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Total absorption of light wave by a two-dimensional array of metal nanoparticles on a metal surface

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A design of a composite film is proposed that provides a significant reduction in reflection from a metal surface (metal film) in a narrow band of the visible spectrum due to the effective absorption of incident light energy. The composite layer is a dielectric film of subwavelength thickness, in the volume of which a two-dimensional array of metal particles of a nanometer size is located. The spectral region of high absorption is specified by the frequency of the localized surface plasmon resonance of nanoparticles. The possibility of complete absorption of incident light near the frequency of the plasmon resonance of nanoparticles is shown with the matching of the parameters of the dielectric film, the array of nanoparticles and its location in the film.

Keywords: nanocomposite coating, localized plasmon resonance, light-absorbing coating.

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1. Introduction

Thanks to the development of nanoparticle synthesis technology, nanoplasmonics has gained rapid development in the last decade [1,2]. Volume composite materials, 2D structures and clusters based on metal nanoparticles (NPs), having spheroidal or more complex shapes, are used in biosensorics, nanoprobing, nanophotonics, optical thermally induced catalysis etc. [3–5]. Wide application of plasmon nanostructures are supported by the ability to adjust their optical characteristics due to variation of the structural and electrodynamic parameters — size, shape and distance between the metal NPs, and also dielectric properties of both the NPs and the host medium [6–8].

Nanocomposite materials with plasmon resonance manifest electrodynamic characteristics, which differ from characteristics of natural materials [9]. Various optical structures are proposed on their basis, which allow to efficiently control frequency and polarization characteristics of electromagnetic waves, localize, capture and transfer electromagnetic radiation energy [10–12]. The design of polarizers and antireflection layers made using 2D arrays of NPs was proposed [13,14]. This paper demonstrated the possibility of full suppression of reflection (due to full absorption) of a light wave from the metal surface (metal film with thickness that is more than the depth of radiation penetration) by a dielectric film with one 2D array of metal NPs of moderate surface concentration (distance between the adjacent NPs exceeds their size several times).

2. Design of nanocomposite coating. Absorption spectra

The design of the considered structure is shown in Figure 1. A nanocomposite coating that represents a dielectric non-absorbing film with a 2D array of metal NPs is placed on the surface of the metal film (substrate). The layered structure is immersed into the medium with refractive index equal to 1 (air). Optical radiation falls normally at the side of the nanocomposite coating. The material of the dielectric film is characterized by the real refractive index n_f. The metal film is made of material with the complex refractive index $\tilde{n}_s = n_s + i\kappa_s$, where n_s and κ_s are refractive and absorption indices, accordingly. The thickness of the metal film considerably increases the thickness of the skin layer, which makes it non-transparent for the electromagnetic wave. It should be noted that such metal film reflects the incident light wave identically to the

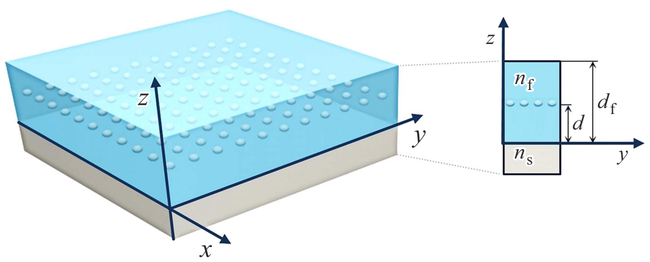

Figure 1. Nanocomposite coating with 2D array of NPs on metal film surface.

