Multiphysical Modeling and Optimization of Nonlinearities and Thermal Behavior in RF MEMS Front-end Components for Mobile Communication Systems

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***Abstract*—In RF integrated circuits for LTE transmitters (Tx), the thermal and nonlinear mechanism between the Power Amplifier (PA) and adjacent RF filters realized by Bulk Acoustic Wave (BAW) technology is crucial for reliability and requires special attention. A co-design of Gallium Arsenide (GaAs) PA, BAW Tx filter and the optimum matching network is created in the silicon-ceramic (SiCer) platform which combines the low temperature co-fired ceramic (LTCC) and silicon thin film processing technology for micro-electro-mechanical systems (MEMS) in a single composite substrate. The linear, nonlinear and thermal results are compared with the same layout design in a printed circuit board (PCB) technology with the silicon substrate. The band-2 BAW filter is based on Solidly Mounted Resonators (SMR) electrically coupled in a ladder type topology.**

I. Introduction

For next generation radio-frequency (RF) communication systems with very narrow gaps between the specified frequency bands, the consideration of temperature- and RF power-induced coupling between the components involved is required. The interaction of power amplifiers (PA) and RF filters, often realised by bulk-acoustic wave (BAW) resonators, have, therefore, to be investigated in terms of heat- or input power-induced variations of the individual components in the chain. Changes of the substrate temperature due to the dissipated power of the PA will impact the properties of nearby components. Especially the passband frequency range of BAW filters, which are used to suppress unwanted output signals of the PA, e.g. harmonic signals as well as adjacent frequency bands, changes according to the temperature coefficient of the materials. Furthermore, non-linear effects, like the generation of harmonics or intermodulation products occur in the PA and even in the BAW/SAW device at high RF power levels [1]. These effects must be considered during the design phase of a transmitter chain to achieve a reliable system performance.

In the first part of this work, the electromagnetic (EM) and circuit co-simulation of PA plus BAW filter is designed and optimized to get an output power of 25.25 dBm and a power added efficiency (PAE) of 10.4%. In the next step, the already designed EM-layout is used as an input file to create a thermal finite element (FEM) simulations model and further the FEM simulation results are optimized with respect to infrared measurements of PA with BAW filter design on PCB and SiCer substrate [2]. The harmonics and third order intermodulation (IMD3) nonlinear measurements of individual PA, BAW filter as well as PA plus BAW filter are compared. In this project, we also present the behavior of main heat and nonlinear source to the overall LTE transmitter design under different temperature and input power conditions and also compares the thermal and nonlinear characteristics of two key substrate technologies.

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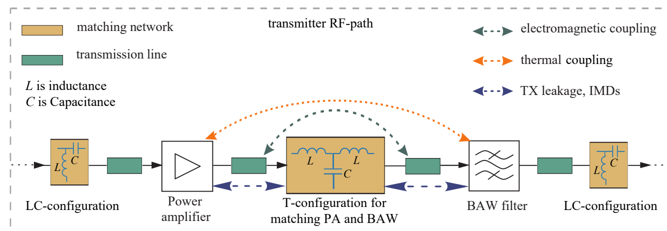

Fig. 1. Using Keysight's ADS, the LTE-transmitter is simulated and passive components are optimized to match the requirements. Therefore, the input and output should be matched with 50 Ω standards, so that reflections can be avoided. The matching networks should be optimized to allow a maximum power transfer from the PA to the output while attenuating the harmonics. The band of interest is the band 2 with a center frequency of 1880 MHz and a bandwidth of 60 MHz covering the frequencies going from 1850 to 1910 MHz.

II. Thermal effects of the TX design chain

The thermal FE simulation was performed using ANSYS R19.0. The model includes the LTCC platform, a model of the PA on the front side and the aluminum heat sink on the back side. The LTCC platform was built up from the layout generated in Keysight ADS. The thermal conductivities of the substrate materials and the metals, processed in the vias and the inner layers, are well-known and incorporated with their respective temperature-dependencies. Convection at an ambient temperature of 22 °C is assigned a value of 6 W/m^{2}K and assumed to cover both convection and radiation effects in the model.

