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Structure and Optical Properties of Hybrid Metal-Dielectric Colloidal Photonic Crystals

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Abstract. Metal-dielectric nanocomposite optical materials based on colloidal crystals have been prepared by electro-thermo-diffusion or magnetron sputtering of silver. Optical properties of these photonic crystals have been studied by angle-resolved reflectance and transmission spectroscopy. The interpretation of observed spectra has been made taking into account the Bragg diffraction, Fano resonance, Fabry-Perot resonance and surface plasmon-polaritons, which excitations contribute to the optical properties of plasmonic-photonic crystals.

Keywords: colloidal crystal, photonic crystals, photonic glasses, plasmonic crystal, nanostructures.

I. INTRODUCTION

Hybrid metal-dielectric photonic crystals have been fabricated on the basis of colloidal crystals [1] with the aim to design the next generation of optical materials.

Novel 3-dimensional *Ag / opal* nanocomposites have been prepared by electro-thermo-diffusion of silver in opal templates [2]. Their reflectance spectra $R_{Ag/opal}(\lambda)$ demonstrate the diffraction resonances. These resonances are red-shifted compared to those of $R_{opal}(\lambda)$ spectra due to higher effective refractive index $n_{Ag/opal} > n_{opal}$. The most striking observation is the pronounced distortion of diffraction resonance band in reflectance spectra of $Ag / opal$ nanocomposite with high metal content that contrasts to almost symmetric Bragg resonance shape of a bare opal. This phenomenon has been interpreted in [2, 3] as the manifestation of the Fano resonance [4, 5] between zero-order diffracted electromagnetic waves and those resonantly scattered by silver dendrites in *Ag / opal* composite.

Alternative approach to metal-dielectric architectures assumes integration of continuous metal films with colloidal crystals [6]. In particular, slab 2-dimensional photonic crystals represented by monolayers (ML) of spheres have been sandwiched between flat and corrugated thin metal films that terminate their bottom and the top sides, respectively, to produce $Ag / ML / Ag$ architecture. Further this structure has been equipped with a corrugated Fabry-Perot microcavity, by adding a silica film and another metal film on top of $Ag / ML / Ag$ to achieve $Ag / cavity / Ag / ML / Ag$ hybrid. The role of the metal layers here is two-fold – to form a microresonator across the structure and to guide surface plasmon polaritons (SPP) along the structure. This approach can be considered as the prototype fabrication technology for the optical chip production.

II. MATERIALS AND METHODS

Synthetic opals under study consist of silica (SiO_2) beads that are self-assembled in closely packed face centered cubic (FCC) lattice [7].

Silica opal samples were characterized by «VEGA // LMU Tescan» Scanning Electronic Microscope (SEM). According to SEM images, the mean sphere diameter of the studied opal is $D \approx 280$ nm. Moreover, some lattice disorder takes place (Fig. 1).

The electro-thermo-diffusion of silver in the 0.8mm thick opal slab has been carried out under electric field of E=3.75 kV/cm at temperature $T \approx 800$ K.

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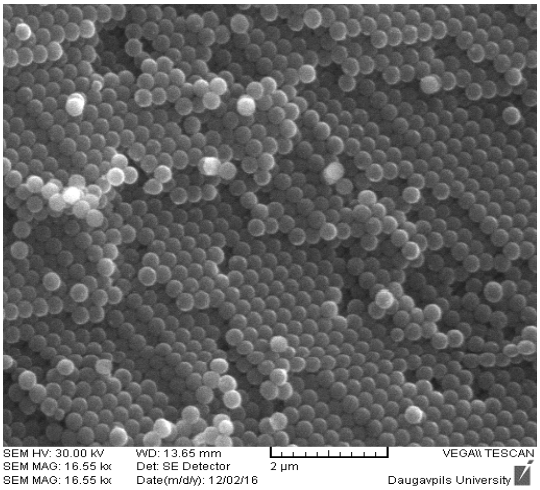

Fig. 1. SEM image of the silica opal matrix under study.

Hexagonally packed monolayer-based metal-dielectric colloidal crystals $Ag / ML / Ag$ and $Ag / cavity / Ag / ML / Ag$ have been prepared by magnetron sputtering of *Ag* in ATC ORION SERIES SPUTTERING SYSTEM [6] and characterized by "ZEISS FIB-SEM GEMINI" Scanning Electronic Microscope.

Angle-resolved reflectance and transmission spectra of the parent opal template and metal-dielectric nanocomposites have been measured using white light illumination from a tungsten lamp. Spectra have been acquired by USB650 Red Tide spectrometer (Ocean Optics).

