SAW Filters for 3G Systems: A Quantum Leap in Size and Passive Integration is Ahead

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Abstract — **Services based on third-generation (3G) cellular phone standards like W-CDMA or cdma-2000 will be launched in the very near future. They will bring together mobile telephony and applications such as internet communication, digital picture transmission or video conferencing that require high data rates. This objective and other provisions in the new standards lead to significantly changed requirements on the surface acoustic wave (SAW) filters employed in the IF and RF stages of 3G cell phones when compared to second-generation (2G) systems. The present contribution discusses the main issues involved in the design of SAW filters for 3G cell phones, with an emphasis on W-CDMA. It is especially emphasized that besides high electrical performance, the key issues for these new generation of SAW filters will be enhanced functionality, miniaturization and integration.**

I. Introduction

Digital, or second-generation (2G), cellular phone systems like GSM (Global System for Mobile Communication), cdmaOne (Code Division Multiple Access One), or PDC (Personal Digital Cellular) are widely used today all over the world. However, their relatively low data rates limit the introduction of mobile non-speech applications like internet access or video conferencing, which require the transmission of high data rates. Clearly, to bring together mobile telephony and non-speech applications, faster transmission standards are needed. They will be available with the upcoming launch of third-generation (3G) cellular phone systems.

The new standards like W-CDMA (Wideband CDMA) or cdma2000 essentially rely on a greater signal bandwidth to accommodate the higher data rates. From GSM's 200 kHz or cdmaOne's 1,25MHz, the bandwidths have been increased to 3,69 or 3,86MHz (cdma2000 and W-CDMA, respectively). This, of course, has a tremendous effect on the channel selection filters in the IF stage.

RF filters are affected by the new standards as the operating frequencies have been shifted above 2 GHz. In Japan and Europe the phone's transmission (Tx) and reception (Rx) frequency bands have been set to 1920…1980 and 2110…2170 MHz, respectively.

At least in Europe dual-mode phones, which combine 2G and 3G, will be the standard for some years to come. It is clear that this puts a lot of pressure for miniatutization on all components, including the surface acoustic wave (SAW) filters used in the IF and RF stages of mobile terminals (Fig.1).

These introductory remarks shed some light on the needs for new SAW solutions. Sections II and III will be devoted respectively to the key requirements for IF and RF filters in 3G cell phones.

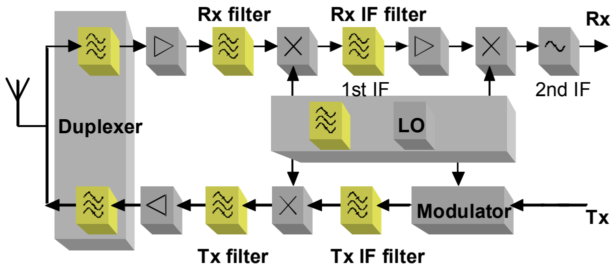

Fig. 1. Cellular phone frontend based on classical heterodyne architecture.

II. IF Filters

SAW IF filters for the Rx path of W-CDMA cell phones have to meet the following requirements [1]:

- The filter should distort the signal fed into it in the least possible manner. Typical limits on the passband amplitude and phase ripples amount to less than 1dB and 3°rms, respectively, where the latter number is the standard deviation of the phase from ideally linear behavior.
- The filter should possess good channel selectivity, i.e., a signal present in the channel adjacent to the desired one should be suppressed by a certain amount. Typical requirements on this adjacent channel suppression, (ACS) range from 15dB to more than 30dB. Given a channel spacing and signal bandwidth of 5 and 3,84 MHz, respectively, and taking into account tolerances, the typical filter is required to have a shape factor (30-dB bandwidth over 3-dB bandwidth) of 1,4 or less.
- The filter loss usually has to be smaller than 8 to 12 dB.
- Footprint area and height of the filter should be as small as possible to reduce the space requirements in the phone.
- First homodyne, or zero-IF, architectures will be available for W-CDMA within a few years. Taking into account the short time to market which is necessary for competitive SAW devices, IF filters have to be based on

> standard materials and techniques. Only this approach can guarantee stable mass production with high yield within a reasonably short time. In contrast, solutions based on 'exotic' materials rely on complicated and expensive wafer processing techniques with inherent risks to large-scale production.

