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PHYSICS

Investigation of Frequency-Selective Devices Based on a Microstrip 2D Photonic Crystal

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Abstract—The frequency-selective properties of structures based on a 2D microstrip photonic crystal have been investigated theoretically and experimentally. It is shown that various microwave devices, including diplexers, bandpass filters, and double bandpass filters, can be designed based on these structures.

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Microwave bandpass filters are known to be very important elements of communication, radiolocation, and radio navigation systems and various kinds of measuring and special radio equipment [1]. However, along with conventional single-pass filters, devices having two operating bands, each of a specified width and central frequency, are often called for [2]. In addition, there is demand for two-channel frequency-selective devices (diplexers), in which a signal arriving at one common input is divided into two independent frequency channels [3]. When developing frequency-selective devices, great attention is paid to microstrip designs, which are small and highly technological [4].

The possibility of designing bandpass filters based on 1D microstrip photonic crystals (PCs), which are periodic structures with strip conductors of alternating width, was demonstrated in [5, 6]. These microstrip PC structures can be used to design high-Q resonators [7], which are applied, in particular, to measure the dielectric characteristics of liquids [8]. In this study, we propose designs of frequency-selective devices based on a 2D microstrip PC, composed of six electromagnetically coupled regular quarter-wave or half-wave resonators, forming an array with a dimension of 3 × 2 in the substrate plane. A high-frequency TBNS ceramic plate with a thickness $h = 1$ mm (having permittivity $\varepsilon = 80$) is used as the substrate.

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DIPLEXER: A FREQUENCY SPLITTER

The first of the devices developed, a diplexer (see the conductor topology in Fig. 1), has an input port connected to an irregular half-wave resonator, electromagnetically coupled with microstrip PC resonators. Two output ports are conductively connected to strip conductors of the extreme resonators of the microstrip structure. A signal arriving at the diplexer input is divided between the channels, each of which is formed by three parallel microstrip resonators. Obviously, resonators with longer strip conductors form the first (low-frequency) pass band, whereas the resonators with shorter conductors form the second (high-frequency) pass band.

The solid and dashed lines in Fig. 1 show, respectively, the amplitude-frequency characteristics of the direct loss in the first (S_{21}) and second (S_{31}) diplexer channels, and the dotted line is the frequency dependence of reflection loss at the diplexer input, S_{11}. The topological sizes of diplexer strip conductors were obtained by parametric synthesis of the design, using numerical electrodynamic analysis of its 3D model in the Microwave Office package. When synthesizing the diplexer, we set for definiteness the central frequencies of its channels, $f_1 = 0.94$ GHz and $f_2 = 1.44$ GHz, and identical relative width of both channels: $\frac{\Delta f_{1,2}}{f_{1,2}} = 9\%$, which was determined at a level of –3 dB of the minimum loss in bandwidth. We also set the maximum allowable level of reflection loss in both bandwidths: $S_{11} \le -14$ dB. The geometric sizes of diplexer strip conductors, numbered in Fig. 1, are listed in Table 1.

The amplitude–frequency characteristic (Fig. 1) shows that the design based on a 2D microstrip PC has rather good characteristics for a diplexer characterized

