Simulation of ultrawide and embedded multilayer RF filters embedded in a printed circuit board

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Abstract. Mathematical simulation is carried out for ultrawideband embedded multilayer RF filters made on the basis of a multilayer printed circuit board. Calculations of key parameters of filters are fulfilled. The results of experimental studies are presented. The calculated and experimental data are compared. The effect of temperature on the characteristics of the filters is established. The advantages of embedded multilayer RF filters are shown as compared with microembedded multilayer RF filters. Recommendations are given on the calculation of parameters, the choice of materials and the structure of a multilayer printed circuit board.

1. Introduction

New generation compact complexes used for protection of multipurpose aircrafts with the functions of electronic intelligence and electronic suppression [1-6] based on VPX technology [7] are currently in high demand.

Telecommunication systems of these complexes support various communication standards and use lots of allocated RF bandwidths using bandpass filters (BPF). Their development trends are aimed at using more and more new bandwidths that demands the increase of the number of RF filters [8].

The prior task in developing ultrawideband radio receiving equipment of these complexes is to reduce overall dimensions and to increase technological effectiveness while simultaneously improving technical characteristics. It is usually that a receive path of the ultrawideband equipment is multichannel and it is built on a superheterodyne circuit with one frequency conversion. Many parameters of a receiving mechanism are determined by characteristics of bandpass filters. Thus, the importance is given to a filter design. At the same time, the filters remain some of the most complicatedly integrated elements of the receive path. This is due to high requirements to their electrical characteristics in state-of-the-art equipment. For example, preselector filters should provide image receiving channel suppression by an amount not less than 60 dB, when weakening within a band pass by not more than 1..3 dB, whereas the filters of the main section (intermediate frequency (IF) filters) should have a -50 dB bandwidth ratio of not less than 0.9. A traditional design of RF badpass filters has a microembedded structure on dielectrics such as Al₂O₃ (polycor) or clad dielectric materials by Rogers. For better electrical characteristics, microembedded multilayer RF filters are to be placed in an electrically sealed microassembly divided by metal partitions. Besides, to protect against the impact of the environment (first, against moisture, frost and dew), the microassemblies should be sealed off and filled with dry nitrogen. Such type of design leads to equipment heaviness and cost increase due to low technical effectiveness and high metal intensity. One of the solutions to reduce overall dimensions and to increase technical effectiveness of RF devices is the use of...
embedded multilayer bandpass RF filters embedded in a printed circuit board (PCB). Multilayer components embedded in PCB possess better thermal characteristics. It is expedient to use planar integrated components in case of network circuits, for example, for signal converters and processors. The advantage of embedded multilayer RF filters over microembedded multilayer RF filters is that the electric field is not radiated into space, but it is concentrated between metal conductive layers. This is to ensure a larger figure of merit, therefore to reduce losses and to improve selectivity. Since there is no input/output air communication in embedded multilayer RF filters, it is possible to build higher-order filters (more than 10th-12th orders) with electrical properties inaccessible for microembedded multilayer RF filters to ensure higher selectivity.

However, the design and simulation methods used for these filters do not sometimes ensure adequate accuracy and complexity. The purpose of this paper is to simulate properties of RF bandpass filters (BPF) and to develop proper design methods for such filters.

2. Choice of materials for embedded multilayer RF filters
When designing embedded multilayer RF filters, we must look carefully at the choice of dielectric materials, since main filter properties will depend upon properties of dielectric materials. The first dielectric material requirement is to possibly fabricate a multilayer structure and to have effective thicknesses in deliverable materials, the minimum thickness variation in manufacture and dimensional stability (especially in Z-direction) on exposure to mechanical impacts (dimension stability) and thermal effects (coefficient of thermal expansion) during operation. The second parameter to be focused on is the stability of the relative dielectric constant of materials with the change of temperature (thermal coefficient of ) and frequency. Finally, the third key parameter in selecting materials used for filters is the dielectric loss tangent . Other parameters such as moisture absorption, thermal conductivity, etc. are of secondary importance.

