Design and Characterization of SAW filters for High Power Performance

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***Abstract*—Driven by the need for high data-rates and improved cell coverage, mobile phone filters are required to process increasingly high RF power levels. The simultaneous demand for smaller filter footprints makes designing a filter for high-power performance a challenge. We report a method for simulating the self-heating effects of high input powers on a surface acoustic wave (SAW) filter. We also report gain compression measurements and infrared microscopy to validate the model.**

***Index Terms*—Surface Acoustic Waves; Non-linear Numerical Modeling; Power Handling; Thermal Modeling**

I. Introduction

The continued reduction in device size while pushing for increased power levels and higher data rates places difficult design constraints on RF acoustic filters for mobile phones. In addition to the challenge of meeting product reliability and lifetime requirements, the RF power dissipated in the uplink filter during transmission also heats the device and distorts the response of the filter. Temperature-compensated SAW (TC-SAW) technology has been developed to address this problem with some success, particularly for hard bands with minimal duplex gaps [1]. Regardless of the SAW technology used, the ability to simulate the effects of self-heating are very useful to design products that meet very challenging specifications.

Various approaches have been taken to develop thermal models for SAW and BAW filters that seek to balance complexity, accuracy and practical utility [2]–[5]. Generally, a simulation incorporating thermal effects requires detailed accounting of the thermal environment, e.g., thermal conductivities, and paths to the thermal ground including boundaries between different materials. Complete FEM simulations are possible but can be burdensome for design engineers and often more practical proxies are desirable [4].

Here we present a technique for rapidly simulating the self-heating effects in a microwave filter composed of SAW resonators without the necessity of careful measurements or FEM simulations of the thermal environment. A key feature of our model is to include the individual temperature of every resonator in the filter. We also report two forms of measurements to confirm the accuracy of the model: 1) infrared microscopy of the RF filter with high input power applied, and 2) microwave measurements of the gain compression. Finally, we discuss an example of how this simulation can be used to improve the high-power performance of a SAW filter.

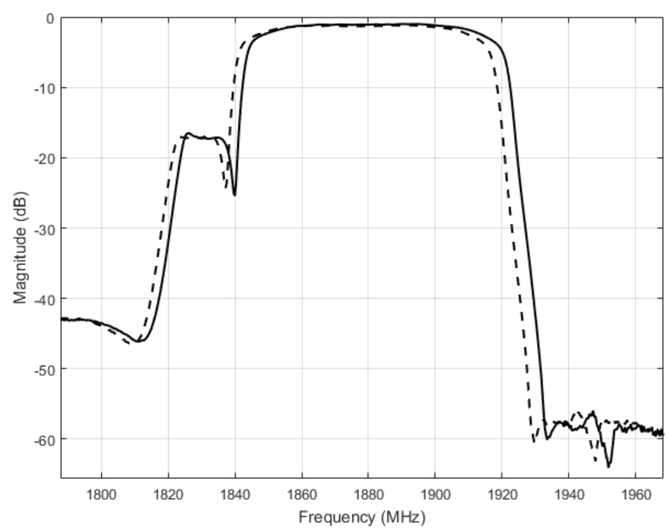

Fig. 1. Measured filter response (S_{21}) of a Band 2 uplink filter measured with low-power input signal at 25°C (solid line) and 85°C (dashed line).

The filter under consideration here is a Band 2 uplink filter made with SAW resonators consisting of Al electrodes deposited on a 250 μm thick 42° $LiTaO_3$ wafer. However, both the measurements and the simulation are more general and have been successfully applied to filters of other bands and SAW technology, e.g., Band 3 and temperature-compensated SAW.

II. High power measurements

Before high-power measurements are performed, the S-parameters are measured at low-power where all non-linear effects are negligible. The S-parameters are measured at 25 and 85°C. S_{21} at both temperatures are shown in Fig. 1.

For all high-power measurements, the input power is slowly swept from 25 to approximately 32 dBm, such that a quasi-static steady-state is maintained. At each step of the input power, and after the response has stabilized, the output power is recorded. In addition, the high-power measurements are performed in a temperature controlled chamber held at 25°C.

