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Optical Properties and Some Applications of Plasmonic Heterogeneous Materials

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1. Introduction

Metamaterials with extraordinary optical properties can find a variety of applications, in particular for manufacturing superlenses, prisms, nonreflecting (absorptive) materials, as well as controlling the optical beam intensity and propagation direction, etc. (Cai & Shalaev, 2010; Hutter & Fendler, 2004). In recent years, a large number of structures have been proposed and theoretically and experimentally investigated, which possess negative, high or small refractive indices (Moiseev et al., 2007; Oraevskii & Protsenko, 2000; Shalaev et al., 2005; Shen et al., 2005; Sukhov, 2005; Yuan et al., 2007), selective absorption of or transparency to optical light (Kachan et al., 2006; Kravets et al., 2008; Protsenko et al., 2007).

The promising candidates for a design of structures with extraordinary optical properties are plasmonic materials. Collective electronic excitations called plasmons lead to strong dispersion and absorption of light in such artificial media. For practical applications, it is important that the optical properties of composite medium incorporating metallic nanoparticles can be controlled by careful selection of geometric parameters of nanoparticles (Moiseev, 2004, 2009; Oraevskii & Protsenko, 2000). By selecting distributions of the form of metallic nanoparticles, it is possible to achieve absorption of electromagnetic radiation in specified spectral regions of visible or near IR radiation (Protsenko et al., 2007). An additional effective way of the plasmon resonance control is by spatial arrangement of metal-dielectric nanocomposites, for example, forming the multilayer systems consisting of metallic nanoparticles separated by dielectric layers (Kachan et al., 2006). It was proposed that such composite materials with controlled absorption of light can be used as cut-of filters and high-absorbing coatings.

In this work, a more detailed investigation of optical properties of a matrix metal-dielectric medium with spheroidal silver inclusions is performed, and the possibility to realize plasmonic structures with beneficial effects in the visible region is considered. In so doing, it is assumed that the characteristic size of inclusions and their volume concentration satisfy the conditions of applicability of the effective medium Maxwell–Garnett model.

2. Main formulae

2.1 Size-dependent dielectric function of silver nanoparticles

From the optics of metal nanosized particles it is well known that their optical properties significantly depend not only on their chemical composition but also on their size, so the permittivity of metal nanoparticles differs from the bulk permittivity of the medium (Khlebtsov, 2008). Throughout this communication, silver nanoparticles are considered (they are chosen because of their lowest absorption in the optical range). In order to estimate variation in the dielectric permittivity ε of a metal nanoparticle in comparison with that of a bulk sample, let us use a classical model taking into account the limitation in the electron free path length due to its collision with the particle boundary (Kreibig & Vollmer, 2004). According to this model, the finite size of a metal particle leads to a change in the relaxation rate of conduction band electrons:

$$\gamma = \gamma_0 + v_F / r , \qquad (1)$$

where γ_0 is the electron relaxation rate in the metal, v_F is the mean electron velocity at the Fermi surface, r is the characteristic particle radius along the electric field direction of external electromagnetic wave. Then, the size-dependent permittivity of the nanoparticle has the form (Yannopapas et al., 2002):

$$\varepsilon(\omega, r) = \varepsilon_b(\omega) + \frac{\omega_p^2}{\omega(\omega + i\gamma_0)} - \frac{\omega_p^2}{\omega(\omega + i\gamma)} , \qquad (2)$$

where ω is the frequency of the incident field, ω_p is the plasma frequency, ε_b is the experimentally determined permittivity for a bulk sample. The tabular data for bulk silver are $v_F = 1.4 \cdot 10^6$ m/s, $\hbar\gamma_0 = 0.02$ eV, $\hbar\omega_p = 9.2$ eV (Yannopapas et al., 2002) and the spectral dependence values of the macroscopic dielectric permittivity $\varepsilon_b(\omega)$ are presented in Ref. (Ordal et al., 1983).

