# Parametric Study of resonant TC-SAW Piston-mode Configurations


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***Abstract*— Recent trends in cellular handsets demand SAW resonators with increased performance. Most importantly, improvements in both the resonators' quality factor (Q) and temperature coefficient of frequency (TCF) are needed. The TC-SAW concept employing buried Cu electrodes in $SiO_2$/128˚Y-$LiNbO_3$ has attracted considerable practical interest in this view, with the requirement that the spurious transverse modes in the structure are suppressed. Thus, practical TC-SAW resonators employ a specific geometry ensuring a piston mode of operation. Here we present a theoretical and experimental parametric study of the piston geometry as function of the resonance frequency and aperture. The extracted scaling rules are subsequently used in the design of RF filters.**



***Keywords—TC-SAW; Buried Electrode; LiNbO3; Resonator; Duplexer;***


## I. Introduction

The attraction of using SAW resonators for the construction of microwave filters has been its low cost and simplicity of fabrication. With the explosive growth of wireless communication and the appearance of new frequency bands for LTE networks, the frequency spectrum has become very crowded, driving the need for duplexers and filters with steeper roll-off and low thermal drift to reduce the gap between bandwidths and to extend the efficiency of use of the bandwidths, respectively. These requirements have initially been met by the thin film bulk acoustic wave technology, while SAW technology is currently undergoing an aggressive development in this technological race. One very promising TC-SAW technology uses layered substrates where a piezoelectric wafer is bonded on to a base substrate with a low coefficient of thermal expansion (CTE), e.g. silicon or sapphire [1-3]. More recently, layered SAW substrates have demonstrated significantly-reduced bulk radiation losses resulting in the so-called "incredibly high performance" SAW technology (IHP) [4, 5]. These approaches come with a cost of significantly increased technological complexity. Another approach that has shown viability and moderate increase in technological complexity employs buried electrodes in a $SiO_2$ overcoat on a 128˚Y-cut $LiNbO_3$ structure [6, 7]. Beyond the increase of technological complexity, this substrate promotes strong transversal modes in SAW resonators stemming from the strong waveguiding characteristics in the aperture direction. Many excellent works have revealed to full extent the underlying physics of these modes and proposed practical topologies enabling high-Q and spurious-free response in the RF range [8 – 11]. The so-called "Piston Mode" technique was proposed, enabling a SAW mode with constant displacement amplitude along the aperture that is perfectly aligned to the constant electric field along the aperture, imposed by the IDT. Since higher-order transverse modes are orthogonal to the fundamental mode (and IDT electric field), they are not excited. In practice, certain couplings always exist because of technological tolerance in the device topology, but these transverse modes will be sufficiently suppressed as far as they maintain sufficiently low $Qxk_t^2$ product.

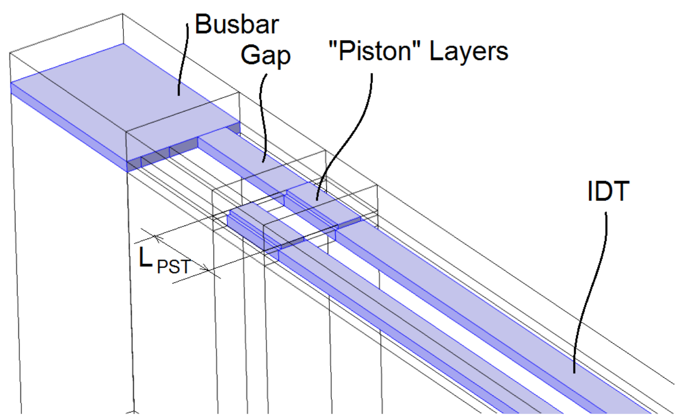


Fig. 1. Close view of a 3D COMSOL model in the vicinity of the border region. The additional layer of piston mass has length is $L_{PST}$ and thickness $d_{PST}$.

The typical "piston mode configuration" (see Fig. 1) consists of transducer region matched to a faster "gap" region through a border (piston) region exhibiting a SAW velocity lower than in the transducer region. At higher frequencies, the piston region is often formed by a thin metal layer over the IDT strips. Layers having a specific thickness $d_{PST}$ and length $L_{PST}$ can ensure matching condition for "piston" shape response. The design of filters and duplexers in a given frequency range requires the knowledge of the scaling rules of the piston mode lengths as function of the grating pitch and device apertures. Knowledge of these scaling rules are of great practical importance for TC-SAW filter design.

