High-Frequency Resonators with Excellent Temperature Characteristics using Edge Reflection

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Abstract— **Currently, some surface acoustic wave (SAW) devices, especially duplexers, are required to have a good temperature coefficient of frequency (TCF), because the bands between a transmission band (Tx) and a receiving band (Rx) of the duplexer such as Personal Communication Services (PCS) mobile phone in US is very narrow (about 1%). However, a 36-48°YX-$LiTaO_3$ substrate, which is used for most SAW radio frequency (RF) filters and most SAW duplexers in mobile phone systems, has an optimum electromechanical coupling factor for their applications but does not have a good TCF. It was reported that the TCF of a transversal SAW filter using thin Al electrodes on $LiTaO_3$ and $LiNbO_3$ substrates with negative TCF was improved by depositing thick SiO_2 film with positive TCF on them. However, most RF SAW filters and most duplexers are composed of resonator type SAW devices such as ladder-type or multi-mode resonator type filters using thick Al-electrodes on the substrate to obtain a large reflection coefficient. When the thick SiO_2 films were deposited on the SAW resonator and the multi-mode SAW resonator filter consisting of thick Al-electrodes/36°YX-$LiTaO_3$ to improve their TCF, their frequency characteristics were markedly deteriorated. Because their coupling factor becomes smaller and their propagation loss larger due to large periodic convex portions as thick as the Al-electrodes produced on the SiO_2 surface. To avoid influence due to these large periodic convex portions, a SiO_2 with thin convex/thin Al-electrodes/$LiTaO_3$ and a flattened SiO_2 without convex/thick Al-electrodes/$LiTaO_3$ structures were examined, but they didn't show good characteristics because of the small reflection at the grating reflectors. On the other hand, it is considered that the reflection of a shear horizontal (SH) wave at a substrate edge of the SiO_2/Al-electrodes/$LiTaO_3$ structure is large regardless of Al or SiO_2 thickness, because the SH wave completely reflects at the free substrate edge. But, it has been considered that it is difficult to form a fine substrate edge for a high-frequency resonator using the edge reflections. This time, by developing of forming method for a fine substrate edge, high-frequency edge reflection type resonators with a good TCF and an excellent frequency characteristic, which were composed of a thick SiO_2 with thin convex/thin Al-electrodes/36°YX-$LiTaO_3$ and a flattened thick SiO_2 without convex/thick Al-electrodes/36°YX-$LiTaO_3$, have been realized for the first time.**

I. INTRODUCTION

Currently, surface acoustic wave (SAW) devices have been widely used as a key device, such as intermediate frequency (IF) filters, radio frequency (RF) filters, and antenna duplexers in the consumer electronic products of TVs, electric toll collections (ETC), mobile phone systems, and so on [1]. A 36-48°$LiTaO_3$ substrate is most widely used for those devices because it has a suitable electromechanical coupling factor. However, its substrate doesn't have a good temperature coefficient of frequency (TCF: -42ppm/°C; a frequency shift per 1°C), so it is not suitable for SAW devices required a good TCF . Thus, this substrate is not suitable for SAW devices requiring a good TCF such as the duplexer for Personal Communication Services (PCS) in US, which requires an excellent TCF, because the band between a transmission band (Tx) and a receiving band (Rx) is very narrow as about 1% of relative band width.

It was reported that the TCF of a transversal SAW filter using thin Al electrodes on $LiTaO_3$ and $LiNbO_3$ substrates with negative TCF was improved by depositing thick SiO_2 film with positive TCF on them[2][3][4]. However, most RF SAW filters and duplexers are composed of resonator type SAW devices such as ladder-type or multi-mode resonator type filters using thick Al-electrodes on the substrate to obtain a large reflection coefficient. When the thick SiO_2 film of thickness 0.2λ to 0.25λ was deposited on the SAW resonator or the multi-mode SAW resonator filter consisting of thick Al-electrodes/36°YX-$LiTaO_3$ to improve their TCF, their frequency characteristics markedly deteriorated[5][6][7][8]. This occurred because the coupling factor becomes smaller and propagation loss larger due to large periodic convex portions as thick as the Al-electrodes produced on the SiO_2 surface as reported in refs.[9][10][11]. To avoid influence due to these large periodic convex portions, a SiO_2 with thin convex/thin Al-electrodes/$LiTaO_3$ and a flattened SiO_2 without convex/thick Al-electrodes/$LiTaO_3$ structures were examined[6][7][12], but they didn't show good characteristics because of the small reflection at the grating reflectors. It was reported by M. Kadota et al. that a high density metal electrode was used instead of the light Al electrode to obtain large reflection at the grating reflectors[5][6][7], but their processes are not simple. One of merits is to use Al electrodes.

