ISSN 1028-3358, Doklady Physics, 2014, Vol. 59, No. 6, pp. 245–248. © Pleiades Publishing, Ltd., 2014.
Original Russian Text © B.A. Belyaev, V.V. Tyurnev, V.F. Shabanov, 2014, published in Doklady Akademii Nauk, 2014, Vol. 456, No. 4, pp. 413–416.

PHYSICS

An Optical Bandpass Filter Based on a Three-Component Multilayer Structure

B. A. Belyaev[a, b, c], V. V. Tyurnev[a, b], and Academician V. F. Shabanov[c]

Received December 16, 2013

DOI: 10.1134/S1028335814060019

Optical bandpass filters usually represent multilayer dielectric structures in which the layers with high (n_H) and low (n_L) refractive indices [1, 2] alternate. In the case when the optical thicknesses of layers are identical, the structure represents a one-dimensional photonic crystal [3] having periodic transparency windows—passbands with central frequencies multiple to the frequency of the half-wavelength resonance, which are separated by the stopbands—the photonic band gaps. The passband width in such structure is approximately proportional reciprocally to the contrast $\frac{n_H}{n_L}$ of refractive indices of dielectric layers; therefore, it is relatively wide for a photonic crystal because the highest possible contrast does not exceed four for real optical materials. It should be noted that, when fabricating an optical bandpass filter based on a photonic crystal, it is necessary to change the refractive indices of several external layers in its structure to decrease the passband ripple that may be too high [4, 5].

Filters with narrow passbands also have a multilayer dielectric structure with alternating layers n_H and n_L; however, a fraction of the layers has a thickness equal to the half-wavelength ($\frac{\lambda}{2}$) at the central passband frequency f_0, while the layers between them have a quarter-wavelength ($\frac{\lambda}{4}$) thickness. The half-wavelength layers are resonators; they form the filter passband, while the quarter-wavelength layers form multilayer dielectric mirrors establishing the necessary value and the proportion of couplings between resonators [6, 7] corresponding to the set passband width.

The reflectance of mirrors, which just determine the value of coupling of resonators with each other and that of the end resonators with the filter input and output, increases both with the contrast ($\frac{n_H}{n_L}$) of refractive indices of adjacent layers and with the number of layers. In the case when the mirror layers have a thickness multiple to the quarter wavelength, their reflectance is largest; in this case, they do not disturb the resonant frequencies of resonators, while the stopbands have an identical depth on both sides of the passband. In such a construction, the filter transmittance $S_{21}(f)$ and reflectance $S_{11}(f)$ are periodic functions of frequency f, the period of which is $2f_0$. Here $S_{ij}(f)$ are the elements of a filter scattering matrix.

The optical filters, the multilayer mirrors in which contain only the quarter-wavelength layers and are fabricated from two materials, have a substantial disadvantage consisting of the high optical passband ripple [1, 8]. It is related to the impossibility of a smooth fine tuning of the reflectance of such mirrors both between resonators and on the input and output of the filter. In [6, 7], to rule out the passband ripple, it is proposed to make one of the materials in each of the filter mirrors differ from the materials of other layers and to tune the filter by selecting its refractive index. However, it is technologically difficult in such a construction, which we call the filter prototype, to provide the required value of the refractive index for lack of that for real materials.

In this work, we present the construction of a new multilayer optical filter using only three real materials with unequal refractive indices. For equalizing the passband ripple through the three-component structure, contrary to the prototype, it is necessary only to choose the thickness of each layer. We propose the

[a] *Kirensky Institute of Physics, Siberian Branch, Russian Academy of Sciences, Krasnoyarsk, 660036 Russia*
[b] *Reshetnev Siberian State Space University, Krasnoyarsk, 660014 Russia*
[c] *Siberian Federal University, Krasnoyarsk, 660062 Russia*
e-mail: belyaev@iph.krasn.ru

method of constructing and synthesizing the optical filter with such a construction.

FILTER CONSTRUCTION

We compare the construction of the proposed filter with that of the above prototype representing a multicomponent multilayer structure [6, 7]. The prototype filter contains resonators in the form of half-wavelength dielectric layers with a low refractive index, each of which is separated from the next resonator or from free space on the input and output of the device by a multilayer dielectric mirror consisting of quarter-wavelength layers. The layers with a high refractive index n_H in all mirrors are fabricated from one material, and we used various low-refractive-index materials in other layers, each of which corresponds to the ith ($i = 1, 2, ..., m$) mirror of the construction. The mirrors between the central resonators contain the largest number of quarter-wavelength layers, but it decreases toward the edges of the layered structure.

