Accurate Modeling and Simulation of SAW RF Filters

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Abstract—**The popularity of wireless services and the increasing demand for higher quality, new services, and the need for higher data rates will boost the cellular terminal market. Today, third generation (3G) systems exist in many metropolitan areas. In addition, wireless LAN systems, such as Bluetooth or IEEE 802.11-based systems, are emerging. The key components in the microwave section of the mobile terminals of these systems incorporate – apart from active radio frequency integrated circuits (RFICs) and RF modules – a multitude of passive components. The most unique passive components used in the microwave section are surface acoustic wave (SAW) filters. Due to the progress of integration in the active part of the systems the component count in modern terminals is decreasing. On the other hand, the average number of SAW RF filters per cellular phone is increasing due to multi-band terminals. As a consequence, the passive components outnumber the RFICs by far in today's systems. The market is demanding smaller and smaller terminals and, thus, the size of all components has to be reduced. Further reduction of component count and required PCB area is obtained by integration of passive components and SAW devices using low-temperature co-fired ceramic (LTCC). The trend of reducing the size dramatically while keeping or even improving the performance of the RF filters requires accurate software tools for the simulation of all relevant effects and interactions. In the past it was sufficient to predict the acoustic behavior on the SAW chip, but higher operating frequencies, up to 2.5 GHz, and stringent specifications up to 6 GHz demand to account for electromagnetic (EM) effects, too. The combination of accurate acoustic simulation tools together with 2.5/3D EM simulation software packages allows to predict and optimize the performance of SAW filters and SAW-based front-end modules.**

I. INTRODUCTION

Low-loss surface acoustic wave (SAW) filters have been key components in mobile phones for years as they provide excellent performance and application-specific functionality within little space. SAW filters have both followed and propelled the major trends in mobile phone market being enhancing performance and functionality while reducing size, height, and overall cost of mobile telephones. Additional functional integration as well as further miniaturization still mark the major goals of current SAW filter development. As performance requirements as given in the filter specifications increase tremendously simulations have to accurately describe the attenuation in the pass band to a few tenths of a dB and the attenuation in the stop bands to few dB at attenuation levels at 40 or 50 dB. Matching has to be predicted to halves of a dB at levels of 10 dB. These accuracy requirements have to be achieved despite the fact that the configurations being investigated have become significantly more complex. Additional functionality, such as, galvanic de-coupling or impedance transformation, has been integrated in the components. Furthermore, the frequency range of RF filters has moved from 1 GHz to above 2 GHz, while sizes have been reduced from 5.8x5.8 mm^2 to 1.4x2.0 mm^2 and below. Summing up, the specifications and the complexity of the components become more and more challenging, while required time to market becomes shorter and shorter. Thus, design engineers need excellent support from the computer aided design (CAD) system in order to allow for efficient, fast, and seamless design processes. Additionally, simulation tools are required that allow to provide filter designs which can be reliably realized in a minimum number of sample production runs.

Starting from the basic idea of an electronic design (ED) system, this paper will discuss important properties of the CAD system which is understood as the core of the ED system. In addition, we will discuss the ED system in the context of electronic design automation (EDA) allowing for efficient and seamless work flow of design engineers working on SAW components. Regarding the CAD system the paper will focus on the modeling and simulation of EM effects. Especially new-type flip-chip or chip-scale packages are taken into account, which represent the state of the art in packaging. The consideration of their performance and especially their effects on the SAW die is absolutely indispensable to allow for an overall optimum design process. We use an integral and extremely flexible design approach including acoustic and EM effects.

II. EDA SYSTEM

A. Design Cycle

In the center of the design cycle is the simulation of SAW components. The simulation and the underlying modeling of SAW components are the key functions within the EDA system allowing for rapid virtual one-shot prototyping. Fig. 1 depicts the situation. The basic processes are covered by the layout tools, the SAW component simulators, the fabrication (FAB) link, and the optimization tools. For an automated CAD system the geometrical description in electronic form is the hub for all the proc-

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esses mentioned: It is worth noting that due to standardization of the interfaces, usually many different tools can be used for the processes mentioned. In the following section we will take a closer look on the simulation process.