On the other hand, it is considered that the reflection of a shear horizontal (SH) wave at a substrate edge of the SiO_2/Al-electrodes/$LiTaO_3$ structure is large regardless of Al or SiO_2 thickness. If a fine substrate edge could be formed, high-frequency resonator devices with a good TCF would be realized in spite of the use of Al electrodes. This time, a high-frequency resonator with a good TCF and an excellent frequency characteristic has been attempted to realize by using the reflection of the SH wave at the substrate edge.

II. Conventional Resonators of SiO_2/Al-Electrodes/$LiTaO_3$ with Grating Reflectors

A. *Coupling factor and Reflection Coefficient of various structures*

Figs. 1 and 2 show the dependencies of the calculated electromechanical coupling factor and reflection coefficient at one finger of three kinds of structures on Al electrode thickness, respectively : (i) Al-electrodes/36°YX-$LiTaO_3$, (ii) SiO_2 with convex/Al-electrodes/36°YX-$LiTaO_3$, and (iii) flattened SiO_2 without convex/Al-electrodes/36°YX-$LiTaO_3$. Here, λ is the wavelength of SAW and the SiO_2 thickness is 0.25λ. As Al thickness increases, the coupling factor and reflection coefficient of the conventional structure of (i) becomes large. But, though the reflection coefficient of the structure of (ii) becomes large, the coupling factor very small, as Al thickness increases. The coupling factor of structure of (iii) does not change but the reflection coefficient stays very small owing to its flattened SiO_2 surface compared with structures of (i) and (ii).

B. *Resonator type SAW devices with grating reflectors after depositing SiO_2*

When the SiO_2 films of 0.2λ thickness were deposited on an one-port resonator and a multi-mode resonator filter composed of an Al interdigital transducer (IDT) and grating reflectors made of thick Al film of 0.08λ thickness on the 36°YX-$LiTaO_3$ substrate to improve the TCF, their frequency characteristics markedly deteriorated as shown in Figs.3 and 4. The impedance ratio of the resonator and the insertion loss of the filter deteriorated from 55dB to 15dB and from 2dB to 32dB in Figs. 3 and 4, respectively. Here, the impedance ratio is 20 log (anti-resonant impedance/resonator one). This occurred because the coupling factor becomes smaller and propagation loss larger due to large periodic convex portions as thick as the Al-electrodes produced on the SiO_2 surface as shown in Fig.1 and ref. [9][10][11], though the reflection coefficient is large as shown in Fig. 2.

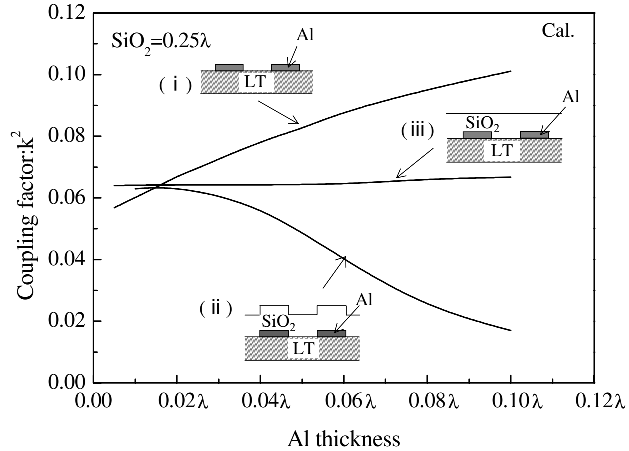

Fig1.Dependencies of coupling factor of three kinds of structures on Al thickness.

