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PHYSICS

A Bandpass Filter—Polarizer Based on a Dielectric Multilayer with Strip Conductor Gratings

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Abstract—A new design of a multilayer bandpass filter is proposed, in which each resonator consists of two identical dielectric layers with parallel strip conductor gratings on their outer surfaces and an orthogonal strip conductor grating between the layers. The filter designed on the basis of crossed gratings works simultaneously as a polarizer transparent in a specified frequency band if the electric field vector of a wave is parallel to the outer strip conductors but reflects waves with an orthogonal polarization. The data from a numerical electrodynamic analysis of a 3D model of the proposed device agree well with the results of the measurements performed on the fifth-order filter—polarizer prototype with a relative bandwidth of 14% and a central frequency of 13.4 GHz. The microwave power loss in the filter passband is ~1.2 dB under parallel polarization of the electromagnetic wave and more than 40 dB under orthogonal polarization.

Keywords: frequency response, return loss, bandpass filter, insertion loss

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It is well-known that the use of electromagnetic waves with a certain polarization in communication, radar, and radio navigation systems and specialized radio equipment not only enhances the noise immunity, but also significantly improves the performance of the equipment. In particular, the use of dual-polarized data transfer in the radio relay communication increases the channel capacity [1] by transmitting signals in one frequency band, but at two orthogonal polarizations of electromagnetic waves. In addition, the use of two alternating orthogonal polarizations in multichannel communication systems with close passbands can significantly reduce the mutual influence of adjacent channels, which is very important when bandpass filters do not ensure the required channel-to-channel isolation.

Modern polarizers are often designed using the so-called frequency selective surfaces (FSSs), which represent dielectric layers with various deposited resonant strip conductor structures. These surfaces make it possible to transform a linearly polarized electromagnetic wave into a wave with circular polarization [2], but in a relatively narrow frequency band, or transmit waves with a certain linear polarization with minimal loss, but effectively reflect waves with orthogonal polarization [3]. In [3–6], it was shown that the FSS-based polarizers work simultaneously as bandpass filters, which can operate in the decimeter, centimeter, millimeter, and submillimeter wavelength ranges. In the optical range, a one-dimensional photonic crystal based on layered dielectric heterostructures can serve as a polarizer [7], which is simultaneously a bandpass filter.

The main drawback of the FSS-based polarizers with strip conductor resonant structures is the relatively low unloaded Q factor of strip resonators, which leads to high power loss in the passband of the devices. More promising structures are dielectric multilayers, in which the dielectric layers represent high-Q half-wavelength resonators and the 1D or 2D strip conductor structures formed on their surfaces serve as mirrors with a specified reflectivity, as was demonstrated for the bandpass filters in [8, 9]. In these devices, the strip structure period was chosen to be much shorter than the wavelength so that their resonant frequencies were significantly higher than the filter passband and did not narrow the high-frequency stopband.

The structure with the 1D regular gratings of parallel strip conductors between the dielectric layers [8] works as a bandpass filter only for linearly polarized electromagnetic waves, i.e., when the electric field vector $\mathbf{E}_{||}$ of the wave is directed along strip conductors (parallel polarization). However, if the electric field

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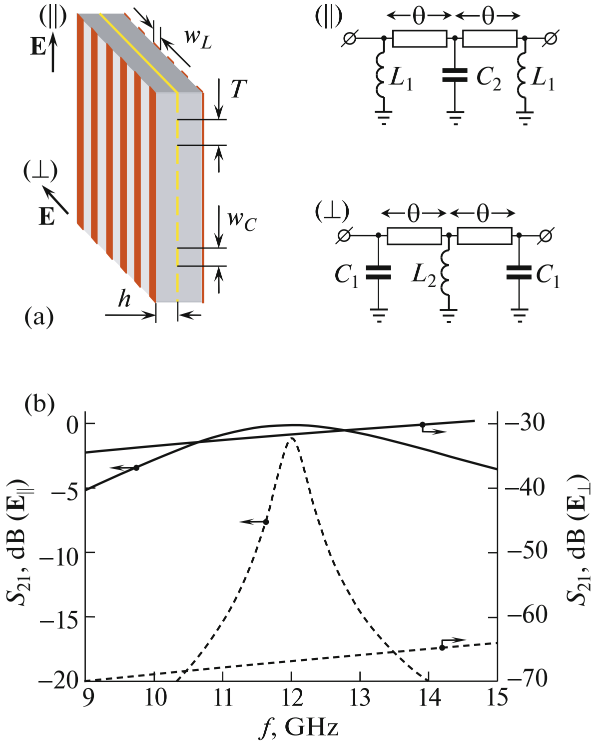

