Low Velocity HAL SAW Resonator Using $LiNbO_3$ Thin Plate on Quartz Substrate

Tzong Lin Chua, Michio Kadota, *Fellow, IEEE*, and Shuji Tanaka, *Fellow, IEEE*

***Abstract*— This paper reports a low velocity hetero acoustic layer (HAL) surface acoustic wave (SAW) resonator using a combination of 11° YX lithium niobate (LN) thin plate and YX quartz (Qz) substrate with copper (Cu) interdigital transducers (IDTs). The fabricated one-port (1-port) SAW resonator attained a low effective velocity of 2416 ms^{-1} at resonance with an impedance ratio (*Z*-ratio) of 80 dB and a relative bandwidth (BW) of 11%. The resonator has temperature coefficient of frequency (TCF) of -129 ppm°C^{-1} at resonance frequency (f_r) and -117 ppm°C^{-1} at antiresonance frequency (f_a). The resonator has a roughly 30% lower velocity compared with the previously developed LT/ Qz HAL SAW resonator and a roughly 40% slower than the metallized SH-SAW velocity on 11° YX LN, indicating its potential for low-band filter applications.**

Keywords—resonators, filters, surface acoustic waves

I. Introduction (*Heading 1*)

Surface acoustic wave (SAW) devices and bulk acoustic wave (BAW) devices are the two mainstream components for radio frequency front-end (RFFE) filters in mobile communication devices. Conventionally, BAW devices are considered superior at high frequencies compared to SAW devices due to their higher Q factor. However, the introduction of SAW devices on multilayered substrates with an ultrathin lithium niobate (LN) or lithium tantalate (LT) as a top layer has sparked new interest in SAW devices since they have been found to greatly improve the characteristics of SAW devices [1], [2], [3]. This new category of SAW devices is categorized as Hetero Acoustic Layer (HAL) SAW devices in the authors' group [4].

BAW devices for the platinum frequency bands (e.g., 700 MHz ~ 1 GHz) is challenging since it requires a thick film of aluminum nitride (AlN), which is easily warped during the fabrication process. On the other hand, SAW devices require a long wavelength, which results in large sizes. The increasing number of cellular frequency bands requires more RFFE filters in mobile communication devices, therefore, there is a strong demand for miniaturized SAW devices to maintain the compactness of mobile communication devices.

The direct solution for SAW device miniaturization is to use a substrate with low phase velocity, because the frequency is determined by the quotient of phase velocity and interdigital transducer (IDT) pitch (wavelength, λ). Previous studies have taken advantage of the mass loading effect in SAW devices by introducing higher density IDTs to reduce the SAW velocities [5], [6], [7]. This work combines the high-performance of ultrathin LN HAL SAW devices and the mass-loading effect to develop a low-velocity HAL SAW resonator.

II. Design and Simulation

Fig. 1 shows the impedance characteristic of a conventional 42°YX LT SAW resonator with aluminum (Al) IDTs (λ = 2.2 µm, 0.08λ thick) used in duplexers. The resonator has a phase velocity of 3903 ms^{-1}, a relative bandwidth of 3.3% and an impedance ratio (*Z*-ratio) of 58 dB. Its high velocity and narrow relative bandwidth have made it being unsuitable for low band filtering purposes.

The impedance characteristics of 42ºYX LT SAW resonator with copper (Cu, λ = 3.78 µm, 0.06λ thick) and gold (Au, λ = 3.78 µm, 0.03λ thick) IDTs is shown in Fig. 2. Both resonators have a slight increase in relative bandwidth to 4.2% with an *Z*-ratio of 52 dB. The Cu/ LT SAW resonator and Au/ LT SAW resonator has phase velocities of 3530 ms^{-1} and 3677 ms^{-1}, respectively, which are still insufficient for low band filters.

The combination of ultrathin LT and quartz (Qz) substrate has realized high *Z*-ratio of 80 dB, low temperature of coefficient frequency (TCF) and spurious-free responses [1]. However, the yielded phase velocities are in the range of resonators in Fig. 2.