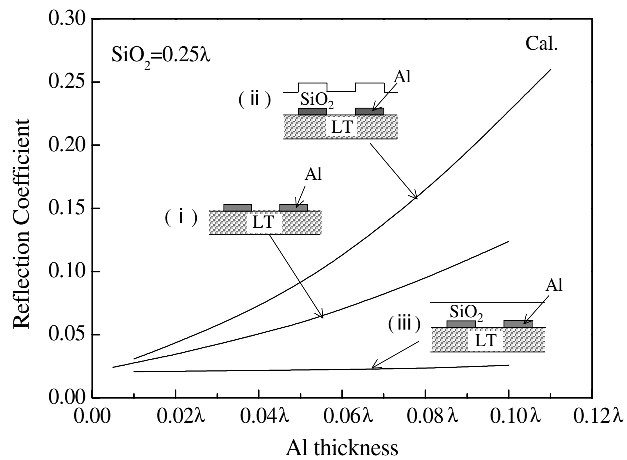

Fig2. Dependencies of reflection coefficient of three kinds of structures on Al thickness.

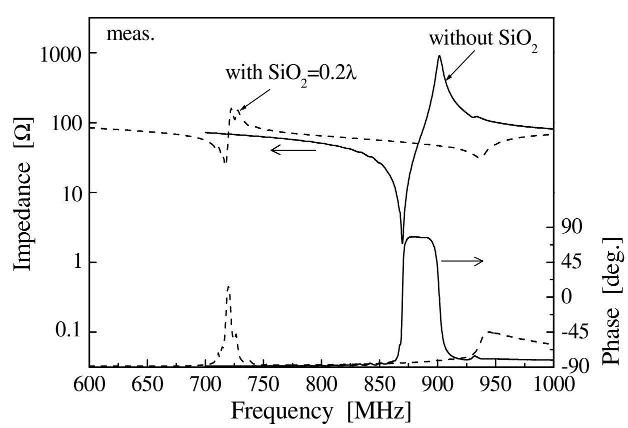

Fig3. Frequency characteristics of one-port-resonator with grating reflectors before and after SiO_2 film (thickness: 0.2λ) deposition on Al electrode (thickness: 0.08λ) on 36°YX-$LiTaO_3$.

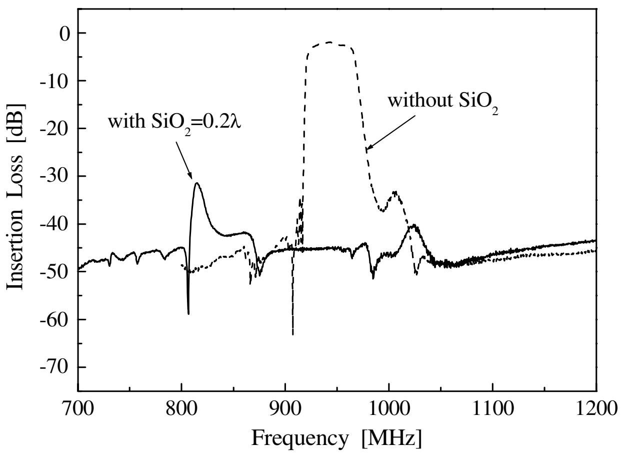

Fig4. Frequency characteristics of multi-mode resonator filters before and after SiO_2 film (thickness: 0.2λ) deposition on Al electrode (thickness: 0.08λ) on 36°YX-$LiTaO_3$.

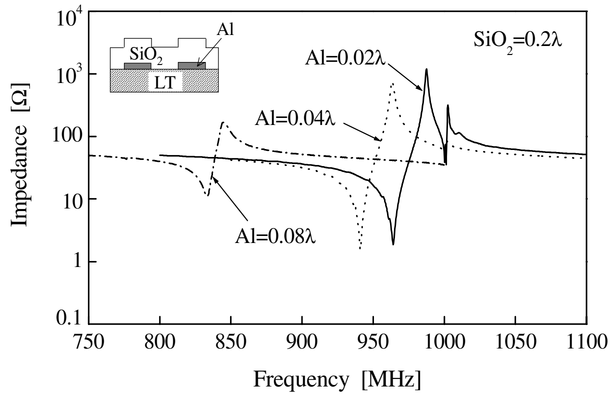

Fig5. Frequency characteristics of conventional resonator with grating reflectors consisting of SiO_2 with convex/Al-electrodes/36°YX-$LiTaO_3$ structure.