Calculations show that the correction taking into account the finite size of the particle leads mainly to a variation of the imaginary part of the permittivity ε (see Fig. 1), while the real
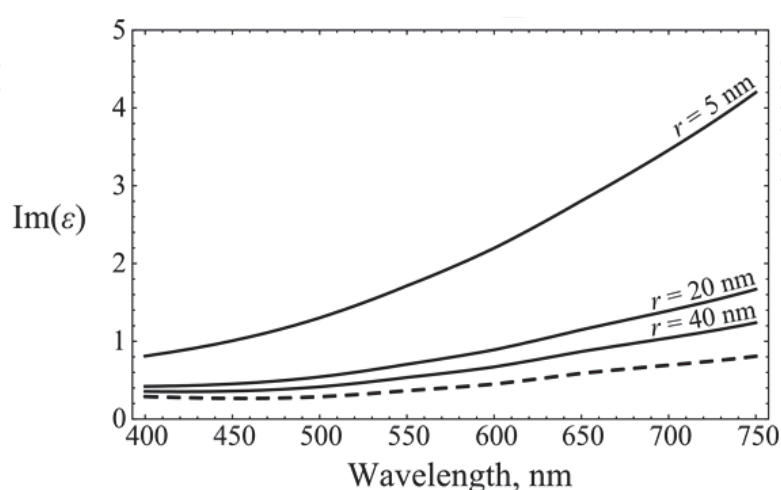

Fig. 1. Imaginary part of the dielectric permittivity of silver bulk sample (*dashed line*) and silver nanoparticles with r = 5, 20, and 40 nm (*solid lines*).

part of ε changes slightly for the particle with radius as large as 5 nm. For instance, for a wavelength of external radiation $\lambda = 400$ nm, the value of ε_b for a bulk silver is equal to $-3.72 + 0.29i$, while calculations via formulas (1) and (2) give the following results: $\varepsilon = -3.72 + 0.36i$ for a spherical particle with the radius $r = 40$ nm, $\varepsilon = -3.72 + 0.42i$ for $r = 20$ nm, and $\varepsilon = -3.68 + 0.81i$ for $r = 5$ nm. It should be noted that in the case of a nonspherical particle the size correction of the Drude model leads to the dependence of the permittivity ε on the direction of the external field.

2.2 Maxwell-Garnett approach

Let the light wavelength significantly exceed the size of particles suspended in a dielectric matrix. If the interference effects on the nanoparticles are ruled out (the spatial positions of the nanoparticles don't have to be periodic and can be random) and their volume fraction is as small as 1/3, it is considered that Maxwell-Garnett approach can be used successfully to analyse the optical properties of such composite medium (Golovan et al., 2007; Moiseev et al., 2007; Moiseev, 2009, 2010). The Maxwell – Garnett relation assumes a generalization for the case of shape anisotropy of the inclusion (particles), thus providing a possibility of analyzing optical characteristics of a composite medium with non-spherical inclusions based on analytical expressions.

For composite medium with uniformly oriented metallic spheroids in a dielectric matrix, the effective permittivity ε_{eff} according to Maxwell-Garnett approach is determined by the following expression (Golovan et al., 2007; Maxwell-Garnett, 1904, 1906):

$$\frac{\varepsilon_{eff} - \varepsilon_m}{L(\varepsilon_{eff} - \varepsilon_m) + \varepsilon_m} = \eta \frac{\varepsilon - \varepsilon_m}{L(\varepsilon - \varepsilon_m) + \varepsilon_m} \, , \tag{3}$$

where ε_m is the matrix permittivity, ε is the permittivity of inclusions (Eq. (2)), η is the volume concentration of the nanoparticles (filling factor), L is the geometrical factor (factor of depolarization) that accounts for the shape of a particle (Bohren & Huffman, 1998). In the long-wavelength limit, factor L is a real value, that depends on the ratio ξ of the length of polar semi-axis a and equatorial semi-axis b of spheroid, $\xi = a / b$. The value of factor L can be written as

$$L_{||} = \frac{1}{1 - \xi^2} \left(1 - \xi \frac{\arcsin \sqrt{1 - \xi^2}}{\sqrt{1 - \xi^2}} \right) \tag{4}$$

for the field directed along the axis of revolution of spheroid and as

$$L_\perp = \left(1 - L_{||} \right) / 2 \tag{5}$$

for the field directed perpendicular to this axis. The case where $\xi < 1$ corresponds to disc-like nanoparticles, $\xi > 1$ – to needle-like nanoparticles, $\xi = 1$ – to spherical nanoparticles, with $L_\perp = L_{||} = 1 / 3$ in the latter case.

