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ELECTRODYNAMICS
AND WAVE PROPAGATION

Analysis of Microstrip Analogues of Bandpass Filters on One-Dimensional Photonic Crystals

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Abstract—Structures composed of connected-in-series sections of microstrip transmission lines with different characteristic impedances and effective permittivities are analyzed. It is shown that such irregular microstrip structures are good analogues of 1D photonic crystals consisting of alternate dielectric layers with abrupt and diffuse interfaces. Behavior of transmitted and reflected waves is studied in a wide frequency band as a function of the design parameters of microstrip models. The results of a quasi-static numerical analysis of these structures agree rather well with experimental data. The results obtained can be used for a substantial improvement of characteristics of bandpass filters built on dielectric photonic crystals.

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INTRODUCTION

Modern technologies for the epitaxial growth of thin films allow manufacturing of multilayer structures composed of alternate layers of different materials whose thickness is comparable to the axial length. Such layers are referred to as superlattices. Superlattices have a number of unique physical properties owing to which such structures are promising candidates for the development of various electronic and optoelectronic devices. In particular, multilayer structures composed of alternate magnetic and nonmagnetic metal layers can serve as magnetic-field sensors because these sensors possess the giant magnetoresistive effect [1]. Superlattices composed of alternate dielectric layers with different permittivities are used as polarizers in switches used in fiber-optic communications devices [2] as well as filters and mirrors for electromagnetic waves of the X-ray band [3].

Superlattices with thicker layers whose thicknesses are comparable to the optical wavelength are referred to as 1D photonic crystals (PCs). Such structures have alternate passbands (transparency windows) and stopbands (photonic band gaps) in the optical frequency band [4, 5]. Modern advances in microelectronic and nanoelectronic technologies, including graphoepitaxy [6], allow manufacturing of not only 1D but also complex 2D and 3D structures with characteristic dimensions of periodic irregularities comparable to the optical wavelength. Such structures are referred to as 2D and 3D photonic crystals, which today are actively studied along with 1D crystals because of their unique properties. The great potential of photonic crystals lies in the fact that physical properties of periodic structures are determined by not only their materials but also structural features of irregularities whose parameters can be varied in a wide range by varying conditions of the manufacturing process. The possibility of efficient control over the propagation of light in photonic crystals makes these structures promising candidates for the development of various optoelectronic devices.

However, manufacturing of even 1D PCs requires unique equipment and has prohibitively high costs. Therefore, it is expedient to perform preliminary experimental and theoretical investigations into properties of photonic crystals with the use of massive (not film) analogues operating at frequencies that are substantially lower than optical frequencies, for example, in the microwave band. These structures can be built on the basis of various periodic guiding structures. Note that, irrespective of their operating frequency band, including the microwave band, such analogues of PCs are also often called photonic crystals [7, 8].

The best microwave analogues of 1D dielectric photonic crystals composed of alternate layers with different values of the refractive index are structures consisting of sections of microstrip transmission lines. Such structures are simple and manufacturable, and the results of numerical analysis of 1D modes of these structures performed in the quasi-static approximation agree well with experimental data [7, 10, 11]. Moreover, microstrip models are closer to a real layered structure than, for example, waveguide analogues because fundamental modes propagating in such structures are quasi-TEM modes with the structure of HF fields close to TEM modes propagating in 1D photonic crystals. In fact, photonic crystals are a system of coupled resonators. This circumstance is the cause of existence of the transparence windows and stopbands [12, 13]. Hence, PCs are of great interest for researchers not only as elements showing promise for the development of future electronic and optoelectronic devices but also as model objects for studying features of propagation