C. *Resonator with convex on SiO_2*

Fig. 5 shows the frequency characteristics with thinner Al electrode of 0.02λ and 0.04λ thickness than one in Figs. 3 and 4, after the deposition of SiO_2 of 0.2λ thickness. Here, the IDT has an aperture of 25λ, a wavelength of 4.12 μm, and 70 finger pairs, and each grating reflector has 60 fingers. In Fig. 5, the resonator composed of the Al electrode of 0.02λ thickness exhibits large spurious responses at the upper limit of the stop band because of its small reflection coefficient due to the thin Al electrode of 0.02λ as shown in Fig. 2. As mentioned above, the large deterioration of the resonator composed of the thick Al electrode of 0.08λ thickness in the frequency characteristics caused because of its small coupling factor and its large propagation loss due to large convex portions on the SiO_2 surface [9][10][11]. So, the structure of (ii) SiO_2 with convex portions/Al-electrodes/36°YX-$LiTaO_3$ can't show any good characteristics regardless of the Al thickness.

D. *Resonator with out convex on SiO_2*

Fig. 6 shows the frequency characteristics at Al electrodes of thickness 0.04λ and 0.08λ in the structure of (iii) obtained after removing the convex portions on SiO_2 and flattening the SiO_2 surface. Their characteristics strongly deteriorated because the reflection coefficient is very small regardless of the Al electrode thickness though the coupling factor is not small as shown in Figs. 1 and 2. As a result, the resonator composed of (iii) the flattened SiO_2 without convex/Al-electrode/$LiTaO_3$ structure does not show good frequency characteristics regardless of Al thickness. In other words, the SAW resonator devices combining the Al electrode, SiO_2 film, and $LiTaO_3$ substrate do not show any excellent characteristics.

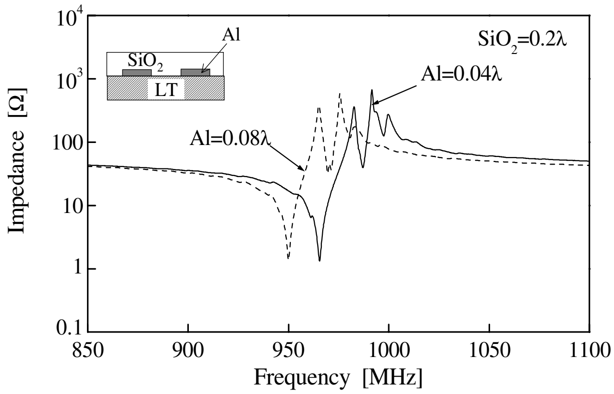

Fig6. Frequency characteristics of conventional resonator with grating reflectors consisting of flattened SiO_2 without convex/Al-electrodes/36°YX-$LiTaO_3$ structure.

III. Resonator with deposited SiO_2 using Reflection of SH Wave at Substrate Edges

A. *Resonators using Reflection of SH wave at substrate Edge*

There are three kind of elastic waves: longitudinal (L) wave, sheer vertical (SV) wave and shear horizontal (SH) wave. A leaky SAW (LSAW) propagating on a 36-48°YX-$LiTaO_3$ substrate has mainly an SH component. The SH wave can reflect completely without mode conversion on a free edge of the substrate with a high dielectric constant as shown in Fig. 7. By using the reflection of the SH wave at the substrate edges, small resonators and multi-mode resonator filters without the grating reflectors on both sides of an IDT, which conventional resonators and resonator filters require, can be realized as shown in Fig. 8[13-16]. Authors have developed and put to practical use the resonators and the multi-mode resonator filters for the additional trap resonator in TVs, the car radio, ETC, and so on by using the reflection of the SH wave at the edges of piezoelectric ceramic substrates [1][15-21]. Large ripples are generated if there are chipping or position errors at the edge[13][15][16]. The no-chipping and the more accurate position at the edge are strongly required as the frequency becomes higher. Thus, it is considered that they are not suitable for high-frequency devices. But, authors developed the new method of forming fine edges based on the optimization of the dicing [22][23]. A 1GHz and 2GHz resonators on the 36°YX $LiTaO_3$ having a good frequency characteristics have been realized[22][23]. However, they didn't have a good TCF because the SiO_2 film was not deposited to improve the TCF.

