INTEGRATED MULTI BAND/MODE FRONTEND MODULES FOR NEXT GENERATION MOBILE PHONES

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Abstract - In the last few years a significant trend towards cellular phones from single band to multi band applications has been observed, especially evident for GSM based devices. About five years ago, there were only a few models offering more than one frequency band of operation. Today, they have been fully substituted by dual-band phones for low-end applications, while triple-band (TB) handsets, previously reserved for the high-end market only, are becoming more and more standard. Due to the increased usage of GSM 850 in the USA there are already a few quad-band GSM phones introduced into the market. Adding third generation services to the existing second generation phones will lead to even more complex systems.

This continuing move towards higher functionality and increased complexity of the antenna interface is in contradiction to the requirements for smaller size, shorter development cycles as well as cost and component count reduction. As passive components outnumber active components these objectives can only be met by a higher level of integration of passive components.

Whereas the digital part is already highly integrated, the RF front-end section consists of a large number of passive and active components assembled on a printed circuit board (PCB). In a first step of integration of the antenna interface starting at the end of the 1990’s the switching between different bands and modes was accomplished by antenna switch modules (ASM). About two years ago higher integrated front-end modules (FEM), based on a combination of the surface acoustic wave receive filters (SAW filters) and a larger number of matching elements together with the ASM, have started to replace these ASMs. LTCC technology (low temperature co-fired ceramics) is the by far most commonly used substrate for these “acoustic” front-end modules. Compared to FR4 or laminates, LTCC is a low loss, high precision substrate allowing to integrate a large number of passive devices in a small volume, e.g., diplexers separating the 1 GHz and 2 GHz frequency bands can be implemented in LTCC with minimum size.

I. INTRODUCTION

The evolution from single band cellular phones to today’s standard dual- and triple-band respective quad-band high-end phone engines has led to a quite complex antenna interface. For every additional RF band, implemented in the phones, an additional front-end preselector filter in the receiver section is required. For full duplex systems a transmit bandpass filter for establishing a diplexer together with the Rx filter is needed, whereas for TDMA systems, like the predominating GSM standard, a low pass filter in the Tx chain might be sufficient.

For the latter systems often a RF switch synchronized to the time slots of the transmit and receive time frames is used for switching between the Tx and Rx branch. For these switches PIN diode based solutions are most widespread. Alternative solutions like GaAs pHEMT switches have gained importance to a certain extent especially in the area of antenna switch modules when moving towards quad-band or multi mode and multi band applications. In case of complex front-end modules there is no need for moving from PIN diode based switching solutions to GaAs switches even for multi band applications. The two Rx SAW filters in the 1 GHz range (GSM850 and EGSM/GSM900) and the two Rx SAW filters in the 2 GHz range (GSM1800 and GSM1900) can be connected to one switch. Complex matching elements are embedded in the LTCC to minimize overall system costs.

Fig. 1: Block diagram of a GSM Triple-Band Front-End

Fig. 1 shows the block diagram of a GSM triple-band front-end module with diplexed 1800 MHz and 1900 MHz Rx filters. The building blocks shown in this diagram (low pass filters LPF, antenna and Rx diplexer, Tx/Rx switches, Rx bandpass filters) plus some more details (switch biasing, filter matching) are approximately constituted of 60 to 70 elements in total. Assuming the usage of PIN diode...
switches). As the RF portion of the phones has not been allowed to increase in size compared to single band phones, moreover even had and still has to shrink, it is obvious that this continuously fueled the need for miniaturization of the individual components, as well as for higher levels of system integration.

Let us assume that this triple-band front-end interface would be built with discrete components on FR4 using standard 0402 components for all Rs, Ls, and Cs, and let us further assume that the diodes for the switches have roughly the same dimensions. Including standard keep out areas required for the SMT process an area of approximately 65 mm² would be occupied. In addition one would need to add the area for the three Rx SAW filters, which would be around 20 mm² (using 2x2.5 mm² packages). So the total size of a completely discrete solution would add up to 85 mm².

Let us assume that this triple-band front-end module with three SAW filters each sized 1.4x2 mm². This device includes all components as discussed above, while measuring only 6.7x5.5 mm². This footprint is less than half of the above discussed board area for a discrete solution.

Within 2004 there will be triple-band front-end modules available in a size of only ~15 mm² by using further size reduced SAW filters (~1.5 mm²) and by using a multi port RF switching die (like GaAs pHEMT) mounted in flip-chip technology instead of SMT mounted discrete PIN diodes. These new FEMs will meet the stringent industry requirements on maximum height of components. The height will be reduced from 1.8 mm to 1.2 mm.

