An Approach to Accurate Measurements of the Electrical Characteristics of SAW RF Filters Using Neutral Test Environments

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Abstract — **The paper discusses and classifies typical measurement setups used for the precise electrical characterization of surface acoustic wave (SAW) radio frequency (RF) components, such as, e.g., SAW filters and duplexers, in the context of nowadays demand for increased accuracy of measured filter data. The measurement setups are divided into test environments and application environments. By means of a couple of case studies the paper exemplifies the impact of printed circuit boards (PCBs) on the measured electrical filter characteristics. The effects observed are investigated by measurements and simulation. Simulation models established and analyzed take both relevant electromagnetic and acoustic effects into account. Comparisons of measurements and simulations indicate excellent agreement. The paper points out the necessity for measurement setups that provide a *neutral* environment to the filter. Here, the notion *neutral* environment implies minimal reflections, minimal feed-through or cross-talk, and minimal losses. It concludes with the proposal of a *neutral* environment, which has been successfully implemented in a couple of use cases. Performing the measurement using a *neutral* environment allows the determination of the filter characteristics without effects caused by the PCB, which is considered an essential prerequisite for an engineering approach to a modular design of a complex system, such as, e.g., the RF section of a mobile terminal.**

I. Introduction

Being key components in the microwave sections of mobile terminals, surface acoustic wave (SAW) radio frequency (RF) filters have been pace makers for the development of wireless applications. In recent years typical form factors of SAW RF filters have decreased from 5.8x5.8 mm^2 to 1.4x2.0 mm^2, while center frequencies have shifted from 1 GHz to above 2 GHz and specification items are found at frequencies extending up to about 6 GHz. Concurrently, there has been a constant improvement of the filter performance, such as, the matching, the close-in selectivity, and the far-off attenuation. Furthermore, additional functions such as impedance transformation or balun functionality have been integrated. Finally, single components such as 2-in-1 filters or duplexers combine the functions of two formerly separate filters in very compact packages. With these components also isolation has been subject of improvement.

Due to these developments the correct determination of the electrical characteristics of individual SAW RF filters has become a major issue for both design engineers of SAW RF filters and design engineers of mobile terminals dealing with SAW RF filters. So far it is well understood that the electrical properties of SAW RF filters largely depend on electromagnetic effects of the chip layout, the bonding structures, and the package. But with smaller form factors, higher frequencies, and increased performance requirements also the measurement setup may have a significant impact on the measured electrical characteristics of the filter.

In Sec. II we start right away exemplifying the impact of printed circuit boards (PCBs) on the measured electrical characteristics by means of a couple of case studies. These case studies will allow us to formulate the statement of the problem in Sec. III. In Secs. IV and V the effects observed are investigated by measurement and simulation. Furthermore, the simulation models being used are discussed, and comparisons between measurements and simulations considering both electromagnetic and acoustic effects are shown to prove the validity of the models used. The paper proposes a design and evaluates an implementation of a neutral environment in Sec. VI. Finally, we conclude in Sec. VII that performing the measurement using a neutral environment allows the determination of the filter characteristics with minimal effects caused by the PCB, which is considered an essential prerequisite for an engineering approach to a modular design of a complex system.

II. Case Studies

In the following we will take a phenomenological approach to get an impression of the problem being discussed. For this purpose we prepared a collection of measurements of different SAW RF filters on different test PCBs. This collection contains a more or less random choice of SAW RF filters soldered onto PCBs showing typical effects. It should be noted that these filters are typical in the sense that they do not include special features which are the prerequisite for the following observations. At this point our major interest is not put on the performance of the filters shown, but on the changes of the per-

