Design Considerations for Hybrid LTCC-RF-Filters

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Abstract

LTCC is a convenient technology for the manufacturing of band pass filters for a frequency band of 380 MHz to 2400 MHz as required by radio telephony systems. This technology provides three major benefits:
firstly, the ceramic nature of the substrate allows the implementation of resonators of significant quality factor; secondly, 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 and thirdly, 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 optimized 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. 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 realized using DuPont's 951 silver system. Solder paste stencil printing was used for bumping.
The paper focusses on the analytical part of a harmonic filter. Influences of overmold for packaging is discussed. General recommendations for hybrid rf-filter designs are derived.

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

Introduction

The area for passive components used on mobile telecom applications is very often determining the overall module size. In the perspective of multi-purpose and multi-band devices a lot of space is required for passive filters. To meet the stringent requirements on narrow transmission bandwidths or noise figures, external passives are required as well.

Passive integration is a helpful method to increase the component density. It is defined as a combination of circuit carrier (substrate, board) with passive components like resistors, capacitors and inductors in one technology. Passive elements may be integrated on the surface or embedded in a multilayer structure of the substrate. The goal is to achieve:

- Reduced module sizes
- Lower costs (component reduction)
- Improved electrical and thermal performance
- Higher reliability (reduced number of I/O)

Functional blocks, like a low pass filter, are integrated in one package which can be handled like one component. This approach has the further advantage of using a known good filter for assembly.

LTCC has an excellent capability for integrating passive elements used at rf-frequencies [1]. Resistors, inductors and capacitors may be integrated as embedded or surface elements. Based on the multilayer capability of LTCC, three-dimensional components can be easily realized (Fig. 1 and 2). Inductors can cover a range from 1 nH up to about 100 nH (considering an area of a few mm²).

Multilayer Metal-Insulator-Metal-Capacitors are mainly limited be the number of layers available, the minimum layer thickness (process capability) and the permittivity of LTCC itself. Using common materials, capacitances up to 10 pF are achievable. Higher capacitances may be obtained by using a high-k-material (tape or paste) [2, 3]. However, most of the high-k-dielectrics show a poor high frequency behavior in terms of dielectric losses. They are not suited for filters with a high selectivity.

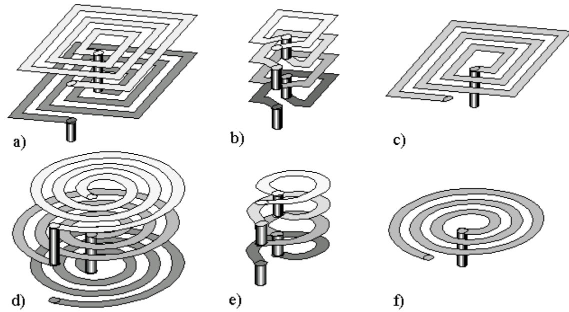

Fig. 1: Inductor shapes in LTCC

Structural design of these passives is accomplished by one or several of the following approaches:

- Closed form equations (capacitors, resistors)
- Semi-empirical formulas (inductors) [4]
- 3D-EM-field simulations
- Database (library with S-parameters of known standardized components)

Especially, the wideband inductor frequency behavior is difficult to predict [5]. It is heavily influenced by inherent parasitics and adjacent component interactions. In most cases, electromagnetic field simualtions are used for finetuning and verification of the design.

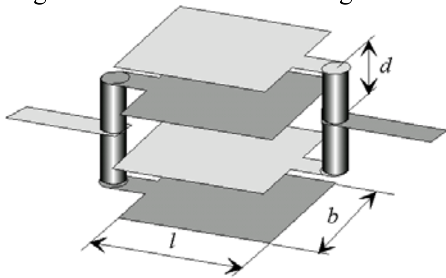

Fig. 2: Multilayer capacitor for LTCC

The concept of hybrid LTCC filters

Hybrid LTCC filters are devices consisting of a LTCC substrate with embedded components and additional surface mounted elements. The back side of the module is populated with solder bumps in a BGA structure for board assembly (fig. 3).

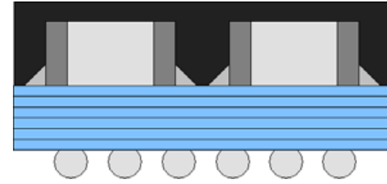

Fig. 3: General construction of a hybrid filter

The reasons for not implementing all passives in the LTCC are:

a) inductors or capacitors might be outside the useful integration range

b) area or number of layers required will be to large (costs)

