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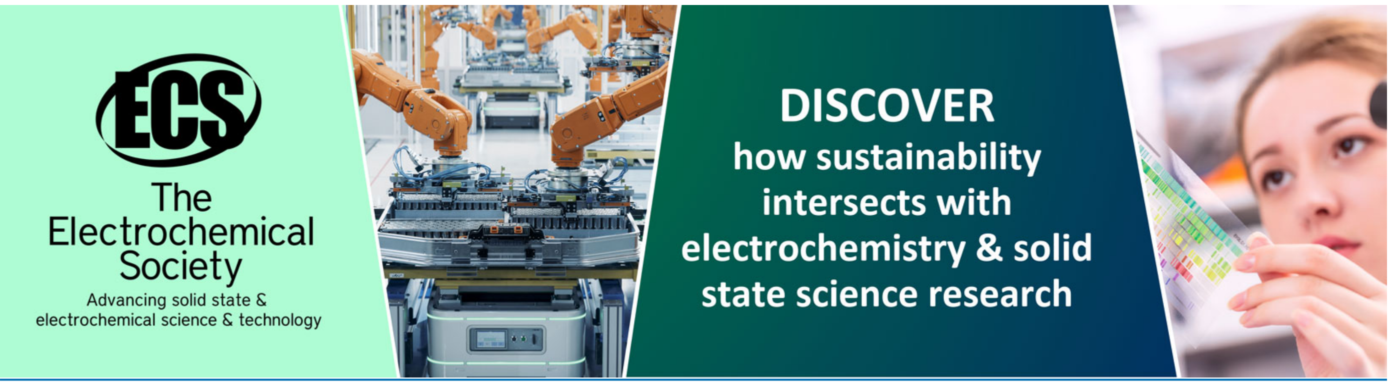

Modelling of microwave filters based on LTCC

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Abstract. Microwave filters made according to the technology of low-temperature co-fired ceramics (LTCC) are considered. The main features of LTCC technology are described. The parameters of the domestic glass-ceramic material are given. The stages of designing an integrated microwave filter, all elements of which are in the volume of ceramics, are considered. In the course of this work, a model of a LTCC microwave filter with a nominal frequency of 300 MHz was developed taking into account the parameters of domestic materials. According to the modeling outcomes, conclusions were made.

1. Introduction

Nowadays, integrated filters made using the technology of low-temperature co-fired ceramics (LTCC) based on three-dimensional structures with components built into the volume of ceramics are becoming more common. Such filters have high selectivity and reliability, as well as low bandwidth losses and overall dimensions.

Such filters, as a rule, are used in the microwave range. In this case, depending on the requirements, embedded elements can be performed with lumped, quasi-focused or distributed parameters. For example, the companies MiniCircuits, Murata, Syfer, and others produce integrated filters made using LTCC technology with frequencies up to 8000 MHz with dimensions of 3.2 × 1.6 × 1.0 mm.

One of the main advantages of LTCC is that this technology allows assembling into a stack structures that were previously located in one plane, which significantly reduces the size of the designed devices, as well as using completely new filter topologies.

The main goal of the work was to develop a model of an integrated microwave LTCC filter, taking into account the peculiarities of the domestic ceramic material and conductive pastes.

2. LTCC technology

Multilayer ceramic boards were originally made of aluminum oxide Al2O3 (High Temperature Cofired Ceramic - HTCC-technology). This material was burned at high temperatures (T ≥ 1500 ° C), therefore the metallization layers were made only of refractory metals: tungsten and molybdenum. It gave a number of limitations in the functionality of devices, in the improvement of technology and reduction of production costs.

Multi-layered ceramics received its further development with the introduction of LTCC technology, when ceramics began to be mixed with special glasses. The firing temperature of ceramics dropped to 850°C, which led to a significant simplification of the production process. Currently LTCC technology includes ceramics fired at temperatures below 1000°C.

Low microwave losses and relatively low production costs are key advantages of LTCC technology for RF and microwave devices. According to the cost, LTCC technology is close to the technology of manufacturing printed circuit boards based on FR-4, and its dielectric characteristics are low-temperature ceramics comparable to alumina ceramics.

MCP LTCC is a multi-level electrical circuit placed in the volume of a monolithic ceramic plate, in which electrical circuits in the form of thick-film conductors are made at different levels, separated with layers of ceramics and connected in the right places with metallized holes.