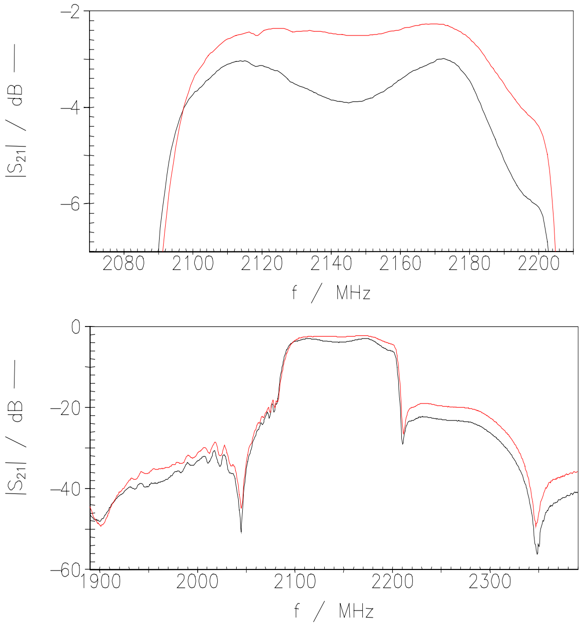

Fig. 1: Comparison of measured transmission functions of identical W-CDMA Rx filters on two different PCBs.

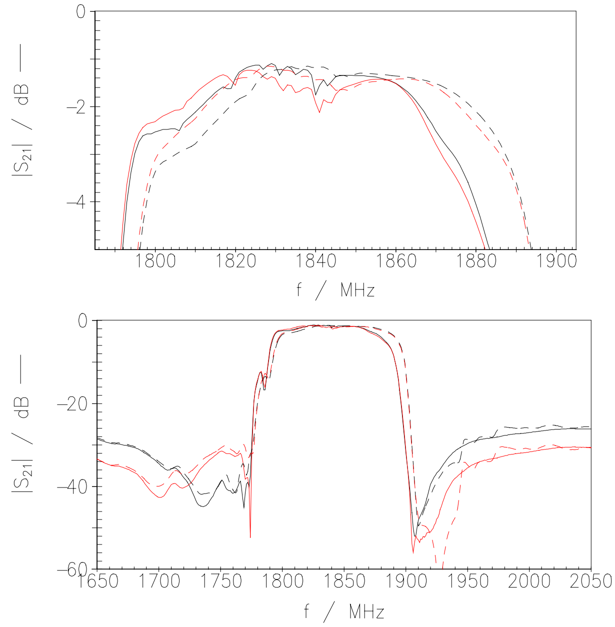

Fig. 2: Comparison of measured (solid) and simulated (dashed) transmission functions of identical PCN Rx filters on two different PCBs.

formance of the filters that can be observed on different PCBs. We will return to the topics of PCB types and the characterization of PCBs by measurement in Sec. IV and to the topic of characterization of PCBs by simulation in Sec. V in more detail.

Fig. 1 shows the comparison of the measured transmission functions of two identical W-CDMA filters on two different PCBs. Regarding the upper part of the figure, providing a detailed view of the pass band, two major impacts can be observed. Firstly, there is an additional constant attenuation of more than approximately 0.6 dB indicating additional losses. Secondly, there is an increase of the filter's amplitude ripple of about 0.6 dB caused by deteriorated matching. In the lower part of the figure the stop band attenuation is depicted. Whereas the locations of transmission zeros are not affected, the attenuation level, especially in the upper stop band, but also in the lower stop band, changed by some 5 dB.

Moving on to Fig. 2, it can be seen in the upper part of the figure that the situation is similar, though, not as pronounced. Again, there is an additional constant attenuation and an increase of the attenuation ripple within the pass band of about 0.1 dB and 0.3 dB, respectively. In the lower part of the figure focusing on the stop band attenuation the situation slightly differs. Whereas similarly to the first case the attenuation levels in the lower and upper stop band differ by some 5 dB, in this case the locations of the transmission zeros and as a consequence the shapes of the stop band attenuation deviate tremendously.

Summing up, we found that basically all filter characteristics have been affected in the cases presented. As shown the pass band attenuation, matching, close-in selectivity, and far-off attenuation, changed. The ways, in which they have been affected, have been similar regarding the pass band, but different regarding the stop bands. In contrast to the examples shown, the effects can also be almost negligible under certain circumstances as shown below.