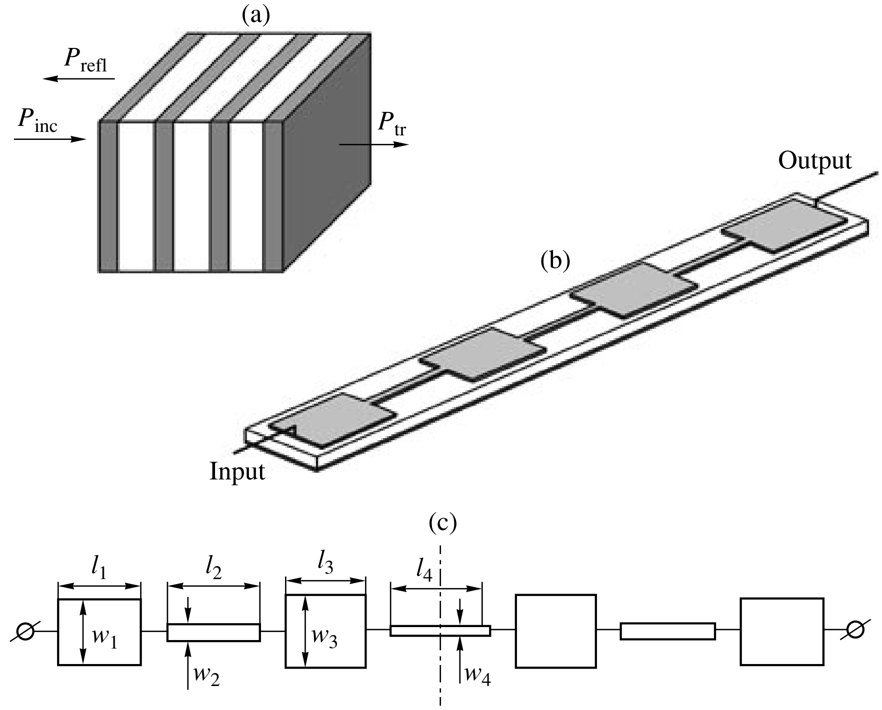

Fig. 1. (a) One-dimensional dielectric photonic crystal, (b) a microstrip analogue of this crystal, and (c) a theoretical model.

and localization of electromagnetic waves in interacting resonators.

BASIC RESULTS OF INVESTIGATIONS

The design principle of microstrip models of 1D photonic crystals consisting of a system of dielectric layers with different permittivities (Fig. 1a) is based on a strong dependence of effective permittivity ε_{eff} of a microstrip transmission line on width w of the microstrip conductor and thickness h of the substrate. The velocity of propagation and, accordingly, the length of the electromagnetic wave excited in this line are determined by the value of ε_{eff}. This value can be calculated from permittivity ε of the substrate and basic design parameters of the line [14]:

$$\varepsilon_{eff} = \frac{\varepsilon + 1}{2} + \frac{\varepsilon - 1}{2}P, \tag{1}$$

where

$$P = \begin{cases} \dfrac{1}{\sqrt{1 + 12h/w}} & \text{for} \quad w \geq h \\ \dfrac{1}{\sqrt{1 + 12h/w}} + 0.04(1 - w/h)^2 & \text{for} \quad w \leq h. \end{cases}$$

It is important that formula (1) is valid for the zero thickness of the stripline conductor and only in the quasi-static frequency domain when transverse dimensions w and h of the microstrip line are substantially less than the length of the electromagnetic wave propagating in this line. As seen from formula (1), decreasing width w at a fixed thickness of the substrate results in a monotonic decrease of the effective permittivity. Therefore, a microstrip structure composed of sections of regular lines with different widths of conductors (Fig. 1b) can serve as a good microwave analogue of a multilayer structure composed of dielectric layers with different refractive indexes. Evidently, the line sections with a large width of the stripline conductor simulate layers with high values of the refractive index, whereas the line sections with a small width simulate layers with low values of the refractive index. For example, a microstrip line on a TBNS ceramic substrate ($\varepsilon = 80$) with $h = 1$ mm has $\varepsilon_{eff} \approx 45$ for $w = 0.1$ mm and $\varepsilon_{eff} \approx 67$ for $w = 10$ mm, while a similar line with an alumina substrate ($\varepsilon = 9.8$) has $\varepsilon_{eff} \approx 5.94$ for $w = 0.1$ mm and $\varepsilon_{eff} \approx 8.37$ for $w = 10$ mm [15]. In microstrip analogues of PCs, the input and output are usually designed as coaxial-to-stripline transitions with the characteristic impedance $Z_0 = 50\ \Omega$. These transitions are conductively connected to stripline conductors of the outermost sections [7, 10, 15].

Numerical analysis of such microstrip structures was performed in the quasi-static approximation with the use of 1D models (Fig. 1c). The model shown in the figure is symmetric relative to its midpoint. This model consists of seven line sections with conductor widths $w_1, \ldots, w_4$ and lengths $l_1, \ldots, l_4$.

