Prospects for design and construction development of integral circuits of LC–filters based on the modern dielectric materials

A S Budyakov¹, L V Cherckesova²*, A E Titov³ and Yu A Shokova²

¹Moscow State University of Technology "STANKIN", Moscow, Russia
²Don State Technical University, Rostov-on-Don, Russia
³Southern Federal University, Rostov-on-Don, Russia

*e-mail: chia2002@inbox.ru

Abstract. An analysis of design and technological solutions related to the production of integrated microwave filters based on modern materials - liquid-crystalline polymers (LCP) and low-temperature ceramics (LTCC) is considered. An important factor in the design of integrated filters based on multilayer printed circuit boards is the limited choice of designs for inductive and capacitive elements. It is proposed to use dielectric materials with more stable parameters and a wide range of operating frequencies (LCP up to 20 GHz, and LTCC up to 40 GHz). The results of comparison of the manufacturing process of microwave filters based on LCP and LTCC technologies are shown. One of the possible schemes and designs of a bandpass filter with a cut-off frequency of 2.9 GHz, a bandwidth of 500 MHz, and an insertion loss of about 1 dB is demonstrated. Experimental characteristics based on computer simulation of the microwave filter are presented. It is concluded that the use of LTCC-technology is preferable for solving the problem of microminiaturization of microwave filters, and the use of LCP-technology is expedient for creating narrower-band filters intended for operation in a higher frequency range of microwave filters.

1. Introduction

The stable trend in the radioelectronic equipment evolution of the XXI century is the necessity for microminiaturization of its components, including devices for frequency selection of signals. Increasing the level of integration leads to the creation of microwave frequency filters in the form of three-dimensional integral structures, which is promising for solving this issue. Of the integral filters, devices with concentrated elements are of the greatest interest, since they provide better electrical parameters, such as the level of attenuation in the far zone, compared to distributed and quasi – distributed elements. From the point of view of design, construction and technological solution, such filters are multilayer structures, in the layers of which the printed inductors and the capacitors made of dielectric materials are located [1].

The difficulty of constructive and technological solutions in the production of such filters of microwave range is considered to take into account the properties of materials from which multilayer printed circuit boards are made. Is the dielectric permeability, tangent of angle by dielectric loss, layer thickness, since the dielectric parameters determine the structure of the filter construction, electrical characteristics and frequency response of the filters under developing.

2. The purpose of this study

The purpose of this investigation is to study the features of the production of integral filters on concentrated elements implemented of modern materials.
These include materials with normalized standardized capacity of Faradflex BC–24M, RBCX – low-temperature ceramics (LTCC, Low–Temperature Co–Fired Ceramics), and materials based on liquid crystal polymers (LCP, Liquid Crystal Polymers, self–reinforcing plastics). Table 1 shows some characteristics of modern dielectric materials applied in the design, construction and production of integral filters [2]

**Table 1. Parameters of modern materials**

| Material     | $\varepsilon$ | $\tan \delta$, | $h$, µm (micron) | Frequency range |
|--------------|---------------|-----------------|------------------|----------------|
| FR–4         | 4,5 – 5,6     | 0,035           | 50 – 3000        | Up to 1 GHz    |
| Faradflex    | 9,2 – 10,0    | 0,02            | 8; 12; 24        | Up to 1,5 GHz  |
| LTCC         | 7,8           | 0,0015          | 96; 140; 216     | Up to 20 GHz   |
| LCP          | 2,9           | 0,0025          | 25; 50; 100      | Up to 40 GHz   |

The base material for the foundation of the multilayer printed circuit boards is usually “steklotextolyte”, armoring glass fiber plastic, or glass – bonded reinforced dielectric material of various markings. Glass fiber plastic electrotechnical sheet is layered fiberglass material obtained by hot pressing of electro–insulating glass fabrics impregnated with thermo reactive binder based on combined epoxy and phenol– formaldehyde resins, epoxy–phenol binder of different markings. The name of marks, adopted in the radioelectronic industry of Russian Federation: “СТЭФ” and “СТЭФ 1”, modified “ТС–ЭТФ”, “ТСЭФ”–tubes with marking: “СТЭФ–У”, “СТЭФ–П”, “СТЭФ–ПУ”, “СТЭБ”, “СТТ”, “СТ–ЭТФ”, “КАСТ–В”, “3240” and “3240–1” [3].

Currently, the production technology of multilayer printed circuit boards (PCB, printed circuit board technology) is mastered well by domestic enterprises, available and widely used. At the same time, there is fairly large spread of parameters, low value of dielectric permittivity and high tangent of dielectric losses by “steklotextolyte”– the armored glass fiber plastic, or glass – bonded reinforced dielectric material of various markings. Therefore, the practical implementation of integral filters fulfilled due this technology has brought good results only with the appearance of new dielectric materials Faradflex BC–24M and RBCX, devoid of the described disadvantages [4].