Fig. 1. (a) Design of the resonator consisting of two dielectric layers with crossed strip conductor gratings and its equivalent circuits for polarizations $\mathbf{E}_{||}$ and $\mathbf{E}_{\perp}$ of the incident electromagnetic wave. (b) Frequency dependences of the insertion loss in the resonator.

vector $\mathbf{E}_{\perp}$ is perpendicular to the direction of the strip conductor (orthogonal polarization), the multilayer structure loses the properties of a filter and becomes almost transparent in a wide frequency range, including the stopbands. Obviously, at the stopband frequencies, the filter [8] can serve as a polarizer, which effectively reflects waves with parallel polarization and transmits waves with orthogonal polarization. A drawback of such a polarizer is the high nonuniformity of the frequency response for the orthogonally polarized waves. In this study, we investigate original multilayer filter–polarizers with the resonators consisting of two layers instead of one [10].

FILTER–POLARIZER DESIGN

A filter–polarizer is based on resonators consisting of two identical dielectric layers with parallel strip conductor gratings on the outer surfaces and a strip conductor grating orthogonal to them between the layers (Fig. 1a). The period T is the same for all the gratings; it is much shorter than the wavelength at the eigenfrequency of the first mode of the resonator oscillations (subwavelength grating). Figure 1a (on the right) shows equivalent circuits of the resonator for the parallel ($\mathbf{E}_{||}$) and orthogonal ($\mathbf{E}_{\perp}$) polarizations of the wave falling from free space. The electric length θ is determined by thickness h of the layers and their permittivity ε. Under parallel polarization of the wave, strip conductors on the outer layers are inductances L_1, which depend on the strip width, while strip conductors on the inner layers form capacitance C_2, which depends on the gaps between conductors. On the contrary, under orthogonal polarization, the outer conductor gratings form capacitances C_1, while the inner ones, inductances L_2.

It is worth noting that the structure under study exhibits resonant properties only for the longitudinally polarized waves, if the gaps between conductors of the outer gratings are not too small. In this case, the coupling of the resonator with the environment and, consequently, its loaded Q factor are governed by the width of strip conductors of the outer (inductive) gratings. With respect to the electromagnetic waves, such subwavelength gratings play the role of mirrors with adjustable reflectivity: the narrower the strip conductors, the weaker the reflectivity, the stronger the coupling with the environment and the lower the Q factor of the resonator. Obviously, with a decrease or an increase in the width of these conductors, the resonant frequency of the structure will decrease or increase, respectively. In addition, the resonant frequency of the structure investigated can be substantially lowered or heightened by decreasing or increasing the gaps between conductors of the inner (capacitive) gratings.

Figure 1b shows the frequency responses of two resonators formed on RO4003C dielectric substrates (Rogers Corporation) with a thickness of $h = 0.508$ mm and a permittivity of $\varepsilon = 3.38$, which were glued with an RO4450B prepreg (Rogers Corporation) with a thickness of 0.127 mm and $\varepsilon = 3.54$. The resonators had different strip conductor widths in the outer (w_L) and inner (w_C) gratings (Fig. 1a); the gratings had the same period of $T = 4.8$ mm. The frequency responses of the resonators for the two linear polarizations of the incident waves were determined by the numerical electrodynamic analysis of their 3D models using the CST Microwave Studio software package. In the first resonator, the characteristics of which are shown by the solid line in Fig. 1b, the conductor width is $w_L = 0.2$ mm; in the second resonator, the characteristics of which are shown by the dashed line, it is $w_L = 2.0$ mm. For correct comparison, both resonators were tuned to the same central frequency $f_0 = 12$ GHz by changing the conductor width w_C of the inner gratings. In this case, we had $w_C = 3.51$ mm for the first resonator and $w_C = 4.52$ mm for the second one. It can be seen that the two-layer resonator has pronounced polarization properties and polarization isolation, i.e., the difference in the microwave power transmission for two polarizations at the resonant frequency is about 30 dB in the first resonator with $Q = 2.5$ and more than 50 dB in the second resonator with $Q = 29$. It should be noted that the high polarization isolation of the resonators is caused by a strong return of the microwave power from the investigated structure under orthogonal polarization of the incident waves. The main drawback of the polarizer based on the resonator investigated is the narrow working frequency band.

