Cutoff interference polymer-crystalline multilayer systems with the passband edge smooth tuning

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Received May 13, 2004

The smooth tuning possibility of the passband edge in an interference polymer-crystalline cutoff filter has been studied. This is attained by using the periodic polymer (L) — germanium (H) structures of uneven optical thickness, i.e., the systems of the $[(H\pm C)(L\pm C]^k(H\pm C)$ type where H and L are quarter-wave layers of high and low refractive index, respectively; C in the thickness unequality parameter; k, an integer. The effect of the C value variation from 0 to 0.3 H on the optical properties of polyethylene-germanium interference structures have been studied theoretically and in experiment. A method has been developed to smooth the secondary extremes in the uneven thickness polyethylene-germanium systems by adding auxiliary polyethylene interference layers.

Исследована возможность плавной перестройки границы отрезания интерференционного полимер-кристаллического фильтра. Она заключается в использовании периодических структур неравной оптической толщины, т.е. систем вида $[(H\pm C)(L\pm C]^k(H\pm C)$, где H и L — четвертьволновые слои с высоким и низким показателем преломления, C — параметр неравнотолщинности, k — целое число. Теоретически и экспериментально исследовано влияние изменения параметра неравнотолщинности C от 0 до 0.3 H на оптические свойства интерференционных структур полиэтилен-германий. Разработан метод сглаживания вторичных экстремумов в системах полиэтилен-германий неравной оптической толщины добавлением дополнительных интерференционных слоев из полиэтилена.

Theoretically, it is possible to prepare a multilayer interference system (MIS) comprising alternating layers of materials having high (H) and low (L) refractive index (RI) adjusted to any wavelength within the optical spectrum. This filter type differs favorably from other types, e.g., from absorbing ones, where the smooth spectral tuning is hindered in principle [1]. The cutoff interference filters made by vacuum evaporation of the H and L layers can be prepared for any wavelength within UV, visible, near IR, and intermediate IR ranges (limited only by the transparence of the materials used), since the quarter-wave H and L layers can be deposited for any wavelength.

As to the polymer-crystalline interference systems, the situation is more complicated. Theoretically, there is no problem, because any layer, including a polymer one, can be prepared at any thickness. In practice, however, it is much more complicated to realize, since the industrial polymer films such as polyethylene, Teflon, nylon ones, are produced in limited thickness set defined by destination thereof [3, 4]. For example, only 12 and 20 μm thick nylon films are produced. Teflon films are available in a somewhat wider thickness set, namely, 5, 6, 8, 10, 15, and 20 μm. This facilitates the work but also restricts significantly the smooth tuning potential of the cutoff edge by using the quarter-wave layers differing in thickness. The polyethylene films are produced in even wider thickness assortment, but it is impossible to select the necessary film for each specific multilayer interference filter, when tenths and even hundredths micrometer fractions are of importance. As to filters for $\lambda < 100$ μm, the polyethylene film thickness set is too restricted at all [5].

A number of tasks can be attained using even such a limited thickness set. In our case, however, it is sufficient only to provide in principle a solution of the problem concerning the preparation of a polymer-crystalline filter (PCF). For a wide practical application, it is necessary to have a possibility to prepare a PCF for any wavelength; otherwise, one of the fundamental MIS advantages over other filter types will be lost.

In this work, a fundamentally new approach to the smooth cutoff edge tuning of an interference PCF is studied. It consists in the use of a periodic structure of uneven optical thickness [6], i.e., a $[(H \pm C)(L \pm C]^k(H \pm C)$ type system where H and L are quarter-wave layers of high and low RI, respectively; C is the thickness unequality parameter; k, an integer.

At present, the interference a periodic structure of uneven optical thickness have no wide practical application. Perhaps this is due to the fact that such systems are of a little interest for UV, visible, near and intermediate IR spectral regions well mastered to date. In the mentioned spectral regions, the traditional quarter-wave systems can be used to tune the cutoff edge, because the interference layer of high and low refractive indices can be prepared for any wavelength in the course of deposition (thermal, electron-beam, etc.). It is just the quarter-wave systems that are best ones for the formation of the cutoff filter spectral characteristic [1]. Moreover, additional technical difficulties in the preparation of structures of uneven optical thickness (UOT) are associated with the necessity to control the non-quarter-wave layer thickness [6].