By a comparison with exact electrodynamical calculation, it was shown in (Moiseev et al., 2007; Moiseev, 2009, 2010) that for matrices with a moderate content of inclusions (0.01 < η < 0.3) results obtained within the Maxwell-Garnett model are in fairly good agreement with the results of exact electrodynamic calculation.

3. Spectral characteristics of Maxwell-Garnett composite with plasmon resonances

Eq. (3) is written for a composite medium with uniformly oriented spheroids, where the field vector is directed either along or perpendicular to the ellipsoid axis. For non-spherical particles, depolarization factors (4), (5) and dielectric permittivity (2) depend on the electric field direction. Therefore in the general case we deal with an anisotropic composite, which possesses properties of uniaxial crystal having an optical axis collinear with the polar axis a of spheroids. A light ray in this medium is ordinary if its propagation direction is collinear with the polar axis of spheroids; in this case, the light polarization vector lies in the equatorial plane of spheroids.

In the case of a spheroid and an applied electric field oriented along a spheroid axis, the static polarizability of nanoparticle is

$$\alpha = \frac{V}{4\pi} \frac{\varepsilon - \varepsilon_m}{L(\varepsilon - \varepsilon_m) + \varepsilon_m} , \tag{6}$$

where V is the particle volume. As follows from Eq. (6), the plasmon resonance frequency depends on the form of the particle. If a transparent dielectric is used as surrounding host medium, the resonance wavelength λ_{res} of metal spheroid can be estimated by using simple algebraic equation

$$\mathrm{Re}\big[\varepsilon(\lambda_{res})\big] + \frac{1-L}{L}\varepsilon_m(\lambda_{res}) = 0 . \tag{7}$$

In the case of spheroidal ($\xi \neq 1$) silver nanoparticle, Eq. (7) has two roots corresponding to two polarizations of the electromagnetic field. One root tends to longer wavelengths due to the absorption of light polarized parallel to the long axis of the spheroid (the case of parallel polarized light). The other root shifts to shorter wavelengths due to the absorption of light polarized parallel to the short axis of the spheroid (the case of perpendicular polarized light). The more different shapes of nanoparticles from the spherical ones, the more is difference in the resonance wavelengths corresponding to two polarizations of the electromagnetic field. Dependence of the plasmon resonance wavelength of a silver spheroid on its aspect ratio is shown at Fig. 2.

Plasmon resonances of nanoparticles give rise to 'extraordinary' values of the effective permittivity $\varepsilon_{eff} = (n_{eff} + ik_{eff})^2$ of mixture. Shown in Fig. 3 are the results of calculation of spectral dependences of the effective refractive index

$$n_{eff} = \sqrt{\frac{\sqrt{(\mathrm{Re}[\varepsilon_{eff}])^2 + (\mathrm{Im}[\varepsilon_{eff}])^2} + \mathrm{Re}[\varepsilon_{eff}]}{2}} \tag{8}$$

and the effective extinction coefficient

$$k_{eff} = \sqrt{\frac{\sqrt{(\mathrm{Re}[\varepsilon_{eff}])^2 + (\mathrm{Im}[\varepsilon_{eff}])^2} - \mathrm{Re}[\varepsilon_{eff}]}{2}} \tag{9}$$

