

## **DESIGN AND EVALUATION OF HYBRID LTCC-RF-FILTERS**

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### **Abstract**

In the perspective of the 3rd generation of mobile systems (3G) and in the current evolution of 2G, multi-mode wireless terminals are developing to provide more services for users. In that context, smart implementation of wide-band VCOs and tuneable filters are compulsory to meet market requirements.

LTCC is a convenient technology for the manufacturing of band pass filters for a bandwidth of 380 MHz to 2400 MHz as required by radio telephony systems. This technology provides three major benefits:

- first, the ceramic nature of the substrate allows the implementation of resonators of significant quality factor;
- second, the hybrid assembly process allows the mounting of a variable capacitor and varactor diodes to provide the tuning of this type of filters as well as a BGA connection to the mother board;
- third, the implementation of embedded passive components like resistors, capacitors and coils, along with the fact that this technology allows a multilayer design which is nearly unlimited (20 layer substrates have been already successfully manufactured), allows an outstanding level of integration

The paper demonstrates an approach for passive LTCC filter modules based on lumped element designs. Beside the electrical requirements these filters had to be compatible with a solder reflow assembly and optimised in terms of size. The maximum layer count defined was eight. Based on design studies, the best choice turned out to be a new hybrid solution with a mix of soldered components on top of the package and embedded components [1]. Components which would require a large area or too many layers to be integrated in LTCC were selected as SMDs.

The embedded components (capacitors and inductors) were designed based on standard or semi-empirical equations and verified by electrical field simulations. Demonstrators were realised using DuPont's 951 silver system. Solder paste stencil printing was used for bumping.

After SMD mounting, the filters were singulated, assembled on a test board and measured. The electrical behaviour of sub-structures was also determined by implementing various test structures in the demonstrator design. By these means, the embedded component interactions and the influence of external SMDs on the buried elements were assessed in detail.

The paper focuses on the analytical part of the work based on a harmonic filter. General recommendations for hybrid rf-filter designs will be derived.

Key words: LTCC, Passive Integration, Radio Frequency, Filter-Design

### **1. Introduction**

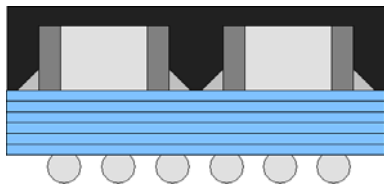
Based on the ability to integrate passive functions into a LTCC multilayer, several filter designs were accomplished within a European funded IST programme [2]. The target application was a handheld device for the Tetra-standard (380 MHz – 430 MHz). One of the demonstrators was a harmonic filter. It's purpose is to let the working frequencies pass and to block the 1<sup>st</sup> and further harmonics. A LC-filter with 2 poles was designed to meet the system's requirements [1].

### **2. The Concept of Hybrid LTCC Filters**

Hybrid LTCC filters combine integrated functionality (inductors, capacitors and resistors) and external components to achieve an optimum in terms of size, performance and costs. This solution allows to incorporate active elements as well (e.g. varactor diodes). They are necessary for tunable filters. The external components are selected based on their usability to be realised as buried components. Typical examples are capacitor with values larger than 5 pF. Considering a fired tape thickness of about 95 µm, an area of about 7.2 mm<sup>2</sup>

is required for a 5.2 pF capacitor. Even with 6 layers, the single plate size measures 1.2 mm by 1.2 mm.

The general construction is shown in Fig. 1. The integrated passives are embedded in the LTCC. Additional components are mounted on top of the substrate. A smooth surface for automated pick & place is achieved by plastic overmold. It's influence on the filter behaviour can be neglected in the frequency range considered [3]. The interconnection to the board is made by solder bumps. The bump diameters are 300  $\mu\text{m}$  and the pitch is 800  $\mu\text{m}$ . Due to the small dimensions of the filters, the thermal mismatch between the LTCC and an organic base board is not critical. Bumps not required for electrical functions are connected to ground and provide additional shielding and higher mechanical strength.



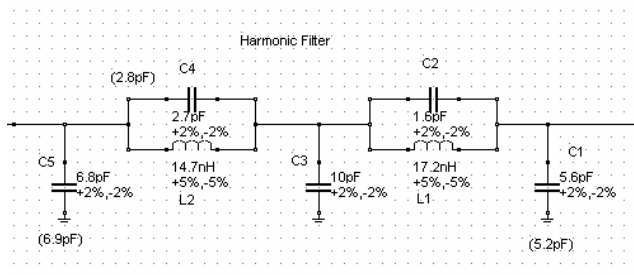
**Fig. 1: General construction of a hybrid filter**

Typically, fully integrated LC filter components are produced by component suppliers like Epcos and Murata. They take advantage of their experience in handling very thin ceramic sheets. However, only mainstream markets are served due to their high volume.

