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A Microwave Bandpass Filter on Dielectric Layers with Metal Grids

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Abstract—A bandpass filter of new design comprising dielectric layers with surface metal grids is developed and studied. Dielectric layers act as half-wave resonators, while metal grids act as mirrors with preset reflectivity and ensure optimum coupling between adjacent resonators and between the boundary resonators and free space. A test prototype of the third-order filter with a central bandpass frequency of ~12 GHz and relative bandwidth ~17% showed good agreement of theory and experiment. The proposed design can be used in making panels radio-transparent within a preset bandwidth for covering microwave antennas.

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In recent years, much research interest has been devoted to studying peculiarities in the propagation of electromagnetic waves incident on layered structures of dielectric plates with interfaces comprising special periodic systems of strip conductors in the form of two-dimensional (2D) gratings or grids. The interest in these structures is related to the possibility of creating frequency-selective surfaces performing the function of bandpass filters in a frequency range from submicron to decimeter wavelengths [1–4]. Elementary strip-conductor cells forming a periodic 2D network (e.g., metallic squares or metal mesh) act as resonators [5]. Using multilayer systems of these structures, it is possible to create various bandpass filters [5, 6]. It is important to note that the wavelength corresponding to the central frequency of these bandpass filters (frequently called "frequency-selective surfaces" [7]) is much greater than the cell size and even much greater than the thickness of dielectric layers.

As is known, the resistance of a conductor at high frequencies grows due to decreasing thickness of a skin layer, which leads (with allowance for substrate roughness) to a decrease in the unloaded Q factor of stripline resonators. For this reason, the main disadvantage of multilayer filters employing resonant structures based on strip conductors is rather large power loss in the passband. A more promising filter design is now believed to be that in which dielectric layers themselves are high-Q resonators, while 1D or 2D structures of strip conductors formed on their surfaces act as mirrors with preset reflectivity [8, 9]. The period of strip structures is selected much shorter than the operating wavelength, so that the resonant frequencies would be possibly above the filter passband. Previously [8, 10], we have obtained formulas for the synthesis of filters with this design possessing preset passband widths and rated return loss in this bandwidth, which allowed determining optimum dimensions of strip conductors on the surface of each dielectric layer.

In the present work, we have studied a third-order bandpass filter based on dielectric resonator layers with metal surface grids and compared the calculated frequency response to those measured for a test prototype of this filter.

Figure 1 shows a schematic diagram of the proposed filter design comprising two identical parallel dielectric plates with relative dielectric constant ε_1 and thickness h_1 separated by a dielectric spacer (e.g., air) with thickness h_2 and dielectric constant ε_2. Dielectric plates bear surface square grids of metal strip conductors with identical periods T. The strip conductor width in the external surface grid is w_1, and that in the internal surface grid is w_2. Evidently, every dielectric plate and the air gap between them in this system are interacting half-wave resonators, which determine the passband of this device.

In tuning the filter, it is necessary to take into account that the central frequency of its passband is determined by the thickness of dielectric layers, while

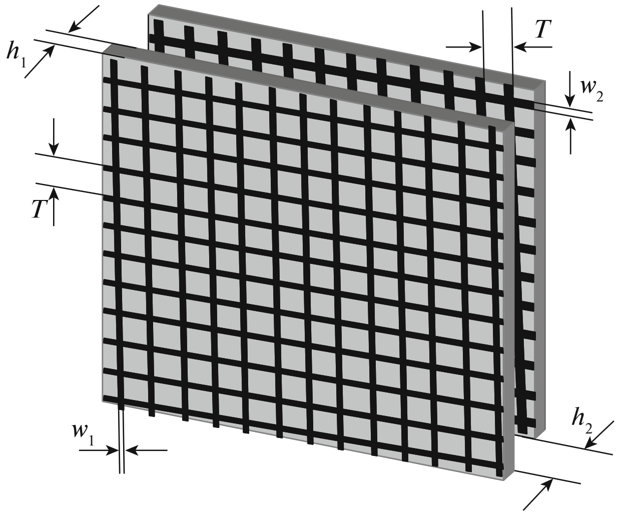

Fig. 1. Design of the proposed third-order bandpass filter based on dielectric resonant layers with surface metal grids.

the passband width and preset maximum level of return loss in the passband is controlled by selecting the widths of strip conductors in the internal and external grids. With increasing w_2 and w_1 values, the coupling between adjacent resonators and that between the boundary resonators and free space decreases, which leads to narrowing of the passband width (and vice versa). Note that metal grids decrease the resonant frequencies of resonators, the more so the greater the coupling between them.

