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Spectral characteristics of a photonic crystal structure with a monolayer of metal nanoparticles

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The possibility of complete absorption of an incident electromagnetic wave in a narrow frequency band by a two-dimensional array of metal nanoparticles placed in the surface layer of a one-dimensional photonic crystal structure is demonstrated. The nature of the influence of the parameters of an array of nanoparticles (particle shape, interparticle distance) on the reflection and absorption spectra of the photonic structure in the photonic band gap is determined.

Keywords: photonic crystal structure, two-dimensional array of nanoparticles, total absorption, localized surface plasmon resonance.

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Photonic crystal structures (PCSs) have been the subject of intensive research for decades. Due to the periodic modulation of the refractive index in the PCS, its transmission spectrum exhibits a photonic band gap (PBG) — a frequency interval in which electromagnetic waves cannot pass through the structure [1]. This property is of interest for practical applications in optics and photonics, since it makes it possible to control the spectral characteristics of optical radiation in waveguide structures. The functionality of devices based on PCSs is significantly expanded when using media with variable characteristics [2,3], two-dimensional structures [4–7] and composite bulk materials, the electrodynamic characteristics of which are not found in natural materials [8–10].

Works [7–11] show the opportunity of controlling PCS modes when varying the parameters of nanocomposite materials and two-dimensional structures by excitation of localized plasmon resonance in metal nanoparticles (NPs). In these structures, high control efficiency is possible due to the strong localization of the electromagnetic field on NPs placed in the resonant cavity region of the PCS. The use of composite media with non-spherical NPs allows to expand the spectral range in which the spectral characteristics of the structure vary in a controlled manner [4,5]. This work demonstrates the opportunity of modifying the spectral characteristics of a dielectric PCs in the optical range using an $2D$ array (monolayer) of metal NPs placed in the surface layer. Using analytical calculations, it is shown that a two-dimensional array of metal NPs almost completely absorbs the energy of incident radiation at frequencies near the plasmon resonance frequency, which allows to realize complete suppression of reflection in a narrow spectral region within the PBG.

Let us review a PCS, which is a Bragg reflector with a unit lattice cell $[AB]$, where layers A and B are made of dielectric materials TiO_2 and SiO_2 with refraction indices n_A and n_B, respectively [12,13]. The total number of binary layers in the PCS is $N = 10$. On the surface of the PCS there is a SiO_2 film, in which a two-dimensional array M of silver NPs [14] is placed. Thus, the entire photonic structure is described by the formula $B_1MB_2[AB]^N$, where B_1 and B_2 are layers with thicknesses d_{B1} and d_{B2} into which the NP array divides the surface layer B (Fig. 1). The thicknesses of the PCS lattice cell layers d_A and d_B correspond to the condition of Bragg resonance reflection at the wavelength $\lambda_0 = 4d_An_A = 4d_Bn_B$. The thicknesses of the layers into which the NPs array divides the surface film B are $d_{B1} = 2d_B$ and $d_{B2} = 3d_B$.

The NP form an ordered two-dimensional array with a square cell. All nanoparticles have the shape of ellipsoids of revolution (spheroids) of the same size, their polar axis is directed perpendicular to the plane of the array. The shape of the NP is determined by the

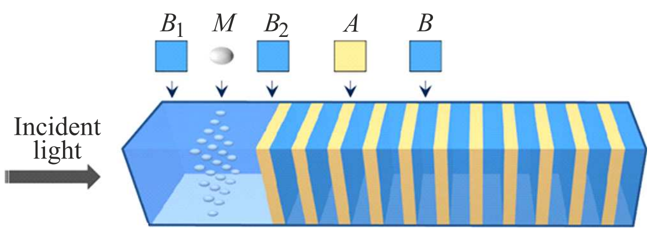

Figure 1. Photonic structure $B_1MB_2[AB]^N$. The Bragg reflector is formed by N binary layers $[AB]$. The surface dielectric layer adjacent to the Bragg reflector is divided by a two-dimensional array of NPs M into layers B_1 and B_2.

