Paper V

Acoustic Radiation Losses in Busbars

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Acoustic Radiation Losses in Busbars

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***Abstract*— Radiation of acoustic waves from the contact electrodes (busbars) of surface acoustic wave devices on high-coupling piezoelectric substrates, such as 42°-LiTaO$_3$, is demonstrated both with Finite-Element-Method simulations and with experimental data. This acoustic radiation, as well as resistive losses, significantly decrease the Q-value of the busbars. Experimental measurements on test structures show Q-values as low as about 10.**

***Index Terms*— Surface acoustic wave devices, Acoustic radiation effects, Busbars, Leaky waves, Losses**

I. INTRODUCTION

LOSSES in surface acoustic wave (SAW) radio frequency (RF) filters have been significantly reduced in the recent years and approach the 1-dB level. Further reduction of losses requires a detailed revision of all loss mechanisms. Acoustic loss mechanisms in interdigital transducers (IDTs) on leaky-SAW substrates have been studied [1]. In low-loss filters, several interconnected IDT sections are often used, resulting in a complicated topology of connecting electrodes (busbars). Typically, the busbars of a SAW IDT are wide compared to the characteristic wavelength of the device. The capacitance of the busbars on LiTaO$_3$ or LiNbO$_3$ substrates is not negligible and can be on the order of a fraction of one picofarad (pF). The influence of stray capacitances and inductances due to busbar structures can be taken into account by electro-magnetic (EM) simulations. In such a simulation, the resistivity of the electrodes is accounted for, but acoustic radiation from busbars is ignored. In reality, RF voltage applied to the busbars results in oscillating charges creating electric fields especially strong at the edges. In strong piezoelectric materials, such fields are capable of generating bulk and surface acoustic waves in a wide frequency range [2].

In this Letter, we report acoustic wave generation in long busbars on 42°-LiTaO$_3$ with simulations and experimental test structures. Both theory and experiment show that the effect of acoustic losses is present, resulting in a non-zero real part of admittance.

II. SIMULATED AND EXPERIMENTAL RESULTS

In order to estimate the radiation of SAW and BAW from busbars, we used a FEM/BEM software developed for the simulation of SAW devices having a finite number of electrodes [3], [4]. The studied electrode structures consist of 3 metal strips oriented perpendicularly to the SAW propagation direction on 42°-LiTaO$_3$ substrate. Two structure sizes were studied: the larger structure has long electrodes, with dimensions of 100 μm×1500 μm, separated by 25-μm gaps, whereas the smaller structure was 50 μm×500 μm, separated by 25 μm gaps. The side electrodes were grounded and voltage was applied to the central electrode. Contact pads for the wafer probe were at the same end for all electrodes. Metallization thickness was 160 nm for both variants. Of the long structure, a double-metallized variant (a 160-nm Au coating on top of the Al electrodes) was realized so as to minimize resistive losses.

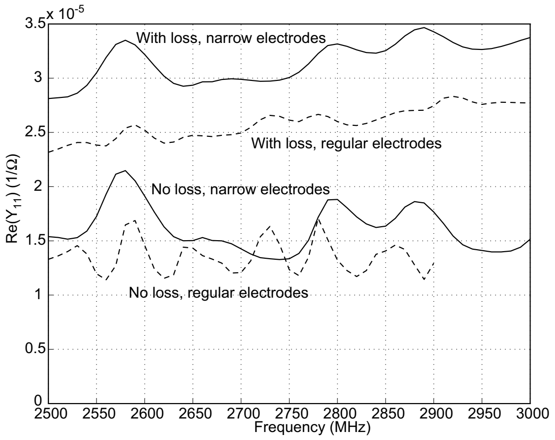

Fig. 1. Simulated (FEM) admittance of short busbars (dashed lines) and a narrow variant (solid lines), with and without materials losses.

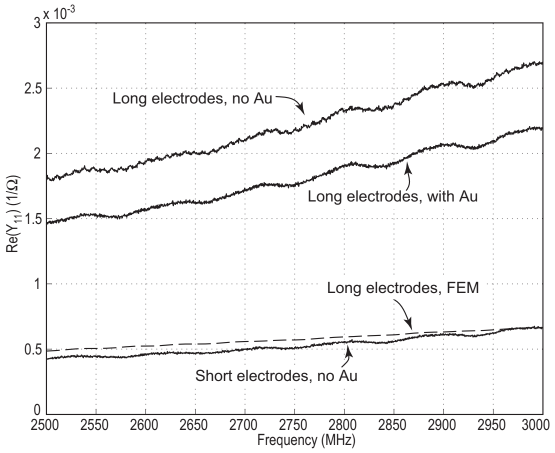

Fig. 2. Measured admittance of long and short busbar structures, with FEM simulation of long busbars (dashed line).

Fig. 1 shows the simulated real part of admittance, corresponding to losses in the structure, for the short electrode structure. Materials-related loss mechanisms were included in the simulations, in addition to which a simulation with materials losses excluded was performed for the smaller structure. Furthermore, a narrow variant of the short structure, having a busbar width of 12.5 μm, was included in the simulations

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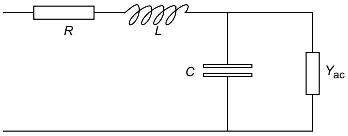

Fig. 3. Equivalent circuit for the busbar structure.

to study the origin of the periodic oscillations observed in the Re(Y).

