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Peculiar properties of surface plasmon-polaritons excitation in metal-dielectric structures based on opals

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Abstract. The paper reports on the study of optical phenomena peculiarities in metal-dielectric nanocomposite materials based on opal matrices caused by the excitation and propagation of surface plasmon-polaritons along the metal-dielectric interface. It is shown that two types of surface plasmon polaritons ('bright' and 'dark') can occur in the studied structures, which manifests itself in the established anomalies of light transmission and absorption.

Keywords: surface plasmon-polaritons, metal-dielectric structures, opals, optical properties

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Особенности возбуждения поверхностных плазмон-поляритонов в металлодиэлектрических структурах на основе опалов

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Аннотация. Представлены результаты исследования особенностей оптических явлений в металлодиэлектрических нанокомпозитных материалах на основе опаловых матриц, обусловленных возбуждением и распространением поверхностных плазмон-поляритонов вдоль границы раздела металл-диэлектрик. Показано, что в изученных структурах могут возникать два типа поверхностных плазмон-поляритонов («светлые» и «темные»), что проявляется в установленных аномалиях пропускания и поглощения света.

Ключевые слова: поверхностные плазмон-поляритоны, металлодиэлектрические структуры, опалы, оптические свойства

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Introduction

Surface plasmon-polaritons (SPPs) propagating at tangential directions along metal-dielectric interfaces [1] allows expanding functionality of photonic crystals [2] that control the flows of electromagnetic (EM) radiation [3–5].

One of the most common techniques for SPP excitation using phase-matching to SPP can be achieved by grating coupling:

$$\beta = k_x + 2\pi l/a, \quad (1)$$

where β and $k_x = k\sin\theta$ are tangential projections of wave vectors of SPP and incident photon, respectively, θ is the angle of light incidence, a is the period of grating, l is an integer. Thus, the peculiarity of SPP excitation by this method is that the metal-dielectric interfaces must be profiled. This can be achieved by covering the surface of opal globule [6] monolayer with a thin metal (usually silver) layer which retains the shape and spatial periodicity of the interface between the opal globules and this layer. To clarify these requirements, optical properties of two metal-dielectric opal-based structures were studied in this paper. Assuming that the optical resonator plays the main role in the studied phenomena, we used the first structure with a profiled optical resonator (Fig. 1, *a*) and the second one (control sample) with a flat resonator (Fig. 1, *b*).

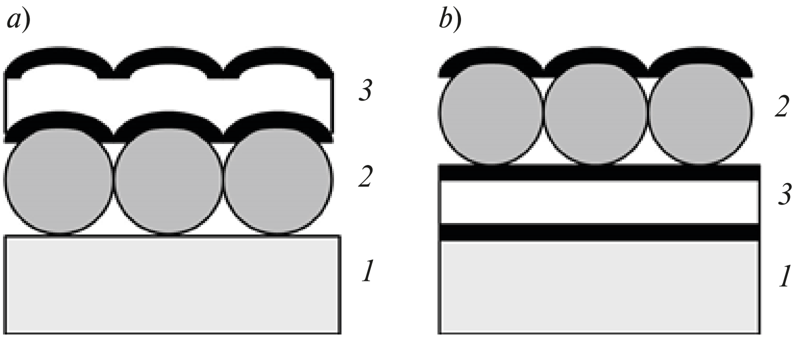

Fig. 1. Schematics of the metal-dielectric opal-based hybrid plasmon-photonic structures: glass substrate *1*, monolayer (ML) *2* of opal globules, $Ag/SiO_2/Ag$ resonator *3*
hybrid plasmon-photonic crystal $Ag/SiO_2/Ag/ML/Ag$ (*a*), hybrid plasmon-photonic crystal $Ag/ML/Ag/SiO_2/Ag$ (*b*)

Materials and Methods

Samples of hybrid plasmon-photonic crystals [7, 8] were fabricated by sequential deposition of metal (Ag) and dielectric (SiO_2) film coatings of a given thickness on a grating that was a monolayer (ML) of opal globules made of polymethyl methacrylate by magnetron sputtering on an ATC Orion Series Sputtering System.