Here we present detailed theoretical and experimental studies of the scaling rules of the piston region regarding the design of TC-SAW resonators with suppressed spurious transverse mode responses. An LTE Band 3 duplexer employing the TC-SAW technology was subsequently designed and fabricated.

## II. 3D Finite Element Simulation

3D finite element analysis has been employed to perform parametric analysis of the scaling rules of the piston mode waveguide as integrated into a TC-SAW resonator on 128˚ Y-rotated X-propagating $LiNbO_3$ as a base substrate (see Fig. 1). Frequency response analysis of a 3D periodic cell was performed, varying the topology of the piston region. The geometry of the loading layers in the piston region was deduced from the requirement of "piston" shape of the Rayleigh SAW mode along device aperture (see Fig. 2). The analysis was performed for the frequency band 1.6 – 2.0 GHz, relevant for LTE duplexers.

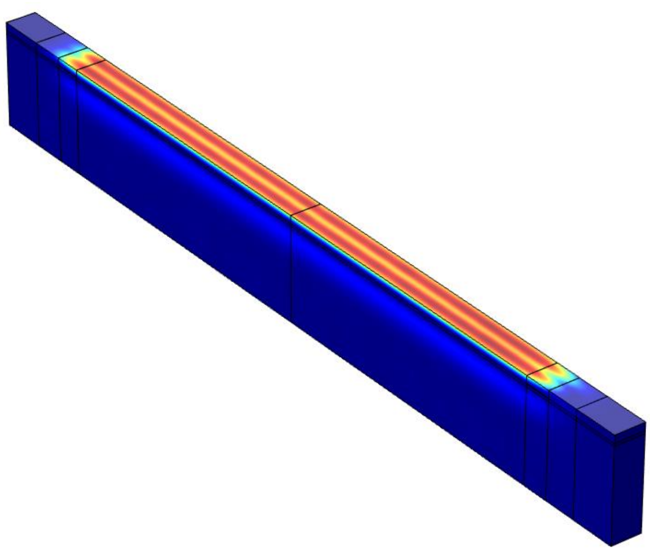

Fig. 2. Uniform SAW displacement amplitude along the aperture of a TC-SAW resonator with properly designed piston mode region. Results are determined from a frequency response COMSOL FEA.

We have examined the use of thinner ($d_{PST}$ =40nm) and thicker ($d_{PST}$ =70nm) Cu loading "piston" layers in the piston region. The basic IDT/$SiO_2$ stack had 175nm thick Cu strips forming periodic gratings with pitch p between 0.9µm and 1.1µm, and with metallization ratio mt=0.5, buried into a 650nm thick $SiO_2$ TC layer. The proposed IDT configurations were selected in order that the unwanted spurious SH-SAW mode was sufficiently suppressed.

Initially, we simulated devices with fixed IDT/$SiO_2$ stack and piston layer thicknesses, while varying the device aperture. Figure 3 shows that the piston layer length, once identified, is not sensitive to device aperture (W) which enables a robust design of the piston mode TC-SAW resonators with different apertures, as required in most practical filter designs. More specifically, a 40nm Cu piston layer with length of $L_{PST}$=0.9λ (λ=2p) is sufficient to ensure piston shape of the fundamental resonance in the aperture range 5λ to 20λ.

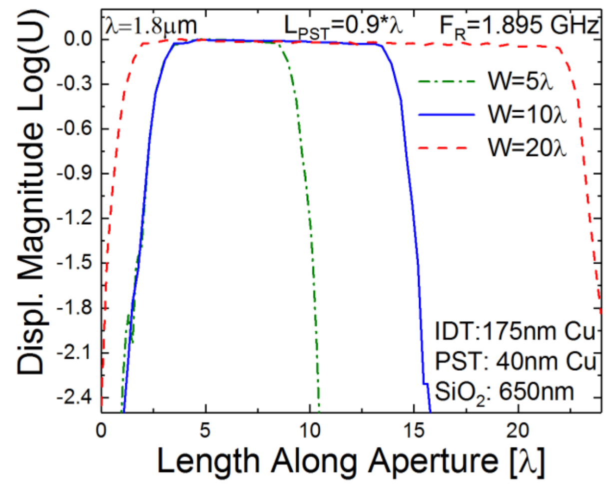


Fig. 3. Simulated distribution of the normalized total displacement magnitude along the aperture of TC-SAW resonators with varying apertures. Resonators with pitch p=0.9 (λ=2p=1.8µm) were simulated while varying the aperture W. The spurious control was seen to be insenstive to this dimension.