The general concept of hybrid filters can be applied by LTCC module manufacturers without changing of their tooling. Due to the very small size of these filters, they can be very cost competitive even in small and medium volume. Compared to an onboard solution they can be tested separately. If necessary, fine tuning of the electrical behaviour could be implemented as well.

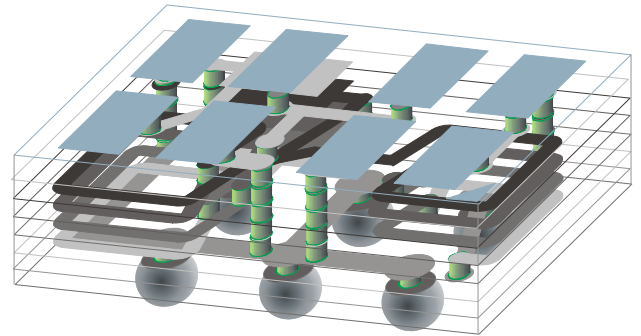
### 3. Harmonic Filter

The designed harmonic filter consists of three embedded passives (2 inductors and 1 capacitor) and four external 0402 capacitors (Fig. 2).



**Fig. 2: Harmonic filter schematic (C1, C3, C4 and C5 are SMDs)**

An eight-layer LTCC substrate was selected for the demonstrator, dictated by the more complex applications on the same substrate. However, only 6 ceramic layers are necessary to implement the harmonic filter (Fig. 3). The lowest two tapes are just feed-trough layers.

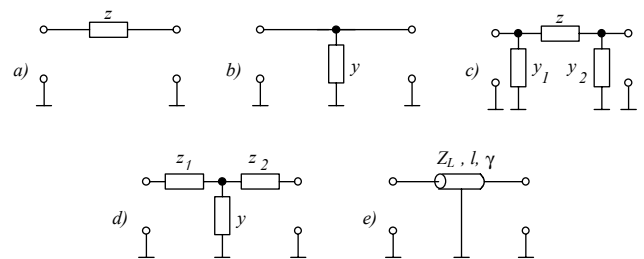


**Fig. 3: 3D-view of the harmonic filter without external capacitors and overmold**

In order to verify the properties of the embedded elements, the full circuit was divided into two sub-circuits. The “cut”-line was drawn in the middle of the substrate, thus dividing the two poles of the filter. Sub-circuit a) consists of C1-3 and L1, sub-circuit b) comprises L2 and C4/5. These sub-circuits were implemented on the demonstrator coupon.

### 4. Parameter Extraction

Simple two-port-circuits can be described by the classic models shown in Fig. 4. Such a device is completely characterised by the full set of S-parameters ( $s_{11} \dots s_{22}$ ). In reality it is rather difficult to realise just a single series or shunt element. Due to parasitics associated to the package or interconnection, further elements are added to the schematic. The result is usually a  $\Pi$ - or T-circuit. The harmonic filter sub-circuits mentioned above comply with the  $\Pi$ -model (Fig. 4c).



**Fig. 4: Typical two-port circuits a) series impedance; b) shunt admittance; c)  $\Pi$ -circuit; d) T-circuit; e) transmission line**

For separating the individual elements, the S-parameter matrix is to be transformed into the ABCD- or chain-matrix (equ. 1).

$$\begin{bmatrix} AB \\ CD \end{bmatrix} = \begin{bmatrix} \frac{1 + s_{11} - s_{22} - (s_{11}s_{22} - s_{12}s_{21})}{2s_{21}} & \frac{1 + s_{11} + s_{22} + (s_{11}s_{22} - s_{12}s_{21})}{2s_{21}} \\ \frac{1 - s_{11} - s_{22} + (s_{11}s_{22} - s_{12}s_{21})}{2s_{21}} & \frac{1 - s_{11} + s_{22} - (s_{11}s_{22} - s_{12}s_{21})}{2s_{21}} \end{bmatrix} \quad (1)$$

The chain parameters of the  $\Pi$ - and T-models are:

$$\Pi\text{-circuit} \quad \begin{bmatrix} AB \\ CD \end{bmatrix} = \begin{bmatrix} 1+zy_2 & z \\ y_1+y_2+z(y_1+y_2) & 1+zy_1 \end{bmatrix} \quad (2)$$

$$T\text{-circuit} \quad \begin{bmatrix} AB \\ CD \end{bmatrix} = \begin{bmatrix} 1+yz_1 & z_1+z_2+y(z_1+z_2) \\ y & 1+yz_2 \end{bmatrix} \quad (3)$$

The elements of the ABCD-matrix can be directly used to calculate the impedances and admittances.