Nevertheless, with changes of several tenths of dB in the pass band and several dB in the stop band it is crucial to understand these effects, as both design engineers of SAW manufacturers as well as the application engineers of SAW components struggle every day to reduce insertion loss by another tenth of dB or increase stop band attenuation by a couple of dB.

III. Statement of the Problem

As the microwave section of radios represents a very complex electrical system, it is pieced together using a hierarchy of subsystems, which ends in subsystems that merely consist of simple electrical components. Piecing these subsystems together only works using the classical engineering approach of modularization. It is the notion of interfaces that is tightly associated with modularization, since the performance of every subsystem is determined with respect to these interfaces. Unfortunately, finding appropriate interfaces and also complying to these interfaces is extremely difficult as form factors of the subsystems, and in our case especially the components, are becoming smaller and smaller, the interfaces extend with each additional functionality, and, finally, the subsystems move closer together with increasing component density on the

PCBs. Moreover, there are usually three interfaces that have to match in pairs:

1. the interface of the component,
2. the interface for the component in the test environment, and
3. the interface for the component in the application environment.

For unit testing the interface of the component has to match the interface of the test environment for that component. Design engineers of SAW RF filters regularly perform these tests to evaluate the performance of the SAW components during the product design and maintenance phases. Application engineers make these tests to verify that the filter meets all specification items required. For the final system testing the interface of the component has to match the interface of the application environment. The tests are performed by the application engineers to verify the operation of the SAW RF filter in the mobile phone.

Hence, the key problem being discussed in this paper is to define and provide an interface, i.e., a neutral test environment, which allows the precise electrical characterization and operation of the filter without intentionally or unintentionally including artifacts of the test setup or application setup. At this point it should be understood that the artifacts considered here in general are not effects that can be removed by calibration or de-embedding. The artifacts are features that actually exist in the setups and that cause relevant electromagnetic effects modifying the filter characteristics.

Violating the concept of neutral test environment, a couple of well-known problems may appear, such as, e.g., the filter performs well on the test PCB, but fails on the phone PCB regarding insertion loss, matching, selectivity, or isolation, resulting from the components provider's point of view in the necessity to spend additional effort in the redesign of the filter or in the loss of business.

In the following we will have a close look at the measurement and simulation procedures as well as at the device under test (DUT).

IV. Measurement Setups and Procedures

Common in all measurement setups is the network analyzer (NWA), which is connected to the test or phone PCBs via coaxial cables. The measurement system is assumed to have 50 Ω. Before starting the actual measurements, the measurement system has to be calibrated using either full-two-port short/open-/load-/through-(SOLT-)calibration or through/reflect/line-(TRL-)calibration. In the latter case special, usually application-specific calibration standards are required.

In case of multi-port components the measurement becomes tedious as depending on the type of NWA all possible 2-ports have to be measured, while unused ports are terminated with the reference impedance. Post-processing the data obtained from successive 2-port measurements an *n*-port scattering matrix is created. For convenience multi-port NWAs easing the procedure for the characterization of duplexers and 2-in-1-filters are available.

For characterization of balanced ports special treatment is required [13], [14]. Using a standard NWA with single-ended ports the mixed-mode scattering-parameters have to be calculated post-processing the measured data. Again, special measurement equipment for directly obtaining mixed-mode parameters is available.

The different types of setups discussed below are the application and test environments, which can be both neutral or non-neutral, respectively, regarding the electrical characteristics measured. Hence, the outline chosen should not yield the impression with the reader that there are three different types of environments. Instead, neutral or non-neutral are properties of the application and test environments.

A. Application Environment

The application environment of the filter is defined by the phone PCB. Usually it is a multi-layer PCB with several stacked signal, ground, and DC supply layers. The separation of RF and DC-layers by a solid ground metalization layer is desirable. Sometimes deviations from this preferred configuration are found. The dielectric layers between the metalizations are kept very thin in order to keep the total PCB thickness small even if using more than a handful of layers.

