SAW Filter Solutions to the Needs of 3G Cellular Phones

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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. The key point is that the need for miniaturization, higher operating frequencies and improved performance can only be met by a proper choice of material system, filter technique and package technology. In particular for the RF filters, it is essential to include in the simulation model a correct electrical description of the miniaturized package. State-of-the-art examples serve to illustrate these points.**

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) today are widely used all over the world. However, their relatively low data rates limit the introduction of mobile non-speech applications like internet access or video conferencing as most of these applications require the transmission of many data. 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 1,25 MHz, the bandwidths have been increased to 3,69 or 3,86 MHz (cdma2000 and W-CDMA, respectively). This, of course, has a tremendous effect on the channel selection filters in the IF stage.

The RF filters, too, are affected by the new standards as the operating frequencies have been extended to more than 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 (2G and 3G) will be the norm for some years to come. It is clear that this puts a lot of miniaturization pressure on all components, including the surface acoustic wave (SAW) filters normally used in the IF and RF stages of mobile phones (Fig. 1).

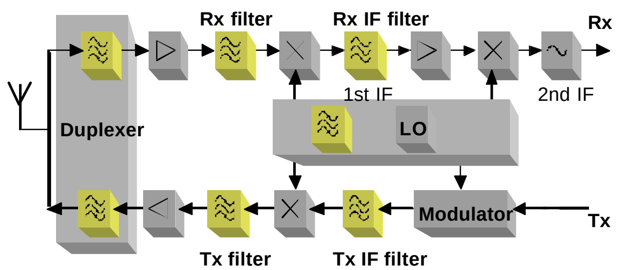

Fig. 1. Cellular phone frontend based on classical heterodyne architecture.

These introductory remarks shed some light on the need 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. It will be shown how to meet these requirements and in what way the simulation and design processes are affected by them.

II. IF Filters

A. Key System Parameters Influencing the Filter Design

The modulation method used in W-CDMA is quadrature phase shift keying (QPSK) or, in the uplink, the related hybrid phase shift keying (HPSK) [1]. 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 [2]. 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

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

where Δa_{rms} and Δj_{rms} are the filter's effective passband amplitude and phase ripple, respectively. The latter are computed from the filter's amplitude response $a(f)$ and phase response $j(f)$ by

$$\left(\Delta a_{\mathrm{rms}}\right)^2 = \frac{1}{f_2 - f_1} \int_{f_1}^{f_2} \left[\frac{a(f)}{a_0} - 1 \right]^2 \mathrm{d}f\ , \qquad (2)$$

$$\left(\Delta j_{\mathrm{rms}}\right)^2 = \frac{1}{f_2 - f_1} \int_{f_1}^{f_2} \left[j(f) - (t_0 \cdot f + j_0) \right]^2 \mathrm{d}f\ . \qquad (3)$$

Here, a_0, t_0 and j_0 are constants to be determined such that Δa_{rms} and Δj_{rms} are minimized [3].

It has been found that the absolute value of the group delay distortion in the passband, i. e.,

$$\Delta t_{\mathrm{gr}} = \frac{1}{2p} \left[\left| \frac{\mathrm{d}j(f)}{\mathrm{d}f} \right|_{\max} - \left| \frac{\mathrm{d}j(f)}{\mathrm{d}f} \right|_{\min} \right], \qquad (4)$$

is of minor importance only. In other words, the shape and frequency of the phase ripple hardly affect the *EVM* [3].

According to the provisions in the W-CDMA standard, the phone must be able to tolerate heavy user traffic in the adjacent channels. This makes the adjacent channel suppression (*ACS*) another decisive system parameter. Depending on the system layout, the SAW filter must contribute 10 to 30 dB to the *ACS* of the entire Rx path, which calls for filters with steep passband skirts. 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.

In contrast, in the Tx path, the emphasis is not on *ACS*, but on far-off selectivity (to suppress the modulator noise) and on loss minimization (to prolong the battery life time).

As already mentioned, the filter size is crucial as well. Unfortunately, the steep filter skirts required for 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, major design efforts have to be undertaken to achieve the high linearity needed for a small *EVM*.

