Considerations on Configurable Multi-Standard Antennas for Mobile Terminals Realized in LTCC Technology

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Abstract. *This paper is an extended version of a paper presented at the EuCAP 2009 conference [1]. We present part of a long term research project that aims on designing a (re-)configurable multi-standard antenna element for 4G (4th Generation) mobile terminals based on LTCC (Low Temperature Co-fired Ceramic) technology. The antenna itself is a coupling element [2] that efficiently excites the chassis of the mobile terminal to radiate as an entire antenna. Coupling is optimized by a reactive tuning circuit. Several of these tuning circuits are realized in a single LTCC component and can be multiplexed to the antenna by a SPnT (Single Pole n Thru) antenna switch integrated into the LTCC component. The coils and capacitor in the LTCC component are configurable on the top-layer of the component. Thus, the component is configurable according to different mobile terminal chassis configurations and multiple bands.*

Keywords

LTCC, reconfigurable antenna, coupling element, 4G antenna, small terminal antenna.

1. Introduction

The 4th generation of mobile communications aims at combining multiple standards and applications seamlessly and mostly invisibly for the user into a single mobile terminal. This shall be done based on a fully integrated IP-based system indicating that the mayor system aspects are treated on the software basis, e.g. SDR (Software Defined Radio). However, the approach also requires reconfigurable hardware which is challenging especially with respect to the antennas because of their fundamental relation to the wavelength.

Current mobile terminals for quad band or penta band operation mostly use antenna elements that consist of a metallic structure which is divided into different long arms providing resonances in the frequency bands of operation to efficiently couple energy to the chassis that acts as the entire antenna [2], [3]. Often it is stated that these antennas are based on the PIFA (Printed Inverted-F Antenna) principle, although this is not correct. However, one can easily understand that this concept of somehow separated resonators becomes more complicated as more frequency bands are desired. Therefore such a concept is no option for a mobile working with a large number of standards. Designing a wideband antenna element would be favorable, but these concepts are based on broadband monopoles that require quite a large space in the terminal when designed also for the lower frequency bands around 1 GHz. The concept of non-resonant coupling elements [2] seems to be a better approach in this sense. In [4] this concept is applied in combination with a tuning circuit to design a DVB-H antenna for a mobile terminal. In [5] we showed, using the same configuration and dimensions of the coupling element in [4], that the concept is in general applicable for multiband operation (and probably in the long term SDR) in terms of total antenna efficiency by using a (re-)configurable tuning circuit composed out of SMD elements. In this paper we present some continuation of this approach with emphasis on the integration of the coupling element together with a configurable tuning circuit into one component by using LTCC technology. The questions to be answered are:

- Is it feasible to achieve a reasonably small component for multiple band operation?
- Is the total efficiency of such a component still sufficient compared to the lower bound that has been estimated for typical applications in [5]?
- Does the concept have a potential for future re-configurable antennas?

2. Conception

A rough description of the idea is shown in Fig. 1: The top part shows the standard coupling element with reactive Π- (or T) tuning circuit as presented in [5]. In the bottom part a) only some tuning circuits are realized in a LTCC component. The different RF modules will be connected to the inputs of the individual circuits. An antenna switch will multiplex the different signals via their tuning circuit to the output terminal of the LTCC component which has to be connected to an external coupling element. In part b) also a small version of the coupling element is integrated into the LTCC component in order to result in just a single compact configurable antenna component.

For both configurations, tunable capacitors and coils have to be designed in the multilayer of the LTCC component. In addition an antenna switch has to be integrated into the LTCC component that provides the possibility to multiplex the different circuits to the coupling element. Such antenna switches are already used as SPnT electronic switches in todays' frontends. Using this concept of a configurable antenna it would be advantageous to relocate this switch into the antenna component.

