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A Review of SiO_2 Thin Film Technology for Temperature Compensated SAW Devices

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Abstract— **This paper describes a review of SiO_2 thin film technology for temperature compensated SAW devices. The SiO_2 thin film is widely used for SAW devices because of good temperature coefficient of frequency (TCF). The authors proposed the SAW devices on the SiO_2/Al/$LiNbO_3$ structure for their sufficient electromechanical coupling factor in addition to good temperature coefficient of frequency. However, in order to use SiO_2/Al/$LiNbO_3$ structure, it is important to suppress spurious responses. In this paper, the suppression method of the spurious response of the Rayleigh mode and the transverse mode are reviewed. Furthermore, for the narrow duplex gap application, SiO_2 thickness must be increased to achieve the good TCF characteristics. This spurious suppression technique could be applied to the thicker SiO_2 structure. Also, this paper describes the suppression of another spurious response, which appears near the first shear wave as the SiO_2 thickness increases. These techniques could be applied to the filters and duplexers, and the SAW devices could exhibit the excellent performances.**

I. INTRODUCTION

Surface acoustic wave (SAW) devices are widely used for SAW filters and duplexers in the mobile phone applications. As the number of frequency bands in mobile phones has increased in recent years, so has the number of SAW devices to be used, and the requirements for device performance has become even more demanding. The electromechanical coupling factor (K^2), temperature coefficient of frequency (TCF), and quality (Q) factor are key parameters for the devices. In the SAW devices, $LiNbO_3$ and $LiTaO_3$ substrates are widely used because of the advantages of K^2 and TCF. Especially in SAW devices, the temperature compensation technology has become somewhat prevalent as a way to enhance performance, and technological development is making progress. As for temperature compensation technology, the dielectric thin films are applied to the SAW devices to improve the performance.

The methods to improve the TCF characteristics of SAW devices have been studied. For temperature compensation method at the point of line expansion, $LiTaO_3$ bonding on the sapphire substrate was introduced [1]. On the other hand, the SiO_2 film was known to be temperature compensating material because of its thermoelastic properties. The SiO_2 film on the $LiTaO_3$ substrate was proposed [2-5]. Shear horizontal (SH) mode propagating on the Y-cut $LiNbO_3$ with SiO_2 film was proposed to obtain a small TCF and large electromagnetic coupling factor K^2 [6, 7]. A flattened SiO_2 film/Cu electrode/$LiNbO_3$ structure [8, 9] and a shape controlled SiO_2 film/Al electrode/$LiNbO_3$ structure were reported for the wide duplex gap applications [10, 11]. Rayleigh mode on the SiO_2/Cu electrode/$LiNbO_3$ structure was proposed to narrow duplex gap applications [12]. The shape controlled SiO_2 film/Al electrode/$LiNbO_3$ structure was reported for the narrow duplex gap application. SiO_2/Al/$LiNbO_3$ structure achieves excellent TCF characteristics and moderate electromagnetic coupling factor K^2. However, this structure also supports unwanted spurious response. Suppression methods of the transverse mode spurious response were reported [13, 14].

In addition, the recent market demands are driving the needs for SAW devices with 0 TCF characteristics. Against this backdrop, discussions are taking place on material characteristics of SiO_2 for the purpose of improving TCF characteristics [15]. There was also a report describing that SAW duplexers with near zero TCF characteristics were realized by depositing a thick SiO_2 film on Cu electrode/$LiNbO_3$ [16, 17].

This paper proposes a technique for the suppression of the spurious response, in Rayleigh mode as well as the transverse and higher modes, of the SAW resonator on the SiO_2/Al/$LiNbO_3$ structure. It also reports how SAW duplexer with near zero TCF was realized using a thick SiO_2 film.

II. FOR WIDE DUPLEX GAP APPLICATION

A. *SAW Resonator Structure*

Figure 1 shows a cross-sectional view of the SiO_2/IDT/$LiNbO_3$ structure. The IDT electrodes and the SiO_2 film are formed on the $LiNbO_3$ substrate. Furthermore, the shape of the SiO_2 film is controlled in a way that the SiO_2 film has a trapezoidal shape above the IDT electrodes.