Subsequently, we performed analysis to obtain scaling rules with respect to the acoustic wavelength λ=2p (i.e to the grating pitch). Table I summarizes the results for piston layers with metallization ratios 0.5, 0.45 and 0.4, and piston layer thicknesses 70nm and 40 nm, respectively. The required length $L_{PST}$ of the border region scales approximately with the wavelength and inversely with piston layer thickness. More specifically, the piston length does not scale linearly with λ since the coefficient of proportionality is dispersive. The latter is due to the dispersion in the mass loading effect of the fixed-thickness piston layer since the acoustic thickness (relative to λ) reduces with the increase of λ. It is to be noted that thicker piston layers demonstrate weaker dispersion of the length than their thinner counterpart. This effect may be beneficial in terms of simplifying the scaling rules as far as the resonators demonstrate sufficient tolerance to piston layer lengths deviating from the optimal condition. Allowing for processing variation in the PST layer to IDT layer registration is also important.

TABLE I. Piston (PST) regions in TC-SAW resonators. $H_{Cu}$=175nm, $M_T$=0.5, $SiO_2$=650nm

| **λ [µm]** | **$F_R$ [GHz]** | **$L_{PST}/d_{PST}$ $m_{PST}$=0.5** | **$L_{PST}/d_{PST}$ $m_{PST}$=0.45** | **$L_{PST}/d_{PST}$ $m_{PST}$=0.4** |
|---|---|---|---|---|
| 1.8 | 1.895 | 0.4λ/70nm<br>0.8λ/40nm | 0.45λ/70nm<br>0.9λ/40nm | 0.5λ/70nm<br>1.0λ/40nm |
| 2.0 | 1.726 | 0.45λ/70nm<br>0.90λ/40nm | 0.50λ/70nm<br>1.0λ/40nm | 0.55λ/70nm<br>1.1λ/40nm |
| 2.2 | 1.586 | 0.5λ/70nm<br>1.0λ/40nm | 0.55λ/70nm<br>1.15λ/40nm | 0.60λ/70nm<br>1.30λ/40nm |

## III. Experimental Verification

Figure 4 compares measured devices with different apertures and the same border region. Transversal spurious SAW modes are sufficiently supressed for all devices, while the SH-SAW contribution seems to get stronger with narrowing the device aperture. A relatively strong plate-guided (Lamb wave) mode in the $SiO_2$ is also present at about 2.55 GHz. Further, a weak reduction in TC-SAW effective coupling (frequency downshift of antiresonance) is observed with narrowing aperture. The results of the tranverse mode suppression are in very good agreement with the modeled predictions confirming the independence of the border topology from the device aperture.

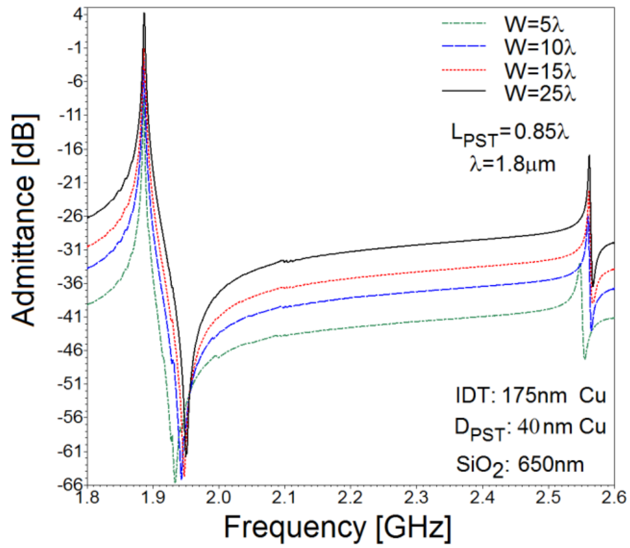


Fig. 4. Measured frequency response of TC-SAW resonators with aperture varying in the range W=5λ to 25λ. Thickness $d_{PST}$ and length $L_{PST}$ of the loading layer at the border region are kept constant in the vicinity of the optimal quantities for piston shape of the mode.