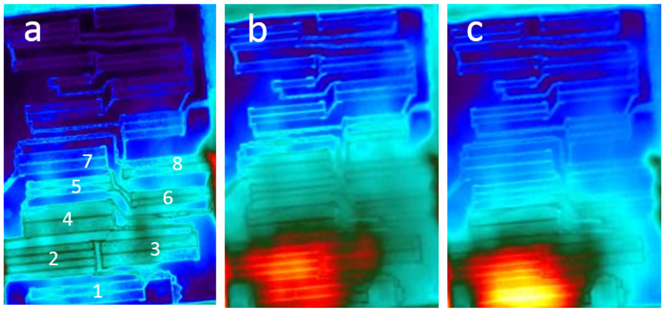

Fig. 2. FLIR infrared microscope images recorded with input frequency 1914 MHz, and three input powers: a) 26, b) 30, and c) 31.5 dBm. The color scale is dynamic and varies in each frame. The maximum temperatures of a, b, and c are approximately 45, 110 and 185 C, respectively. The eight resonators in the uplink filter are labeled $1, \ldots 8$.

A. FLIR infrared microscopy

Although the filter is measured at room temperature, we expect that there should be significant temperature gradients across the SAW die. This results from the small thermal diffusivity of single crystal $LiTaO_3$ – estimated to be several mm^2/sec [6] – and localized heat generation arising within individual SAW resonators [2]. A FLIR infrared microscope with 3.5 μm spatial resolution is used to study the self-heating of the SAW die with the high-power input signal applied. The images of the SAW resonators are recorded through the back side of the $LiTaO_3$. This allows the filter to remain mounted on a package/carrier as it would in a mobile phone.

Figure 2 is a false color infrared image of the SAW die with an input signal at 1914 MHz. The absolute color scale of the three images varies, but the range is roughly 100°C for each. Fig. 2a shows the temperature of the SAW die with input power of 26 dBm. Even at input powers as low as 26 dBm, it is clear that the temperature in not uniform across the SAW die. This filter is part of a duplexer, the upper-half of the image is the downlink filter, which remains relatively cool throughout the measurement.

As the input power increases, the temperature gradient increases and a "hot spot" develops on the surface of the SAW die. Using the dynamic color scale, it is easy to track this hot spot. The most striking feature of this measurement is that the hot spot clearly moves from one resonator to another as the input power continues to increase. There are eight resonators in this Band 2 uplink filter. At low power (Fig.2a), it is difficult to resolve clearly, but the hot spot appears primarily on resonators 2, 3, and 4. At 30 dBm input power, it is clear that resonator 2 is the hottest. At 31.5 dBm input power, resonator 1 is unambiguously the hottest resonator.

B. Compression measurements

A typical high-power test of the filter is to measure the gain compression of an output at a single frequency. Figure 3 shows measured data and simulations of the gain compression near the high-frequency edge of the filter. As demonstrated by Fig. 3a, gain compression occurs at lower values of the input power when the input frequency is higher and insertion loss is greater. The filter performance specifications are often most difficult to meet near the upper edge of the uplink filter. For this reason, significant design effort is focused there.

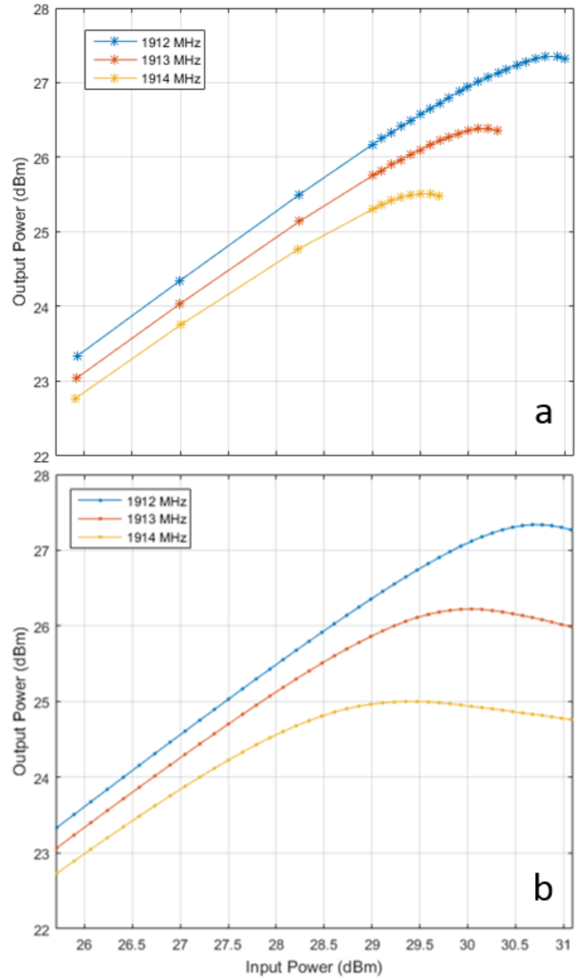

Fig. 3. Measured (a) and simulated (b) plots of output power vs. input power at three different input frequencies showing the compression of the output signal.