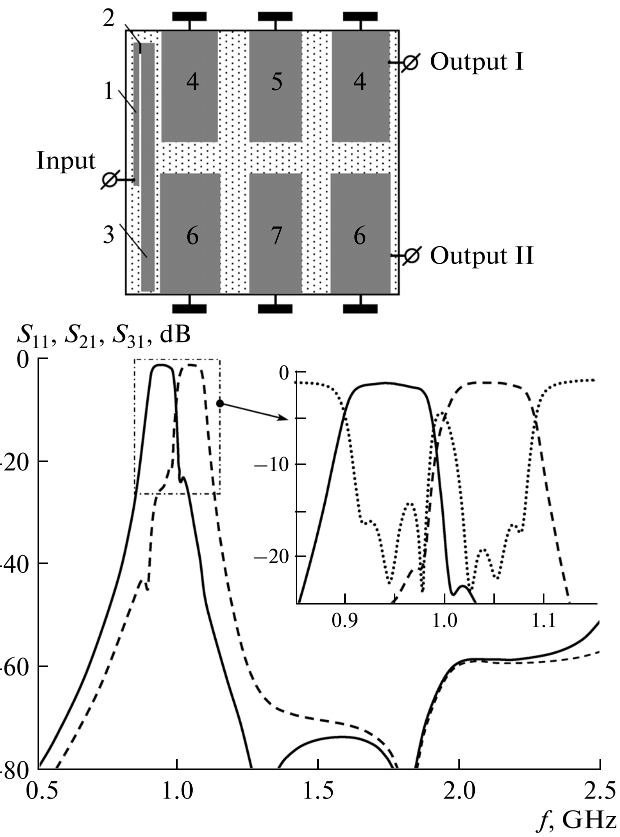

Fig. 1. Topology of the conductors of a microstrip diplexer and its amplitude–frequency characteristics. The regular portions of conductors (black or gray) are enumerated.

by nearly adjacent bandwidths, the channels of which form only third-order filters. This is explained by the presence of attenuation poles, which are pronounced in the amplitude–frequency characteristic, in particular, near the diplexer bandwidths. These poles are due to the interaction of two input quarter-wave diplexer resonators through the input half-wave cavity. Specifically this additional resonator coupling generates poles [9].

Table 1. Topological sizes of strip conductors of a microwave diplexer based on a 2D microstrip PC

Conductor no.	Conductor sizes, mm^2	Gaps between conductors, mm
1	11.50 × 0.20	1 and 4—0.65
2	0.50 × 0.10	1 and 6—0.65
3	20.10 × 0.95	4 and 5—2.55
4	8.80 × 4.55	6 and 7—2.35
5	8.80 × 4.20	4 and 6—2.90
6	9.80 × 4.75	5 and 7—2.90
7	9.80 × 4.20	

The distance between conductor no. 1 and the substrate edge is 0.2 mm.

Note that the minimum levels of microwave power loss in the first and second channels were 0.8 and 1.2 dB, respectively. Obviously, if the frequency-selective properties of a device should be improved, it is only sufficient to increase the number of resonators in its channels. It is also noteworthy that the spacing between channels can easily be increased (to almost an octave) in a diplexer based on a 2D microstrip PC by changing only the ratio of the lengths of the resonators strip conductors. Changing the gaps between strip conductors, one can vary independently (and in wide limits) the channel bandwidth.

DOUBLE BANDPASS FILTER

The design of the above-considered 2D microstrip PC makes it possible to implement a filter with two spaced bandwidths; however (although this is not essential), we will use half-wave rather than quarter-wave cavities to this end (Fig. 2). A signal arriving at the input of this filter, as in a diplexer, is divided between channels, and the signals transmitted through two channels are summed at the device output. Here, as well as in the diplexer, resonators with longer and shorter conductor strips form, respectively, the first and second bandwidths.

The solid lines in Fig. 2 are the amplitude–frequency characteristics of direct loss and loss on reflection, S_{21} and S_{11}, respectively, for the developed double bandpass filter. The topological sizes of its strip conductors were obtained by parametric synthesis of the design using numerical electrodynamic analysis of its 3D model. For definiteness, when synthesizing the double bandpass filter, we set the central frequencies of its bandwidths, $f_1 = 0.80$ GHz and $f_2 = 0.95$ GHz, and the relative channel bandwidths: $\frac{\Delta f_1}{f_1} = 5.0\%$ and $\frac{\Delta f_2}{f_2} = 5.5\%$, which were determined at a level of −3 dB of the minimum loss in the corresponding channel. We also set the maximum allowable level of reflection loss in both bands: $S_{11} \le -14$ dB. The geometric sizes of diplexer strip conductors thus obtained, which are numbered in Fig. 2, are listed in Table 2.