For the  $\Pi$ -model:

$$z = B \quad (4)$$

$$y_1 = \frac{D-1}{B} \quad (5)$$

$$y_2 = \frac{A-1}{B} \quad (6)$$

For the T-model:

$$y = C \quad (7)$$

$$z_1 = \frac{A-1}{C} \quad (8)$$

$$z_2 = \frac{D-1}{C} \quad (9)$$

Calculation results do not include second order effects (e.g. resonances). Therefore, the model is only valid up to the first self resonance frequency.

The complete sub-circuit analysis is performed in the following steps:

- 1) Full 2-port S-Parameter measurement
- 2) De-embedding of feeding lines (if necessary)
- 3) Transformation into ABCD-matrix
- 4) Calculation of lumped elements based on Pi- or T-model
- 5) Generation of a basic lumped model
- 6) Adding of further parasitic elements (e.g. self resonance effects)
- 7) S-Parameter modelling and fine tuning of model

#### 4.1 Sub-circuit analysis

The sub-circuits were measured in the configurations:

- with two SMD caps
- with one SMD cap
- without external components

Element extraction was done in the opposite sequence from simple to complex. Fig. 5 shows the depopulated sub-circuit a). Only the embedded components L1, C2 and the empty SMD land pads contribute to the circuit (Fig. 6). The corresponding model (Fig. 7) and the comparison between measured and simulated S-parameters demonstrate the validity of the model up to the 1<sup>st</sup> resonance point (Fig. 8).

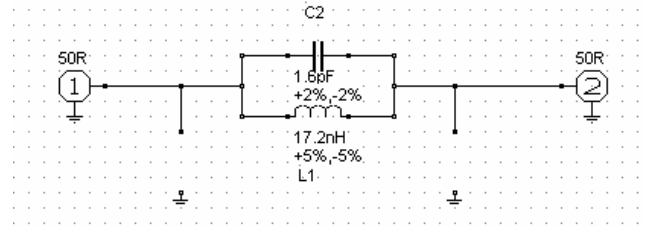


Fig. 5: „Ideal” sub-circuit a) without external components

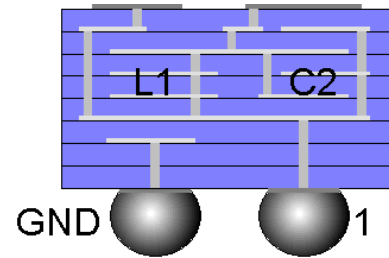


Fig. 6: Cross section of sub-circuit a) without capacitors

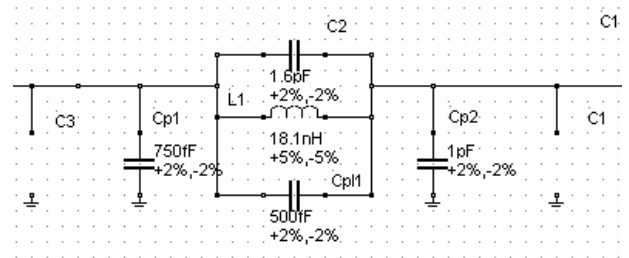


Fig. 7: Calculated elements of sub-circuit a)

Cp1 and Cp2 are parasitic capacitances of the embedded elements to ground. Cp11 is the self capacitance of inductor L1 plus additional capacitances caused by the SMD land pads.

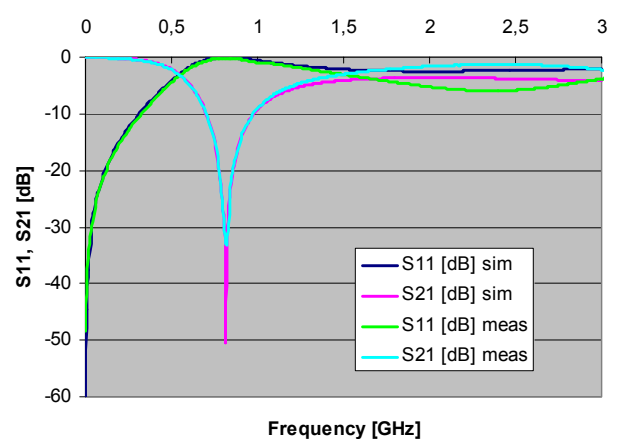


Fig. 8: Comparison measured vs. calculated S-parameters of sub-circuit a)

The same was repeated with C3 mounted (Fig. 9/10).