For the far IR region, the preparation process of the uneven optical thickness structures becomes facilitated when polymer films are used as the low-RI material. When preparing the polymer-crystalline interference structures, there is no difference in practice between the control of the UOT structures and the quarter-wave ones due to separated thickness control of the H and L layers, since in both cases, such a wavelength can be selected for which the high-RI material layers would have a thickness multiple to $\lambda/4$. The polymer films are controlled prior to the high-RI films deposition thereon.

In preparation of such UOT multilayer polymer-crystalline structures, it is just the systems where germanium is used as the high-RI material that are of the most practical interest. This follows from the study results obtained for quarter-wave polymer-crystalline structures. If, for example, KRS-5 or LiF is used in combination with polymer materials, at least 11 to 15 layers are required to set the cutoff edge, because the RI difference is rather small. The suppression band optical width in such systems is rather narrow, therefore, it is difficult to eliminate the background emission therein.

Let us consider theoretically an UOT structure of the $[(H \pm C)(L \pm C]^k(H \pm C)$ type where the period is constant and even to $\lambda/2$. At $C = 0$, such structures are converted into an usual quarter-wave interference system. The spectral characteristic of a system consisting of alternating high-RI (H) and low-RI (L) quarter-wave layers is a series of high reflection (low transmittance) bands separated by high transparence ones. The high reflection bands are formed in the spectral regions where the H and L layers are $\lambda/4$, $3\lambda/4$, $5\lambda/4$, etc., thick.

In the spectral characteristic of a UOT structure, at the same period $\lambda/2$, the high-reflection bands become narrower and additional reflection bands appear [6]. Certainly, the cutoff edge slope changes as well as the residual transmission in the high reflection bands [1]. In this connection, it is unclear if a UOT system can be an elementary filter setting the cutoff edge spectral position and slope. It is to find what are the uneven thickness parameter C limits providing the conservation of the UOT system function as a cutoff filter and what are the cutoff edge tuning limits in a PCF where the same polymer film thickness is used. We have calculated theoretically the optical characteristics in the 40 to 250 μm spectral range for $[(H - C)(L + C]^k(H - C)$ type structures where a polymer and germanium are used. The germanium absorption has been not taken into account in those calculations.

When developing the calculation algorithm for transmission and absorption spectra of the $[(H - C)(L + C]^k(H - C)$ type structures, the recurrent approach [1] was used to describe the optical characteristics of a multilayer system. This technique makes it possible, by using the appropriate selected generalized parameters, to impart to expressions intended for calculation of transmission and absorption a form independent of the number of layers in the coating, that is, to reduce the expressions for a multilayer coating to those for one layer. The method used is based on matrix description of the thin layer characteristics. For example, the expression for the transmission spectrum can be transformed identically in such a manner that it will be not presented as a dependence of the Fresnel transmission and reflection coefficients at the layer boundaries and on the phase oncoming but as a function of matrix elements of the matrix m_k called the interference matrix of k-th layer:

$$m_k = \begin{vmatrix} \cos\frac{2\pi n_k d_k}{\lambda} & -\frac{i}{n_k}\sin\frac{2\pi n_k d_k}{\lambda} \\ -in_k \sin\frac{2\pi n_k d_k}{\lambda} & \cos\frac{2\pi n_k d_k}{\lambda} \end{vmatrix}, \quad (1)$$

where n_k, d_k are the k-th layer refractive index and geometric thickness, respectively; i, the imaginary unity; λ, the wavelength the calculation is made for.

If the interference matrix of a system consisting of N layers is interpreted as the product of interference matrices of individual layers

$$M = \prod_{k=1}^{N} m_k \quad , \quad (2)$$

then the transmission of that system will be described in terms of the matrix components by the expression