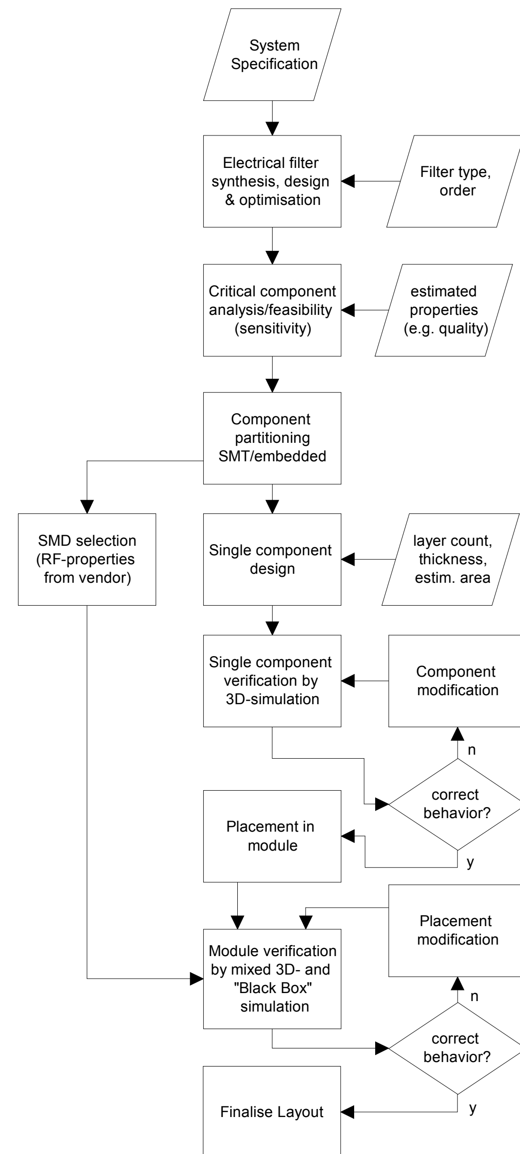

Fig. 4: Design flow for filter development

Hybrid filters are therefore a trade-off between scale of integration, costs and module size. First, the components not to be realized in LTCC are separated. Based on a coarse design of all integratable components using library elements or semi-empirical equations a first placement study and size estimation can be derived (outline and number of layers). If the area of the module is much larger than the area for the SMDs on top, some of the large integrated components should be changed to a SMD-type to get an optimum in module size. The full design flow including electrical filter synthesis is shown in figure 4 [6].

Typical Manufacturing Flow

The substrate is manufactured using standard processing conditions of LTCC. DuPonts 951 tape together with the Ag-system was used in this particular case. The entire substrate is designed as a full cofiring part (no postfire steps) to reduce costs.

A solder with a melting point higher than eutectic lead-tin is utilized for mounting the SMDs.

In order to allow automated pick & placement of these modules, the top surface should be planar and smooth. Therefore, glob top material is dispensed and planarized. This surface can also be utilized for part labelling. The impact of the glob top on the rf-behavior will be discussed later. Before singulating into individual elements by sawing, solder bumps are generated by paste printing and reflow.

Test & Filter Analysis

After manufacturing, the filter was assembled on a test board and measured (fig. 5). Measurement was done with an HP8753 network analyzer up to 6 GHz using SOLT-calibration. The influence of the feeding lines on the PCB were compensated by de-embedding of S-parameters. Testing and evaluation was performed on a harmonic filter (fig. 6). In order to obtain "inside" information of the embedded components, additional sub-structures of this filter were placed on the same LTCC panel. The elements of these sub-circuits remained untouched and similar to the complete filter (number of layers, via positions etc.). Components, not belonging to this sub-circuit were removed. SMD-pads on the surface above the active sub-circuit area were left there to include the parasitic influence of them as well.

By these means, the embedded component interactions and the influence of external SMDs on the buried elements were assessed in detail.

First, the S-Parameters of the filter were measured and compared to simulations made by a project partner using IE3D (Fig. 7). Three general deviations were observed:

- 1st stop band frequency too low
- 2nd stop band frequency "smeared"
- attenuation in stop band too low

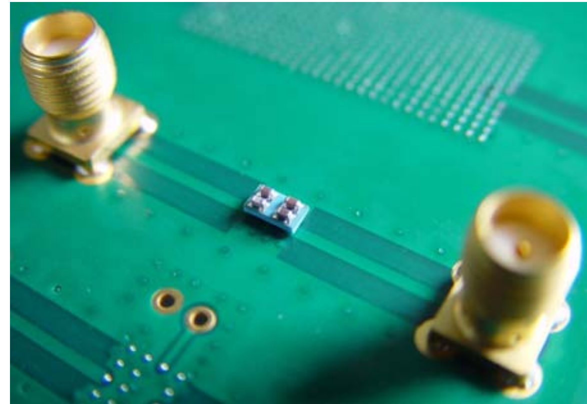

Fig. 5: S-Parameter testboard for filter evaluation

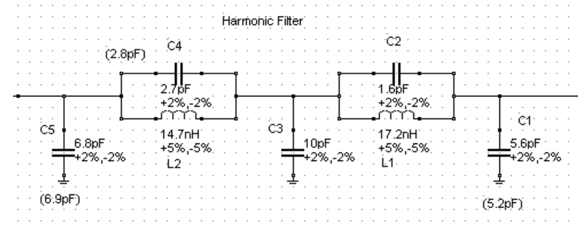

Fig. 6: Harmonic filter schematic (C1, C3, C4 and C5 are SMDs)