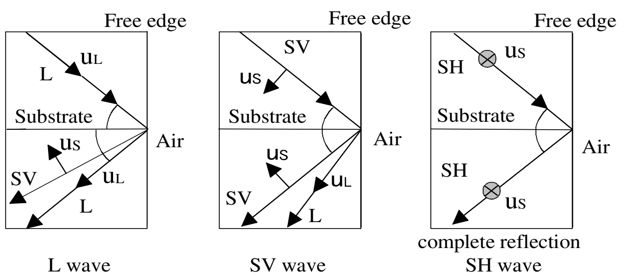

Fig7. Reflection of three kind of elastic wave.

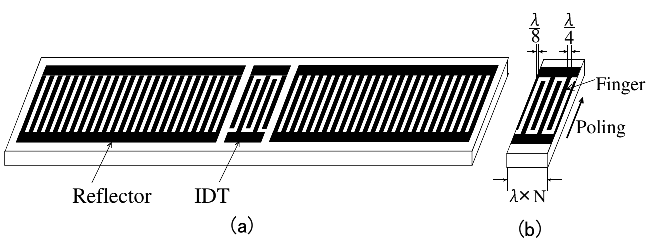

Fig8. (a) Conventional SAW resonator with grating reflectors and edge reflection.

As mentioned above, the structures of the (ii) SiO_2 with convex/thin Al-electrode/$LiTaO_3$ and (iii) flattened SiO_2 without/thick Al-electrode/$LiTaO_3$ structures didn't good frequency characteristics as shown in Figs. 5 and 6 because their small reflection coefficient as shown in Fig. 2. However, it is considered that the resonators using the edge reflections on the same structures can realize good frequency characteristics even after the SiO_2 deposition because of the large reflection coefficient at their edges.

B. Edge reflection Resonator with SiO_2 convex

The resonators using edge reflection were composed of forming the fine substrate edges after depositing SiO_2 films of 0.2λ thickness on a 36°YX-$LiTaO_3$ substrate having Al electrodes of 0.02λ, 0.04λ, and 0.08λ thickness. A 1 GHz edge reflection type resonator with Al electrodes of 0.02λ thickness with the small convex on SiO_2 surface shows good frequency characteristics as shown in Fig. 9, through those consisting of Al electrode of 0.04λ and 0.08λ don't. Namely, its resonator has a large impedance ratio of 60dB and a relative wide bandwidth of 2.3%. Although periodic small ripples due to chipping on SiO_2 film, which was produced upon forming the edges with SiO_2, are observed outside the band between resonant and antiresonant frequencies, it was confirmed that there is no problem when it is applied to voltage controlled oscillators (VCOs) and other circuits. But, the edge reflection type resonators with Al electrodes of 0.04λ and 0.08λ thickness don't also show good frequency characteristics because their coupling factor is too small as shown in Fig. 1 and propagation loss large.

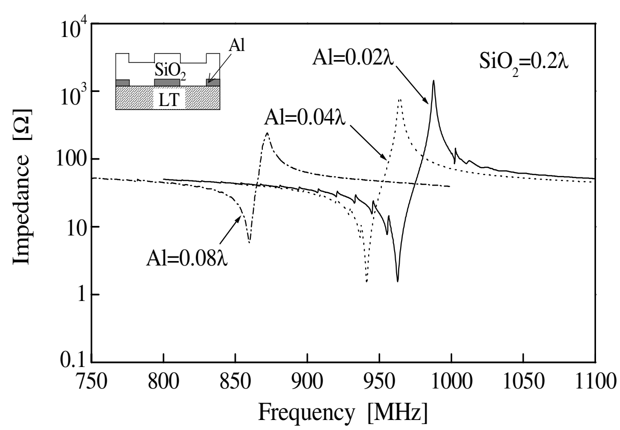

Fig9. Frequency characteristics of edge reflection type resonators consisting of SiO_2 with thin convex/Al-electrodes/36°YX-$LiTaO_3$ structure of three kinds of Al thickness.