The working frequency band can be broadened significantly with simultaneous enhancement of the isolation for the two polarizations of transmitted electromagnetic waves by using multiresonator structures. Figure 2 shows the designs of filter–polarizers consisting of three (Fig. 2a) and five (Fig. 2b) interacting resonators. In addition, Fig. 2 presents the frequency responses of these devices, which have the same relative bandwidth $\Delta f/f_0 = 14\%$ at a level of –3 dB of the minimum loss level and the same central frequency $f_0 = 40$ GHz of the passband. Since the input and output of the filter–polarizers are surrounded by free space, the structures are symmetric relative to the central plane. The multilayers consist of Rogers Corporation RO3035C dielectric plates with a thickness of h = 0.25 mm and a permittivity of $\varepsilon = 3.5$ metallized with a 9-μm-thick copper layer. The layers were glued with each other with a RO4450B prepreg with a thickness of 0.127 mm and a permittivity of $\varepsilon = 3.54$. In both structures, the strip conductor period was $T = 2$ mm for all the gratings.

The passband of the devices operating as bandpass filters for the incident wave polarization $\mathbf{E}_{||}$ was tuned by manual parametric synthesis using numerical electrodynamic analysis of 3D models in the CST Microwave Studio software package. The filters were considered tuned when the maximum microwave power return levels in the $S_{11}(f)$ dependences were no higher than –20 dB, which ensured a high uniformity of insertion loss $S_{21}(f)$ in the passband. The optimal tuning of the coupling between the resonators and between the edge resonators and the free space was obtained, as in [8], by selecting the strip conductor width w_{Li} (i = 1–3) in the inductive gratings. However, the resonant frequencies of the resonators were adjusted by selecting the strip conductor width w_{Ci} in the capacitive gratings, in contrast to [8, 9], where the dielectric layer thickness was selected. The strip conductor widths in all the gratings of the optimally tuned filters are given in Table 1.

The comparison of the frequency responses of the (*1*) three- and (*2*) five-resonator filter–polarizers shows (Fig. 2c) that polarization isolation at the passband frequencies is more than 60 dB for the former and more than 100 dB for the latter. However, the minimum microwave power loss in the passband was 0.48 dB for the first device and 0.84 dB for the second one. As expected, the frequency selective properties of the filter–polarizer with a larger number of resonators are much higher.

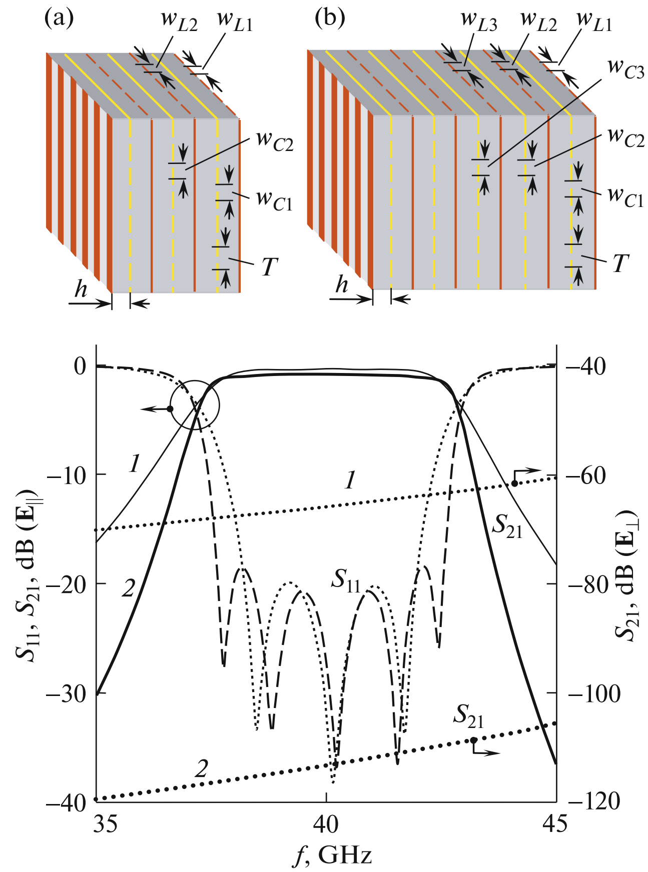

Fig. 2. Design of the (a) third- and (b) fifth-order filter–polarizers and their frequency responses (*1* and *2*, respectively). Solid lines correspond to the incident wave polarization $\mathbf{E}_{||}$, and dots, to the polarization $\mathbf{E}_{\perp}$.

