Design study on a compact, high performance SAW duplexer

Andreas Fleckenstein[*], Jürgen E. Kiwitt[◇], F. Maximilian Pitschi[◇], Michael Jakob[◇],
Karl Ch. Wagner[◇], Wolfgang Menzel[*]

[◇] EPCOS AG, Anzinger Str. 13, 81617 Munich, Germany
[*] University of Ulm, Albert-Einstein-Allee 41, 89081 Ulm, Germany
Email: andreas.fleckenstein@uni-ulm.de

Abstract — **In this paper various design aspects concerning SAW duplexers are presented. Special focus is placed on an integrated lumped matching network, which allows to save space within the LTCC package. This corresponds with the trend of miniaturization of RF front-end components for cellular phones. To show the feasibility of this approach a SAW duplexer has been designed accordingly. In the design process two different modelling techniques for the electromagnetic computation of the package are compared in terms of their accuracies. Simulation and measurement of the device agree very well.**

I. INTRODUCTION

In mobile applications a trend to passive integration of RF front-end components can be observed. For example receiving (Rx) and transmitting (Tx) filter together with a phase shifting network are combined to form the so called duplexer, as depicted in Fig. 1. Its task is to split up Tx and Rx signal on a frequency basis and to attenuate out of band signals. The filters are connected at the common antenna port (port 2) and provide a separate port for the following transmitter (port 1) and receiver stages (port 3), respectively.
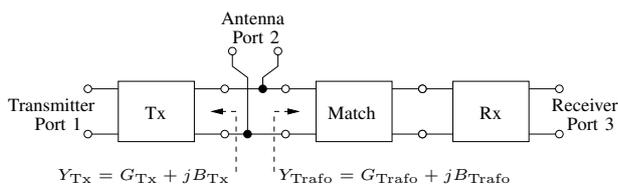

Fig. 1. Principle duplexer set up.

Duplexers in state-of-the-art cellular phones are mainly realized by acoustic components. They exhibit a small size caused by the low phase velocity of acoustic waves compared to electromagnetic waves. So the required miniaturization of the duplexing devices becomes feasible. The acoustic resonators are usually arranged in a ladder-type structure to form the Tx and Rx filter.

To maintain the advantage of small size, a compact package design is required, too. Therefore, flip-chip technology together with LTCC is the prefered packaging approach. The necessary matching network and possible tuning circuitry have to be integrated within the multilayer ceramic part. A small size of these elements is an important prerequisite for a compact package. For the presented duplexer the package footprint has been reduced to $3\,\text{mm} \times 2.5\,\text{mm}$.

Besides space considerations, there are special electrical constraints on duplexing components for mobile applications. In order to ensure a long operation time of the phone, low losses within the RF front-end are aimed at. This results in a strict specification for the insertion loss within the Tx filter passband.

The power level of the received signal is several orders of magnitude lower than the signal at the output of the transmitter power amplifier. To prevent the receiver LNA from being blocked by the Tx signal, a high isolation between port 1 and port 3 of the duplexer and a high selectivity of the filters is required. For the presented duplexer an isolation of $52\,\text{dB}$ and $40\,\text{dB}$ for transmit and receive band is aimed at.

II. DESIGN

A. Matching

Direct connection of Tx and Rx filter at the common antenna port leads to a mismatch within the passbands of the filters. For illustration of this effect the characteristic input reflection coefficient of a SAW-filter is depicted in Fig. 2. The input impedance around the passband can be divided into three regions. Below the passband the filter input acts as a low-impedance load, whereas above the input impedance is high, acting as a small capacitance. Within the passband the filter is well matched.
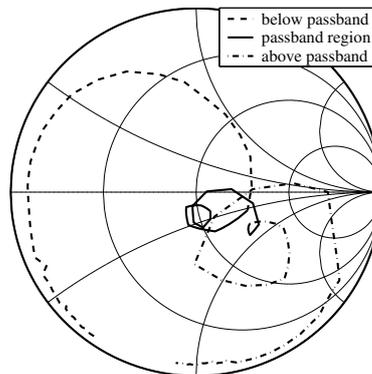

Fig. 2. Input reflection coefficient of a SAW filter.

