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Spectral characteristics of cascade photonic crystal structures with interdomain defects

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The spectral characteristics of one-dimensional photonic crystal structures formed by Bragg reflectors with different grating periods are studied. The influence of the geometric chirp of the periods of Bragg reflectors and the thickness of the separating layers on the amplitude and total number of defect transmission modes of the photonic structure is established.

Keywords: photonic crystal structure, geometric chirp, defect modes, frequency comb.

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Photonic crystal structures (PCSs) have the property of selectively transmitting and reflecting individual spectral components of electromagnetic radiation. By analogy with crystalline materials, in which there are forbidden energy bands for electrons, photonic band gaps (PBGs) may exist in the spectrum of the PCS —- wavelength ranges that are completely reflected from the PCS [1] . The spectral width and position of the PBG can be controlled by changing the structural or optical parameters of the PCS. In addition, disruption of the periodicity of the PCS by introducing one or more defect layers (made of a material different from the materials that make up the alternating layers, or simply having a different thickness) leads to the appearance of narrow transmission peaks in the PBG - the so-called „defect" modes [2–4]. Modification of spectral characteristics of the PCS by the introduction of defects is used in the development of reflectors, filters, multiplexers and other photonics and optoelectronics devices [5].

To expand control over the spectral characteristics of the PCS, liquid crystalline materials [6,7] are used, nanocomposite materials [8–10], two-dimensional structures [11,12], etc. An alternative approach is based on varying the topology of the PCS, for example, by introducing heterogeneity into the distribution of the refractive index and layer thickness of the PCS [13–15]. Apodized (with a refractive index modulation profile varying along the PCS) and chirped (with different layer thicknesses) PCS allow to obtain PBG of different widths, as well as to form defect modes at different resonance frequencies. In this work, dielectric PCS with a stepwise (cascade) profile of changes in the Bragg period are considered and the nature of the influence of the chirp of Bragg reflectors and the thickness of the separating layers on the characteristics of the frequency comb in the transmission spectrum is established.

Let us review a cascade PCS, which is a combination of symmetrical Bragg reflectors — domains with the topology $M_i = [A_iB_i]^N A_i$, where N is the number of periods in the domain (the same for all domains), the index $i = 1, 2, \ldots, K$ indicates the serial number of the domain, counted from the side of incidence of electromagnetic wave (Fig. 1). The PCS borders on a medium with dielectric permittivity 1 (air). The domains are formed by alternating layers of non-absorbing materials A and B with refractive indices n_A and n_B, respectively, the thicknesses of which in the i-th domain $d_{A,i}$ and $d_{B,i}$, correspond to the condition of Bragg reflection at the vacuum wavelength $\lambda_i = 4d_{A,i}n_A = 4d_{B,i}n_B$. The domains are separated by layers of non-absorbing material D_i of thickness d_i. The structure of the entire PCS is described by the formula $M_1D_1M_2D_2\ldots M_{K-1}D_{K-1}M_K = \left(\sum_{i=1}^{K-1} M_iD_i\right)M_K$, where where K is the total number of domains.

To calculate the spectral characteristics of a lamellar periodic structure, the transfer matrix method is used [16]. The transfer matrix for the entire structure is formed by sequentially multiplied interface matrices (obtained from the boundary conditions at each Fresnel interface) and the transfer matrices through the material layers.

All calculations in this work were carried out for the following fixed parameters: $n_A = 2.89$ (AlAs), $n_B = 3.35$ (GaAs) [17], $N = 12$. The thickness of the separating layers d_i, the Bragg wavelength λ_i, which determines the thickness of the A and B layers in domains, as well as the number of domains K in PCS vary. The separating layers D_i are made of material B and have a thickness of $d_i = \alpha(d_{B,i} + d_{B,i+1})$, where the parameter α takes values from 0 to 2. The Bragg wavelengths of the domains starting from the second one ($j \geq 2$) are related to the Bragg wavelength of the first domain $\lambda_1 = 1.55\,\mu$m by