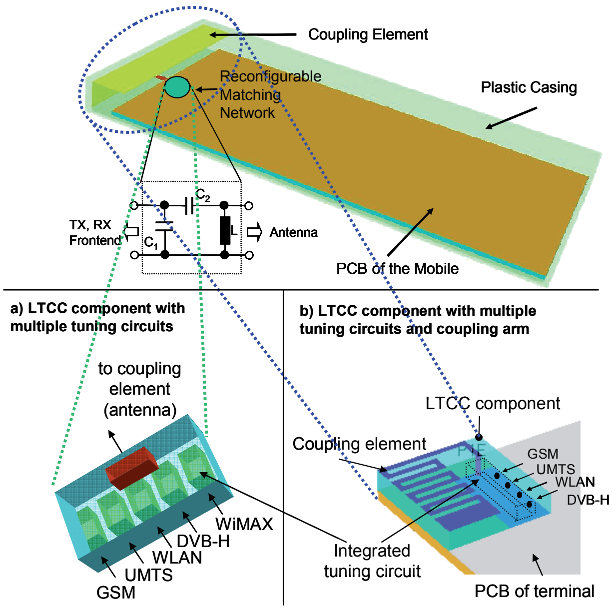


Fig. 1. Concept of a configurable coupling element antenna (top) and two principle realizations: a) Multiple configurable reactive circuits in a compact LTCC component connected to an external coupling element and b) Multiple configurable reactive circuits integrated together with a coupling arm into a compact LTCC component.

2.1 Configurable Coils and Capacitors in Multilayer LTCC Technology

As core material we use the LTCC material Dupont 943 with $\varepsilon_r = 7.4$ and tan $\delta = 2e\text{-}3$. The unfired tape thickness is 114 μm. We use 8 layers for our component. In order to account for conduction losses of the conductive paste we use a surface conductivity for the layer metallization of $\sigma = 4.1e7$ (Ωm)-1 with a wideband loss model in the EMPIRE FDTD [8] software. This has proven to provide realistic results in prior modelling of LTCC components.

Keypoint of the concept is the design of configurable coils and capacitors for the Π- or T-tuning circuits. The multilayer capacitor consists of stacked plates realized in the different layers of the component as it is shown schematically in the right part of Fig. 2. The straight connection from one plate to the next is realized on the top layer of the component as shown on the left side of Fig. 2. Thereby it is possible to lower the capacitance from the initial value in multiple steps by just cutting different connections on the top layer. In order to have sufficient tuning flexibility, 3 different sets of capacitors are designed each with 10 tuning steps. The area occupied on the LTCC component by such a capacitor is 2.65 x 2.1 mm².

The design of the configurable coils follows a similar principle. It consists of stacked windings in the different layers of the multilayer. The interconnections of the different windings are realized on the top layer of the component allowing to cut-off windings from the initial coil and thereby lowering the inductance from the initial value in several steps. Four different sets of coils have been designed; - each of them provides 10 tuning steps. The area occupied by such configurable coils is 2.25 x 2.25 mm².

10 – steps configurable multilayer capacitors:

Version 1: 1.15 < C [pF] < 2.25
Version 2: 2.20 < C [pF] < 5.60
Version 3: 4.25 < C [pF] < 8.80

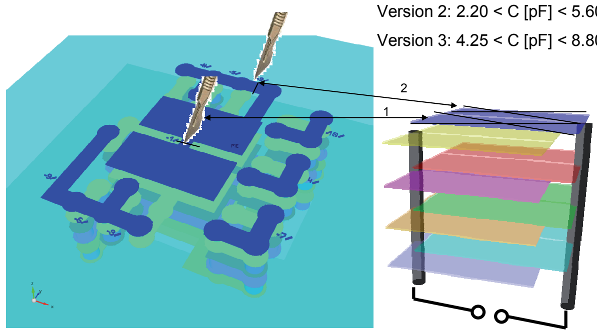


Fig. 2. Configurable multilayer capacitor in LTCC technology. By cutting the bridges on the top layer the capacitance can be reduced from the initial value in 10 steps. Three different versions according to the initial capacitance are realized.