The construction of the filter under consideration also consists of resonators in the form of half-wavelength dielectric layers with a low refractive index, but differs from the prototype as follows: in each multilayer mirror, each quarter-wavelength layer with the refractive index n_i is replaced by an equivalent symmetric three-layer structure with the refractive indices n_M–n_L–n_M. The values of n_L and n_M can be chosen arbitrary, but they must satisfy the inequalities

$$n_L < n_i < n_M < n_H, \quad i = 1, 2, ..., m. \qquad (1)$$

This situation means that all layers of multilayer dielectric mirrors of the filter are fabricated only from three materials with the refractive indices n_L, n_M, and n_H. In this case, a certain ratio between the thicknesses of two materials with the indices n_L and n_M replaces an arbitrary material with the low refractive index n_i in the mirrors of the prototype filter. It is obvious that it is easy at such an approach to select three real materials, the refractive indices of which satisfy inequalities (1).

The symmetric three-layer structure replacing the one quarter-wavelength layer is equivalent to it if its transfer matrix (in the literature, it is also called the characteristic matrix or *ABCD* matrix) coincides with the transfer matrix of this replaced layer. The severe equivalence of matrices can be provided only at one frequency; it is obvious that it is necessary to choose f_0 as this frequency. Because the compared structures are symmetric and reciprocal from the viewpoint of electric circuits, it suffices to compare only one of two diagonal and one of two nondiagonal matrix elements [9].

As a result, the requirement of coincidence of diagonal elements in the matrices under comparison results in the equation

$$\frac{2n_M n_L}{n_M^2 + n_L^2} = \tan 2\theta_{Mi} \tan \theta_{Li}, \qquad (2)$$

where θ_{Mi} and θ_{Li} are the electric thicknesses of layers with the refractive indices n_M and n_L in the ith multilayer mirror. This equation is the condition that the effective thickness of the equivalent three-layer structure corresponds to the quarter wavelength. The requirement of coincidence of nondiagonal elements results in the equation

$$n_M[\sin 2\theta_{Mi}\cos\theta_{Li} + (n_L n_M^{-1}\cos^2\theta_{Mi} - n_L^{-1} n_M \sin^2\theta_{Mi})\sin\theta_{Li}] = n_i. \qquad (3)$$

The left-hand side of this equation is an effective refractive index of the three-layer structure replacing the quarter-wavelength layer with the refractive index n_i in the ith mirror of the prototype.

The solution of the set of Eqs. (2) and (3) is

$$\theta_{Mi} = \arctan\sqrt{\frac{\sqrt{(n_M^2+n_L^2)^2(n_M^2-n_i^2)^2 + 4n_M^2(n_M^4 - n_L^2 n_i^2)(n_i^2 - n_L^2)} - (n_M^2+n_L^2)(n_M^2-n_i^2)}{2(n_M^4 - n_L^2 n_i^2)}}, \qquad (4)$$

$$\theta_{Li} = \arctan\left(\frac{n_L^2 + n_M^2}{2n_L n_M}\tan(2\theta_{Mi})\right). \qquad (5)$$

From Eq. (4), it can be seen that inequalities (1) are sufficient conditions of the existence of the solution of the set of Eqs. (2) and (3).

It is important to note that the replacement of all quarter-wavelength layers with low refractive indices n_i in the prototype for the equivalent symmetric three-layer structures with the refractive indices n_M–n_L–n_M results in changing frequency response (FR) of the construction only far from the central frequency of the filter passband.

EXAMPLE OF FILTER DESIGNING

We consider the principles of designing the device by the example of the synthesis of the bandpass filter of the fifth order, the layers with the highest refractive index in which are fabricated from silicon ($n_H = 4$), the layers with the lowest refractive index are aerial ($n_L = 1$), and all five half-wavelength resonators (Fig. 1) are also aerial. For the layers with an intermediate refractive index, it is convenient in this case to use silicon oxide (SiO_2) as is shown below. Therefore, such a ridge construction of the filter consisting in this case of five air resonators and six multilayer mirrors can be made of a monolithic silicon (Si) wafer with using, for example, the technologies of dry ion etching with the subsequent compulsory oxidation of surfaces of separate edges or the technologies of wet anisotropic etching of grooves in silicon and the subsequent thermal oxidation of the surfaces [10].