In the Tx path the emphasis is not on *ACS*, but on far-away selectivity to suppress the modulator noise and on minimization of loss to prolong the battery life time.

Although the various values depend on the specific phone architecture, the W-CDMA system standard stipulates some phone characteristics that inevitably affect the filter requirements. In the following this is demonstrated on the required linearity of the signal.

The modulation method used in W-CDMA is quadrature phase shift keying (QPSK) or, in the uplink, the related hybrid phase shift keying (HPSK) [2]. In essence, the digital bit stream is transferred onto an RF carrier by making the carrier's phase take on one of four (HPSK: eight) values at the data clock transition times. Hence, at the sampling times, the RF signal phasor should point to one of four (eight) discrete points in the complex plane.

In reality, however, the received phasor will deviate from this ideal phasor by the so-called error vector owing to modulation and transmission errors. The total error vector magnitude (*EVM*) is defined as the standard deviation of all error vector magnitudes observed in the received data stream [3]. The W-CDMA standard stipulates that this important system parameter may not exceed 17,5 %.

The SAW filter contribution to the *EVM* of the entire signal chain must usually stay below 6 to 8 %. Quite good an estimate of this contribution is given by

$$EVM_{\mathrm{SAW}} \approx \sqrt{(\Delta a_{\mathrm{rms}})^2 + [\tan(\Delta\varphi_{\mathrm{rms}})]^2} \qquad (1)$$

where Δa_{rms} and $\Delta\varphi_{\mathrm{rms}}$ are the filter's effective passband amplitude and phase ripples, respectively.

This example illustrates how the requirements on a system parameter (*EVM*) result in upper bounds on some filter characteristics (amplitude and phase ripples).

The filter phase linearity is not only related to the integral measure of standard deviation of the phase from ideally linear behavior, but also to the peak-to-peak group delay distortion in the passband. It was found, however that the latter quantity is of minor importance only. In other words, the shape and frequency of the phase ripple hardly affect the *EVM* [4].

A careful examination of the requirements on the IF filters listed above reveals that they contradict one another. For instance, size is crucial, but the steep filter skirts required a high *ACS* imply long impulse response times. To keep the geometrical size small in spite of this, one must resort to resonant devices and space-saving packaging technologies. Since resonant devices inherently have a non-linear phase response, the design must focus on the high linearity needed for a small *EVM*.