In the microwave band, this structure operates as a low-pass filter; however, depending on the tuning features, it can also serve as bandpass filter. As an example, Fig. 2 presents amplitude–frequency responses (AFRs) of insertion and return losses of the microwave power transmitted through a microstrip structure (solid and dashed lines, respectively). The curves in Fig. 2a were plotted for a filter designed on an alumina substrate ($\varepsilon = 9.8$) with $h = 1$ mm. The filter's center frequency was $f_0 = 3$ GHz and the relative bandwidth measured at a level of –3 dB from the minimum loss level was $\Delta f_3/f_0 = 40\%$. The parametric synthesis of this seven-section design was performed with the help of numerical analysis of the structure in the quasi-static approximations. In addition to the aforementioned parameters (the center frequency and the relative bandwidth), we specified also the maximum level of reflections in the structure $L_r = -14$ dB. The filter was tuned by correcting lengths and widths of stripline conductors in each regular section.

Evidently, regular sections of the microstrip structure under study that model corresponding dielectric layers of a photonic crystal are resonators. Therefore, the number of minima of the return loss in the passband of this microstrip structure exactly equals the number of regular sections in the structure. It is important that, similar to tuning of any multisection bandpass filter, tuning of a PC model requires fulfillment of three conditions. First, a required value of coupling between outer resonators (sections) and input and output transmission lines should be ensured. This value is determined by the specified bandwidth of the device. Second, the mutual balance of couplings between all sections should be ensured. Third, resonance frequencies of all sections must coincide with the center frequency of the filter's passband. Certainly, the value of coupling between adjacent resonators is mainly determined by the difference in characteristic impedances of the microstrip lines forming these sections. In the quasi-static approximation, these characteristic impedances can be calculated from the formulas [14]

$$Z = \begin{cases} \dfrac{120\pi/\sqrt{\varepsilon_{\rm eff}}}{1.393 + w/h + 0.667\ln(w/h + 1.444)} \\ \text{for} \quad w \ge h, \\ \dfrac{60}{\sqrt{\varepsilon_{\rm eff}}}\ln\left(\dfrac{8h}{w} + \dfrac{w}{4h}\right) \quad \text{for} \quad w \le h. \end{cases} \qquad (2)$$

Coupling between outer resonators and an external circuit is determined by the difference in the characteristic impedance of the external transmission lines, $Z_0 = 50\ \Omega$, as well as the characteristic impedances of the corresponding microstrip sections used in the model. Note that coupling between sections of this microstrip structure depends on both abrupt changes in characteristic impedances and values of the loaded Q of the resonators used in the structure. The loaded Q affects amplitudes of HF fields in resonators, which, as is well known, are higher in inner sections [15]. As a result, ensuring a specified value of coupling between inner resonators requires a slightly larger stepwise change in characteristic impedances of the inner sections forming these resonators as compared to sections forming outer resonators. This fact is reflected in the values of design parameters obtained from the parametric synthesis of the considered microstrip model (see table). For comparison, this table contains also the design parameters of a similar filter with the relative bandwidth $\Delta f_3/f_0 = 60\%$.

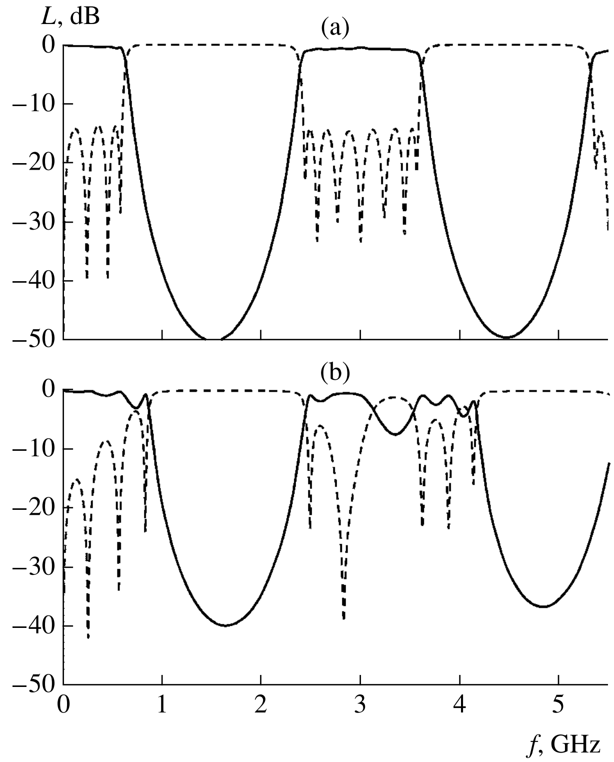

Fig. 2. Frequency characteristics of (solid lines) losses in the transmitted wave and (dashed lines) return losses for a microstrip model of a photonic crystal with (a) optimized parameters of layers and (b) equal thicknesses of alternate layers.

