Proceedings of the 2003 IEEE International Frequency Control Symposium and PDA Exhibition
Jointly with the 17th European Frequency and Time Forum

IF SAW FILTERS WITHOUT LOVE WAVE'S SPURIOUS CONSISTING OF ZNO FILM AND SPECIFIC CUT ANGLE QUARTZ SUBSTRATE

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Abstract – **The substrate with large electromechanical coupling factor and excellent temperature coefficient of frequency (TCF) is required to realize surface acoustic wave filters for the first intermediate frequency stage (1st IF). One of the authors (M. Kadota) realized a Rayleigh wave substrate with an excellent TCF and a large electromechanical coupling factor by a combination of a specific quartz substrate (ST-cut 35°X propagation: ST- 35°X) having a positive TCF with a ZnO film having a negative TCF. But, it has been clarified that the SAW filter having of a single electrode (strip) or single-phase unidirectional transducer (SPUDT) on the ZnO/ST-35°X-quartz substrates, often had a large spurious response due to the Love wave which was a higher-order-mode of the Rayleigh wave. The new cutting angle and the propagating direction (26-27°Y-X) on quartz has been developed in order to suppress the spurious response. The IF SAW filters for the Wide-band and the Narrow-band Code Division Multiple Access (W-CDMA: 380MHz and N-CDMA: 183.6MHz) have been developed by combining this 26-27°YX quartz with the ZnO film. The IF filters which have a small-size, an excellent TCF, a low insertion loss, a cost advantage in their applications, and no spurious responses due to the Love wave have been realized. Their frequency shift per 1°C from –20°C to 80°C was less than 0.37 ppm/°C, which was better than a Rayleigh SAW on an ST-cut X propagation quartz.**

Keywords – **ZnO film, quartz, excellent TCF, large coupling factor**

I. Introduction

Surface acoustic wave (SAW) filter are widely used as key parts for mobile telecommunication systems. The SAW filter for the first intermediate frequency stage (1st IF) is strongly required to have a small size, low cost, and low insertion loss. Most of 1st IF SAW filters require a narrow band and a good temperature stability. The Rayleigh SAW on an ST-cut X-propagation (ST-X) quartz substrate are used to realize such IF filters. This substrate has a good temperature coefficient of frequency (TCF≅0.9ppm/°C), but its electromechanical coupling factor k_s is small (k_s^2=0.014). One of the authors (M. Kadota) reported substrates with an excellent TCF and a large electromechanical coupling factor by a combination of a specific (cut-angle or propagation-direction) quartz substrate having a positive TCF (+10~25 ppm/°C) with a zinc oxide (ZnO) film having a negative TCF based on theoretical and experimental investigations [1][2][3][4]. As the results of experimental investigations combining the ZnO film with an ST-cut 35°X (ST-35°X) quartz substrate, which is readily available and has a positive TCF and zero degree power flow angle (PFA), an excellent TCF (≅0ppm/°C) and large electromechanical coupling factor were realized with a zero degree PFA. Where the ST-35°X represents that the SAW propagates in the direction of 35° from the X-axis on the ST-cut quartz substrate.

The Rayleigh wave on the ZnO film on the ST-35^{o}X quartz substrate was tried to apply to various IF filters in this study. In this process, it was clarified that a transversal SAW filter consisting of an interdigital transducer (IDT) of a single electrode (strip) or a single-phase unidirectional transducer (SPUDT) generated a spurious response due to a high-order-mode SAW (Love wave) of the Rayleigh wave[3][4][5]. As a result of their further investigation, a new cut angle of quartz has been developed. The ZnO/quartz SAW filter did not generate the spurious response due to the Love wave, and had a zero TCF, a large electromechanical coupling factor, and zero degree PFA[5]. In this paper, the SAW filters using the ZnO film on this new cut angle quartz substrate for various IF are reported.