B. MODELING AND SIMULATION

Many techniques for SAW modeling are known that have been successfully applied in research and industry. They are extensively described in the literature [1-7]. Two essentially different types of approaches are worth being distinguished: specialized procedures, such as, coupling-of-modes (COM) or P-matrix models, and generic tools, such as, finite element method (FEM) or boundary element method (BEM).

In contrast to acoustic modeling, EM modeling of SAW components is a rather new area of interest [8-10]. With low-loss SAW RF filters entering the GHz-range, EM modeling has become more and more important. The reason is that modern SAW RF filters, whose typical representatives are SAW reactance and dual-mode SAW (DMS) filters, use the reactances of resonating, acoustically active structures, composed of transducers and reflectors, in order to create the desired filter characteristic. Known SAW reactance filters connect the immittances of SAW one-port resonators in ladder-type or lattice-type topologies. The SAW one-port resonators serve as major building blocks within the branches each providing a series resonance making a short-circuit and an anti resonance make an open-circuit. In addition, each one-port resonator defines a certain impedance level. Thus, the immitances shape the filter characteristic in a unique, but non-trivial way. Consequently, parasitic reactances caused by EM effects change or even overwhelm the acoustic reactances, considerably affecting the filter performance. They originate from the on-chip layout connecting the acoustic structures, the package, and, depending on the bonding technology used, the bonding wires or bumps. Almost all filter characteristics, such as, band width, shape factor, pass band attenuation, close-in and far-off stop band attenuation, as well as matching, are influenced by EM effects. With more elaborate filter types, such as, duplexers or 2-in-1 filters, the list of affected filter characteristics is extended by isolation, which is primarily a matter of EM coupling. The same is true with balanced/balanced or single-ended/balanced filters, whose symmetry is besides other effects determined by the EM coupling.

Specialized approaches were reported for confined configurations of transducers some time ago. They tried to empirically determine or describe some EM effects by measurement or application-specific models. Often measurements were used to fit EM models by minimizing the disagreement of measurements and simulations. The very

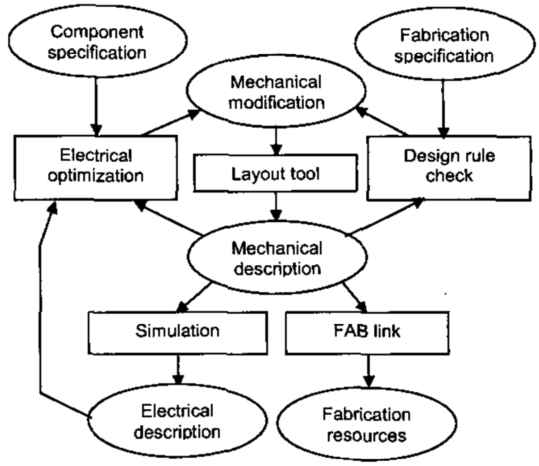

Fig. 1: Typical setup of an EDA system supporting the design engineer's work flow for SAW components.

problems of these models were the necessity of measurements, i.e., samples, and the large effort to determine the relevant parameters. On the other hand, the range of validity of such models was limited. Furthermore, these models were static without relevant dependencies and sometimes not even physically correct, as many different effects were crunched in the models.

Generic approaches have been reported in recent years. They apply proprietary or commercial off-the-shelf EM simulators to describe the relevant EM effects. Although the numerical part of the problem is usually reliably solved by these tools, challenges still remain regarding the problem-specific discretization, i.e., optimal accuracy by given computer resources and computation time as well as the correct setup of the problem interfaces, i.e., boundary conditions and excitations. In practice there also exist combinations thereof. Most often simplified, specialized models are plugged into or combined with generic models. Thus, the overall simulation of the SAW components is composed of different types of acoustic and EM models. Thereby, both specialized and generic acoustic/electromagnetic models are used in order to meet the design engineers requirements on accuracy and computer resources.