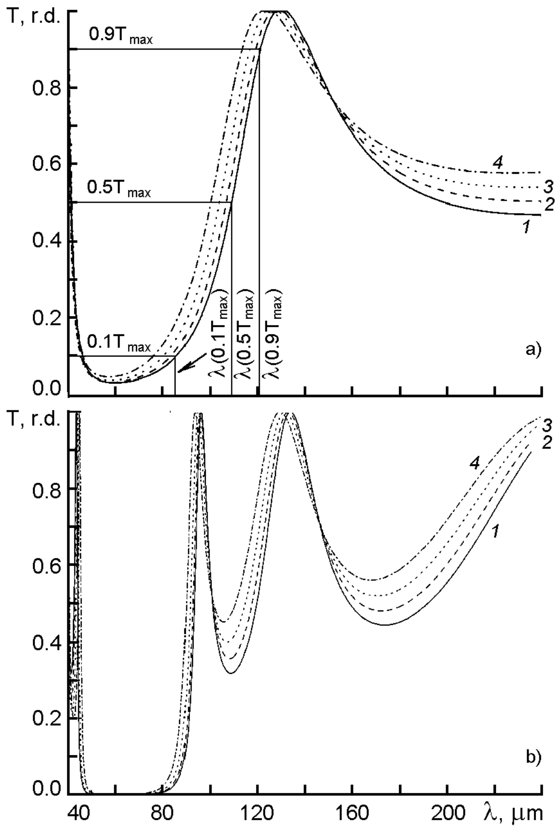

Fig. 1. Theoretically calculated transmission spectra at fixed optical thickness of the structure period for 3-layer Ge-PE-Ge system (a) and 7-layer PE-Ge system (b) at the thickness unequality parameter values C = 0 (*1*), 0.1 H (*2*), 0.2 H (*3*), 0.3 H (*4*).

$$T = \frac{4n_1 n_s}{|(M_{11} + n_s M_{12})n_1 + M_{21} + M_{22}n_s|^2}, \quad (3)$$

where n_s is the RI of the last semi-infinite medium, that is, of the substrate. Thus, to determine the multilayer system transmis-

Table 1. Parameters of a 3-layer Ge-PE-Ge system depending on the thickness unequality parameter C

Parameter	C				
	0	0.1 H	0.2 H	0.3 H	
				Calc.	Exper.
Max. transmission, T_{max}, %	100	100	100	100	94
Cutoff edge					
$\lambda(0.5\ T_{max})$, μm	109	107	104	75	74
$\lambda(0.1\ T_{max})$, μm	85.5	83	80	57	57
$\lambda(0.9\ T_{max})$, μm	121.5	119.5	117	85	84
Cutoff edge slope, χ	0.7	0.69	0.68	0.67	0.67

sion, it is sufficient to find the interference matrix M for the whole system by multiplying successively m_k and to calculate T using (3). Fig. 1 presents the calculation results for spectral characteristics of 3- and 7-layer systems. The main parameters thereof are summarized in Tables 1 and 2, respectively.

In Fig. 1(a), shown are the calculated transmission characteristics for a 3-layer germanium-polymer-germanium (Ge-PL-Ge) system $(H-C)(L+C)(H-C)$ at various C values. It is seen that increase of that parameter from 0 to 0.3 H results in that the high reflection region becomes narrowed and the residual transmission therein increases by about 3 or 4 %. At the same time, the long-wavelength transparence region shows some changes. These changes, although worsening somewhat the spectral characteristic parameters as compared to the quarter-wave system (C=OH), are not so significant and thus do not exclude the possibility to use such systems to set the cutoff edge of a filter.

Fig. 1(b) presents the calculated transmission characteristics for a 7-layer polyethylene (PE)-germanium (Ge) systems $[(H-C)(L+C)]^3(H-C)$ at various C values. It follows from the Figure that even the system where the optical thickness of high-RI layers is only a half of that of PE ones ($C = 0.3$ H; $H = L = 15$ μm) has a steep slope of the cutoff edge (see Table 2):

$$\chi = \frac{\lambda(0.1T_{\max})}{\lambda(0.9T_{\max})} = 0.93, \qquad (4)$$

where T_{max} is the maximum transmission; $\lambda(0.1T_{max})$ and $\lambda(0.9T_{max})$, the wavelengths corresponding to the $0.1T_{max}$ and $0.9T_{max}$ transmission levels. For the 7-layer PE-Ge structures, as well as for 3-layer ones, increase of the C parameter from 0 to 0.3 H results in that the high reflection region becomes narrowed and the residual transmission therein increases somewhat; the secondary extremes in the transparence region decrease. The result obtained evidence that, at any studied C values, the 7-layer interference structures can be used to set the cutoff edge in a PCF at a sufficiently steep slope (Table 2).