10 – steps configurable multilayer coils:

Version 1: 2.4 < L [nH] < 3.9
Version 2: 3.6 < L [nH] < 7.4
Version 3: 6.5 < L [nH] < 11.1
Version 4: 10.1 < L [nH] < 16.1

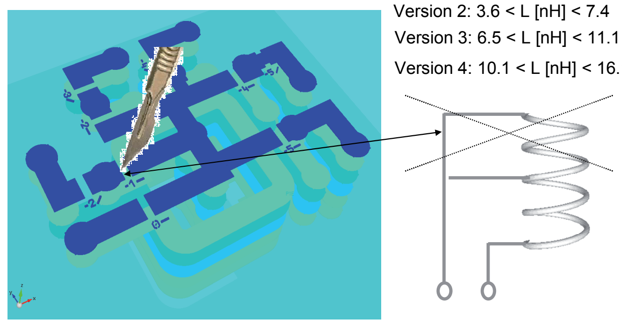


Fig. 3. Configurable multilayer coil in LTCC technology. By cutting the bridges on the top layer the inductance can be reduced from the initial value in 10 steps. Four different versions according to the initial inductance are realized.

Note that both, the capacitors and the coils can only be used in a limited frequency range due to their resonance frequencies caused by parasitic inductance in the capacitors and parasitic capacitance in the coils which are especially caused by the large number of via interconnections. Although a lot of effort has been taken in the design to avoid too low resonance frequencies, the higher value sets of the coils can only be used for lower frequency circuits (e. g. f < 1 GHz). This has to be taken into account when choosing components for a specific tuning circuit later.

2.2 Compact LTCC Component Containing Multiple Configurable Tuning Circuits

As mentioned in Section 1, first a compact multi-port tuning component is designed. The component will have several RF terminals connected to the different front ends and one terminal which is connected to the external coupling element as shown schematically in Fig. 1a. The component includes several configurable tuning circuits composed out of the capacitors and coils presented in Section 2. Additionally it includes a footprint for an antenna switch that multiplexes the different paths to the coupling element terminal. In our design the footprint is made for a standard SP8T switch that allocates an area of 4 x 4 mm² when SMT packaged. Later, also unpackaged chips can be used because in the LTCC process it is possible to realize cavities in the multilayer component that package and fully integrate the chip. Thereby the switch does not add additional height to the LTCC component. The functional diagram of the switch is shown in Fig. 4.

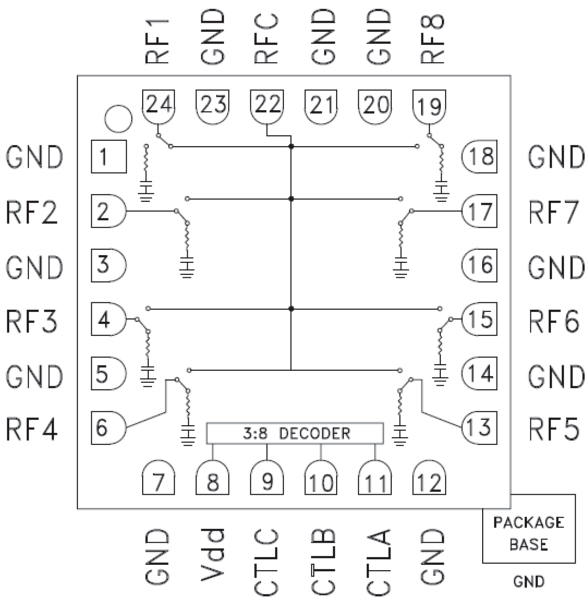


Fig. 4. Functional diagram of the Hittite HMC253LC4 GaAs MMIC SP8T switch [6].