III. Simulation

The full simulation calculates the frequency-dependent admittance or S-parameters of the filter. The algorithm is implemented on a PC running Matlab. Both the electromagnetic environment and the electro-acoustics of the SAW-die are simulated. The temperature of the real device will affect the response and must also be considered in the simulation. Typically, SAW resonators are the components most sensitive to the temperature variations. As such, the temperature dependence of the surrounding metal and dielectrics can be ignored for the simulation and the temperature dependence is restricted to the resonators. The Temperature Coefficients of frequency (TCF) of the SAW resonators is determined empirically and parameterized accordingly.

Ideally, one would have a complete account of the thermal environment before undertaking a full simulation, e.g., thermal conductances to ground through vias, resonator proximity to edges, etc. However, we describe a simple approach where most thermal details are ignored. Instead, we make the assumption that temperature of each resonator is proportional to the power dissipated by that resonator, divided by the area of the IDT resonator. In particular, the temperature T of the n^{th} resonator is given by

$$T^{(n)} = T_0^{(n)} + \alpha D(T^{(n)}) \tag{1}$$

where T_0 is the initial, usually room, temperature, and $D = $ Power dissipated/Area. The fitting parameter α is determined by comparison with data. Each resonator within a design may require a unique α depending on its thermal environment. For simplicity, we assume each resonator has the same α.

A. Perturbation theory

The crux of the simulation relies on:

- calculating the temperature of each resonator,
- using this temperature to adjust the admittance of each resonator,
- then calculating the full response of the filter.

The difficulty with this approach is evident in Eq. 1. The power dissipated density of each resonator, D, is itself a function of the full filter response and therefore the temperature of all the resonators. Equation (1) is an implicit equation for temperature with no closed form solution. Inspired by the physical measurement technique of slowly ramping the input power from a small to high value, we employ a perturbative method to approximate the temperature for each resonator.

Assume the input power is ramped from 0 to P_{M-1} in M fictitious time steps, $P_{in} = \{0, P_1, ..., P_{M-1}\}$. Assuming the difference between P_m and P_{m+1} is small, we identify a temperature for each resonator at each time step. The approximate solution to Eq. 1 for the n^{th} resonator in the filter is given by

$$\begin{aligned} T_1^{(n)} &= T_0 + \alpha D^{(n)}(T_0) \\ T_2^{(n)} &= T_1^{(n)} + \alpha D^{(n)}(T_1^{(n)}) \\ &\vdots \\ T_M^{(n)} &= T_{m-1}^{(n)} + \alpha D^{(n)}(T_{M-1}^{(n)}). \end{aligned}$$

The power dissipated density for each resonator is first calculated at T_0 using the simulation of the full circuit. By choosing a sufficiently slow ramp rate for the input power, the product αD is small for realistic filters and can be treated as a perturbation to the initial temperature. For the lowest input power, at the start of the power ramp, all resonators begin at the same initial temperature. The temperatures for the subsequent time steps are approximated using the temperatures from the previous steps. Using this method, we calculate the s-parameters of the filter at each value of P_{in}.

