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Multilayer bandpass filter with extended lower and upper stop bands

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We propose a novel design for a multilayer bandpass filter in which every resonant dielectric layer is separated from adjacent dielectric layers or from the ambient by a nonresonant grating of strip conductors on the layer interface. Here, every grating acts as a mirror with specified transparency. Relative to the conventional multilayer bandpass filter with multilayer dielectric mirrors, the proposed filter has multiply extended stop bands below and above the passband. Additionally, we provide formulas for computing the filter's frequency response. A comparison between the computed frequency responses for the proposed and conventional filters with the same passband is presented.

OCIS codes: (230.7408) Wavelength filtering devices; (310.4165) Multilayer design; (230.4555) Coupled resonators; (050.2770) Gratings.

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Optical bandpass filters are usually composed of a stack of dielectric layers in which the refractive index alternates between high and low values [1,2]. Some of the dielectric layers in the filter are resonators. The phase thickness of each of these layers at the center frequency f_0 is equal to or is a multiple of π. All other dielectric layers in the filter are arranged into groups that function as multilayer mirrors. These mirrors ensure proper coupling between neighboring resonators or between the input/output resonator and free space. The phase thickness of each dielectric layer in the mirror is usually equal to $\pi/2$. The number of resonators defines the order of the filter, which sets the number of reflection zeros in the frequency response within the passband. The number of layers in the mirrors between the resonators of internal resonator pairs is, as a rule, greater than that between the resonators of external resonator pairs, and it increases as the passband width of the filter is narrowed.

The resonances of the whole dielectric structure, including mirrors and resonators, generate spurious transmission peaks below and above the passband [3]. These spurious peaks in the frequency response make the stop bands very narrow. This effect considerably degrades the frequency selectivity of a filter with multilayer dielectric mirrors.

In this Letter, we propose a novel design for a multilayer bandpass filter that has extended stop bands below and above the passband. We provide formulas for computing the frequency response of this filter.

Figure 1 shows the cross section of the proposed filter, which is composed of some resonant dielectric layers and nonresonant gratings formed from strip conductors on the interfaces between the dielectric layers. The phase thickness of every dielectric layer is approximately equal to π. All strip conductors in the filter are parallel to each other. The electric fields of the incident ($\mathbf{E}_{\rm in}$), reflected ($\mathbf{E}_{\rm ref}$), and transmitted ($\mathbf{E}_{\rm tr}$) waves are assumed to be directed along the strip conductors. We shall characterize every grating in terms of a period, T, and the spacing between strip conductors, s. Their optimal values are defined in the first place by the passband width of the filter, but they may differ for the gratings situated on the external and internal resonators, which are labeled in Fig. 1 with the ordinal numbers 0, 1, and 2.

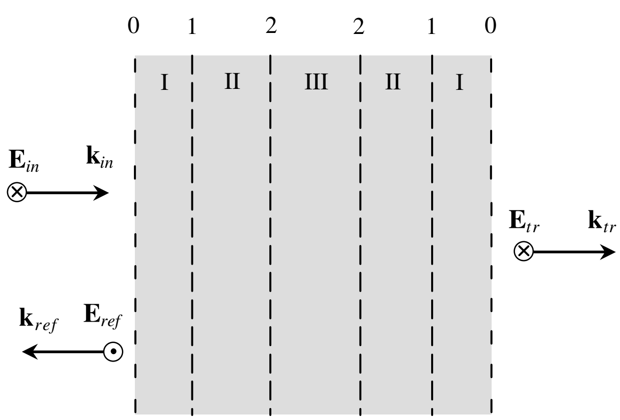

Fig. 1. Cross section of the proposed multilayer filter. (Here, arrows indicate the wave vectors of incident, reflected, and transmitted waves, and Arabic and Roman numerals number the gratings and layers, respectively; the strip conductors and electric fields of the waves are orthogonal to the cross section.)

It is important that the inequality $T < 0.4\lambda_n$ be satisfied where λ_n is the wavelength in the dielectric layer at f_0. This constraint enables (1) the suppression in the dielectric layers of the propagation of higher modes generated by the gratings and (2) the shifting of the resonances of the gratings up to a higher-frequency range. These conditions prevent the formation of spurious passbands in the frequency response of the filter. Additionally, the above inequality is the condition for the usability of the quasi-static approximation for the near-field region of the grating [4].

Each grating of strip conductors in the proposed filter acts like a mirror with a specified transparency. Its function is to ensure the proper degree of coupling of the single-layer dielectric resonator with its neighbor or the ambient. The resonator couplings in a tuned filter decay from the external pairs of resonators to the central pair(s) [5]. Such decaying of the resonator couplings may be attained by decreasing the ratio s/T or decreasing the period T of the gratings [6]. One should bear in mind that the presence of the gratings on the boundaries of the resonators lowers their resonant frequencies. That is why the thickness of each resonator in the filter should be less than $\lambda_n/2$.

Figure 2 shows the equivalent circuit of the proposed filter, which consists of cascaded transmission-line sections, which are equivalent to the dielectric layers, and shunt inductances at the junction points in the cascade of transmission lines, where these inductances are equivalent to the gratings formed by the strip conductors. This circuit is an adequate model of the filter. It enables the estimation of the main selective properties of the filter.