For definiteness, we set the central filter-passband frequency of the $f_0 \approx 3$ THz corresponding to the wavelength $\lambda = 100$ μm, the fractional passband width $\frac{\Delta f}{f_0} = 0.5\%$ at the level of –3 dB, and also the highest reflection level $S_{11\max} = -15$ dB in the passband. We begin the synthesis of the filter from synthesizing its prototype. This process consists of selecting an optimum number of quarter-wavelength layers and finding the optimum values of refractive indices n_i for each mirror in the prototype corresponding to desired passband parameters. The optimization is carried out by the method of consecutive corrections of parameters of the construction using the general rules of optimization of filters described in [6]. The current FR was calculated by multiplying the transfer matrices of all layers in the multilayer structure [2].

The construction of the prototype filter is symmetric relative to its central half-wavelength resonator; therefore, we consider only its left-hand half numbering the mirrors from the construction edge to its center. Because the half-wavelength resonators and the external medium at the filter input and output are aerial, all mirrors should have quarter-wavelength layers with a high refractive index $n_H = 4$ at the boundaries of resonators and also on the input and output of the construction under consideration.

As a result of synthesizing the prototype, we find that the first mirror on the input of the filter contains three quarter-wavelength layers, and the internal layer of this mirror has the refractive index $n_1 = 1.414$. The second mirror contains seven quarter-wavelength layers, and there are layers with the refractive index $n_2 = 1.237$ in its composition in addition to the layers with the refractive index $n_H = 4$. The third mirror of the prototype also contains seven quarter-wavelength layers; however, there are layers with the refractive index $n_3 = 1.133$ in its composition in addition to the layers with the refractive index $n_H = 4$. The obtained results enable us to choose silicon dioxide ($n_M = 1.95$) as the third

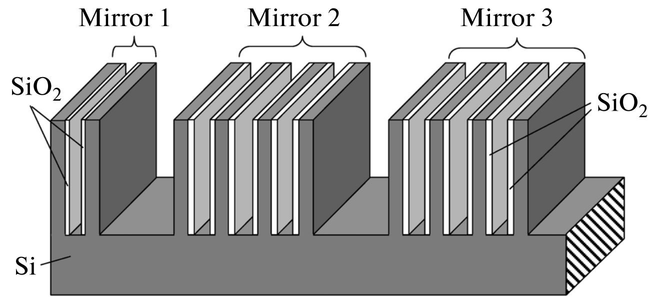

Fig. 1. Construction of the bandpass filter of the fifth order (left-hand side).

material of the filter, the refractive index n_M of which satisfies inequalities (1).

As a result, the thickness of layers of half-wavelength air resonators is obviously 50 μm for the chosen central frequency $f_0 \approx 3$ THz of the synthesized filter, and the thickness of quarter-wavelength layers from silicon in all multilayer mirrors is 6.25 μm. Calculated from Eqs. (4) and (5), the thicknesses of three-layer structures in the filter mirrors, the central layer in which is aerial and those on the edges are from silicon dioxide, are listed in the table. Thus, the total thickness of the entire filter construction together with all resonators and mirrors consisting of 67 dielectric layers is 625.255 μm.

In Fig. 2, we present the frequency dependences of direct losses and losses on reflection for the synthesized filter calculated in a narrow frequency range near the passband. The filter passband ripple is less than 0.18 dB. In Fig. 3, the FRs of the synthesized filter and its prototype are shown in a wide frequency range. We note that the FRs of the developed filter and its prototype ideally coincide in the passband region; however, far from it, a certain deviation is observed, which is expressed, first, in the shift of barrier-band boundaries into the high-frequency range resulting in a small narrowing of the low-frequency stopband and an extension of the high-frequency stopbands. Second, the attenuation depth decreases in the low-frequency stopband and increases in the high-frequency band; i.e., the FR becomes asymmetric with respect to the passband center.

