Acoustic resonator with excellent wide-band reflection coefficient by LiNbO$_3$ bonded on support substrate structure

Rei Goto*, Yuya Hiramatsu
Skyworks Solutions, Inc., Osaka, Japan
*E-mail: Rei.Goto@skyworksinc.com

2023 IEEE International Ultrasonics Symposium (IUS) | 979-8-3503-4645-9/23/$31.00 ©2023 IEEE | DOI: 10.1109/IUS51837.2023.10306996

Abstract*— Cellular handsets include multiplexers where several RF filters are connected to a common antenna. As band count and carrier aggregation (CA) requirements continue to expand, filter loading loss becomes increasingly important. Filters load each other as their out-of-band reflection coefficients are decreased by dissipated energy within their acoustic resonators. TC-SAW, composed of SiO$_2$/LiNbO$_3$, exhibits loading losses at frequencies above the passband, due primarily to guided mode effects. These loading losses lead to insertion loss degradation within the multiplexer as a whole. Reduction of the loading loss will therefore contribute to performance improvement of the multiplexer. This study proposes 12[x]°YX-LiNbO$_3$ bonded on a high impedance substrate to provide a wide-band clean reflection coefficient. By using the proposed substrate configuration, the reflection coefficient improves significantly over a very wide frequency range because of better acoustic wave trapping by a support substrate. To verify the mechanism of this feature, a parametric sweep study was conducted by piezoelectric simulations. Experimental resonators were fabricated and verified, exhibiting a good reflection performance over a wide frequency span. This paper proposes 12[x]° YX-LiNbO$_3$ bonded on a high impedance substrate as a candidate structure for high-performance multiplexer solutions. Simulated and fabricated resonator responses show excellent reflection coefficient over a wide frequency span.

***Keywords*—SAW, Bonded substrate, SiO$_2$, LiNbO$_3$, Multiplexer**

I. INTRODUCTION

Surface acoustic wave (SAW) devices are widely used in modern communication systems thanks to their high performance and low cost. Many novel device structures have been proposed to meet the growing demand for temperature stability, low loss and wide bandwidth. Among various innovations, TC-SAW devices using a SiO$_2$ film on a LiNbO$_3$ (LN) substrate have been widely employed in filters and duplexers for applications in the cellular handset market [1]-[13].

Figure1 shows a cross-sectional view of a TC-SAW IDT structure. The TC-SAW with SiO$_2$/LN structure has satisfactory Q and TCF and moderate k^2_{eff}. However, with tighter requirements on device performance, spurious modes, such as the transverse mode and the SH spurious mode in the passband and SiO$_2$ Guided mode in out of band are becoming critical problems [11-14].

Recently, Carrier Aggregation (CA) technology has been used for high-speed mobile communications. Importance of multiplexer is increasing due to CA requirement to expand. In these situation, SiO$_2$ guided modes in TC-SAW excited on 1.2 f_0 and 1.8f_0 from main response frequency f_0 have critical effect

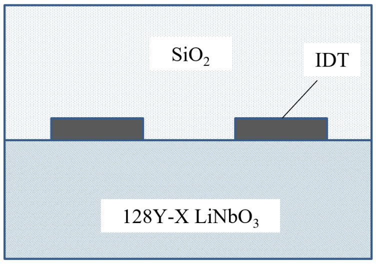

Fig. 1. Cross Sectional View of TC-SAW.

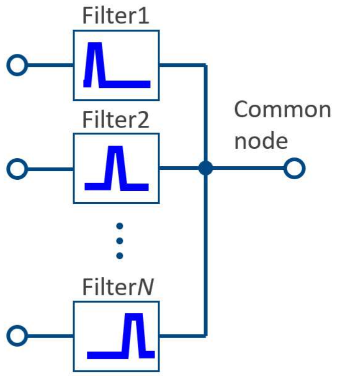

Fig. 2. Schematic diagram of multiplexer.