The amplitude–frequency characteristic in Fig. 2 shows that the design developed has rather good characteristics of the double-bandpass filter, the channels of which are formed by third-order filters. This fact is explained (as in the case of diplexer) by the presence of attenuation poles in the amplitude–frequency characteristic, which are due to the additional couplings, formed by the input and output device resonators between the channel resonators adjacent to them. Obviously, an increase in the number of resonators in channels should improve the frequency-selective properties of the device. It is noteworthy that the spacing between channels in the design of double-bandpass filter can easily be increased or decreased by changing only the ratio of resonator strip lengths; the channel bandwidth can be varied independently in wide limits by changing the gaps between strip conductors.

To test the electrodynamic calculation accuracy for the 3D model of the double-bandpass microstrip filter, we fabricated a prototype based on the geometric sizes found by synthesizing the device conductor topology. Figure 2 shows a photograph of the filter prototype, with conventional substrate sizes: 30 × 48 mm. The measured amplitude–frequency characteristics of the filter are shown in Fig. 2. The small discrepancies between the measured and calculated filter characteristics are primarily due to the errors in fabricating the strip conductor pattern. However, the measured levels of minimum microwave power loss in the first and second channels of the filter prototype coincide well with the calculated values and amount to 1.4 and 1.7 dB, respectively.

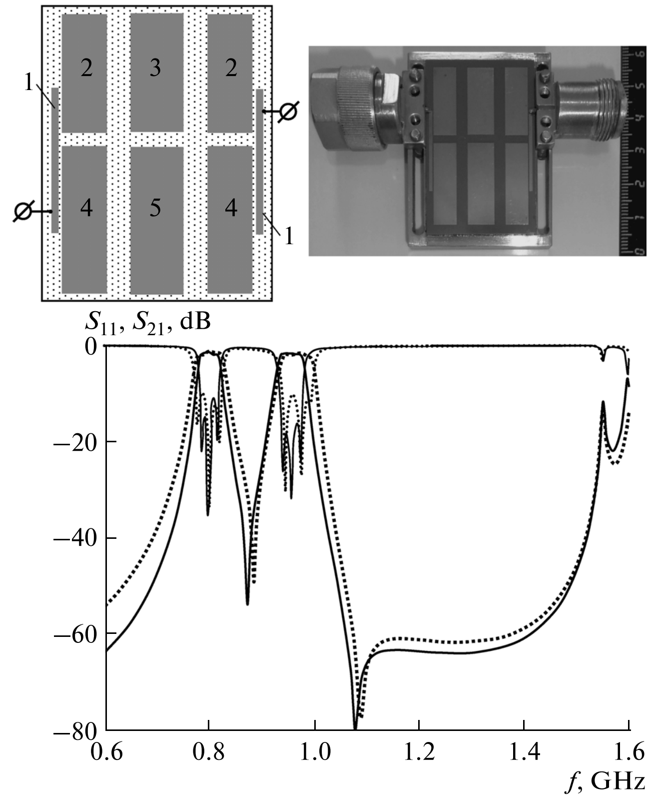

Fig. 2. Topology of the conductors of a microstrip double-bandpass filter and its (solid lines) calculated and (points) experimental amplitude–frequency characteristics. A photograph of prototype filter is given in the top right corner.

BANDPASS FILTER

An analysis of the 2D microstrip PC showed that a bandpass filter of original design can be developed on its basis; its conductor topology is shown in Fig. 3. There are half-wave irregular resonators at the filter input and output, which are electromagnetically coupled with quarter-wave microstrip PC resonators. A signal arriving at the filter input, as well as in the above-considered devices, is divided between two channels, each of which is formed by a circuit of three parallel resonators. The signals passing through these channels are summed at the output. However, it should be noted that, since the half-wave resonators at the filter input and output have some irregularities, they have different degrees of coupling with the channels. In the design under consideration, the input resonator is more strongly coupled with resonator 4 (see Fig. 3) than with resonator 6, while the situation at the filter output is the opposite. Specifically this fact makes it possible to form a filter bandwidth using the resonances of lower oscillation modes of all eight structure resonators.