STUDY OF THE EXPERIMENTAL FILTER–POLARIZER SAMPLE

To check the operability of the investigated multilayer filter–polarizer experimentally, we fabricated its prototype consisting of five two-layer resonators with an area of 300 × 300 mm^2. A ten-layer structure was made of RO4003C dielectric plates with a thickness of h = 0.508 mm, a permittivity of $\varepsilon = 3.38$, and a dissipation factor of $\tan\delta = 1.5 \times 10^{-3}$, which were metallized with a 16-μm copper layer. According to the multilayer printed circuit board technology, the dielectric plates were packed in a monolithic structure using a

Table 1. Strip conductor width in gratings of the fifth- and third-order filter–polarizers with a central passband frequency of 40 GHz

Number of resonators	w_{L1}, mm	w_{C1}, mm	w_{L2}, mm	w_{C2}, mm	w_{L3}, mm	w_{C3}, mm
3	0.20	1.25	0.93	1.42	–	–
5	0.16	0.90	0.93	1.23	1.42	1.42

Table 2. Conductor width in metal gratings of the fifth-order filter–polarizer with a relative bandwidth of $\Delta f/f_0$ = 14% and a central passband frequency of f_0 = 13.4 GHz

w_{L1}, mm	w_{C1}, mm	w_{L2}, mm	w_{C2}, mm	w_{L3}, mm	w_{C3}, mm
0.20	4.13	2.63	4.47	2.69	4.48

RO4450B prepreg with a thickness of 0.127 mm, a permittivity of $\varepsilon = 3.54$, and a dissipation factor of $\tan\delta = 4.0 \times 10^{-3}$. Before that, the device was also synthesized by manual parametric synthesis using the numerical electrodynamic analysis of its 3D model in the CST microwave Studio software package. For definiteness, the periods of the inductive and capacitive strip conductor gratings for all resonators were set equal to T = 4.8 mm and the width of conductors of the inductive gratings of the outer resonators was fixed at w_{L1} = 0.2 mm (Fig. 2b). Under these conditions, the synthesis yielded the following characteristics of the device: a relative bandwidth of $\Delta f/f_0$ = 14%, a central passband frequency of f_0 = 13.4 GHz, a minimum microwave power loss of 1.2 dB in the passband, and a polarization isolation of more than 200 dB. The dimensions of the strip conductors of the synthesized filter–polarizer are given in Table 2.

