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Physical approaches to the design of functional metal-dielectric systems based on opals in photonics

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The possibilities of practical implementation of physical approaches to the design of metal-dielectric photonic crystal systems based on opals, which allow controlling the propagation of electromagnetic waves, are shown. The implemented approaches are based on the effects of excitation of surface plasmon-polaritons capable of propagating along the metal-dielectric interface in plasmonic-photonic layered heterostructures, and modification of the photonic-energy structure of the nanocomposite as a result of dispersion of silver in the opal matrix. Experimental results are presented indicating the occurrence of extraordinary transmission and absorption of light in plasmonic-photonic heterostructures, as well as the asymmetric shape of curves in the reflection spectra of nanocomposites, which is associated with the Fano resonance.

Keywords: photonic crystals, opals, surface plasmon-polaritons, metal-dielectric systems, Fano resonance.

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Introduction

The dynamic increase of physical knowledge to be mastered, inherent in the development of electronics and photonics, updates the designing of devices at the physical level, which is reflected in the academic literature of the past years (for instance, [1]). This approach is applied in this paper to functional metal-dielectric systems of photonics.

A prominent place among the functional materials of photonics, which allow for control of electromagnetic (EM) radiation flows by directional modification of light transmission and reflection spectra is held by photonic crystals (PCs) [2,3], having a spatial periodicity of the refraction index (RI), which gives rise to forbidden energy states for light with a wavelength comparable to the period of structure — photonic bandgaps (PBGs).

Many devices of contemporary photonics were developed based on plasmon-photon heterocrystals (PPHC) [4], being various combinations of PC layers in contact with thin metal films. Functional improvement of such systems as compared to conventional PCs is performed by energy transfer along the metal−dielectric interface by surface plasmon polaritons (SPP) [5], movement of which can be controlled, as predicted by the theory [6–8]. These effects are of interest for the creation of waveguide structures in the SHF [9], terahertz [10] and visible [11] ranges, new types of lasers [12] and light-emitting diodes [13], fiber-optic refractometers [14], sensors [15,16], optical logic elements [17], high-speed optical data transmission channels [18], as well as for loss reduction in Bragg gratings [19], size reduction, increase of operating frequency and efficiency of information processing and transmission devices [20].

Designing of plasmon-photonic device should take into account the fact that, in addition to SPPs that propagate along the metal−dielectric interface, when certain conditions are met (as a rule, with normal light incidence onto the light „metal−PC" interface [21]), Tamm optical states originate in the form of standing surface waves which do not carry the energy along the surface and can be experimentally found according to the narrow transmission peak in the PBGs of PCs [22].

Another approach to engineering of functional metal-dielectric systems with specified properties consists in modification of the specimen's photonic energy structure through dispersion of the metal in the dielectric matrix of opal.

In order to implement both approaches, in this paper we have conducted experimental studies of model layered metal-dielectric systems which contained silver (it was the main plasmon material having the minimum losses in the visible and near infrared spectrum regions [12]), as well as PCs based on „solid" synthetic opals consisting of identical spheres (globules) having a diameter of hundreds of nanometers [23], which can act as three-dimensional PCs [24–28].

1. Use of SPP to modify optical properties of opal-based PPHCs

It is known that SPP excitation is performed using special experimental methods [11] developed by A. Otto, E. Kretschmann and other researchers. One of these methods creates a periodic texture at the metal–dielectric interface, which ensures simultaneous fulfillment of the energy conservation law and the impulse law upon SPP excitation. We have implemented this periodic texture by application of a metal film on intermittently arranged opal globules (Fig. 1) [29]. In this case, the impulse law upon light incidence onto a grating with period a can be written as [11]:

$$\beta = k_x + 2\pi l/a, \tag{1}$$

where β and k_x are projections of the SPP wave vector and the incident light wave onto the interface respectively, l is an integer.