In the total volume of marketed dielectric multilayer PCB materials, the Rogers RO3000 Series material optimally meets requirements for fabrication of high-quality embedded multilayer RF filters. This Series includes materials with different dielectric constants and those operating on frequencies of up to 40 GHz. Principal material properties are given in Table 1.

| Board material | Relative dielectric constant | Dielectric loss tangent | Temperature coefficient of variation of , ppm/oC |
|----------------|-----------------------------|-------------------------|----------------------------------------------|
| RO3003         | 3.00                        | 0.0010                  | -3                                           |
| RO3035         | 3.60                        | 0.0015                  | -45                                          |
| RO3006         | 6.50                        | 0.0020                  | -262                                         |
| RO3010         | 11.20                       | 0.0022                  | -395                                         |

We would like to highlight the RO3003 material because of its high stability. To ensure the geometrical accuracy of a filter topology pattern, the thickness of a conductive copper layer (foil) should be selected from the two values: 17 µm (½ oz.) or 9 µm (¼ oz.). To reduce losses caused by surface roughness (relevant on frequencies of more than 10 GHz), preference (to be pointed out at order of materials) should be given to rolled copper foil. Energy losses in bandpass filters need to be minimized when designing.

3. Energy losses in bandpass filters
The principal parameters of amplitude-frequency characteristics of bandpass filters are as follows: the center frequency \( f_0 = \sqrt{f_1 \cdot f_2} \); a band width \( \Delta f = f_2 - f_1 \); a level of in-band attenuation \( L_I \); a level of off-band attenuation \( L_O \); the frequency selectivity defined by gain slope; the in-band reflection coefficient \( S_{11} \); and in-band insertion losses for real filters composed of dissipative elements.

Minimum insertion losses are achieved on the center bandwidth frequency \( f_0 \). The losses \( L_A \) [dB] inserted by the bandpass filter on the center frequency \( f_0 \) are defined by the following formula [9,10]:

\[
L_A = 10 \log_{10} \left( \frac{1}{1 + \left( \frac{f}{f_0} \right)^2 + \left( \frac{f}{f_1} \right)^2} \right)
\]
where $N$ is a filter order, $g_i$ is the standardized parameters of a low-frequency prototype, $\Delta f$ is a passband width, $Q_0$ is the basic Q-factor of resonators.

The in-band insertion losses $\Delta f$ may be evaluated using the approximation formula from [11]:

$$L_A(f_0) = \frac{10}{\ln(10)} \frac{f_0}{\Delta f} \sum_{i=1}^{N} g_i Q_0 \cong 4,343 \frac{f_0}{\Delta f} \sum_{i=1}^{N} g_i Q_0,$$

(1)

where $\tau_i$ and $\tau_0$ are a group delay on the frequencies $f_i \in [f_1; f_2]$ and $f_0 = \sqrt{f_1 \cdot f_2}$, respectively; $f_1$ and $f_2$ are low-frequency and upper-frequency limits of a passband.

According to (1) and (2), the losses ($L_A$) inserted by the filter in the passband, depend upon a relative bandwidth ($\Delta f / f_0$), the basic Q-factor of resonators ($Q_0$) and the filter order (number of used resonators $N$).

High Q-factor resonators are needed to build low-insertion-loss filters.

The resonator Q-factor takes into consideration the energy scattered in the resonator on the resonance frequency and is determined as a ratio of the stored energy of the resonator to the rate of losses over a vibration period [9]:

$$Q_0 = \frac{w_n w_n}{p_p},$$

(3)

where $W_n$ is the reactive energy stored in the system in a steady-state vibration mode; $P_{pow}$ is the power scattered in a resonance system.

The Q-factor is determined by a resonator electrodynamic structure, i.e. by distributing electric and magnetic fields in the resonator.

Real lumped circuit element losses are caused by the factor of merit of real inductive and capacitive elements, as well as by conductor and dielectric losses in connective sections of planar transmission lines.

The planar transmission line losses are determined by the attenuation coefficient of the electromagnetic wave [12]:

$$\alpha = \frac{R_1}{2Z_0} + \frac{G_1 Z_0}{2},$$

(4)

where $R_1$ is the line conductor resistance, $G_1$ is the running conductivity of a dielectric medium, $Z_0$ is the wave making resistance.