C. Edge reflection Resonator without SiO_2 convex

On the other hand, Fig. 10 shows the frequency characteristics of the 1GHz edge reflection type resonators with Al electrodes of 0.04λ and 0.08λ thickness composed of the flattened SiO_2 without convex/Al-electrode/36°YX-$LiTaO_3$ structure. Though the conventional resonators with grating reflectors after flattening SiO_2 surface did not show good frequency characteristics as shown in Fig. 6 regardless the Al electrode thickness. However, the edge reflection type resonators shown in Fig. 10 show good frequency characteristics, especially, one consisting of the thick Al electrode of 0.08λ thickness has an impedance ratio of 52 dB and a

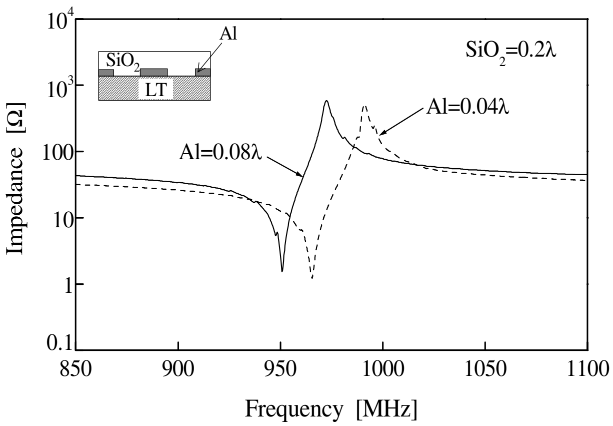

Fig10. Frequency characteristics of edge-reflection-type resonators consisting of flattened SiO_2 without convex/Al-electrodes/36°YX-$LiTaO_3$ structure.

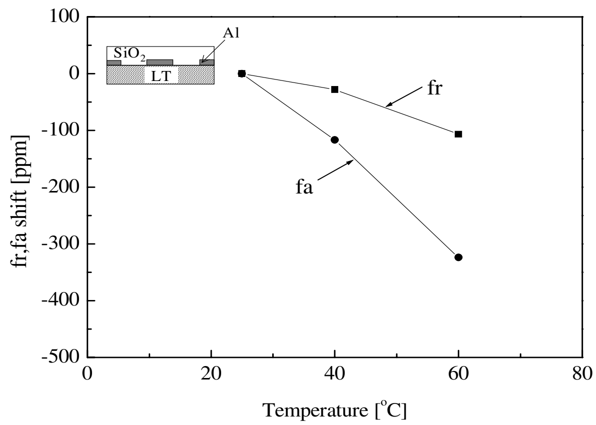

Fig11. Temperature characteristics of edge reflection type resonators consisting of flattened SiO_2 without convex/Al-electrodes/36°YX-$LiTaO_3$ structure.

bandwidth of 2.2%.

As mentioned above, both edge reflection type resonators composed of the SiO_2 with thin convex/thin Al-electrode/36°YX-$LiTaO_3$ and flattened SiO_2 without convex/thick Al-electrodes/36°YX-$LiTaO_3$ structures show good frequency characteristics with large impedance ratios of 60dB and 52 dB, respectively. This is realized because the reflection at the free edges is large (reflection coefficient =1) regardless of the Al electrode thickness.

D. *TCF of Edge Reflection Resonator*

Fig. 11 shows the temperature characteristics of the resonant and antiresonant frequencies of the edge reflection type resonator consisting of the flattened SiO_2 of thickness 0.2λ without convex/thick Al-electrodes of 0.08λ/36°YX-$LiTaO_3$ structure. The values of their TCF at resonant and antiresonant frequencies are excellent, being -2.9 and -9.1 ppm/°C, respectively.

IV. Conclusion

A 1 GHz high-frequency resonator with an excellent TCF (-2.9ppm/°C at fr) using the reflection of the SH wave at the edges of 36°YX-$LiTaO_3$ substrate was successfully realized for the first time using our newly developed method of forming fine edges.

Conventional resonators with grating reflectors combining SiO_2 film, Al electrodes, and $LiTaO_3$ substrate such as the following two kinds of structures do not show good frequency characteristics regardless of Al thickness: (ii) a SiO_2 with convex/Al-electrodes/$LiTaO_3$ structure and (iii) a flattened SiO_2 without convex/Al-electrodes/$LiTaO_3$ structure. This is because the coupling factor or the reflection coefficient is too small. However, the reflection of SH waves at the free substrate edges is large (reflection coefficient =1) regardless of the Al film thickness, even if the combination of SiO_2 film, the Al-electrode, and the $LiTaO_3$ structure is used. The edge reflection type resonators composed of the SiO_2 with convex/thin Al-electrodes/$LiTaO_3$ structure and the flattened SiO_2 without convex/thick Al-electrodes/$LiTaO_3$ structure can show good frequency characteristics and the excellent TCF. The TCF of the resonant frequency of the latter resonator is -2.9ppm/°C.

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