**3. Factors in the design of integrated filters**

An important factor in the design and construction of integral filters implemented on the ground of multilayer printed circuit boards is the small choice of designs alternatives for inductance and capacitance. In addition, all three–dimensional filters are characterized by fairly limited number of circuit solutions, which is due to the use of planar structures as elements of the filter, since the manufacture of stack inductances and capacitances complicates the design of the filter, due to the difficulties of performing deaf or blind apertures. Further, due to the difficulties of controlling the change in the width of the conducting pattern (picture), the values of filter elements are obtained with a large tolerance during the etching process, which manifests itself the more the thickness of the foil is greater. This causes the actual filter characteristics to deviate from the set parameters. This is why, when designing the simple filters at the frequencies no higher than 1 GHz, the implementation of integral filters fulfilled by multilayer printed circuit boards technology, emphasis is placed on the low–frequency filters (LFF), the parameters of which are not subject to such strict requirements.

The following criteria are applicable for the choice of design of elements the filter:

− In the design of capacitors, multilayer structure should not be used, because it is necessary to introduce the dielectric material with normalized capacity into the structure of the printed circuit board substrate.

− Integral filters based on multilayer printed circuit board use printed inductances without deaf or blind apertures. The applications of such apertures in the different layers of the printed circuit board
significantly complicates the design of the filter, and in the production cycle of multilayer printed circuit boards, the manufacture of such device would become almost impossible.

– Technology of production of multilayer printed circuit board provides for changing the width of the conducting pattern (picture) during etching process, and the interval of spread of the measurements raises with the increase in the foil thickness. The greatest spread in the values of the conductor width will be observed in dielectrics with standard foil thickness of 35 μm (microns), at which the spread will be more than 50 μm. When using dielectrics with ultra–thin foil in this process, it is possible to achieve the accuracy of reproducing the current–conducting pattern (picture) ± (5–10) μm.

Since the precision of the conducting pattern (picture) is low, then the characteristics of such integral filter will differ significantly from the expected ones.

One from possible variants of such low–pass filter with cutoff frequency of 660 MHz is shown in the figure 1, and its amplitude–frequency characteristics [5], both calculated and experimental, are shown in the figure 2.

![Figure 1. Low–pass filter: a) electrical schematic diagram (basic circuit); b) appearance of the experienced sample (prototype) based on the Multilayer Printed Circuit Boards Technology (MPCB); c) appearance of the experienced sample based on the technology of Liquid Crystal Polymers, self–reinforcing plastics (LCP)](image)

This circuit is suitable for the production in an integral form, due to the absence of capacitors in the longitudinal branches, and the presence of grounded capacitors in the transversal branches. Figure 3 shows the appearance of the experienced sample (prototype), its dimensions are only 10 × 25 mm. From the presented characteristics, it can be seen that the experimental results and calculated characteristics are well correlated with each other. The irregularity (non–uniformity) of the characteristic relatively to the attenuation in the pass transmission band of the researching filter is about 1.5 dB, and increases with raising of frequency, which is caused by low Q–factor (quality factor) of elements determined by the parameters of the materials used [6].

![Figure 2. Amplitude – frequency characteristics of the low–pass filter with cutoff frequency 660 MHz in the simulation (upper curve) and the experienced sample (prototype) (lower curve)](image)
To expand the range of operating frequencies and find new circuitry solutions for the design of integral filters, it is proposed to use new dielectric materials. This substances possess the more stable parameters, wide range of operating frequencies and lower tangent of the angle of dielectric losses – for example, LCP (Liquid Crystal Polymers, self-reinforcing plastics), and LTCC, (Low–Temperature Co–Fired Ceramics). The use of such materials will remove many of the disadvantages inherent in the production technology of multilayer printed circuit boards (MPCB).

4. Application of LCP-technology

The production of integral filters based on multilayer printed circuit board and liquid crystal polymer technologies is similar in the general terms, but the production of LCP–based filters requires much higher sintering temperature of the materials. Liquid crystal polymers have better stability of parameters, so they do not need to use surplus additional layers of materials with normalized parameters [7].

This means that the application of LCP technology also makes sense for the production of relatively simple filters, such as low–pass ones.

Figure 4 demonstrates the characteristics of low–frequency filter, both calculated and experimental, made on liquid–crystal polymers using LCP technology, with cutoff frequency of 2.4 GHz, according to the circuit shown in figure 1.

