Miniaturization and Advanced Functionalities of SAW Devices

Hans Meier, *Member, IEEE*, Thomas Baier, and Gerd Riha, *Member, IEEE*

***Abstract*—Apart from the active semiconductor chips a multitude of surface acoustic wave (SAW) filters are the key components that make modern RF circuits for mobile telecommunication and multimedia applications work. The latter are the most sophisticated and delicate species of passive components of which today's RF applications contain several hundred. While active integration has led to decreasing numbers of semiconductors inside a phone, at the time being, the passive components outnumber the actives by far. Obviously, the highest potential for further miniaturization lies in the passive components. As the market asks for further miniaturized mobile phones and digital tuners EPCOS AG, Munich, Germany, tackles this challenge not only by further shrinking the SAW filters, but also by integrating additional functions into the SAW filters, which were originally not SAW related at all. This paper briefly presents several applications for such highly miniaturized SAW filters offering superior filter performance combined with additional features like impedance transformation, balun functionality, or double balanced operation, allowing for smaller and cheaper designs by effectively reducing printed-circuit-board space, as well as component count.**

***Index Terms*—Multimedia applications, SAW mobile radio filters, SAW packaging.**

I. Introduction

THE last decade has seen an increasing demand for personal communication mobility. The need for on-demand broad-band channel capacity for all kinds of users of communication has also increased at a remarkable speed as a consequence of the use of the Internet.

One of the main reasons for the high penetration of mobile phones worldwide is that size and weight of cellular phones have been decreased very rapidly within the last 3–5 years. As a result today, size and weight are some of the most important specifications of mobile phones. [1]–[3].

The key components that make modern RF circuits for mobile telecommunication and multimedia applications work are—apart from the active semiconductor chips—a multitude of highly miniaturized surface acoustic wave (SAW) filters. While the active integration led to decreasing numbers of semiconductors inside a phone, at the time being, the passive components outnumber the actives by far. Obviously, the highest potential for further miniaturization lies in the passive components. However, the challenge is not only to further shrink the passive components in general, but also to achieve a higher degree of integration. SAW filters are the key for passive integration since additional functions can be easily integrated into them.

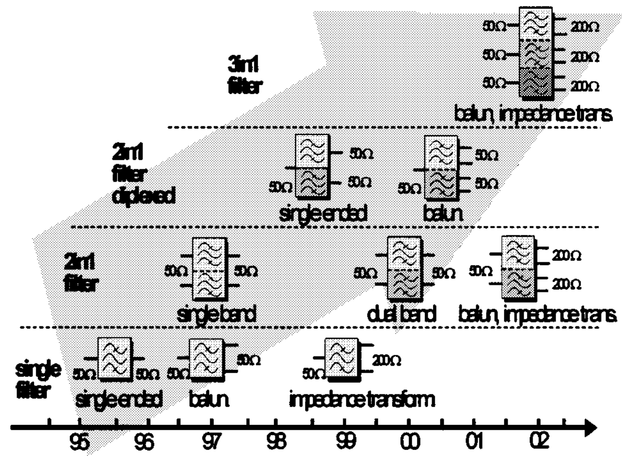

Fig. 1. Evolution of functional integration achievable with SAW filters: year 1995–2002.

In the receiver (RX) RF stages, SAW filters are responsible for keeping unwanted signals away from low-noise amplifiers and mixers, thus allowing for power-saving designs and cost-efficient semiconductor solutions, while in the transmitter (TX), they effectively hinder spurious signals from being emitted, thus avoiding interference. In the IF stage, SAW filters efficiently limit the signal bandwidth without distorting the signal to make life easier for the subsequent digital signal processor, which, in turn, can save on battery power.

However, SAW filters can do more than that. Today's highly miniaturized SAW filters offer superior filtering performance in combination with additional features, like impedance transformation, balun functionality (= balanced drive at one port, unbalanced drive at the other port), or double balanced operation [4]. Fig. 1 shows the evolution of functional integration achievable with SAW filters within the near future. Obviously, modern SAW filters are supporting cheaper and smaller designs by effectively helping to cut down on component count, on printed-circuit-board (PCB) space and on power consumption in today's and future mobile telecommunication and multimedia applications.