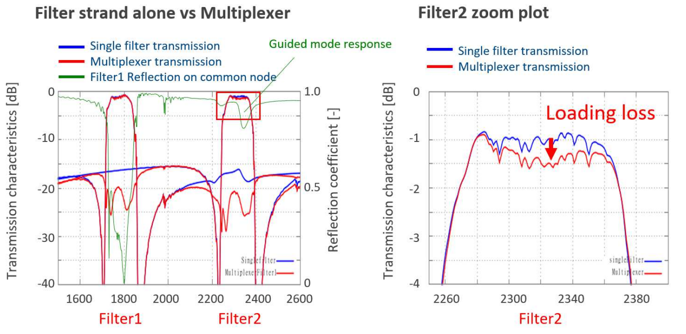

Fig. 3. TC-SAW single filter and duplexer transmission characteristics with common node reflection characteristics.

on multiplexer operation. Figure 3 shows single filter and duplexer transmission characteristics of a TC-SAW duplexer. The duplexer is composed with a lower frequency filter1 and a higher frequency filter 2. The filter1 reflection characteristics is also shown in the plot. In case an SiO_2 guided mode response overlaps in the filter 2 passband, the multiplexer response of the filter 2 is degraded by the loading loss. Authors have proposed to use the phase cancelling circuit to reduce the impact of SiO_2 guided mode to reduce the impact of the guided modes [15]. This method is effective to secure enough rejection on CA pair band, but is-difficult to remove the loading loss completely.

TF (Thin Film)-SAW devices using a sub-wavelength piezo layer bonded on a support substrate are proposed. For example, I.H.P SAW structures show high Q, high K^2 and high-power durability [16]. I.H.P SAW wave modes are trapped in the thin piezo layer and the functional layers as a waveguide. It's means I.H.P structures possibly excite a strong higher order guided mode in a high frequency area. Using such layered structure gives opportunities to flexible designing of the substrate stack to manipulate acoustic properties. Higher order mode responses can also be tuned by the layered structure. 128YX-LN Rayleigh mode is known as having a relatively less radiation to bulk wave. The main mode of 42YX-$LiTaO_3$ (LT) is fundamentally a leaky mode and the radiation for the bulk wave is relatively strong. By manipulating the guided mode responses in the 128YX-LN substrate, a single mode operation over a wide band frequency is possible.

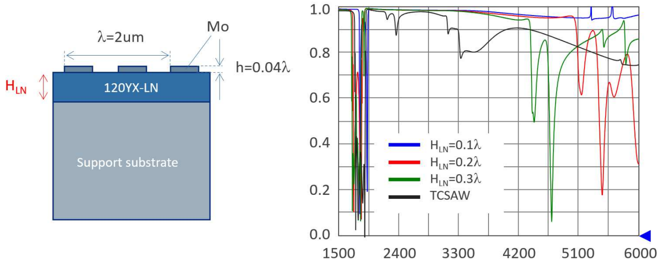

Fig.4 Simulated reflection characteristics various piezo layer thickness.

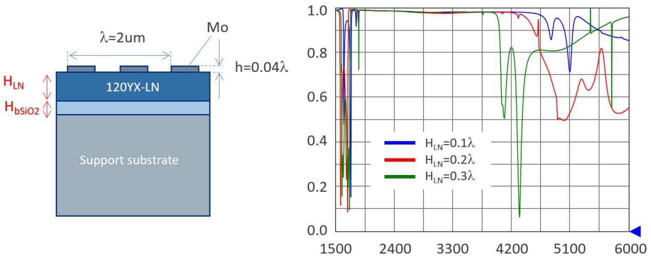

Fig.5 Simulated reflection characteristics various piezo layer thickness with bottom SiO_2 layer.

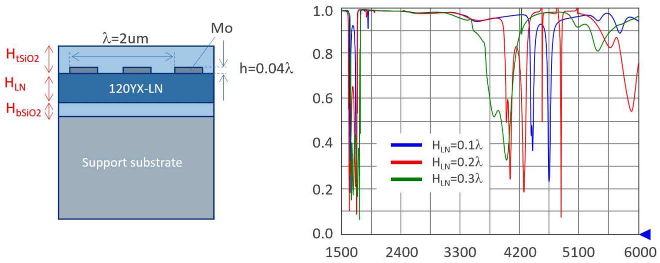

Fig. 6. Simulated reflection characteristics various piezo layer thickness with both top and bottom SiO_2 layer.