Conductor losses are calculated by the following formula:

$$\alpha_c = 8,868 \frac{R_1 + R_2}{2Z_0},$$

(5)

where $R_1$ and $R_2$ are screen resistances of a strip conductor and grounded screen, respectively (Figure 3.2). They are in turn determined by the surface resistance of the conductor material $R_{pow}$ and by the geometry of a microstrip line [12]:

$$R_{1,2} = \frac{R_{pow} 1,2}{W}.$$  

(6)

If the metal thickness exceeds the depth of electromagnetic field penetration in the conductor, i.e. the depth of a skin layer on the given frequency ($\delta_{ck} = \sqrt{2/\omega \mu_0 \sigma}$), the surface resistance can be defined as follows [9-12]:

$$R_{pow} = \frac{1}{\delta_{ck}} = \sqrt{\frac{\omega \mu_0}{2\sigma}},$$

(7)

where $\sigma$ is the electrical conductivity of materials.

The dielectric losses are determined by the dielectric loss tangent $\tan \delta$ and can be calculated by the following formula:

$$\alpha_d = 27.3 \frac{\varepsilon_r (\varepsilon_{eff} - 1)}{\varepsilon_{eff} \varepsilon_r - 1} \tan \delta,$$

(8)

where $\varepsilon_r$ is the relative dielectric permittivity of a substrate material, $\varepsilon_{eff}$ is the effective dielectric permittivity, $\lambda_0$ is a free-space wavelength.
4. Simulation of embedded multilayer RF filters
Electric circuit theory methods and electrodynamic simulation numerical techniques were used to calculate and to study embedded multilayer RF bandpass filters. It was proposed to use electromagnetic simulation software such as CST Studio Suite by Dassault Systemes and Microwave Office by National Instruments Company.

CST STUDIO SUITE software allows us to make 3-D electromagnetic simulation, design and optimization of structures of electronic and telecommunication devices operating in a wide range of frequencies at high precision and speed. It has an intuitive and user-friendly interface.

It allows us to computerize preparation and solution of various kinds of tasks using the VBA embedded macro language. It is an ideal software product for calculating wideband devices in which periodic boundary conditions are used. It has a boundary mode calculator within boundary ports. A geometrical scanning angle may be used in place of a phase shift in order to describe a radiation direction that enhances the accuracy of calculating active phased arrays.

The following procedure of electrodynamic simulation was used. At the first stage, the full waveform analysis of the electromagnetic field was performed using the CST Studio electromagnetic software package in a planar structure, which was an embedded multilayer printed circuit board. A frequency dependant matrix of S-parameters of the structure calculated by a numerical method was produced in output.

At the second stage, the calculated S-matrix was imported into Micro Wave Office software. In this case, four-layer boards with modeling description and experimental S-parameter versus frequency dependencies of strip lines were connected to ports of the structure under study.

At the third stage, the resulting circuit S-matrix was calculated in the same software package using the circuit simulation methods. During this process the electrodynamic analysis results for the frequency characteristics and the developed PCB and strip line parameters were taken into account.

Topology calculation for the embedded multilayer RF filter was iterative in nature. At first, boundary values of passband and stopband frequencies were assigned. Then a minimum attenuation value was specified in a stopband. Using synthesis utilities for electric filters embedded in electromagnetic field simulation software, a filter type (Chebyshev, elliptical, etc.) and the number (order) of filter cascades were determined to ensure the specified characteristics. Then we proceeded to the selection of materials and a structure of the embedded multilayer RF filter to be possibly implemented. We were therefore limited by the range of thicknesses of the selected dielectric material. The conductor width/gap accuracy and the influence of width variations over the filter properties in production were taken into consideration when selecting the structure. So, when fabricating by grade 5, the conductor width/gap accuracy of 0.1/0.1 mm was ensured.

5. Experimental study of embedded multilayer RF filters
Various types of filters can be implemented in stripline models such as low-band filters (LBFs), high-band filters (HBFs), bandpass filters (BPFs) and bandstop filters (BSFs).