B. Filter Solutions

It is reasonable to assume that homodyne, or zero-IF, architectures will be available for W-CDMA within a few years. In view of this, the SAW IF filters have to be based on standard materials and techniques; after all, the return of investment in new processes or equipment associated with "exotic" solutions would not seem to be guaranteed.

As it turns out, the Rx IF filter task can be performed by recursive filters on LTX or quartz. Such a device is an analog infinite impulse response (IIR) filter obtained by introducing resonant cavities in common single-phase unidirectional transducer (SPUDT) designs [4].

Fig. 2 shows some typical results for two-track recursive filters, the cases presented being a 190-MHz filter on LTX and a 380-MHz filter on quartz. The respective package sizes are 6x3,5 and 5x3 mm^2. The package technology employs flip-chip bonding onto a ceramic carrier barely larger than the SAW die (chip-size SAW package, or CSSP; for further details cf. [5]).

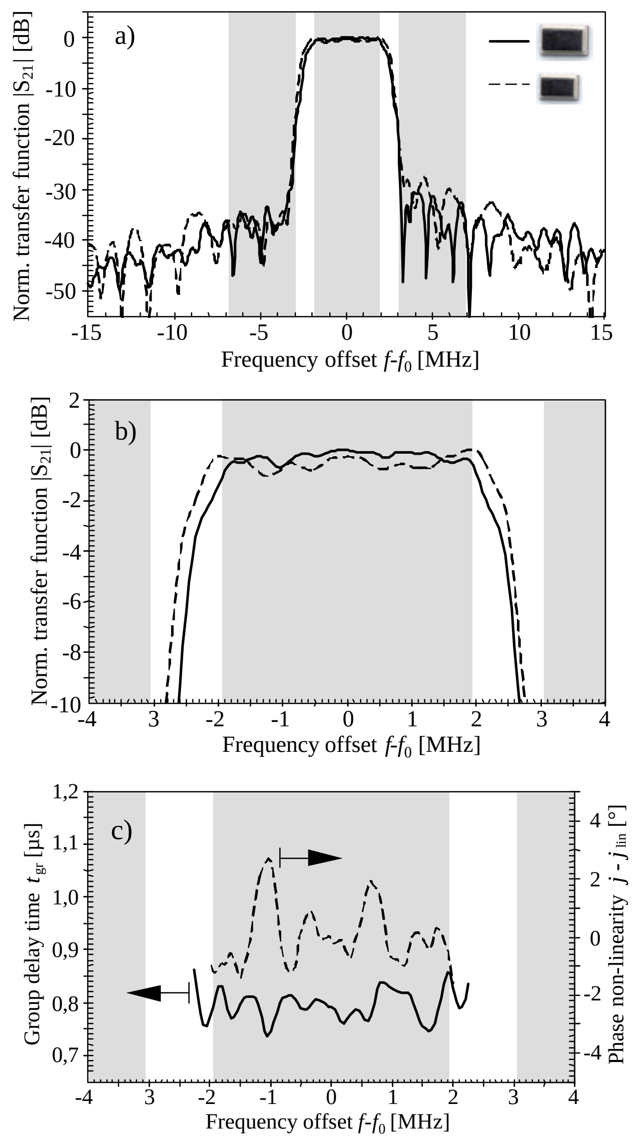

Fig. 2. W-CDMA Rx IF filters at 190 and 380 MHz (solid and dashed lines, respectively). a) Broadband and b) narrowband plot of amplitude. c) Group delay or phase. The shaded areas mark the center channel and the left and right adjacent channels.

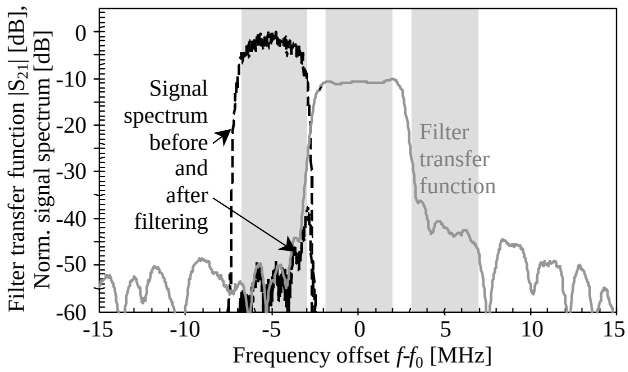

Fig. 3. ACS properties of 380-MHz filter on quartz.