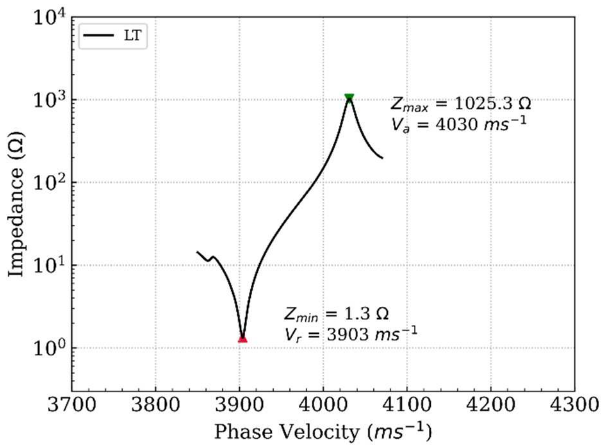

Fig. 1. Impedance characteristic of a conventional standard 0.08λ Al/ 42ºYX LT SAW resonator.

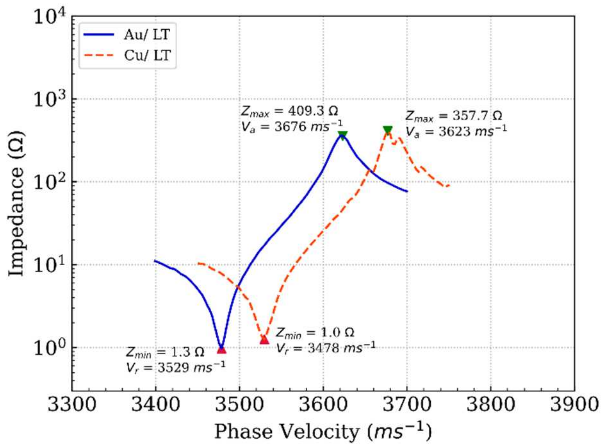

Fig. 2. Impedance characteristics of 0.06λ Cu/ 42ºYX LT SAW resonator and 0.03λ Au/ 42ºYX LT SAW resonator.

Referring to the simulation and experimental results provided by Kadota *et al.* in [1], using a LT/ SiO_2/ Si multi-layered structure might not be suitable due to the presence of large spurious higher-order modes. The spurious responses are caused by Sezawa wave, which is a higher-order mode of Rayleigh wave and excited by the higher velocity of Si in ZnO/ Si structure [8]. The spurious response in the LT/ SiO_2/ Si multilayered structure might be analogous to the mismatch in wave velocities of the substrates.

Based on the previously mentioned results, the combination of an ultrathin LN plate and a Qz substrate was experimented in this work to obtain a suitable BW and high *Z*-ratio. Cu is used for the IDTs for their excellent electrical conductivity, high compatibility with LN SAW resonators reported in [9], [10], [11], and high reflection coefficient [9], which will aid in miniaturization by reducing the number of IDTs and reflector fingers [12], [13].

A. SH-Leaky SAW velocity

The propagation velocity of SAWs in a resonator is influenced by the material density [7] and normalized thickness [14] of the IDTs. For determining the required Cu IDT thickness, the effective SH-leaky SAW (SH-LSAW) velocities were simulated as a function of normalized Cu IDT thickness (metallization ratio, MR = 0.5) on (0°, 102.5°, 0°) LN/ (0°, 90°, 0°) Qz substrate. The results in Fig. 3 shows that a normalized Cu IDT thickness of at least 0.12λ is required to reduce effective SH-LSAW velocities below 3000 ms^{-1}.

B. Impedance Ratio and Relative Bandwidth

The optimum Euler angle of the LN and Qz substrate is determined to be the angle where the 1-port SAW resonator exhibits the largest *Z*-ratio [1]. The *Z*-ratio and relative bandwidth of the 1-port LN (0.8λ thick)/ (0°, 90°, 0°) Qz HAL SAW resonator with a normalized Cu IDT thickness of 0.12λ and a MR of 0.5 were simulated as a function of LN Euler angles (0°, θ_{LN}, 0°) in Fig. 4.