Figure 2b shows frequency characteristics of the insertion (solid line) and return (dashed line) losses for the studied microstrip structure in the case when all regular sections have the same length equal to the length of the first section, $l_1 = l_2 = l_3 = l_4 = 17.19$ mm. The widths of conductors in regular sections with low characteristic impedance are equal to the width of the conductor in the first section, $w_1 = w_3 = 3.92$ mm, while the widths of conductors in sections with high characteristic impedance are equal to the width of the conductor in the second section, $w_2 = w_4 = 0.10$ mm. This design corresponds to a 1D photonic crystal consisting of seven alternate layers with the same thickness and the permittivities $\varepsilon_1 = 7.58$ and $\varepsilon_2 = 5.94$ (see table). As is seen,

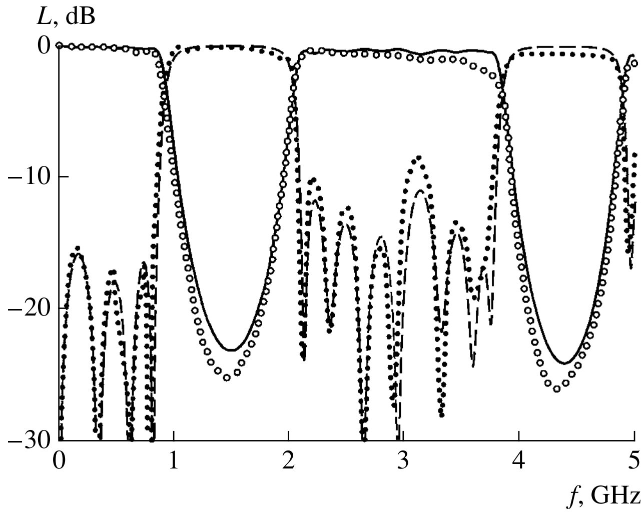

Fig. 3. Amplitude–frequency responses of insertion and return losses for a microstrip model of a seven-layer photonic crystal. Solid lines and dots correspond to theoretical and experimental results, respectively.

this structure demonstrates (i) strong reflections of the microwave power in the passband, which causes unacceptably high ripples on the amplitude–frequency response, and (ii) a substantial widening of the passband and a noticeable lowering of rejection levels situated to the left and to the right of the passband. Evidently, these effects are caused by not only higher eigenfrequencies of the layers with low permittivity, whose resonances are clearly seen on the AFR, but also unbalanced couplings between resonators. Hence, characteristics of bandpass filters built on a 1D photonic crystal or a superlattice will be rather low if these structures consist of alternate layers having different permittivities but the same thickness.

An experiment performed with several microstrip models of photonic crystals manufactured using the varnish etching technology has demonstrated good agreement with the numerical results [16]. As an example, Fig. 3 depicts experimental values of insertion and return losses (dots) for a seven-element filter with the relative bandwidth $\Delta f_3/f_0 = 60\%$. The filter was calculated by the method of parametric synthesis and built on an alumina substrate with $h = 1$ mm. This figure shows also theoretical curves (solid lines) obtained for the model with real design parameters of the microstrip structure that were measured (in mm) after manufacturing: $w_1 = 2.10$, $l_1 = 18.95$, $w_2 = 0.44$, $l_2 = 19.69$, $w_3 = 3.15$, $l_3 = 18.09$, $w_4 = 0.33$, and $l_4 = 19.88$.

These investigations demonstrated that, by increasing the stepwise change in the characteristic impedances of the microstrip sections forming the bandpass filter in the PC models under study, we can reduce the relative bandwidth of this device up to $\Delta f_3/f_0 = 1\%$. Large stepwise changes of the characteristic impedances that are required for implementation of this bandwidth can be obtained with composite (hybrid) substrates containing different materials. For example, substrates with large permittivity can be used for low-resistivity sections of transmission lines and substrates with small permittivity can be used for high-resistivity sections.

