Liquid Crystal and Infrared Thermography on Coated SAW Devices

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***Abstract*—Reliability of micro-electronic devices is one of the most important issues in mobile communication systems and is significantly influenced by the thermal behavior of the components. The present contribution demonstrates Liquid Crystal Thermography (LCT) and Infrared Thermography (IRT) in exemplary investigations of self-heating effects in a half-section ladder-type Surface Acoustic Wave (SAW) filter with thick SiO_2 coating. Conventionally, mean temperature values are obtained indirectly by evaluating measured frequency shifts under load using the Temperature Coefficient of Frequency (TCF). In contrast to TCF based evaluations, LCT and IRT provide spatially resolved measurements of the temperature distribution on the component and serve as an independent and direct scheme for thermal characterizations. The results of LCT and IRT measurements are compared with simulations of the temperature distribution and show good agreement.**

I. Introduction

Modern UMTS and LTE mobile communication systems make high demands on RF filtering applications. Devices based on Surface Acoustic Wave (SAW) technology meet these requirements very well. However, despite many years of research and development, domains such as reliability and lifetime are still subject of current investigations [1]. They need to be thoroughly studied especially since mobile applications require continuous reduction in component size. One of the important issues deteriorating the device reliability is the increase of internal temperature due to power dissipation in the component [2]. This self-heating causes crucial frequency shifts of the filter characteristics at high electrical power levels as well. Therefore, investigating the temperature behavior of SAW resonators is an important task regarding reliability and is also necessary to optimize the filter design.

A common method uses the frequency shift of the transfer function in order to determine the component's temperature indirectly. Variation of ambient temperature results in the Temperature Coefficient of Frequency (TCF) which serves as a quantity to map the frequency shift to an accurate value of the temperature increase. However, temperatures determined that way are attributed homogeneously to the entire chip without taking local inhomogeneities into account. Additional problems arise using this indirect approach as soon as other effects causing a frequency shift play a role. Hence, the study of temperature dependent effects necessitates a direct measurement method to precisely ascertain the spatial distribution of the device temperature.

Sec. II introduces the physical background of the thermographic techniques used in this work. In Sec. III the experimental procedure for self-heating measurements is described and in Sec. IV measurement and simulation results are presented and discussed.

II. Thermography Background

There are numerous different approaches for nondestructive temperature measurements available, such as electrical and optical methods which can be physically contacting as well as noncontacting [3]. For conventional uncoated SAW devices only noncontacting methods can be used, while their coated counterparts investigated in this work also allow the application of contacting measurement techniques. This is due to the negligible amplitude of the acoustic wave at the surface which is passivated with a thick TCF reducing SiO_2 layer. As we intend to measure the temperature distribution of the entire component, only techniques are considered which are capable of thermal mapping. In this study, the contacting Liquid Crystal Thermography (LCT) and the noncontacting Infrared Thermography (IRT) are examined.

A. Liquid Crystal Thermography

LCT is a popular temperature measurement technique in nondestructive testing of electronic devices and relies on Thermochromic Liquid Crystals (TLCs) which selectively

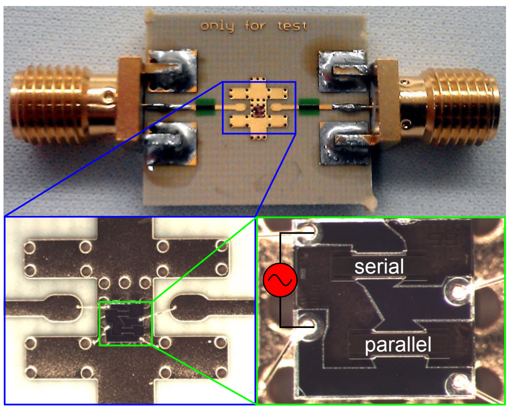


Fig. 1. The investigated device is a half-section ladder-type SAW filter consisting of one serial and one parallel resonator with the former next to the input. It is passivated with a thick SiO_2 coating and mounted on a PCB by an epoxy adhesive.

reflect incident white light depending on their temperature [4, 5]. TLCs are organic compounds with a molecular structure intermediate between a crystalline solid and an isotropic liquid. Thus, they possess some of the mechanical properties of liquids and some of the optical properties of solids. The TLC molecules are helically structured with a periodicity in the order of the wavelength of visible light. Due to the temperature dependent pitch of the helix TLCs scatter incident white light selectively by wavelength, with the selectivity being a function of temperature. Thus, the apparent color of the observed region changes as its temperature changes (see Fig. 2).

