respectively, and electrode thickness is determined so that acoustic velocity at resonant frequency becomes 3000 m/s. These results indicate that frequency and impedance ratio of the higher-order mode spurious response are dependent on electrode materials as well as θ, and electrode thickness. In Fig. 6, the response of Cu electrode case is the largest, and in the W electrode case frequency of the response is the highest among all electrodes calculated in this study.

Although the cause of these variations, frequency and intensity, of the spurious response according to electrode material is not well understood, we presume that this is caused by variation of acoustic velocity or K^2 of the spurious mode resulting from mass density or elastic constants of electrode materials.

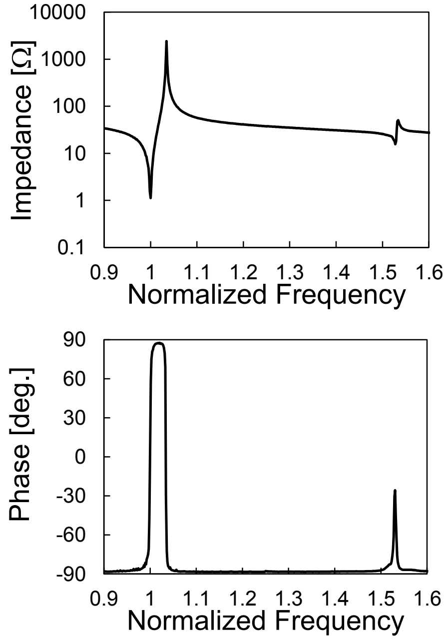
III. Experimenal Results

We fabricated one port resonators using LAV-Rayleigh SAW (sample A) and conventional Rayleigh SAW (sample B) and evaluated their higher-order mode spurious responses. H_{Pt} and θ are 0.092λ and 120° for sample A, and 0.022λ and 128° for sample B, respectively. H_{SiO2} is 0.33λ for both samples. Fig. 7 shows impedance characteristics of fabricated resonators. In the characteristics of sample A, the frequency difference is larger and the response is smaller than those of sample B, as expected from the calculation results. Thus, the advantages of LAV-Rayleigh SAW are experimentally confirmed.

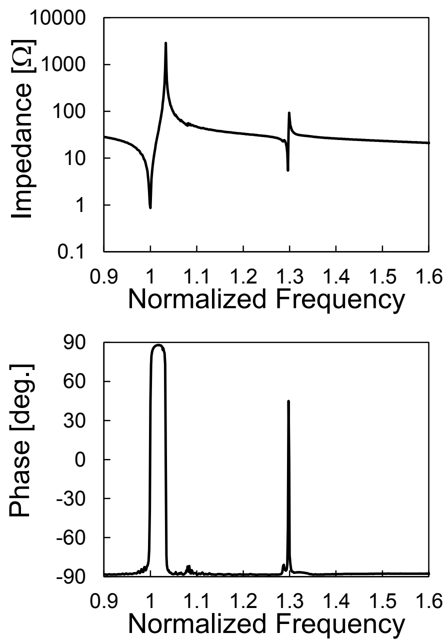
In the characteristics of Fig. 7, there is no response in frequency range between the main and spurious responses. If these resonators are applied to the lower frequency band filter of a multiplexer, insertion loss of the higher band filter whose passband is in this frequency range is not degraded by the lower band filter. While frequency ratio of the spurious and main modes of sample B is 1.3, that of sample A is as large as 1.5. This value is larger than ratio of center frequency of band 8 and band 28, which have the highest and lowest frequency respectively among low-band (700MHz~ 1GHz) of 4G and 5G systems. Therefore, the LAV-Rayleigh SAW technology is demonstrated to have high applicability to multiplexers of every low-band CA combinations.

IV. Conclusions

We have investigated the behavior of the higher-order mode spurious response of the LAV-Rayleigh SAW structure compared to the conventional Rayleigh SAW both theoretically and experimentally. From the impedance characteristics, it has been confirmed the developed structure has two advantages; 1) larger frequency difference between the main and spurious



(a) Sample A: LAV-Rayleigh SAW



(b) Sample B: conventional Rayleigh SAW

Fig. 7. Measured impedance characteristics of the LAV and conventional Rayleigh SAW including higher-order mode spurious response.

responses, and 2) smaller response size. Several FEM simulations of acoustic velocity, K^2, and field distribution indicate that these advantages are the effect of both thick Pt electrode layer and cut angle of 120° Y-X. The frequency difference of the LAV-Rayleigh SAW is large enough to apply to multiplexers of every low-band CA combinations. Therefore, this developed structure is promising technology for next generation mobile communication systems due to out-of-band characteristics as well as small size, high Q, low TCF, SH spurious response free, and so on.