![Figure 4. Amplitude–frequency characteristics of low–pass filter with cutoff frequency 2.4 GHz in the simulation (upper curve) and the experienced sample (prototype) (lower curve)](image)

Figure 5 shows the appearance of experienced sample (prototype) manufactured according to the circuit in the figure 1, to compare it with the sample in figure 3.
Figure 5. Appearance of the experienced sample (prototype) made using Liquid Crystal Polymers, Self–Reinforcing Plastics (LCP)

Comparison of data and correlation of the figures 2 and 4, 3 and 5, proves that integral low–pass filters manufactured on the base of LCP–technology have better electrical characteristics compared to filters on the ground of MPCB–technology (Multilayer Printed Circuit Boards), in much larger frequency range. This is determined by the parameters and characteristics of applied dielectric materials. Another important advantage is that when designing and construction of the integral filters based on liquid crystal polymers, it is not necessary to use surplus additional layers of other materials for the production of various filter elements – capacitances, inductances, etc., which makes it possible to apply other circuitry solutions by using the simple stack structures in their construction. This means that the application of liquid crystal polymers makes it possible to design both low–pass filters and band–pass filters.

Advantages of integral filters on liquid crystal polymers [8]:
– Fine tuning of the filters characteristics is not required, which means shrinkage the time taken to fabricate the device and reducing the cost of production.
– Possibility of the serial preparation of filters without reconfiguration of production, as required in the standard technology of multilayer printed circuit boards.
– Repeatability of characteristics in the same batch of experienced samples (prototypes).
– Protection of elements from influence of external environment, not by integrating of elements into the substrate structure, but by applying the protective coating.

LCP–based filters have not such disadvantages inherent in the filters, fulfilled on the base of technology of multilayer printed circuit boards (MPCB – based filters), due to significant improvement in the characteristics of the materials used.

If MPCB – based filters can work only in the narrow frequency range up to few gigahertz, and, are generally, not suitable for microwave frequencies, then the frequency range of LCP–based filters reaches 40 GHz (Table 1). A large tolerance for shrinkage of materials, applying in the MPCB – technology, leads to the difference in the characteristics of real filters and the simulation results obtained during design, which is not observed for LCP–based filters. In addition, the features of design and construction of integral MPCB–based filters limit the possibility of circuitry and design solutions. At the same time, for LCP–based filters, such opportunities only increase. Finally, in the MPCB – technology for the implementation of capacitors there is required to applicate the layer with normalized capacity in the multilayer structure of the printed circuit board, and for LCP – based filters this is not necessary [9].

5. Application of LTCC-technology
However, LCP–technology based on liquid crystal polymers is not free from disadvantages compared to low–temperature co–fired ceramics (LTCC) technology.

Application of LTCC–technology allows reducing significantly the overall dimensions of devices by using stack capacitances and inductance coils (capacitors and inductors) of various designs and constructions, which entails the significant expansion of circuitry solutions suitable for implementation in production. Low–temperature co–fired ceramics are applicable to work in the microwave range; it
has been used for a long time in the development of Wi-Fi, Bluetooth, GPS, GSM modules, small-size directional couplers, and other microwave devices [10].

The main advantages of LTCC – technology for the production of microwave filters:

- Ability to create the integral filters in the frequency range up to 20 GHz;
- Getting the pass transmission band of integral filters from 10% to 100%;
- High repeatability of device characteristics at the serial production;
- High electrical parameters and characteristics;
- Minimal loss in the pass transmission band;
- High reliability and fault tolerance;
- Microminiaturization of overall dimensions;
- Wide selection of element designs and circuitry construction solutions;
- High technological efficiency of production of microwave filters.

The criteria for selecting the elements of design and construction of microwave filter for their production using LTCC–technology of low-temperature co-fired ceramics are:

- The ability to give the design and construction of capacitors any shape – circle, triangle, rectangle, parallelogram, polygon, etc., and have the multilayer structure. Since the value of the dielectric constant is approximately equal to \( \varepsilon = 7.8 \) (Table 1), then the capacitance can be realized by using the base itself as the dielectric [11].

- Implementation of the deaf and blind apertures, which complicate the design, construction and production of microwave filters in other technologies, in particular, in the MPCB–technology (multilayer printed circuit boards), due to the separate preparation of each layer of ceramics for the stack independently of other layers. That is why the production of integral filters based on LTCC–technology allows the application of inductance coils of any known designs and constructions [12].

- Precision of reproduction of the current–conducting pattern (picture), depending on the procedure of application, varies within the range of: ± (10 – 20) \( \mu \)m (microns) by photo–method; ± (20 – 50) \( \mu \)m by stencil (template) printing method. Due to the high precision of the reproducing of current–conducting pattern (picture), the characteristics of the experienced samples (prototypes) accurately repeat the simulation results, without significant deviations [13].