The frequency response of a filter is usually characterized by a scattering matrix $\mathbf{S}(f)$, which relates the normalized electric field amplitudes of outgoing waves (b_k) with the corresponding amplitudes of incoming waves (a_k) on both sides (that is, through port 1 and port 2) through Eq. (7):

$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \mathbf{S}\begin{pmatrix} a_1 \\ a_2 \end{pmatrix}. \tag{1}$$

Here, the amplitudes a_k and b_k are normalized such that the total power P_k that comes into port k per unit square is expressed by the following equation:

$$P_k = \frac{1}{2}|a_k|^2 - \frac{1}{2}|b_k|^2. \tag{2}$$

Then, $|S_{11}|^2$ and $|S_{22}|^2$ are the reflection coefficients, whereas $|S_{21}|^2$ and $|S_{12}|^2$ are the transmission coefficients.

The scattering matrix $\mathbf{S}$ of a multilayer structure may be easily computed if the transfer matrix $\mathbf{M}$ for each component of the structure is known. The matrix $\mathbf{M}$ is also called the characteristic matrix or the ABCD matrix [7]. Such a matrix relates the tangential electric and magnetic field strengths on the first and the second surfaces of a planar structure through the following equation:

$$\begin{pmatrix} E_1 \\ Z_0 H_1 \end{pmatrix} = \mathbf{M}\begin{pmatrix} E_2 \\ Z_0 H_2 \end{pmatrix}, \tag{3}$$

where the free-space characteristic impedance is $Z_0 = (\mu_0/\varepsilon_0)^{1/2}$.

The transfer matrix of an entire multilayer structure is equal to the product of the transfer matrices of each component of the structure [1].

The matrices $\mathbf{M}$ and $\mathbf{S}$ are related by the formulas [7]

$$\mathbf{M} = \begin{pmatrix} \frac{1+S_{11}-S_{22}-\det[S_{ik}]}{2S_{21}}\sqrt{\frac{n_2}{n_1}} & \frac{1+S_{11}+S_{22}+\det[S_{ik}]}{2S_{21}\sqrt{n_1 n_2}} \\ \frac{1-S_{11}-S_{22}+\det[S_{ik}]}{2S_{21}}\sqrt{n_1 n_2} & \frac{1-S_{11}+S_{22}-\det[S_{ik}]}{2S_{21}}\sqrt{\frac{n_1}{n_2}} \end{pmatrix}, \tag{4}$$

$$\mathbf{S} = \begin{pmatrix} 1 - 2\frac{M_{21}+M_{22}n_2}{d} & 2\frac{\sqrt{n_1 n_2}}{d}\det[M_{ik}] \\ 2\frac{\sqrt{n_1 n_2}}{d} & 1 - 2\frac{M_{11}n_1+M_{21}}{d} \end{pmatrix},$$
$$d \equiv M_{11}n_1 + M_{12}n_1 n_2 + M_{21} + M_{22}n_2, \tag{5}$$

where n_1 and n_2 are the refractive indices of the media that are adjacent to the planar structure to which the matrices refer.

The transfer matrix of the kth dielectric layer has the form [1]

$$\mathbf{M} = \begin{pmatrix} \cos\theta_k & \frac{-i}{n}\sin\theta_k \\ -in\sin\theta_k & \cos\theta_k \end{pmatrix}, \theta_k \equiv \frac{2\pi f}{c} n h_k, \tag{6}$$

where n is the refractive index of the dielectric layers, h_k is the thickness of the kth layer, and i is the imaginary unit as is found in the time-dependent factor $\exp(-i2\pi f t)$.

Using the formulas for the reflection and transmission coefficients that were derived in [6] with the use of the quasi-static approximation, we obtain the scattering matrix for the grating:

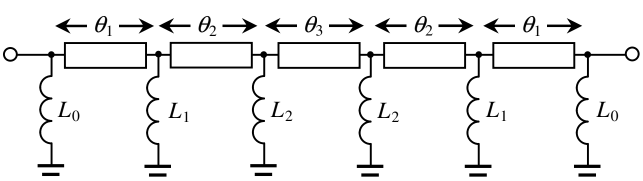

Fig. 2. Equivalent circuit of the proposed filter.

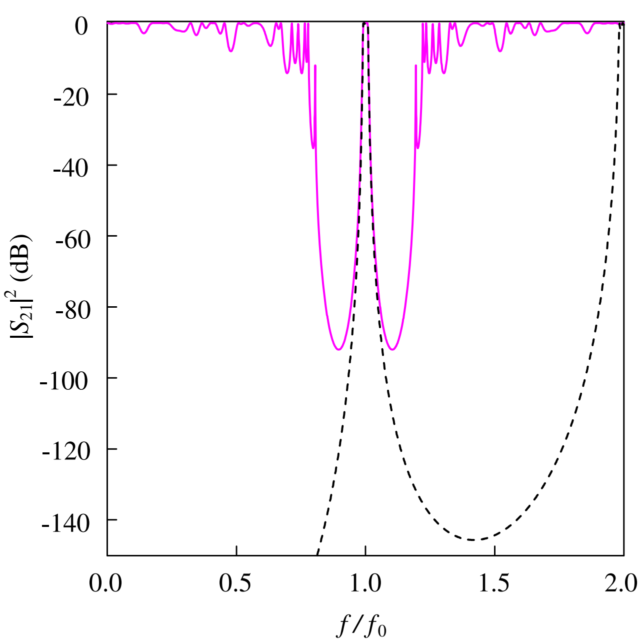

Fig. 3. Computed frequency responses of conventional (solid line) and proposed filter (dashed line) over a wide frequency range.