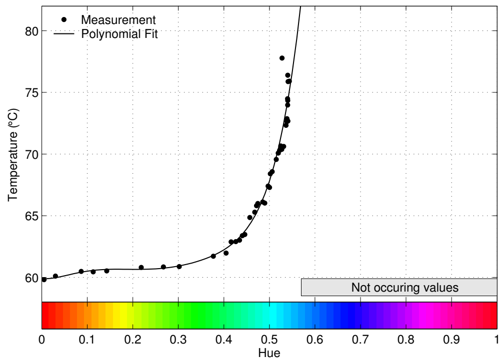


Fig. 2. TLC calibration by means of a sixth order polynomial fit to measured results. It is used for post-processing of self-heating measurements by LCT.

B. Infrared Thermography

IRT is probably the most common optical technique for measuring temperatures. It relies on the fact that all matter spontaneously emits radiant energy above absolute zero as a consequence of its temperature. The spectral, hemispherical emissive power per unit area of a black body in thermal equilibrium at an absolute temperature T is described by Planck's law of radiation:

$$E_\lambda(T) = \frac{2\pi hc^2}{\lambda^5[\exp(hc/\lambda k_B T) - 1]} \ , \tag{1}$$

where λ is the wavelength of the emitted radiation, h the Planck constant, k_B the Boltzmann constant, and c the speed of light. Integrating (1) over all wavelengths yields the Stefan-Boltzmann law for the total emissive power per unit area of a black body in terms of its temperature:

$$E(T) = \sigma T^4 \ , \tag{2}$$

where σ is the Stefan-Boltzmann constant. However, a real body does not absorb all incident radiation and consequently emits less total power than a black body ($\varepsilon = 1$) which is characterized by an emissivity $0 < \varepsilon < 1$:

$$E(T) = \varepsilon\sigma T^4 \ . \tag{3}$$

Thus, with knowledge of the emissivity the temperature of a body can be determined by measuring its total emitted radiation. Temperature measurements are usually conducted in the infrared region of the electromagnetic spectrum since the spectral emittance from bodies in the typical temperature range of interest peaks in this wavelength range.

III. Experimental Procedure

In the following, the experimental procedure for the thermal mapping of coated SAW devices using LCT and IRT is described. This study focuses on a half-section ladder-type SAW filter consisting of one serial and one parallel resonator (see Fig. 1). Since this represents the constitutive element of each RF duplexer it contains ample information for subsequent filter designs. The sample is mounted on a PCB by a thermal conducting epoxy adhesive.

A. Sample Preparation

Before actually measuring the temperature distribution of the Device Under Test (DUT) it needs to be thoroughly prepared. For this purpose, additional thin layers are deposited on the component's surface by an airbrush system. The first layer is a light absorbing black backing paint (Hallcrest SPB100) which is IR opaque and highly emitting. It offers improved optical analysis for LCT due to the well-defined background. Additionally, even if not required for IRT this layer ensures good comparability between both measurement techniques due to equal thermal boundary conditions and uniform emissivity of the entire surface. While this layer is sufficient for IRT, LCT requires a second layer which serves as the actual temperature expressing layer. It is composed of micro-encapsulated TLCs with an active temperature bandwidth of 20 K starting at approximately 60°C (Hallcrest R60C20W).

B. Emissivity Correction (IRT)

Quantitative temperature measurements using IRT necessitate knowledge of the emissivity which can be calculated according to (3). Therefore, the DUT is heated homogeneously on a hotplate to a well-known temperature and its emitted radiation is measured. In our case, due to the highly emitting IR opaque lacquer on the sample surface the emissivity is close to that of a black body and uniform all over the surface which simplifies the correction scheme performed. In general, on uncoated SAW devices black paint may not be deposited on the sample and thus, the emissivity has to be determined separately for each single material on the surface. In this way, temperature determination of materials with low emissivity due to high reflectivity or transmissivity requires additional correction models which go beyond the scope of this paper.

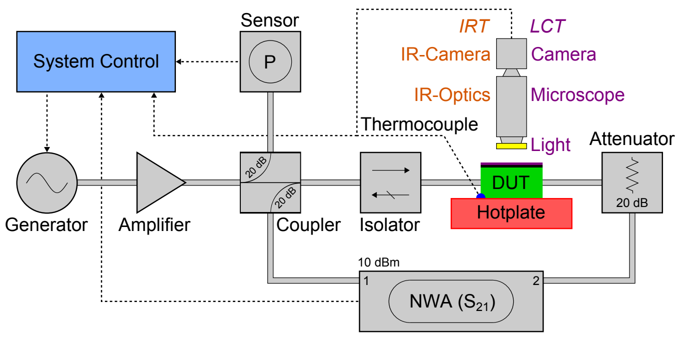


Fig. 3. Experimental setup for self-heating measurements by LCT and IRT.