MCP LTCC is made with sintering a laminated blank of "raw" ceramics consisting of several ceramic cards. In this case, both internal conductors and structural elements such as resistors, capacitors, and inductances can be made on the inner layers.

3. Domestic LTCC material

In the production of LTCC materials, manufacturing companies create materials systems that include ceramic-conductor bundles. The most complete development of the domestic low-temperature ceramics of the LTCC-SCM system was carried out by JSC RPC "Istok" named after Shokina [1], and conductive pastes agreed with her are LLC "Scientific-Production Enterprise Delta-Pasty". Table 1 shows the properties of the ceramics of this system.

Table 1. Properties of low-temperature ceramics of the SCM system.

Parameter	Value
Oxides in the composition of the material SCM	SiO_2, Al_2O_3, B_2O_3, CaO, MgO, ZnO, ZrO_2, CuO
Thickness of ceramic sheets, micron	100±10; 150±15; 250±20
Sizes, mm	(130×130)±0.5 (152×152)±0.5 (200×203)±0.5
Dielectric permeability (at 10 GHz)	7.2 – 0.2
The tangent of dielectric loss angle (at 10 GHz)	0.0012
Insulation resistance, Ohm · cm	10^{12}
Electric strength, kV / mm	$\geq 10^4$
Firing temperature, ° C	860
Shrinkage (*X*, *Y*), %	8.2±0.3
Scaling factor (*X*, *Y*)	1.089
Shrinkage (*Z*), %	15.0±0.4
Scaling factor (*Z*)	1.176
Density, g / cm^3	3.1
Bending strength, MPa	260
Heat conductivity coefficient, W / (m · K)	3.0
Surface roughness, micron	1.25
Curvature of the surface, micron / cm	20

The SCM ceramic material is manufactured according to technical conditions 6366-004-07622667-2012 in the form of powder, and the "raw" ceramic film is manufactured according to technical conditions 6366-001-07622667-2008 in the form of sheets.

The SCM system includes conductive pastes based on Ag, Au and their alloys Ag / Pd and Ag / Pt, Au / Pd. Pastes are compatible with SCM ceramics for roasting shrinkage and are produced by LLC "Scientific-Production Enterprise Delta-Pasty" (technical conditions 6365-023-59839838-2012).

Summary data on the appointment of pastes are given in table 2 [2].

Table 2. Conductors of LLC "Scientific-Production Enterprise Delta-Pasty".

The name of the parameter	PP - 111	PP - 112	PP - 121	PP - 131	PP - 132	PP - 141	PP - 151	PP - 152	PP - 153
1. Appearance	Viscous homogeneous mass from dark gray to black								
2. Metals of the conductive phase	Ag	Ag/Pb	Ag		Ag/Pb		Au	Au/Pt	Au
3. Conventional viscosity at a temperature of 20 ... 22 ° C, mm	15-20	15-20	18-23		19-24		19-24		15-20

4. Synthesis of the filter

Electromagnetic modeling of microwave structures and the design of multilayer ceramic boards are recommended to be made in the program Microwave Office, ADS, Sonnet, CST, etc.

The synthesis of the microwave filter is called the design of a filter with known forms of amplitude-frequency and phase-frequency characteristics (AFC and PFR). Synthesis is usually carried out in two stages. The task of the first stage is the choice of the element base, the composition and structure of the microwave device. The task of the second stage is to determine the values of the parameters of the elements.

The process of designing a filter on lumped elements includes the following steps:

• calculation for a given operating characteristic of the filter of the normalized values of the elements of the low-frequency prototype filters;

• determination of the values of lumped elements of the equivalent filter circuit;

• selection of a constructive implementation of lumped elements of an equivalent filter circuit;

• calculation of the geometrical dimensions of constructions being implemented;

• multiparameter numerical optimization of the filter design, taking into account parasitic connections and manufacturing technology;

• making samples of the filter, measuring their amplitude-frequency characteristics, setting (if necessary and possible);

• production of samples taking into account the correction of the topology (values of the elements) according to the results of measuring characteristics, setting (if necessary and possible), etc.

