# Electromagnetic Modeling, Simulation, and Design of Balanced Ceramic IF SAW Filters

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*Abstract*— **The trend of improving the performance of surface acoustic wave (SAW) filters requires accurate software tools for the simulation of all relevant effects and interactions affecting the filter performance. Acoustic tracks are geometrically complex structures that typically feature hundreds of fingers and stubs with extreme aspect ratios. Moreover, one filter consists of potentially many acoustic tracks. Thus, electromagnetic effects of the details of the acoustic tracks are typically neglected.**

**In this paper, it is shown that for some filters having a considerable acoustic track area, such as, for example, the intermediate frequency (IF) filter presented, acoustic tracks can have a decisive influence on electromagnetic feedthrough, affecting the filter performance. Especially the stop band rejection may suffer from uncontrolled electromagnetic feedthrough.**

**A new model accounting for the electromagnetic interaction of acoustic tracks with other potentially relevant structures, for example neighboring structures such as pads, is presented. The approach is applied to an IF filter for Wireless Local Area Network (WLAN) applications at 462 MHz in a 5 mm×5 mm ceramic package for Surface Mount Technology (SMT).**

**The performance of the filter is improved by means of minor changes of the layout based on the accurate simulation of acoustic and electromagnetic effects.**

**The influence of acoustic tracks on electromagnetic feedthrough is investigated with the help of a method for the experimental suppression of surface acoustic waves.**

## I. Introduction

Highly selective SAW filters are preferably realized as, e. g., Resonant Single Phase Unidirectional Transducer (RSPUDT), Double Mode SAW (DMS) and *fan* filters. The challenging specifications for filter performance lead to acoustic tracks of a considerable area. As a result of this, the influence of acoustic tracks on electromagnetic feedthrough becomes important, being able to determine the selectivity of SAW filters. For this reason, acoustic tracks should be properly considered by the electromagnetic simulation. However, acoustic tracks are geometrically complex structures, which may consist of hundreds or thousends of fingers. Thus, the consideration of finger electrodes by a commercial all purpose electromagnetic simulator would be very time consuming and is only in some cases viable [1].

Simulation approaches described in [2] typically provide an accurate description for RF SAW filters and duplexers. The electromagnetic feedthrough is usually computed neglecting the detailed characteristics of the acoustic tracks, such as the complex geometry of the interdigital transducers (IDTs) and reflectors.

However, in our experience ordinary electromagnetic models for acoustic tracks may be insufficient in case of filters having an important electromagnetic interaction between acoustic tracks and other potentially relevant structures. Especially for highly selective filters, electromagnetic phenomena must be considered, since they may degrade considerably the achievable acoustic selectivity.

The requirements put on the accuracy of electromagnetic simulation of geometrically complex structures, such as, for example, RSPUDT cells, demand for new approaches to the efficient computation of electromagnetic effects.

## II. Influence of Acoustic Tracks on Electromagnetic Feedthrough

Electromagnetic feedthrough is determined by the electromagnetic properties of acoustic tracks and other potentially relevant structures, such as, for example, on-chip metalizations. Due to the complexity of the geometry of acoustic tracks, the influence of acoustic tracks on electromagnetic feedthrough does not always receive the proper attention.

The impact of electromagnetic couplings concerning acoustic tracks is shown by means of an example. Fig. 1 shows a highly selective ceramic IF SAW filter including RSPUDT cells, Filter A. It is a broadband (usable passband 18.8 MHz) IF filter for WLAN applications, which is operated in balanced mode. The balanced ports are understood to be between pads 1 and 2 as well as 3 and 4, respectively.

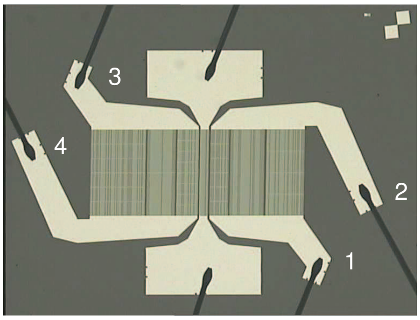


Fig. 1. Layout of the reference filter, Filter A, including port numbers.

Fig. 2 compares measured scattering parameters, $S_{14}$ and $S_{23}$, for Filter A without matching network, characterized as a four port device using the port numbers shown in Fig. 1.

One should observe the major coupling level between ports 2 and 3 in spite of the similar pad configuration with respect to ports 1 and 4. Applying the method presented in Sec. VI, it could be shown that the stop band performance of $S_{14}$ and $S_{23}$ is mainly determined by electromagnetic couplings.

