About the possibility of metamaterials application at the band–pass microwave filters designing with superwide pass transmission band

A S Budyakov¹, L V Cherchesova₂, D V Kleimenkin²* and Yu A Shokova²

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

*e-mail: K-Dima-01@mail.ru

Abstract. A band-pass filter with an extended operating frequency range based on composites - metamaterials is considered. Two design stages are presented, when, at the first stage, a two-stage microstrip filter on a resonator with a stepwise change in impedance, an SIR filter, is developed. At the second stage, the SIR-filter is remodified by adding to it a cell of mixed combined right-handed and left-handed transmission lines made of metamaterials. At lower frequencies, in the bandwidth, insertion loss is about 4 dB in the 3.1–4.2 GHz frequency range, due to the difficulty of meeting the impedance requirements of the mixed right-hand and left-hand transmission line, for all six phases throughout the ultra-wide frequency band is required. It was found that such methods are quite applicable for the design of other radio-electronic devices, in which impedance matching in an ultra-wide frequency band is required.

1. Introduction
Composite materials (composites) possess the unique characteristics that have not only the properties of their constituent elements, but an artificially created periodic structure also. This structure consists of macroscopic elements of arbitrary sizes and shapes. Such composites are called metamaterials, and the filling compounds that make up their structure are macroscopic elements. Usually, in the first approximation, they are considered and analyzed as super – large atoms, which was incorporated artificially into the source material [1].

Metamaterials with negative refraction index are the left – handed isotropic media (left–handed material, LHM); accordingly, metamaterials with positive refraction index are considered as right–handed isotropic media (right – handed material, RHM) [2].

Today, the number of separate frequency bands are used in the communications. However, the signal transmission can occur in the single superwide band (SWB), at low power, at frequencies of 3.1–10.6 GHz [3].

For such purposes, the band–pass filter (PF) with superwide frequency band on the ground on composites – the metamaterials, which combine the mixed right – hand and left – hand (RLH) transmission lines (their combination) was developed [4].

2. Development of the filter
The band–pass microwave filter with superwide frequency band, range of 3.1–10.6 GHz, is developed on the ground of modified microstrip filter, on the resonator with stepped change of the total resistance. Instead of microstrip filter, it uses the transmission line made of metamaterial. The size of band–pass
filter itself is only $23.4 \times 20 \text{ mm}^2$, which solves the problem of the size minimizing. Such filter has twice as many transmission poles: 6 instead of 3, which were used in the original classical design [5].

It is known that the USA Federal Communications Commission has approved the application of $3.1-10.6 \text{ GHz}$ frequency band for indoor and outdoor communication systems [6]. At the same time, the band-pass filter with superwide frequency band and minimal dimensions is one of the key components of such communication systems. Thus, this frequency band will be used all over the world, including in Russia.

Various approaches were used previously to cover this frequency band, but all the filters had the disadvantage of being too large. Superwide band-pass filters have been developed also in the mixed way – with the assistance of conjunction and combining the advantages of band-pass filters and low-pass filters (LPF) to reduce the size.

However, they cannot provide the sharp signal weakening in the stop-band of the filter (filter barrage band), which is their disadvantage [7].

The mixed combined transmission lines created from metamaterials have characteristic of *nonlinear phase shift*. The application of such transmission lines allow to reduce the sizes of many microwave devices, not just filters [8].

The mixed right-hand and left-hand transmission lines (their combination) have the nonlinear positive or negative phase response, depending on the frequency. Due to this property, they are used in the compact band-pass filters. This approach makes it possible to develop compact filters with superwide pass transmission band and high selectivity [9].

At the same time, an increase in the number of transmission poles leads to the implementation of band-pass microwave filter with superwide pass transmission band, with high level of selectivity and minimal dimensions [10].

3. Design of the filter

The process is carried out in two stages. At the first stage, the classic two-cascade band-pass filter is developed (in other words, the modified microstrip filter on resonator with stepped change in the total resistance, figure 1, a). At the second stage, it is refined and remodeled by adding the cell of mixed combined right-hand and left-hand transmission lines made from metamaterials (figure 1, b).

![Figure 1. Design stages: a) development of conventional classical filter; b) modernization of the developed filter](image-url)

The classic two-cascade band-pass filter is manufactured on the RT/duroid 6010 board manufactured by Rogers. The permittivity (dielectric constant) of the board material is 10.2. The filter is made of material with the thickness of $h = 0.625 \text{ mm}$.
The bandpass filter is implemented with the assistance of two cascades with impedances \( Z_1 = 20 \, \text{Ω} \) (Ohms) and \( Z_2 = 32 \, \text{Ω} \) (Ohms), and different electrical lengths \( \theta_1 \) and \( \theta_2 \), accordingly. The length of each section is \( L = 3.8 \, \text{mm} \).

The input impedance of the filter \( Y_i \) is calculated using the expression:

\[
Y_i = \left( j Y_2 \right) \frac{2(1+k)(k-tg^2\theta)tg\theta}{\left( k^2 - 2 \right)(1+k+k^2)(tg\theta)}
\]

where \( k = Z_1 / Z_2 \); \( \theta = \theta_1 = \theta_2 \).

Zero input conduction \( (Y_i = 0) \) is provided at the frequencies 4.5; 7.0; 9.25 and 13.4 GHz. These frequencies should be at the beginning, the middle, and the end of the filter band – pass. This means that the resonant lengths are \( \theta_0 = 52^\circ \); \( \theta_{l1} = 90^\circ \); \( \theta_{l2} = 127^\circ \); \( \theta_{l3} = 180^\circ \) at the frequencies of 4.5; 7.0; 9.25 and 13.4 GHz, respectively.

