

Design of Duplexer “Inserts” for Mobile Phone Module Applications

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Abstract — Especially in the context of the upcoming requirement put on wireless terminals, such as mobile phones, to support both multiple standards and multiple bands there has been a continuous trend of integrating and miniaturizing the front-ends of wireless terminals. This has been achieved by means of shrinking the sizes of key components as well as integrating them along with many passive and also some active components in front-end modules. As some mobile communication standards are based on full duplex operation, SAW or FBAR duplexers need to be integrated into such modules. They are among the most demanding passive acoustic components regarding their simulation and design due to their high performance regarding both the isolation in the Tx and Rx bands as well as the suppression of the Rx and Tx bands by the Tx and Rx filters, respectively. Hence, up to now duplexers have been available only as standalone components. The paper reports about integrating the functionality of duplexers into modules. While mounting the SAW or FBAR dies on top of the modules using available technologies, the LTCC sections of the duplexers are seamlessly dissolved within the modules. We call the result duplexer “inserts.” Focusing on electromagnetic issues regarding simulation and design of duplexer “inserts” we present experimental results of a feasibility study comprising prototypical W-CDMA 850 and W-CDMA 1900 duplexer “inserts.”

Index Terms — Duplexer, duplexer “insert”, FBAR, front-end module, HTCC, LTCC, SAW.

I. INTRODUCTION

Wireless terminals used for mobile communication have gone through a considerable evolution during the last years. This can be easily verified by counting the wireless standards and the bands that are supported by the microwave sections of their radios. The development started with single band radios two decades ago. Then, those mobile terminals were as large as small executive cases. Nowadays, state-of-the-art mobile terminals support several of a variety of mobile communication standards and bands in order to interact with existing 2G and 3G mobile communication systems, such as, for instance, the Global System for Mobile Communication (GSM) or Wideband Code Division Multiple Access (W-CDMA). In addition, they are usually equipped with radios for short range standards like Digitally Enhanced Cordless Telephone (DECT), IrDA, Bluetooth, IEEE 802.11, et cetera. Although having a plus of functionality in the orders of magnitude, their sizes have been reduced by orders of magnitude becoming as small as to just allow handling by human beings. Furthermore,

the addition of FM and DVB-H capability is of topical interest. So far, there seems to be no end of this development.

Before going into the details we will shortly discuss some general issues regarding duplexers as well as the motivation for the introduction of duplexer “inserts” in Secs. II and III. After a short and general discussion on modularization in Sec. IV, we will describe the various parts of our duplexer “inserts,” i.e., the acoustic dies, their packages, as well as their corresponding LTCC sections in Secs. V through VII, respectively. Finally, we present experimental results in Sec. VIII and draw our conclusions in Sec. IX.

II. DUPLEXERS

With the rise of 3G standards in mobile communication implying full duplex operation with concurrent reception and transmission of signals, such as, e.g., W-CDMA, the receiver and transmitter contained in the microwave section need to be permanently connected to the antenna.

Duplexers realize the required permanent connection. They are passive components that beyond the pure handling of the receive (Rx) and transmit (Tx) paths provide the Rx and Tx front-end filtering as well as their matching especially towards the antenna. Special interest is put on the isolation between the Tx and Rx ports in the transmit and receive bands.

There are many challenges in designing and manufacturing high performance duplexer components with small form factors using SAW or FBAR technology. Successful approaches for standalone components, which are designed for mounting on printed circuit boards (PCBs), have been reported [1]–[4]. Different solution approaches have been developed to cope with the problems specific to the duplexers required for the various bands. Thus, for instance, cellular (AMPS) duplexers, having large acoustic structures due to the low center frequency below 1 GHz, suffer most from space limitations being forced into compact packages. For personal communication system (PCS) duplexers, the key issue is the very small duplexing band gap separating the Tx and Rx bands. As a consequence, frequency shifts due to fabrication and temperature must be kept very small. In contrast to PCS duplexers struggling with the narrow duplexing band gap, the challenge for UMTS duplexers tends to be the broad duplexing band gap making it quite difficult to provide the

necessary suppression together with an extremely low insertion loss.

The common and particularly critical specification items are the stop band attenuation of the Rx and Tx filters in the Tx and Rx bands, respectively, as well as the Tx and Rx isolation. Especially, the Tx isolation determines the amount of power originating from the power amplifier (PA) in the Tx path that leaks into the Rx path jamming the low noise amplifier (LNA) resulting in a reduced receiver sensitivity.