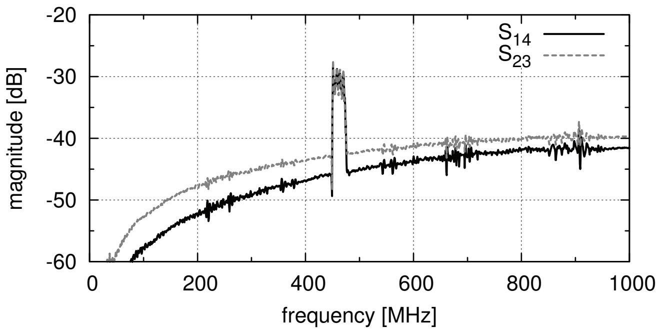


Fig. 2. Measurement of $S_{14}$ (solid line) and $S_{23}$ (dashed line) of Filter A.

The increased coupling level of $S_{23}$ can be explained by couplings among different acoustic tracks as well as between acoustic tracks and pads. Note that this effect could lead to a strong asymmetry in couplings, even for symmetric configurations of on-chip pads, bonding wires, package and printed circuit board (PCB).

Acoustic tracks can affect decisively the filter performance in stop band operation, since the electromagnetic feedthrough of the filter for balanced mode operation is mainly determined by asymmetries in electromagnetic coupling [3].

## III. Electromagnetic Simulation of SAW Filters

The overall simulation of the SAW components is composed of different types of acoustic and electromagnetic models, as described in [2]. Electromagnetic simulators are required to describe all relevant electromagnetic effects, allowing the prediction and optimization of the filter performance.

### A. Electromagnetic Modeling of SAW Filters

The modeling of SAW devices comprehends the following topics.

*1) Characterization of acoustic tracks:* The electro-acoustic properties of acoustic tracks, including interdigital capacitances as well as finger resistances, can be efficiently computed assuming a one dimensional approximation by the P-matrix model, as described in [4]. However, although this approach can compute the capacitances within one acoustic track, the interaction of different acoustic tracks and other potentially relevant structures is neglected.

*2) Characterization of on-chip structures:* The electromagnetic effects of the on-chip structures, such as, pads and bonding wires, can be simulated using a quasistatic or even a full wave analysis. See, for instance, [5–7].

*3) Interaction between acoustic tracks:* The interaction between different acoustic tracks is properly described by the 2D P-Matrix model. This model, which considers diffraction and reflection simultaneously, can characterize SAW devices providing a high degree of accuracy [8]. Thereto, reflection and coupling is considered localized at a longitudinal grid. Between the grid points free diffraction is assumed.

*4) Interaction between acoustic tracks and rest of relevant structures:* First approaches, based on commercial electromagnetic simulators, employ an internal interface between electromagnetic and acoustic simulation. These approaches can provide satisfactory results, as demonstrated in [7, 9] for RF filters and duplexers, respectively.

However, this model neglects the characteristics of the complex geometry of the fingers and their influence on electromagnetic effects. Hence, this approach may be insufficient for filters having a relevant electromagnetic interaction between acoustic tracks and other potentially relevant structures, such as, for example, the IF filter presented.

The accuracy of the electromagnetic simulation of IF filters is improved by a new acoustic track model, accounting for electromagnetic couplings among acoustic tracks as well as acoustic tracks and other potentially relevant structures.

This new approach, which goes beyond the method described in [8], is implemented in a new software tool, which is integrated in our proprietary simulation environment.

### B. Simulation Results

Measurement and simulation results using the proposed model show a good agreement, as can be seen in Figs. 3 and 4 for single path and mixed mode scattering parameters, respectively. The results obtained from the conventional simulation are also represented to demonstrate the advantage of the electromagnetic acoustic track model presented above. The

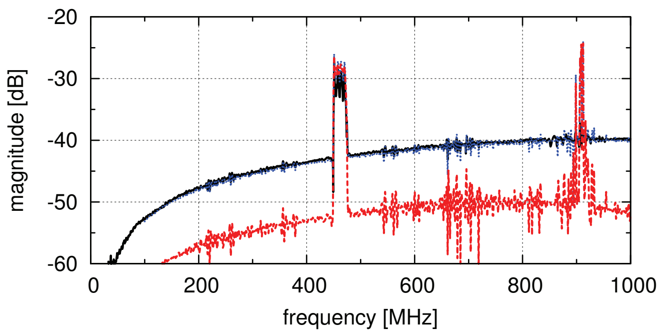


Fig. 3. Measurement (solid line), conventional simulation (dashed line) and new simulation (dotted line) of $S_{23}$ of Filter A.

conventional simulation provides similar attenuation levels for $S_{14}$ and $S_{23}$, indicating the origin of this asymmetry as a consequence of the influence of acoustic tracks on electromagnetic effects.