Investigations also revealed that we cause not only formation of AFRs with steeper slopes but also almost exponential growth of attenuation in the stopbands by increasing the number of sections (layers). These results are confirmed in Fig. 4 that depicts AFRs of filters with the relative bandwidth $\Delta f_3/f_0 = 60\%$ that contain 3 to 11 sections and are built on an alumina substrate. As seen from the figure, addition of a successive pair of sections into this structure causes an almost 10-dB increase of attenuation in the stopbands situated to the left and to the right of the passband.

In the analyzed multilayer structures, the permittivity changes stepwise at the interfaces between layers. However, in real photonic crystals and, especially, superlattices, interfaces between layers are more or less diffuse. This finding means that the change in ε that occurs between each two layers is not stepwise, but gradual, at some thickness δ whose value depends on the material and quality of the substrate as well as on the layer materials and manufacturing conditions. Evidently, characteristics of the devices and, in particular, filters built on such multilayer structures will depend on

Parameters of regular sections of microstrip lines used in the models of PC filters with seven layers and relative bandwidths of 40 and 60%

Parameter	Layer number							
	1, (7)		2, (6)		3, (5)		4	
$\Delta f_3/f_0$, %	40	60	40	60	40	60	40	60
w, mm	3.92	2.47	0.10	0.50	6.44	3.54	0.05	0.36
l, mm	17.19	17.62	20.49	19.66	17.14	17.78	20.69	19.92
ε_{eff}	7.58	7.22	5.94	6.32	8.00	7.50	5.84	6.22
Z_N/Z_0	0.43	0.59	2.16	1.33	0.29	0.46	2.52	1.49

both the lengths of the interface regions with varying permittivity ε and the behavior of dielectric properties in these regions.

It is convenient to investigate the influence of various interfaces on AFRs of photonic crystals using microstrip analogues of these crystals in which the behavior of permittivity in an interface region between the PC layers is simulated by the corresponding law of variation of the conductor width in the microstrip structure [17]. For simplicity, we will perform these investigations on bandpass filters containing only three layers. We assume that the low-permittivity layer is placed between identical high-permittivity layers. In the case of a stepwise change of permittivity in the interface region, the conductor of the microstrip analogue of such a photonic crystal is shaped as a rectangular dumbbell. In the case of diffuse interfaces, the conductor is shaped as a smooth dumbbell.

For the numerical analysis of microstrip structures with gradual variation in the conductor width, we used the approach proposed in [18], where 1D models of bandpass filters built on the smooth-dumbbell resonators with parallel coupling were studied in the quasi-static approximation. In that study, the microstrip structure with a complex shape was divided along its axis into a set of sections and represented as a set of connected-in-series sections of regular microstrip lines. In each section, the width of the stripline conductor was equal to the width of the real conductor averaged over the length of this section. It has been shown in [18] that, for microstrip structures in which the shapes of conductors were specified by conjugate circles, theory agrees well with experiment.

Here, we consider different laws of variation of the width of a stripline conductor simulating the interface region between layers of a photonic crystal. It is assumed that the length of this region can be equal to not only a part but also the entire period of the photonic crystal. In particular, we considered linear and quadratic variations in the conductor width as a function of coordinate x directed along the structure axis as well as conductors whose widths varied as a harmonic or elliptic sine function.

Figure 5 presents AFRs of the insertion and return losses for several microstrip analogues of bandpass filters built on photonic crystals with diffuse interfaces between layers. To perform an unbiased comparison, the center frequency of the first passband of all bandpass filters built on an alumina substrate with ε = 9.8 was tuned to 3 GHz. The relative bandwidth of these filters was 40% and the maximum level of the return loss in the passband was –14 dB. Tuning was performed by means of parametric synthesis and the subsequent change of the topology of conductors of the microstrip structure with a fixed shape of the interface regions. It has been found that, if the length of the region of variation of the layer permittivity between the layers is less than 1/4 of the PC period, this length has only a slight influence on selective properties of the bandpass filter (see Figs. 5a–5d), irrespective of the character of this interface region. However, as the thickness of the interface region increases, attenuation in the LF stopband increases monotonically as well and attenuation in the HF stopband decreases. This feature is also independent of the character of the interface region (Figs. 5e, 5f). Note that, if the conductor width varies as a harmonic sine function, the attenuation depth is minimal in the HF stopband and maximal in the LF stopband. Moreover, at certain relationships between wide and narrow sections of the conductor, the HF stopband can be eliminated [19].