The solid line in Fig. 3 is the amplitude–frequency characteristic of direct loss S_{21} for the filter developed, and the dashed line is the frequency dependence of its reflection loss S_{11}. The topological sizes of strip conductors were obtained, as previously, by parametric synthesis of the design, using numerical electrodynamic analysis of its 3D model. For definiteness, when synthesizing the filter, we set the central frequency of its bandwidth, $f_1 = 1.0$ GHz, and its relative width, $\frac{\Delta f_1}{f_1} = 20\%$, which was determined at a level of –3 dB of the minimum loss in the bandwidth. We also set the maximum allowable level of reflection loss in the bandwidth: $S_{11} \leq -14$ dB. The found geometric sizes of filter strip conductors, numbered in Fig. 3, are listed in Table 3.

Table 2. Topological sizes of strip conductors of a double-bandpass microwave filter based on a 2D microstrip PC

Conductor no.	Conductor sizes, mm^2	Gaps between conductors, mm
1	22.1 × 0.9	1 and 2—0.2
2	18.7 × 6.3	1 and 4—0.2
3	18.4 × 7.3	2 and 3—3.0
4	22.3 × 6.3	4 and 5—3.0
5	22.4 × 7.3	2 and 4—2.1

The distance between conductor no. 1 and the substrate edge is 10.1 mm.

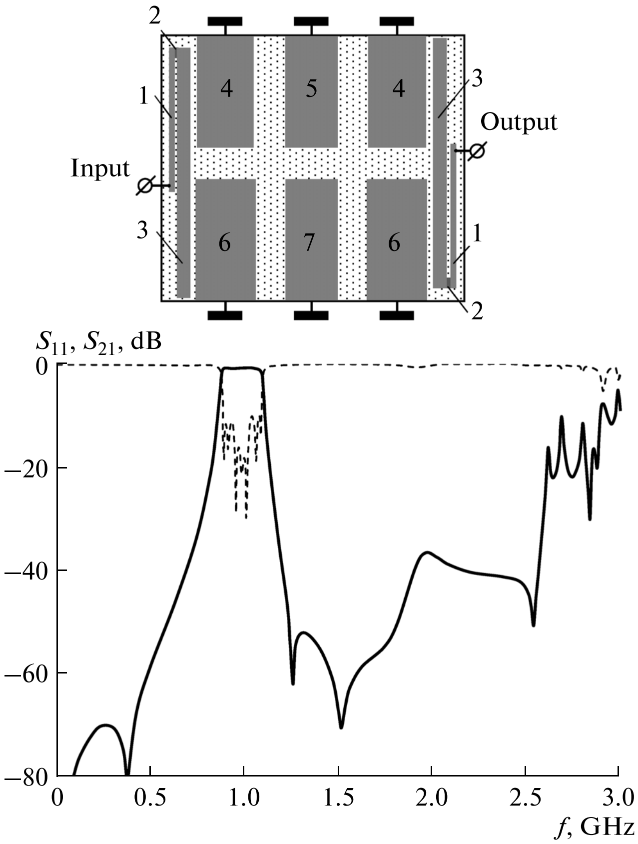

Fig. 3. Topology of the conductors of a bandpass filter and its amplitude–frequency characteristics. The regular portions of conductors are enumerated.

It can be seen in Fig. 3 that the developed design of the eight-order bandpass filter has a number of advantages. These are, first, a high steepness of slope of amplitude–frequency characteristic; second, a rather wide high-frequency stop band; and, third, a high damping level of microwave power in the stop band. Obviously, all these advantages are related to the presence of attenuation poles in the amplitude–frequency characteristic of the filter, which, as was explained above, originate from the additional couplings [9] between the extreme resonators of microstrip PC at the input and output of the device; these couplings are due to the irregularity of half-wave resonators.