Moreover, the demand for further miniaturization the reduction of total cost, performance enhancements, and less R&D efforts have been the driving forces for the wireless industry to move forward from ASM to FEM. The challenges associated with this trend of outsourcing a significant part of the system design and development include appropriate trade-off between integration, flexibility, and short turn around times in the component and system development cycles.

The introductory section has shown the need for suitable circuit architectures, integration substrates, and miniaturized sub-systems to enable a further miniaturization and integration of the cellular phone front-end. First examples have shown the great potential which is offered by front-end modules comprising SAW filters on LTCC substrates. Section II will deal with the technology requirements and features for both, the substrate with integrated RF components as well as the assembly technologies for mounting the remaining components on top of the carrier substrate. Section III will be devoted to the design related issues concentrating on latest architectures and performance optimizations achieved herewith.

II. TECHNOLOGY FEATURES AND REQUIREMENTS

A. KEY REQUIREMENTS ON THE SUBSTRATE PROPERTIES

The major requirements on a substrate used for integration of RF components are quite obvious. The losses within the Tx and Rx bands of the cellular phone systems have to be minimized, especially for the front-end components, in order to not degrade the receiver sensitivity and to avoid an increase of the power consumption in the transmit mode.

Therefore, materials with high quality factors are needed for forming the embedded inductors, transmission lines, and capacitors of an ASM or FEM. This means they should exhibit low dielectric losses (small tan δ) in the substrate and allow a high conductivity of the metalization used to form the embedded structures. LTCC offers both, low dielectric losses and low ohmic losses, as materials with a low sintering temperature of around 900 °C can be used together with highly conductive metalization layers made, e.g., of Ag.

Of course there are also other combinations of substrates and metalizations exhibiting similar loss features (e.g., FR4 with Al or Cu). But they have drawbacks with respect to other performance criteria required for front-end circuits. Due to a low dielectric constant of 2 to 4 compared to a permittivity εr of 7.8 for LTCC the size of embedded transmission lines and capacitors would be larger. Moreover the reproducibility of critical RF structures is better defined for LTCC due to the small thickness variations of the layers and the highly reproducible permittivity. For further reducing the size of embedded components one could also deploy the technology of co-sintering different ceramic materials designed for the same sintering tem-
temperature profile, i.e., combine the standard ceramic material with $\varepsilon_r = 7.8$ (for layers with inductors and transmission lines) together with material with $\varepsilon_r$ around 20 (mainly for capacitors).

Another approach for substrates for ASM and FEM seen recently from semiconductor manufacturers on the market is the combination of FR4/laminate with IPDs (integrated passive devices). These IPDs form the diplexers and low pass filters on special silicon or GaAs dies which are mounted onto the FR4 module carrier. While offering quite high accuracy by using photolithography for structuring the embedded passives the range of element values and Q factors are smaller than for circuits based on LTCC substrates.

The FEM's presented in this paper are produced on a non-shrinkage LTCC. Two alumina cover sheets on top and bottom of the layer stack, which typically contains in between 10 to 15 ceramic layers for an ASM or FEM, help to avoid lateral shrinkage during the firing process step. This production technology is appropriate for a panel sizes up to 8” without sacrificing yield due to reduced accuracy of embedded RF structures. Applying this technology the demanding cost targets of the wireless market can be met. Some basic material properties of the LTCC substrate are summarized in table 1.

The typical performance requirements for the Tx and Rx sections of a front-end for a GSM multi band FEM are summarized in table 2.

### Table 1: Material Properties of EPCOS LTCC

<table>
<thead>
<tr>
<th>Material</th>
<th>K8, K 20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fired thickness of dielectric layer</td>
<td>30 µm to 130 µm</td>
</tr>
<tr>
<td>Density</td>
<td>3.11 g/cm³ ± 0.65 %</td>
</tr>
<tr>
<td>Dielectric constant $K$</td>
<td>7.82 (19) ± 3.5 %</td>
</tr>
<tr>
<td>Dissipation factor</td>
<td>$1.1 \times 10^{-4}$</td>
</tr>
<tr>
<td>Dielectric strength</td>
<td>&gt; 23 kV / mm</td>
</tr>
<tr>
<td>Thermal coefficient of Dielectric constant TCK</td>
<td>6.21 ppm / K ± 4 %</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>3.05 W / m·K ± 3.5 %</td>
</tr>
<tr>
<td>Shrinkage (X,Y)</td>
<td>0.202 % ± 0.07 %</td>
</tr>
<tr>
<td>Shrinkage (Z)</td>
<td>45.2 % ± 0.4 %</td>
</tr>
<tr>
<td>Young’s Module</td>
<td>111 GPa ± 4 %</td>
</tr>
<tr>
<td>Flexural strength</td>
<td>270 MPa</td>
</tr>
</tbody>
</table>