The interfaces profiled layer of silver–monolayer of opal globules' and profiled layer of silver–air, which ensure compliance of the morphology of a cohesive metal coating with peculiarities of the surface of the initial PC, were obtained by magnetron sputtering of the substance using the ATC ORION SERIES SPUTTERING SYSTEM. The methods for preparation and study of specimens of $Ag/SiO_2/Ag/ML/Ag$ PPHC, produced by application of a silver layer (Ag), a dielectric layer (SiO_2) and a monolayer (ML) of opal globules onto a glass substrate in the specified sequence are described in [30–32].

SPP excitation causes the formation of maxima that correspond to extraordinary transmission (EOT) in the transmission spectra of these specimens of $Ag/SiO_2/Ag/ML/Ag$ PPHC. Thereat, as seen from Fig. 2, the spectral position of these maxima correlates with the position of the deep minima in the reflection spectra of the studied specimens (in this case, they are close to the wavelengths $\lambda_1 = 489$ nm and $\lambda_2 = 584$ nm). The latter indicates that the energy of an incident EM wave is partially consumed for SPP excitation. Apparently, the condition (1) in the given spectrum regions is met for the interfaces between the profiled metal film and air (at the wavelength λ_1) and the solid dielectric (at the wavelength λ_2).

Fig. 3 shows angular dispersion of the spectral position of the long-wave maximum which corresponds to extraordinary transmission of the hybrid $Ag/SiO_2/Ag/ML/Ag$ plasmon-photonic crystal. The position of the short-wave maximum of EOT, as demonstrated by the experiment, is almost independent of light incidence angle.

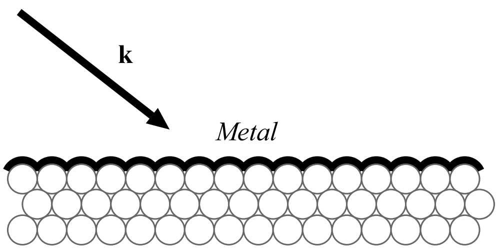

Figure 1. Use of the periodic texture at the metal–dielectric interface for SPP excitation (**k** — wave vector of the incident electromagnetic wave) [29].

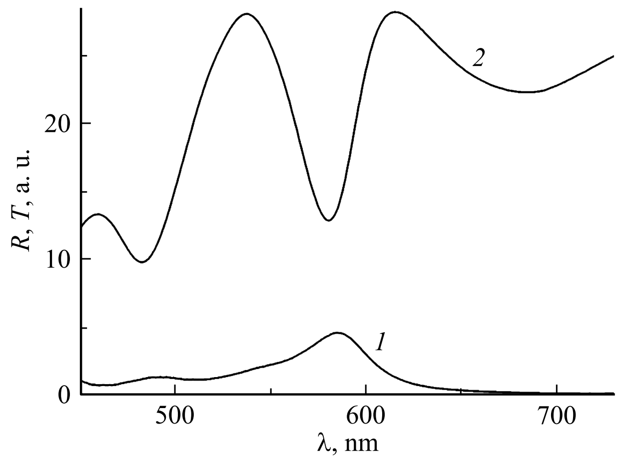

Figure 2. Transmission (*1*) and reflection spectra (*2*) of a hybrid $Ag/SiO_2/Ag/ML/Ag$ plasmon-photonic crystal with the light incidence angle $\theta = 16°$.