Several applications from the mobile communication area will be presented in this paper. Another example discussed here is a cable modem for internet access, where conventional tuner architecture will be continuously substituted by semiconductor chip solutions. These so-called up/down converter tuners will also make use of a most advanced RF SAW filter.

Manuscript received October 26, 2000; revised January 8, 2001.

The authors are with the Surface Acoustic Wave Components Division, EPCOS AG, D-81617 Munich, Germany.

Publisher Item Identifier S 0018-9480(01)02898-8.

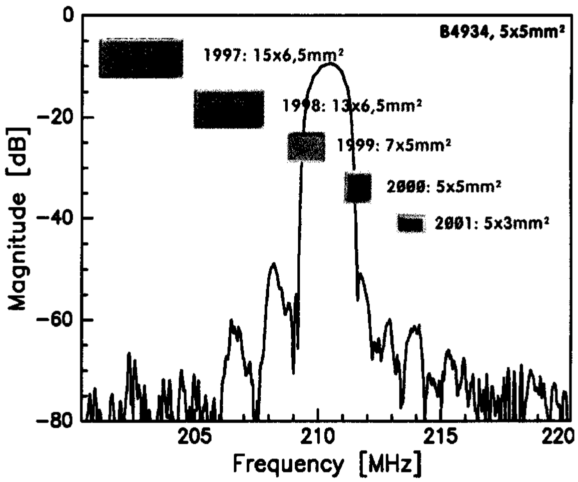

Fig. 2. Genealogy of IS-95 CDMA 1900 IF SAW filters.

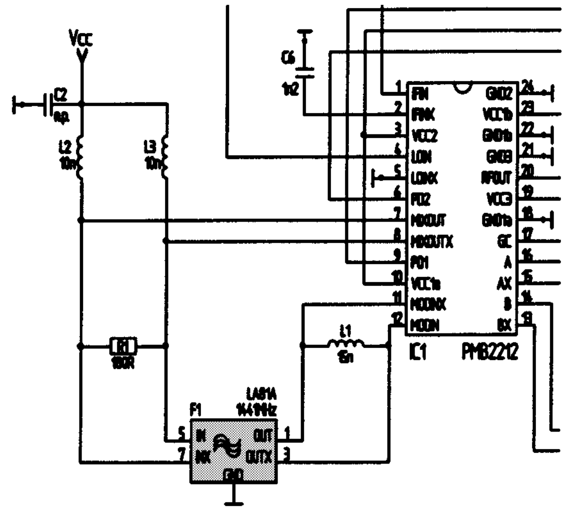

Fig. 3. Double-balanced SAW filter in a modulator application [8].

II. Mobile Phone Applications

A. IF SAW Filter for IS-95 CDMA 1900 System

The introduction of the code-division-multiple-access (CDMA)-based IS-95 system has imposed new and challenging requirements for IF SAW filters. A relatively wide passband with highly linear phase and a rather low insertion attenuation is being combined with a small transition bandwidth and, thus, steep skirts and high stopband attenuation. Additionally, smallest possible component sizes are needed [1].

Fig. 2 gives an impression of the miniaturization potential, which still lies within SAW technology. This figure shows the genealogy of IS-95 CDMA1900 RX IF SAW filters and their migration to smaller and smaller sized packages. While zero IF systems (IF $= 0$ MHz, direct conversion RX), which do not require an IF SAW filter, can quite easily be implemented in time-division multiple-access (TDMA) systems like global system mobile (GSM) where unused timeslots are utilized to measure and compensate dc offsets, the full duplex character of the IS-95 system forbids this strategy, hence, making a direct conversion architecture unfavorable. Here, the RX IF SAW filter is crucial in offering at the same time very low signal distortion in amplitude and phase and extremely high interferer suppression in the adjacent channels. EPCOS AG, Munich, Germany, is using a combination of the recursive- and Z-path design technique with crosstalk compensation to achieve the extremely small 5×5 mm^2 package size with high performance [5]–[7]. While the Z-path design technique helps to almost divide the acoustical length by a factor of two through dividing input and output transducer into separate parallel tracks and redirecting the acoustical wave, following a Z-shaped path by inclined reflector gratings, the transversal proximity of the input and output transducer make a delicate electrical feedthrough compensation necessary. The introduction of a recursive design approach (= internal resonance like resonant single-phase unidirectional transducers (R-SPUDTs) into the transducers further helps to shrink the total structure length. As can be seen in Fig. 2, within four years, the filter footprint area could be reduced by a factor of 1/6.5 without sacrificing the filter performance.