Table 3. Topological sizes of strip conductors of a bandpass microwave filter based on a 2D microstrip photonic crystal

Conductor no.	Conductor sizes, mm^2	Gaps between conductors, mm
1	11.10 × 0.15	1 and 4—0.65
2	0.60 × 0.15	1 and 6—0.65
3	20.00 × 1.05	4 and 5—1.80
4	8.80 × 4.45	6 and 7—2.05
5	8.80 × 4.40	4 and 6—2.60
6	9.80 × 4.60	5 and 7—2.60
7	9.80 × 3.60	

The distance between conductor no. 1 and the substrate edge is 0.1 mm.

Note that the minimum level of microwave power loss in the filter bandwidth is 1.4 dB. When the frequency-selective properties of the device must be improved, it is also sufficient to increase the number of resonators in its channels. To vary the filter bandwidth, it is necessary to change simultaneously the ratio of the resonator strip lengths in the channels and the gaps between strip conductors. When the bandwidth must be narrowed, one has to reduce the difference in the strip conductor lengths in the channels and increase the gaps between conductors; when the bandwidth must be increased, the reverse must occur.

RESULTS AND DISCUSSION

An analysis of the designs based on the 2D microstrip PC showed that various microwave devices can be developed on their basis, including diplexers, bandpass filters, and double bandpass filters. In all these devices, a microwave signal arriving at the input is divided between two channels formed by coupled microstrip PC cavities. The diplexer, which has two output ports, provides frequency separation of signals between ports, whereas in the case of bandpass and double-bandpass filters, signals are summed at the output.

Within the approach proposed here, one can design frequency-separation devices with the number of channels exceeding two. For example, a three-channel frequency-separation device can easily be developed based on a 2D microstrip PC with a dimension of 3 × 3. In this case, all resonators of the PC structure can be half-wave and the configuration of the strip conductor for an irregular resonator at the device input must be chosen so as to provide for its coupling with three extreme resonators of the PC structure. Obviously, using a PC with a dimension of 3 × 3, one can design a triple-bandpass filter and a high-order single-bandpass filter. In these devices, it is also necessary to choose a configuration of the strip conductor of the irregular resonator at the input and output of the device that would provide necessary matching with the microstrip PC.

The small sizes of the developed designs of frequency-selective microwave devices based on microstrip PC structures and their good electric characteristics make them promising for application in communication systems, radiolocation, radio navigation, and special radio equipment.

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REFERENCES

1. B. A. Belyaev, S. A. Khodenkov, R. G. Galeev, and V. F. Shabanov, Dokl. Phys. **60** (3), 95 (2015).
2. B. A. Belyaev, A. M. Serzhantov, and V. V. A. Tyurnev, Microwave Opt. Technol. Lett. **55** (9), 2186 (2013).
3. B. A. Belyaev, M. A. Serzhantov, and V. V. Tyurnev, Tech. Phys. Lett. **38** (16), 743 (2012).
4. J.-S. Hong and M. J. Lancaster, *Microstrip Filters for RF/Microwave Applications* (Wiley, New York, 2001).
5. B. A. Belyaev, A. S. Voloshin, and V. F. Shabanov, Dokl. Phys. **49** (4), 213 (2004).
6. B. A. Belyaev, A. S. Voloshin, and V. F. Shabanov, Dokl. Phys. **50** (1), 7 (2005).
7. B. A. Belyaev, A. S. Voloshin, and V. F. Shabanov, Dokl. Phys. **50** (7), 337 (2005).
8. D. A. Usanov, A. V. Skripal', A. V. Abramov, A. S. Bogolyubov, M. Yu. Kulikov, and D. V. Ponomarev, Tech. Phys. **80** (8), 1216 (2010).
9. B. A. Belyaev, A. M. Serzhantov, Y. F. Bal'va, V. V. Tyurnev, A. A. Leksikov, and R. G. Galeev, Microwave Opt. Technol. Lett. **56** (9), 2021 (2014).

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