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Prediction of a region with high transmission (reflectance) for bandpass interferential filters by using the method of pointer function

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Abstract. The analysis of transmission spectrums of periodical multilayer interference thin-films systems is carried out. Spectral dependences of pointer function from wavelength for interference bandpass filters are obtained. These dependences allow to prognostic of regions of high transmission or reflectance for different periodical multilayer systems.

Keywords: interference filter, pointer function.

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1. Introduction

A lot of interesting and useful phenomena arise at propagation of electromagnetic radiation through periodical structures. They are used in different optical devices such as: diffraction gratings [1, 2], photonic crystals [3], lasers [4] and filters [5, 6]. Actually, thin film optics can be constructed in the best way by using the electromagnetic theory. This theory provides relatively full and consecutive consideration of interference and polarization effects in all types of film multilayer systems. Multilayer thin-film coatings for visible and infrared spectral regions are the object of researches for plenty of researchers [7-11], so far as they are important elements for electronics, photonics, laser technique and telecommunications. It should be noted that production of filters with given band width of transmission is enough difficult work, for example, filters used in multiplexing or demultiplexing consist of more than one hundred individual layers with rigorous tolerances. In most cases, these interferential systems have structures that include a large number of periods.

It's known that periodical multilayer systems are equivalent to the one-dimension photonic crystals that are the volume structures made of material transparent in a certain wavelength region. The dielectric permittivity of them is described by a periodical function. Typical interferential effects at every boundary with increasing or decreasing the total reflectance (transmission) for different wavelengths appear for light passing through the structure of one-dimensional (1D) photonic crystal with periodical variations of the certain layer thickness and different refractive index (n). Interferential mirror coatings are the most known example of 1D photonic crystal. At correct choice of refractive indices and optical thickness of layers, in transmission spectra one can observe the bands with maximal coefficient of reflectance for a certain wavelength region – the so-called photonic bandgaps appear.

In the work [12], the methods to calculate a bandgap in 1D photonic crystal is proposed. It is reduced to solving the eigenvalue problem of $TX = \rho X$ type and verification of the absolute value of eigenvalue ρ (if it is equal to unity). The square matrix T has the dimension 2×2. The frequency ν and component of the wave vector k_x are given; in this method, the component k_z is defined with the eigenvalue ρ. The photonic bandgap can be constructed when we have the frequency ν and component k_z. The only spur of the matrix should be known to define the eigenvalue. The eigenvectors are possible to be determined when eigenvalues ρ are known. In this case, the electromagnetic field of wave propagating through the crystal can be calculated. In this work, the transmissions of interferential mirror have been calculated using this method. It is necessary to note that the spectral dependence $(T_{11} + T_{22})/2$ exactly identifies the boundary between allowed and forbidden frequencies. Thus, this dependence is possible to be called as the pointer function $P(\lambda)$.

Taking into account that periodical multilayer systems are equivalent to a one-dimension photonic crystal, in this work we investigated the possibility to predict the region of transmission (reflectance) in multilayer interferential bandpass filters by using the pointer function, which was applied to photonic crystals. The analysis of transmission spectra of periodical multilayer thin-film interferential systems is conducted using the matrix method.

2. Periodical multilayer interferential bandpass filters

There are two moments in designing the thin-film filters: the first one is connected with the low reflectance (transmission) for certain wavelength region and the second – simplicity of the constructed structures, which facilitates their production. The periodical multilayer structures with equal-thickness layers are used most often [13], they consisted of layers with high and low refractive indices, which are repeated. The resources of obtaining the filters with a relatively wide transmission band based on these systems are rather limited. There are different methods of narrowing or widening the main transmission band. Shown in the work [14] is that narrowing the high transmission band and widening the transmission band in a multilayer system take place at the modification of the thickness of individual layers in period and at the invariable total thickness of period. In [15], we proposed the bandpass filter with $(HLH)^nS$ type structure, when H and L are dielectric layers with high and low refractive indices, respectively, and with unequal thicknesses. Taking into account that the system is periodical and consists of only two components like interferential mirrors, it would be pertinent to verify the possibility to predict the transmission region by using the pointer function. In the two-component three-layered periodic structure, the pointer function $P(\lambda) = (t_{11} + t_{22})/2$ will be as follows:

$$\begin{aligned} P(\lambda) &= \cos\Phi_1 \cos\Phi_2 \cos\Phi_3 - \\ &- 0.5(n_1/n_2 + n_2/n_1)\sin\Phi_1 \sin\Phi_2 \cos\Phi_3 - \\ &- 0.5(n_1/n_3 + n_3/n_1)\sin\Phi_1 \sin\Phi_3 \cos\Phi_2 - \\ &- 0.5(n_2/n_3 + n_3/n_2)\sin\Phi_2 \sin\Phi_3 \cos\Phi_1 , \end{aligned} \quad (1)$$

where $\Phi_1 = 2\pi n_1 d_1/\lambda$, $\Phi_2 = 2\pi n_2 d_2/\lambda$, $\Phi_3 = 2\pi n_3 d_3/\lambda$; n_1, n_2, n_3 – refractive indices of dielectric layers; d_1, d_2, d_3 – geometric thicknesses of dielectric layers.

The base wavelength is equal to 5 μm, $n_1 = n_3 = 4.02$, $n_2 = 1.44$, $d_1 = d_3 = 3.11$ μm, $d_2 = 0.87$ μm are used for calculating this system with four periods was selected. From the dependence shown in Fig. 1, it is the possibility to immediately say in which spectral region the transmittance can be high. The region of transmission corresponds to the range of $-1 \le P \le 1$.

When using only two different materials within the period of a periodical multilayer system ($n_1 = n_3$ and $d_1 = d_3$), then the formula (1) will be:

$$\begin{aligned} P(\lambda) &= \cos 2\Phi_1 \cos\Phi_2 - \\ &- 0.5(n_1/n_2 + n_2/n_1)\sin 2\Phi_1 \sin\Phi_2 . \end{aligned} \quad (2)$$

If the pointer function tends to zero at the base wavelength $\lambda = 5$ μm, then the simplest solutions will be as follows:

1. $\Phi_1 = m\pi$ and $\Phi_2 = \pi/2$.
2. $\Phi_1 = m\pi/2 + \pi/4$ and $\Phi_2 = \pi$.
3. $\Phi_1 = m\pi/2 \pm \pi/8$ and $\Phi_2 = \text{arctg}(1/(n_1/n_2 + n_2/n_1))$.
4. $\Phi_1 = m\pi/2 \pm \text{arctg}(1/(n_1/n_2 + n_2/n_1))/2$ and $\Phi_2 = \pi/4$,

where m is an integer.

The spectral curve of the system with the thickness of layers calculated for the first variant of the solutions at $m = 5$ will agree with the spectral curve shown in Fig. 1. Interference system with layers (their thicknesses are obtained from the solution 2), will have the transmission band within the limits that are defined by the pointer function. However, the spectral curve has numerous deep valleys, and their number increase with increasing the number of periods. Thus, the solution 2 cannot find any practical application. The solutions 3 and 4 provide perfectly useful characteristics. For example, the spectral curve corresponds to system with layers, thicknesses of which are calculated in accordance with the solution 4 (see Fig. 2).

The transmission band can be widened practically by one and a half, if the repeated period of the multilayer system is constructed from three different materials, and if it has ABCBA structure, where A, B and C are layers of the equal optical thickness with refractive indices n_A, n_B, and n_C, respectively [16, 17].

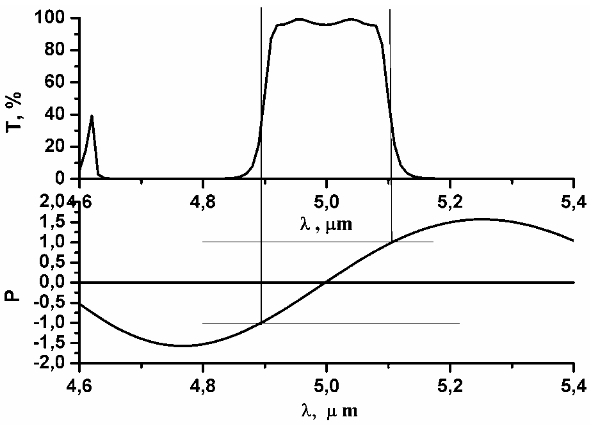

Fig. 1. Wavelength dependences of transmission for the interferential filter of the type $(HLH)^nS$ and of the pointer function.