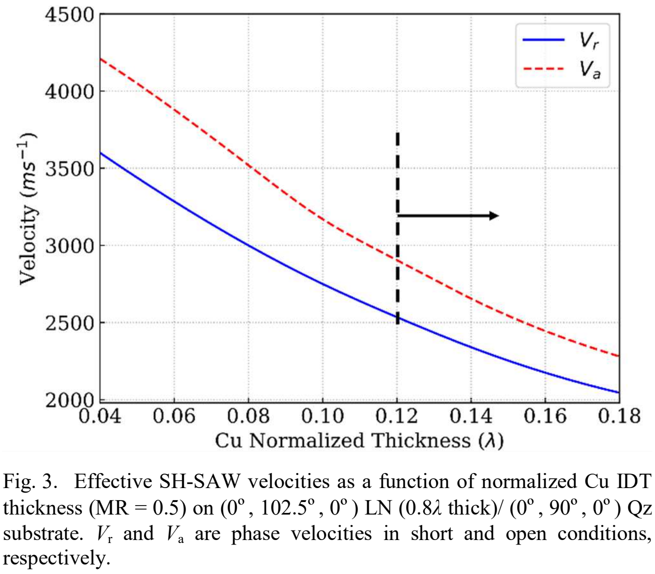

Fig. 3. Effective SH-SAW velocities as a function of normalized Cu IDT thickness (MR = 0.5) on (0°, 102.5°, 0°) LN (0.8λ thick)/ (0°, 90°, 0°) Qz substrate. V_r and V_a are phase velocities in short and open conditions, respectively.

On the other hand, the *Z*-ratio and relative bandwidth of the 1-port (0°, 102.5°, 0°) LN (0.8λ thick)/ Qz HAL SAW resonator with the same Cu IDT thickness and MR were simulated as a function of Qz Euler angles (0°, θ_{Qz}, 0°) in Fig. 5. Here, the mechanical loss $1/Q_m$ of LN was assumed to be 0.005.

From the simulated *Z*-ratio, the optimum Euler angle for the LN substrate is from 100° to 103°, while the optimum Qz substrate is found to be around 90°.

III. Fabrication

1-port SAW resonators were fabricated on an 11° YX LN substrate and a 12.5° YX LN (~1.7 μm)/ YX Qz HAL substrate. The HAL substrate was fabricated using wafer direct bonding process, while IDTs and wiring of the device were fabricated using lift-off process [1].

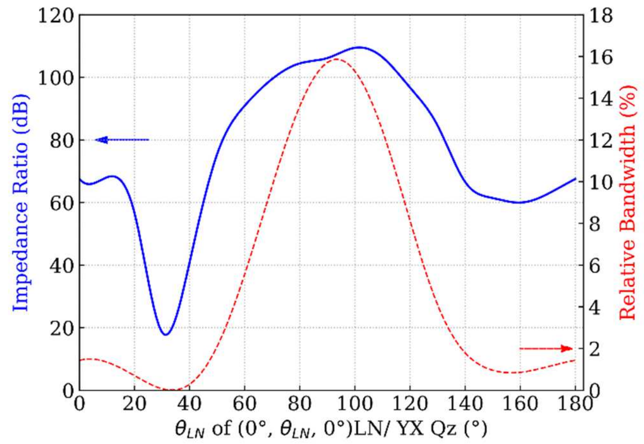

Fig. 4. Z-ratio and relative bandwidth against of θ_{LN} of Cu (0.12λ thick, MR = 0.5)/ (0°, θ_{LN}, 0°) LN (0.8λ thick)/ (0°, 90°, 0°) Qz resonator.

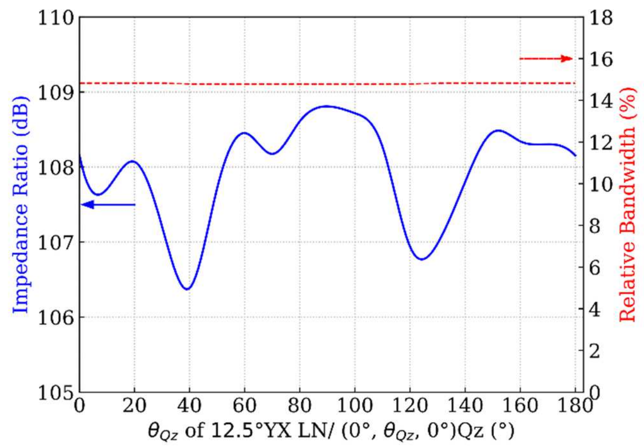

Fig. 5. *Z*-ratio and relative bandwidth against θ_{Qz} of Cu (0.12λ thick, MR = 0.5)/ (0°, 102.5°, 0°) LN (0.8λ thick)/ (0°, θ_{Qz}, 0°) Qz resonator.