B. Advanced Functionalities of RF SAW Filters

As an example of how a customized SAW can help to save space by reducing the number of passive components, Fig. 3 shows a modulator section of a mobile phone TX for the Japanese personal digital cellular (PDC) standard operating at 1.5 GHz [8]. The PMB2212 direct modulator integrated-circuit (IC) translates the TX baseband signal on its input to the final TX RF frequency on its output with various internal mixers and oscillators. To efficiently suppress spurious signals generated thereby, a highly selective SAW filter is necessary in the internal IC signal path. The silicon chip layout is completely symmetric, internally offering its highest performance with differential signal sources and loads. Thus, the customized SAW filter was chosen to operate in double-balanced mode, which could easily be implemented using the dual-mode SAW (DMS) filter design. The DMS technique also facilitates to design the SAW filter to match the IC's high impedance levels ($\approx$200 Ω) such that only shunt inductors, also serving for dc power supply, are required for impedance matching. Since SAW filters can handle several volts of dc without damage or change in performance, dc blocking capacitors are not present.

If a standard single-ended filter had been used in this application, seven additional passive components like inductors, capacitors, and baluns would have been required.

Not long ago, such highly selective customized double-balanced and balun RF SAW filters were only available up to the 1-GHz range, where they are widely used, e.g., in GSM phones. EPCOS AG's proprietary design technique (patent pending) made such products available today with even higher performance for the 2-GHz range also where they readily attract interest not only for GSM1800 and personal communications system (PCS) applications, but also for next-generation universal mobile network telecommunication system (UMTS) transceiver designs. Fig. 4 shows a high-performance and highly miniaturized 2×2.5 mm^2 extended global system mobile (EGSM) RX SAW filter with balun functionality and impedance transformation from 50 to 200 Ω combined with its transfer function and pin configuration. The extraordinarily

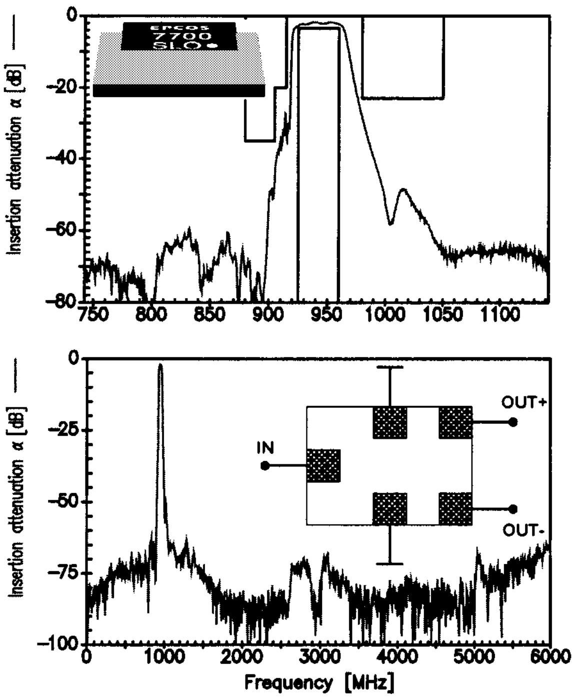

Fig. 4. EGSM RX SAW filter B7700.

high selectivity from over 60 dB to up to 6 GHz together with high amplitude and phase balance could only be achieved by using the geometrically totally symmetric five-pin package layout. The above-mentioned new proprietary design technique, which is also used here, is based on the well-known DMS approach using special measures to reduce acoustic losses. It allows us to achieve a low insertion attenuation as low as typically 3 dB over the full EGSM bandwidth without external matching elements.