II. SAW properties on ZnO/ST-35^{o}X quartz

One of authors (Kadota) reported that a Rayleigh wave substrate with an excellent TCF and a large electrome-chanical coupling factor was realized by a combination of an ST-35°X quartz substrate having a positive TCF (+15 to +20ppm/°C) with a ZnO film having a negative TCF [1][2][3][4]. Figs.1, 2 and 3 show their results. Figs.1 and 2 show SAW velocities and electromechanical coupling factors as the function of normalized ZnO film thickness. In Figs. 1 and 2, solid lines and circles show the calculated and experimental results on ZnO/29°45' Y-35°X quartz and the broken lines and dots show those on ZnO/42°45'Y-35°X quartz, respectively. Fig.3 shows TCF and Δf/f values of SAW filters of the ZnO film on the 29°45'Y-35°X and 42°45'Y-35°X quartz substrates as the function of the normalized ZnO thickness. Where TCF is calculated as equation (1) and Δf/f shows the frequency shift per 1°C from -20°C to 80°C as equation (2). The Δf/f corresponds to TCF if the frequency shows linear shift with respect the temperature.

$$TCF=(V(35°C)-V(15°C))/V(25°C)-\alpha \quad \text{------- (1)}$$

V: velocity at 15°C, 25°C or 35°C

α: linear expansion coefficient

$$\Delta f/f = \frac{\text{(total frequency shift)}}{\text{((frequency at 20°}\times\text{(measured total temperature range))}} \quad \text{--------(2)}$$

In Fig 3, the solid line and white marks (○ and △) show calculated results (TCF) and measured results (Δf/f) on the ZnO/29°45'Y-35°X quartz, respectively. The broken line and black marks (● and ▲) show those on the ZnO/42°45'Y-35°X quartz. As seen in Fig.3, TCF≅0 and Δf/f≅0 were obtained at the normalized ZnO thickness H/λ=0.15 to 0.3[1][2][3][4]. At the ZnO thickness yielding TCF≅0 or Δf/f≅0, the SAW velocity (2800 to 2900 m/s) is about 10% lower and the electromechanical coupling factor is larger (6 to 20 times in k_s^2) than that of the Rayleigh wave on the ST-X quartz. Thus, compared with the ST-X quartz, the ZnO/ST-35°X quartz substrate has numerous features. This substrate was tried apply to various IF filters.

III. Cut angle of quartz without spurious response due to Love wave

It has been clarified that the spurious response was generated at the frequency range of 1.1 times the Rayleigh wave on the ZnO/42°45'Y35°X quartz as shown by a broken line in latter-mentioned Fig. 5 and solid line in Fig. 6 in the reference [4]. This spurious response was generated due to high-order-mode SAW shown in Figs. 1 and 2. Figs.4(A) and (B) show distributions of the displacements (U_1,U_2,U_3) of the Rayleigh wave and its high-order-mode SAW at the normalized ZnO thickness H/λ=0.3 on 42°45'Y-

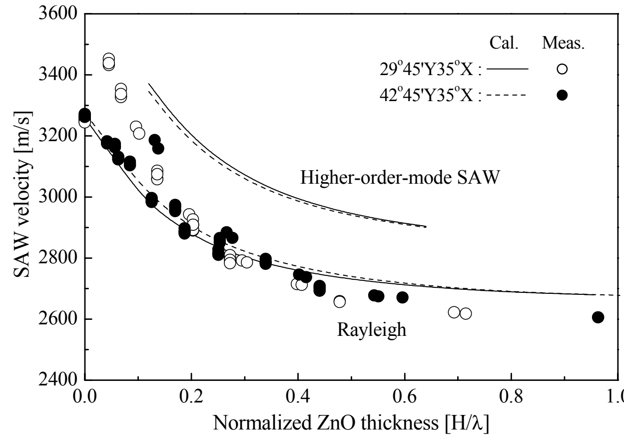

Fig.1 SAW velocity relative to ZnO thickness(1)~(4).