A PCB layout drawing (Figure 1) with 17 different filters (LBFs, HBFs, BPFs) of different topology over a broad frequency range was manufactured in order to study embedded multilayer RF filters and to evaluate calculation methods.

A structure of the multilayer PCB with embedded multilayer RF filters is given in Table 2.

![Figure 1. Layout drawing of a multilayer PCB with embedded multilayer RF filters.](image-url)
Table 2. PCB layout structure with embedded multilayer RF filters.

| Layer No. | Layer name       | Material | Thickness, mm |
|-----------|------------------|----------|---------------|
| 1         | Top (GND)        | copper   | 0.018         |
|           | RO3003           |          | 0.254         |
| 2         | Signal           | copper   | 0.018         |
|           | RO3003           |          | 0.127         |
| 3         | Bottom (GND)     | copper   | 0.018         |

Figure 2 shows the topology of the 7th order embedded multilayer RF filter in a prototype board with the following overall dimensions: 34.55 x 10.0 x 0.435 mm.

Figure 2. Topology and overall dimensions for the embedded multilayer RF filter in electromagnetic simulation software.

Figure 3. Graphs for the transmission coefficient S21 of the embedded multilayer RF filter for model-designed (a) and experimental (b) prototypes.

Let us compare the designed and experimental characteristics (Figure 3) of the seven-tier bandpass filter given in Figure 2. The simulated filter frequency responses possess the following characteristics: the center frequency $f_0 = 9.95$ GHz, the passband attenuation $IL_0 = 1$ dB, the -2dB bandwidth $BW(2 dB) = 2.6$ GHz, the bandwidth ratio on relative attenuation levels of 2 and 60 dB $K_2/60 \approx 2.2$. From the experimental graph of the transmission coefficient $S21$ it follows that a prototype filter is very close by its characteristics to the designed filter, so the frequency bias is not more than 50 MHz or 0.5% in relative units. It is caused by geometry and topology fidelity and by dielectric width accuracy when manufacturing PCB, and also by the distinction between real and estimated dielectric material permittivity. The frequency bias can be somehow taken into account by setting the model parameters updated after the experiment. Additional attenuation of 1.5 dB is caused by RF losses in PCB connectors, hole vias and transmission microembedded lines of the prototype board.

To study stability of filter characteristics on changes in ambient temperature, the prototype board was placed in a thermal chamber. Comparative characteristics of the transmission coefficient $S21$ at
temperature change in a range from 25°C to -60°C and from 25°C to 85°C are given in Figures 4, a and 4, b, respectively.

![Figure 4.](image)

(a)

![Figure 4.](image)

(b)

**Figure 4.** Comparative graphs for the transmission coefficient S21 of the embedded multilayer RF filter at a temperature of -60°C (a) and 85°C (b).

Experimental data showed that at temperature change in a range from -60°C to 85°C the frequency bias is 59 MHz or 0.4 MHz/°C on a frequency of 11 GHz. Such thermal frequency bias can be compared with the filter thermal frequency bias on Al₂O₃ (polycor) that is 0.52 MHz/°C on a frequency of 11 GHz/°C.

6. Conclusion

A new design approach for high selectivity embedded bandpass filters is proposed. The CST software product was integrated into an RF filter design flow available on the shop floor based on EDA and CAD systems. It allowed us to improve the accuracy of numerical simulation of the filters and GHz-range converters (up to 11GHz) and to reduce the analysis time for electromagnetic compatibility and signal integrity in PCBs.

The results of electromagnetic simulation and experimental data confirm the reliability of theoretical calculations and proposed design approaches.

It is defined that for the purposes of miniaturization and increasing technological effectiveness of radioelectronic microwave equipment, microembedded multilayer RF filters performed on Al₂O₃ (polycor) may be replaced with embedded multilayer RF filters embedded into a multilayer printed circuit board.

The results of calculated and experimental studies of characteristics of ultrawideband embedded multilayer RF filters embedded in a multilayer printed circuit board are presented. The effect of temperature on the filter characteristics is shown. Recommendations are given on the calculation of parameters, the choice of materials and the structure of a multilayer printed circuit board.

7. References

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