obtained from the Maxwell–Garnett relation (3). As a matrix, we chose a non-absorbing medium with the refractive index $n_m = \sqrt{\varepsilon_m} = 1.5$. One can see from Fig. 3 that due to plasmon resonance of silver nanoparticles the effective refractive index of composite medium differs considerably from the one of matrix. Moreover, in the vicinity of the plasmon resonance the effective refractive index assumes the values $n_{eff} < 1.25$ not observed in natural materials. From the practical point of view it is interesting that n_{eff} can achieve values equal or less than one as well as values much greater than one. Unfortunately, these 'extraordinary' values of n_{eff} are observed together with the effective extinction coefficient different from zero. An increase in the concentration of inclusions extends the range of attainable values of n_{eff}, but at the same time gives rise to higher values of k_{eff} in the resonance region.
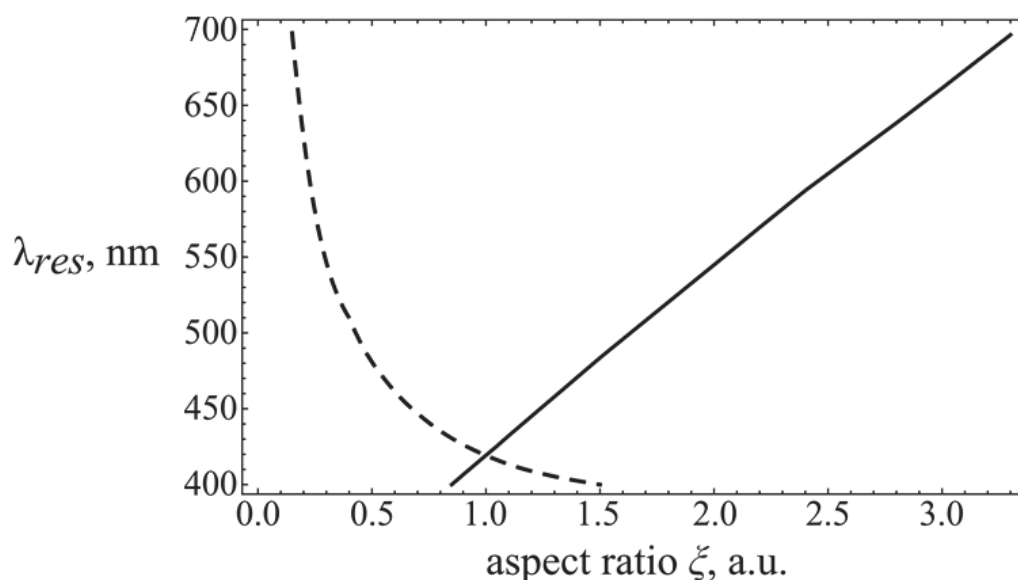
Fig. 2. Dependence of the plasmon resonance wavelength λ_{res} of a silver spheroid on the aspect ratio ξ obtained from Eq. (7) for parallel (*solid line*) and perpendicular (*dashed line*) polarized light. Dielectric function of the matrix ε_m= 2.25.

4. Applications of plasmonic heterogeneous materials

4.1 Heterogeneous composite with the unite refractive index

Let us have a closer look at the conditions where a unit effective refractive index ($n_{eff} = 1$) is observed in a composite medium with a comparatively low extinction coefficient ($k_{eff} << 1$). This medium is attractive from the point of view that a light ray falling on it from the air is nearly non-reflective (Sukhov, 2005). Indeed, using the Fresnel formulas we can readily obtain the following expression for reflectance: $R \approx (k_{eff} / 2)^2 << 1$. In this case, the reflectance depends only on the absorption coefficient of the medium and decreases very fast with k_{eff}. A comparatively thick film ($h \geq \lambda / k_{eff}$) manufactured from this material near the plasmon resonance frequency would possess properties of a weakly reflecting absorbing coating.

The conditions where an effective refractive index is observed could be derived analytically directly from the Maxwell – Garnett relation (3). For a fixed refractive index $n_{eff} = 1$, the real

and imaginary parts of Eq. (3) form a system of two equations, wherein it makes sense to consider quantities k_{eff} and η as independent variables. We do not cite the solutions to this system of equations due to their awkward form but merely present the dependences obtained with them, which are shown in Fig. 4.