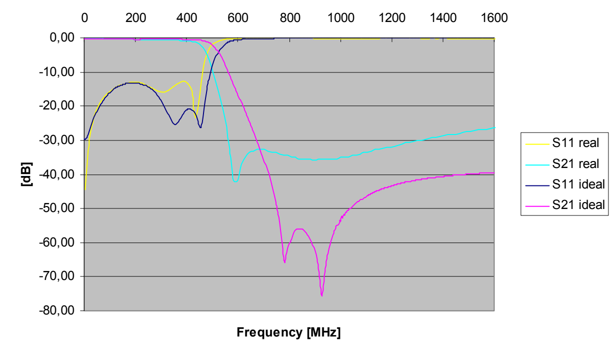

Fig. 7: Simulated vs. real filter behavior

Sub-circuit analysis

The sub-circuits were chosen to allow a description as a Π- or T-model. Both structures are suitable for component element extraction based on S-parameters. The full 2-port S-parameter results are converted into the chain- or ABCD-matrix. The elements of this matrix are directly related to the impedance of the model elements. The component behaviour derived is only suitable up to the 1st

resonance frequency (e.g. self resonance of inductor) since 2nd order effects cannot be described by a single Π- or T-model. The harmonic filter was divided in two sub-circuits. The test structures with the connected SMD-caps were step-by-step measured

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

The model of the sub-circuit was derived the opposite way. Starting with the most simple circuit, the model elements were calculated. Next, the same was done on the circuit with one SMD capacitor. Additional elements were added to the 1st model. After repeating this procedure with the 2nd external capacitor, the full model of the sub-circuit was established. Following this approach helped to develop a better understanding of the parasitic influences of capacitors mounted directly above integrated passives. It was very conclusive to see the impact of a shunt SMD cap to the self capacitance of a series inductor in its vicinity.

Fig. 8 shows sub-circuit 1 without the external capacitors C4 and C5. Based on the S-parameters of this structure, the Π-model elements of inductor L2 were calculated (fig. 9). Cp1 and Cp2 are parasitic capacitances of the printed structure to the ground plane. Cp3 is the inductor's self capacitance, responsible for the self resonance frequency.

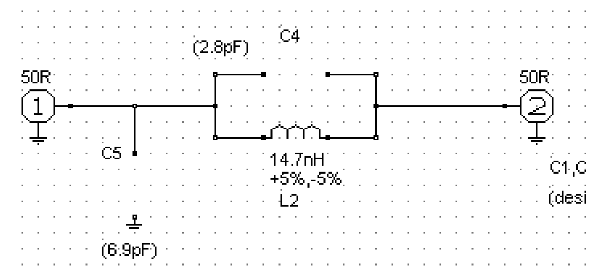

Fig. 8: Ideal schematic of filter sub-circuit 1

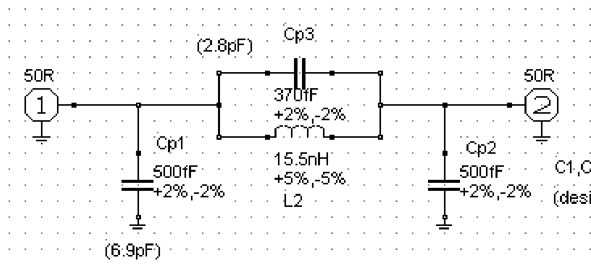

Fig. 9: Π-model elements of the series inductor L2 calculated from S-parameters (valid up to the 1st resonance frequency)

The same circuit with both SMD capacitors resulted in the schematic in fig.10. The capacitances of the SMD capacitors were measured separately. Mounting of C5 not only increased the shunt capacitance. It showed also a contribution to the self capacitance of inductor L2 (Cp5).

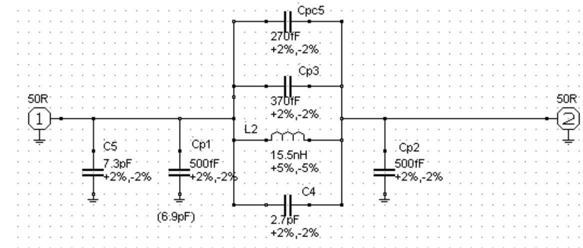

Fig. 10: Π-model elements of sub-circuit 1 calculated from S-parameters (valid up to the 1st resonance frequency)

A comparison of simulated and measured S-parameters reveals the validity of the model up to about 1 GHz (fig. 11). This model does not contain the self-parasitic effects of the external capacitors. These are included in the full model shown in fig. 12. The resulting simulated S-parameters are in good agreement to the measured ones (fig. 13).