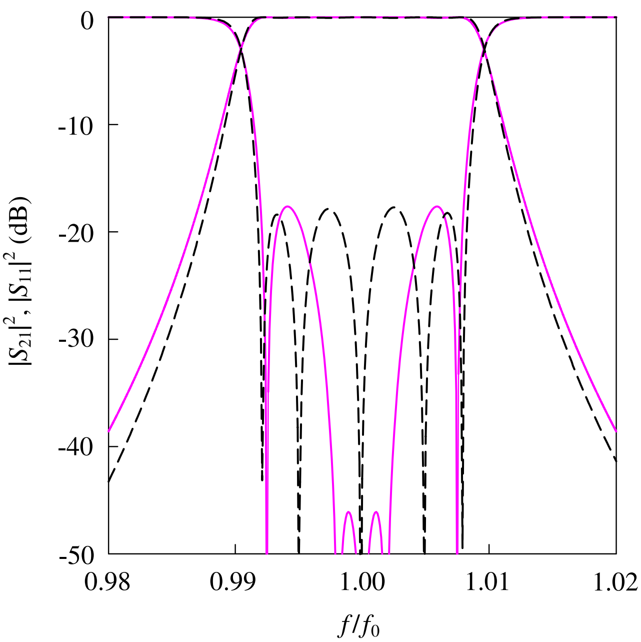

Fig. 4. Computed frequency responses of conventional (solid line) and proposed filter (dashed line) over a narrow frequency range.

$$\mathbf{S}(n_1, n_2, f, s, T) = \begin{pmatrix} \frac{n_1 - n_2 - i\Lambda}{n_1 + n_2 + i\Lambda} & \frac{2\sqrt{n_1 n_2}}{n_1 + n_2 + i\Lambda} \\ \frac{2\sqrt{n_1 n_2}}{n_1 + n_2 + i\Lambda} & \frac{-n_1 + n_2 - i\Lambda}{n_1 + n_2 + i\Lambda} \end{pmatrix},$$

$$\Lambda \equiv c/\left[fT \ \ln \ \sec\left(\frac{\pi s}{2 \ T}\right)\right]. \quad (7)$$

Thus, using Eqs. (4)–(7), we may compute the frequency response of the proposed filter.

Figure 3 shows the computed frequency responses of the conventional and proposed bandpass filters over a wide frequency range. As the conventional filter, we took the multilayer filter of the fifth order that is described in Fig. 8.25 of [1]. It has a total of 49 dielectric layers, of which the outer four layers on each side make up two external mirrors, and the remaining layers form five resonators (where these resonators are composed of five single layers) and four internal mirrors (each of which is formed from nine layers).

The proposed filter has the same order and the same fractional bandwidth (1.92%) at the center frequency $f_0 = 1$ THz. It has a symmetrical structure. Its components have the following parameters: $n = 1.871$, $T_0 = 40$ μm, $T_1 = T_2 = 30$ μm, $s_0 = 29.13$ μm, $s_1 = 10.43$ μm, $s_2 = 9.06$ μm, $h_1 = 74.12$ μm, $h_2 = 79.16$ μm, $h_3 = 79.30$ μm, and $\lambda_n = 160.2$ μm. The filter is a symmetrical and reciprocal two-port network. Thus, $S_{11} = S_{22}$ and $S_{21} = S_{12}$.

One can see in Fig. 3 that the lower stop band of the proposed filter extends down to DC, whereas the upper stop band extends up to almost $2f_0$.

Figure 4 shows the same computed frequency responses as in Fig. 3 but for a narrower frequency range. One can see that the proposed filter has a passband with steeper slopes than the conventional filter. This is accounted for the proposed filter, which has a Chebyshev frequency response for $S_{11}(f)$ within the passband because the proportion of all its couplings is optimally performed [5,8]. One can also see that the lower slope in the proposed filter is steeper than the upper slope, which is a distinctive feature of the proposed filter. This steepness results from taking into account the frequency dispersion of the matrices $\mathbf{S}(n_1, n_2, f, s, T)$ for each grating of the strip conductors.

Thus, we have proposed a new multilayer bandpass filter design that incorporates on both sides of every resonant dielectric layer a nonresonant grating formed from strip conductors. Our calculations show that this design results in wide and deep lower and upper stop bands relative to a conventional multilayer bandpass filter with multilayer dielectric mirrors. The simplicity of this design should make it an appealing option for applications that can benefit from optical filters with superior stop-band suppression.

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