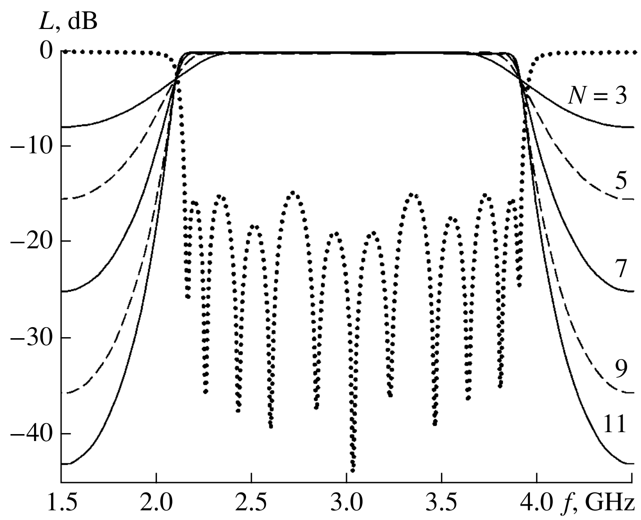

Fig. 4. Amplitude–frequency responses of microstrip models of filters on photonic crystals with 3 to 11 layers. Dots correspond to the return loss for a filter with $N = 11$.

The accuracy of calculating the microstrip analogues of photonic crystals with diffuse interfaces between layers was tested experimentally on a sample of a bandpass filter built on an alumina substrate (ε = 9.8) with $h = 1$ mm. A three-section structure in which lines bounding the stripline conductor are described by an elliptic sine was chosen. In the theoretical model, wide regions of the conductor were divided into seven sections and the narrow region was divided into five sections. The filter was synthesized for the center frequency of the passband f_0 = 3.2 GHz and the relative bandwidth $\Delta f_3/f_0$ = 40%. The length of the stripline conductor was no more than 60 mm (the length of a standard alumina substrate). Theoretical and experimental frequency dependences of insertion and return losses of this filter are shown in Fig. 6. For the unbiased quantitative comparison of theoretical and experimental results, we used real dimensions of the topology of the filter conductor that were measured with a digital microscope after manufacturing of the device and entered into a computer program used for the analysis of the microstrip structure under study. As expected, the presence of diffuse interfaces between wide and narrow