As single-band phones become more and more the exception, the average number of RF SAW filters inside a phone basically multiplies with the number of frequency bands, which need to be covered. In the near future, three-band phones like EGSM + GSM1800 + GSM1900 are expected to become the standard. Multimode phones like CDMA + FM call for multiple IF SAW filters per phone serving the different standards. Today, one can even find phone designs in the market using up to ten SAW filters per phone. A first step in passive integration is to combine two RF SAW filters for different bands for the same transceiver stage into one and the same package. To date, these so-called dual-band two-in-one filters for EGSM + GSM1800 are readily available for single-ended operation at 50 Ω. In the near future, integrated solutions for three and more bands including impedance transformation and balun functionality will be available as well (see Fig. 1) [9], [10].

While today's GSM-based phones utilize TDMA allowing for switches to separate the TX and RX signals going to and coming from the antenna the evolution of GSM to general packet radio service (GPRS) allows for full duplex operation, where transmission and reception is performed simultaneously. In this case, an antenna duplexer is necessary to separate TX and RX signals. The established IS-95 CDMA system, the analog advanced mobile phone system (AMPS) system, and

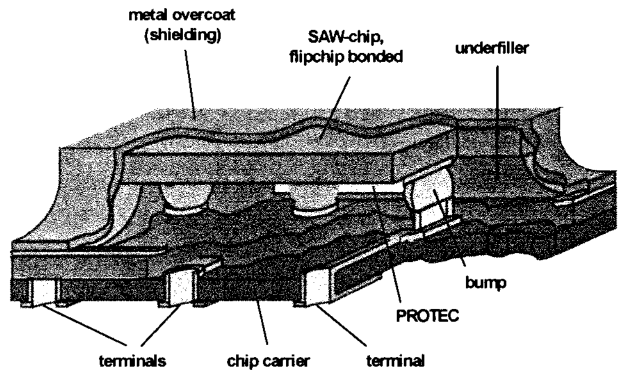

Fig. 5. CSSP package technology.

the future UMTS system are also full duplex systems requiring an antenna duplexer. An antenna duplexer consists of an RX filter blocking the TX signal and a TX filter blocking TX noise falling into the RX band. It has one common port being connected to the phone's antenna and two ports being connected to the RX input and TX output, respectively. As such a duplexer is positioned in the transceiver frontend, it must be able to handle up to several watts of RF power. The usage of SAW filters in such high-power applications was only made possible by recent advances in design and production technology [11]–[13]. These applications were traditionally the domain of dielectric filters. They are already being replaced today by highly miniaturized SAW filters offering a clear size advantage in the 1-GHz range.

C. Chip-Sized SAW Package Technology

The key technology for further passive integration is EPCOS AG's proprietary chip-sized SAW package (CSSP). Fig. 5 shows the basic construction of a CSSP package. The SAW chip is flip-chip mounted onto a chip carrier serving as bottom of the package [14]. The electrical connections to the chip are realized with solder bumps. Underfiller attaches the SAW chip solidly to the chip carrier such that the backside of the chip can already serve as part of the package. While this mounting technology is quite straightforward for silicon chips, it only became attainable for SAW filters by EPCOS AG's proprietary PROTEC chip passivation, leaving a cavity on the surface of the chip for undisturbed propagation of the acoustic waves. The cavity is being built on the wafer with a photolithographic process in two steps. First, a closed polymeric wall is being processed around the filter structure. The wall is then covered with a roof using the same process. This technology allows for a further miniaturization of SAW filters beyond a 1 mm^2 footprint area.

The world's currently smallest SAW filter realized in a $2 \times 2 \times 0$ 8-mm^3 CSSP package is shown in Fig. 6 on the left-hand side. Today, EPCOS AG offers these highly miniaturized SAW filters for all 2-GHz applications, like personal communication network (PCN), PCS, and UMTS. They cover the full system bandwidth and can directly replace standard 3×3 mm^2 ceramic surface-mounted device (SMD) products. Both DMS and ladder-type SAW filter designs can be realized. The high duplex suppression of these products even allows for the usage in IS-95 CDMA systems.