Typical characteristics are losses around 10 dB, an *EVM* contribution of some percent (e. g., the 190-MHz filter shown in Fig. 2, exhibits effective amplitude and phase ripples of 2,1 % and 1,7°, respectively), and an *ACS* better than 30 dB. The good channel selection properties of the filters are illustrated in Fig. 3. Especially the temperature stability of quartz filters is quite intriguing in this context as the guaranteed *ACS* including all tolerances stays within a few dB of the typical value.

Tx IF filters are best realized as well-known dual-mode SAW (DMS) structures. The resulting solutions, e. g., at 380 MHz, feature a small size (3x3 mm^2) and low losses (less than 2 dB), albeit at the cost of hardly any *ACS*.

III. RF Filters

A. Key System Parameters Influencing the Filter Design

Many requirements on the RF filters follow from the 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 must usually exceed 30 dB.

In addition, many more requirements result from the specific system layout. These comprise the suppression of the local-oscillator and image frequencies (the exact location of which depends, of course, on the choice of IF). They also comprise 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 190 MHz 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.

Furthermore, as for IF filters, there is a need for miniaturization. Since the frontend chipsets will more and more use differential inputs and outputs to improve the crosstalk behavior of the silicon circuits, the SAW filters should accept a symmetrically driven source or load without additional elements like baluns (Fig. 4).

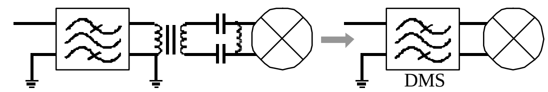

Fig. 4. Integration of functionalities (symmetrization and impedance transformation) in a SAW filter.

B. Filter Solutions and Modeling Issues

Basically, one can only choose from two very well-established SAW RF filter techniques, the reactance, or ladder-circuit, filter and the dual-mode SAW (DMS) filter. From the discussion on the requirements above, it is obvious that a loss-minimized Tx filter must be realized as a reactance filter, whereas Rx filters with integrated additional functionalities like symmetrization and impedance transformation are the domain of DMS filters (Fig. 4).

Fig. 5 shows a typical result for a DMS Rx filter on $LiTa_2O_3$. The package is a 5-pin, 2x2,5-mm^2 CSSP. To achieve this small size and the excellent stopband characteristics, the package must be carefully designed and its electromagnetic behavior must be included in the simulation of the SAW device.

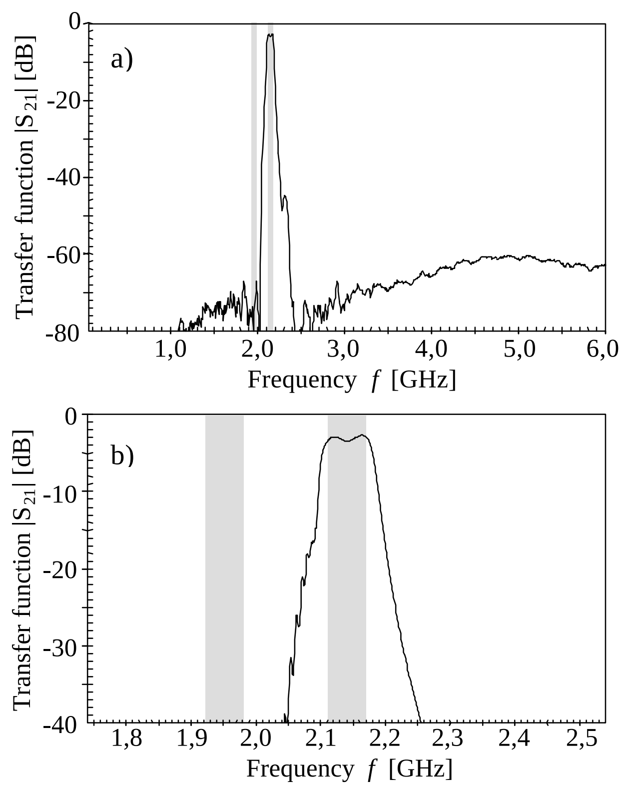

Fig. 5. Single ended-to-balanced W-CDMA Rx filter in a 2x2,5-mm^2 CSSP. a) Broadband and b) narrowband plot of amplitude. The shaded areas mark the Rx and Tx bands.