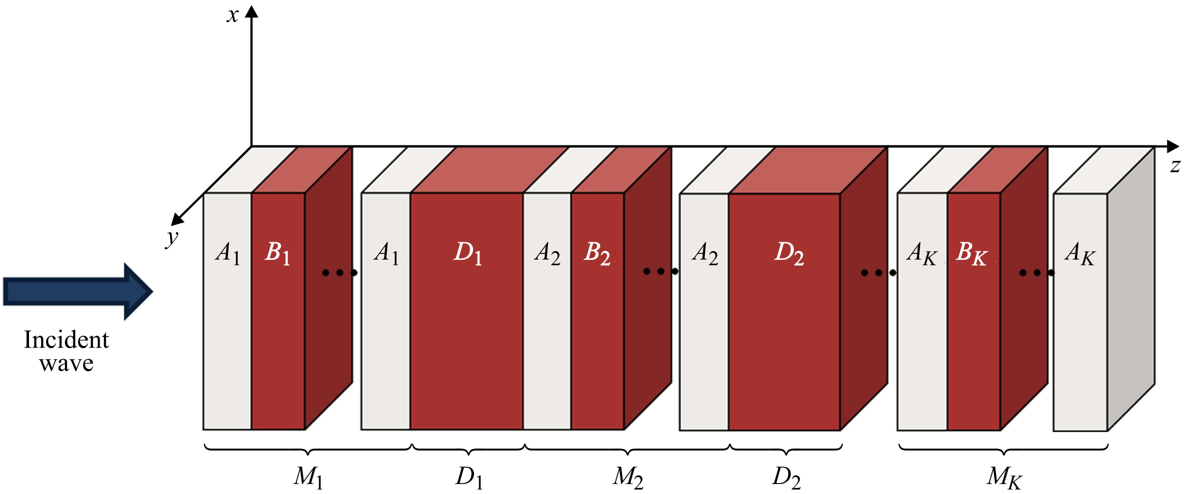

Figure 1. Geometry of the problem. Cascade PCS has an architecture $M_1D_1M_2D_2\ldots M_K$, where $M_i = [A_iB_i]^N A_i$ are symmetrical Bragg reflectors (domains), made of layers A_i and B_i, D_i are separating layers, N is the number of periods $[A_iB_i]$ in domains, K is the number of domains in the PCS.