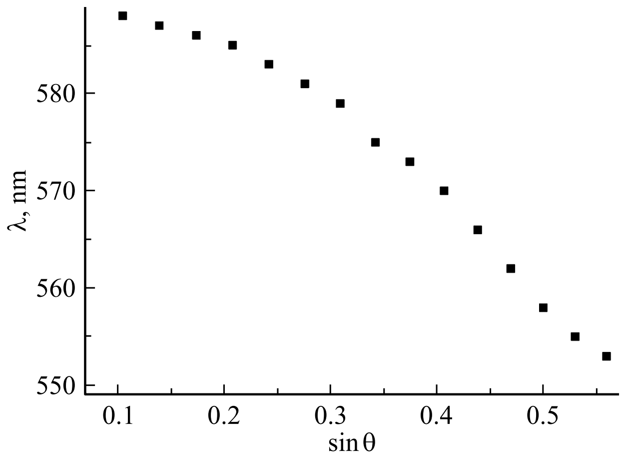

Figure 3. Angular dispersion of the spectral position of the long-wave maximum of EOT for the hybrid $Ag/SiO_2/Ag/ML/Ag$ plasmon-photonic crystal.

The law of SPP dispersion at the metal to dielectric interface with the refraction index n can be presented as [11,29]:

$$\beta^2 = (\omega^2 n^2/c^2)\{1 + (\omega^2 n^2/[\omega_p^2 - \omega^2(1 + n^2)]\}, \tag{2}$$

where c is the speed of light in vacuum, while the plasma frequency for silver ω_p considerably exceeds the EM wave frequency $\omega = 2\pi c/\lambda$. Estimation of the effective RI of the opal globule monolayer in the implemented PPHC using formulas (1) and (2) with the experimentally obtained wavelengths λ_1 and λ_2, which correspond to the extraordinary transmission maxima at a small light incidence angle, period $a = D\sqrt{3}/2 \approx 357$ nm of the studied two-dimensional grating of polymethylmethacrylate globules having the diameter $D \approx 413$ nm [32,33] gives $n \approx 1.27$. This magnitude is slightly lower than the calculated value of the effective refraction index for the monolayer ($n_{\mathrm{eff}} \approx 1.32$ [32]), which is apparently due to the loose packing of opal globules in the monolayer.

Our experiments have demonstrated that, along with extraordinary transmission (EOT), intensive extraordinary absorption (EOA) also occurs in the considered systems under certain conditions [31,32]. We think that the observed phenomena are related to excitation of superficial plasmon-polaritons of two types: „light", accountable for extraordinary transmission, and „dark" ones, causing extraordinary absorption; they propagate along the profiled metal layer−dielectric interfaces.

An $Ag/SiO_2/Ag$ resonator (interference filter) was added into the structure successively with a monolayer of Ag/ML/Ag opal globules for monitoring of extraordinary absorption; the $Ag/SiO_2/Ag/ML/Ag$ PPHC was created as a result. Approaches to interpretation of transmission spectra of such a layered system and its components have been suggested in [31,32].

If we suppose that the Ag/ML/Ag plasmon-photonic crystal and the $Ag/SiO_2/Ag$ resonator (with transmission coefficients $T_1(\lambda)$ and $T_2(\lambda)$ respectively) convert the EM radiation as two series-connected independent passive optical elements, then an evident equality would exist for the transmission coefficient of $Ag/SiO_2/Ag/ML/Ag$ PPHC: $T_3(\lambda) = T_1(\lambda)T_2(\lambda)$, so that the $r = T_3(\lambda)/\big(T_1(\lambda)T_2(\lambda)\big)$ ratio in the entire studied spectrum region would be equal to one. As has been experimentally shown, the reality is different: quantity r depends on wavelength, while the spectral dependence $r(\lambda)$ (Fig. 4, curve *1*) demonstrates deep minima of EOA (at 392 and 760 nm for the incidence angle $\theta = 16°$), the position of which almost coincides with the minima in the resonator reflection spectrum (Fig. 4, curve *2*) at all angles of light incidence onto a specimen.