B. Test Environment

To verify the performance of packaged SAW RF filters, they have to be measured using specific test PCBs. Both design engineers of SAW RF filters as well as application engineers use test PCBs for checking the performance against design goals and specification items. The test PCBs can be regarded as simplified application environments, which should reproduce the RF signal transmission paths of the corresponding application environments. The very goal is the presentation of an environment to the SAW component that is similar to the one found later on the phone PCB. Of course, due to differences in the layer stack the test PCB can merely be an approximation of the phone PCB. Furthermore, it can only consider a small part of the phone PCB, i.e., the area of the phone PCB that is in the immediate vicinity of the SAW RF filter. It may, though, contain provisions to add matching components at the filter ports.

Nevertheless, despite these approximations test PCBs should allow the correct prediction of the operation of the SAW component within the complete system. Hereto, the bare filter performance is required. Although being an obvious requirement, determining the bare filter performance is not common practice, since, by experience and as shown before, the results of such measurements tend to depend on the specific measurement setup.

C. Neutral Environment

Searching for an environment that fulfills both requirements imposed by unit and system testing, an environment is needed that combines the properties of the test and application environments. Since it is basically simpler to remove or at least minimize an effect than to design an effect to have a certain magnitude, the combination of the properties is done in the sense of finding the smallest common denominator. Thus, a minimal set of effects is chosen ending up in a neutral environment. Such an environment is designed to match the measurement system impedance at its external ports. Moreover, reflections along the complete signal path as well as parasitic feed-through or cross-talk between the ports are minimized. Thus, the filter performance should be accessible as original as possible. Put the other way: The filter performance should not be modified by the measurement setup.

V. Simulation Tools and Procedures

The simulation and the underlying modeling of SAW components are the key functions that are required in an electronic design automation (EDA) system to allow rapid virtual one-shot prototyping.

With SAW components being on the market for decades, many techniques for SAW modeling have been successfully applied in research and industry and have been reported in the literature [1]-[7]. There are two essentially different types of approaches: 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).

With the appearance of low-less SAW RF filters and their introduction in applications in the GHz-range during the last years, EM modeling, compared to acoustic modeling, is a rather new area of interest [8]-[11], which gained considerable importance. The reason is that modern SAW RF filters, such as, e.g., 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. Thus, for instance SAW reactance filters use 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 of the filters each providing a series resonance making a short-circuit, an anti resonance making an open-circuit, and defining a certain impedance level. With the immittances shaping the filter characteristics in a unique, but non-trivial way, parasitic reactances caused by EM effects change or even overwhelm the acoustic effect, considerably affecting the overall filter performance. The EM effects originate from

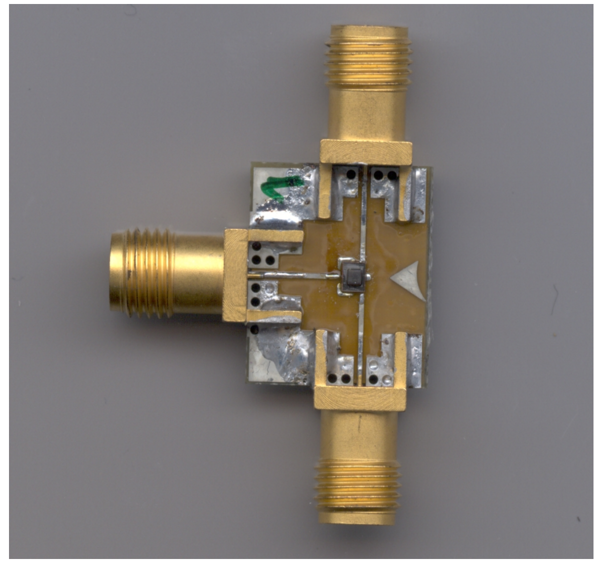

Fig. 3: Top view of test PCB providing a neutral environment to the SAW component.

the on-chip layout connecting the acoustic structures, the package, and, depending on the bonding technology being used, the bonding wires or the bumps in case of wire or flip-chip bonding, respectively. Finally, EM effects may also be introduced by the PCB.

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.

Having seen the impact which PCBs can have on the filter performance measured it is easy to accept that the simulation model has to be extended by the PCBs being used. After having them included, excellent agreement of measurement and simulation can be found, as shown in Fig. 2. We will take advantage of this fact by using simulations for further investigation of the effects and also for the optimization of the structures to minimize the effects where they are disturbing.