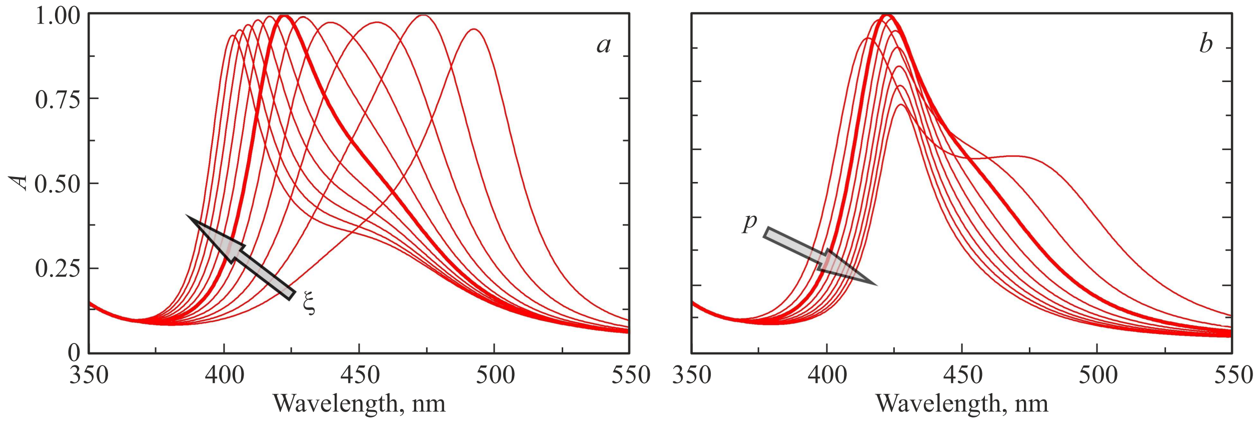

Figure 2. Dependence of absorption spectra in laminar structure with NP array on a) shape of NPs (aspect ratio of NPs ξ changes in the range from 0.5 to 1.5 with increment 0.1, interparticle distance $p = 60$ nm) and b) distances between NPs (interparticle distance p changes in the range from 40 to 120 nm with increment 10 nm, aspect ratio of NP $\xi = 1$). Structure parameters: thickness of dielectric film $d_f = 350$ nm, distance between NP array and metal film $d = 210$ nm. The bold line in the curves corresponds to the case of the array of spherical NPs ($\xi = 1$) with interparticle distance of $p = 60$ nm.

half-infinite metal medium, therefore the results obtained are also applicable to the case of the half-infinite underlying medium.

All metal NPs have the same size and the shape of spheroids. The model of spheroidal NPs makes it possible to use the known analytical expressions to calculate the spectral characteristics of 2D arrays of NPs [15]. The shape of the NP is determined by the 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 dielectric film: $2a,\ 2b \ll \lambda_0/n_f$, where λ_0 is wavelength in vacuum. For simplification, a case is analyzed, when the polar axis of NP is directed perpendicularly to the surface of the metal film. NPs form a 2D array with a square cell, which is positioned at the distance from the metal film of d, $a < d < d_f - a$, where d_f is a dielectric film thickness.

To calculate the spectral characteristics of the layered structure, the transfer matrix method is used, within which each structural element is associated with a matrix that determines the relationship of the fields at its two interfaces [16]. For the interfaces between the continuous media, the transfer matrix is defined with the help of Fresnel reflection and transmission coefficients. The NP array is considered as an interface (a layer of quasi-zero thickness) with non-Fresnel transmission and reflection coefficients, to which a specific transfer matrix is associated [17]. The resulting transfer matrix of the entire structure is obtained through the sequential multiplication of the transfer matrices for homogeneous layers and 2D NP array in accordance with the order of their occurrence in the direction of propagation of the incident electromagnetic wave. The transmissivity, reflectivity and absorptivity (A) of the entire structure are determined via the elements of the resulting transfer matrix.

In this paper the numerical calculations are made for the case, when the metal film and particles are made of silver (Ag), dielectric film — of glass (SiO_2) with the corresponding complex refractive indices [18,19]. To simplify the analysis, the following parameters of the structure have the fixed values: the length of the polar semi-axis of NP is $a = 10$ nm, the thickness of the metal film is equal to 200 nm.

From the dependences shown in Figure 2 one can see that the absorptivity of the structure with 2D array of silver NPs in a certain spectral range takes on values close to 1. Dissipative losses in the system of „composite film with NP array — metal film" are maximum near the frequency of the localized surface plasmon resonance of NPs. As a result of shift of the plasmon resonance frequency as the shape of the particle changes, with the rising aspect ratio ξ (when changing from the oblate to the elongated shape of NP) the maximum of the absorption curve is shifted to the short-wave region of the spectrum, and vice versa (Figure 2, a). The change in the interparticle distance mainly results in the change of the maximum value of absorptivity (Figure 2, b). The exception is the case of the relatively dense array of NPs, when its spectral characteristics begin to be determined by both the characteristics of individual NPs and effects of collective electrodynamic interaction in the NP array, resulting in the rearrangement of its resonances (see curves in Figure 2, b for $p < 70$ nm).