Measured Re(Y) for all structures and FEM simulation for the long busbars are depicted in Fig. 2. From simulations, the calculational capacitance of the structures can be estimated to be $C \approx 1.01$ pF for the long electrodes and 0.3 pF for the short electrodes (Im(Y)$\sim 2\pi f C$). The periodic oscillations seen in Fig. 1, having a period of 70 – 80 MHz, probably correspond to the interference of SAWs generated by the edges of the busbars. The calculated frequency (for wave velocity $v = 4000$ m/s) is approximately 40 MHz for the 100 μm-wide electrodes and 80 MHz for the 50 μm-wide electrodes. For the narrow electrodes in Fig. 1, the simulated period increases, as expected. The oscillations are more clearly seen in the narrow electrodes, because the propagation path of the leaky SAW is shorter and the attenuation under the electrodes is reduced.

The oscillations predicted by FEM simulations are present on the experimental admittance curves. Their period is 60 – 90 MHz for both electrode structures. On the measured admittance curves, one can also see small periodic ripples with period of approximately 8 MHz, probably corresponding to bulk acoustic resonances in the 350-μm thick substrate.

III. DISCUSSION

The non-zero Re(Y) in both simulations and measurements corresponds to loss of energy in the busbar structure. However, there may be several loss mechanisms affecting the Re(Y), including resistive loss, generation of acoustic waves, dielectric loss, and EM radiation loss.

To describe the loss mechanisms, an equivalent circuit shown in Fig. 3 is considered. It consists of the resistance R, inductance L and capacitance C of the strips, with a parallel real-valued acoustic admittance Y_{ac} accounting for the loss due to generated acoustic waves.

The approximate admittance of the circuit shown in Fig. 3 is

$$Y \approx \omega^2 C^2 R + j\omega C(1 + \omega^2 LC) + Y_{\mathrm{ac}}. \qquad (1)$$

Experimental capacitance and inductance of the structure can be extracted by fitting the imaginary part of Eq. 1 to the measured Im(Y). The Q-factor of the electrode structure can be estimated as

$$Q \approx \frac{\mathrm{Im}(Y)}{\mathrm{Re}(Y)}. \qquad (2)$$

Values for simulated and measured Q-factors, inductances and capacitances at 3 GHz are summarized in Table I. Capacitances derived from the measurements correspond well to those predicted by simulations. Experimental Q-factors, however, are an order of magnitude lower than simulated. The measured Re(Y) for both structures is many times higher than the simulated one. Reasonable estimates of resistivity cannot explain such a difference.

TABLE I

EXPERIMENTAL AND SIMULATED PARAMETER VALUES FOR SHORT AND LONG BUSBAR STRUCTURES.

	Simulated		Measured	
	Short	Long	Short	Long
Q (lossy/no Au)	186	32	13	8.5
Q (lossless/with Au)	253	–	–	10.5
Capacitance (pF)	0.3	1.01	0.46	1.11
Inductance (nH)	–	–	0.33	0.22

The presence of a gold layer of the same thickness as the Al metallization on top of the electrodes should decrease the resistance by 50%. However, the experimental data in Fig. 2 shows only 20% reduction in Re(Y). This indicates that other loss mechanisms than resistive losses are of comparable significance.

Losses due to EM radiation may be pronounced in the open-circuited test devices. The size of the devices, however, is significantly smaller than the wavelength of EM waves at the studied frequencies. Therefore, the contribution of EM radiation to the losses should not be dominant. Furthermore, accurate measurement of small admittance values from such structures can be challenging at 3 GHz.

IV. CONCLUSIONS

Generation of acoustic waves in the connecting electrodes of low-loss SAW devices can constitute a visible part of losses, especially on strong piezoelectric substrates and for long busbars. The presence of acoustic radiation in the studied 3-electrode structure is predicted by FEM simulations and confirmed by experimental data. Simulations yield Q-values of 30–180 for the system, whereas measurements show Q-factors as low as about 10. Furthermore, eliminating materials losses in FEM simulations still yields a non-zero Re(Y), which we believe to mainly correspond to losses due to acoustic wave radiation. A similar effect is seen experimentally for double-metallized busbars: the difference in Re(Y) is about 20%, when a 50% reduction would be expected.

FEM simulations qualitatively reveal the presence of the acoustic radiation, but there are numerous effects present in real devices that are not taken into account by the FEM/BEM model. These include, e.g., EM radiation, the inductance of the system, and 3-D effects such as the generation of waves by the short ends of the busbars, the presence of an EM field extending all the way through the substrate with a finite thickness, and acoustic radiation and reflection from the bottom of the substrate. Furthermore, the topology of the test devices used in this work seems to be sensitive to EM perturbations, such as stray capacitances due to the measurement setup. Nevertheless, the results indicate that acoustic busbar radiation constitutes a noticeable loss mechanism in low-loss SAW devices. The effect merits further studies in terms of both simulations and experiments. Long busbars on strong piezoelectric substrates can have very low Q-factors, and to minimize losses, their use should be avoided.

ACKNOWLEDGEMENT

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