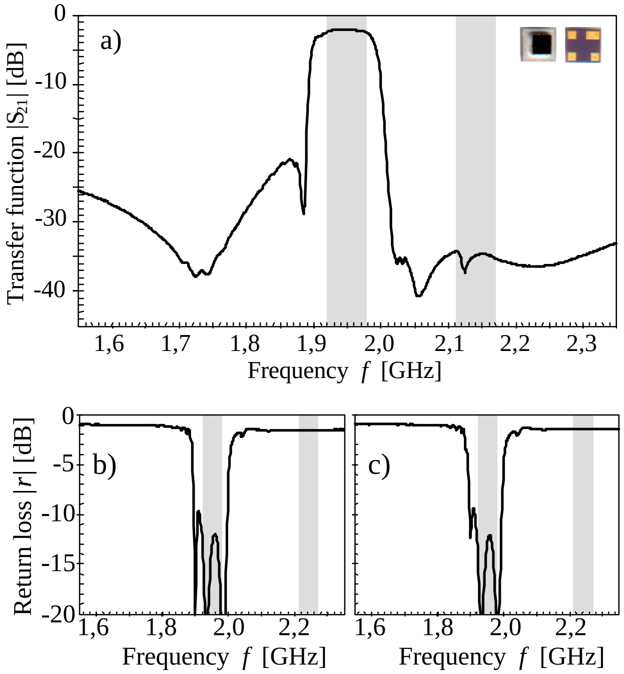

Fig. 6. Single-ended W-CDMA Tx filter in a 2x2-mm² CSSP. a) Transfer function. b) Input and c) output return loss. The shaded areas mark the Rx and Tx bands.

Another example, a reactance Tx filter on $LiTa_2O_3$, is shown in Fig. 6. Apart from the fact that this is the smallest SAW filter to date (4-pin, 2x2-mm² CSSP), such a high performance can only be achieved by an accurate simulation.

In fact, the high performance can be considered a direct consequence of a complete electromagnetic modeling of the CSSP. Note for instance that a flip-chip bond as employed in the CSSP results in parasitics markedly different from those associated with a wire bond. Both the acoustically active elements and the package contribute to the overall filter characteristics. Hence, one can neglect neither one in the simulation and design without compromising the resulting characteristics.

We model 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 [6]. In essence, this amounts to a hybrid approach, i. e., the combination of electromagnetic simulation programs and acoustic network analysis tools.

The benefits of this approach are not limited to the filter frequency characteristics. For example, the amplitude and phase balances at the balanced port of a SAW filter are, of course, strongly affected by the package design. By carefully combining the optimum package and filter technologies, it is even possible to obtain symmetry values superior to those of conventional baluns. As a consequence of such an extensive integral design approach, the typical passband amplitude and phase imbalances of the filter associated with Fig. 5 are a mere 0.25 dB and 1°, respectively.

Finally, let it be mentioned that the contradicting requirements of higher functionality and smaller space will be met by an integration of discrete passive and active components in future cellular phone applications. In this sense, SAW filters in flat CSSP's lend themselves very well to an inclusion in frontend modules based on (low temperature cofired) ceramic carriers. For 3G systems, the integration of a Tx/Rx duplexer will be a major task.

IV. Conclusion

The central requirements on W-CDMA filters are bandwidth, *EVM*, *ACS*, and size for Rx IF filters, and insertion attenuation, *EVM*, and also size for Tx IF filters. On the RF side, the key issues are insertion attenuation, stopband suppression, passive integration, and again size. It has been demonstrated that these requirements can be met by specially adapted SAW filters: recursive filters on LTX or quartz as Rx IF filters, DMS filters on $LiTa_2O_3$ as Tx IF filters, and DMS or reactance filters on $LiTa_2O_3$ in the RF stage. The miniaturization is supported by a chip-size package technology (CSSP). A hybrid approach towards including electromagnetic effects in the device simulation has been found to yield an excellent agreement between measurement and simulation, even at high frequencies.

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