IV. EVALUATION

The 1-port S-parameters were evaluated using Keysight's E5071C ENA Vector Network Analyzer equipped with Cascade Microtech's ACP40-GS-250 RF probe. The impedance characteristics of the 0.065λ Cu/ 11° YX LN and 0.12λ Cu/ 12.5° YX LN/ YX Qz SAW resonator are shown in Fig. 6. The LN SAW resonator has an effective velocity of 3078 ms^{-1} at resonance and achieved an *Z*-ratio of 67 dB with a relative bandwidth of 15%. The LN/ Qz HAL SAW resonator on the other hand has an effective velocity of 2416 ms^{-1} at resonance and achieved an *Z*-ratio of 80 dB with a relative bandwidth of 11%.

The frequency drift due to temperature change of the resonators are shown in Fig. 7. The 11° YX LN SAW resonator has a TCF of -129 ppm° C^{-1} at resonant frequency and -135 ppm° C^{-1} at anti-resonant frequency, while the 12.5° YX LN/ YX Qz HAL SAW resonator has a TCF of -129 ppm° C^{-1} at resonant frequency and -117 ppm° C^{-1} at anti-resonant frequency.

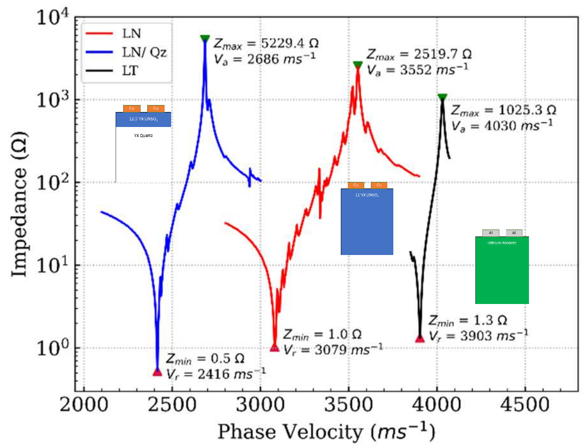

Fig. 6. Impedance characteristics of 11° YX LN SAW resonator and 12.5° YX LN/ YX Qz HAL SAW resonator.

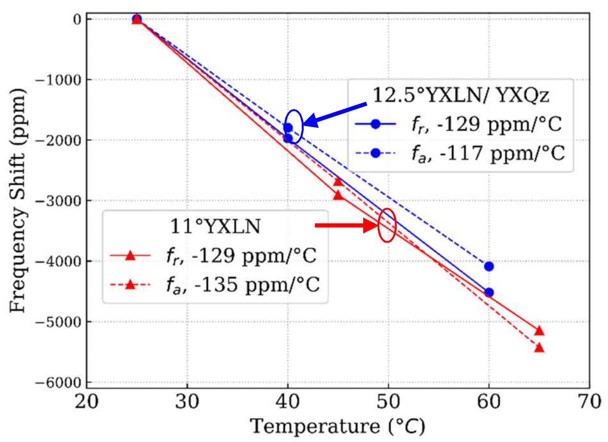

Fig. 7. Temperature drift of 11° YX LN SAW resonator and 12.5° YX LN/ YX Qz HAL SAW resonator.

V. CONCLUSION

The ultrathin LN and Qz HAL SAW resonator attained a low effective velocity of 2416 ms^{-1} at resonance and an *Z*-ratio of 80 dB. Compared to the conventional Al/ 42° YX LT SAW resonator, the phase velocity was 40% smaller and the *Z*-ratio increased by 22 dB. On the other hand, using a Qz substrate with minus TCF Euler angle has resulted in a large TCF value of -129 ppm° C^{-1} and -117 ppm°C^{-1}. It is expected that the TCF values can be further lowered by substituting the YX Qz with a Qz with positive TCF Euler angle or with materials with lower coefficient of linear thermal expansion (CTE).

REFERENCES

[1] M. Kadota *et al.,* "Suprious-Free, Near-Zero-TCF Hetero Acoustic Layer (HAL) SAW Resonators Using $LiTaO_3$ Thin Plate on Quartz," Proc. 2018 IEEE Int. Ultrason. Symp., Kobe, Japan, 2018, doi: 10.1109/ULTSYM.2018.8580111.