C. TLC Calibration (LCT)

Following the sample preparation, the TLCs need to be calibrated to allow for an accurate quantitative temperature analysis of LCT measurements. Therefore, the illuminated DUT is heated homogeneously across its active temperature range using a hotplate. Simultaneously, a digital color camera takes snapshots through an optical microscope and a thermocouple measures the current temperature of the DUT. The camera provides RGB images which are transformed into HSV color space in order to enable a scalar color evaluation based on hue values. The measured mean hue value of a predefined calibration area on the component as a function of its temperature is shown in Fig. 2. A sixth order polynomial fit to this data serves as the TLC calibration in the actual self-heating measurements for post-processing of hue images in order to determine the corresponding temperature values. Details regarding image processing and calibration procedure as well as possible calibration errors such as illumination and viewing arrangement or hysteresis and aging of TLCs are extensively discussed elsewhere [6–9].

D. Measurement Setup

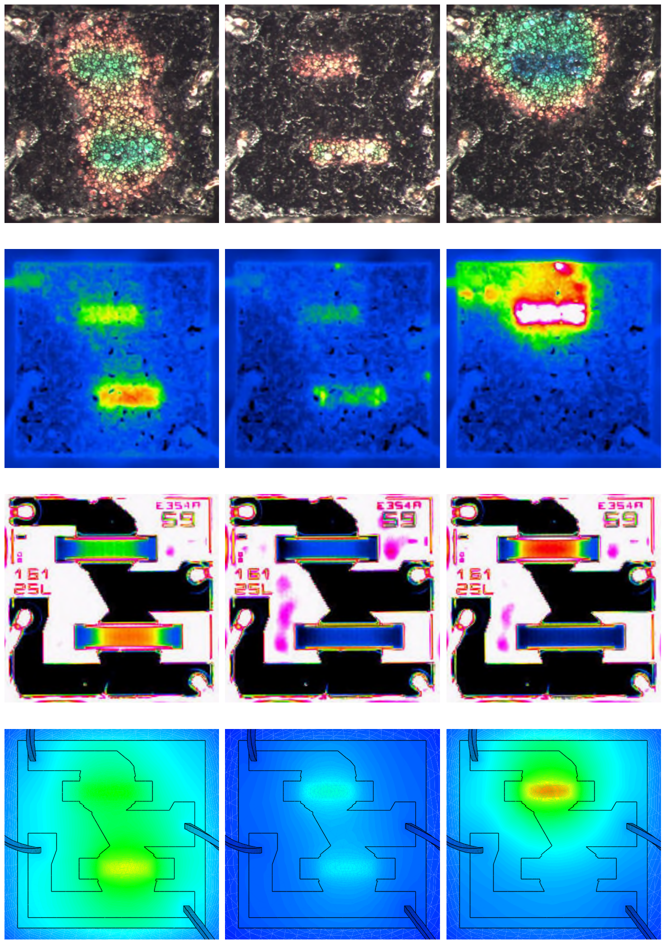
The schematic in Fig. 3 illustrates the experimental setup used for self-heating measurements presented in this paper. The RF generator is connected to the power amplifier which feeds the DUT via a directional coupler. A power sensor detects the applied power and a Network Analyzer (NWA) measures the transfer function of the DUT. Protection of the NWA and the power amplifier is ensured by an attenuator and an isolator. The signal path and its frequency-dependent power attenuation is calibrated for all load frequencies. In order to raise the ambient temperature narrowly below the TLC's active temperature range the DUT is placed on a hotplate, the temperature of which is measured by a thermocouple. A digital color camera captures the LCT color distribution on the illuminated DUT via a microscope while adjusting gain and exposure time automatically for each image. The IR camera (InfraTec ImageIR) records thermal maps of the DUT taking into consideration its previously determined emissivity. The entire measurement setup is controlled by a LabVIEW program which sets load frequency and power at the RF generator and reads out the NWA, the power sensor, the thermocouple, and both cameras.

E. Evaluation Process (LCT)

The recorded LCT color distribution images require post-processing to allow for an accurate temperature evaluation. On the one hand, hue values at every pixel need to be converted to the according temperature values using the aforementioned TLC calibration curve. On the other hand, corrections have to be applied to account for reflective areas as well as uncolored pixels caused by imperfections in the TLC coating. While the former is corrected by means of difference considerations based on a reference image without load, uncolored pixels are taken into account by truncated filtering of brightness values.

IV. Results and Discussion

In Fig. 4 qualitative temperature distributions of the DUT under load are visualized. The top panel illustrates raw LCT images at three different load frequencies, at the left skirt, at the passband center, and at the right skirt of the filter. Since these images are not post-processed and converted to temperature values, they reveal the actual TLC color distribution on the component's surface ranging from red to blue corresponding to approximately 60°C and 80°C, respectively (see Fig. 2). The second and third panel show the associated IRT measurements with and without black backing paint. According FEM simulation results are depicted in the bottom panel. The basis for the simulation of the temperature distribution are losses resulting from simulated acoustic and electromagnetic energy fields. In this context, heat conduction and convection of the entire sample comprising chip, PCB, bond wires and epoxy adhesive are taken into account.