Figure 2 shows the input admittance Y_{11} of the SAW resonator. Here, the cut angle of Y-cut $LiNbO_3$ is 5°. The IDT pitch and SiO_2 thickness were set at 1 μm and 0.2 λ. The Al electrode thickness was 0.05 λ. As shown in Fig.2, the Rayleigh mode spurious response occurs at lower frequency side from resonant frequency. And, the transverse-mode spurious response occurs between resonance and anti-resonance frequencies. For applying the SAW resonator on a $SiO_2/Al/LiNbO_3$ structure to the duplexers, both Rayleigh mode and transverse-mode spurious responses need to be suppressed.

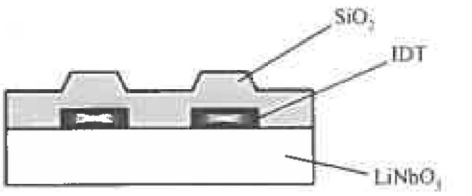


Figure 1. A cross-sectional view of the $SiO_2/IDT/LiNbO_3$ structure with controlled SiO_2 film.

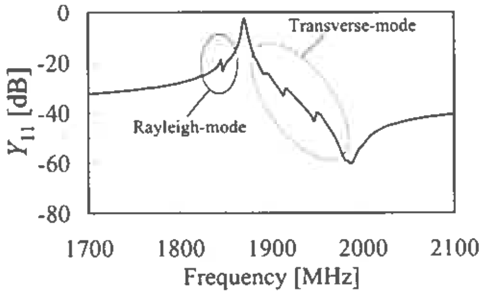
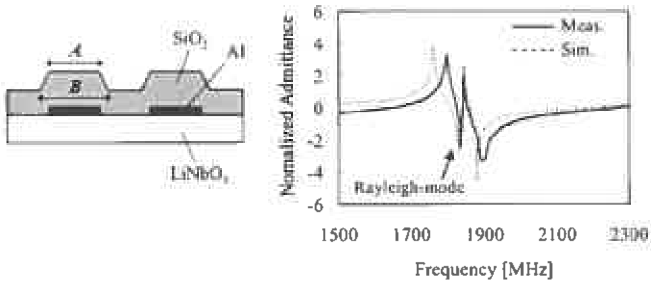
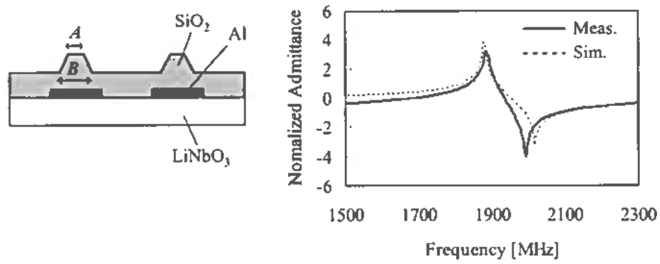


Figure 2. A cross-sectional view of the $SiO_2/IDT/LiNbO_3$ structure with controlled SiO_2 film.



(a) $SR=A/B=0.78$



(b) $SR=A/B=0.38$

Figure 3. Simulated and experimental results of a SAW resonator on a non-flat $SiO_2/Al/LiNbO_3$ structure.

B. Rayleigh Mode Spurious Supression

By controlling the SiO_2 shape [10, 11], we have developed a Rayleigh-mode spurious response suppression technique. In practice, the SiO_2 shape becomes almost similar to that of a trapezoid. So, we expanded FEM/SDA to process the SiO_2 film into a shape of a trapezoid [18-20]. Figure 2 shows the simulated and experimental results of normalized admittance of a SAW resonator fabricated on the non-flat $SiO_2/Al/LiNbO_3$ structure. Here, the cut angle of Y-cut $LiNbO_3$ is 5°, the Al thickness is 0.08 λ, the SiO_2 thickness between the two IDT fingers is 0.2 λ, and the IDT pitch is 1 μm. In the figure, the SiO_2 shape ratio *(SR)* is defined as the ratio of the upper and lower bases of the trapezoidal SiO_2 film region ($SR=A/B$). As shown in Fig. 2(a), the Rayleigh-mode spurious response was observed between the resonance and anti-resonance frequencies in both the simulated and experimental results. In Fig. 2(b), where *SR* was reduced to 0.38, the Rayleigh-mode spurious response cannot be observed. The experimental result also confirms that the admittance characteristic at anti-resonance was not badly affected by bulk wave radiation. Furthermore, K^2 was experimentally estimated to be about 0.15. It is concluded, therefore, that the non-flat $SiO_2/Al/LiNbO_3$ structure is able to support high coupling SAW of SH type with suppressed bulk wave radiation. And, the experimental results of the SAW resonator were in good agreement with simulations.