### Table 2: Performance Requirements for a GSM FEM

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insertion Attenuation Tx EGSM</td>
<td>880-915MHz</td>
</tr>
<tr>
<td>Insertion Attenuation Rx EGSM</td>
<td>925-960MHz</td>
</tr>
<tr>
<td>Insertion Attenuation Rx DCS</td>
<td>1805-1880MHz</td>
</tr>
<tr>
<td>Insertion Attenuation Rx PCS</td>
<td>1930-1990MHz</td>
</tr>
<tr>
<td>TT GSM Suppression</td>
<td>880-915MHz</td>
</tr>
<tr>
<td>TT DCS Suppression</td>
<td>1710-1755MHz</td>
</tr>
<tr>
<td>Harmonic Attenuation (Tx.mode)</td>
<td>2.8, 3.8, 5.8</td>
</tr>
<tr>
<td>Far Out Selectivity (Rx mode)</td>
<td>40 dB</td>
</tr>
<tr>
<td>Switch Off Isolation (Tx-ANT)</td>
<td>Passband</td>
</tr>
<tr>
<td>Tx-Rx Isolation</td>
<td>Passband</td>
</tr>
<tr>
<td>Harmonic Generation</td>
<td>Pin=35dBm for EGSM</td>
</tr>
<tr>
<td>Harmonic Generation</td>
<td>Pin=35dBm for DCS</td>
</tr>
</tbody>
</table>

On the Tx side focus is on very low insertion attenuation (less than 1 dB to 1.5 dB) and high suppression of harmonics of the power amplifier (greater than 30 dB to 35 dB) as shown in fig. 3. The harmonics suppression in a
conventional ASM and FEM is achieved by the combination of attenuation poles of the LPFs (one per RF band, i.e., 1 GHz and 2 GHz), the elements of the antenna diplexer, as well as by transformed impedances of the Rx shunt diodes. On the Rx side focus is on lowest insertion attenuation together with steep skirts to suppress the adjacent Tx band and close in blocker signals on the upper side of the Rx band. Out of band the general GSM requirements concerning blocking interferers have to be met (23 dB rel.) from DC up to 12.75 GHz.

With the direct conversion chipsets dominating the market nowadays one would have expected that these items would cover all requirements as there is no need for attenuation of image frequencies. But it became obvious that there is a need to suppress harmonic frequencies of the Rx VCO to a higher amount to avoid leakage and DC offsets [2]. The additional specification needles at 2.7 GHz and 4.5 GHz are shown in fig. 4 for the EGSM Rx wideband response of the FEM.

Recently DMS filters have been further enhanced concerning reduced insertion attenuation. Filters for the 2 GHz band (insertion attenuation less than 2 dB typically and about 2.5 dB max.) enable the use of LNAs integrated into transceiver ICs based on CMOS. Integration of such low loss filters into FEMs further reduces the losses in front of the LNA by a much more compact phone PCB layout and eliminating interface losses. Therefore, FEMs play an important role to enable the introduction of cost optimized chipsets reducing the overall cost of the RF portion of a mobile phone. Figure 5a and 5b show the performance of the GSM1800 Rx branch of one of the most recent triple-band designs achieved by integrating these low loss 2GHz SAW DMS filters into the FEM. The insertion attenuation from the antenna port to the Rx output port exhibits less than 3 dB.

For direct conversion systems with differential IC input these higher attenuation requirements can be met with the outstanding broadband suppression behavior of 50/200 Ohm DMS-type SAW filters in 1.4x2 mm² packages [1]. No degradation of pass band attenuation or skirt steepness can be seen (fig. 4).

For the chipsets on the market with single ended LNA inputs the situation is a bit different. If a ladder-type filter is used, the out of band attenuation is limited and also flyback might occur The missing extra rejection can be provided for example within the ceramic carrier or by combining impedance effects in the interaction of the SAW filter with the LTCC carrier. By that partitioning of the specifications the ladder-type filter can be optimized on passband and skirt steepness without trade-off. The situa-
tion is shown in figure 6. The behavior is precisely predicted by an accurate EM (electro-magnetic) simulation of the complete module. Remaining violations for the most demanding specs (like spec 2 in fig. 6 for attenuation of the VCO harmonics) can be eliminated by choosing a single ended DMS-type SAW filter even for the 2GHz band (fig. 7).