In wireless communication systems the Tx band is located below the Rx band. This means that the input impedance of the Rx filter at transmission frequencies is very low. A direct shunt connection of both filters at the antenna port would result in short circuiting the Tx filter. In order to reduce the influence on the Tx filter, the input impedance of the Rx filter has to be transformed to a high-impedance value.

At receive frequencies, the Tx filter input acts as a small capacitor. This can be compensated for by transforming the Rx filter input impedance to the inductive region. To accomplish the necessary transformations, a matching network is included in front of the Rx filter, as shown in Fig. 1. The mentioned requirements concerning the matching circuitry can be summarized in the following equations:

$$
\begin{array}{c|c}
\text{Tx band} & \text{Rx band} \\
G_{\text{Trafo}} \approx 0\dfrac{1}{\Omega} & G_{\text{Trafo}} \approx \dfrac{1}{50}\dfrac{1}{\Omega} \\
B_{\text{Trafo}} = -B_{\text{Tx}} & B_{\text{Trafo}} = -B_{\text{Tx}}
\end{array} \tag{1}
$$

G_{Trafo}, B_{Trafo} and B_{Tx} denote input conductances and susceptances, as defined in Fig. 1. Usually a quarter-wavelength-line is used to fulfill these equations. However this approach is not ideal in terms of space requirement.

A promising alternative is the use of lumped components for matching. In this context a lot of different topologies are feasible. There are some publications on duplexers for wireless communication systems, mentioning the use of lumped elements for matching. In [1] matching has been realized by the lumped equivalent circuit of a quarter-wavelength-line. The properties of the line have been synthesized by the application of two inductors and one capacitor. A combination of several L-shaped structures, consisting of inductors and capacitors, are used in [2] and [3]. Phase-shifting of the Rx filter input impedance and matching of both filters is accomplished by separate structures. The utilized lumped elements were realized externally. Fig. 3 summarizes these matching approaches. In [4] an alternative method, loading the individual filter branches with serial or parallel inductors, is described. So the input impedance of Tx and Rx filter is tuned in a way, that they can be connected at the antenna port without an additional matching network.
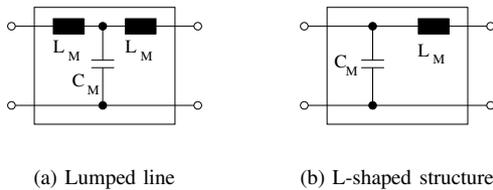
(a) Lumped line   (b) L-shaped structure

Fig. 3.   Proposed lumped matching networks.

For the presented duplexer a simple, compact matching circuit was aimed at. An L-shaped network, as shown in Fig. 4, was chosen. It consists of a parallel inductor, which can be integrated in the multilayer LTCC package, and in addition to that a SAW resonator, which is implemented on the acoustic chip. Its acoustic resonance is placed in the

receive band. Therefore, the simplified equivalent circuit diagrams of the matching network, depicted in Fig. 5, can be derived.
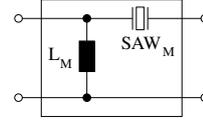
Fig. 4.   Realized lumped matching network.
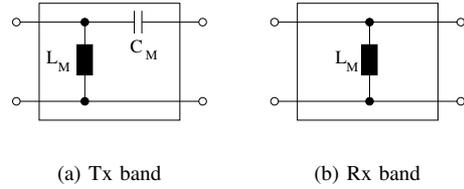
(a) Tx band   (b) Rx band

Fig. 5.   Simplified matching circuit model.