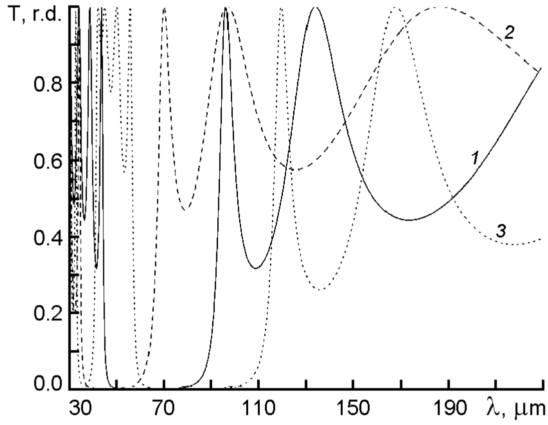

Fig. 2. Theoretically calculated transmission spectra of a 7-layer PE-Ge system at the thickness unequality parameter values $C = 0$ (*1*), 0.33 H (*2*), −0.2 H (*3*), the PE optical thickness being fixed.

The curves of Figs. 1a and 1b relate to the systems where the C parameter was varied but the optical thickness of the structure period remained unchanged. The simple estimations show that, when changing both C and the structure period, it is possible, using one and the same PE film thickness, the spectral position of the filter cutoff edge can be shifted continuously within a range of about $0.5\lambda_0$, where $\lambda_0 = 60$ μm is the wavelength for which the system is a quarter-wave one ($C = 0$). This is provided by depositing the Ge layers differing in thickness.

Table 2. Parameters of a 7-layer PE-Ge system depending on the thickness unequality parameter C

Parameter	C						
	0	0.1 H	0.2 H	0.3 H		0.33 H	−0.2 H
				Calc.	Exper.		
Max. transmission, T_{max}, %	100	100	100	100	72	100	100
Cutoff edge							
$\lambda(0.5\ T_{max})$, μm	93.5	93	92	75	73	67	116
$\lambda(0.1\ T_{max})$, μm	89.5	89	87.5	71.5	64.5	64	111.5
$\lambda(0.9\ T_{max})$, μm	95	94.5	93.5	77	77	69	118.5
Cutoff edge slope, χ	0.94	0.94	0.93	0.93	0.83	0.93	0.94

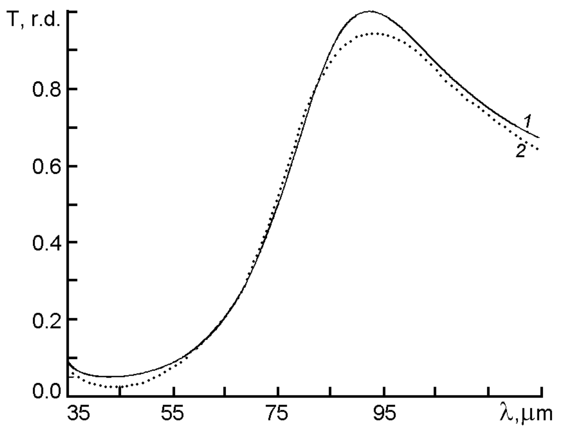

Fig. 3. Calculated (*1*) and experimental (*2*) transmission characteristics of a 3-layer Ge-PE-Ge interference structure with C = 0.3 H.

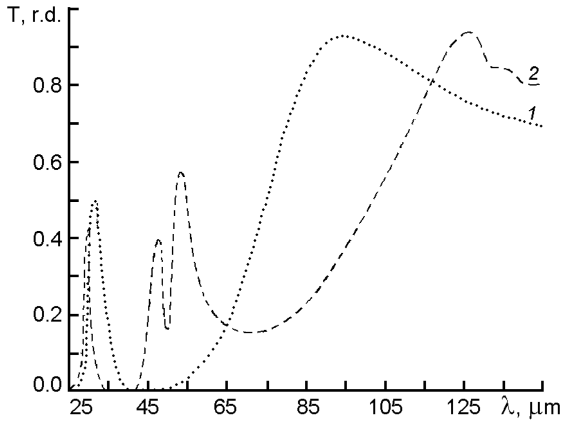

Fig. 4. Spectral characteristics of 3-layer Ge-PE-Ge interference structures with C = 0.3 H (*1*) and C = 0.5 H (*2*).