Note that this specific switch has been chosen mainly due to short term availability for the set up of the functional prototype. Furthermore this specific switch is not applicable for real GSM or UMTS input power of more than 30 dBm. However, with respect to a final product there is quite a good choice of components available on the market.

The entire configuration of the LTCC component including 6 configurable tuning circuits (without the switch) is shown in Fig. 5. Its total size is 20 x 13 x 0.8 mm³.

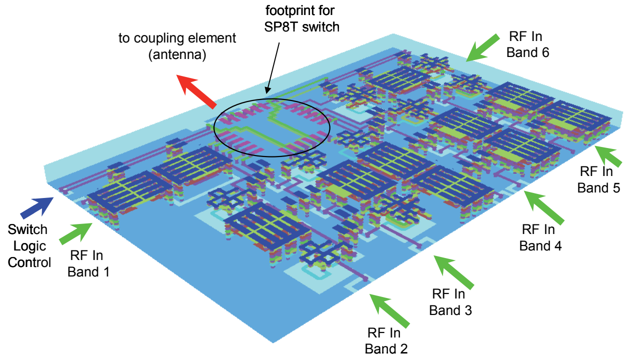


Fig. 5. LTCC component containing 6 reactive tuning circuits and a footprint for a SP8T switch.

In [5] Π-tuning circuits have been designed for the configuration in figure 1 (top) for a wide frequency range using standard SMD capacitors and coils. For these circuits high values especially for the coils are only used in the low frequency range because of the above mentioned problem of parasitic resonance of the coils and capacitors. Fig. 6 shows the initial total efficiency of the coupling element without tuning circuits (straight green line) and several narrowband improvements using the different tuning circuits consisting of standard SMD coils and capacitors (blue lines). In addition lower bounds of the minimum required total efficiency for different applications have been roughly estimated in [5]. They are marked in Fig. 6 as horizontal black lines.

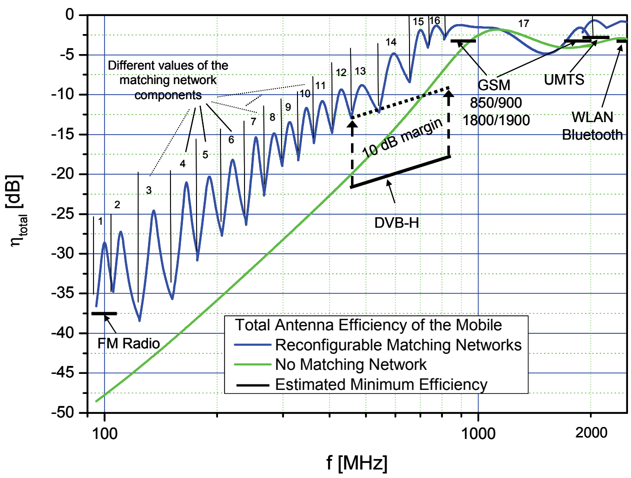


Fig. 6. Total efficiency of the mobile with reconfigurable tuning circuit and estimated minimum requirements for various applications [5].

Fig. 7 shows the values of the components used in the different tuning circuits. It can be observed that especially for the low frequency range, high values for the inductance of the coil have to be used. According to the values of the

LTCC coils and capacitors designed in Section 2 we are able to cover only the frequency range from approx. 700 MHz on (biggest available coil is L = 16 nH in Fig. 3).