REFERENCES

[1] K. Yamanouchi and S. Hayama, "SAW properties of SiO_2/128° Y-X $LiNbO_3$ structure fabricated by magnetron sputtering technique," IEEE Trans. on Sonics and Ultrason., SU-31, pp. 51-57(1984).

[2] M. Kadota, "High performance and miniature surface acoustic wave devices with excellent temperture stability using high density metal electrodes," Proc. IEEE Ultrason. Symp.(2007) pp. 496-506.

[3] T. Nakao, M. Kadota, K. Nishiyama, Y. Nakai, D. Yamamoto, Y. Ishiura, T. Komura, N. Takada, and R. Kita, "Small 3 × 2.5 mm^2 sized surface acoustic wave duplexer for US-PCS with excellent temperature and frequency characteristics," Proc. IEEE Ultrason. Symp.(2007) pp. 1681-1684.

[4] K. Hashimoto, M. Kadota, T. Nakao, M. Ueda, M. Miura, H. Nakamura, H. Nakanishi, and K. Suzuki, "Recent development of temperature compensated SAW devices," Proc. IEEE Ultrason. Symp.(2011) pp. 79-86.

[5] B. Abbott, R. Aigner, A. Chen, K. Gamble, T. Kook, J. Kuypers, M. Solal, and K. Steiner, "Theoretical investigation into spurious modes content in SAW devices with a dielectric overcoat," Proc. 4th International Symp. on Acoustic Wave Devices for Future Mobile Communication Systems (2010) pp. 199-209.

[6] B. Abbott, A. Chen, T. Daniel, K. Gamble, T. Kook, M. Solal, K. Steiner, R. Aigner, S. Malocha, C. Hella, M. Gallagher, and J. Kuypers, " Temperature compensated saw with high quality factor," Proc. IEEE Ultrason. Symp., 2017, pp. 1-4, doi: 10.1109/ULTSYM.2017.8092294.

[7] R. Goto, J. Fujiwara, H. Nakamura, and K. Hashimoto, "Multimode coupling of modes model for spurious responses on SiO_2/$LiNbO_3$ substrate," Jpn. J. Appl. Phys, vol. 57, no. 7S, p. 07LD20, 2018.

[8] K. C. Wagner, C. Bauer, T. Bauer, I. Bleyl, and C. Eggs, "Technological innovations in SAW components for frontend modules with high function density," Proc. 7th International Symp. on Acoustic Wave Devices for Future Mobile Communication Systems, 2018, 1A-3.

[9] M. Mimura, T, Yamane, D. Tamazaki, "A suppression method of second order mode spurious responses for boundary acoustic wave filters," Proc. IEEE Ultrason. Symp., 2012, pp. 823-826.

[10] R. Goto, J. Fujiwara, H. Nakamura, T. Tsurunari, H. Nakanishi, and Y. Hamaoka, "Study of spurious response near the fast shear wave in SiO_2/Al/$LiNbO_3$ structure," Jpn. J. Appl. Phys, vol. 52, no. 7S, p. 07HD12, 2013.

[11] M. Kadota, Y. Ishii, T. Shimatsu, M. Uomoto and S. Tanaka, "Suprious-free, near-zero-TCF hetero acoustic layer (HAL) SAW resonators using $LiTaO_3$ thin plate on quartz," Proc. IEEE Ultrason. Symp., 2018, pp. 1-4, doi: 10.1109/ULTSYM.2018.8580111.

[12] S. Inoue and M. Solal, "Spurious free SAW resonators on layered substrate with ultra-high Q, high coupling and small TCF," Proc. IEEE Ultrason. Symp., 2018, pp. 1-4, doi: 10.1109/ULTSYM.2018.8579852.

[13] M. Mimura, D. Ajima, C. Konoma, and T. Murase, "Small sized band 20 SAW duplexer using low acoustic velocity Rayleigh SAW on $LiNbO_3$ substrate," Proc. IEEE Ultrason. Symp., 2017, pp. 1-4, doi: 10.1109/ULTSYM.2017.8092596.

[14] M. Mimura, D. Ajima, C. Konoma, and T. Murase, "Low acoustic velocity Rayleigh SAW technology for miniaturization of high performance TC-SAW devices," Proc. 7th International Symp. on Acoustic Wave Devices for Future Mobile Communication Systems, 2018, 2B-1.

[15] M. Mimura, D. Ajima, and C. Konoma, "SH-type spurious response free TC-SAW resonators using low acoustic velocity Rayleigh SAW on $LiNbO_3$ sutbstate," Proc. IEEE Ultrason. Symp., 2018, pp. 1-4, doi: 10.1109/ULTSYM.2018.8580200.