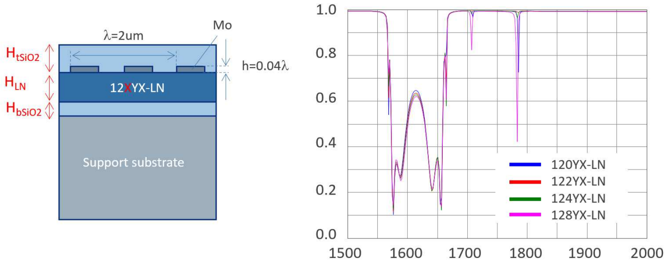

Fig. 7. Simulated reflection characteristics various piezo cut angle with both top and bottom SiO_2 layer.

II. STRUCTURE OPTIMIZATION BY 2D FEM SIMULATION

In this section, 2D FEM simulation performed to determine an optimal structure for a wide band clean reflection. The FEM simulation as performed by FEM/SDA [17][18]. Figure 4 shows a cross-sectional view of a 120YX-LN/Support substrate structure and a 2D FEM reflection characteristics simulation result. The TC-SAW response is plotted in a black line. The wide frequency range with the clean reflection is observed in a thinner H_{LN} condition. Figure 5 shows the structure adding a SiO_2 layer between the piezo layer and the support substrate. By changing the thickness of SiO_2, flatness of reflection is manipulated. Figure 6 shows a structure adding a top SiO_2 to Figure 5 structure. Adding the top SiO_2 is necessary to control and maintain the TCF similar to the level of the current TC-SAW. Figure 7 is the result of a parametric sweep of an LN cut angle. 122YX-LN shows minimum response of a SH mode just above the pass band. As a result of the parameter sweep study, H_{tSiO2} = 0.2 λ, H_{LN} = 0.2 λ, H_{bSiO2} = 0.2 λ, 122YX-LN are proposed to realize the wide clear reflection and a reasonable k^2_{eff} and TCF. Figure 8 is a comparison between TC-SAW, I.H.P.SAW and the proposed structure. The I.H.P SAW geometry used in this study is described in the published article [19]. TC-SAW and I.H.P SAW have unwanted reflection responses in the higher frequency area. On the other hand, the proposed structure shows a wide clean response up to the near 2xfo frequency range.

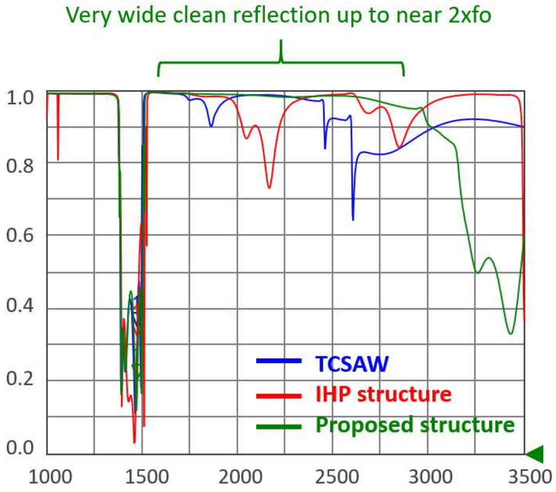

Fig. 8. Comparison of simulated reflection characteristics of TC-SAW, I.H.P. SAW and proposed structure.

III. EXPERIMENTAL VERIFICATION

In this section, fabricated devices are evaluated to verify the simulation results. Fabrication was done with 128YX-LN instead of 122YX-LN in this time. Figure 9 is a comparison between a simulated and a measured reflection response of TCSAW and the proposed structure. On the measurement result, spikes due to not fully optimized LN cut angle remained, but overall, a wide clean reflection without SiO_2 guided mode response is successfully observed. These spikes will be managed by changing the LN cut angle to 122YX. Except for the spikes, the simulated and the measured results show a good agreement.