With increasing demand for integration in the RF front-end additional constraints are put on the sizes and especially the heights of standalone duplexers. In order to arrive at acceptable overall module heights there are stringent limits for the maximal heights of standalone filters and, in particular, duplexers, which shall be mounted on top of the LTCC. Several well-known concepts exist that focus on reducing the component heights of standalone filters and duplexers [5]. Developments in packaging technologies – from wire-bonding to flip-chip bonding – have been propelling the height reduction. Additionally, process enhancements allowed reducing the heights of the ceramic layers as well as the crystal substrates.

III. FROM DUPLEXERS TO DUPLEXER “INSERTS”

Two essentially new approaches are being discussed. The common concept is to integrate at least a part of the package of the standalone duplexer within the module. Thus, a part of the package is moved away from the die into the module. Since, in general, the acoustic structures need protection in order to allow undisturbed operation, only the part of the package providing the electrical functionality usually implemented in LTCC can be moved away. The protective part of the package or packaging technology must be retained.

The first approach uses bare dies directly mounted on the module. The second approach minimizes the package functionality to housing the filter die or dies and rewiring the fine solder ball connections with the soldering pads that offer mounting via the well-established surface mount technology (SMT). As a consequence, the electrical functionality of the duplexer package has to be integrated into the module, where we have to cope with mutual interference and, of course, limited space. Eventually, the LTCC section of the duplexer is seamlessly dissolved within the module. We call the result a duplexer “insert.” Taking the point of view of a manufacturer of SAW and FBAR components the duplexer “insert” consists of two parts:

- a hardware part consisting of the SAW or FBAR die or dies providing the filtering functionality assuming a certain interface and
- a software part comprising the knowledge how to provide the interface required by the LTCC section of the module, which could be manifested in an appropriate design kit for the LTCC section.

Both parts have to be carefully optimized to obtain competitive, overall performance. In our study we designed and fabricated prototypical W-CDMA 850 and W-CDMA 1900 duplexers mounted/integrated on several module variants in order to get an overall impression of the different, specific challenges that such an approach implies.

IV. MODULARIZATION AND INTERFACE DEFINITION

As the microwave section of radios represents a very complex electrical system, it is composed of subsystems, which ends in subsystems that merely consist of simple electrical components. Having a closer look at these components reveals that even within the components, such as modules, duplexers, or filters, there exist further hierarchies referring to parts that are mechanically and/or functionally separated and that provide their unique contribution to the overall electrical performance.

The classical engineering approach of modularization, i.e., splitting a system into small subsystems, that can be separately designed, and piecing these subsystems together, is tightly associated with the notion of interfaces. As a matter of fact, modularization presupposes a good understanding and definition of the interfaces between the subsystems. Unfortunately, finding appropriate interfaces and also complying to these interfaces is extremely difficult between the various parts forming a component, i.e., the acoustic die, its package, and the integration platform.

V. ACOUSTIC DIES

We use SAW dies to realize the filtering function. Both the Tx and Rx filters are located on the same dies. The single-ended or unbalanced Tx is essentially self-matched to $50\ \Omega$. The Rx port is balanced and self-matched to $100\ \Omega$. The basic building blocks of our duplexer are the Rx and Tx band pass filters using surface acoustic wave (SAW) resonators as well as dual mode SAW (DMS) structures. Thus, the Tx filter is realized as a pure ladder-type filter having typically seven resonators. The Rx filter is implemented as a combination of ladder-type and DMS filter. Besides its frequency characteristic, the DMS filter contributes the balun functionality and impedance transformation enabling the balanced Rx output matched to $100\ \Omega$.

VI. PACKAGING TECHNOLOGY

In our case, packaged duplexers are used to simplify their handling. The simplification arises on several sides. Regarding the final testing of the duplexer components standard test equipment can be used. Since our duplexers feature balanced Rx ports, 4-port network analyzers in combination with software matching allow the precise characterization of the components. The interesting properties can also be extracted from measurements obtained with high accuracy from

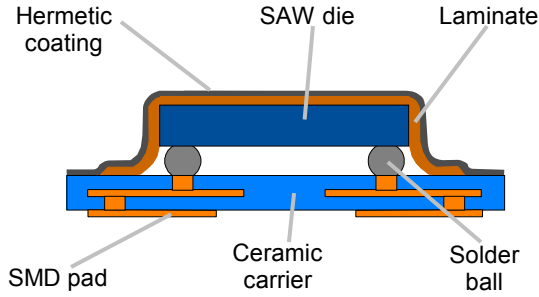


Fig. 1 Simplified cross-section of CSSPlus package.

components soldered on test PCBs. Thus, the critical properties can be tested against the specification.