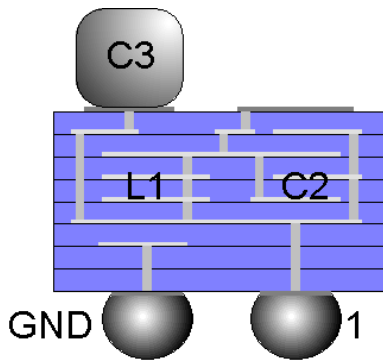


Fig. 9: Cross section of sub-circuit a) with capacitor C3

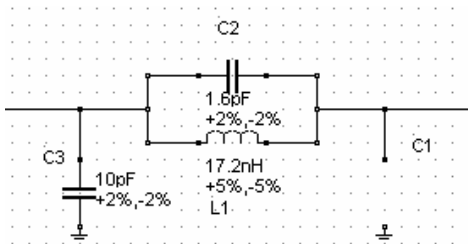


Fig. 10: Sub-circuit with C3

The calculated model elements (Fig. 11) reveal the impact of C3 on the self capacitance of L1 (Cpc3). Not only the land pads of C3 contribute to the additional capacitance (already included in the first model). Even with the air-gap between the SMD body and the LTCC, the high k-ceramics adds almost 1 pF.

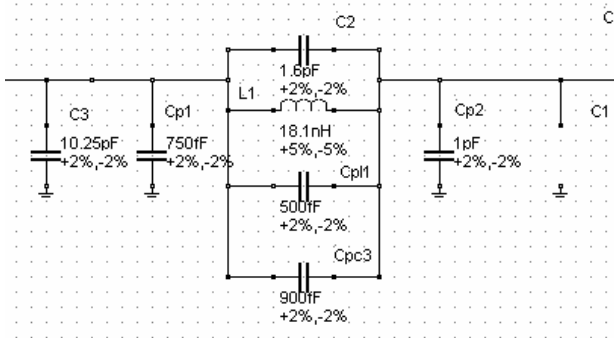


Fig. 11: Calculated elements of sub-circuit a) with C3

The entire sub-structure a) is shown in Figs. 12 and 13.

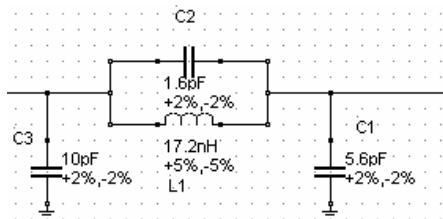


Fig. 12: Fully populated sub-circuit

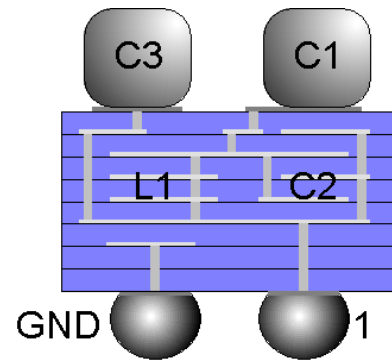


Fig. 13: Cross section of sub-circuit a)

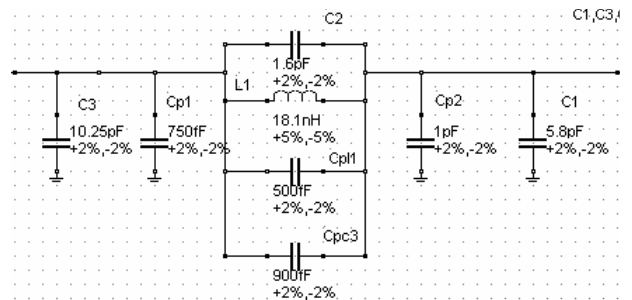


Fig. 14: Calculated elements of sub-circuit a)

Capacitor C1 does not contribute to additional parasitic capacitances. The lumped element model was further improved by adding of some inductances (Fig. 15). Simulated and measured S-parameters are in good match up to 1.8 GHz (Fig. 16).