Fig. 2 presents the calculated transmission spectra for a 7-layer PE-Ge system at $C = 0$ (1), $C = 0.33$ H (2), $C = -0.2$ H (3), the PE optical thickness being fixed. It follows from Fig. 2 and Table 2 that, if the PE film has the unique thickness of 10 μm (optical thickness 15 μm), then at $C = 0$, $H = L = 15$ μm, the cutoff edge for the 7-layer PE-Ge system answers to $\lambda = 93.5$ μm. For Ge layers of 7.5 μm optical thickness (i.e., $C = 0.33$ H), the cutoff edge becomes shifted towards short-wave region ($\lambda = 67$ μm). If the Ge optical thickness exceeds the PE one, the cutoff ed ge will be shifted towards longer wavelengths ($\lambda = 116$ μm at $C = -0.2$ H). It is to note that the H layers exceeding in thickness the L ones to a great extent ($C \geq |-0.2$ H$|$) are not advisable, since in this case, the secondary extreme in the transparence band of a short-wave cutoff filter become increased, so those are to be smoothened. Furthermore, in our example, the increased optical thickness of Ge layers results in an attenuated transmission due to absorption that shows germanium in the $\lambda < 100$ μm spectral region. Therefore, it is practically favorable to use the thinner Ge layers as compared to PE ones. Moreover, in systems where the high-RI layers are thinner than the low-RI ones, the depth of secondary extremes in long-wave region from the 1st high reflection band decreases, thus facilitating the further forming of the spectral characteristic of a short-wave cutoff filter.

If the 20 μm thick PE film is used, the cutoff edge of a short-wave cutoff filter can be shifted from about 140 μm to about 200 μm by changing the optical thickness of Ge layers. At the 15 μm thick PE film, the PE-Ge systems overlapping the 100 to 140 μm range are also realizable. Thus, with PE films of three thickness values only (10, 15, and 20 μm), combining those with Ge layers, the short-wave cutoff interference PCF can be realized with cutoff edges for any wavelength within the $\lambda = 70$ to 200 μm range.

The experimental studies of interference PCF with layers of uneven optical thickness were carried out taking the 3-layer and 7-layer systems as examples. The transmission spectra of Ge-PE-Ge $(H - C)(L + C)(H - C)$ systems with the thickness unequality parameter $C = 0.3$ H (Fig. 3) show a good agreement between the experimental results (curve 2) with calculated data (curve 1). Such a coincidence in parameters for 3-layer Ge-PE-Ge systems has been obtained at smaller C values, too. It has been found in experiment that for those systems, a further C increase ($C > 0.3$ H) makes it possible in principle to form the high reflection bands, but the residual transm ission therein increases. For example, at $C = 0.5$ H, the residual transmission in the first high reflection band at the long-wavelength side is about 15 % (Fig. 4). Nevertheless, the high reflection band width is large enough even at such C values, so, by increasing further the number of layers, the cutoff edge of a short-wave cutoff PCF could be formed in such structures, too.

Using thin (5 μm) Teflon films in combination with germanium makes it possible to form the PCF cutoff edge even at $\lambda \approx 40$ μm in the uneven optical thickness structures.

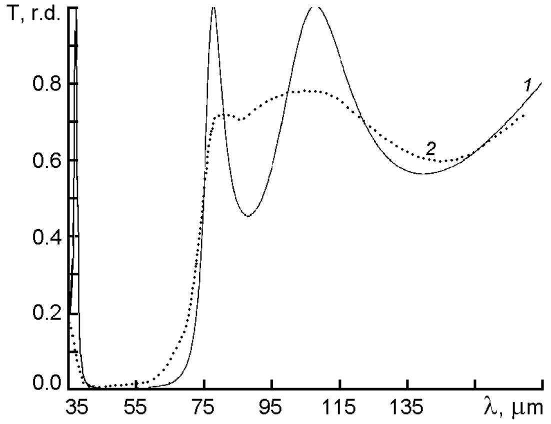

Fig. 5. Calculated (*1*) and experimental (*2*) transmission characteristics of a 3-layer PE-Ge system with $C = 0.3$ H.

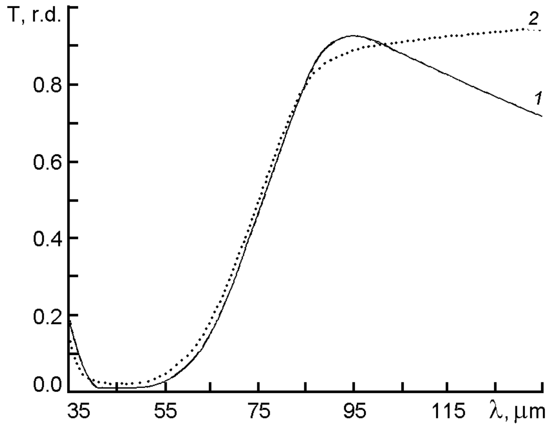

Fig. 6. Spectral characteristics of non-optimized (*1*) and optimized (*2*) 3-layer Ge-PE-Ge cutoff structures with $C = 0.3$ H.