As it was shown in papers [13,20], in the layered composite structure the efficiency of interaction of the NP array with the electromagnet wave is higher when the NPs are placed in the region of local maxima of the electric field strength of the wave. In the considered case this condition plays an important role too. Figure 3 shows the distribution of the field inside the dielectric film (along the coordinate axis Oz) depending on the wavelength of the incident radiation, and also presents the absorption spectra

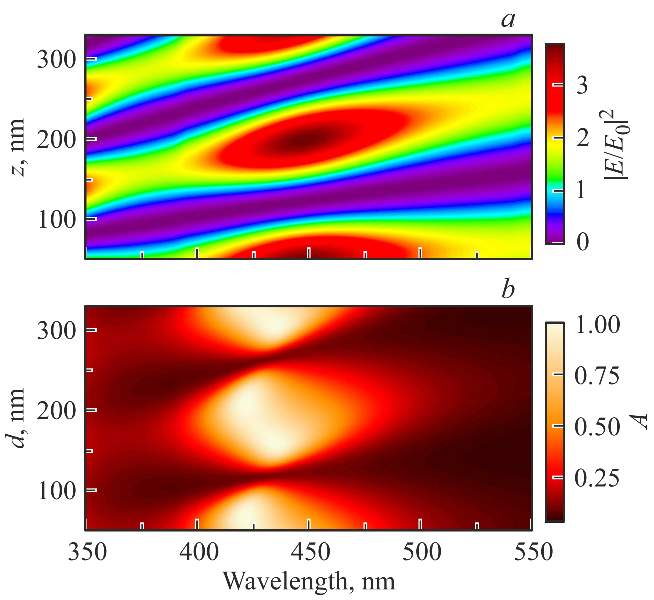

Figure 3. *a*) Distribution of electric field inside dielectric film without NPs depending on the wavelength of the incident light wave. *b*) Absorption spectra when NP array is placed at different distance d from the metal film, NP array parameters: aspect ratio of NPs $\xi = 1$, interparticle distance $p = 60$ nm, distance d takes on values in the range from 50 to 330 nm. Other parameters are the same as in Figure 2.

at different location of the NP array inside the dielectric film (different distance d between the NPs and the metal film). From comparison of these dependences one can see that the absorption is higher when the NP array is located in the areas of light wave localization, arising as a result of interference of the incident and reflected waves in the dielectric film. The absorption is observed near the plasmon resonance of the NP array, and its maximum is in the wavelength range from 415 to 445 nm (the absorption maximum moves as the distance d changes between the NP and the metal film).

3. Conclusion

It is shown that using a single layer of metal NPs with moderate surface concentration (around 250 NPs in the area of $1\,\mu\text{m}^2$), placed in the dielectric film of the subwavelength thickness, one may considerably reduce the intensity of the reflected wave from the metal surface (up to complete suppression of reflection) in the spectral band with width of several dozens of nanometers. The reflection is suppressed by effective absorption of energy of the incident light wave by conducting (metal) components of the structure. Outside the spectral area of plasmon resonance, the NP array practically has no impact at the reflection from the metal surface. The described effect has a resonant nature, and for its implementation, it is necessary to select the spectral and structural parameters, including the thickness of the dielectric film, shape and surface concentration of the NPs in the 2D array, and its location in the dielectric film. In the composite structures based on the materials differing from the ones considered in this paper (semiconductor films, quantum dots, graphene particles, carbon nanotubes, nanoparticles of gold and other metals), the effect of resonance absorption may be implemented for other frequencies, including beyond the boundaries of the visible spectral domain of electromagnetic radiation.

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Conflict of interest

The authors declare that they have no conflict of interest.

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