Cross-sectional images of the samples (Fig. 2, 3) were obtained after processing them with a ZEISS FIB-SEM GEMINI scanning electron microscope (SEM). It should be noted that focused ion beam treatment (FIB-technology) probably enhances defect concentration in the $Ag/ML/Ag/SiO_2/Ag$ sample as compared with the $Ag/SiO_2/Ag/ML/Ag$ sample which has higher mechanical strength due to a rather thick SiO_2 layer deposited on the opal globes.

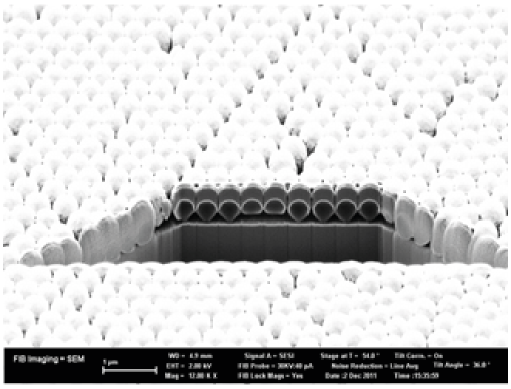

Fig. 2. SEM image of the sample of hybrid plasmon-photonic crystal $Ag/SiO_2/Ag/ML/Ag$

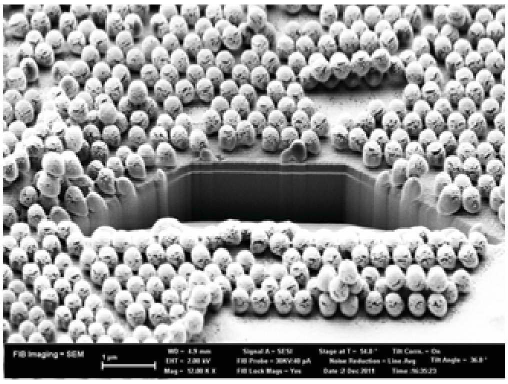

Fig. 3. SEM image of the sample of hybrid plasmon-photonic crystal $Ag/ML/Ag/SiO_2/Ag$

The transmission and reflectance spectra of *s*- and *p*-polarized light by layered thin-film heterostructures (when the vector of the electric field of the EM wave is perpendicular or parallel to the plane of incidence, respectively) were studied with angular resolution using an experimental setup based on the OceanOptics QE65000 spectrometer.

At large angles θ, Bragg reflectance spectroscopy was successfully complemented with spectral ellipsometry due to the main ellipsometric equation [9, 10]:

$$\tan \Psi \cdot e^{i\Delta} = r_p / r_s, \qquad (2)$$

where r_p and r_s are the amplitude reflectance coefficients for two types of light polarisation, Ψ and Δ are the ellipsometric parameters. In this work, ellipsometric measurements were carried out with the Ellipse-1891 spectral ellipsometer. As can be seen from Fig. 4, experimental results obtained by both optical methods are similar.

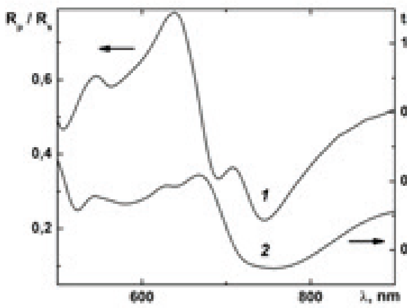

Fig. 4. Optical spectra of hybrid plasmon-photonic crystal $Ag/ML/Ag/SiO_2/Ag$ obtained from the ratio of its reflectance coefficients R_p/R_s (*1*) and from the ellipscometric parameter Ψ (*2*). Angle of light incidence θ = 50°