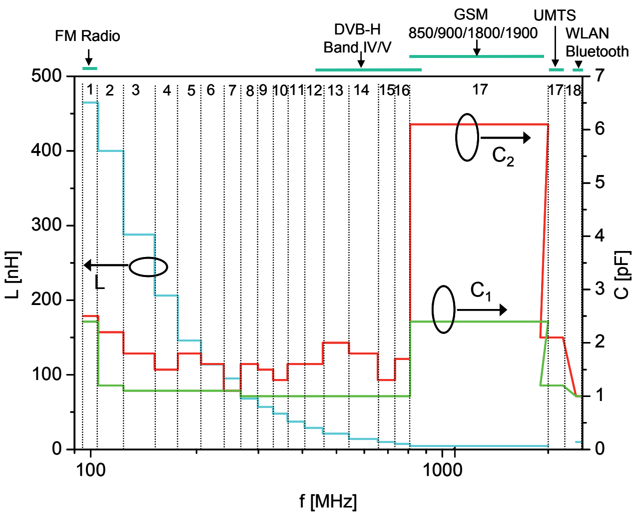


Fig. 7. Values of the tuning circuit elements for optimum efficiency in various frequency bands [4].

When we put together the 6 Π-tuning circuits in our component we are able to do a pre-selection of the elements using the results in Fig. 7. E. g. according to Fig. 6 a tuning network for GSM900 will consist of a 5 nH coil, a 2.5 pF capacitor and a 6 pF capacitor when we use the same coupling element and the same chassis like in Fig. 1. Therefore our pre-selection will be a version 2 coil ($3.6 < L$ [nH] < 7.4), a version 2 capacitor ($2.2 < C$ [pF] < 5.6) and a version 3 capacitor ($4.35 < C$ [pF] < 8.8). Based on these initial values we hope to be able to do fine tuning which might be necessary due to a slightly different coupling element or chassis configuration later on using the tuning capability on the top layer of the LTCC. This fine tuning can also be used to adapt the antenna to different prototyping stages during the design of the mobile terminal. Once we have the final terminal at the end of the design phase we have to adapt only the top layer of the LTCC component according to the final settings and do the mass production of the LTCC tuning component.

2.3 Compact Configurable Antenna Element in LTCC Technology

One could still see it as a drawback that the coupling element and the tuning component are separate components. It would be somehow nice to have both together in one compact configurable antenna component.

Figure 8 shows one approach to design such a component that includes the configurable tuning circuits and a small coupling arm mounted on a generic PCB of a mobile terminal. The size of the entire component containing 5 configurable tuning circuits is 20 x 15 x 0.8 mm³.

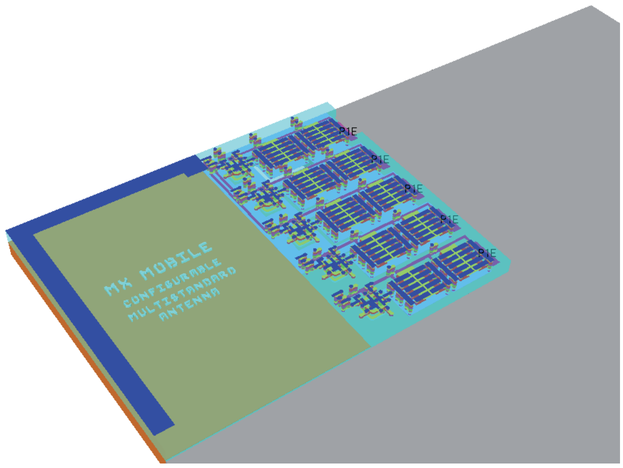


Fig. 8. LTCC component containing 5 reactive tuning circuits, a footprint for a SP6T switch and a small coupling arm.

Due to the smaller size of the integrated coupling arm compared to the coupling element in Fig. 1 we can predict that the coupling will be less optimum and the available efficiency without the tuning circuits will be smaller. This is verified in Fig. 9. Due to the low initial efficiency especially at the low frequencies the improvement by using the tuning circuits is not sufficient for GSM850 and GSM900 according to the minimum requirements estimated in [5].