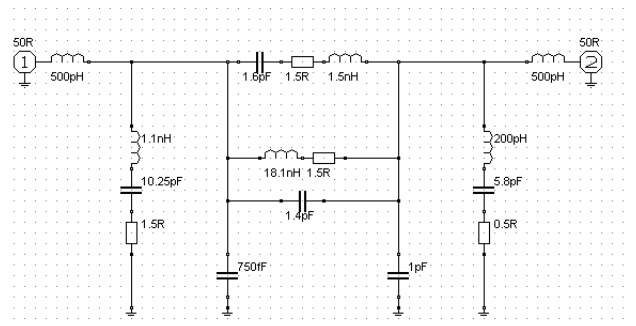


Fig. 15: Detailed model of sub-circuit a)

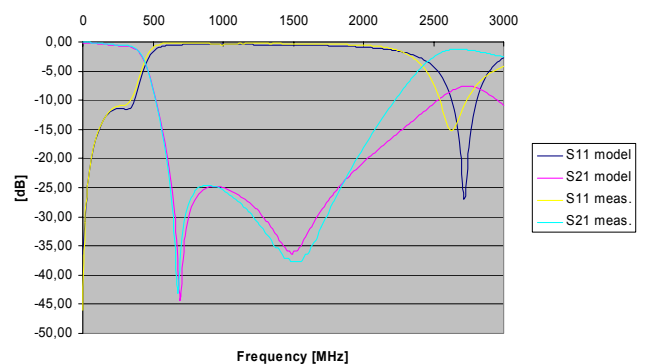


Fig. 16: Measured vs. simulated S-parameters for sub-circuit a)

Similar parameter extraction was done on sub-circuit b) and finally on the full circuit without any SMD component mounted. The latter provides also coupling information between L1 and L2 (magnetic field coupling) as well as C2 and L2 (capacitive coupling). Fig. 17/18 show the model of this circuit and the corresponding S-parameters.

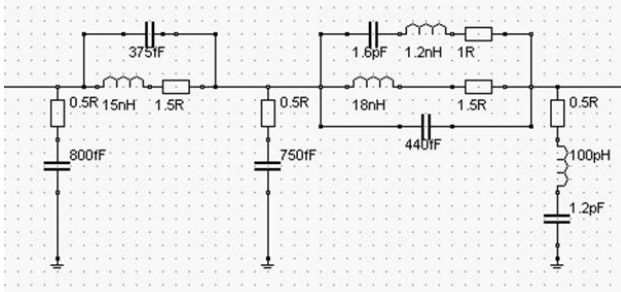


Fig. 17: Model of Harmonic filter without SMDs

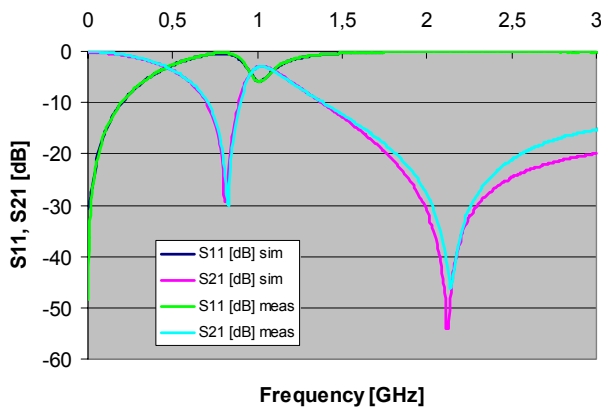


Fig. 18: Measurement vs. simulation of Harmonic filter without SMDs

#### 4.2 External Component Analysis

The influence of additional SMD capacitors on the filter behaviour can not be neglected. In general, the quality factor is reduced with increasing frequency and the self inductance (mainly determined by the construction) leads to a certain self resonance frequency. This property can cause problems in applications requiring a stable capacitance over a wide frequency range. On the other hand, it may also be helpful to add further poles to the filter. One solution to cope with the undesired resonances is offered by face-down chip capacitors [4]. However, the line inductance caused by the substrate itself must be addressed in the design.

Fig. 19 shows measured and simulated S-parameters for a 5.6 pF capacitor. The quality factor at the resonance frequency was about 40.