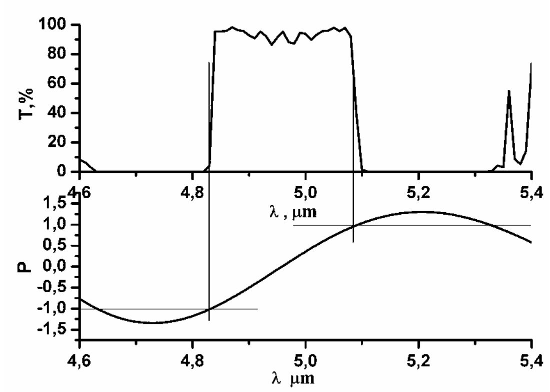

Fig. 2. Wavelength dependences of transmission for the interferential filter of the type $(HLH)^{10}S$ and of the pointer function.

In the work [18], expressions for determination of the effective refractive index N for ABCBA period are presented. Obtained with these expressions are the relations that connected with the refractive indices n_A, n_B, and n_C. At these relations take place in simultaneous suppression of the two band high reflectance.

To predict the region of transmission in these filters, we will use the system that is presented in [16], where all the layers have the optical thickness equal to one fourth of the wavelength and with the refractive indices $n_A = 1.38$, $n_B = 1.90$, and $n_C = 2.30$, respectively. The pointer function is simply calculated by application of mathematics software. The expression has rather cumbersome view, so it is not presented here. Fig. 3 shows that the pointer function exactly indicates on the region of wavelengths where the high transmittance is possibly achieved at given parameters of the structure.

The transmission bands can be more widened when multilayer systems that consist of periods ABCCBA or ABCDDCBA will be used. Widened transmission bands of these systems take place when the sideband of high transmission is suppressed. The number of different materials in the period defines the maximal number of high transmission bands that are suppressed, the number of the layer in the period indicates on spectral location of these bands [19].

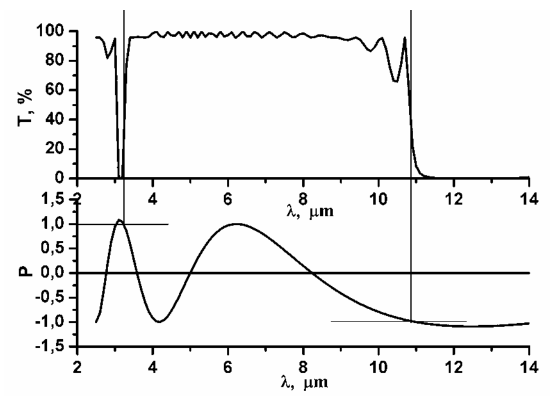

Fig. 3. Wavelength dependences of transmission for the interferential filter of the type $(ABCBA)^{10}S$ and of the pointer function.

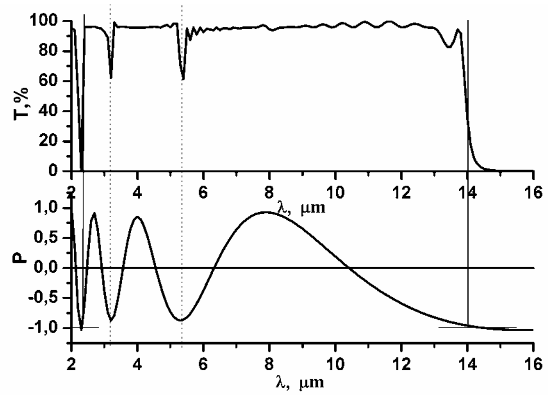

Fig. 4. Wavelength dependences of transmission for the interferential filter of the type $(ABCDDCBA)^5S$ and of the pointer function.