The frequency response of the proposed filter for normally incident electromagnetic waves is most simply calculated by the matrix method in a quasi-static approximation. For the entire filter, the *ABCD* matrix (classical transmission matrix) can be calculated as the product of *ABCD* matrices of all components of the structure [11], i.e., each layer and grid. For certainty, we assume that time dependences of the electromagnetic field components is described by $\exp(-i\omega t)$ factor. In this case, the normalized *ABCD* matrix of each dielectric layer is calculated by the following formula [11]:

$$\begin{pmatrix} A_{1,2}^d & B_{1,2}^d \\ C_{1,2}^d & D_{1,2}^d \end{pmatrix} = \begin{pmatrix} \cos\theta_{1,2} & -i\dfrac{\sin\theta_{1,2}}{n_{1,2}} \\ -in_{1,2}\sin\theta_{1,2} & \cos\theta_{1,2} \end{pmatrix},$$

where $n_{1,2} = \sqrt{\varepsilon_{1,2}}$ are the refractive indices of layers, $\theta_{1,2} = \dfrac{\omega}{c} n_{1,2} h_{1,2}$ are the phase thicknesses of layers, and superscript d indicates that the *ABCD* matrix refers to the dielectric layer.

The scattering matrix of an infinitely thin perfectly conducting metal mesh at the interface of media with refractive indices n_1 and n_2 is described in a quasi-static approximation by the following expressions [12]:

$$\begin{pmatrix} S_{11}^m & S_{12}^m \\ S_{21}^m & S_{22}^m \end{pmatrix} = \begin{pmatrix} \dfrac{n_1 - n_2 - iZ_0Y_{1,2}}{n_1 + n_2 + iZ_0Y_{1,2}} & \dfrac{2\sqrt{n_2 n_1}}{n_2 + n_1 + iZ_0Y_{1,2}} \\ \dfrac{2\sqrt{n_2 n_1}}{n_2 + n_1 + iZ_0Y_{1,2}} & \dfrac{n_2 - n_1 - iZ_0Y_{1,2}}{n_2 + n_1 + iZ_0Y_{1,2}} \end{pmatrix},$$

$$Y_{1,2} = \frac{2\pi}{\omega\mu_0(T - w_{1,2})\ln\left(\operatorname{cosec}\left(\dfrac{\pi w_{1,2}}{2T}\right)\right)} - \omega\varepsilon_0 T\frac{n_1^2 + n_2^2}{\pi}\ln\left(\sec\left(\frac{\pi w_{1,2}}{2T}\right)\right),$$

where superscript m indicates that the matrix refers to the metal mesh and Z_0, μ_0, ε_0 are the characteristic impedance, absolute magnetic permeability, and absolute dielectric permittivity, respectively, of the free space. Then, the normalized *ABCD* matrix elements of the metal mesh are eventually calculated by the following formulas [11]:

$$A^m = (1 + S_{11}^m - S_{22}^m - \det[S_{ik}^m])n_2/(2S_{21}^m n_1),$$

$$B^m = (1 + S_{11}^m + S_{22}^m + \det[S_{ik}^m])/(2S_{21}^m n_1 n_2),$$

$$C^m = (1 - S_{11}^m - S_{22}^m + \det[S_{ik}^m])n_1 n_2/(2S_{21}),$$

$$D^m = (1 - S_{11}^m + S_{22}^m - \det[S_{ik}^m])n_1/(2S_{21}^m n_2).$$

By multiplying *ABCD* matrices of each component of the structure, it is possible to calculate matrix elements A, B, C, and D of the transmission matrix for the entire filter structure.

The selective properties of any filter are characterized by the frequency dependences of matrix elements of its scattering matrix **S**. The reflection coefficients are represented by matrix elements S_{11} and S_{22}, while the transmission coefficients are represented by S_{21} and S_{12}. Since the structure under consideration is a symmetric reciprocal two-port network [11], it obeys the relations $|S_{11}| = |S_{22}|$ and $S_{21} = S_{12}$. Once the *ABCD* matrix elements of the filter are calculated, the reflection and transmission coefficients are given by the following formulas [11]:

$$S_{11} = \frac{A + B - C - D}{A + B + C + D}, \qquad S_{21} = \frac{2}{A + B + C + D},$$

where the filter is assumed to be surrounded by medium with refractive index $n = 1$.

Based on the above formulas, a computer program for analysis of the proposed third-order filter design (Fig. 1) was written and used for a parametric synthesis of the filter structure. In this filter, the dielectric layers with metal grids on their surfaces were assumed to be Rogers TMM3 metallized plates with substrate thickness h_1 = 5.08 mm, relative dielectric constant ε_1 = 3.41, and copper-layer thickness 17.5 μm. The

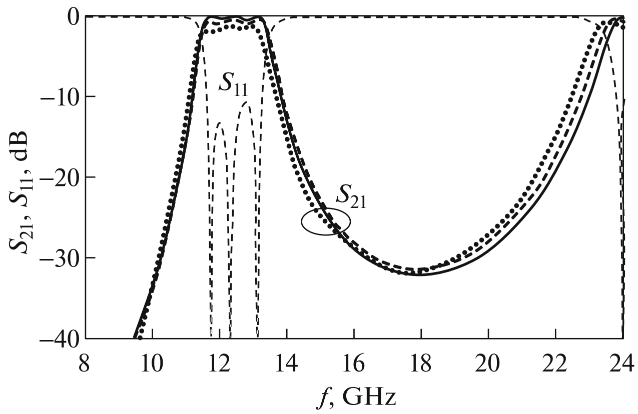

Fig. 2. The frequency response of the third-order bandpass filter based on dielectric resonant layers with surface metal grids: (solid line) quasi-static calculation; (dashed line) electrodynamic simulation of 3D model; (dotted line) experiment.