C. Transverse Mode Spurious Supression

We propose a new technique to suppress the spurious responses of the resonator on the $SiO_2/Al/LiNbO_3$ structure. Figure 4 shows the schematic view of the SAW resonator. In the technique, the SiO_2 overlay is selectively removed from the dummy electrode region for enhancing the SAW energy confinement in the active electrode region. In Fig. 8, (a) and (b) are a top view and a sectional view, respectively. In the dummy region, the SiO_2 film is removed. The SiO_2 film is only covered on the IDT region. In this structure, the SAW velocity (v_d) in the dummy region could make faster than the SAW velocity (v_i) in the IDT region. Therefore, the SAW could be confined in the IDT region when $v_i < v_d$.

Figure 5 shows the characteristics of the SAW resonators. In Fig. 5, the dashed line shows the characteristics of the SAW resonator with normal type IDT for comparison. The transverse-mode spurious response could be completely suppressed by adopting the weighting. And, the minimum insertion loss is not degraded. The value is 0.18 dB, the same as one of SAW resonators with normal type IDT.

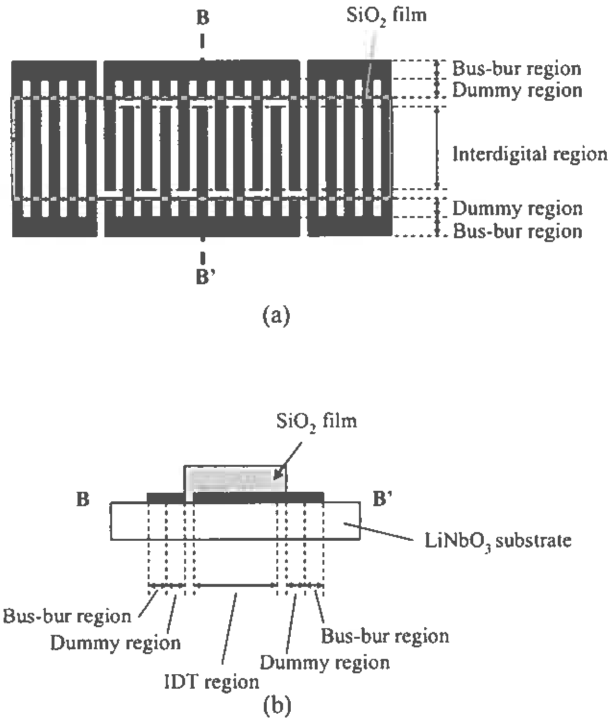


Figure 4. The schematic view of the SAW resonator with the selective removal of the SiO_2 overlay from the dummy electrode region. (a) and (b) are a top view and a sectional view, respectively.

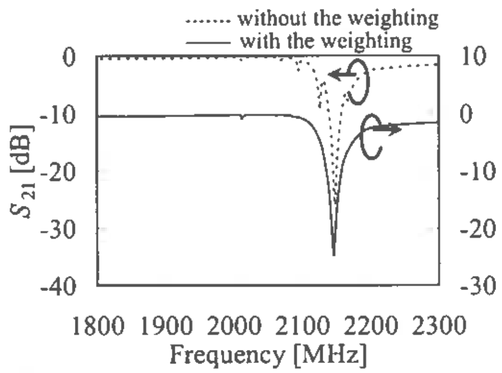


Figure 5. Characteristics of the SAW resonators with the scattered dummy electrode weighting.

D. *Duplexer Performances for Band 1 Application*

Figure 6 shows the transmission characteristics from the Tx to ANT ports and from the ANT to Rx ports, respectively. It is seen that sufficient performance is achieved for the current application: the Tx to ANT insertion loss and suppression in the Rx band are 1.2 dB and 45 dB, respectively, for the Tx filter, while the ANT to Rx insertion loss and suppression in the Tx band are 1.9 dB and 51 dB, respectively, for the Rx filter. Figure 6 shows the isolation between the Tx and Rx ports. Sufficient isolation levels of 53 dB and 45 dB are obtained for the Tx and Rx bands, respectively.