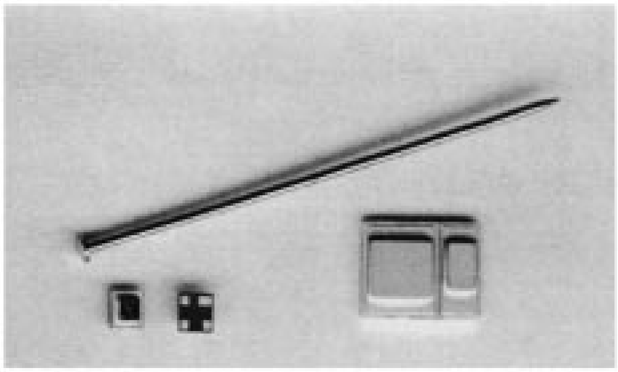

Fig. 6. Left-hand side: EPCOS AG's $2 \times 2 \times 0$ 8-mm^3 SAW filter almost fits on a pin head. Right-hand side: Prototype SAW module.

However, more importantly, the CSSP technology also allows for a higher complexity in passive integration. One chip carrier can carry a multitude of chips, not all of which need to be SAW filters. In addition, the chip carrier does not need to be a mere chip carrier, but by planar integration, it can contain a multitude of functionalities like diplexers, low-pass filters, matching components, delay lines, …. The right-hand side of Fig. 6 gives an impression of what such a SAW module might look like. The module on display is a prototype of an integrated SAW duplexer, including the RX filter, TX filter, and antenna matching network, which makes it more than a mere two-in-one SAW filter.

This quantum-leap forward in passive integration will lead to a revolution in transceiver frontend design. There are unlimited possibilities for products like antenna switches with integrated SAW filters, SAW duplexers, multiband SAW duplexers with integrated diplexers, …. Even active building blocks like low-noise amplifiers (LNAs) can readily be integrated into these SAW modules based on a multilayer ceramic substrate made of a low-temperature cofired ceramic (LTCC) material.

III. Multimedia Applications

Broad-band access networks are the driving force in the multimedia area, where Internet-related applications such as interactive TV, electronic commerce, and several other broad-band services are offering new and interesting possibilities for consumers. The parallel introduction of digital TV reception via satellite, cable, or via terrestrial is also offering additional features, e.g., enhanced picture quality. As shown in Fig. 7, a strong increase of such multimedia applications is expected within the next three to five years. Therefore, newly emerging markets will be created for tuner manufacturers.

Up to now, SAW filters are only used in the IF stage of conventional TV tuners where they are key components in obtaining the appropriate channel selectivity. In contrast to the main board of cable modems or set-top boxes, conventional tuners are usually individual shielded modules utilizing a conventional analog RF technique.

Therefore, sophisticated manual tuning is necessary. New multimedia tuners using the up/down- (or dual-) conversion principle, described below, do not need any adjustment. Additionally, a 100% surface-mounted component placement is

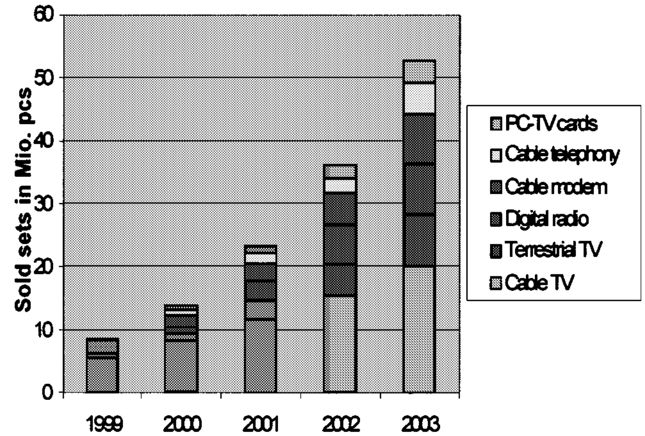

Fig. 7. Market overview digital applications, sold sets in a billion pieces worldwide: year 1999–2003.