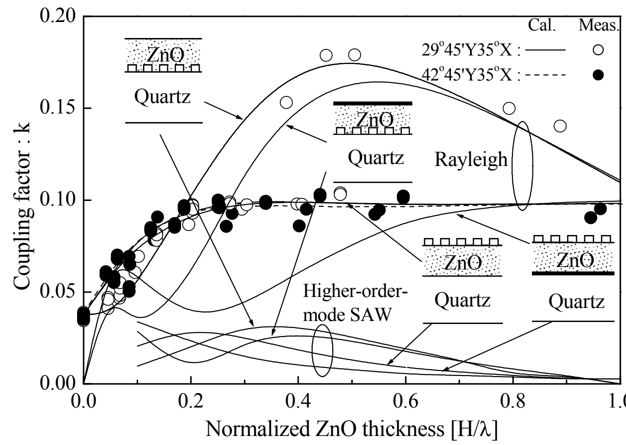

Fig.2 Coupling factor relative to ZnO thickness(1)~(4).

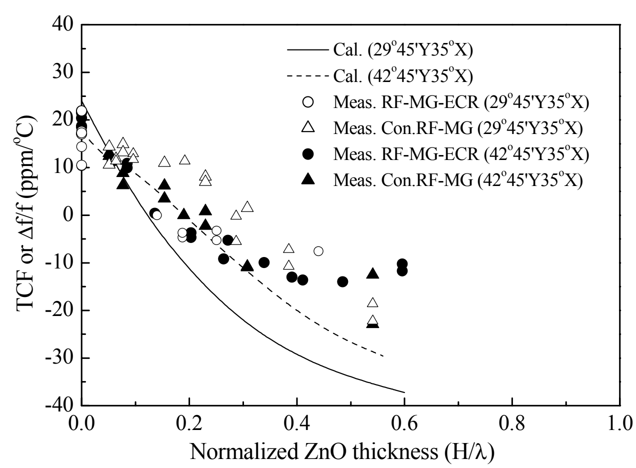

Fig.3 Values of TCF and 8f/f as the function of various ZnO thicknesses on IDT/ ZnO/ST-35° X quartz.

35°X quartz, respectively. Where U_1 is a shear vertical (SV) component, U_2 is a shear horizontal (SH) one, and U_3 is a longitudinal (L) one. It is reconfirmed that the wave shown in Fig. 4(A) is the Rayleigh wave with three components of U_1, U_2, and U_3, which is a main component. It is considered that the high-order-mode SAW shown in Fig.4(B) is a Love wave, which has mainly U_2(SH) components. Though the electromechanical coupling factor k_{LOVE} of this Love wave is small ($k^2_{LOVE} \cong 0.01$), its mutual-coupling coefficient κ_{12} at a single strip is not small (more than 0.02). Therefore, a transversal SAW filter consisting of IDT such as a single electrode or SPUDT, which causes an acoustic reflection generates a large spurious response due to this Love wave. In the practical use, it is necessary to suppress this spurious response. The cut-angle and propagation direction of the quartz substrate having a small electromechanical coupling factor and a small κ_{12} value of the Love wave on the ZnO/IDT/quartz substrate was calculated at the ZnO thickness H/λ=0.3, under the condition that the Rayleigh wave had an excellent TCF, a zero degree PFA, and a large electromechanical coupling factor. Fig. 6 shows the coupling factors of the Love wave as the function of the angle θ at Euler angle (0°, θ, 0°). It was clalified that the ZnO films with H/λ=0.03 on a new cut-angle of 26° to 27° rotated-Y X-propagation quartz substrate (Euler angle: (0°, 116° to 117°, 0°)) almost has the coupling factor of zero in the Love wave. Moreover, the Rayleigh wave on this substrate has a large coupling factor (k_s^2=0.018), an excellent TCF (≅0 ppm/°C), and a zero degree PFA.

Table I shows SAW properties of various substrate having relatively good Δf/f such as an ST-X quartz, $Li_2B_4O_7$, $La_3Ga_5SiO_{14}$ and X-cut 112° Y-$LiTaO_3$ in addition to the ZnO/IDT/quartz structure. Among them, the ZnO/IDT/26-27°Y-X quartz has the lowest SAW velocity, the largest electromechanical coupling factor, and the best Δf/f (TCF). Thus this substrate is most suitable for the transversal SAW IF filter. This substrate was applied to various IF SAW filters.