The final result of the modeling and simulation of acoustic and EM effects is a netlist, see Fig. 2, with the equivalent circuit (EC) description that consists of a variety of equivalent circuit parameters, such as, P-matrices, admittance matrices, scattering matrices, or resistance, inductance, capacitance, or conductance (RLCG) elements or matrices. In a final step the netlist is analyzed using an electrical circuit simulator to obtain the scattering parameters of the complete SAW component in the relevant mode of operation. The mode of operation includes

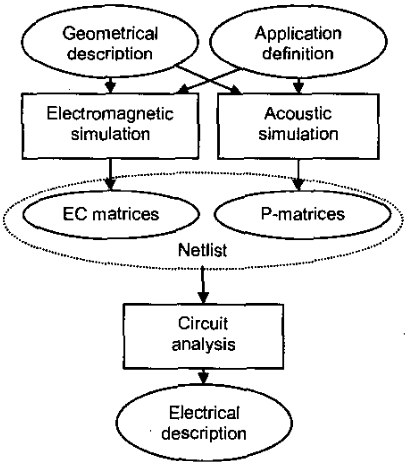

Fig. 2: Detailed flow of SAW component simulation.

matching networks, terminations, and excitations necessary to reflect the operating conditions of the filter within the mobile terminal.

C. *ACCURACY VS. COMPUTER RESOURCES*

Regarding the set of models which exist for the acoustic structures as well as the connecting structures, there exists an extremely powerful and flexible simulator for SAW filters. Depending on the application, e.g., simulation during optimization or final electrical design verification, the available models can be combined in order to provide the best trade off between accuracy and computer resources required.

In this context accuracy seems to be a difficult notion. To our understanding, an accurate model implies two basic properties. Assuming modifications of the configuration that are considered in the model, the response of the simulation should on the one hand qualitatively predict the trend of change and on the other hand quantitatively predict the amount of change. Thus, comparing two simulations with corresponding measurements, the absolute deviation between the simulations and the corresponding measurements should be small and, furthermore, the deviation between the predicted and the measured change should be small. Below, these properties are referred to as absolute and relative accuracy. It is good and common practice to verify the accuracy of individual models by themselves using test structures for which measurements, results of other simulators, or analytical solutions exist with known accuracy. Furthermore, sets of test structures being in well known relations to one another are used.

Whereas for individual models absolute and relative accuracy are obvious and consistent, for complex simulation systems that are composed of many individual models, accuracy becomes a major issue. Especially deviations or uncertainties of the overall simulation result should stay small. For instance, enhancing one model by considering a so far neglected effect, does not need to have any impact on the overall system. In contrast, by interference with other models both the trend and the amount of a change might be wrong. Furthermore, good agreement of measurement and simulation might deteriorate.

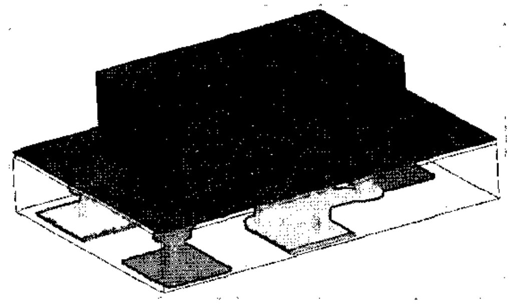

Fig. 3: 3D model for EM simulation. The ceramic layers have been removed in order to allow insight in to the connecting structures.

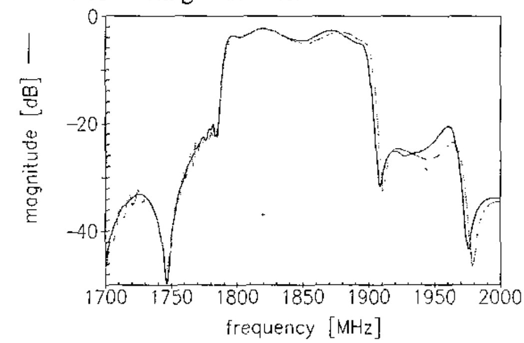

Fig. 4: Comparison of measurement (black solid) with simulations using 2.5D (red dash-dotted) and 3D (green dashed) descriptions of packages. For simplicity neither measurement nor simulations include required matching components.