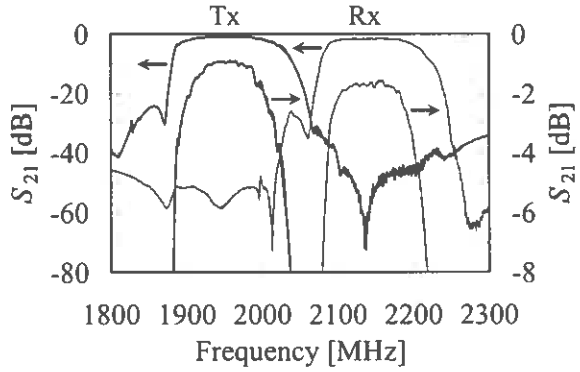


Figure 6. Tx and Rx transmission responses of the unbalanced-type SAW duplexer for Band 1 application.

III. FOR NARROW DUPLEX GAP APPLICATION

A. *SAW Resonator Structure and Performances analysis*

In this section, a higher mode spurious mode suppression technique is described. Firstly, the $SiO_2/Al/LiNbO_3$ structure was analyzed to obtain the SAW propagating property by FEM/SDA [18-20]. The cause of the spurious near the fast-shear wave and suppression method is discussed. Fig.7 shows the cross-sectional view of the $SiO_2/Al/LiNbO_3$ structure. Fig.8 shows calculated TCF and K^2 characteristics dependence of the SiO_2 thickness H_2 shown in Fig.1. The TCF performance is strongly affected by the thickness of the SiO_2 layer. Almost zero TCF is achieved near the $H_2 = 0.3\lambda$ and $K^2 = 9.5[\%]$. Here, the cut angle of Y-cut $LiNbO_3$ is 2.5° fixed, and $H_1 = 0.08\lambda$, and metallization ratio is 0.5λ. TCF is improved by increasing the H_2. H_3 is determined by the shape of the SiO_2 surface. In this case, $H_3 = 0.04\lambda$ is used. Fig.9 shows the calculated admittance characteristics varying the SiO_2 thickness H_2. As the SiO_2 thickness is increased, spurious response is strongly excited near the frequency corresponding to the fast shear bulk wave velocity. To achieve the good TCF characteristics and electrical performances, the suppression of this spurious response is necessary.

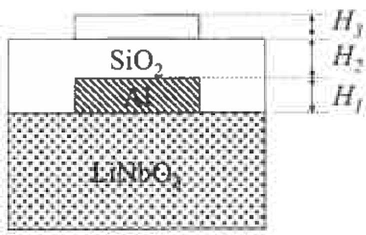


Figure 7. Cross-sectional view of the $SiO_2/Al/LiNbO_3$ structure.

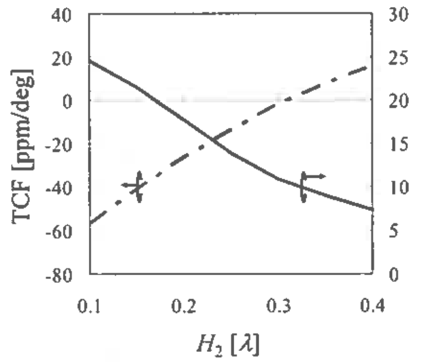


Figure 8. Calculated TCF and K^2 varying the SiO_2 thickness.

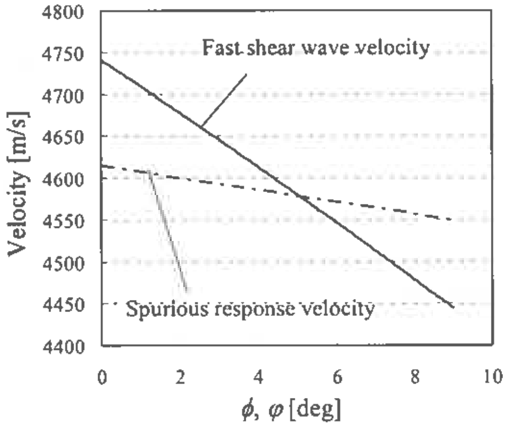


Figure 10. Calculated fast shear wave verocity.