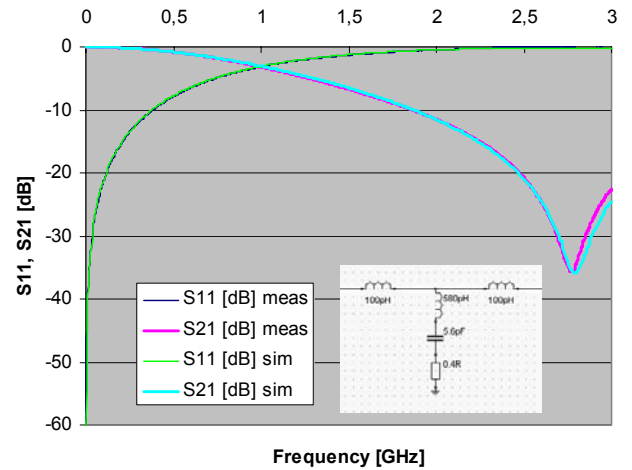


Fig. 19: Frequency response of a 5.6pF 0402 capacitor connected as a shunt element.

#### 5. Filter Fine Tuning

The entire filter did not satisfy the design expectations [3]. Based on the results of the sub-circuit analysis, it was easily possible to simulate the frequency response depending on modified external components. New filters were assembled with the optimised components. Fig. 20 shows the change in the behaviour before and after optimisation. An improvement of about 6-22 dB was obtained in the reject band. The second pole could be tuned by the external capacitor C4. The first pole however, could not be shifted towards higher frequencies due to the embedded realisation. This issue can be addressed in the redesign.

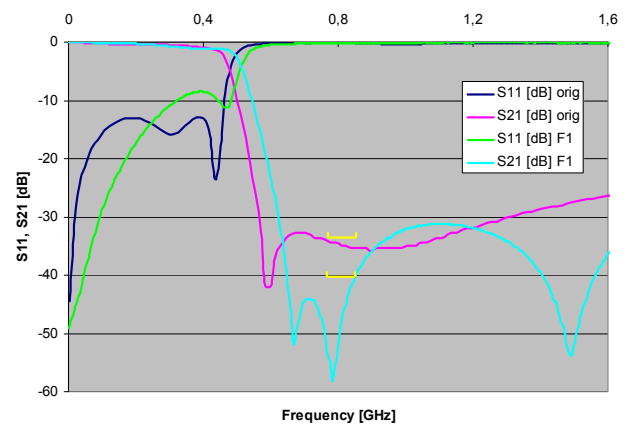


Fig. 20: Comparison of S-parameters prior and after component optimisation

One concern was the repeatability of these filters in manufacturing. There are three major contributors for filter distortion:

- material tolerances (tape thickness,  $\epsilon_r$ )
- manufacturing tolerances (line width, stacking alignment)

- component tolerances

Since all filters were processed with one manufacturing lot, the material is identical for all. The material vendor offers a tape thickness lot-to-lot variation of less than 7 % [5]. For the quantities of interest one large tape lot could be used for the product. The thickness tolerances within one manufacturing lot are very small.

Manufacturing tolerances can be monitored on different laminates within one production lot. Three filters from three different substrates or laminates were evaluated (Fig. 21). They reveal a very close fit over the frequency range of interest.

Component tolerances are specified by the vendor. Their impact on the filter behaviour can be predicted with the lumped circuit model.

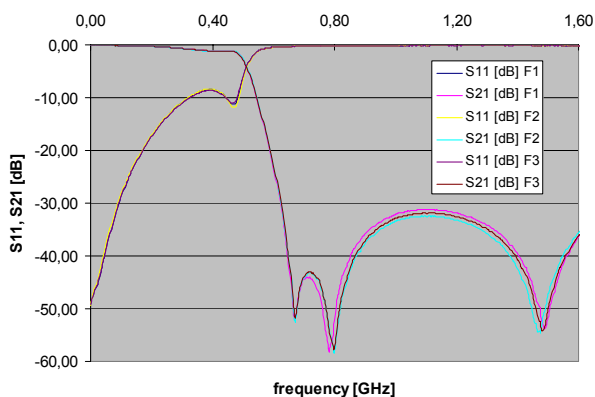


Fig. 21: Behaviour of 3 different harmonic filters

## 6. Summary and Conclusion

The proposed hybrid filter concept is suitable for low and medium production volumes. It offers high flexibility in the design and leads to cost and size optimised designs. The BGA-package allows testing of the filter and easy assembly on the board. Due to the small dimensions, underfill is not required to achieve highly reliable interconnections.

Including the sub-structures is an important tool to analyse the elements and their interactions in the design and prototype phase. They demonstrate also the impact of the SMDs and support either fine-tuning by component change or redesigns.

Further work will be conducted to establish a design library with “standardised” components. The goal is to develop also parametric models for these components to shorten the design phase. Furthermore, these elements can be used to verify simulation software for upcoming designs.

## 7. Acknowledgements

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