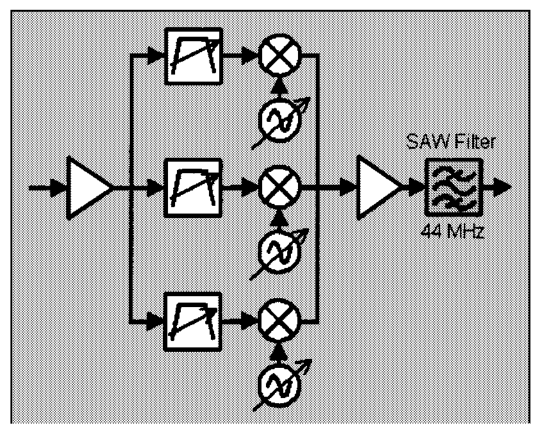

Fig. 8. Block diagram: single-conversion tuner.

possible. Hence, the whole tuner can be surface mounted onto the motherboard.

Nowadays, it is possible to integrate the complex RF circuits in silicon (or GaAs) chips by making use of the up/down conversion principle. These so-called "one chip tuner" solutions are offering advantages to reduce the overall component costs, as well as saving PCB space. Highly miniaturized RF SAW filters are key components in this new generation of multimedia tuners.

A. Comparison Single-Conversion Tuner/Dual-Conversion Tuner

In conventional single-conversion tuners, a tremendous effort is necessary to split the RF input signal into different paths and performing a preselection with tracking filters. The tracking filters are needed for image frequency rejection and must always be adjusted to the actual carrier frequency received. Due to the insufficient steepness, low-sidelobe suppression, and the limited tuning range of these tracking filters, the image frequency attenuation is not very effective and frequency dependent (Fig. 8). Therefore, the input RF signal band is usually subdivided into three RF signal bands in order to achieve the appropriate preselection.

In dual conversion tuners, no tracking filters are used and also no splitting of the input RF signal is done. The RF signal is

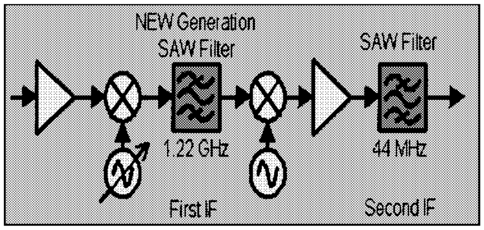

Fig. 9. Block diagram: dual-conversion tuner.

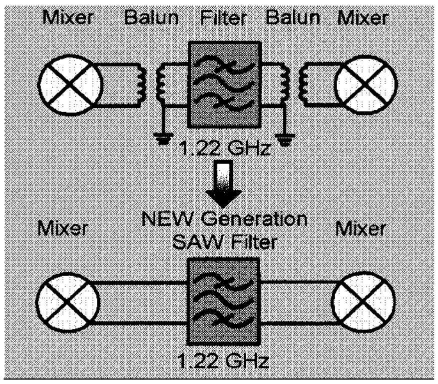

Fig. 10. Balun functionality integrated into the RF SAW filter for dual-conversion tuners.

mixed to a fixed "first" intermediate frequency (up conversion), with a typical center frequency in the range of 1.0–1.4 GHz. The desired frequency band or TV channel is then filtered with a customized RF SAW filter and again mixed down (down conversion) to the traditional IF frequency where the well-known IF stage with SAW filter is performing the further signal processing (Fig. 9).

B. RF SAW Filter for Dual-Conversion Tuner

The usage of RF SAW filters in dual-conversion tuners, instead of microwave ceramic- or discrete *LC* filters, has several advantages as follows:

- high stopband attenuation (local oscillator (LO) and image frequency rejection, typically 55, ..., 65 dB);
- low insertion attenuation and flat passband frequency response;
- balanced input and output self-matching to the IC impedance (e.g., in the range of 50–200 Ω);
- small SMD ceramic package.

Due to the superior performance of RF SAW filters and the balanced operation at the input and output ports in combination with the smallest possible size, they are perfectly suited for the application in dual- conversion tuners. The input and output ports of state-of-the-art gain sensitive RF image rejection mixers can be directly connected to the RF SAW filter. Thus, balun and matching components can be omitted, and component count as well as PCB space can be saved (see Fig. 10). As a result, the whole RF circuit design is simplified.

Table I summarizes the technical specification of such a customized RF SAW filter at a center frequency of 1220.0 MHz. The frequency response is shown in Fig. 11.