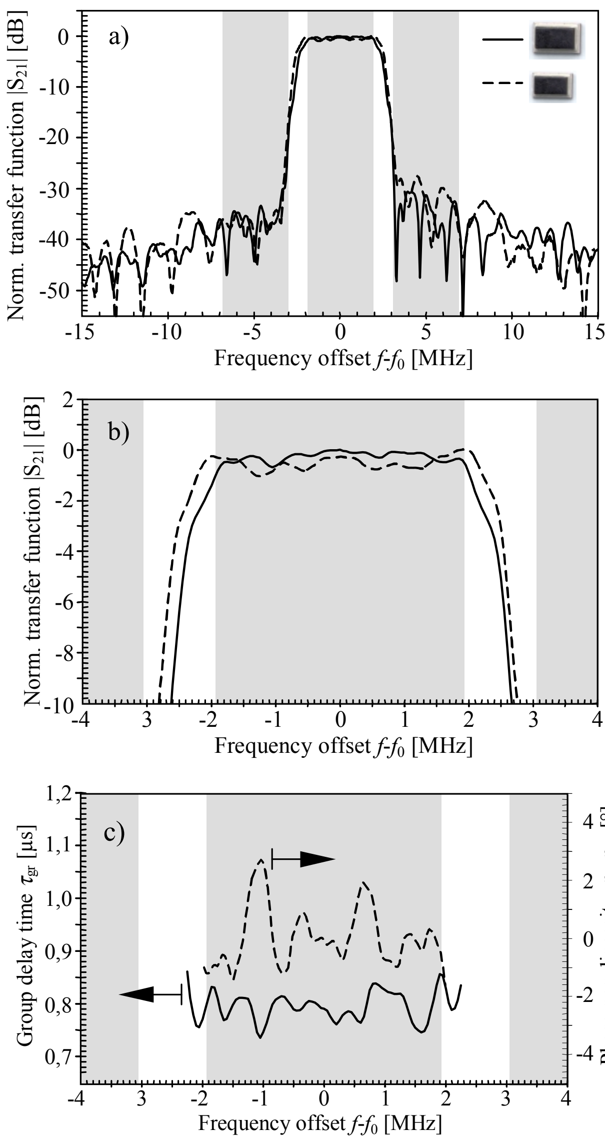

Fig. 2. W-CDMA Rx IF filters at 190 and 380 MHz (solid and dashed lines, respectively). a) Broadband and b) narrowband plot of amplitude. c) Group delay or phase. The shaded areas m ark the center channel and the left and right adjacent channels.

As it turns out, the best compromise between linearity, steepness of skirts, insertion attenuation, and size is achieved with recursive filters. These are analog infinite impulse response (IIR) filters obtained by introducing resonant cavities in common single-phase unidirectional transducer (SPUDT) designs [5].

Our approach is to select the number of IDT electrodes that fit in the target package and then optimize the filter topology to meet the overall requirements on the amplitude and phase behavior.

At lower frequencies such as 190MHz the preferred substrate is commonly available LTX because it leads to a smaller insertion attenuation than quartz filters, whose bandwidths are limited owing to the small electroacoustic coupling factor k^2 of quartz. At higher frequencies such as 380MHz quartz devices are the best solution due to their temperature stability.

Fig. 2 shows the results for two miniaturized two-track recursive filters, a 190-MHz filter on LTX and a 380-MHz filter on quartz. The respective package sizes are 6x3,5 and 5x3mm^2. Typically, one measures an *EVM* contribution of some percent. The 190-MHz filter exhibits effective amplitude and phase ripples of 2,1dB and 1,7°, respectively, an *ACS* better than 30dB, and an insertion loss around 10dB. The good channel selection of such a filter is illustrated in Fig.2. The used package technology employs flip-chip bonding onto a ceramic carrier barely larger than the SAW die (chip-sized SAW package, or CSSP) [6]. This CSSP approach guarantees maximum performance on minimum space by allowing for a large acoustic active area despite small lateral dimensions of the whole filter.

Tx IF filters are best realized as dual-mode SAW (DMS) structures. This results in small sizes (e.g. 3x3 mm^2 at 380MHz) and low losses (less than 2 dB), albeit at the cost of hardly any *ACS*.

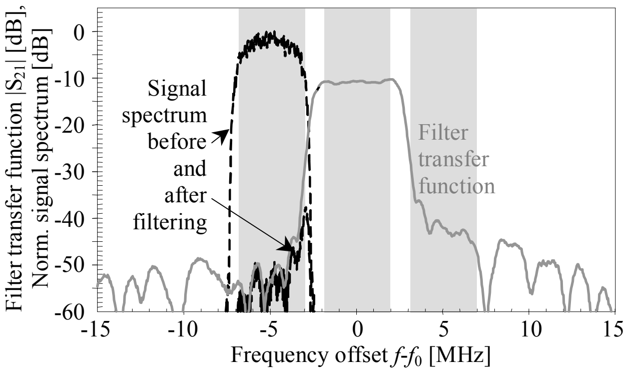

Fig. 3. ACS properties of 380-MHz filter on quartz.