Within the Rx band the matching circuitry is dominated by the parallel inductor. It is used to compensate for the susceptance of the Tx filter input. At transmission frequencies, the series SAW resonator acts as a capacitance. So the combination of inductor and capacitor is used to perform the phase-shift of about $180°$ for the input reflection coefficient of the receive filter.

There are several possibilities to realize a package integrated inductor. For example one can take advantage of the multilayer stack-up of the LTCC package and design a three dimensional structure, as depicted in Fig. 6a. The required area for this layout is very low. But layer misalignment, which can occur during the LTCC production, has some effect on its inductance value. A planar inductor, shown in Fig. 6b, is fairly independent of any layer misalignment. Yet it requires more area within the package.

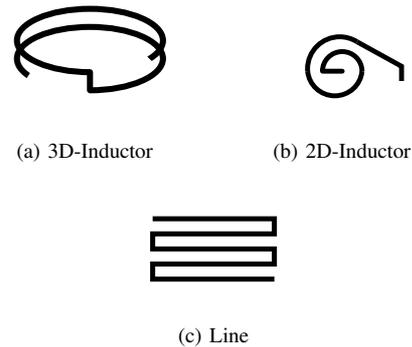(a) 3D-Inductor   (b) 2D-Inductor

(c) Line

Fig. 6.   Layout of matching elements (not drawn to scale).

Another aspect regarding the inductor design is the quality factor. Electromagnetic simulations indicated, that a circular shape is superior to a square shape in this context [5]. This is due to the lack of field intensity peaks in the more continous circular structure. Fig. 7 shows a comparison of computed quality factors of a square and circular inductor, respectively. The frequency axis is normalized to the duplexer's design frequency f_0.
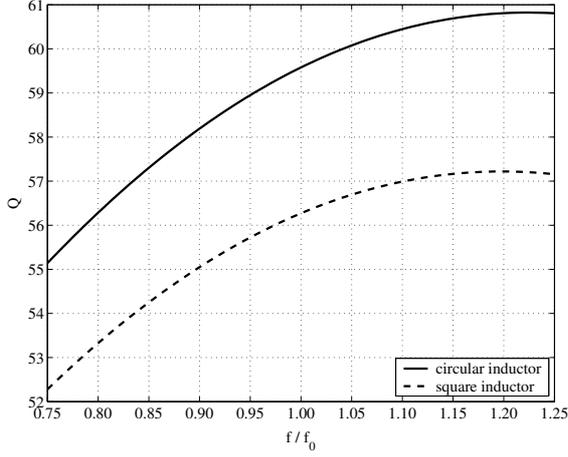
Fig. 7. Simulated quality factor of planar inductors.

Fig. 8. Worst-case-estimation for error propagation caused by the combination of inaccurate raw s-parameters.

For the presented duplexer a planar, circular spiral inductor has been chosen as matching element. The conventional quarter-wavelength matching approach would lead to a line length of about $1\,\mathrm{cm}$ in LTCC at $2\,\mathrm{GHz}$. Even if this line is arranged in a meander like shape, as shown in Fig. 6c, some space can be saved by using the lumped matching approach.

B. Isolation

In connection with a reduction of package size and small distances within the ceramic part, crosstalk problems become more severe. Its main effect can be observed on selectivity of the filters and isolation between transmitter and receiver port. To get some insight into the interaction of package and chip, their s-parameters are considered separately (s^{pkg}, s^{chip}). For computing the duplexer's s-parameters (s) corresponding ports of chip and package are connected. In a mathematical sense this means, that respective wave amplitudes have to be equated. So the following expression can be derived:

$$s_{x,y} = s_{x,y}^{\mathrm{pkg}} + s_{x,\vec{a}}^{\mathrm{pkg}} \cdot \left((s^{\mathrm{chip}})^{-1} - s_{\vec{a},\vec{a}}^{\mathrm{pkg}}\right)^{-1} \cdot s_{\vec{a},y}^{\mathrm{pkg}} \quad (2)$$

Indices x and y denote port numbers of the duplexer. Concerning isolation $x = 3$ and $y = 1$ has to be inserted. Vector $\vec{a}$ references the ports of the package, which are connected to the chip.