The high frequency plate-guided mode is leaky and its resonance can be significantly damped through decreasing of the $SiO_2$ thickness.

Complementary experimental results confirm, to a large extent, the Finite Element Analysis (FEA) predictions regarding the scaling of the border region. Spurious free responses were accordingly measured (see Fig. 5 and Fig. 6).

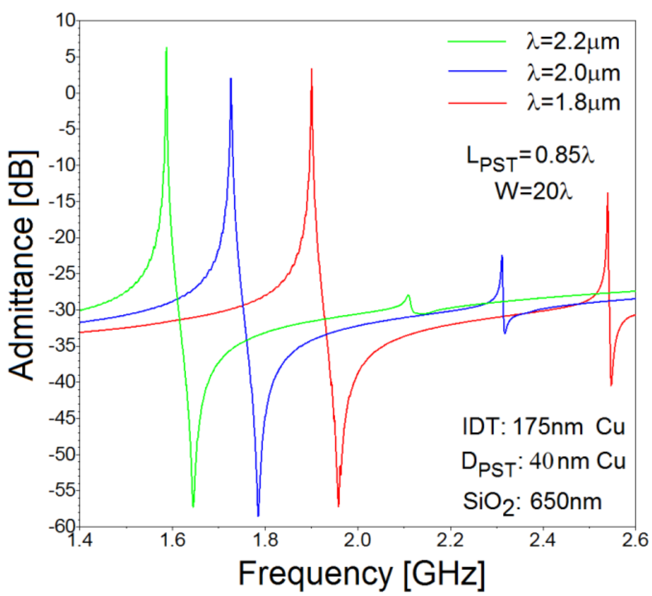


Fig. 5. Measured resonance frequency response of spurious-free TC-SAW resonators with thinner "piston" layer (40 nm) in the border region. All devices have aperture W=20λ, and wavelengths λ=1.8μm λ=2.0μm and λ=2.2μm.

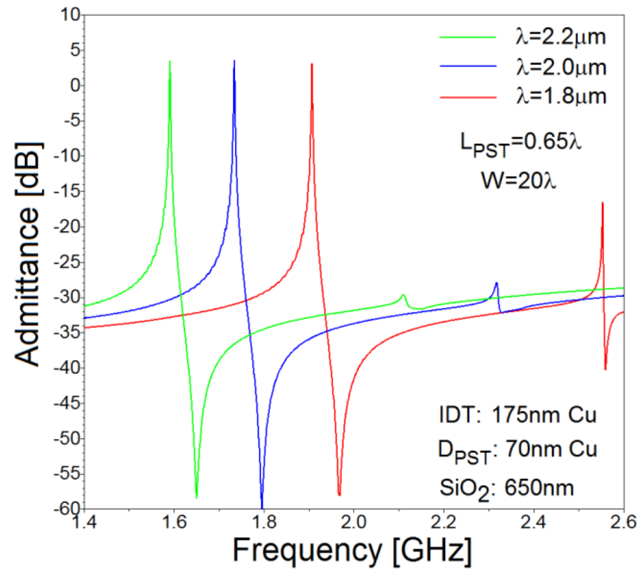


Fig. 6. Measured resonance frequency response of spurious-free TC-SAW resonators with thicker "piston" layer (70 nm) in the border region. All devices have aperture W=20λ, and wavelengths λ=1.8μm λ=2.0μm and λ=2.2μm.

In this TC-SAW fabrication the lengths of the border regions were designed to be 0.65λ, 0.75λ and 0.85λ for each device. The measurements show that TC-SAW resonators having thicker PST layer in the border regions demonstrate spurious-free responses at the low end of the designed border lengths. The TC-SAW resonators with thinner PST layers in the border region have demonstrated spurious-free response at the upper limit of the designed border lengths. It is to be noted that this border length was on the edge of not being sufficient for spurious free response, since some of the devices still showed spurious transverse modes. In our previous fabrication of this type of structure we measured spurious-free responses for piston length of about 0.95λ, which is in very good agreement with the theoretical predictions. When looking at the performance of TC-SAW resonators with thicker PST layers in the border regions we also found that in many cases the 0.65λ border length was a bit too much leading to a splitted resonance peak. Thus the optimal length of the PST layer in the border region seems smaller than 0.65λ and thus closer to the theoretically predicted $L_{PST}$ in the range 0.45λ – 0.55λ. The latter observations further indicate that devices in this frequency range show sufficient tolerance with respect to the length of the border regions. This in turn makes the practical design rules more robust.