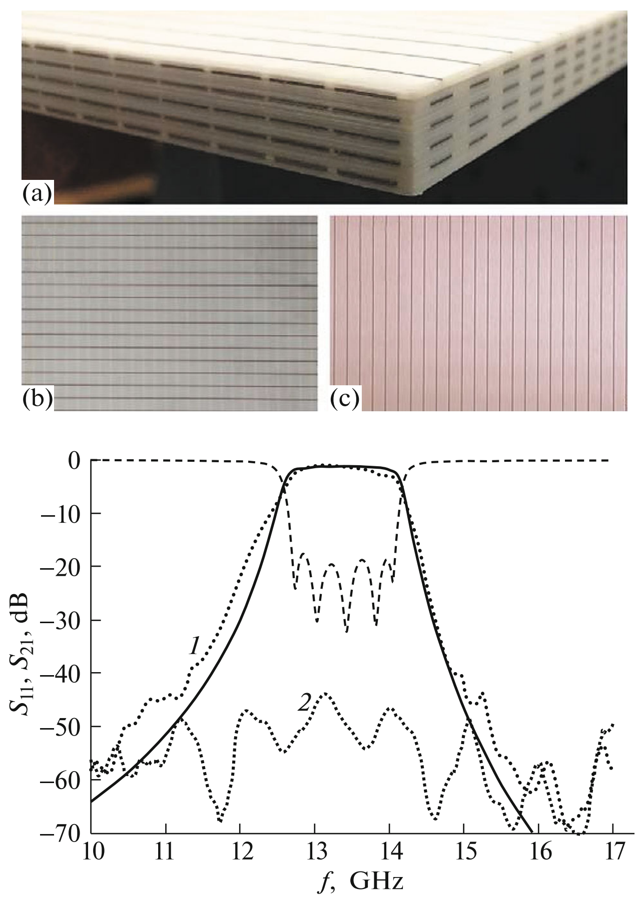

Fig. 3. The calculated frequency responses of the fifth-order filter–polarizer for the incident wave with polarization $\mathbf{E}_{\parallel}$; the solid line corresponds to the insertion loss, and the dashed line refers to the return loss. Dots show the measured characteristics of the insertion loss of the prototype: (*1*) $\mathbf{E}_{\parallel}$ and (*2*) $\mathbf{E}_{\perp}$. On the top: photographs of (a) the device and fragments of its (b) outer and (c) inner strip conductor gratings.

Figure 3 shows a photograph of the fabricated monolithic device (Fig. 3a) and photographs of fragments of the outer (inductive, Fig. 3b) and central (capacitive, Fig. 3c) strip conductor gratings taken before pressing the layers. The solid line under the photographs shows the frequency dependence of insertion loss S_{21}, and the dashed line shows the frequency dependence of return loss S_{11} determined by the electrodynamic analysis of the 3D model of the filter–polarizer. The measurements of the insertion loss $S_{21}(f)$ obtained on the fabricated filter–polarizer sample for the (*1*) parallel and (*2*) orthogonal polarizations with an R&S ZVA 40 vector network analyzer are shown by dots in Fig. 3. The measured relative bandwidth $\Delta f/f_0$ = 14% of the prototype and its central frequency f_0 = 13.4 GHz agree well with the values calculated for the 3D model. However, although the measured polarization isolation exceeds 40 dB, it is much smaller than the calculated value, which is obviously due to the small area of the experimental filter–polarizer sample. Indeed, in the experiment, the distance between measuring antennas and the experimental sample cannot be very small to prevent the destruction of the planar electromagnetic wave. However, even at relatively small distances between the antennas and the sample, a partial transfer of the microwave power from the transmitting antenna to the receiving one is observed due to diffraction of waves at the edges of the multilayer. Certainly, this effect is especially pronounced under orthogonal polarization of the incident electromagnetic waves, when they are strongly reflected from the filter–polarizer.

CONCLUSIONS

Thus, a new original design of a multilayer bandpass filter, which is simultaneously a polarizer of electromagnetic waves, was proposed. The filter is transparent in the passband for waves of one linear polarization, but effectively reflects waves with the orthogonal polarization. To obtain this effect, each resonator in the device is made of two dielectric layers with parallel strip conductor gratings on the outer surfaces of the bilayer and the orthogonal strip conductor grating between the layers. All the gratings are subwavelength; i.e., their period is much shorter than the wavelength at the frequency of the first resonator oscillation mode. The gratings on the outer surfaces of the resonator are mirrors with the reflectivity controlled by the strip conductor width. This makes it possible to tune the optimal couplings between the resonators in the multiple filter and between the edge resonators with free space when forming a specified passband. At a certain linear polarization of the incident electromagnetic waves, in the device operating as a bandpass filter, the conductor gratings between the layers of each resonator play the role of lumped capacities, but they also work as inductances for the orthogonal polarization, thereby ensuring strong reflection of the waves at the input. It is important that, in changing the gaps between conductors in these intraresonator gratings, one can change the resonator frequencies in a wide range, which is necessary for tuning the characteristics of a specified filter passband. The possibility of changing the resonator frequency not only allows one to use identical dielectric layers in the filter–polarizers, which is a certain advantage of the design, but also to change the central frequency of the device passband in a wide range.

The high electrical characteristics of the filter–polarizer and good agreement between the results of the electrodynamic analysis of its 3D model and the measurements on the experimental sample make the proposed design promising for application in radio engineering systems, in particular, in microwave relay systems under dual-polarized data transfer, which increases the channel capacity.

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