At the first stage, the number of filter links and the normalized values of the elements of low-frequency prototype filter are determined in accordance with a typical method and according to the set filter options. They are boundary frequencies of the passbands and obstacles, non-uniformity of attenuation in the passband and attenuation level at the boundary frequencies of the obstacle, load resistances filter and selected type of characteristics. For polynomial filters with Butterworth and Chebyshev characteristics, one can use analytical expressions [3] or tables [3, 4], for filters with elliptic characteristics of Kawer there are tables [4].

At the second stage of transition from low-frequency prototype filter to the equivalent circuit of the low-pass filter (LPF), the high-pass filter (HPF) and the band-pass filter (BPF), taking into account the corresponding frequency conversion of the characteristics of the low-frequency prototype filter:

• for a polynomial low-pass filter, the successive elements of the staircase chain of low-frequency prototype filter are transformed into inductances, parallel - into capacitance;

• for a polynomial high-pass filter, successive elements of the staircase chain of low-frequency prototype filter are transformed into capacitances, parallel - into inductance;

• for a polynomial BPF, the successive elements of the staircase chain of the low-frequency prototype filter are converted into serial LC circuits, parallel - into parallel LC circuits.

The method of converting an equivalent circuit of a polynomial filter into an equivalent circuit of an elliptic characteristic filter involves the additional replacement of some elements L and C of equivalent circuits of a polynomial filter with serial or parallel LC circuits [4, 5, 6]. In modern programs of automated design of electrical circuits there are utilities that implement these stages of filter design without taking into account the resonant properties of real L and C and parasitic connections.

Calculation of the geometric dimensions of the film inductive and capacitive elements of various forms for given parameters can be performed using the formulas [7] or nomograms and graphs [9]. The evaluation of parasitic capacitive and inductive couplings in integral filters can be carried out using formulas and graphs [8]. Formulas, graphs and nomograms [7, 8, 9] have limits of applicability and can lead to significant errors.

In the most general case, the relationship between the parameters of the equivalent circuit and the geometry of inductive and capacitive elements of various forms can be established using electromagnetic or physical modeling of these elements. When a test element is switched on according to a two-pole or four-port circuit [7], its scattering matrix is determined with analyzing its electromagnetic model or with experimentally investigating its physical model (layout). The parameters of the extended equivalent circuit of the element, which takes into account the resonant properties (frequency dependence) and the final Q-factor, are determined from the scattering matrix. Below there are the variants of equivalent inductance circuits (figure 1) and capacitance (figure 2), included in the quadrupole scheme and formulas connecting the parameters of equivalent circuits with the coefficients of the scattering matrix and equivalent schemes with scattering matrix coefficients.

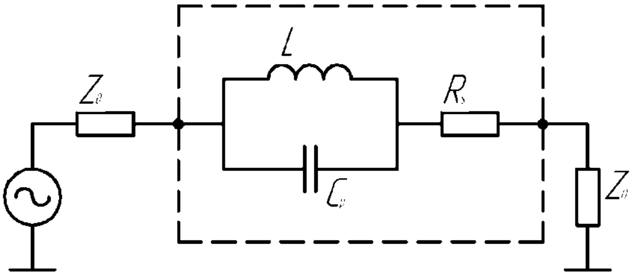

Figure 1. Equivalent inductance circuit.

Elements of the equivalent circuit (figure 1) are determined according to the formulas:

$$L = \frac{2Z_0\, Im\, S_{21}}{(Re\, S_{21})^2 + (Im\, S_{21})^2} \frac{1-\left(\frac{\omega}{\omega_p}\right)^2}{\omega}; \tag{1}$$

$$R_s = 2Z_0\left[\frac{\operatorname{Re} S_{21}}{(\operatorname{Re} S_{21})^2 + (\operatorname{Im} S_{21})^2} - 1\right]; \tag{2}$$

$$C_p = \frac{1}{L\omega_p^2}, \tag{3}$$

where R_s – the loss resistance;
C_p – parasitic capacitance;
ω_p – the parallel resonance frequency $\omega_p = \omega_{|S_{21}|=0}$

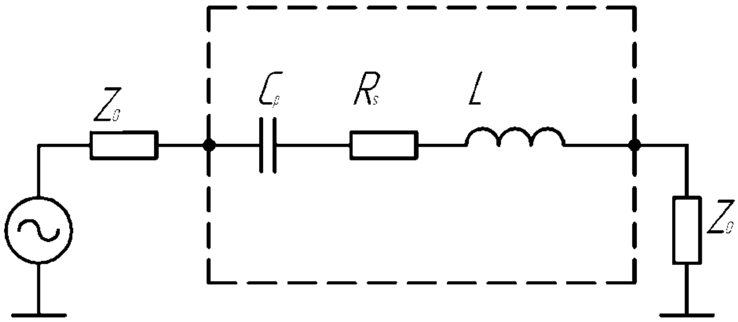

Figure 2. Equivalent Capacity Scheme.