The dependences plotted in Figs. 3 and 4 imply that the conditions $n_{eff} = 1$, $k_{eff} \ll 1$ cannot virtually be satisfied at the same time, if the inclusions are spherical ($\xi = 1$). For the volume fractions of nanoparticles larger than 0.06, the condition $n_{eff} = 1$ is fulfilled near the external radiation wavelength 400 nm, but for a comparatively large extinction coefficient $k_{eff} > 0.6$. For a smaller fraction of silver, the unit refractive index cannot be obtained within the entire optical range.

The situation is different when inclusions are nonspherical ($\xi \neq 1$). In such composite media the influence of the dispersion subsystem on the effective optical characteristics is stronger, and the condition $n_{eff} = 1$ is fulfilled for a much smaller (by a few factors or even an order of magnitude) effective extinction coefficient. To illustrate this, let us consider the results of calculations presented in Fig. 3c: in the short-wave spectral region the effective refractive index acquires the values close to unity for all ξ, while for the spherical, flattened and elongated particles the absorption coefficient is different, $k_{eff} > 1$, $k_{eff} \sim 1$, and $k_{eff} < 0.1$, respectively. It should be noted that in those cases where the unit value of the effective refractive index is attained for several values of k_{eff}, we consider the smallest of these values.

The dependences presented in Fig. 4 also demonstrate that k_{eff} assumes small values predominantly in the short-wave spectral region and in the case of nonspherical inclusions only. Unlike the case where $\xi = 1$, an increase in the concentration of nonspherical inclusions, rather than giving rise to an increase in absorption of a composite medium, results in a decrease in the absorption of a medium with a unit refractive index, however, to a certain limit, since the function $k_{eff}(\eta)$ exhibits a local minimum falling within the visible region for certain $\xi \neq 1$. In the case corresponding to Fig. 4c, k_{eff} assumes minimum values at $\lambda = 434$ nm. For these parameters, the reflectance of the composite would be less than 10^{-3}.

4.2 Transparent Maxwell-Garnett composite with the unite refractive index

It follows from the Maxwell-Garnett formula (3) that because the permittivity of the metal particles is complex, condition of optical transparency

$$\mathrm{Im}(\varepsilon_{eff}) = 0 \tag{10}$$

cannot be satisfied exactly for the matrix with real ε_m. Let us try to compensate the effect of the imaginary part of the metal permittivity on the optical properties of the entire composite medium by choosing an amplifying medium as the matrix. For this purpose, we will simulate the optical parameters of the amplifying medium by adding an imaginary part to the permittivity (Moiseev et. al., 2007):