VI. Neutral Test PCB

A. Functional Parts Of PCB

Regarding the test PCB in Fig. 3 there are four regions that can be distinguished. From outside to inside these are the SMA connectors, transitions from the SMA connectors to the microstrip lines (MSLs), the microstrip lines, and the landing area for the device under test. The latter three are

Table I
Dimensions and properties of 50-Ω-microstrip line.

Substrate height h	200	µm
line width w	340	µm
metal thickness t	35	µm
height of solder resist s	0	µm
relative permittivity ε_r	4.5	
line impedance Z	50.6	Ω

located on the PCB substrate making the PCB substrate material and layer stack especially important.

B. PCB Substrate Material and Layer Stack

The substrate material used is FR4 and was chosen to conform to the phone PCB. It is known to be a cheap material in comparison to RF materials making it a good choice for cost-effective solutions. On the other side, it is also known to have pretty poor RF properties and to considerably suffer from large fabrication tolerances.

The basic material parameters of FR4 are its dielectric loss, $\tan\delta \approx 0.02$, and its permittivity, $\varepsilon_r = 4.5 \pm 0.3$. Both are quite high compared to RF substrate materials.

Fabrication tolerances of ±5% and more have been reported in all dimensions, e.g., line width, slot widths, substrate thickness, and metalization thickness, as well as material parameters, e.g., the substrate permittivity. Also the alignment of layers as well as the positioning of vias go with considerable tolerances.

Our test PCBs consist of three dielectric layers allowing for four metalized layers. The thickness of the outer dielectric layers are given in Table I. The height of the center dielectric layer serving as the carrier is uncritical. In the following the four metalized layers are referred to as top side, upper ground, lower ground and bottom side metal layer.

C. Design Proposal for Neutral Test PCB

During a project we precisely investigated the effects of the SMA connectors, the transitions from SMA connectors to MSLs, and the landing areas for DUTs. The investigations have been done by simulation using commercial EM field simulators, after verification of the results on many test configurations.

We optimized the electrical properties in order to yield a neutral PCB aiming at:

- minimal reflections,
- minimal feed-through or cross-talk, and
- minimal losses.

The dimensions of the MSL are summarized in Table I. Although the dimensions have been carefully designed to meet the required line impedance of 50 Ω, remembering Sec. VI.B, fabrication tolerances result in large spreads of the line impedance and the need for prior verification.

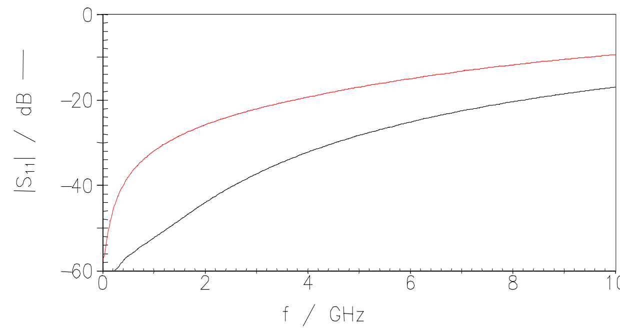

Fig. 4: Comparison of simulated reflection functions for old (red) and new (black) transitions from SMA connector to MSL.

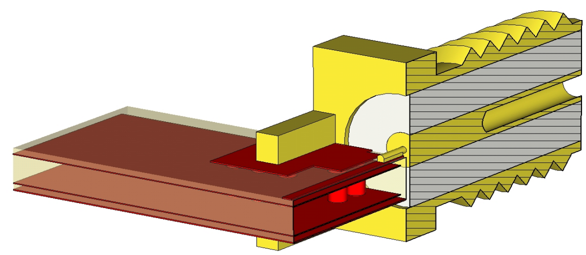

Fig. 5: Perspective view of optimized transition from SMA connector to MSL.

The transition from the SMA connector to the MSL has been optimized to cause minimal reflections. Regarding Fig. 4 an improvement of around 20 dB has been obtained in the relevant frequency range from 1 to 2 GHz. In Fig. 5 the detailed layout of the transition can be seen. Note that the upper ground layer is solid, i.e., not partially removed in the area of the solder pads of the connector.