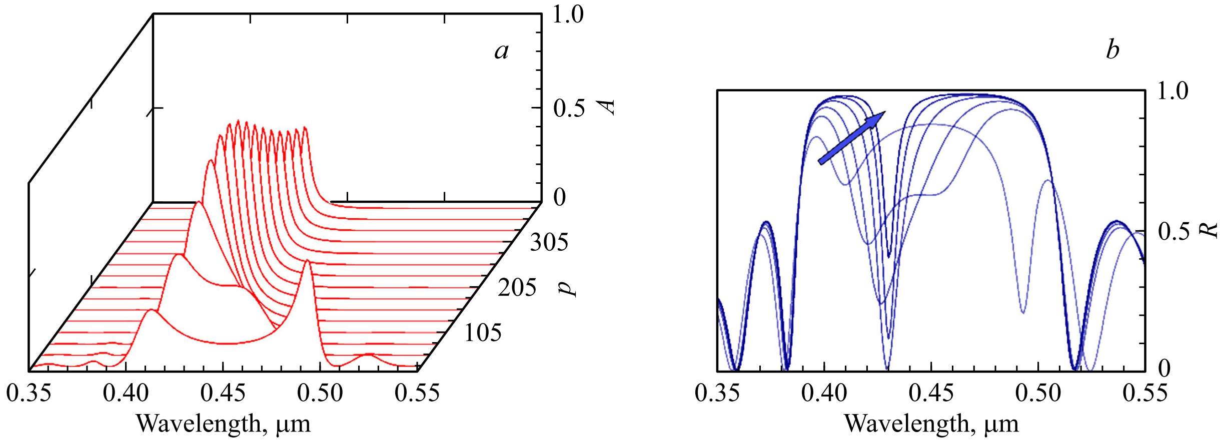

Figure 2. Dependence of the absorption spectra (a) and reflection spectra (b) of the photonic structure on the interparticle distance p in a two-dimensional array of silver NP. In the figure (b), the interparticle distance takes values of 30, 55, 105, 180, 280, 380 nm, the direction of increase p is shown by an arrow. Aspect ratio of NP $\xi = 1$.

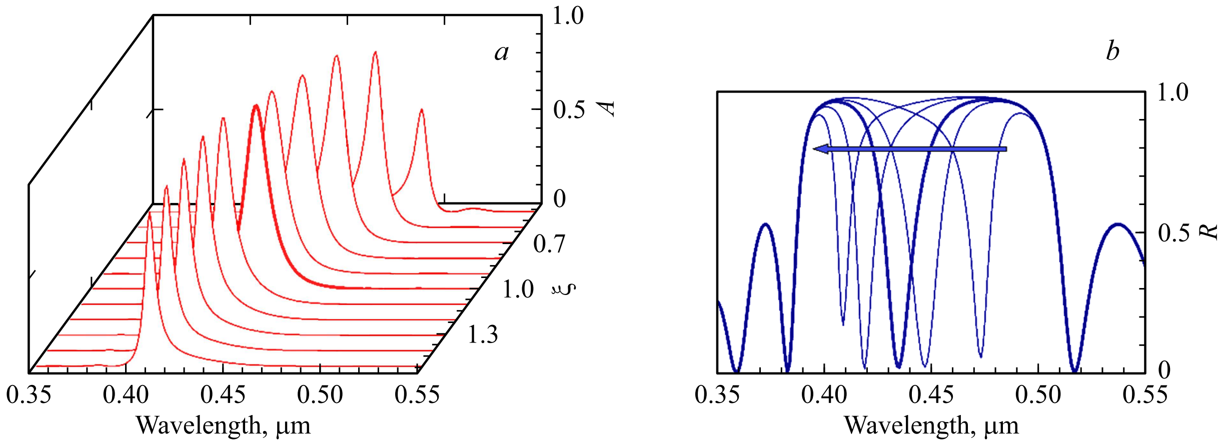

Figure 3. Dependence of the absorption spectra (a) and reflection spectra (b) of the photonic structure on the aspect ration ξ in silver NPs. In the figure (b), the aspect ratio of NPs takes values of 0.6, 0.8, 1, 1.2, 1.5, the direction of increase ξ is shown by an arrow. Interparticle distance $p = 130$ nm.