A second example for the advantages of optimized and reduced number of interfaces when moving towards FEMs is the avoidance of interferences of the Tx paths with the Rx filters of the other RF bands. In a typical development flow of the RF portion of a mobile phone the board layout will be made in parallel to the ASM samples and Rx filter samples. For the ASM and Rx filter the target transfer characteristic is well defined at the beginning of the development. Nevertheless, out of band impedances of the components to be connected on the PCB by transmission lines and additional matching elements are not precisely predictable. When building up the RF board one might encounter problems with dips in the passband of the Tx to antenna transfer function. Those dips are for example caused by a conjugate complex matching of the transformed 1GHz Rx filter impedance with the 1GHz antenna diplexer input. As a consequence the LPF section of the diplexer might not perform properly in that frequency range any more and some portion of the energy of the 2 GHz Tx signal is lost at the common antenna port. The effect is depending on the layout of the PCB due to the transformation of the 1GHz filter input impedance by the connection lines. By combining the components into one FEM such unwanted surprises in the development stages of a phone can be avoided as they are predicted by the device simulation and may be compensated for prior to prototyping, reducing the number of design cycles and R&D effort for the phone design engineers. This effect is depicted in fig. 8. The first two curves are the measurement (blue) and simulation (red) of a properly designed TB-FEM, and the third curve (green) shows the response of a discrete assembly with an ASM, a discrete EGSM Rx SAW, and a phase shifting line in between causing a dip in the transfer function when connected to each other.

![Fig. 6: Wideband DCS Rx Frequency Response Using Ladder (single ended) Filter (green=simulation, red=measurement, blue=SAW filter alone)](image)

![Fig. 7: DCS Rx Wideband Using DMS (single ended) (red=FEM, blue=SAW filter alone)](image)

A very essential part of the FEMs is the embedded filter matching. This does not just improve performance, but also helps to reduce component count and the associated costs. Two different kinds of matching have to be realized. The first one is the input matching in between switches and filters. The second one is the output matching of the module towards the IC. We are focusing on the more popular balanced type chipsets in the next paragraphs.

![Fig. 8: DCS/PCS Tx Passband (red=simulation, green=measurement of not optimized solution, blue=measurement of optimized solution)](image)

By designing a higher integrated module one can adjust the interface of the switch and the filter input with an additional degree of freedom by having the power matching to the required complex impedance. The required matching will be embedded as a LC circuit in the ceramic carrier. The achieved matching is highly reproducible due to the exact and stable locations of the components and minor material property fluctuations. On the output side the FEM allows to adjust to the various IC impedances by buried inductors and capacitors. By this approach one only needs one RF filter design per frequency band for different chipset impedances. Filters with best performance with respect to insertion attenuation, steepness of the skirts, and stopband rejection are used. Matching to different...
impedances is realized in the ceramic carrier. The re-use of
the same CSSP filter for different modules reduces the
effort for the design and fabrication of the SAW filters.
Finally both matching circuits in the Rx sections of a FEM
fit into the ceramic layer stack without extra size penalty.

The achieved matching performance is verified in fig. 10
and 11 comparing the transfer function $S_{21}$ and the VSWR
on the output side of the DCS path of the FEM with the
frequency response of the filter.

This approach has been first implemented in a Rx filter
bank integrating all 4 receive filters of a quad-band system
into one module used now in high volume. Fig. 11 shows as
an example the realized impedances in a 50 Ohm smith
chart for the high impedance one 1 GHz branch and table 3
gives the initial target values of the LNA matching within
the board layout for all 4 bands. The obtained impedances
are in good agreement with the initial target values
(fig. 11).

### Table 3: Complex Rx-Load Impedances of Filterbank

<table>
<thead>
<tr>
<th>GSM 850 Load</th>
<th>378 Ohm</th>
<th>0.72 pF</th>
</tr>
</thead>
<tbody>
<tr>
<td>EGSM Load</td>
<td>316 Ohm</td>
<td>0.74 pF</td>
</tr>
<tr>
<td>DCS Load</td>
<td>93 Ohm</td>
<td>0.88 pF</td>
</tr>
<tr>
<td>PCS Load</td>
<td>64 Ohm</td>
<td>0.78 pF</td>
</tr>
</tbody>
</table>

A key function of a triple-band module is the co-existence
of the Rx DCS and Rx PCS paths. Three different
circuits are suitable for the combination of these two bands,
when using pin-diode switches.