[2] T. Takai *et al.*, "High-Performance SAW Resonator on New Multilayered Substrate Using $LiTaO_3$ Crystal," IEEE Trans. Ultrason. Ferroelectr. Freq. Contr., vol. 64, no. 9, pp. 1382-1389, 2017, doi: 10.1109/TUFFC.2017.2738119.

[3] T. Takai *et al.,* "I.H.P. SAW technology and its application to microacoustic components," Proc. 2017 IEEE Int. Ultrason. Symp., Washington, DC, USA, 2017, doi: 10.1109/ULTSYM.2017.8091876.

[4] M. Kadota *et al.*, "Surface Acoustic Wave Resonators with Hetero Acoustic Layer (HAL) Structure Using Lithium Tantalate and Quartz," IEEE Trans. Ultrason. Ferroelectr. Freq. Contr., vol. 68, no. 5, pp. 1955-1964, 2021, doi: 10.1109/TUFFC.2020.3039471.

[5] M. Mimura *et al.,* "Small sized band 20 SAW duplexer using low acoustic velocity Rayleigh SAW on $LiNbO_3$ substrate," Proc. 2017 IEEE Int. Ultrason. Symp., Washington, DC, USA, 2017, doi: 10.1109/ULTSYM.2017.8092596.

[6] M. Mimura *et al.*, "SH-Type spurious response free TC-SAW resonators using low acoustic velocity Rayleigh SAW on $LiNbO_3$ substrate," Proc. IEEE Int. Ultrason. Symp., Kobe, Japan, 2018, doi: 10.1109/ULTSYM.2018.8580200.

[7] R. Nakagawa *et al.*, "Low Velocity I.H.P. SAW Using Al/Pt Electrodes for Miniaturization," Proc. 2019 IEEE Int. Ultrason. Symp., Glasgow, United Kingdom, 2019, pp. 2083-2086, doi: 10.1109/ULTSYM.2019.8925860.

[8] M. Kadota and M. Minakata, "Properties of high quality ZnO films deposited by an RF magnetron mode electron cyclotron resonance (ECR) sputtering system," Proc. 1996 IEEE Ultrason. Symp., San Antonio, TX, USA, 1996, vol. 1, pp. 303-308, doi: 10.1109/ULTSYM.1996.583979.

[9] M. Kadota *et al*., "Small Surface Acoustic Wave Duplexer for Wide-Band Code-Division Multiple Access Full-Band System Having Good Temperature Characteristics," Jpn. J. Appl. Phys, Vol 46, 2007, pp. 4714, doi: 10.1143/JJAP.46.4714.

[10] K. Hashimoto *et al*., "Wideband Love wave filters operating in GHz range on Cu-grating/rotated-YX-LiNbO/sub 3/-substrate structure," IEEE Ultrasonics Symposium, 2004, 2004, pp. 1330-1334 Vol.2, doi: 10.1109/ULTSYM.2004.1418039.

[11] T. Omori *et al*., "Suppression of Transverse Mode Responses in Ultra-Wideband SAW Resonators Fabricated on a Cu-Grating/15°YX-LiNbO 3 Structure," in IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, vol. 54, no. 10, pp. 1943-1948, October 2007, doi: 10.1109/TUFFC.2007.487.

[12] M. Kadota *et al.,* "Resonator filters using shear horizontal-type leaky surface acoustic wave consisting of heavy-metal electrode and quartz substrate," IEEE Trans. Ultrason. Ferroelectr. Freq. Contr., vol. 51, no. 2, pp. 202-210, 2004, doi: 10.1109/TUFFC.2004.1320768.

[13] T. Nakao *et al.*, "Smaller Surface Acoustic Wave Duplexer for US Personal Communication Service Having Good Temperature Characteristics," Jpn. J. Appl. Phys, Vol 46, 2007, pp. 4760, doi: 10.1143/JJAP.46.4760.

[14] M. Kadota *et al.*, "Ultra wide band resonator composed of grooved Cu-electrode on $LiNbO_3$ and its application to tunable filter," Proc. 2009 IEEE Int. Ultrason. Symp., Rome, Italy, 2009, pp. 2668-2671, doi: 10.1109/ULTSYM.2009.5442043.