In all the cases, refractive indices must strongly correspond to certain relations [18]. When multilayer systems with repeated ten-layer periods are used, it is the possibility to suppress high reflectance bands of 4^{th}, 5^{th}, and 6^{th} orders, etc. [19]. In Fig. 4, the wavelength dependences of transmission of interferential filters of the type $(ABCDDCBA)^5$ and the pointer function are presented. All layers in the offered system have the equal optical thickness (one fourth of the wavelength) with the refractive indices $n_A = 1.65$, $n_B = 1.95$, $n_C = 2.30$, and $n_D = 2.70$, respectively.

Thus, the pointer function exactly indicates on the region of high transmission in multilayer repeated system such as in previous cases. The spectral curve has two valleys in the region of wavelengths 3 and 5 μm. The height can be modified by varying the number of periods. So, the pointer function indicates on the same regions ($P \cong 1$), where certain peculiarity takes place.

3. Conclusions

The term of the pointer function based on the theory of 1D photonic crystal is introduced. The spectral dependences of the pointer function for bandpass and wide-bandpass interferential filters are obtained. These dependences allow to predict the region of high transmission (reflectance) for periodic multilayer systems with different structures and to indicate the regions with certain particularities. The base advantage of using the pointer function is that with its help one can easily indicate the region of high transmission (reflectance) in bandpass and cut-off filters. For periodical systems consisting only of two different materials, there is the possibility to simply calculate necessary thicknesses of individual layers to provide maximal transmission for a certain range of wavelengths. Thus, the pointer function facilitates design of optical filters that have comparatively complicated structure. It is known that the modern bandpass thin-film filters include more hundred layers, and the process of calculation of transmission or reflectance coefficients take enough large volume of time.

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References

1. V.B. Yafaeva, and A.S. Valeev, Wideband systems for band-pass filters // *Optiko-mekhanich. promyshlennost*' **7**, p. 28-32 (1969) (in Russian).
2. A. Thelen, Design of multilayer interference filters / *Physics of Thin Films,* Eds. G. Hass, M Francombe. Mir, Moscow, 1972, p. 46-84 (in Russian).
3. N. Borisovich*, Infrared Filters.* Nauka and Tekhnika, Minsk, 1971 (in Russian).
4. B. Li, S.Y. Zhang, J.C. Jiang *et al*., Recent progress in improving low-temperature stability of infrared thin-film interference filters // *Optics Express* **13** (17), p. 6376-6380 (2005).
5. M. Lisitsa, S. Orlov, Yu. Pervak, I.V. Fekeshgazi, Multilayer coatings with suppression of two neighboring bands of high reflection // *Zhurnal Prikladnoy Spektroskopii* **47**(2), p. 283-285 (1987) (in Russian).
6. V.U. Pervak, Spectral properties of interference filter than constructed multiple repetition three-component stacks // *Optich. Zh.* **70**(10), p. 91-96 (2003) (in Russian).
7. I.V. Fekeshgazi, V.Yu. Pervak, Yu.A Pervak, Properties and application of the unequal thickness two-component interference systems // *Semiconductor Physics, Quantum Electronics & Optoelectronics* **3**(3), p. 371-378 (2000).
8. B.J. Chun, C.H. Hwangbo, J.S. Kim, Optical monitoring of nonquarterwave layers of dielectric multilayer filters using optical admittance // *Optics Express* **14**(6), p. 2473-2479 (2006).
9. T.N. Krilova, *Interference Coatings*. Mashinostroenie, Leningrad, 1973 (in Russian).
10. B. Maitland, M. Dunn, *Laser Physics*. North-Holland, Amsterdam-London, 1969.
11. Yu.Yu. Fircak, N.I. Dovgoshej *et al.,* Reflecting multilayer systems on the basis of vitreous chalcogenide for IR lasers // *Optiko-mekhanich. promyshlennost*' **8**, p. 48-52 (1983) (in Russian).