Thicknesses of layers of multilayer mirrors of the synthesized filter

Number of the mirror	Thickness of layers, μm		
	Si	SiO_2	Air
1 (6)	6.25	4.116	7.523
2 (5)	6.25	3.073	11.360
3 (4)	6.25	2.281	14.553

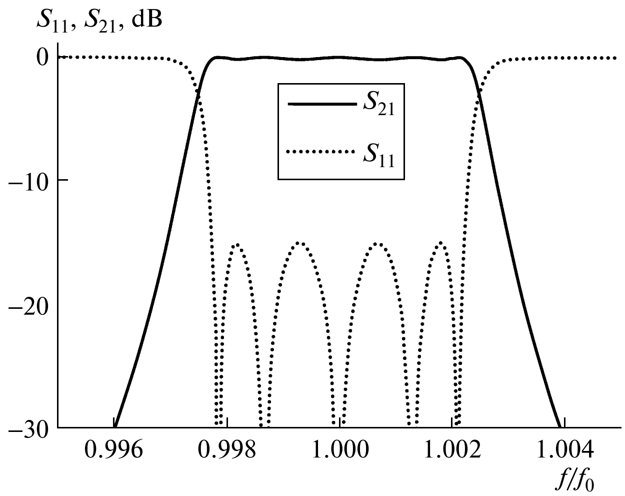

Fig. 2. Frequency dependences of the direct losses (solid line) and losses on reflection (points) in the passband of the filter of the fifth order synthesized on a three-component-layer structure.

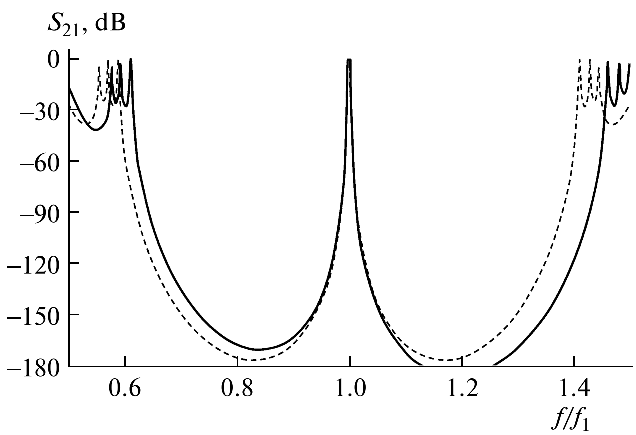

Fig. 3. FR of the synthesized filter of the fifth order (solid line) and that of the prototype filter (dashed line) in a wide frequency band.

Thus, we proposed here a new construction of the optical bandpass filter fabricated on the basis of the three-component multilayer structure, obtained the formulas for determining the thickness of layers in mirrors, and gave the technique of its synthesis by the example of a filter of the fifth order.

ACKNOWLEDGMENTS

This work was supported by the Siberian Branch, Russian Academy of Sciences, Integration project no. 109.

REFERENCES

1. H. A. Macleod, *Thin-Film Optical Filters* (CRC Press, Boca Raton, 2010).
2. J. Li, Opt. Commum. **283**, 2647 (2010).
3. V. F. Shabanov, S. Ya. Vetrov, and A. V. Shabanov, *Optics of Real Photonic Crystals. Liquid Crystal Defects, Inhomogeneities* (Izd-vo SO RAN, Novosibirsk, 2005) [in Russian].
4. B. A. Belyaev, A. S. Voloshin, and V. F. Shabanov, Dokl. Phys. **49** (4), 213 (2004).
5. B. A. Belyaev, S. A. Khodenkov, and V. F. Shabanov, Izv. Vyssh. Uchebn. Zaved., Fiz. **51** (9/2), 150 (2008).
6. B. A. Belyaev, V. V. Tyurnev, and V. F. Shabanov, Izv. Vyssh. Uchebn. Zaved., Fiz. **56** (12), 55 (2013).
7. B. A. Belyaev, V. V. Tyurnev, and V. F. Shabanov, Dokl. Phys. **59** (2), 73 (2014).
8. M. H. Asghar, M. Shoaib, F. Placido, and S. Naseem, Central Europ. J. Phys. **6** (4), 853 (2008).
9. K. Gupta, R. Gardzh, and R. Chadkha, *Computer-aided Construction of Microwave Circuits* (Radio i svyaz', Moscow, 1987) [in Russian].
10. A. Baldycheva, V. A. Tolmachev, T. S. Perova, Y. A. Zharova, E. V. Astrova, and K. Berwick, Opt. Lett. **36** (10), 1854 (2011).

Translated by V. Bukhanov