An important improvement of the simulation accuracy can also be observed in Fig. 4 for balanced-to-common and common-to-common mode transfer functions. The conversion of a balanced mode into a common mode and vice versa can be heavily influenced by asymmetries in electromagnetic coupling. Thus, for the description of such mechanisms it is necessary a high precision simulation, involving the electromagnetic effects of acoustic tracks.

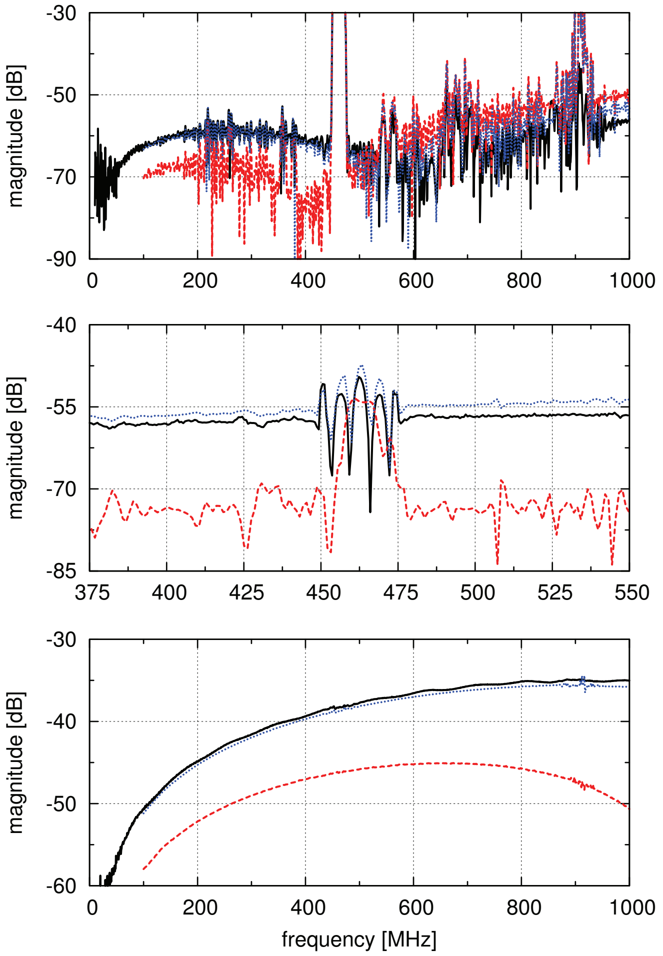


Fig. 4. Measurement (solid line), conventional simulation (dashed line) and new simulation (dotted line) of Filter A for balanced-to-balanced (top), balanced-to-common (middle), and common-to-common (bottom) mode operation.

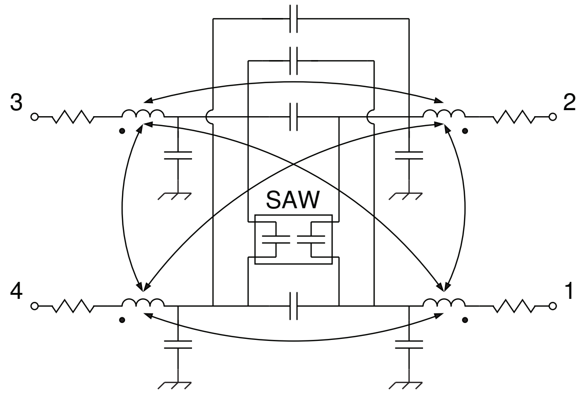


Fig. 5. Equivalent circuit including parasitics for Filter A.