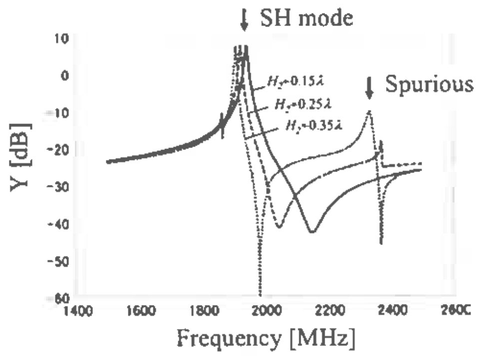


Figure 9. Calculated admittance characteristics dependence of H_2.

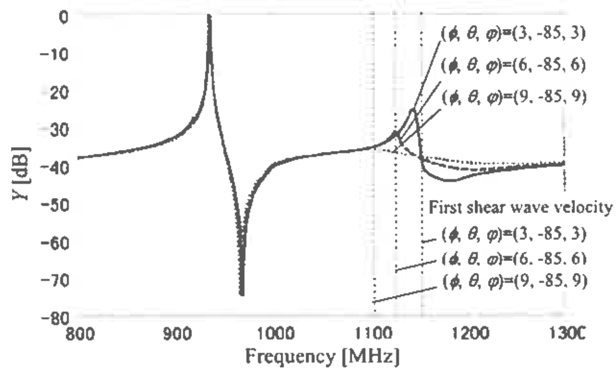


Figure 11 Calculated admittance characteristics.

B. Higher Mode Spurious Supression

The spurious response occurs near the frequency corresponding to the velocity of the fast shear bulk wave. If SAW velocity is faster than the bulk wave velocity, SAW energy is radiated into the substrate. The fast shear wave velocity is determined by the crystal cut angle of substrate. Spurious response thought to be suppressed by radiating as the fast shear bulk wave to select the crystal cut angle properly. The fast shear velocity is calculated by changing the cut angle. Here, both parameters rotating cut angle ϕ and propagating angle φ defined on Euler angles (ϕ, θ, φ) are changed to consider the PFA (power flow angle) condition. Fig. 10 shows the fast shear wave velocity and that of corresponding to the spurious response by changing the cut angle ϕ and propagating angle φ to keep the condition $\phi = \varphi$. The fast shear wave velocity is decreased by increasing the cut angle and the propagating angle. The fast shear wave velocity becomes slower than that of the spurious response at $\phi = \varphi = 5$[deg.]. At this condition, the spurious response could be suppressed by the bulk wave radiation as the fast shear wave. Fig. 11 shows the calculated admittance characteristics by changing the cut angle and the propagating angle. First shear wave velocity is also shown in the figure. The first shear wave velocity decreases lower than the spurious response by increasing ϕ and φ. As the result, the spurious response is suppressed.

Fig.12 shows the measured admittance characteristics. Spurious response is suppressed by increasing ϕ and φ. The main response is almost unchanged in both calculated and measured characteristics. Calculated results and measurement results show good agreement. Fig. 13 is measured response (S_{21}) of the resonators. Spurious response near the fast shear wave velocity is suppressed successfully.

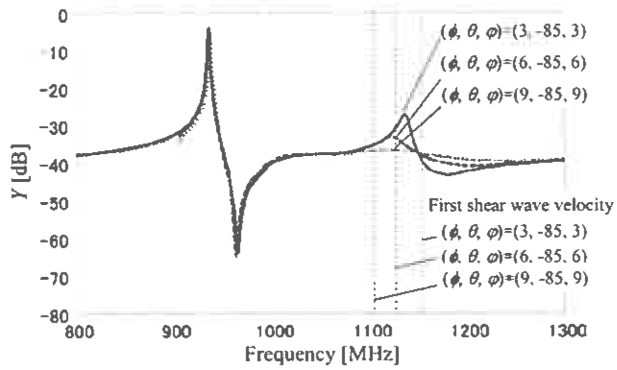


Figure 12. Measured admittance characteristics.