III. RESULTS

In order to demonstrate our simulation, we have chosen a filter in a 5-pin surface mount device (SMD) chip-sized SAW package (CSSP) for single-ended/balanced filters. Fig. 3 shows the 3D model for the EM simulation. The ceramic layers of the package are not displayed, though being part of the simulation model, in order to visualize the complex metal structures consisting of traces (horizontal connections) and vias (vertical connections). Fig. 4 shows the measured and simulated transfer functions of a PCN Rx filter. Besides filtering the filter provides both balun functionality allowing for single-ended/balanced operation and impedance transformation from 50 to 200 Ω. The center frequency is 1842.5 MHz. The design technique employed is DMS. Since the component has been designed to operate with an additional matching

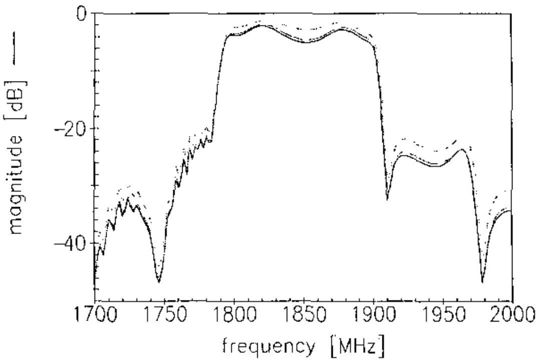

Fig. 5: Comparison of three simulations: Complete simulation including EM effects of package and on-chip layout (black solid), simulation with EM effects of the layout (red dash-dotted), and no EM effects (green dashed).

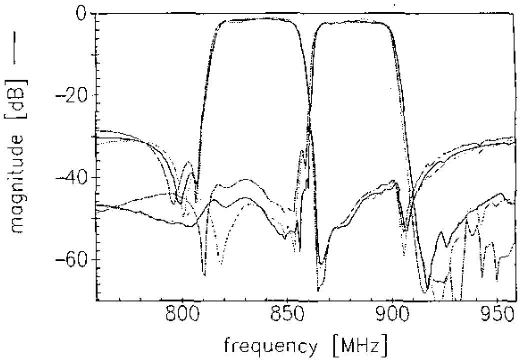

Fig. 6: Comparison of measurement (black solid) and 2.5D (red dashed-dotted) and 3D (green dashed) simulations of package.

component that has neither been incorporated in the measurement nor in the simulations, the pass band performance seems to be poor. Nevertheless, comparison without matching components has been chosen in order to focus on the simulation of the SAW component itself. By inspection of Fig. 4 the measurement and simulations agree very well. Center frequency and band width are accurately predicted. The attenuation levels and shapes given by measurement and simulations agree very well.

Comparing the two component simulations using 2.5D and 3D EM simulators for the electrical characterization of the filter package indicates that, in this case, the two types of simulations are almost identical. This interesting fact will be further detailed.

Hereto, in Fig. 5 the number of EM effects taken into account is systematically reduced compared to the 3D simulation as shown in Fig. 4 to a purely acoustic simulation. Comparing the three simulations it turns out that in this configuration the major part of the EM effects originates from the connecting structures on the chip. Due to the geometrical symmetry of the package and balanced-type mode of operation, the EM effects are almost completely cancelled. Capacitive couplings to both sides of the balanced output are equal and, therefore, not visible in the differential mode signal. Thus, no impact of 2.5D and 3D simulation of EM effects in the package can be observed. To stress this fact we will have a look on a purely single-ended component.

The component chosen is an American AMPS-duplexer, whose ports are all single-ended and matched to 50 Ω. Fig. 6 shows the Rx and Tx transfer functions. The duplexer is housed in an 8-pin SMD CSSP. By inspection, the simulation using the 3D EM description of the package agrees better with measurement than the one using the 2.5D description of the package.

IV. Conclusion

The paper presented an EDA system for SAW components. Special emphasis has been put on the EM simulation, which in case of SAW RF filters is of particular relevance. 2.5D and 3D EM simulations have been compared. It turned out that depending on the application both 2.5D and 3D EM simulations yield good results if used correctly. While 2.5D and 3D simulations showed almost identical results with simple configurations, deviations could be observed with complex configurations.

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