Left skirt (890 MHz) | Passband center (930 MHz) | Right skirt (970 MHz)

Fig. 4. Qualitative temperature distributions on a half-section ladder-type SAW filter with thick SiO_2 coating under load ($P = 25$ dBm): Measured by LCT (top panel), measured by IRT with (second panel) and without (third panel) black backing paint, and simulated using FEM (bottom panel). All are shown for three different load frequencies, at about the left skirt, at the passband center, and near to the right skirt of the filter.

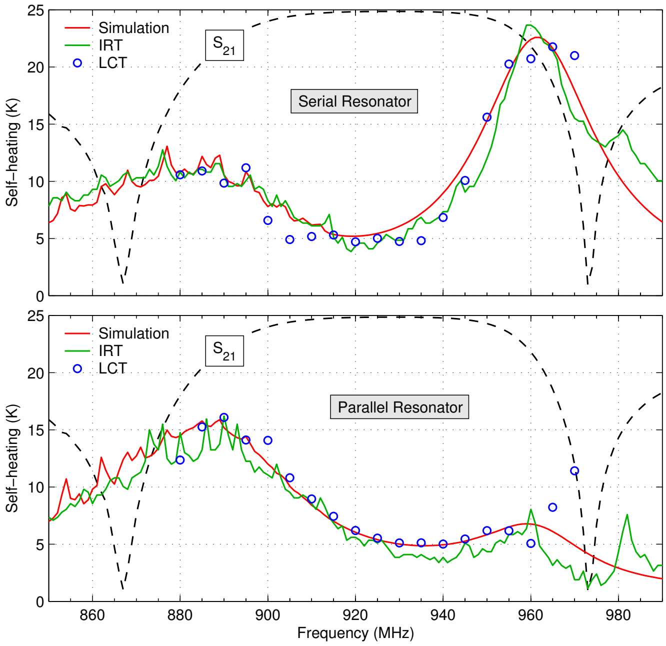


Fig. 5. Self-heating of both resonators as a function of load frequency at a load power of $P = 25\,\mathrm{dBm}$: Simulation compared with IRT and LCT measurement results. The transfer function S_{21} of the filter is shown as a reference in arbitrary units.

The right skirt of a half-section ladder-type filter is mainly dominated by the serial resonator, whereas the parallel resonator basically defines the left skirt. Hence, loading the filter at the upper edge of the passband, where the serial resonator is near to its antiresonance, particularly heats up the serial resonator. Due to the small power transfer the parallel resonator is only affected by heat conducted from the serial resonator.

Loading the filter at the left skirt or the passband center results in heating of both resonators because RF power is dissipated in both of them. By applying RF power at the lower edge of the passband, where the parallel resonator is near to its resonance, the power transferred from the serial resonator is dissipated in the parallel resonator due to its lower impedance compared to the matched output.

At the passband center, near the serial resonator's resonance and the parallel resonator's antiresonance, neither is heated significantly. Due to the large impedance of the parallel resonator power passed through the serial resonator is mainly discharged at the load.

In Fig. 5 the measured and simulated self-heating of both resonators is analyzed quantitatively as a function of load frequency by evaluating their maximum temperature rise. Using the maximum occurring temperature value defined by the TLC calibration the heat transfer coefficient in simulation is adjusted to fit the measurement. Thereby, good agreement between results of both measurement methods and simulation is observed. The noticeable distortions below the resonance frequency of each resonator are caused by Fabry-Pérot interferences due to the finite dimensions of the resonators. At the right filter skirt deviations between LCT measurement and simulation of the parallel resonator occur which are explainable since the TLCs are below their active temperature range resulting in undefined hue values (see Fig. 4). This issue can be overcome by setting the hotplate's temperature within the TLC's active bandwidth. This problem doesn't arise with IRT due to its almost unlimited temperature range which is the main advantage over LCT besides its inherent feature of measuring noncontactingly. Nevertheless, there are small deviations between IRT and simulation results at the right filter skirt. These local temperature maxima measured by IRT at about 960 MHz and 980 MHz originate from spurious modes which are out of the simulation's scope.

V. Conclusion

In this work, we presented LCT and IRT in exemplary investigations of self-heating effects in a half-section ladder-type SAW filter with thick SiO_2 coating. On top of mean temperature values obtained indirectly by conventionally evaluating measured frequency shifts using TCF values, LCT and IRT provide spatially resolved measurements of the temperature distribution on the component. Moreover, both techniques eliminate measurement uncertainties caused by other effects resulting in a frequency shift. In this regard, they serve as independent and direct measurement schemes unlike TCF based evaluations. The results of LCT and IRT measurements are compared with FEM simulations and in very good agreement. Further investigations will include comparison with TCF based temperature evaluation and unitarity violation which quantifies the entire power loss in the device.

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