Figure 7, as compared to Fig. 6, clearly shows that the required geometry ($L_{PST}$, $d_{PST}$) for the border region matching is practically insensitive to 100nm shift of the $SiO_2$ thickness, while the magnitude of the plate-guided waves are significantly affected. This plate-guided mode can interfere with the adjacent filter in the duplexer and, thus, a careful tradeoff is required when selecting the $SiO_2$ thickness since the amount of temperature compensation and the the requirement for signal supression in the frequency range above the filter band are competing requirements.

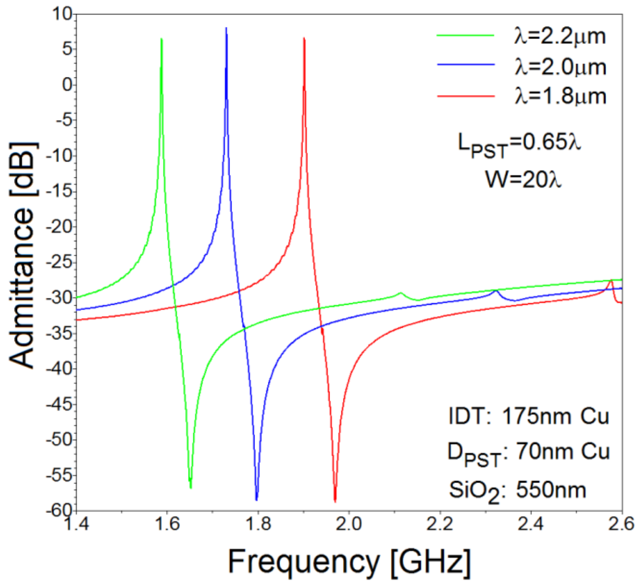


Fig. 7. Measured frequency response of TC-SAW resonators with aperture W=20λ, and wavelengths λ=1.8µm λ=2.0µm and λ=2.2µm. The thickness $d_{PST}$ and length $L_{PST}$ of the loading layer at the border region are kept constant in the vicinity of the optimal quantities for the piston mode.

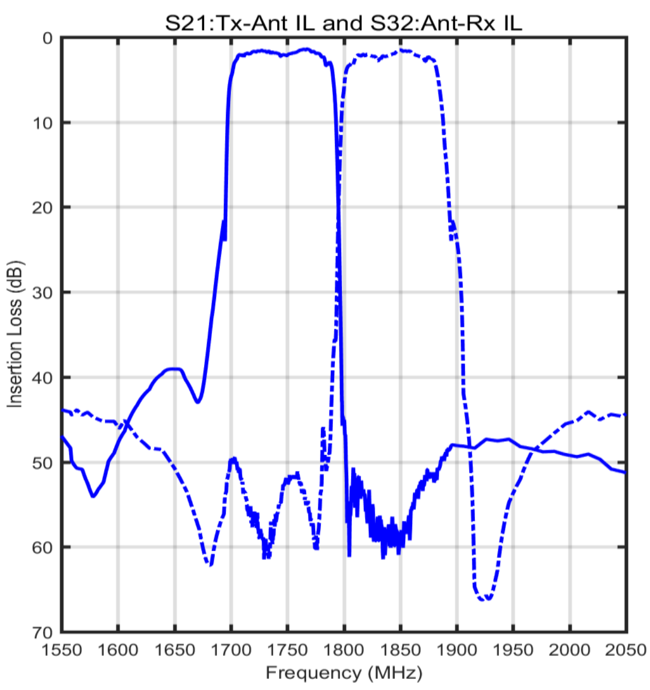


Fig. 8. Measured frequency response a fabricated B3 duplexer employing TC-SAW resonators with piston mode design following the deduced scaling rules.

The deduced scaling rules have been subsequently employed towards the design of a B3 duplexer meeting the LTE specifications. In Fig. 8 the measured frequency response of a B3 duplexer is shown as fabricated.

## IV. Conclusions

We performed a detailed study on the parametrisation of the border region in spurious-free TC-SAWs employing a piston shape of mode excitation. The investigations were done in order to support challenging mid-band cellular duplexer design. Practical scaling rules were deduced and subsequently employed in the design of a B3 duplexer.

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