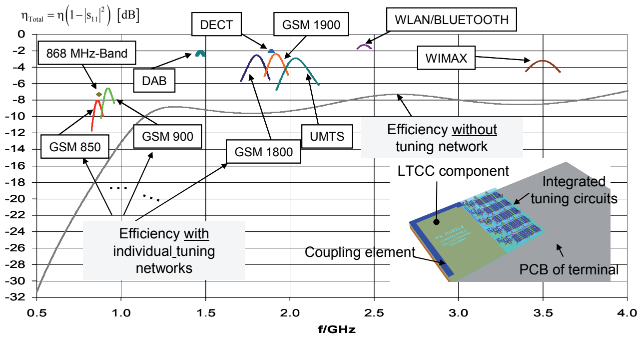
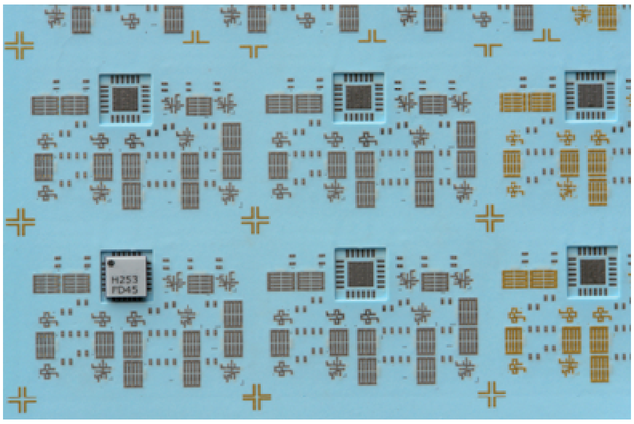


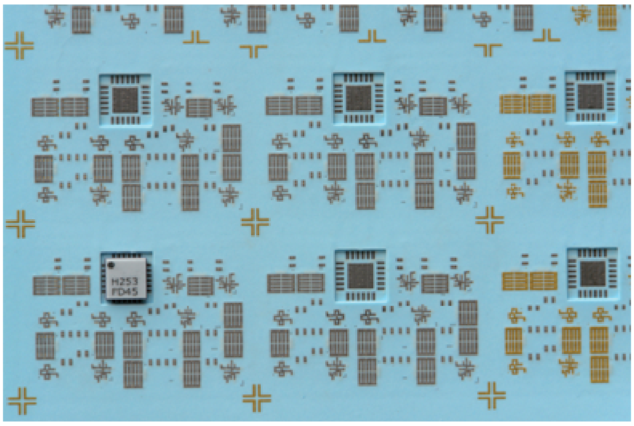
Fig. 9. Total efficiency of the compact antenna components mounted on the reference platform (100 mm x 40 mm) using different configurations of the integrated tuning circuits in comparison with the total efficiency of the coupling element without any tuning circuit [5].

3. Realized LTCC Prototypes

IMST possesses an in-house fab for the production of prototypes and small quantity series in LTCC technology. Both versions of the components are realized using this prototyping facility. Fig. 10 shows the produced tiles that contain several components of both versions presented in Section 2.2 and 2.3. The prototyped version of the combined component consisting of circuits and small coupling element according to Section 2.3 is slightly different to Fig. 9. Instead of a coupling arm the prototyped version in Fig. 10b consists of a coupling plate.



a) LTCC tile of the components containing multiple tuning circuits according to Section 2.2.



b) LTCC tile of the compact configurable antenna element according to Section 2.3.

Fig. 10. LTCC tile containing both versions of the component.

Both versions contain a cutout part where later on the packaged SP8T switch will be integrated. This reduces the profile of the component. Using LTCC technology such cutout parts can be realized without a problem. For our prototypes a packaged SP8T switch is used. Later also unpackaged switches can be used in cavities of the LTCC component. This will further reduce the size of the entire component.

Fig. 11 shows the test mock-up. It consists of a printed circuit board (PCB), a coupling element and the LTCC component according to Section 2.2 containing 6 configurable tuning circuits and the packaged SP8T switch. 5 of these circuits are tuned to optimize the coupling between the coupling element and the chassis in different frequency bands. In order to tune the circuits the impedance of the coupling element without the circuits has been measured first. The estimates for the values of the coils and capacitors for the different tuning circuits are calculated. In order to tune the coils and the capacitors the tuning bridges on the top layer have to be cut as shown in Fig. 2 and Fig. 3. For our LTCC prototypes this job is done by a trimming laser. The 5 rf inputs are accessible at the SMA connectors. In order to control the switch a logic circuit and a battery are located in a metal box at the other end of the PCB.