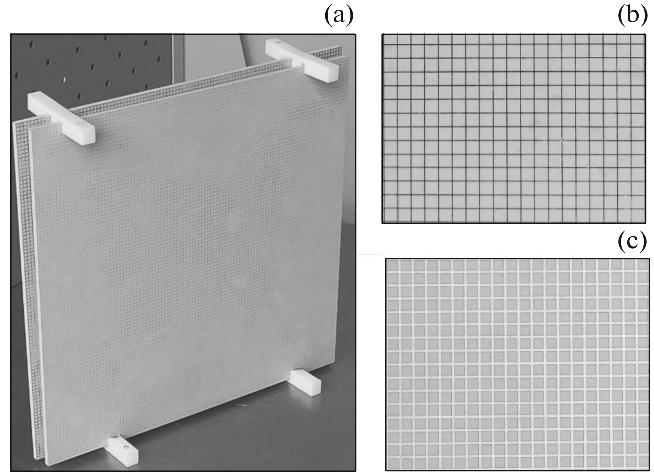

Fig. 3. (a) General view of a test prototype of the third-order bandpass filter based on dielectric resonant layers with surface metal grids and (b, c) fragments (magnified) of the external and internal meshes, respectively.

half-wave resonant frequency ($\lambda_1/2 = h_1$) in the dielectric layer is $f_1 \approx 15.96$ GHz. However, the presence of metal grids in the filter reduces its passband central frequency f_0 below the f_1 value.

With allowance for the condition that the grid period must be smaller than $\lambda_1/2$ [12], let us select $T = 3$ mm for the proposed filter and, for certainty, assume that the maximum reflection in the passband does not exceed −14 dB. Evidently, optimum levels of coupling between adjacent resonators and between the boundary resonators and free space correspond to definite w_1 and w_2 values. For the sake of simplicity, let us fix the width of strip conductors in external grids at $w_1 = 0.1$ mm.

Taking into account all the conditions mentioned above, the parametric synthesis of the proposed filter reduces to selecting only two structural parameters: strip conductor width w_2 in the inner metal grids and airgap width h_2 between dielectric plates. According to the results of computer-aided synthesis, these parameters take the following values: $w_2 = 0.58$ mm and $h_2 = 11.15$ mm. Figure 2 (solid line) shows the calculated frequency response of insertion loss $S_{21}(f)$ of the synthesized filter. The passband central frequency is $f_0 = 12.44$ GHz and the fractional passband width at a level of −3 dB from the minimum loss level is $\Delta f/f_0 = 16.7\%$.

To check the accuracy of obtained approximate formulas, the frequency responses of a 3D model of the filter were calculated using the CST Microwave Studio electrodynamic program package (Fig. 2, dashed line). Allowance for the ohmic loss in grid strip conductors increased the minimum loss in the passband from 0 to 0.32 dB, but the shapes of the $S_{21}(f)$ and $S_{11}(f)$ curves remained almost unchanged. The passband central frequency is $f_0 = 12.41$ GHz, and the fractional passband width at a level of −3 dB from the minimum loss level is $\Delta f/f_0 = 16.8\%$.

The experimental verification of calculations was carried out using a test prototype filter made of Rogers TMM3 metallized dielectric plates with substrate thickness $h_1 = 5.08$ mm and lateral dimensions of 300 × 300 mm. Figure 3a presents a photograph of the layered-filter prototype, while Figs. 3b and 3c show fragments (magnified) of the external and internal meshes, respectively. After manufacturing, the copper grids were covered with silver for protecting them against oxidation. In the filter assembly, the plates were fixed parallel at a distance of $h_2 = 11.15$ mm by two pairs of small Teflon holders. The frequency response of the test prototype filter (Fig. 2, dotted line) was measured using Rohde & Schwarz ZVK Vector Network Analyzer equipped with broadband antennas. The measurements yielded fractional passband width $\Delta f/f_0 = 16.5\%$ at a level of −3 dB from the minimum loss level, passband central frequency $f_0 = 12.29$ GHz, and minimum loss of 1.15 dB in the passband.

In concluding, the proposed filter design comprising dielectric layers separated by metal grids can serve as a bandpass filter. It should be noted that the structural layers can be made same or different materials. Evidently, panels manufactured using these layered structures can be used in designing radio-transparent shells for protecting parabolic antennas and antenna arrays [13].

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