TABLE I
SPECIFICATION EPCOS AG RF SAW FILTER B1603 FOR DUAL-CONVERSION TUNERS

Item	Specification
Center frequency fc	1220.0 MHz
Insertion attenuation	5.8 dB max.
Usable passband	8.0 MHz
fc - 44 MHz, LO attenuation	50 dB min.
fc – 88 Mhz, image freq. rejection	50 dB min.
Differential input and output impedance	200 Ω
Package	3.8 x 3.8 mm^2
Operating temperature range	-40 to +85 ° C

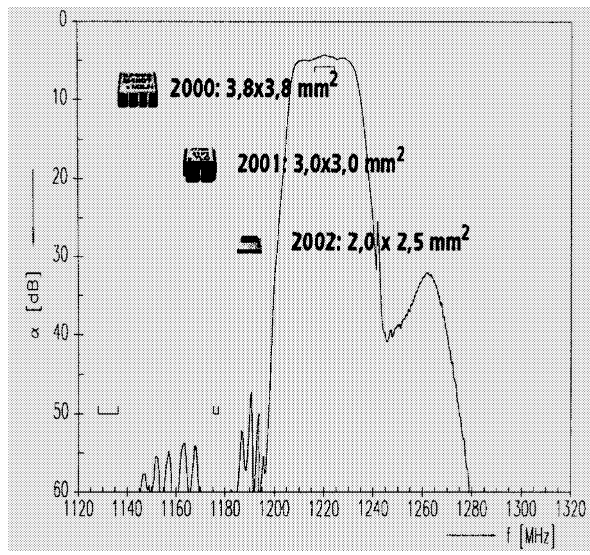

Fig. 11. EPCOS AG RF SAW filter B1603 for dual-conversion tuners.

Additionally, the estimated further miniaturization potential within the next two years is also indicated in Fig. 11. Performance and size are only achievable by using our advanced design and package know-how.

IV. CONCLUSION

As the driving factor for today's RF circuit design is cost and the SAW components are, in most cases, indispensable key components, the most prominent task of SAW suppliers is to bring down the costs of the individual SAW filters and to integrate as many external functions as possible into the SAW components.

Several examples of how EPCOS AG pursues these two tasks have been presented. Firstly, it has been demonstrated, that SAW filters for modern TX and RX RF stages can be extremely miniaturized, which helps to bring down the costs. Secondly, they can be realized in combination with additional features, such as impedance transformation, balun functionality, and integration of two or even three filter functions into one package. These features effectively reduce the overall component count and, thus, the total costs, but system miniaturization is also supported as well.

The ultimate miniaturization level is the LTCC module technology also described in this paper. The LTCC modules will have to compete with cost-effective discrete components, e.g., the CSSP package. The CSSP technology, in contrast to standard SMD ceramic technology, still offers a tremendous potential for further cost reduction coming with increasing production volume and additional component size reduction.

It has been demonstrated that SAW filters are key components in today's mobile communication and multimedia applications, and that SAW technology has by far not yet reached its end. New packaging and design approaches still offer the potential for further performance improvements, cost reductions, and miniaturization.

References

[1] Y. Yamamoto, H. Kawahara, N. Sakairi, Y. Takahashi, and R. Kajihara, "Intermediate frequency SAW filters for mobile phone application in Japanese markets," in *Proc. IEEE Ultrason. Symp.*, 1999, pp. 333–340.

[2] J. D. Kim and D. W. Weiche, "Trends and requirements of SAW filters for cellular system applications," in *Proc. IEEE Ultrason. Symp.*, 1997, pp. 293–301.

[3] N. Tanaka, Y. Hirao, Y. Kobayashi, H. Okano, T. Usuki, and K. Shibata, "Small SAW filters using optimized high reflection coefficient reflectors," in *Proc. IEEE Ultrason. Symp.*, 1998, pp. 87–90.

[4] G. Endoh, M. Ueda, O. Kawachi, and Y. Fujiwara, "High performance balanced type SAW filters in the range of 900 MHz and 1.9 GHz," in *Proc. IEEE Ultrason. Symp.*, 1997, pp. 41–44.

[5] S. Freisleben, A. Bergmann, U. Bauernschmitt, C. Ruppel, and J. Franz, "A highly miniaturized recursive Z-path SAW filter," in *Proc. IEEE Ultrason. Symp.*, 1999, pp. 347–350.