aspect ratio $\xi = a/b$ of the lengths of the polar a and equatorial b semi-axes: $\xi < 1$corresponds to an oblate spheroid („disk“), $\xi > 1$ — prolate spheroid („needle“), $\xi = 1$ — ball. The NP size is much smaller than the wavelength in the medium B $(a, b \ll \lambda_0/n_B)$. In numerical calculations, the length of the polar semi-axis is taken equal to $a = 10$ nm.

The analysis of the spectral characteristics of the complex photonic structure was carried out using numerical calculations using the transfer matrix method, within which each PCS layer is associated with a matrix that determines the relationship of the fields at its two interfaces [15]. The NP array is considered as an interface (a layer of quasi-zero thickness) with non-Fresnel transmittance and reflection coefficients, to which a specific transfer matrix is associated within the dipole approximation [16,17]. The resulting matrix of the entire photonic structure is obtained through the sequential product of the transfer matrices of the PCS layers and the 2D NP array in accordance with the order of their occurrence in the direction of propagation of the incident electromagnetic wave. In this work, the case of normal radiation incidence on the surface of a photonic structure is considered.

From the dependences presented in Figs. 2 and 3, it is clear that in the presence of a two-dimensional array of silver NPs in the surface layer of the PCS, the spectral absorbance A of the entire structure in a relatively narrow spectral range takes values close to 1. Complete absorption of radiation is realized due to the matching of the PBG, the frequency of the plasmon resonance of the NPs and their location in the surface layer, which provides an interference enhancement of the interaction and, as a consequence, high dissipative losses in the system „array of NPs — Bragg reflector“. In the region of resonant absorption, the reflectivity of the structure R is significantly reduced and takes values close to 0 (Fig. 2, b and Fig. 3, b).

The position of the absorption band is controlled by the aspect ratio and surface concentration of NPs. The dependence of absorption on the interparticle distance is not monotonic (Fig. 2): with increasing p it increases, reaches a maximum ($A \approx 1$) at $p \approx 130$ nm, and decreases with a further increase of p. When the shape (aspect ratio ξ) of the NPs changes, there is mainly a shift in the absorption band along the PBG (Fig. 3): the transition from the flattened to the elongated shape of the NPs is accompanied by a shift of the absorption band to the short-wavelength region of the spectrum. Thus, a change in the surface concentration of NP mainly leads to a change in the absorbance value, while a change in the shape of the particles leads to a frequency shift in the maximum of the absorbance curve. Changes in the amplitude and frequency of absorption bands are correspondingly manifested in the reflection spectra.

Thus, the photonic structure under consideration can be used as a frequency filter (for reflection) or an absorber, the spectrum of which is characterized by the presence of a relatively wide reflection region (spectral width is more than 150 nm) with a narrow defect absorption band. The shape and position of the absorption band are controlled by the concentration and shape of nanoparticles organized in monolayer inside the the surface dielectric layer. By selecting the PCS materials and the aspect ratio of nanoparticles, it is possible to implement a narrow-band absorption filter for predetermined frequencies of the visible or near-IR (when using semiconductor materials) spectral regions. In combination with other recently proposed solutions (based on the use of liquid crystals or materials whose properties can be controlled by a magnetic or electric field), such a structure will be useful in the development of sensors, polarizers and other elements of photonics, integrated and fiber optics.

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Conflict of interest

The authors declare that they have no conflict of interest.

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