A variety of different landing areas for the SAW RF filter has to be handled, since the landing areas are laid out according to the required footprints of the packages of the SAW components as well as the modes of operation of the SAW components. In general, good connection to ground for ground pads and good shielding of signal pads implies the use of many vias between the top side and the upper ground metalizations. Again, the upper ground metalization is solid. For details refer to Fig. 6, which shows the relevant part of a test PCB.

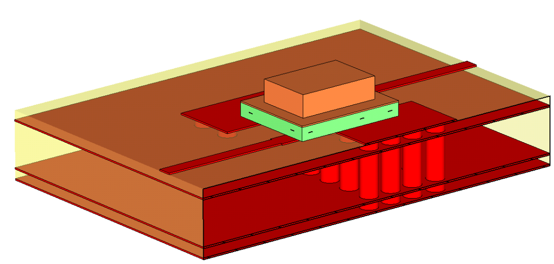

Fig. 6: Perspective view of landing area extracted from test PCB.

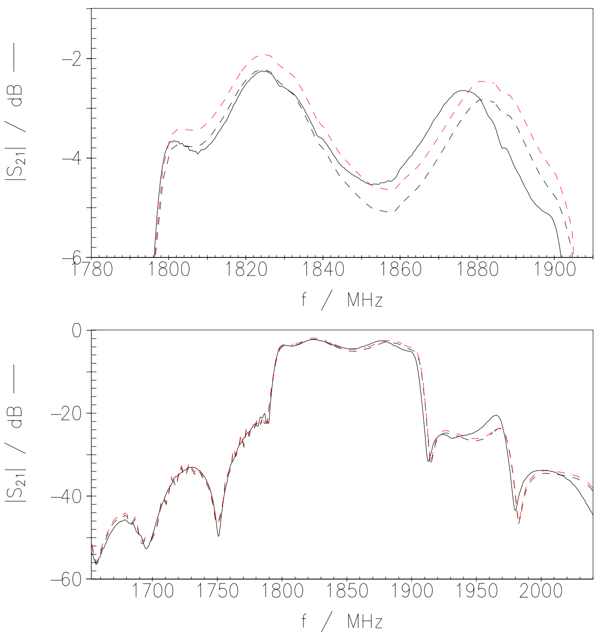

Fig. 7:**Comparison of measurement (black solid) and simulation (back dashed) of EGSM Rx filter soldered on neutral PCB and simulations on ideal PCB (red dashed).**

D. Results

In order to prove our concept we performed a simulation using an ideal PCB. Here, an ideal PCB is defined as a PCB that provides ideal connections. Since being a virtual construct for which one cannot provide the measurement, we think that the simulation of an ideal PCB is a suitable substitute remembering the agreement of measurement and simulation as shown in Fig. 2. In Fig. 7 we show the measurement and simulation of an EGSM Rx filter soldered on a neutral PCB in comparison to the simulation of the complete component soldered on an ideal PCB. Again, the agreement of measurement and simulation is very good. By inspection, the simulated performance of SAW RF filter obtained on the neutral PCB is (almost) identical to the performance simulated on the ideal PCB. Differences arise in the pass band. The constant additional insertion loss can be assigned to losses in the PCB, which are, as mentioned above, neglected in the ideal PCB.

VII. Conclusion

The paper showed the impact of the measurement setup on the measured performance of SAW RF filters. It proposed a design methodology based on a neutral environment. Performing the measurement using a neutral environment allows the determination of the filter characteristics almost without other effects. Thus, the bare performance of the SAW RF filter can be gained and taken into account during system design. Doing so is an essential prerequisite for an engineering approach to a modular design of a complex system.

The SAW RF filter performs identically in the test and application environments, if these environments have the same EM effects added on the performance of the filters. Since, by definition, test and application environments are implemented by two physically different configurations, electrically identical configurations are best achieved by minimizing EM effects, i.e., by heading for neutral environments in both situations.

VIII. References

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