III. RF Filters

A. Key Requirements Influencing the Filter Design: Electrical Performance and Size

Many requirements on RF filters result from the mobile phone standard. Clearly, the center frequency and the bandwidth (60 MHz) belong to this class of requirements, as does the Rx (Tx) suppression of the Tx (Rx) filter. The latter value usually has to exceed 30 dB.

Other requirements stem from the specific RF-chipset which is used. These comprise the suppression of the local-oscillator and image frequencies, the exact location of which depends on the choice of the IF frequency. Yet more demands involve the close-in selectivity derived from out-of-band blocking requirements described in the system standard. It is the latter requirements that can make a design challenging, although at first sight one would have concluded from the large duplex distance of 190MHz that filters with flat passband skirts should suffice. The insertion attenuation is one of the most important parameters for RF filters, in particular for the Tx filter.

In addition, miniaturization of components is an important prerequisite for supporting ever shrinking PCB sizes. On the one hand, miniaturization can be accomplished by shrinking package sizes. As already pointed out, this is very well pursued by CSSP, where the package itself is hardly larger than the die. For RF filters the critical parameter of package height is already set to 0.80mm with EPCOS' standard CSSP technology. Today, this technology supports lateral filter dimensions down to 2.0x2.0mm^2. A new approach will allow to shrink these dimensions down to app. 1.4x2.0mm^2 for all different kinds of RF-filters.

On the other hand, a reduction of PCB space can also be accomplished by extensive passive integration. Functionalities such as symmetrization of a signal or impedance transformations can be performed by high performance SAW filters themselves, without the need of further baluns (Fig. 4). These solutions will get especially important for upcoming homodyne chipset architectures, where balanced driving modes can help to tackle the difficult DC-offset problem.

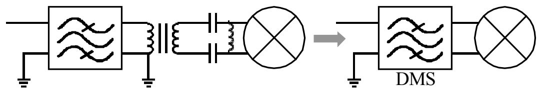

Fig. 4. Integration of functionalities (symmetrization and impedance transformation) in a SAW filter.

An important question arising from balanced sources or loads is the extent of amplitude and phase symmetry, which is required between the two balanced output or input paths. It will be shown later that by carefully combining the right package and filter technologies, it is possible to obtain an amplitude as well as phase balance which is superior to that delivered by conventional baluns.

Enhanced functionality and space reduction are basic driving forces for further integration of SAW filters into whole front end SAW modules (FEMs). High performance SAW filters can be mounted together with active components on a low temperature cofired ceramic (LTCC) substrate. Despite an effective reduction of component count and required PCB space this also results in enhanced performance (see section C for details).

B. Discrete RF-Filter Solutions

Basically, one can choose from two very well-established SAW RF filter techniques: the reactance or ladder-circuit filter and the dual-mode SAW (DMS) filter. Both show different characteristics concerning electrical performance. Typically the first one has an lower insertion attenuation, whereas the latter one is superior in out of band rejection.

It is obvious that the right filter design has to be carefully chosen according to the required application. E.g., a loss-minimized Tx filter is commonly realized as a reactance filter. Rx filters with integrated additional functionalities such as symmetrization and impedance transformation are the domain of DMS filters.

Fig.5 shows plots of a high performance DMS Rx filter on $LiTa_2O_3$. The employed package is a 5-pin CSSP in 2x2,5-mm^2. To achieve this small size and the excellent stopband characteristics, electromagnetic behavior of the package has to be included in the simulation of the SAW device. Another consequence of this extensive integral design approach is the excellent symmetry, which can be achieved with that filter (Fig. 6).

A reactance Tx filter on $LiTa_2O_3$ is shown in Fig.7. This 4-pin, 2x2-mm^2 CSSP device is the smallest SAW filter in mass production to date.