[6] J. Machui and W. Ruile, "Z-path IF filters for mobile telephones," in *Proc. IEEE Ultrason. Symp.*, 1992, pp. 147–150.

[7] A. Bergmann, U. Bauernschmitt, J. Gerster, S. Freisleben, and C. C. W. Ruppel, "High selectivity IF filters for CDMA mobile phones," presented at the Proc. IEEE Ultrason. Symp., 2000.

[8] Infineon Technol. AG, Munich, Germany, Applicat. Note PMB2212 V1.2, 1999.

[9] M. Hikita, N. Matsuura, N. Shibagaki, and K. Sakiyama, "New SAW antenna duplexer for single- and dual-band handy phones used in 800 MHz and 1.8 GHz cellular radio systems," in *Proc. IEEE Ultrason. Symp.*, 1999, pp. 385–388.

[10] N. Shibagaki, N. Matsuura, K. Sakiyama, and M. Hikita, "An integrated SAW antenna duplexer for EGSM/DCS1800/PCS triple band cellular phone systems," presented at the Proc. IEEE Ultrason. Symp., 2000.

[11] M. Hikita, N. Shibagaki, T. Akagi, and K. Sakiyama, "Design methodology and synthesis techniques for ladder-type SAW resonator coupled filters," in *Proc. IEEE Ultrason. Symp.*, 1993, pp. 15–24.

[12] ——, "SAW filters for high-power use in cellular radio portable phones," in *Electron. Commun. Japn. 77*, 1994, pp. 38–50.

[13] N. Shibagaki, T. Akagi, K. Hasegawa, K. Sakiyama, and M. Hikita, "New design procedures and experimental results of SAW filters for duplexers considering wide temperature range," in *Proc. IEEE Ultrason. Symp.*, 1994, pp. 129–134.

[14] H. Yatsuda, T. Horishima, T. Eimura, and T. Ooiwa, "Miniaturized SAW filters using a flip-chip technique," *IEEE Trans. Ultrason., Ferroelect., Freq. Contr.*, vol. 43, pp. 125–130, Jan. 1996.

Hans Meier (S'91–M'95) was born in Regensburg, Germany, in 1961. He received the Dipl.Ing. degree in electrical engineering and the Dr.Ing. degree for his fundamental work on propagation characteristics of leaky surface acoustic waves from the Technical University Munich, Munich, Germany, in 1990 and 1993, respectively.

From 1990 to 1993, he was a Research Engineer at the Institute of High Frequency Engineering, Technical University Munich. Since 1993, he has been within the Development Group, Siemens Matsushita Components (EPCOS AG), Munich, Germany. In 1997, he became Director of product development of SAW filters for consumer and multimedia applications. His research interests include SAW propagation, SAW filter modeling, and SAW filter applications in multimedia systems.

Thomas Baier born in Blaubeuren, Germany, in 1962. He received the Masters degree in physics from the University of Oregon, Eugene, in 1987, and the Diploma degree in mathematical physics, the Masters degree in mathematics, and the Doctors degree in semiconductor physics from the University of Ulm, Ulm, Germany, in 1989, 1993, and 1994, respectively.

Being a radio amateur, his strong interest in RF technology led him into the field of SAW devices for mobile communication. Since 1994 he has been with the SAW Group (both in research and development and product development for mobile communication SAW components), Siemens Matsushita Components (now EPCOS AG), Munich, Germany. Since 2000, he has been Director of product development for mobile communication wireless terminal SAWs.

Gerd Riha (S'76–M'80) born in 1949. He received the Dipl.-Ing. degree in electrical engineering and the Ph.D. degree from the Technical University of Vienna, Vienna, Austria, in 1974 and 1979, respectively.

From 1974 to 1979, he was a Research and Teaching Assistant at the Technical University of Vienna. He then joined the Research and Development Department, Siemens Matsushita Components (now EPCOS AG), Munich, Germany, where he focused on the research and development of SAW devices. He became Head of laboratory in 1984, and Head of the Research and Development SAW Components Department in 1986. In 1990, he became Director of the Research and Development Department for SAW Components, where one of his chief interests is the buildup of the technological product basis for the mobile communications business and multimedia applications.