Elements of the equivalent circuit (figure 2) are determined according to the formulas:

$$C = \left[1 - \frac{\omega^2}{\omega_s^2}\right] \frac{(\operatorname{Re} S_{21})^2 + (\operatorname{Im} S_{21})^2}{2\omega Z_0 \operatorname{Im} S_{21}}; \tag{4}$$

$$R_s = 2Z_0\left[\frac{\operatorname{Re} S_{21}}{(\operatorname{Re} S_{21})^2 + (\operatorname{Im} S_{21})^2} - 1\right]; \tag{5}$$

$$L_s = \frac{1}{C\omega_s^2}, \tag{6}$$

where R_s – the loss resistance;
L_s – parasitic inductance;
ω_s – the serial resonance frequency $\omega_s = \omega_{\mathrm{Im}S_{21}=0}$.

In the specific case of filter design, the calculation is made taking into account the fact that all elements are found in a small volume of a multilayer integrated ceramic board. Under such conditions, elements cannot be calculated without taking into account the influence of all external factors, for example, the geometric dimensions of neighboring elements, as well as the distance between them.

When calculating the size of the topological pattern applied to blanks of "raw" ceramics, one should take into account the coefficient of thermal shrinkage of the material during firing along with topological fragments applied to the blank. The shrinkage factor is indicated in the passports for the supplied batch of material.

Under such specified conditions, it is rational to make calculations in a CAD system, for example, Microwave Office, CST Microwave Studio, etc. When synthesizing a microwave filter using CAD, performance depends on the following factors:

• compliance of the selected filter manufacturing technology with the conditions specified in the TOR;
• the correctness of the choice of design parameters;
• the accuracy of the initial values of the elements and their dimensions;
• Electromagnetic Analysis Method;
• optimization method.

The main advantage of using CAD over the classical method is the ability to build AFC models in real time, changing the values of the elements.

Based on the synthesis method described above, a PRP model was developed with a nominal frequency of 300 MHz. In the synthesis, the parameters of the domestic materials described above were used.

5. Developed model

According to the TOR, PRP should have the values of electrical parameters presented in table 3.

Table 3. The values of the electrical parameter PRP.

Nominal frequency, MHz	Pass bandwidth, MHz, not less than	The squareness coefficient at the level of 20/3 dB, not more	Insertion attenuation, dB, not more than	Guaranteed relative attenuation, dB, not less
300	230	4.0	3.5	30.0

Based on the values of the parameters, the specialists of JSC "SKTB RT" developed a schematic diagram of the device (figure 3) and determined the number and values of capacitive and inductive elements.

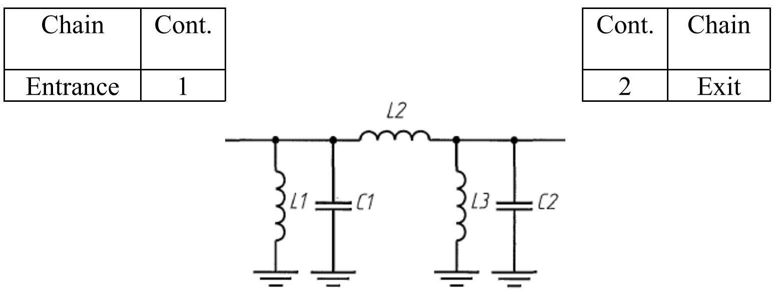

Figure 3. Schematic diagram of the VFS -440 MHz.

Element Values:
C1 - 0.023 pF;
C2 - 0.028 pF;

L1 - 26.54 nH;
L2 - 19.30 nH;
L3 - 16.29 nH;

Based on this scheme, a filter model was developed, shown in figure 4.