After confirming the resonator evaluation result, filters with the proposed structure were evaluated. Figure 10 shows the duplexer evaluation result with the proposed substrate on the lower frequency filter 1 and TC-SAW used for the higher frequency filter 2. Comparing with the plot of Figure 3, although the Filter 2 is the same TC-SAW filter, the duplexer insertion loss is significantly improved. A clean reflection on the filter 1 contributes a lot to reduce the loading loss on the filter 2 insertion loss. By using the proposed substrate, a multiplexer free from the loading loss is provided.

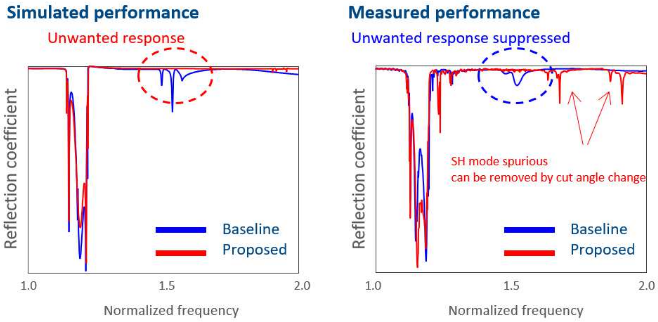

Fig. 9. Comparison of simulated and measured reflection characteristics.

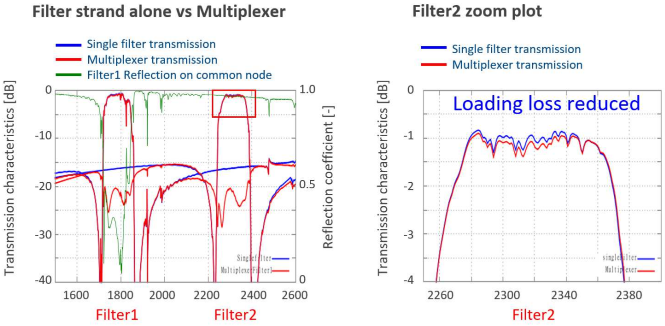

Fig. 10. Single filter and Multiplexed transmission characteristics with proposed structure used on lower frequency filter 1.

IV. CONCLUSIONS

In this study, the SiO_2/122YX-LN/SiO_2/Support substrate structure to perform the very wide clean reflection is proposed. The loading loss due to the worse reflection on the common node could be fixed with this proposed structure. The 2D FEM simulation is performed to understand the behavior of the higher frequency response in the proposed optimized structure. The experiments of the resonator demonstrated to see the good correlation between the simulation and the measurement. The experiments on the filters and the duplexers demonstrated a significant loading loss reduction under the multiplex condition with the proposed structure.

REFERENCES

[1] K. Yamanouchi, S. Hayama, “SAW Properties of SiO_2 /128ºY-X $LiNbO_3$ Structure Fabricated by Magnetron Sputtering Technique”, IEEE Trans. on Sonics and Ultrason., SU-31, (1984) pp. 51-57.

[2] M. Kadota, ”High Performance and Miniature Surface Acoustic Wave Devices with Excellent Temperature Stability Using High Density Metal Electrodes,” IEEE Ultrasonics Symp., pp. 496-506 (2007).

[3] Y. Nakai, T. Nakao, K. Nishiyama, and M. Kadota, ”Surface Acoustic Wave Duplexer Composed of SiO_2 film with Convex and Concave on Cu-electrodes/$LiNbO_3$ Structure,” IEEE Ultrasonics Symp., pp. 1580-1583 (2008)

[4] 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 Ultrasonics (2017), p. 1.

[5] Y. Wang, K. Hashimoto, T. Omori, and M. Yamaguchi, “A Full-Wave Analysis of Surface Acoustic Waves Propagating on a SiO_2 Overlay/Metal Grating/Rotated Y-Cut X-Propagating $LiNbO_3$ Substrate Structure”, Jpn. J. Appl. Phys. 48, 07GG06 (2009).