Results and Discussion

Both types of hybrid plasmon-photonic crystals under study (Figs. 1, 2 and 3) can be considered to be metal-dielectric optical systems consisting of two optical elements (monolayer of opal globules and resonator with transmission coefficients T_1 and T_2, respectively), series-connected and located one after another. In the absence of interaction between these ‘passive’ optical elements one can calculate the total transmission coefficient *T* of this system from the relation $T = T_1 \cdot T_2$, hence, the ratio $r = T/(T_1 \cdot T_2) = 1$. Experiment confirms this assumption [11] only for the control sample, the hybrid plasmon-photonic crystal $Ag/ML/Ag/SiO_2/Ag$ with a flat resonator (Fig. 3), but not for the $Ag/SiO_2/Ag/ML/Ag$ system (Fig. 2), where the outer surface of a thin layer covering the opal globules retained the shape and spatial periodicity characteristic of the interface between the opal-like film and this layer. In this case, excitation of surface plasmon-polaritons of various types at the interfaces profiled metal layer—monolayer of opal globules takes place. Consequently, the ratio r demonstrates a pronounced spectral dependence with the maxima at about 489 and 584 nm and the minima at 392 and 760 nm (Fig. 5, curve *3*).

We attributed these maxima to an extraordinary transmission (EOT) and the minima to an extraordinary absorption (EOA) associated with the excitation of ‘bright’ and ‘dark’ surface plasmon-polaritons, respectively [7, 8]. It should be noted that EOT maxima which can be seen in transmission spectrum of a hybrid plasmon-photonic crystal $Ag/SiO_2/Ag/ML/Ag$ (Fig. 5, curve *1*) correspond to the minima in its reflectance spectrum (Fig. 5, curve *2*). At the same time, we emphasize that the spectral positions of EOA (Fig. 5, curve *3*) correlate with the minima in the reflectance spectrum of the resonator (interference filter itself) $Ag/SiO_2/Ag$ (Fig. 5, curve *4*).

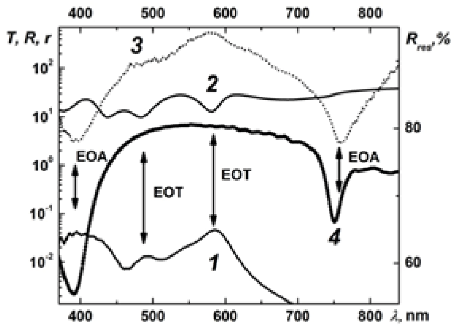

Fig. 5. Transmission ($T(\lambda)$, curve *1*) and reflectance ($R(\lambda)$, curve *2*) spectra of the hybrid plasmon-photonic crystal $Ag/SiO_2/Ag/ML/Ag$ in comparison with the ratio $r(\lambda)= T/(T_1 \cdot T_2)$ (curve *3*) and reflectance spectrum of resonator (interference filter) $Ag/SiO_2/Ag$ ($R_{res}(\lambda)$), curve *4*). Angle of light incidence θ = 50°

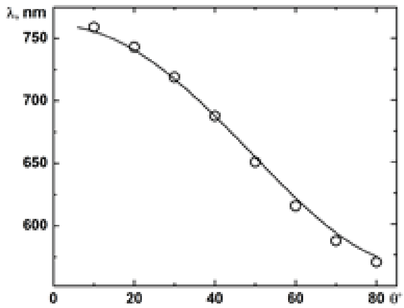

Fig. 6. Angular dispersion of the long wavelength EOA position and that of the corresponding minimum in the reflectance spectrum of resonator $Ag/SiO_2/Ag$ (circles). Solid line shows the angular dependence of the resonator transmission peak ($\lambda = 2d\sqrt{n^2 - \sin^2\theta}$, $d \approx 250$ nm, $n \approx 1.5$)

We observed this correlation for all the light incidence angles θ [7], as can be seen from Fig. 6 where the angular dispersion of the long wavelength EOA position and that of the corresponding minimum in the reflectance spectrum of resonator $Ag/SiO_2/Ag$ (circles) are demonstrated. The solid line shows angular dependence of the resonator transmission peak according to the well-known equation

$$\lambda = 2d\sqrt{n^2 - \sin^2\theta}, \tag{2}$$

where $d \approx 250$ nm is the dielectric layer thickness, $n \approx 1.5$ is its refractive index.

Conclusion

Excitation of surface plasmon-polaritons (SPPs) in opal-based hybrid plasmon-photonic crystals with a complex architecture is possible when the phase synchronism condition is met.

Two types of surface plasmon-polaritons may be excited in such metal-dielectric structures: these are 'bright' SPP, responsible for extraordinary transmission (EOT), and 'dark' SPP causing extraordinary absorption (EOA).

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