The first part of the right hand side of (2) is referred to as basic term. It is related to the transmission and reflection properties of the package itself. The rest of the right hand side of (2) describes the interaction of package and chip. It considers the transmission from the selected duplexer input (y) to all chip-package-connections and vice versa to the output (x). For an ideal package, without any influence on the duplexer's characteristics, these transmission factors would amount to one for a signal feed through and to zero otherwise. The basic terms would vanish. To come close to this state the signal feed throughs as well as the ground connections have to be carefully designed, regarding the different coupling mechansims.
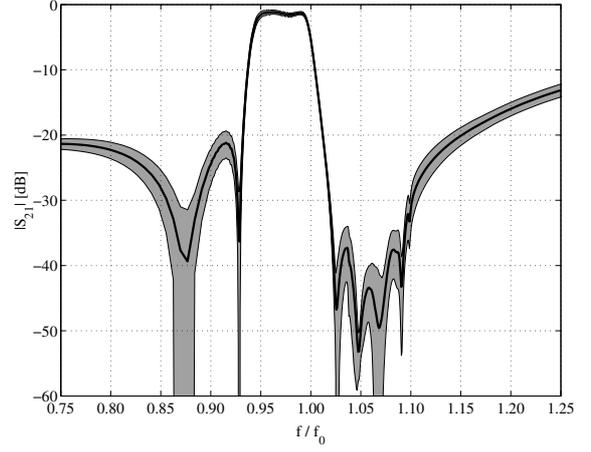
III. PACKAGE SIMULATION

Realization of highly miniaturized duplexers, which have to meet strict specifications, requires a complex simulation approach. Accurate prediction of the electromagnetic behaviour of the LTCC package is a crucial part of this procedure. It has been shown in former publications that full wave methods are most appropriate to this task [6], [7]. For the simulations reported here, a commercial 3D finite elements tool has been applied.

In general, chip and package characteristics of a SAW-device are computed separately. Interfaces are provided by corresponding internal ports in both models. The resulting s-parameter matrices can be combined applying (2). The separation leads to a simplification of the simulation model. Field couplings between package and chip are not taken into account and the field distribution is slightly altered by introducing internal ports.

The effect of inaccuracies in the raw s-parameters on the combined result has to be examined. A worst-case-estimation for this error propagation can be derived by forming the total differential of (2).

$$
\begin{aligned}
\Delta|s_{x,y}| = \sum_m \sum_n \Bigg(& \left|\frac{\partial|s_{x,y}|}{\partial\mathfrak{Re}\{s_{m,n}^{\mathrm{pkg}}\}}\right| \cdot |\Delta\mathfrak{Re}\{s_{m,n}^{\mathrm{pkg}}\}| \\
& + \left|\frac{\partial|s_{x,y}|}{\partial\mathfrak{Im}\{s_{m,n}^{\mathrm{pkg}}\}}\right| \cdot |\Delta\mathfrak{Im}\{s_{m,n}^{\mathrm{pkg}}\}| \Bigg) \\
+ \sum_p \sum_q \Bigg(& \left|\frac{\partial|s_{x,y}|}{\partial\mathfrak{Re}\{s_{p,q}^{\mathrm{chip}}\}}\right| \cdot |\Delta\mathfrak{Re}\{s_{p,q}^{\mathrm{chip}}\}| \\
& + \left|\frac{\partial|s_{x,y}|}{\partial\mathfrak{Im}\{s_{p,q}^{\mathrm{chip}}\}}\right| \cdot |\Delta\mathfrak{Im}\{s_{p,q}^{\mathrm{chip}}\}| \Bigg)
\end{aligned} \quad (3)
$$

Fig. 8 shows the resulting error band $\Delta|s_{21}|$ for the transmission from port 1 to port 2. An inaccuracy of 1% for the raw data has been assumed. One can observe main error amplification in the region of transmission zeros.