[6] H. Nakamura, H. Nakanishi, T. Tsurunari, K. Matsunami, Y. Iwasaki, K. Hashimoto, and M. Yamaguchi, “Miniature Surface Acoustic Wave Duplexer Using SiO_2 /Al/$LiNbO_3$ Structure for Wide-Band Code-Division Multiple-Access System”, Jpn. J. Appl. Phys. 47, pp. 4052–4055 (2008).

[7] H. Nakanishi, H. Nakamura, T. Tsurunari, H. Kamiguchi, Y. Hamaoka, R. Goto, and Y. Iwasaki, “Miniature Surface Acoustic Wave Duplexer with Wide Duplex Gap on SiO_2 /Al/$LiNbO_3$ Structure”, Jpn. J. Appl. Phys. 48, 07GG04 (2009).

[8] H. Nakamura, H. Nakanishi, R. Goto, and K. Hashimoto, “Suppression of transverse-mode spurious responses for saw resonators on SiO_2 /Al/$LiNbO_3$ structure by selective removal of SiO_2”, IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control, Vol.58, No.10, pp.2188 – 2193, 2011.

[9] H. Nakamura, H. Nakanishi, R. Goto, K. Hashimoto, and M. Yamaguchi, “Analysis of Rayleigh-Mode Spurious Response Using Finite Element Method/Spectrum Domain Analysis for Surface Acoustic Wave Resonator on Nonflat SiO_2 /Al/$LiNbO_3$ Structure”, Jpn. J. Appl. Phys. 49, 07HD20 (2010).

[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. 52, 07HD12 (2013).

[11] 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. 57, 07LD20 (2018).

[12] R. Goto , H. Nakamura and K. Hashimoto, "The modeling of the transverse mode in TC SAW using SiO_2 /$LiNbO_3$ structure", Jpn. J. Appl. Phys. 58, SGGC07(2019).

[13] R. Goto, H. Nakamura and K. Hashimoto, "Spurious free TC-SAW duplexer using the SiO_2 /$LiNbO_3$ structure," 2019 IEEE International Ultrasonics Symposium (IUS), 2019, pp. 2075-2078, doi: 10.1109/ULTSYM.2019.8925829.

[14] G. Tang, R. Goto and H. Nakamura, "Modeling and Suppression Method for Guided Mode in TC-SAW Devices," 2019 IEEE International Ultrasonics Symposium (IUS), 2019, pp. 2087-2090, doi: 10.1109/ULTSYM.2019.8925671.

[15] R. Goto, G. Tang, T. Tsurunari and H. Nakamura, "Modeling and Suppression of SiO_2 Guided Mode on TC-SAW with a Cancelling Circuit," 2021 IEEE International Ultrasonics Symposium (IUS), Xi'an, China, 2021, pp. 1-4, doi: 10.1109/IUS52206.2021.9593595.

[16] T. Takai et al., "Incredible high performance SAW resonator on novel multi-layerd substrate," 2016 IEEE International Ultrasonics Symposium (IUS), 2016, pp. 1-4, doi: 10.1109/ULTSYM.2016.7728455.

[17] G. Endoh, K. Hashimoto and M. Yamaguchi, “Surface Acoustic Wave Propagation Characterization by Finite Element Method and Spectral Domain Analysis”, Jpn. J. Appl. Phys. 34, pp. 2638-2641 (1995).

[18] K. Hashimoto, T. Omori, and M. Yamaguchi, “Characterization of Surface Acoustic Wave Propagation in Multi-Layered Structures Using Extended FEM/SDA Software”, IEEE Trans. Ultrason., Ferroelec., and Freq. Contr., Vol. 56, 2009, pp.2559-2564.

[19] T. Takai et al., "High-Performance SAW Resonator on New Multilayered Substrate Using LiTaO3 Crystal," in IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, vol. 64, no. 9, pp. 1382-1389, Sept. 2017, doi: 10.1109/TUFFC.2017.2738119.