The first possibility is to use two cascaded lambda-
quarter transmission lines, each terminated with a shunt
diode and an additional series diode, branching of from the
connection point of the two lines. In this configuration the
Rx PCS path is formed by the series diode which is
switched together with the second shunt diode. The
advantage of this circuit is the good isolation in Tx mode.
For maximum isolation in the overlap region of the Tx PCS
band with the Rx DCS band and second
shunt diode are biased together with the first shunt diode,
yielding 40 dB Tx PCS – Rx DCS isolation, a critical
parameter for some transceivers, due to the cross-talk
within the transceiver. However, using two transmission
lines is detrimental for the insertion loss, as the DCS signal
is attenuated by two lambda-quarter lines and the
corresponding diodes.

The second possibility uses only a single quarter-lambda
transmission line, the series diode for the PCS branch being
connected to the beginning of the line. For each of the
receive bands the insertion loss improves now by 0.2-
0.3 dB as the signal is not attenuated by the second
transmission line as in the previous configuration and one

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Fig. 9: Comparison of the DCS Rx Path of the FEM with
the Filter (150 Ohm differential Load) (blue=FEM, red=SAW filter alone)

Fig. 10: Comparison of the VSWR of the DCS Rx Path of
the FEM with the Filter (150 Ohm differential Load) (blue=FEM, red=SAW filter alone)

Fig. 11: Complex Matching for GSM850 branch

The idea for integrating the output matching of the Rx
filters into the substrate of the FEM is now exploited to
allow for further miniaturization and system cost reduction.
So far the mobile phone manufacturers requested certain
standard Rx interface impedance levels like 50 Ohm, 150
Ohm, or 200 Ohm. For very high volume platform
developments having a standardized RF layout across a larger
number of phone models it might be attractive to embed
not only those matching networks to a few standard load
impedance, but to offer really a conjugate complex power
or noise matching towards the LNA within the fixed PCB
environment. This will help eliminating all discrete matching
elements on the phone PCB in between the FEM and the
RF-IC/LNA.
shunt diode can be removed as well. On the other hand is the minimum high band Tx – Rx DCS isolation now determined by the one remaining shunt diode.

Fig. 12 shows the Rx PCS receive path of a triple-band module incorporating the DCS as well as the PCS SAW filter and using a pin-diode switch with a single transmission line.

Fig. 12: PCS receive path of module with a pin-diode switch, using a single transmission line. Switch in Rx PCS position.

A third possibility is the diplexing of the DCS and PCS SAW filters, using a combining network that consists of inductive and capacitive components. One transmission line with the associated shunt diode is still needed for the Tx-mode, but the module does not draw any current in receive mode, which will allow for longer stand-by time. (For the first two possibilities at least in Rx PCS mode about 1-2mA of current are needed).

Fig. 13 shows the Rx DCS and Rx PCS transfer curves for a triple-band module where the two bands are combined by an appropriate combining network. The Tx-Rx DCS isolation is determined, similar two the switch with one line, by the sole shunt diode.

IV. SUMMARY AND OUTLOOK

The requirements for front-end systems for cellular phones range from extremely demanding electrical specification parameters to continuous pressure for further miniaturization accomplished by increased functionality and higher integration levels. All those items have to be met under tremendous cost targets. It has been demonstrated that miniaturized front-end modules based on LTCC ceramic substrate with optimized SAW filters are perfectly suited to fulfill these requests. The successful implementation of these FEMs requires also the improvement of other key components like RF switches, for appropriate assembly technologies using batch processes in an efficient manner and to adjust the circuit design and topology accordingly to the strength of the individual components forming the modules. Examples have been presented.

Nevertheless, integration will not stop with the incorporation of the Rx front-end filters into the ASM building an FEM, Power Switch Modules (PSM) combining the power amplifier with the antenna switch or even with the front-end module (PA-FEM) are already ahead. In the longer run one can also clearly see higher integrated Rx transceiver modules [3] or even modules containing the complete RF part of a mobile phone. SAW-Filters, LTCC substrates, the appropriate assembly technologies, and the design methodologies described will play a key role for these higher integrated modules. Different partitioning of the RF portion of cellular phones resulting in alternative solutions are possible.

FEMs will have a significant share of the market and play an important role for the RF front-end of mobile phones for the next years. This will be ensured by continuous miniaturization (e.g., ~15 mm² area requirement for 2005 for triple-band functionality vs. 35...37 mm² today), further performance enhancement (like the loss reduction shown) and feature enrichment (diplexed Rx branches for elimination of current consumption in all Rx standby modes, complex matching to the RF-IC).

V. REFERENCES