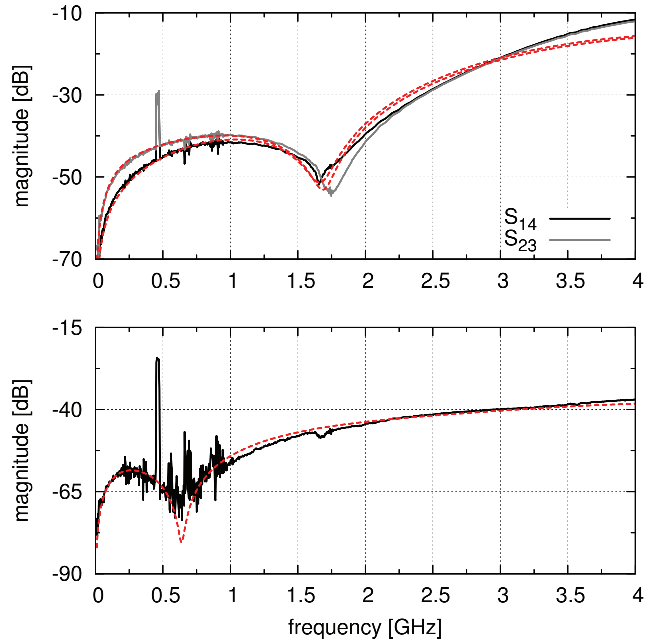


Fig. 6. Measurement (solid line) and equivalent circuit simulation (dashed line) of Filter A for single paths $S_{14}$ and $S_{23}$ (top), and balanced mode operation (bottom).

## IV. Analysis of Electromagnetic Feedthrough

Electromagnetic feedthrough can be analyzed on the basis of the accurate simulation results. Relevant electromagnetic effects in Filter A, including four port characterization, can be properly described using the equivalent circuit shown in Fig. 5. It models the electromagnetic interaction between the four ports of the filter in a general way. Values of circuit elements were obtained by fitting the simulation results obtained from our new simulation software. This equivalent circuit may be suitable for both single-ended and balanced filters.

Simulation results are compared to measurement results in Fig. 6 for single paths and balanced mode operation.

## V. Design Example for Improvement of Nearband Selectivity

The proposed equivalent circuit helps to get an understanding of the relevant electromagnetic effects and their effect on the electromagnetic resonance. It can be employed for investigating the way to adjust the electromagnetic resonance.

The modification of the interdigital capacitance in acoustic tracks could be used for the adjustment of the resonance, but it would imply an important variation of port impedances. More conveniently, the position of the electromagnetic resonance can be adjusted using small capacitance changes in transmission paths, as reported in [10].

The frequency position of the resonance could be adjusted by minor changes in the chip layout for Filter B, providing a considerable improvement in the nearband selectivity. We fabricated samples of the original filter, Filter A, and the improved filter, Filter B. Because of the precise simulation, only one design iteration was needed. Measurements of the original and improved variants of the filter without matching network are compared in Fig. 7.

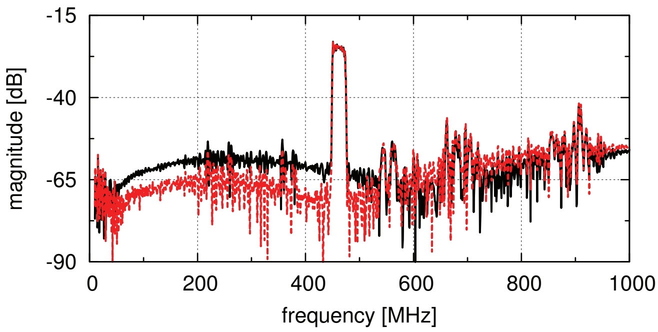


Fig. 7. Measurement of filter variants A (solid line) and B (dashed line) for balanced mode operation.

## VI. Suppression of Surface Acoustic Waves

Measurements provide the total of electromagnetic and acoustic phenomena. Hence, the separation of SAW and electromagnetic effects can become very difficult or even impossible. This holds true especially in case of SAW and electromagnetic feedthrougs having similar attenuation levels.

A way to directly measure the electromagnetic effects in SAW devices without rather concealing SAW effects is the suppression of SAWs. It can be easily achieved varnishing carefully the acoustic tracks with a non-conductive lacquer.

As the dielectric permittivity of the substrate is very high ($LiTaO_3$, having a relative dielectric permittivity exceeding 40), the lacquer should not affect importantly the capacitive couplings. Thus, this approach can avoid the propagation of SAWs without modifying the electromagnetic properties.