IV. Characteristics of IF SAW Filter

A. Spurious response due to Love wave

The transversal SAW filters were composed of the ZnO film on two sets of normal single IDTs on the 27°Y-X quartz substrate. Where the normalize thicknesses (H/λ) of

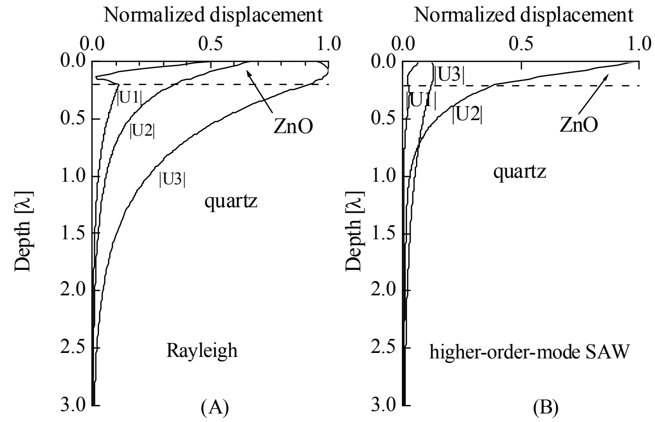

Fig.4 Distributions of the displacements (U_1,U_2,U_3) of (A) Rayleigh wave and (B) Love wave at the normalized ZnO thickness H/λ=0.2 on 29°45'Y-35°X quartz.

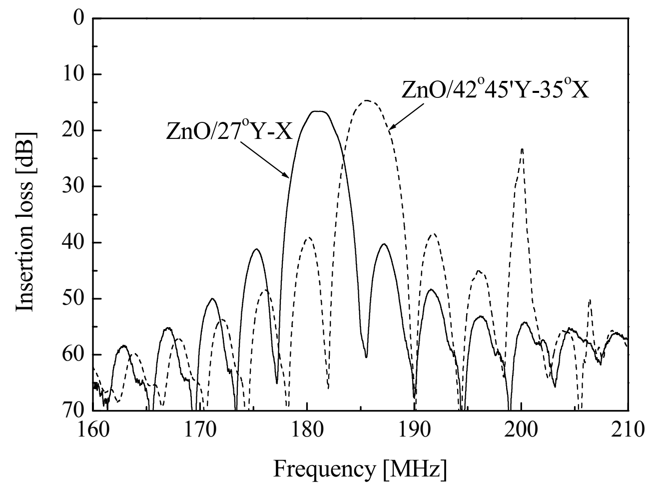

Fig.5 Frequency characteristics of transverse SAW filters consisting of ZnO/ST-35 ° X quartz (broken line) and ZnO/27 ° Y-X quartz (solid line).

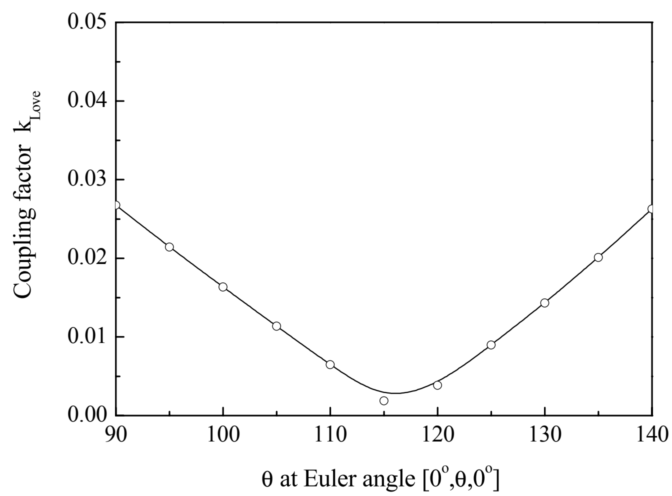

Fig.6 Euler angle dependence of calculated coupling factor of Love wave at the ZnO thickness of H/λ=0.3 on quartz.