An alternative simulation procedure is based upon a common model for chip and package. In this case only the acoustic resonators are computed separately and included in the electromagnetic simulation results using network methods [8]. This approach promises a higher accuracy,

but raises computational cost compared to the approach using a separated model.

IV. MEASUREMENT RESULTS

The measured duplexer characteristics together with simulation results are shown in Figs. 9 and 10. A very good match can be observed in a narrowband as well as in a broadband view. Measurement results prove the feasibility of the lumped matching network.
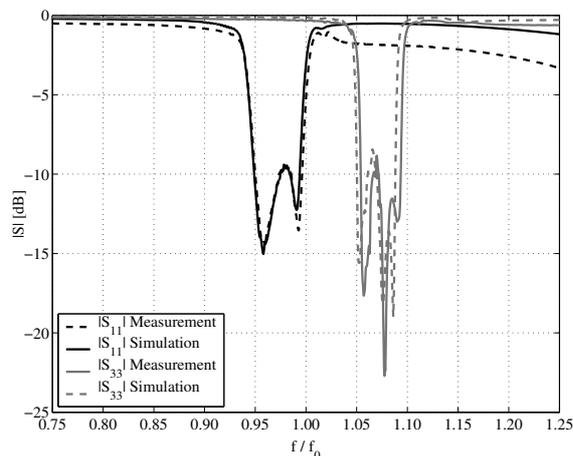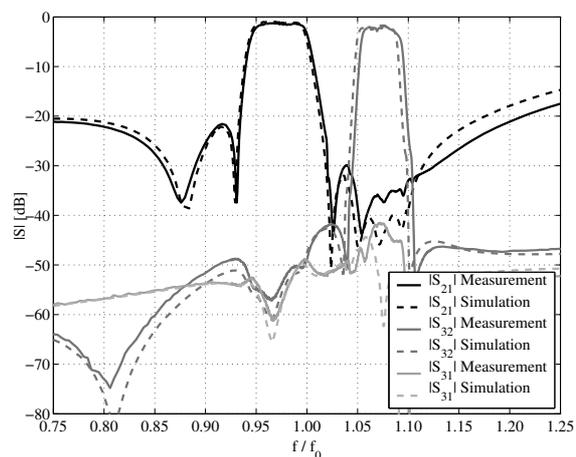

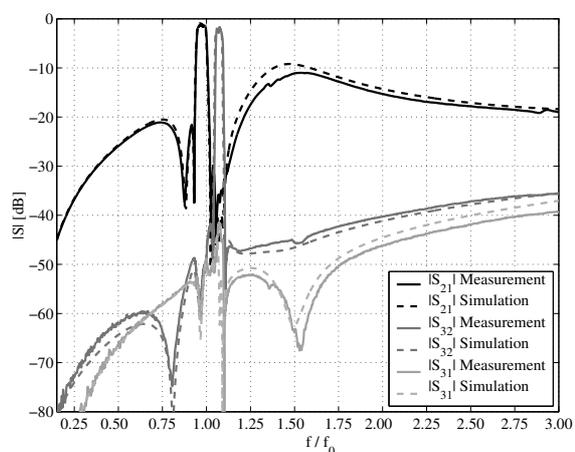Fig. 9.   Reflection properties of the SAW duplexer.

V. CONCLUSION

A new compact SAW duplexer has been designed. Matching of Tx and Rx filter has been realized by a lumped element network, consisting of a parallel inductor and a series SAW resonator. This circuitry is advantageous in terms of space requirement compared to the typically applied quarter-wavelength line.

Different ways of modelling the device for electromagnetic simulation were compared regarding their accuracy. Measurements show a very good agreement with simulation results and demonstrate the practicability of the lumped element matching network.

(a) Narrowband

(b) Wideband

Fig. 10.   Transmission properties of the SAW duplexer.

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