III. RESULTS AND DISCUSSION

Figure 2 shows SEM image of the silver infiltrate in one of the defect regions of the *Ag / opal* composite, confirming infiltration of opal. Silver concentration within these defect regions (e.g., near microscopic cracks, grain boundaries etc.) may be rather high (up to few atomic %).

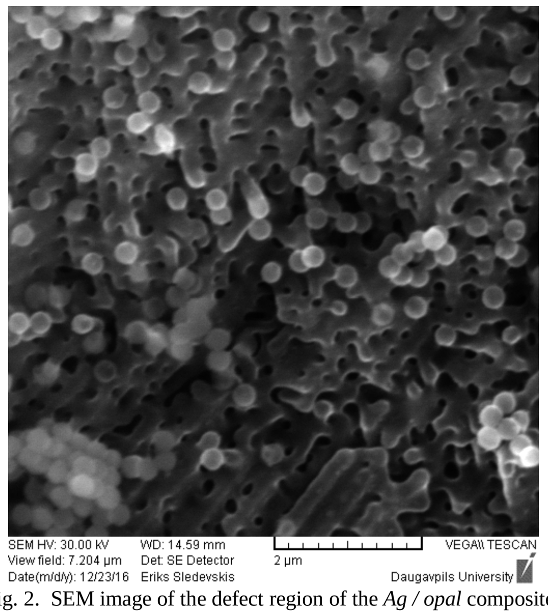

Fig. 2. SEM image of the defect region of the *Ag / opal* composite.

Reflectance spectra of opal template and those of nanocomposite *Ag / opal* at two different angles of light incidence are shown in Fig. 3.

One can see three maxima in the reflectance spectra of the opal template (Fig. 3, curves 1, 2), but only one of them (the left one in Fig. 3) demonstrates distinct angular dispersion. At small angles, the resonance wavelength is $\lambda \approx 2dn \approx 600$ nm , where $d = 0.816D$ is the interplane distance of (111) planes in FCC lattice and *n* represents the effective refractive index of the photonic crystal. Hence, the maximum centred at ~600 nm can be attributed to the zero-order (111) Bragg diffraction resonance.

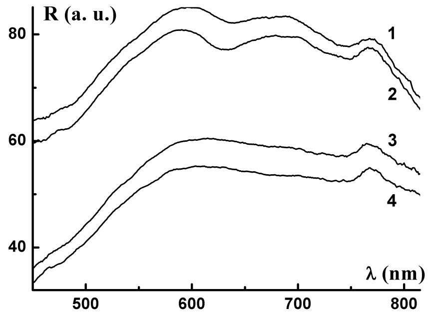

Fig. 3. Reflectance spectra of silica opal template (1, 2) and those of nanocomposite *Ag / opal* (3, 4) at the angles of incidence 25^o (1, 3) and 30^o (2, 4).

The positions of two other maxima (near 690 nm and 770 nm – see Fig. 3) seem insensitive to the angle of light incidence**.** These maxima are presumably attributed to light scattering in partially disordered opal lattice structure ("photonic glass" [8] – [10]).

The diffraction band in the reflectance spectra of Ag / opal composite (Fig. 3, curves 3, 4) differs from the Bragg resonance shape in the spectra of a bare opal (Fig. 3, curves 1, 2). As we already mentioned in Section I, this phenomenon is the manifestation of the Fano resonance [2] – [5] between two flows of electromagnetic waves: one is diffracted in the photonic crystal and the other is resonantly scattered by silver dendrites.

Figure 4 demonstrates SEM image of the hybrid colloidal plasmonic-photonic crystal [6]. This image shows the $Ag / ML / Ag$ hybrid integrated with $Ag / cavity / Ag$ resonator that is formed on top of the monolayer surface.

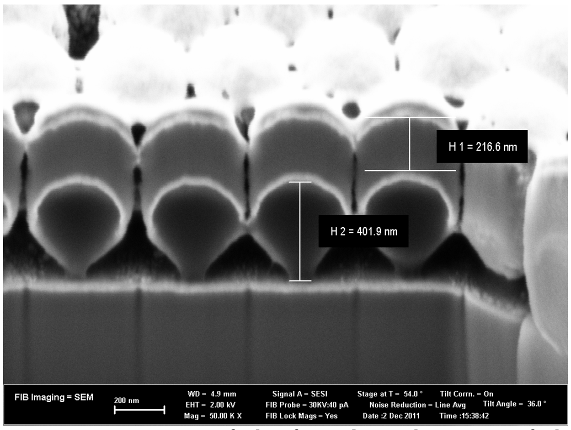

Fig. 4. SEM image of the focused ion beam cut of the *Ag / cavity / Ag / ML / Ag* hybrid colloidal plasmonic-photonic crystal under study [6].