Table I

Rayleigh SAW properties of various substrates having good Δf/f

Substrate	Velocity (m/s)	k_s^2	Δf/f0 (ppm/°C)
ST-X quartz	3158	0.0014	0.9
$La_3Ga_5SiO_{14}$(12°,152.7°,37°) [7)]	2835	0.0046	1.55
$Li_2B_4O_7$(110°,90°,90°) [8)]	3480	0.010	6.8
ZnO/IDT/quartz(27°Y-X)	2700	0.018	0.37
Refrence			
$LiTaO_3$(X-112°Y) [9)]	3290	0.0064	18

the Al-IDT and the ZnO film are 0.02 and 0.3, respectively. The solid and broken lines in Fig.5 show frequency characteristics of the SAW transversal filters consisting of ZnO films on 27°Y-X quartz and 29°45' Y-35°X quartz by solid and broken lines, respectively. It has been clarified by experiment that the spurious response due to the Love wave is suppressed by using 27°Y-X quartz substrate. It is considered that the spurious characteristics on three other types of structures (short-plane/ZnO/IDT/quartz, IDT/ZnO/quartz, and IDT/ZnO/short-plane/quartz) would also show similar results. Thus, the ZnO/27°Y-X quartz substrate is most suitable for the IF filter consisting of a transversal SAW filter.

B. SAW filter for CDMA IF

Fig. 7 shows the frequency characteristic of a 380 MHz SAW filter consisting of ZnO/IDT/27°Y-X quartz for an IF stage (receive side (Rx)) at Wide-Band Code Division Multiple Access (W-CDMA). The normalized thicknesses (H/λ) of the ZnO film and the Al-IDT are 0.3 and 0.02, respectively. The ZnO film was deposited using a conve-ntional RF magnetron sputtering system. The IDT electrode structure is a transversal type using the SPUDT, and the package size, which was bonded wires to connect the electrodes on the chip to those on the package, is small, being 3.2×5.0mm^2. The insertion loss and 3 dB bandwidth are 5.8dB and 4.6MHz, respectively. Compared with the insertion loss of 9.4 dB in an IF SAW filter for W-CDMA (Rx) consisting of the ST-X quartz substrate [10], that of our newly developed SAW filter consisting of the ZnO/IDT/quartz is 3.6dB lower. The adjacent channel selectivity (ACS) is large for 38.0 dB/35.3 dB at the room temperature, and 36.1 dB/35.0 dB over the entire tempe-rature range from –20°C to 100°C under the conditions of BW=3.84MHz, OFFSET=±5MHz, and rolling off ratio α=0.22. Thus, this filter has the optimal properties in terms of insertion loss, ACS, and size for the W-CDMA IF stage.

Fig.8 shows a frequency characteristic of a 183 MHz SAW filter consisting of ZnO/IDT/26°Y-X quartz for an IF stage (receive side (Rx)) at Narrow Band CDMA (N-CDMA). The normalized thickness (H/λ) of the ZnO film and the Al-IDT consisting of SPUDT are 0.27 and 0.026, respectively. The ZnO deposition was performed using a conventional RF magnetron sputtering system. The package size using bonded-wires is small, 5×7mm^2. The insertion loss and 5 dB bandwidth are 4.3dB and 1.3MHz, respec-tively. This insertion loss is 4.4 dB lower than that of our previous SAW filter consisting of the ST-X quartz substrate.

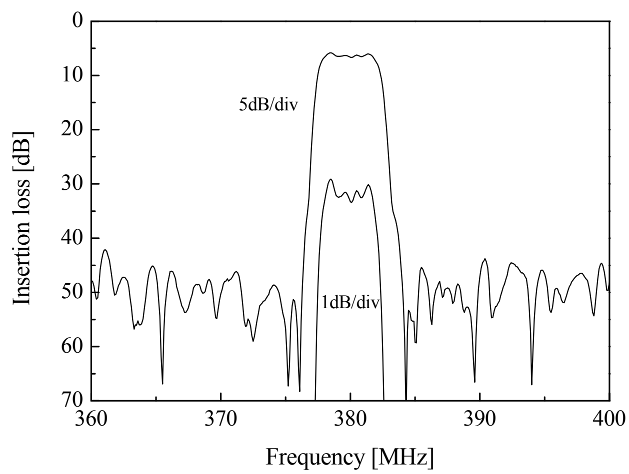

Fig.7 Frequency characteristics of 380MHz IF filter for W-CDMA consisting of ZnO/IDT/27° Y-X quartz.