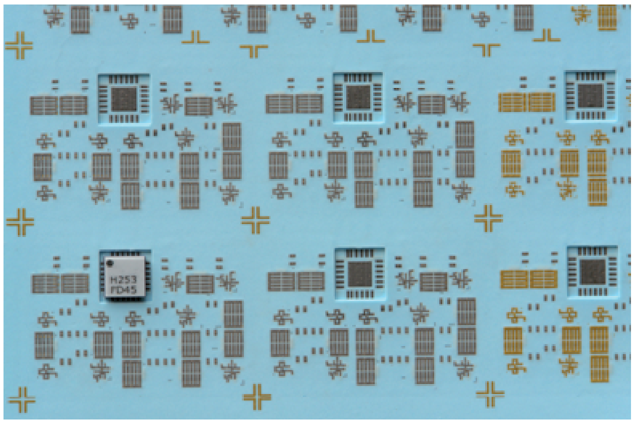


Fig. 11. Test mock-up consisting of a PCB (100 mm x 40 mm) a standard coupling element and the LTCC component containing 6 tuning circuits. 5 RF terminals are connected via SMA connectors. The metal box contains a logic to control the switch.

Fig. 12 shows the return loss measured at the 5 different terminals. It can be observed that sufficient matching is obtained in all the bands under investigation.

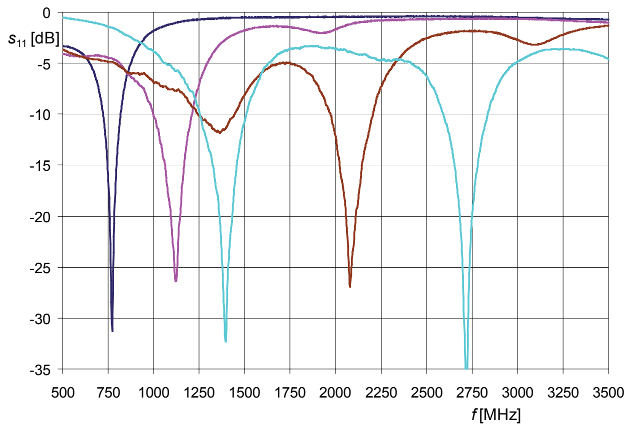


Fig. 12. Return loss of the antenna measured at the 5 different terminals.

As mentioned earlier, the matching of the antenna alone is not a sufficient measure quantifying the antenna performance because of the non-ideal components of the tuning circuits that can contain a certain amount of ohmic losses. If the radiation resistance of the antenna itself is low, these losses can be significant although the LTCC material used is quite high quality. Therefore the total antenna efficiency

$$\eta_{total} = \left(1 - \left|s_{11}\right|^2\right)\eta = \frac{P_{rad}}{P_{in}} \tag{1}$$

which accounts for the losses and the mismatch is measured. In (1) s_{11} is the return loss of the antenna and η is the efficiency of the antenna, P_{rad} is the total power radiated by the antenna and P_{in} is the constant feed power delivered by the source. The total radiated power is obtained by measuring the three-dimensional far field around the antenna in an anechoic chamber. The 3-dimensional measurement set up consists mainly of an elevation positioner, which is installed on a turntable. The turntable performs an azimuth turn θ, whereas the positioner establishes an elevation scan ϕ. The resulting elevation over azimuth positioner allows fully 3-dimensional characterization of the radiation patterns. The elevation positioner carries the mobile phone, either mounted on an artificial head phantom, or without any users influence on a special *free space* fixture. The mobile phone is controlled via a base station simulator to transmit with its highest possible transmit power on a specified frequency. A receive antenna is mounted on the other side of the chamber in 4.5 m distance. Both sides are connected to a VNA and thus the s_{21} is measured. The centre point of the mock-up as well as the receive antenna are at a height of 1.5 m above the ground plane of the chamber. Both polarisations are measured by turning the receive antenna automatically. Using an appropriate calibration, the complete field is calculated from both field components. The radiated power is calculated by integration of the power density over the entire sphere. A typical accuracy of such a system is approx. ± 1 dB.