The power dissipation by the PA was assumed as 2.7 W. The measured temperature differences of about 60 °C between the top of the PA package and the metal conductors immediately next to the package indicate a high level of insulation, which was modelled by a thermal conductivity of the packaging material between 0.1 and 0.5 W/mK. While the top side

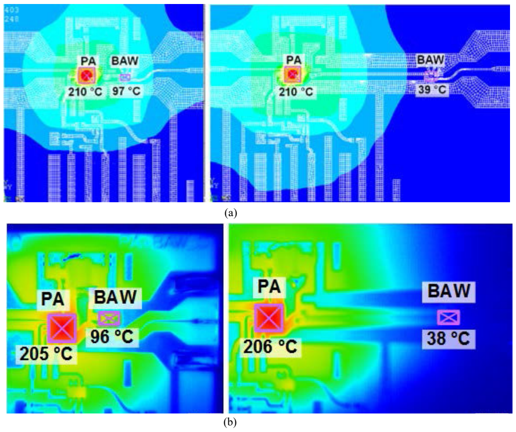

Fig. 2. (a) ANSYS simulation of heat distribution for the compact and the substrate design. (b) Measured lateral temperature distribution on the substrate surface for the compact and large version of the TX filter temperature differs by 58 K between both layouts.

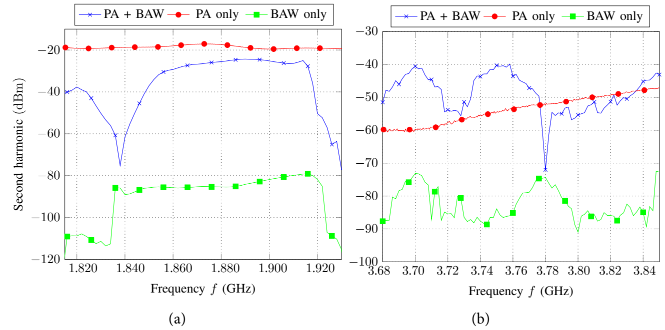

Fig. 3. (a) Second harmonic output of the three modules for an sub-harmonic input signal at f1 with an input power of +10 dBm. (b) Measured lateral temperature distribution on the substrate surface for the compact and large version of the TX filter temperature differs by 58 K between both layouts. (b) Second harmonic output for an input signal of +10 dBm.

of the package reached a temperature of about 200 °C, the temperature at the heat sink was about 100 °C uniformly over the entire surface. The substrate temperature at the BAW position for the compact and large layout is 97 °C and 39 °C, respectively. Therefore, the BAW temperature differs by approximately 58 K between the layouts, leading to different frequency responses of the BAW filter [3]. For the thermal verification, both substrates were measured using an infrared camera system, FLIR Thermovision A40, to record the thermal profile, presented in Fig. 2. The measured results agrees well with the ANSYS simulation.

III. RF Power dependent nonlinear effects

For the investigation of non-linear effects, three devices were fabricated on the LTCC substrate to perform nonlinear sub-harmonic and harmonic measurements at an input power of +10 dBm: A module, containing PA and BAW filter (PA+BAW), a module containing the power amplifier only (PA only), and a module comprising the BAW filter only (BAW only). For the sub-harmonic case, as depicted in Fig. 3(a), the range of the fundamental input frequency is between 900 MHz to 970 MHz and the output frequency at the second harmonic is between 1.80 GHz to 1.94 GHz (LTE band 2).

The second harmonic signal, generated by the PA in the PA only module, is, outside of its passband range, suppressed by the BAW filter in the BAW+PA module. The acoustic nonlinearity contribution from the BAW filter alone is much lower as in the PA+BAW module. For the second harmonic, as illustrated in Fig. 3(b), the input frequency is between 1.84 GHz and 1.925 GHz and the output frequency range is between 3.68 GHz to 3.85 GHz. Here, the spurious level in the PA+BAW filter module differs across the frequency range. Peak values at 3.7 GHz and 3.75 GHz can be caused by contributions due to the electrical non-linearities of the internal resonators inside the BAW filter, exited by the second harmonic signal generated by the PA. The electrical nonlinearity of the BAW filter itself, measured at the BAW only module, is not so dominant in comparison to the PA+BAW module.

IV. Conclusion

A combined thermal and electrical simulation approach was proposed, which allows for a calculation of the impact of heat dissipation on adjacent thermal sensitive devices. Thus, a temperature-induced deviation of the electrical properties of the TX module with respect to a given layout can be computed early in the design phase, ensuring a compliance to the electrical specification and the compact module layout, simultaneously. The approach enables a consistent and robust design of compact RF modules under consideration of the multiphysical coupling between the thermal and electrical domain.

V. Career plan, MTT Fellowship Impact and IMS

I intend to pursue a career in industry. With the microwave industrys growing interest in micro-wave and mm-wave systems for communication system, I believe industrial research in this field is required to solve major challenges of high frequency systems.

The authors gratefully acknowledge the funding of parts of this work by the IEEE MTT-S society has provided me through this Graduate fellowship. It has allowed me to gain a valuable research experience which has confirmed my interest to further my technical skills in microwave and mm-wave engineering.

I strongly encourage any eligible person to apply for this scholarship and gain experience by meeting the industry and academic experts using the travel grant from IEEE MTT-S for attending the International Microwave Symposium (IMS).

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