6. Comparative analysis

Because of fulfilled investigations, the band–pass filters based on the low–temperature co–fired ceramics LTCC and liquid crystal polymers LCP were developed and implemented. To compare the results of the manufacturing process of microwave filters based on both technologies, figure 6 shows one of the possible circuits and constructions of the band–pass filter with cutoff frequency of 2.9 GHz, and with pass transmission band of 500 MHz. The size of the filter is 10 × 6 mm; the insertion loss is about 1 dB. Figure 7 shows the calculated and experimental characteristics of such microwave filter, showing the graphical coincidence of the results of computer modelling and experiment, as well as the possibility of production implementation of the integral band–pass microwave filters and their high–quality fabrication with high electrical parameters [6].

![Figure 6](image_url)

**Figure 6.** a) Band–pass microwave filter circuit based on LTCC technology with cut–off frequency 2.9 GHz; b) Appearance of experienced sample (prototype) fulfilled using planar technology; c) Appearance of experienced sample (prototype) made using three–dimensional technology
High stability of dielectric permittivity, low tangent of the angle of dielectric losses and ability to operate in the wide frequency range provide high electrical parameters of microwave filters made on the base of low–temperature co–fired ceramics LTCC [14].

Figure 7. Amplitude–frequency characteristics of band–pass integral microwave filter made using LTCC–technology according to the circuit in figure 6. The insertion loss is about 1 dB.

Figure 8 shows the appearance and dimensions of this filter, 10 × 6 mm. From the graphs shown in the figures, it can be seen that the considered microwave filters have sufficiently high electrical characteristics, and their calculated and experimental frequency characteristics have significant graphical coincidence.

Figure 8. Appearance and dimensions of the band–pass integral microwave filter, made using LTCC–technology. The filter dimensions are 10 × 6 mm.

Figure 9 demonstrates the similar band–pass filter fulfilled using liquid crystal polymer LCP–technology, with central frequency of 2.9 GHz, also made according to the circuit shown in figure 6. Appearance and dimensions of this filter are shown in figure 10. The size of the prototype is 10 × 28 mm.

The amplitude–frequency characteristics of the experimental sample of microwave filter in the pass transmission band repeats completely the amplitude–frequency characteristics (response) obtained as result of computer simulations and modelling. Sample parameters: the insertion loss in the pass transmission band is no more than 1 dB, at the pass transmission band of 15%, the attenuation in the retention (delaying) band has value of at least 40 dB, up to 5 GHz [6].

Carrying out the comparative analysis, it can conclude that both technologies allow to produce band–pass integral filters of the microwave range with high electrical characteristics. At the same time, the overall dimensions of identical filters will be larger for filters based on LCP–technology due to the low value of the dielectric constant and the restrictions imposed on the design and construction by the manufacturing technology itself.
Figure 9. Amplitude–frequency characteristics of the band–pass integral microwave filter fulfilled using LCP–technology according to the circuit in figure 6. The insertion loss is about 1 dB.

Figure 10. Appearance and dimensions of the band–pass integral microwave filter, made using LCP–technology. The filter dimensions are 10 × 28 mm.

In addition, LCP–based filters have difficulties maintaining high attenuation values in the retention (delaying) band, due to the limited choice of elements design and construction. At the same time, integral filters made using LCP–technology allow implementing the same pass transmission bands as filters made using LTCC–technology, but the irregularity (non–uniformity) in the pass transmission band is much less.

7. Conclusion

Application of the modern dielectric materials allows designing, constructing and fabricating the various types of integral filters with high performance and operating parameters. The choice of material is determined by strict requirements for the technical parameters of the microwave filter: the type of frequency characteristics, frequency range, losses level, irregularity in the pass transmission band, etc. For example, low–pass (low frequency) filters operating in the range up to 1.5 GHz, whose electrical parameters are not subject to such strict requirements, can be implemented in integral form using the technology of multilayer printed circuit boards [15].

To create microwave filters intended and designed to operate in higher frequency range, much stricter to electrical characteristics requirements must be met, so it is recommended to use new dielectric materials, such technologies as low–temperature co–fired ceramics (LTCC) and liquid crystal polymers (LCP) [16].

Production of integral band–pass filters is possible on the base of both technologies. At the same time, the application of LTCC–technology is preferable for solving the problem of microminiaturization of microwave filters for creating devices with minimal dimensions. The use of LCP–technology is advisable for creating narrow–band, designed to work in higher frequency range of microwave filters, which do not have too strict requirements for mass and size indicators [17].
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