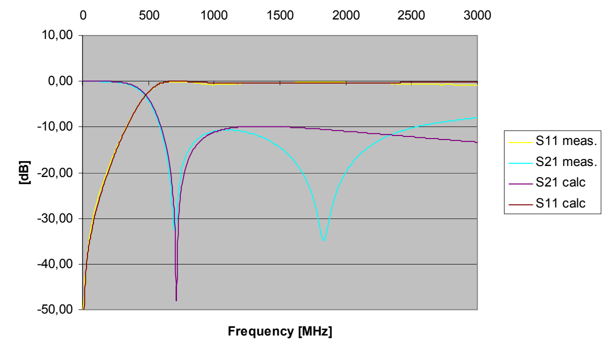

Fig. 11: Measured vs. simulated S-parameters for sub-circuit 1

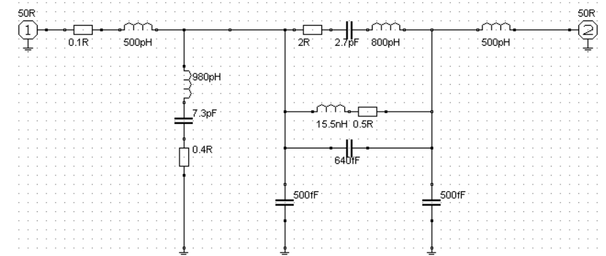

Fig. 12: Full model of sub-circuit 1

The elements of the 2nd sub-circuit were similarly calculated. The full model however, could not be obtained by combining the models of both sub-circuits. Interactions between them are not covered by the analysis performed. Therefore, all SMDs were removed from a full circuit. Based on the measure-

ment results of this circuit and the sub-circuits, a complete model of the filter was developed.

Fig. 13: Measured vs. simulated S-parameters for the full model of sub-circuit 1

Filter optimization

Based on the results of the filter synthesis the differences to the "ideal" filter become obvious. However, the external components can be used to compensate internal parasitic capacitances. Table 1 shows the changed values.

Table 1: Changed SMD capacitor values

Component	C1	C3	C4	C5
Old value	5.6pF	10pF	2.7pF	6.8pF
New value	4.7pF	8.2pF	1.5pF	5.6pF

The final schematic is given in fig. 14. Unfortunately, the parallel resonant circuit L1//C2 could not be taylored since both elements are embedded. The internal parallel capacitance is too high leading to a lower parallel resonance.

Fig. 14: Final model with modified external passives

The proposed modifications were made on the filter. Its resulting frequency behavior is getting close to the designed filter curve. As expected, the first pole is at a too low frequency (C2//L1). This issue needs to be addressed in a redesign.

Fig. 15: S11 and S21 of the modified harmonic filter

Influence of the glob top encapsulant

After filter optimization, glob top was manually dispensed on the external components (fig. 16). It was expected to get a further change of the filter curve by adding more parasitic capacitances between SMDs. However, the electrical test showed no significant change of the filter properties. The S21-curves in fig. 17 are almost identical. A very slight frequency shift can be observed at the 3rd pole.

Fig. 16: Harmonic filter with glob top encapsulation

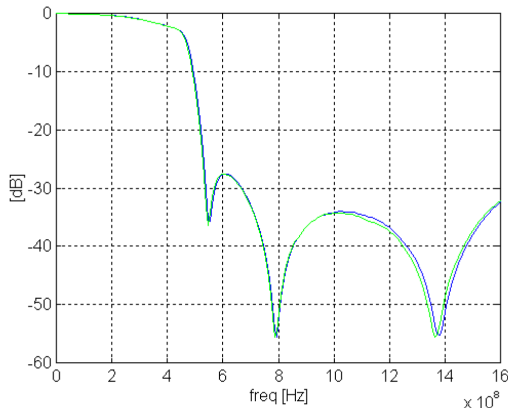

Fig. X: Comparison of filter behavior with and without glob top encapsulation

Summary and Conclusions

Hybrid filters using embedded inductors and capacitors together with external SMDs allow highly integrated designs. However, mixed component designs are difficult to simulate accurately. Interactions between embedded elements and external components may become a dominating factor in the electrical function.

It has been extremely valuable to integrate test structures for de-embedding of buried passives on the first hardware run. Influences of adjacent components were investigated. Based on the results, filter optimization could be performed to some extend on the existing module.

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 optimized 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.

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