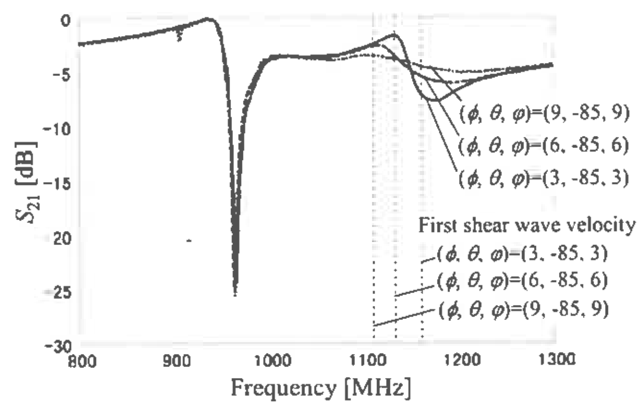


Figure 13. Measured responses (S_{21}).

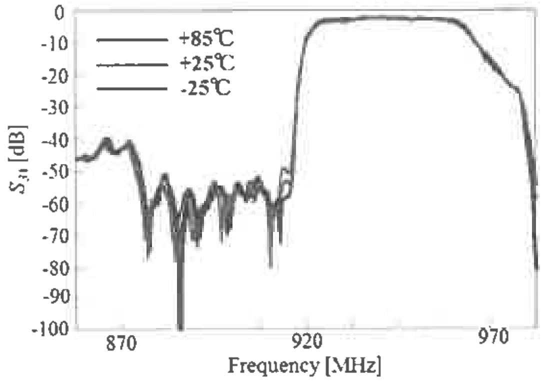


Figure 15. Measured responses from the ANT to Rx ports.

C. *Duplexer Performances for Band 8 Application*

Figure 14 shows the transmission characteristics from the Tx to ANT ports (S_{21}), and Figure 15 shows the transmission characteristics from the ANT to Rx ports (S_{31}). It is seen that sufficient performance is achieved for the current application: the Tx to ANT insertion loss and suppression in the Rx band are 2.1 dB and 45 dB, respectively, for the Tx filter, while the ANT to Rx insertion loss and suppression in the Tx band are 2.4 dB and 50 dB, respectively, for the Rx filter. The figure shows the waveforms at temperatures +85 ℃, +25 ℃, and -25 ℃, and as for TCF performance, near zero TCF is achieved.

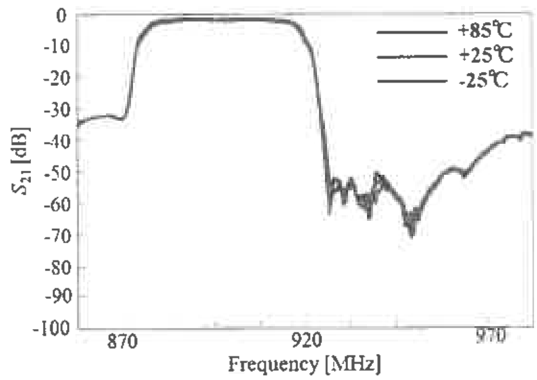


Figure 14. Measured responses from the Tx to ANT ports.

IV. CONCLUSION

This paper describes a review of SiO_2 thin film technology for temperature compensated SAW devices. The SiO_2 thin film is widely used for SAW devices because of good temperature coefficient of frequency.

As for the wide duplex gap application, we have developed the novel spurious suppression techniques for the SAW resonator on a $SiO_2/Al/LiNbO_3$ substrate. For the Rayleigh-mode spurious response, it could be suppressed by controlling the SiO_2 shape of the SAW resonator on the $SiO_2/Al/LiNbO_3$ structure. For the transverse-mode spurious response, it could be suppressed by using the scattered dummy weighting technique. The developed spurious suppression techniques for Rayleigh-mode and transverse-mode spurious responses were applied to the unbalanced-type SAW duplexer for UMTS Band 1 application. SAW duplexer demonstrated good performance.

As for the narrow duplex gap application, suppression mechanism of the spurious response near the fast-shear wave was cleared. Suppression method of the spurious response is proposed. Using this method, the spurious suppression could be achieved without degradation of the SH SAW responses by selecting the crystal cut angle. The developed spurious suppression techniques were applied to the SAW duplexer for UMTS Band 8 application. SAW duplexer had near zero TCF characteristics and demonstrated good performance.

SiO_2 thin film is a very effective means to improve the TCF characteristics of SAW devices. The key to improve the performance of SAW devices using SiO_2 thin film on the $LiNbO_3$ substrate is the spurious suppression. The spurious suppression method described in this paper is a very useful technology in realizing SAW devices using SiO_2 thin film in years to come.

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