Besides the handling of the duplexers their packages do not have any electrical functionality. Thus, they just rewire the connections on the dies to the corresponding pads on the LTCC.

A. Chip-sized SAW plus (CSSPlus) package

All duplexers are housed in high temperature co-fired ceramic (HTCC) surface mount device (SMD) packages using our CSSPlus technology. Their sizes are $3.0 \times 2.5 \text{ mm}^2$. As indicated in Fig. 1 the package consists of a carrier which is formed by two ceramic layers. The solder pads located on the bottom side of the package are connected to the lead-free solder balls by an inner, structured metal layer. The SAW die is flip-chip bonded to the lead-free solder balls and sealed by a patterned and metalized laminate creating the hermetic cavity that allows the undisturbed propagation of the acoustic waves on the surface of the die.

B. Footprint and Pinning

The unique footprint is the result of optimizing the individual solder pads and the connections behind them according to their primary purposes. Main goals have been to minimize electrical effects, such as capacitive, inductive, or galvanic coupling, making the package feedthroughs as electrically neutral as possible.

We chose a large number of solder pads and solder balls. That way maximal flexibility is achieved regarding the design of the LTCC section of the module and the die. The LTCC has a major impact on the performance of the duplexer. First of all it contains the phase shifting or matching network, such as, for instance, quarter wave length lines or matching coils. Furthermore, parasitic inductances and capacitances can be used to modify the performance of the SAW die in many subtle ways. E.g., inductances and capacitances found in the series or shunt branches affect the matching or the bandwidth of the SAW filters. Furthermore, inductances and capacitances can be applied to control the stop band behavior.

Regarding Fig. 2 the HTCC package has only little effect on the performance of the SAW die. The simulations with and

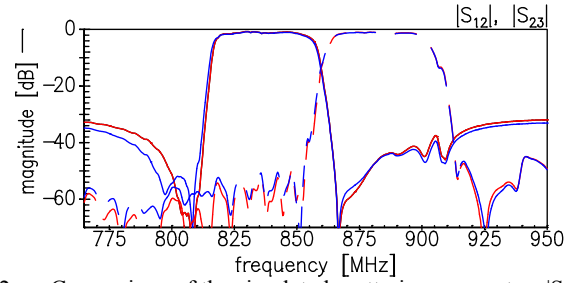


Fig. 2 Comparison of the simulated scattering parameters $|S_{12}|$ and $|S_{23}|$ of the Tx (solid line) and Rx (dashed line) paths, respectively, considering the die with (blue) and without (red) HTCC package.

without HTCC package are almost identical suggesting that reflections of the feedthroughs and couplings between feedthroughs are negligible. Ports 1, 2, and 3 refer to the Tx port, the antenna port, and the Rx port, respectively. Using mixed-mode scattering parameters port 3 will always be understood as the differential mode of the balanced Rx output.

Following the concept and guide lines of neutral PCBs [6] results in a suitable interface between the duplexer component and its environment. It allows obtaining predictable performance of the HTCC duplexer components in the test environments, i.e., soldered on the test printed circuit boards (PCB) as well as mounted on the test fixture of the automated test equipment, respectively.

VII. INTEGRATION PLATFORM

Since the duplexer is not realized as a standalone component having its own, optimized LTCC layer stack, it must be fitted into the layer stack that is pre-defined by the module. Special care must be taken to properly realize the impedances required on each of the solder pads. Electrical coupling must be avoided where it deteriorates the performance and created where it improves the performance. Usually, this is done by subtle changes in the routing of the feedthroughs.

Finally, the relevant sections need to be carefully isolated from the rest of the modules in order to avoid additional leakage paths that deteriorate the suppression in the stop bands and, in consequence, the isolation of the duplexers.

VIII. EXPERIMENTAL RESULTS

Figs. 3 and 4 show the measured data of the two duplexer “inserts” in combination with two different module environments. By inspection of the broadband measurements shown, the performance of all duplexer “inserts” within the modules is good regarding the level of stop band attenuation and isolation indicating that our design approach yielded a good overall electromagnetic behavior.