As already pointed out, these miniaturized, high performance SAW filters can only be achieved by an accurate simulation. The flip-chip bond employed in the CSSP results in markedly different parasitics from those associated with a wire bond. Both the acoustical active elements and the package contribute to the overall filter characteristics. One can neglect neither one in the simulation and design without compromising the resulting characteristics.

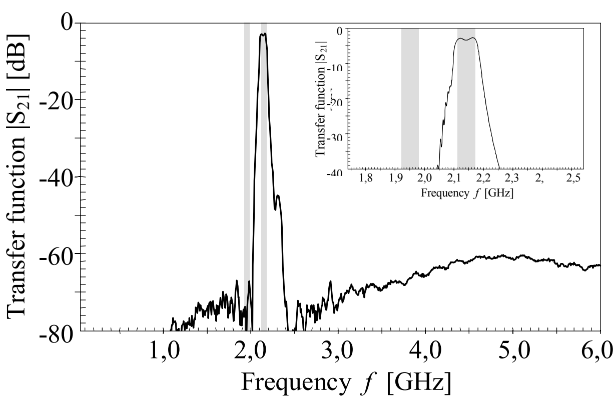

Fig. 5. Single ended-to-balanced W-CDMA Rx filter in a 2x2,5-mm^2 CSSP. Broadband and narrowband (inset) plot of amplitude. The shaded areas mark the Rx and Tx bands.

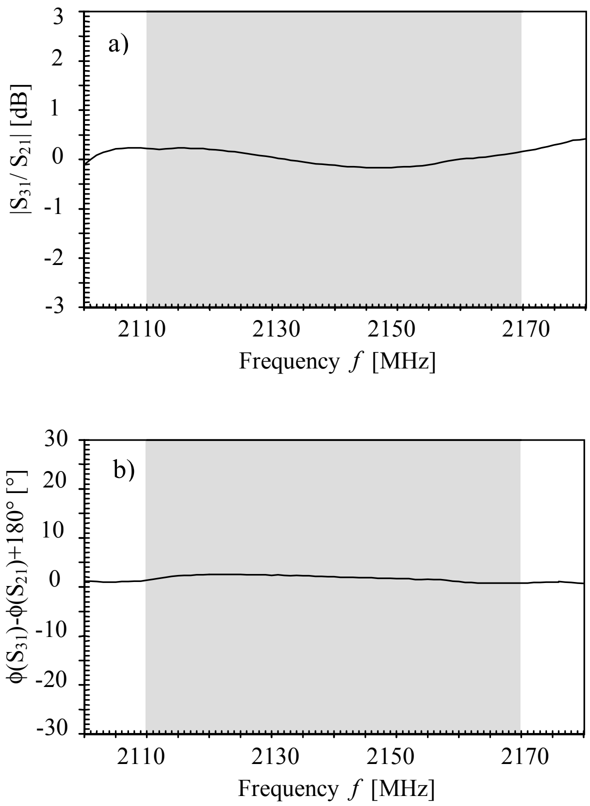

Fig. 6. Single ended-to-balanced W-CDMA Rx filter in a 2x2,5-mm^2 CSSP. a) Amplitude and b) phase balance within the pass band (shaded).

EPCOS models the CSSP-type filter packages by electromagnetic simulation programs. They can derive equivalent electrical circuits that describe the coupling between all terminals of interest. These electrical circuits are then combined with the results of the standard acoustic simulation by, for instance, equivalent-circuit or P-matrix models [7]. In essence, this amounts to a hybrid approach, i.e., the combination of electromagnetic simulation programs and acoustic network analysis tools.

C. Further Integration of SAW filters

As already pointed out, the contradicting requirements of higher functionality and smaller space can only be met by heading forward towards integration of discrete passive and active components for future mobile phone applications. A natural evolution of the aforementioned CSSP technology is the implementation of this kind of package together with active components to form highly integrated FEMs on LTCC. For 3G systems the integration of a Tx/Rx duplexer will be a major task.