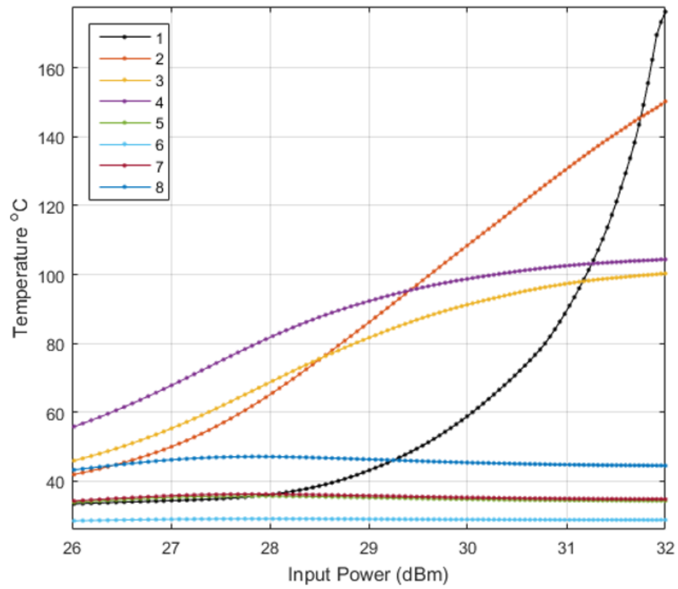

Fig. 4. Simulated temperatures of each resonator vs. input power, at 1914 MHz.

B. Compression simulation

The results of the simulation for gain compression are shown in Fig.3b. Both the measurement and the simulation show an inflection point, which is the input power point at which the output power has slope equal to zero. The fitting parameter, α, was determined by matching this inflection point for the simulation with the measured data. The agreement with the measured data is reasonable. The simulation shows a broader transition through the inflection point than the data. We speculate that this is due to a shortcoming of the underlying model for the temperature dependence of the resonators.

C. Resonator temperature simulation

Figure 4 shows the simulated temperatures for each of the eight resonators in the filter. Of particular interest are the relative temperatures near 29.5 and 31.5 dBm input power. At these powers, the hottest resonators within the filter change from resonator 4 to 2, and then from 2 to 1. The simulation clearly captures this behavior shown in Fig. 2.

One important caveat for design of filters with this method: The value for α determined this way is unique to the particular package and layout of this Band 2 duplexer. However, minor variations of the SAW geometries do not significantly affect α. And variations of this filter can be simulated reliably without changing α. However, if there is a significant change to the package, SAW die size, or SAW technology, then the value for α must be determined from a relevant measurement.

IV. Filter design guidance

Although the agreement is imperfect, the simulation does capture features of the data which are helpful with the design of the filter. The relative temperature simulations in Fig. 4 are particularly helpful to a filter designer. Consider the relative temperatures of the resonators at 32 dBm. The problematic resonators are 1, 2, 4, and 3. Increasing the area of these resonators (while holding the admittance as constant as possible) will reduce the power dissipated density and lower their temperatures. Since the total area of the SAW die is a constraint, other resonators must sacrifice size to make room. The area of the remaining four resonators, 5 - 8 can shrink without increasing the power dissipated density to unsafe levels.

V. Conclusions and Discussion

Spatially-resolved infrared measurements revealed a highly non-uniform temperature across the SAW die. Making the simple assumption that the temperature of each resonator is proportional to the power dissipated density of that resonator, we constructed a simple model that captures this. Using a perturbative numerical method to calculate the temperatures of each resonator, we find good agreement between the measurements and the model. Despite the simplicity of this model, it is an effective guide to the design of high-power filter designs.

References

[1] K. Hashimoto, M. Kadota, T. Nakao, M. Ueda, M. Miura, H. Nakamura, H. Nakanishi, and K. Suzuki, *Recent Development of temperature compensated SAW devices*, IEEE Intl. Utrasonics Symp., 2011.

[2] C. Huck, H.P. Zidek, T. Ebner, K.C. Wagner, and A. Wixforth, *Thermal Characterization of Surface Acoustic Wave Devices*, IEEE Joint UFFC, EFTF, and PFM Symp., 2013.

[3] T. Suzuki, T. Nishizawa, and O. Kawachi, *Analysis of Heat Dissipation Improvement using Bonded Wafer in Chip Size SAW Device Structure*, IEEE Joint UFFC, EFTF, and PFM Symp., 2013.

[4] M. Fattinger, P. Stokes, G. Fattinger, *Thermal Modeling of WLP-BAW Filters*, IEEE Intl. Ultrasonics Symp., 2015.

[5] K. Gamble and W. Buettner, *Steady-State and Transient Thermal Modeling for a SAW Duplexer*, IEEE Intl. Ultrasonics Symp., 2016.

[6] A. Oleaga, V. Shvalya, A.S. Sefat, and A. Slazar, *Transport Thermal Properties of $LiTaO_3$ Pyroelectric Sensor from 15K to 400K and Its Application to the Study of Critical Behavior in $EuCo_2As_2$*, Int. J. Thermophys., Vol. 37, 2016.