It is to note, however, that the presence of an absorption band at $\lambda \approx 50$ μm in Teflon does not allow to increase the number of this material layers due to a significant increase of the absorption intensity. Therefore, it is feasible to use the Teflon films as low-RI layers in cutoff PCF with the cutoff edge at $\lambda \geq 50$ μm. For shorter-wave range, only one Teflon layer (i.e., a Ge-Teflon-Ge trilayer) is to be used. In this case, the transmission attenuation due to absorption at $\lambda \approx 50$ μm is still insignificant.

The spectral characteristic of the prepared 7-layer $[(H-C)(L+C)]^3(H-C)$ PE-Ge structure with $C = 0.3$ H is presented in Fig. 5. The actual structure is seen to differ quantitatively from the calculated data in the cutoff edge slope that is lower than the calculated one (Table 2) as well as in that the secondary extremes in the transmission region are deformed in part. These quantitatively differences in the transmission spectra of the 7-layer PE-Ge systems seem to be explainable by local inhomogeneities in the PE film thickness resulting in blurring of the secondary extremes, especially of the 1st interference maximum adjacent to the high reflection band that is most sensitive to the thickness errors.

Nevertheless, the cutoff edge slope values ($\chi \approx 0.83$) attained in the 7-layer PE-Ge system (Table 2) are high enough, thus, such structures are of good prospects in the cutoff edge setting of a short-wave cutoff filter. It is to note that the cutoff edge slope values of about 0.83 have been attained in the spectral region of $\lambda = 70$ to 80 μm where the all known filter types are of low efficiency. As to the relatively far IR region ($\lambda > 100$ μm), the UOT systems allow to expect even higher cutoff edge slope values due to the fact that thicker PE films exhibit lower relative local thickness inhomogeneities.

Now let us consider the problem of the secondary extreme smoothing in the transparence band of a short-wave PE-Ge cutoff filter. A specific feature of the $[(H-C)(L+C)]^k(H-C)$ structures consists in that the extremes are smoothened in part therein as compared to the quarter-wave ones [2]. Therefore, the structures where the low-RI layers exceed the deposited high-RI ones in the optical thickness are of a practical interest for the cutoff edge setting. The studied have shown that a method similar to that used to optimize the cutoff interference filters with the quarter-wave layers can be applied to the UOT systems. To that end, the spectral characteristic of the prepared system is to be recorded, the transmission minimum spectral position is to be determined, and additional PE interference layers are to be added. The additional layer optical thickness should be $\lambda'/4$, where λ' is the wavelength at which the system transmission is minimum. As an example, Fig. 6 presents the spectral characteristic (curve 1) of non-optimized $(H-C)(L+C)(H-C)$ filter ($C = 0.3$ H) and that of the optimized system (curve 2) made by adding the interference PE layer. The optimized system is seen to exhibit a better performance in the operating region. The addition of the framing PE layers results, however, in an increased residual transmission in the high reflection band as compared to the systems consisting of the quarter-wave layers.

To conclude, the effect of the thickness unequality parameter C variation from 0 to 0.3 H on the optical properties of PE-Ge interference structures has been studied theoretically and in experiment. The smooth cutoff edge tuning possibility has been studied for a PE-Ge PCF where the PE films of one and the same geometrical thickness are used. The cutoff edge has been stated to be smoothly tunable within the spectral range equal to a half of the wavelength for which the PE film is the quarter-wave one. In experiment, the cutoff edge slope $\chi \approx 0.83$ has been attained for a PCF with uneven optical thickness layers within the $\lambda < 100$ μm spectral range.

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Відрізаючі інтеренференційні полімер-кристалічні багатошарові системи із плавною перебудовою границь

А.І.Беляєва, С.М.Коломієць

Досліджено можливість плавної перебудови границі відрізання інтерференційного полімер-кристалічного фільтра. Вона полягає у використанні періодичних структур нерівної оптичної товщини, тобто систем виду $[(H\pm C)(L\pm C]^k(H\pm C)$, де H і L — чвертьхвильові шари з високим і низьким показником заломлення, C — параметр нерівнотовщинності, k — ціле число. Теоретично й експериментально досліджено вплив зміни параметра нерівнотовщинности C від 0 до 0.3 H на оптичні властивості інтерференційних структур поліетилен-германій. Розроблено метод згладжування вторинних екстремумів у системах поліетилен-германій нерівної оптичної товщини додаванням додаткових інтерференційних шарів з поліетилену.