Fig. 8 shows the measured transfer function for balanced mode operation of Filter B in case of plain and varnished layouts, respectively. As the filter cover had to be removed in order to apply the lacquer, the filter was measured without

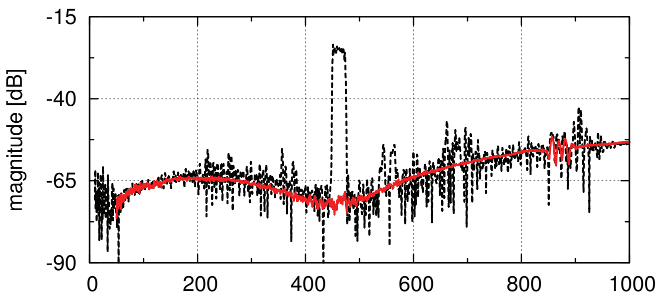


Fig. 8. Measurement of Filter B in case of plain layout (dashed line) and varnished layout for suppression of surface acoustic waves (solid line) for balanced mode operation. In both cases, the filter was measured without cover.

cover in both cases. Electromagnetic feedthrough can be clearly appreciated in this way, even if the electromagnetic feedthrough level is under the acoustic feedthrough level, as, for example, occurs in the pass band.

The presented technique may be applied to other SAW filter structures helping to identify electromagnetic effects.

## VII. Conclusion

The influence of couplings between acoustic tracks and other relevant structures on electromagnetic feedthrough is shown in this paper. The characterization of electromagnetic effects is realized with the help of a method for the experimental suppression of surface acoustic waves.

A new model accounting for the electromagnetic interaction of acoustic tracks with other potentially relevant structures in a high rejection IF filter for WLAN applications has been developed and implemented in our proprietary simulation environment. We obtained excellent agreement of measurement and simulation.

Electromagnetic feedthrough of the filter studied can be analyzed using the proposed equivalent circuit, which describes electromagnetic parasitics in a simplified but interpretable way.

The performance of the filter could be improved by means of accurate acoustic and electromagnetic simulation considering all relevant effects.

## Acknowledgement

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## References

[1] S. Zhgoon, K. Bhattacharjee, A. Loseu, J. Rao, and J. Flowers, "Modeling of Electromagnetic and Acoustical Properties of RF SAW Filters from On-Chip Layout Including all Electrodes and Comparison with Experimental Data," in *Proc. IEEE Ultrason. Symp.*, vol. 3, 2004, pp. 1914–1917.

[2] F. M. Pitschi, J. E. Kiwitt, C. C. W. Ruppel, and K. C. Wagner, "Accurate modeling and simulation of SAW RF filters," in *Proc. IEEE MTT-S Int. Microw. Symp. Dig.*, vol. 3, 2003, pp. 2009–2012.

[3] J. Kiwitt, F. M. Pitschi, K. Wagner, and M. Lorenz, "Novel Approaches to the Electromagnetic Design of CSSP RF Filters with Improved Selectivity," in *Proc. IEEE Ultrason. Symp.*, vol. 3, 2004, pp. 1992–1995.

[4] G. Kovacs, "A generalised P-matrix model for SAW filters," in *Proc. IEEE Ultrason. Symp.*, vol. 1, 2003, pp. 707–710.

[5] J. J. Caron and S. Malocha, "Electrical Parasitic Modeling in SAW RF Filters," in *Proc. IEEE Ultrason. Symp.*, vol. 1, 2002, pp. 361–364.

[6] T. Makkonen, V. P. Plessky, S. Kondratiev, and M. M. Salomaa, "Electromagnetic Modeling of Package Parasitics in SAW-Duplexer," in *Proc. IEEE Ultrason. Symp.*, vol. 1, 1996, pp. 29–32.

[7] S.-H. Lin, K.-H. Lin, S.-C. Chiu, and C.-Y. Chen, "Full Wave Simulation of SAW Filter Package and SAW Pattern inside Package," in *Proc. IEEE Ultrason. Symp.*, vol. 2, 2003, pp. 2089–2092.

[8] K. Wagner, M. Mayer, A. Bergmann, and G. Riha, "A 2D P-Matrix Model for the Simulation of Waveguiding and Diffraction in SAW Components," in *Proc. IEEE Ultrason. Symp.*, 2006, pp. 380–388.

[9] M. Solal, P. Girard, M. Aguirre, A. Bayram, C. Carpenter, F. Sinnesbichlerand, K. Cheema, S. Malocha, and B. Abbott, "Some Recent Advances in SAW Duplexers and PA Duplexers Modules," in *Third Int. Symp. on Acoust. Wave Dev. for Fut. Mob. Commun. Syst.*, 2007.

[10] J. J. Rao, A. S. Loseu, and K. J. Gamble, "Modeling and Design of a Wire bonded Low Loss Single Ended DMS Filter having broadband rejection of -45dB," in *Proc. IEEE Ultrason. Symp.*, 2007, pp. 941–944.