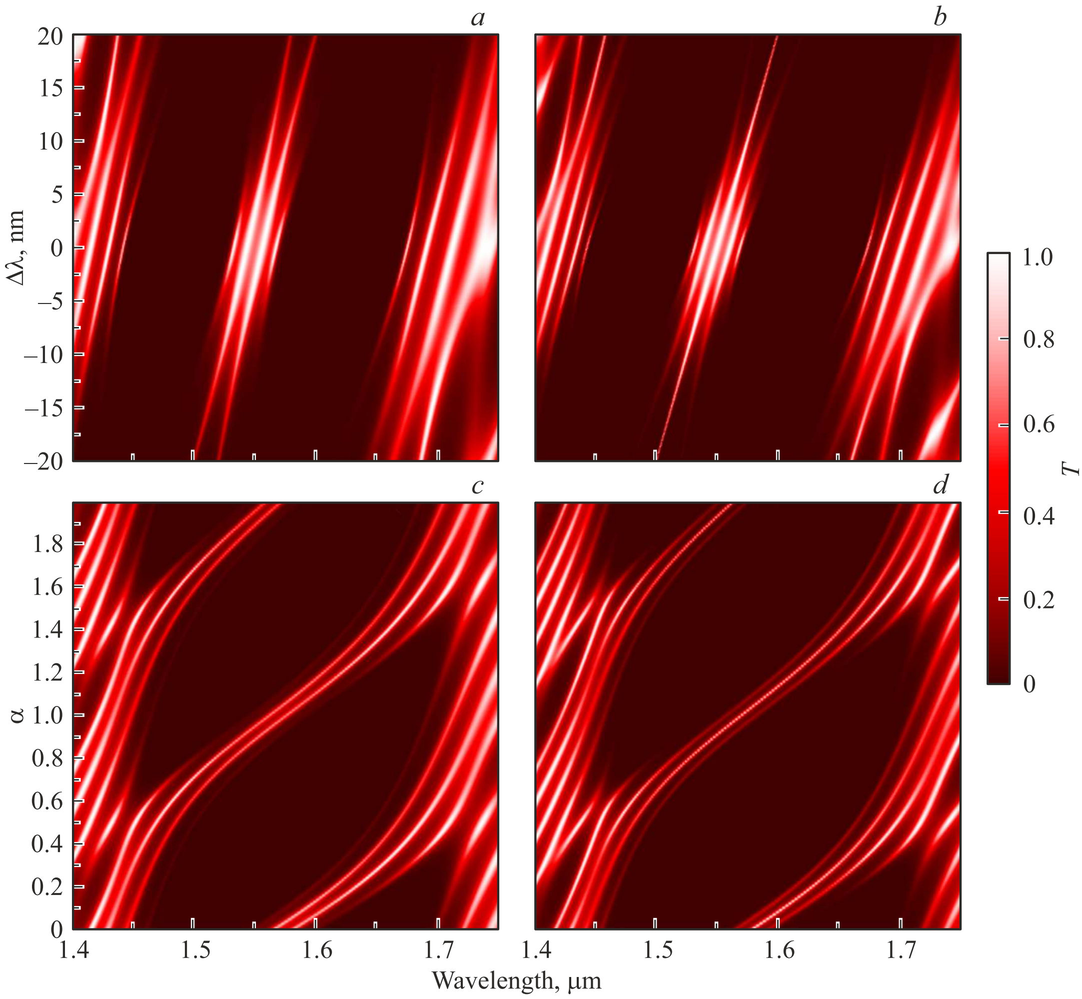

Figure 2. Dependence of the transmission spectra $(a),(c)$ of a five-domain $(K = 5)$ and $(b),(d)$ six-domain $(K = 6)$ PCS on the detuning $\Delta\lambda$ of the Bragg wavelengths of the domains and the thickness of the separating layers. Calculation parameters: $N = 12$, $\lambda_1 = 1.55\,\mu$m; $(a),(b)$ — $\alpha = 1$; (c), (d) — $\lambda_2 = 1.56\,\mu$m, $\lambda_3 = 1.57\,\mu$m, $\lambda_4 = 1.58\,\mu$m, $\lambda_5 = 1.59\,\mu$m, $\lambda_6 = 1.60\,\mu$m.

the relation $\lambda_j = \lambda_1 + \Delta\lambda(j-1)$, where $\Delta\lambda$ is the detuning of the Bragg wavelength due to the geometric chirp.

Figure 2 shows the calculation results of the transmission spectra of the PCS, with five ($K = 5$) and six ($K = 6$) domains. All presented spectra are characterized by the presence of a PBG near a wavelength of $1.55\,\mu$m with several transmission modes (frequency combs), which we will call „defect " by analogy with the transmission modes of photonic crystals with broken periodicity of the structure [3,4,9,14]. The total number of defect modes is one less than the number of domains of PCS, i. e. coincides with the number of layers separating the domains, equal to N-1.

Fig. 2, *a, b* shows the dependence of the transmission spectra of cascade PCS on the wavelength detuning $\Delta\lambda$ (values $\Delta\lambda$ vary in the range from –0.02 to $0.02\,\mu$m) with a fixed thickness of the separating layers D_i. It can be seen from the figure that a change in the mismatch between domain periods leads to a spectral shift and a change in the amplitude of defect modes. As the geometric chirp increases, the PBG and defect mode comb receive a unidirectional shift towards the long-wavelength region of the spectrum, and vice versa. The spectral distance between defect modes increases with increasing detuning of the Bragg wavelengths of the domains. The transmittance of the PCS at frequencies of defect modes is maximum near the center of the PBG (for $\Delta\lambda = 0$) and decreases with increasing detuning of $\Delta\lambda$. Let us also note that additional transmission modes are formed near the edges of the PBG (most pronounced at small $\Delta\lambda$), the amplitude of which decreases with increasing $\Delta\lambda$, similar to defect modes near the center of the PBG.