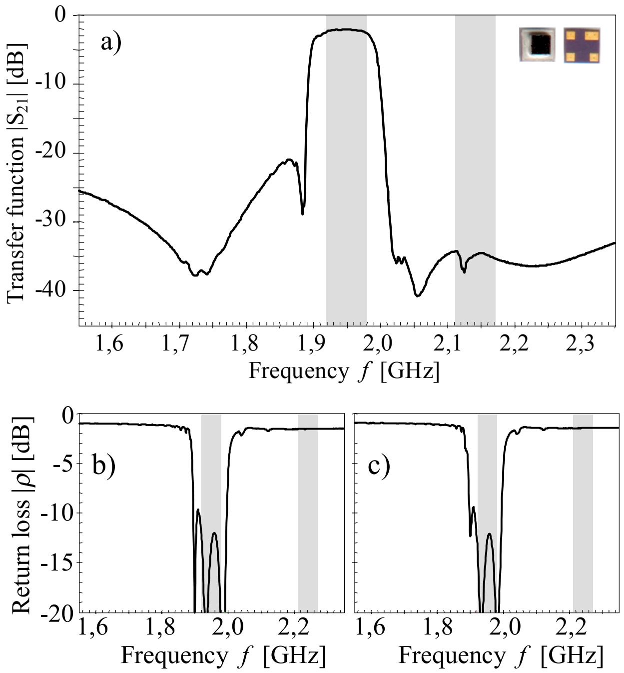

Fig. 7. Single-ended W-CDMA Tx filter in a 2x2-mm^2 CSSP. a) Transfer function. b) Input and c) output return loss. The shaded areas mark the Rx and Tx bands.

By embedding SAW filters into the front-end module, there are several possibilities for further optimizing the system performance:

- The integration of an input and output matching network for the filter allows to optimize the performance of the SAW chip, thereby offering minimized insertion attenuation to the system. Furthermore, the output impedance can be tuned to the desired input impedance of the following LNA stage of the RF chipset. A differentiation between various chipsets can thus be supported by distinct modules incorporating the same SAW chip.
- A low loss passive combination of the input ports of SAW filters can be achieved by an integrated diplexing network. The accurate placement of the components within the module and the well defined phase conditions of the components to each other lead to a very stable and reproducible performance.
- The rejection requirements of the complete front-end can be ideally split into rejections provided by the SAW and rejections provided by the buried structures in the LTCC substrate. By this approach the strength of the SAW device, i.e. the higher close in rejection compared to alternative technologies, can be used without sacrifising insertion attenuation. This is especially valid for reactance filters, where a limited out of band attenuation of the SAW device can be overcome by additional suppression from the diplexer stage.

EPCOS is working on FEMs combining 2G dual and triple band designs with 3G functionality. The current, first generation modules are based on LTCC substrates and use very low profile CSSP SAW filters as SMD mounted components on top of the ceramic substrate. To be able to further reduce the height and size of the modules, it is planned to use a flip-chip technology similar to the existing CSSP process for bare die attachment of the SAWs direct to the LTCC substrate surface.

IV. Conclusion

The requirements on SAW filters for 3G systems extend from optimum electrical performance to extensive miniaturization and integration. Apart from small size the central requirements on W-CDMA IF filters are bandwidth, *EVM* and *ACS* for Rx filters, and insertion attenuation and *EVM* for Tx filters. Regarding RF filters the key issues are insertion attenuation, stopband suppression, passive integration as well as size.

It has been demonstrated that these requirements can be met by distinct SAW filter solutions: recursive filters on LTX or quartz for Rx IF filters, DMS filters on $LiTa_2O_3$ for Tx IF filters, and DMS or reactance filters on $LiTa_2O_3$ in the RF stage. Performance optimization, miniaturization and integration of functionalities are supported by a chip-sized SAW package technology together with comprehensive modelling. CSSP is of special importance for future module solutions, where the height of the available components will be one of the most critical parameters.

V. References

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