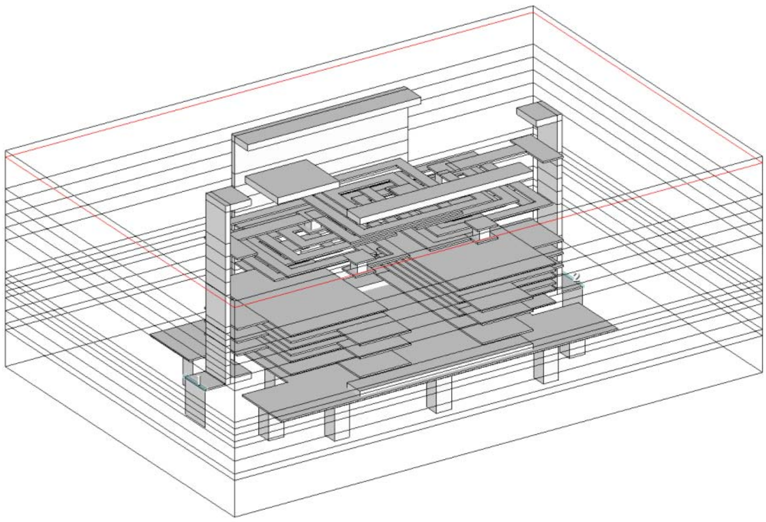

Figure 4. Model of the PRP - 300 MHz.

The device is implemented in the form of a ceramic block with dimensions: 5x3x1.1 mm and consisting of 12 layers with a topological pattern.

At the next stage of the filter calculation, AFC is built with the help of CAD system. AFC PRP -300 MHz is presented in figure 5.

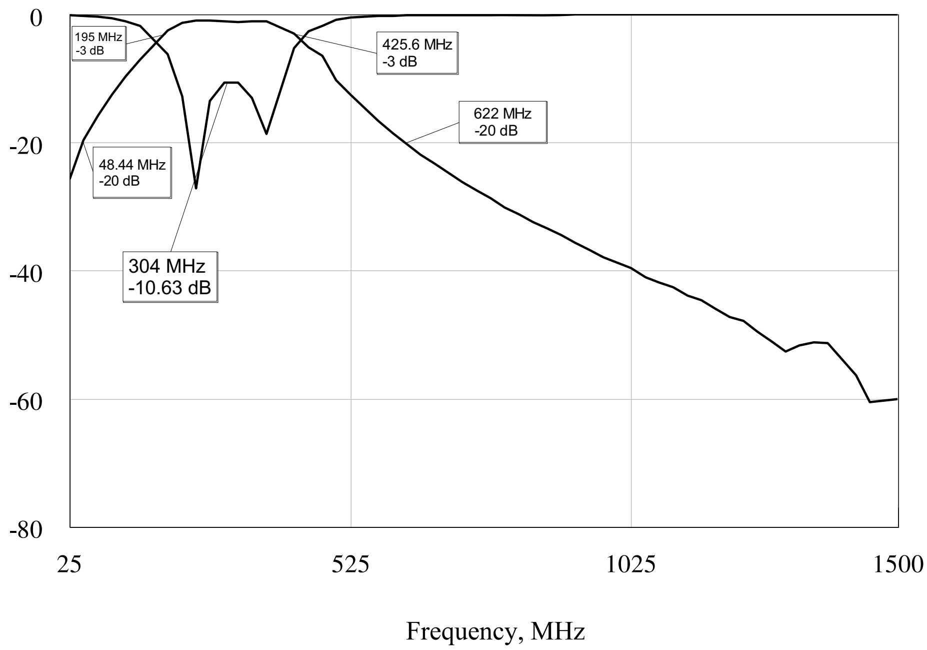

Figure 5. AFC PRP -300 MHz.

Table 4 presents a comparison of the values of the model parameters and the values specified in the TOR.

Table 4. Comparison of calculated parameters with given in TOR.

	Nominal frequency, MHz	Pass bandwidth, MHz, not less than	The squareness coefficient at the level of 20/3 dB, not more	Insertion attenuation, dB, not more than	Guaranteed relative attenuation, dB, not less
TOR	300	230	4.0	3.5	30.0
Model	310.3	230.6	2.49	1.12	35.0

From the data presented in table 4, we can conclude that the resulting model corresponds to the values stated in the TOR.

6. Conclusion

In this paper, we considered the design features of integrated microwave filters made according to LTCC technology from domestic materials.

The main stages of the microwave filter synthesis are described and, on their basis, a PRP model with a nominal frequency of 300 MHz is developed, the parameters of which correspond to the values specified in the technical specifications.

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