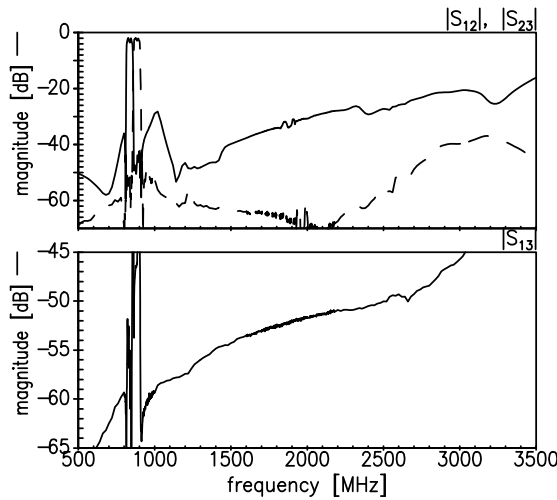


Fig. 3 Measured mixed-mode scattering parameters $|S_{12}|$ and $|S_{23}|$ of the Tx (solid line) and Rx (dashed line) paths (top graph) as well as Tx-Rx isolation (bottom graph) of the W-CDMA-850 duplexer.

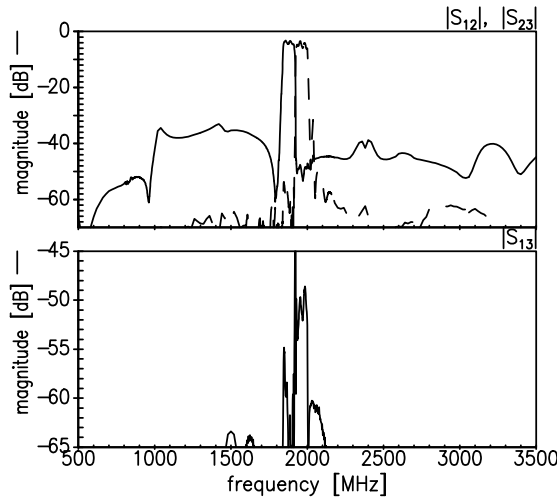


Fig. 4 Measured mixed-mode scattering parameters $|S_{12}|$ and $|S_{23}|$ of the Tx (solid line) and Rx (dashed line) paths (top graph) as well as Tx-Rx isolation (bottom graph) of the W-CDMA-1900 duplexer.

The agreement of measurement and simulation is good. It is the very prerequisite for an efficient design of such complex structures, which implies the subtle control of parasitic inductances and capacitances. The quality of the simulation can be judged from Fig. 5 showing the W-CDMA-850 duplexer “insert.” It is characterized in a minimized version of a module. The performance of the duplexer “insert” itself might seem to have potential for improvement, but it is designed for optimal performance within the module. The rest of the regular version of the module will contribute to the performance to obtain the good performance as shown in Fig. 3.

IX. CONCLUSION

We successfully integrated the functionality of W-CDMA 850 and W-CDMA 1900 duplexers by means of

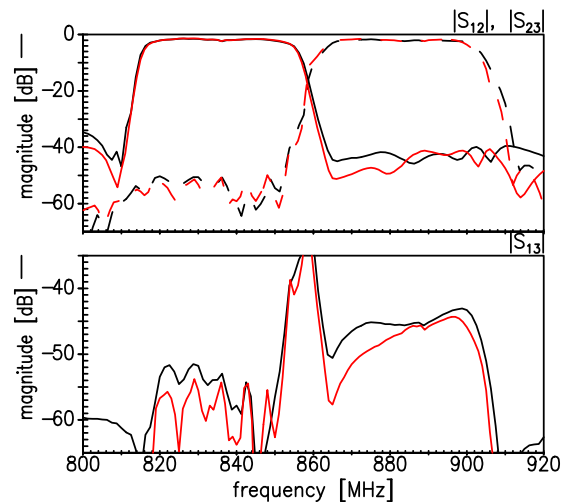


Fig. 5 Comparison of the measured (black) and simulated (red) scattering parameters $|S_{12}|$ and $|S_{23}|$ of the Tx (solid line) and Rx (dashed line) paths (top graph) as well as Tx-Rx isolation (bottom graph) of the W-CDMA-850 duplexer “insert.”

duplexer “inserts” into modules. As expected, the electrical interaction between the duplexer “inserts” and the rests of the modules cannot be neglected. There exist strong coupling effects that need special consideration and design measures making a highly accurate simulation the very prerequisite.

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