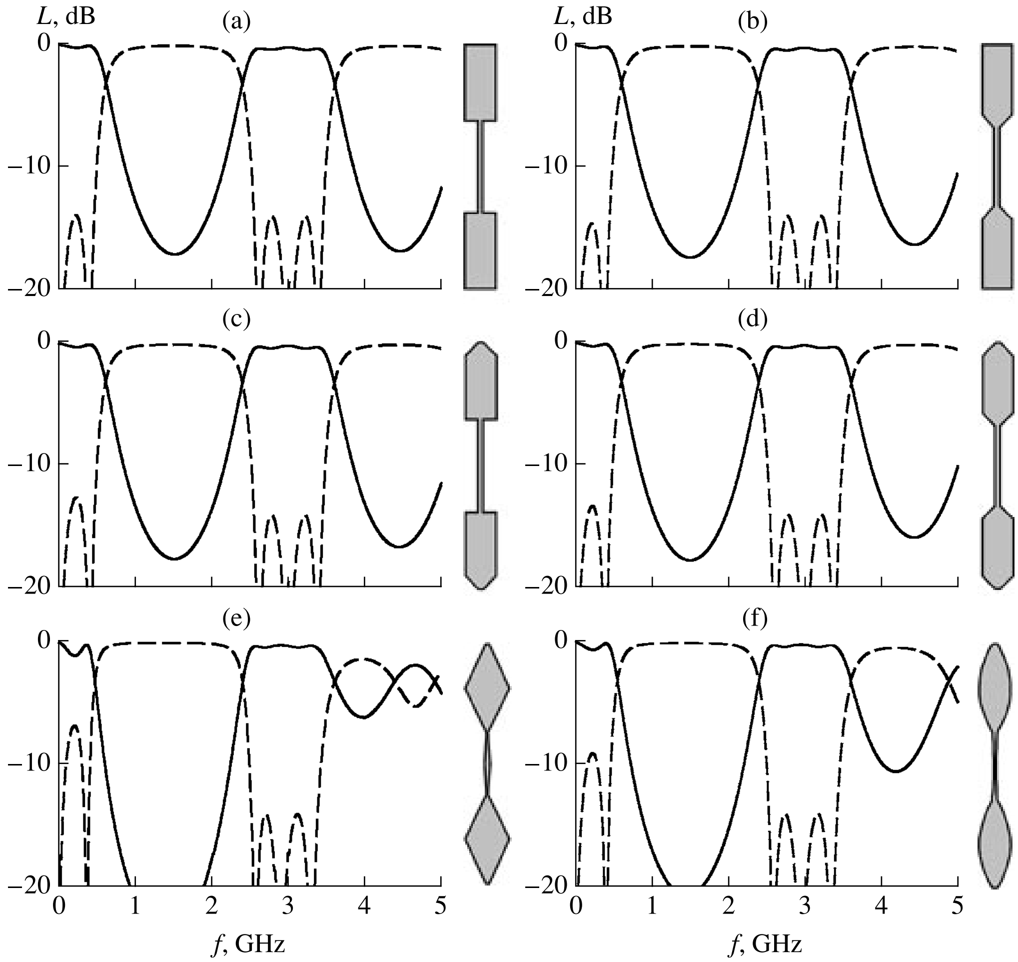

Fig. 5. Amplitude–frequency responses of microstrip models of bandpass filters built on three-layer photonic crystals with different interfaces.

sections of the stripline conductor caused more than a 5-dB increase of attenuation in the LF stopband as compared to the HF stopband. Sufficiently good agreement between the theoretical and experimental results demonstrates the propriety of the models used and the calculation techniques.

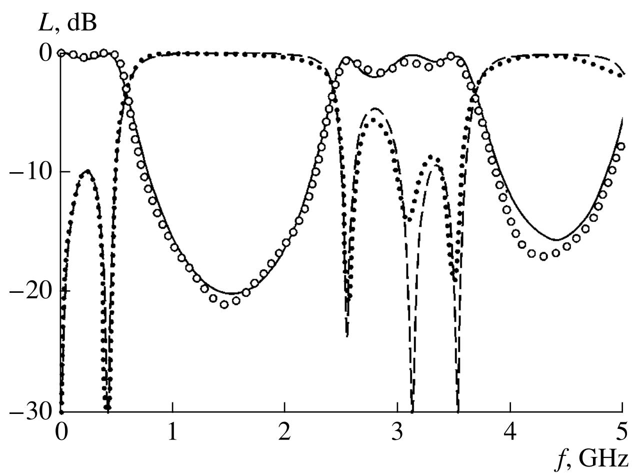

Fig. 6. Amplitude–frequency responses of insertion and return losses in a microstrip model of a three-layer photonic crystal with gradual variation of permittivity in interface regions between layers. Solid line and dots correspond to theoretical and experimental results, respectively.

CONCLUSIONS

In this study, we have investigated microstrip analogues of photonic crystals consisting of alternate layers with different values of permittivity. Good agreement between the results delivered by the quasi-static analysis of 1D models and experimental data has allowed obtainment of parameters of bandpass PC filters with prescribed characteristics. The simple manufacturing procedure and the low cost of microstrip structures allows preliminary experimental testing of devices in the chosen microwave band. Investigations have revealed that, even for a comparatively small number of layers in a photonic crystal, this structure can serve as a good bandpass filter. The design of such a filter involves the following steps:

(i) Formation of a required stepwise junction between the characteristic impedances of outer layers of the superlattice and the characteristic impedances of the input and output lines. The step value is determined by the specified bandwidth of the device.

(ii) Formation of a balance between couplings of the PC layers by choosing values of the layer permittivities. Values of these couplings should also correspond to the specified bandwidth.

(iii) Establishing the coincidence of the eigenfrequencies of all layers, operating as resonators, with the center frequency of the filter passband.

The influence of interface regions on frequency-selective properties of microstrip analogues of PC filters with gradual variation of permittivity in the interface regions between layers has been studied as well. It has been shown that the character of the interface region has no influence on selective properties of the device if the length of the interface region is less than 1/4 of the PC period. Evidently, this approach can be used for simulation of not only PC filters but also optical mirrors.

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