Computer modelling using software simulator were performed on two–cascade filter models. Figure 2 shows the resulting distributed parameters (S–parameters).

**Figure 2.** Results of S–parameters modelling

The calculated value of pass transmission band is 3.1 – 10.6 GHz, but the filter has poor suppression coefficient at the lower and upper cutoff frequencies. Thus, the two–cascade filter has three transmission poles: 4.5; 7.0 and 9.25 GHz.

At the second stage, 20 Ω (Ohm) transmission line is replaced by cell combining the mixed right–hand and left–hand transmission lines, made of metamaterials, with 20 Ω Ohms (figure 1, b). Such cell contains the left–side section formed by two sequential counter–pin capacitors, and two shunting chokes. Next to, it is section of right–hand microstrip transmission line with impedance of 20 Ω (Ohms) (figure 1, b). Figure 3 demonstrates the equivalent circuit of mixed right–hand and left–hand transmission line (their combination).

**Figure 3.** Equivalent circuit of mixed right – hand and left – hand transmission line.
Figure 1, b demonstrates the optimal values for capacitors and chokes. The transmission line is symmetrical. Left – hand and right – hand sections have identical characteristic impedances. Characteristic impedance $Z_{RLS}$ and phase shift $\phi_{RLS}$ of symmetrical mixed right – hand and left – hand transmission line are described by:

$$Z_{RLS} = Z_{RH} = \sqrt{\frac{L_R}{C_R}} = Z_{LH} = \sqrt{\frac{L_L}{C_L}};$$

$$\phi_{RLS} = \frac{1}{\omega \sqrt{(C_L L_R)}} - \frac{\omega \sqrt{(C_R L_R)}}{2}.$$  

(2)

4. Constructioning

The main task to be solved is to balance the 20 Ω (Ohm) line for all frequency bands. The next task is to optimize the phase of the left – hand and right – hand sections to fulfill the resonant conditions and create additional poles in the frequency range of superwide band – pass. To do this, it is necessary that the following conditions must be satisfied inside the pass transmission band of the filter:

$$\theta_0 = 52^\circ; \theta_{s1} = 90^\circ; \theta_{s2} = 127^\circ; \theta_{s3} = 180^\circ.$$ 

To achieve these purposes, in 20 Ω (Ohm) mixed combined right – hand and left – hand transmission line, the lower cutoff frequency in the left – hand section is 3 GHz, and the upper cutoff frequency in the right – hand section is 11 GHz. The transition frequency between the right – hand and left – hand bands is 8 GHz. The transition frequency is selected so that it is possible to control the nonlinear phase shift in the left – hand band, and thus provide the best resonant conditions.

Then the optimization was performed. Computer modeling was applied, using the specialized commercial CAD programs (OrCAD, NL5 Circuit Simulator, McCAD) [11–13]. At modelling, the amount of insertion losses and the phase of the band – pass filter with superwide pass transmission band varied (figure 4).

Figure 4. The simulation results

The figure 4 shows that the phase 90° is reached twice inside the band at two resonant frequencies: 3.1 and 7.0 GHz. The phase –52° occurs twice also, at frequencies of 4.5 and 9.2 GHz. The phase 180° is observed at the frequencies of 6.0 and 10.3 GHz.

The final version of the superwide pass transmission band of the filter was produced on the printed circuit board thickness of 0.625 mm. The microstrip line impedance is 50 Ω (Ohms). Figure 5, a, shows...
the structure of the filter being developed, and figure 5, b, shows its appearance. The filter size is 23.4 × 20 mm.

Figure 5. Metamaterial – based filter: a) structure; b) appearance

The optimization of the filter was performed once again when cascading of mixed right – hand and left – hand transmission line and 30 Ω (Ohm) transmission line. The optimal length of the segment $L_C$ is 4.2 mm.

Figure 6 demonstrates the S–parameters of the filter, measured experimentally and simulated (modelled), and it is obvious that they are corresponding. The value of the insertion losses diverges by 0.5 – 1 dB in the frequency range 4.2 – 10.6 GHz.

Figure 6. The measured and calculated S – parameters of the filter

At lower frequencies, in the pass transmission band, the insertion loss is about 4 dB in the frequency range 3.1 – 4.2 GHz. It is due to the complexity of compliance the requirements for the impedance of the mixed right – hand and left – hand transmission line, for all six phases in the entire superwide frequency band.

The filter has 6 poles in the range of 3.1 – 10.6 GHz. Computer simulation results show that the transmission poles are located at the frequencies 3.1; 4.5; 6.5; 9.2; 10.2 and 10.5 GHz. However, the measured value of the reverse loss shows only five transmission poles that differ due to difficulties in manufacturing the circuit.
Figure 7 shows the measured and calculated group delay value of the microwave filter with superwide pass transmission band. Computer simulation results show that developed filter has almost constant group delay (0.35 ns) inside the pass transmission band. However, the group delay deviation exceeds the value 0.1 ns in the bands 3.1 – 4.5 and 10.0 – 10.6 GHz. The measurement results show that the group delay is 0.2 ns in the range of 4.5 – 10.0 GHz. It increases to 0.5 ns approximately, in the pass transmission band of 3.0 – 4.5 GHz.

5. Conclusion
The application of combined mixed right–hand and left–hand transmission lines created from metamaterials in band – pass filters provides good results. Such band – pass filters with superwide pass transmission band are promising for using in the frequency range from 3.0 to 11 GHz and higher [14].

However, the manufacturing process of such filters requires improvement, in order to be able to take effectively advantage of all benefits of this method of design. The close correspondence between the simulation results and the measurements performed shows that this approach is applicable to the design of other radioelectronic devices that require the matching of impedances in superwide frequency band [15].

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