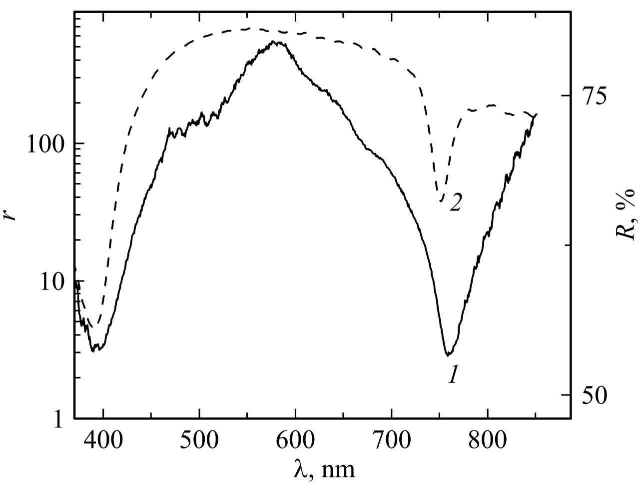

Figure 4. Spectral dependence of $r = T_3(\lambda)/\big(T_1(\lambda)T_2(\lambda)\big)$ (*1*) ratio and reflection spectrum $R(\lambda)$ of $Ag/SiO_2/Ag$ resonator (*2*). Light incidence angle $\theta = 16°$.

It is interesting to note that the inherent effects of superficial plasmon-polaritons were not observed in the control experiments with the $Ag/ML/Ag/SiO_2/Ag$ PPHC with a reverse sequence of layers, when opal globules were in contact with a flat silver resonator film (and not a profiled one with the same morphology as the layer of opal globules). In this case the monolayer of Ag/ML/Ag opal globules and the $Ag/SiO_2/Ag$ interference filter in fact operated as two series-connected independent passive optical elements, the $r = T_3(\lambda)/\big(T_1(\lambda)T_2(\lambda)\big)$ ratio was close to one, while the above-mentioned noticeable EOT and EOA effects were not observed. It again emphasizes the importance of the use of a profiled interface between the metal film and the dielectric for SPP excitation in periodic structures.

The aforesaid is also confirmed by the experimental results obtained in [34], according to which SPPs were not excited in cases when silver was deposited on opal globules not in a continuous layer, but in the form of separate widely spaced clusters, which hindered the „overflow" of plasmon-polaritons.

It should be noted that when silver in PPHC was replaced by gold [32], the specimens' transmission spectra also contained no peculiarities indicative of SPP excitation. In our opinion, this fact can be explained by strong absorption of light due to interband transitions in gold, which fall within the spectral region under study, as distinct from the corresponding transitions in silver [11,20,35]. It must be noted that the authors of [36,37] have observed effects related to the formation of plasmons at the Au-opal globules interface, in the specimens' reflection and Raman scattering spectra.

2. Directional change in the energy structure of photon-crystalline materials through the injection of metal nanoparticles into the opal matrix

Functional capabilities of a metal-dielectric specimen in control of EM-radiation flows can be also enhanced through directional modification of photon-energy structure (PES) of the nanocomposite based on a „solid" opal. It is known that metal-dielectric systems based on such opals can be made by metal injection into a porous dielectric matrix. This can be done using both chemical methods [26,38,39] and electric thermal diffusion [29–32].

Dispersion of various substances in a regular system of opal matrix cavities usually causes an increase of the refraction index (RI) and decrease of its contrast, which, in its turn, causes a long-wave shift of the maxima in the Bragg reflection spectra and decrease of the photonic bandgap (PBG) (widening of the PBG is usually possible only in inverted opals) [29].

Our experiments have shown that the maxima in the Bragg reflection spectra demonstrate a standard long-wave