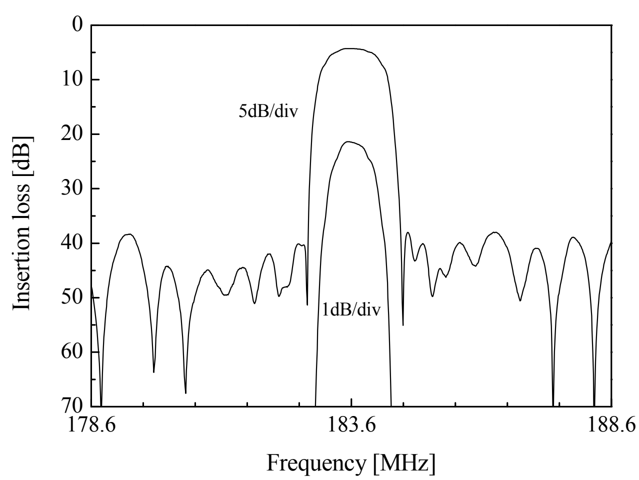

Fig.8 Frequency characteristics of 183MHz IF filter for N-CDMA consisting of ZnO/IDT/26° Y-X quartz.

The solid line and broken line in Fig.9 show the frequency shift of 183MHz SAW IF filters consisting of ZnO/IDT/26°Y-X quartz and IDT/ST-X quartz with respect to the temperature change, respectively. The total frequ-ency shifts of the former and the latter from –20°C to 80°C are 37 and 100 ppm, respectively, and the frequency shifts per 1 °C (Δf/f) are 0.37 and 1.0 ppm/°C, respectively. Thus, the temperature property of the former filter is better than that of the latter one.

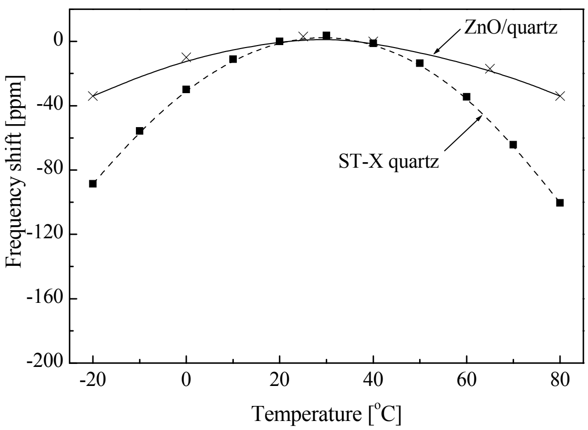

Fig.9 Frequency shifts of 183MHz IF filter for N-CDMA consisting of ZnO/IDT/26° Y-X quartz (solid line) and ST-X quartz (broken line) relative to temperature.

V. Conclusions

One of the authors (M. Kadota) realized substrates with an excellent TCF, a large electromechanical coupling factor, and a low velocity by a combination of an ST-35°X quartz substrate having a positive TCF with a ZnO film having a negative TCF. When this ZnO/ST-35°X quartz was tried to apply to various IF filters, the spurious response due to the Love wave was generated at the frequency range of 1.1 times the main response. The new cutting angle and the propagating direction (26-27°Y-X) on quartz were develop-ed in order to suppress the spurious response due to the Love wave. The Rayleigh SAW on this ZnO/IDT/26°-27°Y-X quartz has a low velocity (2800m/s), an excellent TCF (Δf/f 0.37 ppm/°C), a large electromechanical coupling factor (k_s^2=0.018), and a zero degree PFA at the normalized ZnO thickness H/λ≅0.3. The IF filters for W-CDMA and N-CDMA without the spurious response due to the Love wave were developed by applying this substrate. IF filters having small packages, low insertion losses (which are 3.6~4.4 dB lower than those of ST-X quartz), an excellent TCF (which was about one-third that of ST-X quartz), cost advantage in application and an excellent ACS in the entire temperature range from –20 to 80°C (W-CDMA) were realized.

Acknowledgement

The authors thank co-researchers in this developemnt.

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