The bare monolayer of spheres shows several resonances that correspond to the diffraction of guided resonances propagating along the monolayer (Fig. 5a, curve 1). Sandwiching a monolayer between Ag films results in the surprisingly weak transmission reduction, which is counteracted by two extraordinary transmission peaks (EOT) at 596 and 489 nm. These peaks appear due to excitation of surface plasmon polaritons (SPPs) propagating at the interfaces of flat and corrugated silver films with ML and air, respectively (curve 2). The transmission enhancement manifests the enhancement of the optical density of states in surface plasmon polaritons. Peak at 400 nm is due to the intraband transitions of silver. Curve 5 in Fig. 5b illustrates relative changes introduced by metal films represented by the ratio $r_5(\lambda) = T_2(\lambda)/T_1(\lambda)$.

If another resonator *Ag / cavity / Ag* with resonances at 770 and 385 nm (curve 3, Fig. 5a) is series connected to *Ag / ML / Ag* one, the transmission is further reduced, but this reduction occurs selectively stronger at the Fabry-Perot resonances of the cavity (curve 4). Remarkably, the transmission peaks of the microcavity are converted in transmission minima of the hybrid architecture. This is clearly illustrated by the ratio $r_6(\lambda) = T_4(\lambda)/(T_2(\lambda) \times T_3(\lambda))$, which demonstrates further enhancement of the EOT peaks and minima for cavity resonances (curve 6 in Fig. 5b). This effect can be tentatively interpreted as the extraordinary absorption (EOA). It occurs due to excitations of SPPs in the corrugated cavity in contrast to SPP absence in a microcavity with flat mirrors. Overall, one and the same architecture is capable of both enhancing and suppressing light transmission. Since both effects relate to guided SPP resonances, one can say that the transmission is enhanced owing to "bright" SPPs, whereas the absorption is enhanced owing to the cavity-related activation of normally "dark" SPPs.

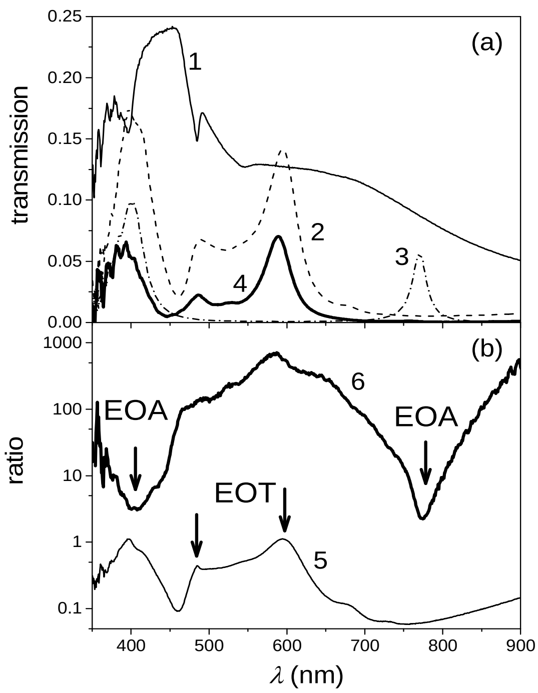

Fig. 5. (a) Transmission spectra of the monolayer ($T_1(\lambda)$, curve 1), plasmonic-photonic crystal *Ag / ML / Ag* ($T_2(\lambda)$ curve 2), microresonator ($T_3(\lambda)$, curve 3), plasmonic-photonic crystal with microresonator *Ag / cavity / Ag / ML / Ag*, ($T_4(\lambda)$, curve 4) at the normal light incidence $\theta = 0^\circ$. (b) The ratios $r_5(\lambda) = T_2(\lambda)/T_1(\lambda)$ (curve 5), $r_6(\lambda) = T_4(\lambda)/(T_2(\lambda) \times T_3(\lambda))$ (curve 6).

IV. CONCLUSIONS

The light diffraction in *Ag / opal* photonic crystals is affected by the light scattering at silver species. This interaction leads to Fano-type distortion of the Bragg resonance shape.

Engineering of optical properties of plasmonic-photonic crystals has been achieved via the architecture topology. Hybridization of different resonances results in either the extraordinary transmission or extraordinary absorption of light.

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