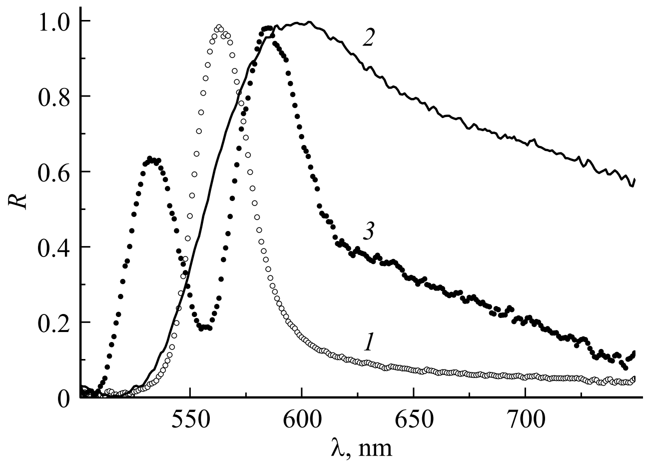

Figure 5. Normalized spectra of Bragg reflection at the light incidence angle $\theta = 30^\circ$: *1* — for the initial opal matrix, *2* — for the Ag/opal nanocomposite specimen obtained by electric thermal diffusion, *3* — for the Ag/opal specimen after heating in iodine vapors.

offset in case of a low concentration of silver nanoparticles in an opal matrix. However, as current density increases upon silver injection into the opal by electric thermal diffusion, we can see not only a significant shift of the maxima of Ag/opal photonic crystal's Bragg reflection to the „red" region at fixed values of the light incidence angle, but also a significant widening of the band in the reflection spectrum, which, moreover, becomes asymmetrical (Fig. 5, curves *1* and *2*).

Such a profile is typical for the Fano resonance [40–43] which is caused by interference of two wave processes. One of these processes in this case can be a sharp Bragg diffraction resonance in the PC, while the second one is broad-band radiation scattered on random defects of the opal matrix structure and discontinuities — dendrites which, as seen in the electron microscope images [29–31], originate during high-temperature electrolysis at points of silver penetration into the opal matrix.

It should be noted that, as a result of treatment of the Ag/opal nanocomposite in iodine vapors, an unusual „blue" offset of the maximum of the initial opal specimen's Bragg reflection (Fig. 5, curve *3*) is observed in some cases, along with a decrease of width and asymmetry of the long-wave band in the reflection spectrum, which is due to the presence of silver in the nanocomposite. It can be assumed that inhomogeneity of the Ag/opal specimen as a result of its treatment with iodine vapors considerably increases, so that the long-wave and short-wave bands on curve *3* (Fig. 5) correspond to different specimen areas. Thereat, the main contribution to the „blue" shift of the maximum in the opal matrix reflection spectrum is apparently made by the decrease in the effective refraction index of the specimen, which indicates a local increase of its porosity.

This fact can be related to the partial breakdown of dendrites due to metal interaction with iodine vapors and formation of additional voids in the composite material structure. Such a short-wave shift of the reflection spectrum, not observed in I/opal [44] and AgI/opal nanocomposites [45], provides additional possibilities of directional modification of the PES of a composite photonic crystal based on an opal matrix.

Conclusion

The paper has described the possibilities of physical-level designing of two types of model photonic-crystal metal-dielectric opal-based systems intended for control of electromagnetic radiation propagation:

1) layered structures obtained by successive deposition of metal and dielectric films onto a monolayer of opal globules;

2) Ag/opal nanocomposites based on „solid" opal matrices where silver was injected by electric thermal diffusion.

The use of opals as PCs in systems of the first type makes it easy (from the technological viewpoint) to ensure the required compliance of the morphology of the deposited metal coating with the peculiarities of the initial PC, so that the necessary phase synchronism condition for SPP excitation at the metal–dielectric interface is met. Both extraordinary optical transmission (EOT) and extraordinary optical absorption (EOA) take place, and the corresponding minima are observed in the specimens' reflection spectra in both cases.

Dispersion of silver into the opal matrix in systems of the second type has modified the system's photon-energy structure, which resulted in widening and asymmetry of bands in the specimens' reflection spectra conditioned by the Fano resonance.

The considered approach can be of interest for developers in the creation of optical systems of photonics and nanoplasmonics using photonic-crystal materials having controlled properties.

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Conflict of interest

The authors declare that they have no conflict of interest.

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