Figure 2, *c, d* shows the calculation results of the dependence of the transmission spectra of cascade PCS on the thickness of the layers separating the domains D_i. The thicknesses of the layers in the domains are determined by the Bragg wavelength of the first domain $\lambda_1 = 1.55\,\mu$m and the detuning $\Delta\lambda = 0.01\,\mu$m: $\lambda_2 = 1.56\,\mu$m, $\lambda_3 = 1.57\,\mu$m, $\lambda_4 = 1.58\,\mu$m, $\lambda_5 = 1.59\,\mu$m, $\lambda_6 = 1.60\,\mu$m. From the presented dependences it is clear that a monotonic change in the thickness of the separating layers leads to a unidirectional displacement of the defect mode comb. The central modes have the greatest amplitude for any thickness of the separating layers. The side modes have an intensity comparable to the intensity of the central modes only when they are located near the edges of the PBG. In contrast to the case presented in Fig. 2, *a, b*, when the thickness of the separating layers changes, the position and spectral width of the PBG do not alter.

By varying the geometric chirp and the thickness of the layers separating the domains, it is possible to rearrange the transmittance spectrum, and achieve the split of the frequency comb. As an example, Fig. 3 shows the spectrum of a structure with a broken linear distribution of the thicknesses d_i of the separating layers along the PCS with a separate narrow defect mode.

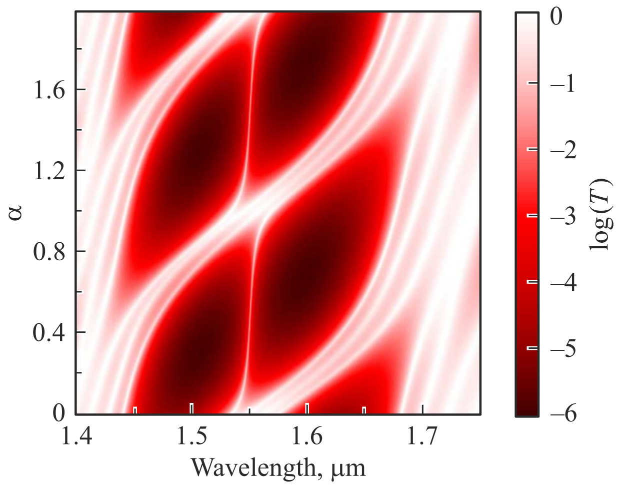

Figure 3. Dependence of the transmission spectrum (in a logarithmic scale) of a five-domain ($K = 5$) PCS on the thickness of the separating layers. The thickness of the third separating layer is fixed. Detuning the Bragg wavelengths of the $\Delta\lambda = 1\,\mu$m. Other calculation parameters are the same, as in Fig. 2.

It should be noted that the amplitude of defect modes in the frequency comb is not the same: the height of the transmittance peaks decreases in the direction from the central to the side modes. In this case, in the transmission spectrum of an PCS with an odd number of domains, the most intense are two central modes, while for an even number of domains there is one the most intense mode — the central mode. Additional studies show that this feature is preserved for any number of domains in the PCS (from two or more domains). It is also found that with an increase in the total number of domains, there is a decrease in the amplitudes of all defect modes, including the most intense central modes. The latter is associated with an increase in the role of PBG of different domains in the formation of the transmission spectrum of the structure with an increase in the number of domains with different Bragg wavelengths.

As a conclusion, we note that cascade structures with geometrically chirped Bragg reflectors are of interest from the point of view of developing the design of multichannel resonant cavity structures, sensors and optical filters with a comb transmission spectrum against the background of a wide PBG. The Q factor, the total number and position of defect modes in the transmission spectrum can be controlled by the number of domains and the detuning of their Bragg wavelengths, the number of lattice cells in them, as well as the thickness of the separating layers.

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Conflict of interest

The authors declare that they have no conflict of interest.

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