The measured values in Fig. 13 show that the total antenna efficiency is lower than predicted by the simulations in Section 2. This can be explained by the additional losses of the SP8T switch that has not been taken into account in the simulation in Section 2.

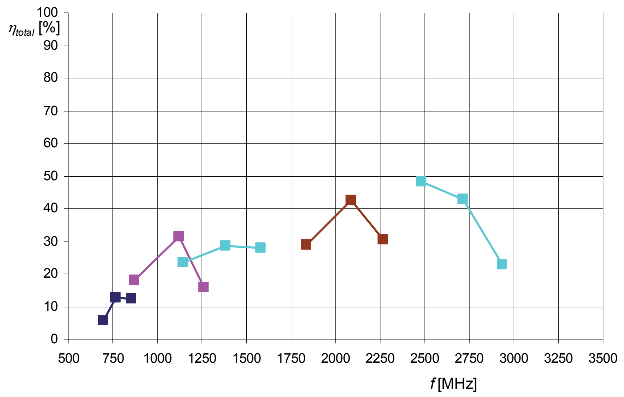


Fig. 13. Measured total efficiency of the mock-up.

However such a switch is already part of the frontend of state of the art mobile phones, as it is located before the antenna we typically do not see the effect of the losses on the antenna efficiency. Regarding the proposed concept we can think about relocating this switch in the frontend between the tuning circuit and the coupling element. Although it then accounts for the antenna efficiency the total power loss in the entire rf part of the mobile should be the same.

4. Conclusion and Future Work

Configurable coils and capacitors have been designed using the LTCC multilayer technology. Reactive tuning circuits have been assembled using these elements in order to set up a compact configurable multistandard antenna tuning component. Using this component together with a standard coupling element antenna shows promising results regarding the achievable efficiency. A standard packaged SPnT switch is used to select different rf ports. Integrating additionally a small coupling arm into the component leads to a compact configurable antenna component, but the performance is significantly lower due to the smaller size and non-optimum arrangement of the coupling element. The proposed concepts have been verified by prototyping one of the components in LTCC technology. Although the testing proofs the overall concept, the efficiency is somewhat lower compared to the simulation. This can be explained by additional losses of the switch that has not been taken into account in the simulation. However it might be less a problem because this switch is intended to replace the already existing switch in the frontend before the antenna. Therefore the amount of losses in the rf chain should not be increased.

The simulation results in this paper are obtained using the EMPIRE^{TM} [8] FDTD software. LTCC prototypes of the components have been produced using IMST's in-house facilities.

Configurability by manual manipulation of the top layer on the LTCC component is already a nice feature with respect to adaptation of a standard component according to different mobile terminals. Reconfigurability would even be even nicer with respect to e. g. cognitive radio applications or adaptive retuning the effect of the users hand on the antenna. Such reconfigurability could be achieved by mounting electronic switches or MEMS on the top layer of the component in order to reconfigure the values of the coils and capacitors. However there will be more research necessary until this goal can be reached.

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Peter UHLIG received his degree in Electrical Engineering in 1984. At Wandel & Goltermann he started with the development of microwave components for spectrum analyzers in 1984. From 1988 on he was responsible for the thin film circuits of the microwave front-end in these instruments. He joined IMST GmbH in 1993 where he is heading the hybrid microelectronics laboratory which includes the LTCC prototyping line