$$\varepsilon_m = n_m^2 - g^2 - 2in_m g, \tag{11}$$

where $g > 0$ is the gain (extinction coefficient), which is equal to the gain coefficient multiplied by $\lambda / 2\pi$.
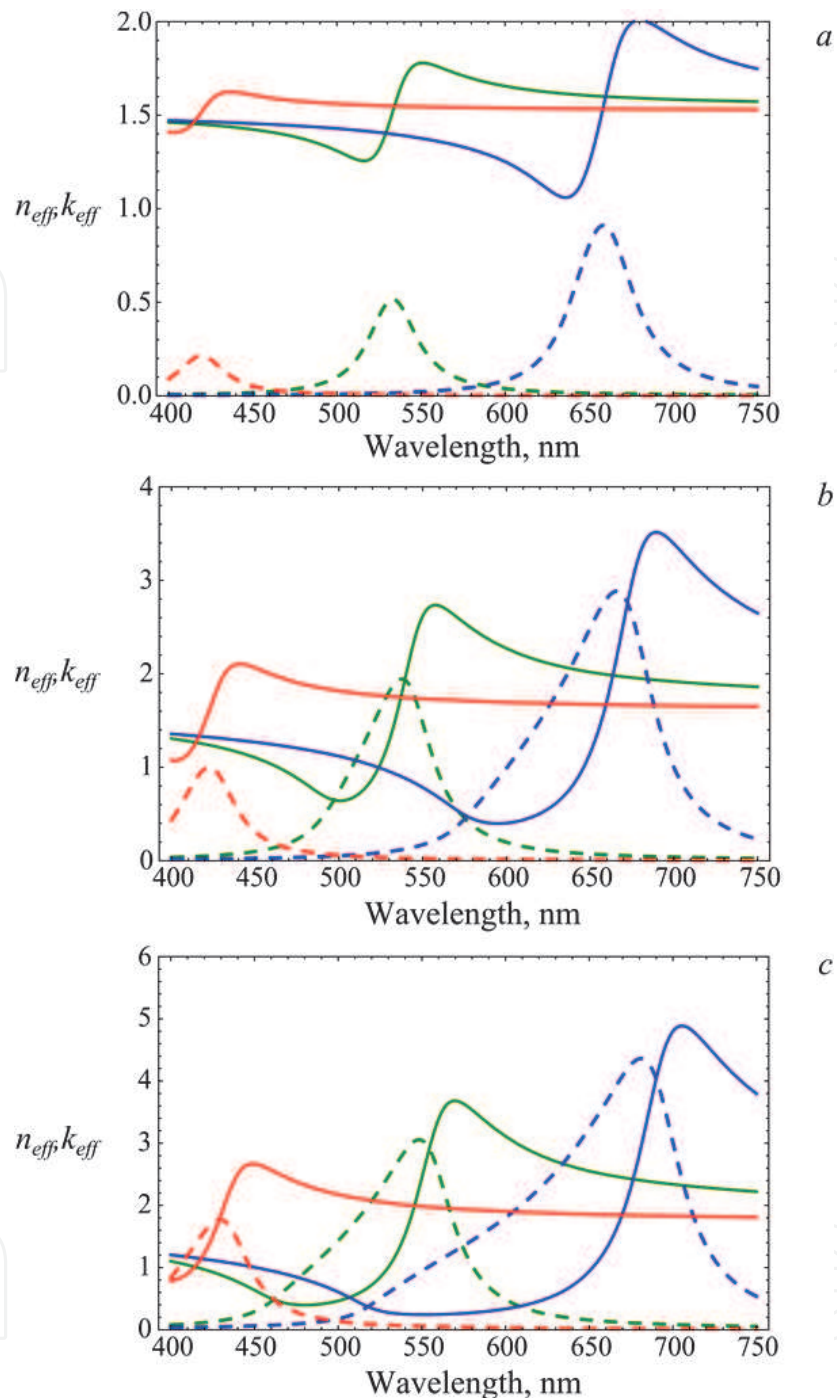
Fig. 3. Spectral dependences of n_{eff} (*solid lines*) and k_{eff} (*dashed lines*) of composite media with spherical inclusions ($\xi = 1$, *red lines*), inclusions shaped as flattened ($\xi = 1/3$, *green lines*) or elongated ($\xi = 3$, *blue lines*) spheroids for the volume fractions of inclusions 0.01 (a), 0.05 (b) and 0.1 (c). The radius of the spherical particle is equal to 7 nm, the lengths of the spheroid semi-axes are selected such that their volume is equal to that of a spherical particle. In the case of elongated spheroids, the light wave field is directed along the axis of rotation of particles, while in the case of flattened spheroids, the light vector lies in their equatorial plane.
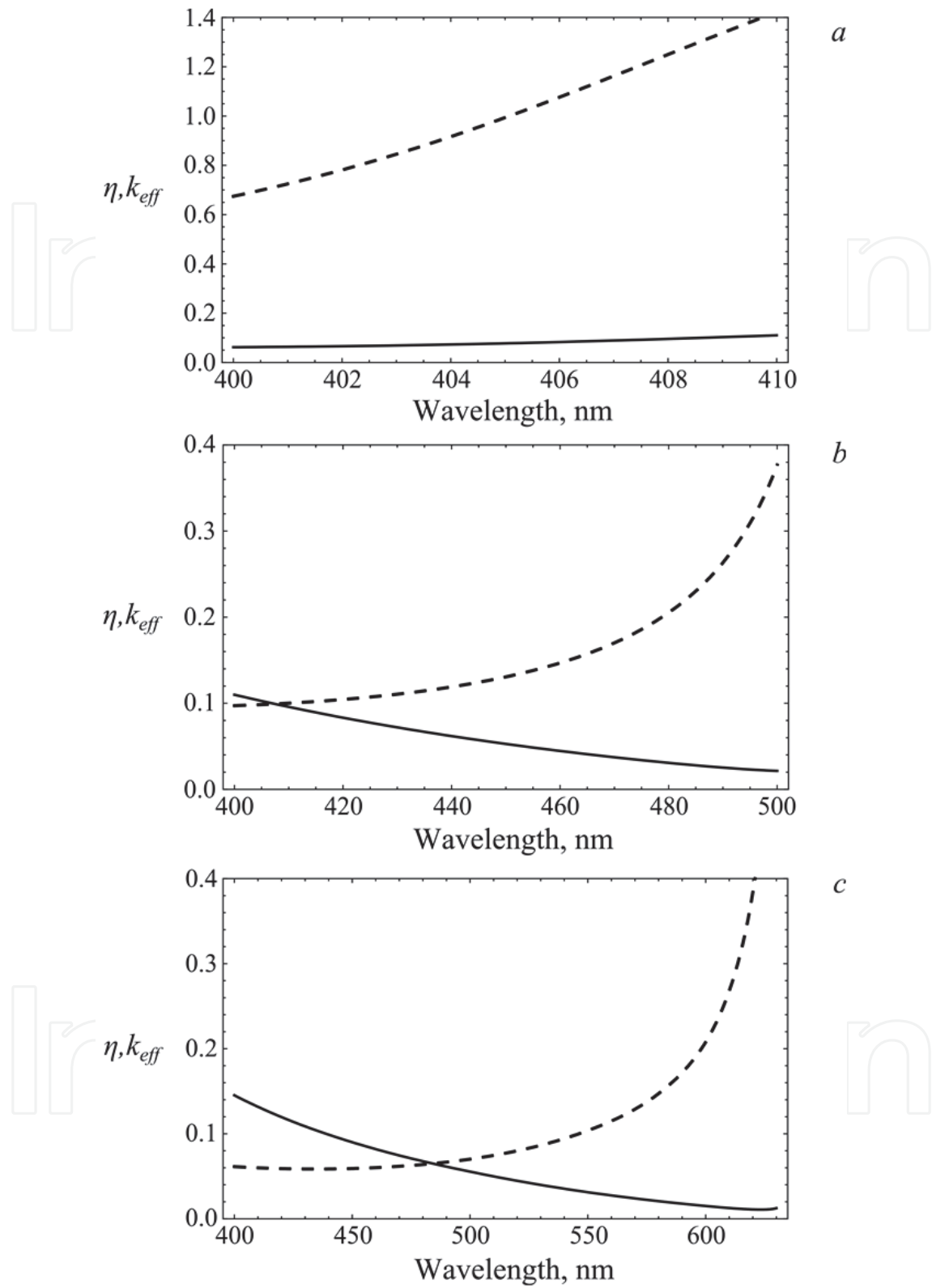
Fig. 4. Effective extinction coefficient k_{eff} (*dashed lines*) and the volume fraction of inclusions η (*solid lines*) of a composite medium with the unit effective refractive index. Silver inclusions are spherical particles (*a*) and flattened (*b*) and elongated (*c*) spheroids. Particle parameters are the same as given in Fig. 3.

Consider the dependence of the gain g, which is required for compensating the absorption of external electromagnetic radiation, on geometric and material parameters of composite medium. When the gain of the matrix is much smaller than its refractive index, from equation (3) one can obtain

$$g \approx \frac{\eta}{1-\eta} \frac{n_m^3}{2\left((1-L)n_m^2 + L\,\mathrm{Re}(\varepsilon)\right)^2 + 2(1-L)L\left(n_m^2 - \mathrm{Re}(\varepsilon)\right)^2 \eta}\,\mathrm{Im}(\varepsilon)\,. \qquad (12)$$

Unlike other metals, the permittivity of silver has comparatively small imaginary part. Thus, having taken silver inclusions we result in decreasing in the required gain. Decrease in the volume concentration of the nanoparticles contributes to decrease in the gain g, although this way is not worth considering because $n_{eff} \approx n_m$.

From equation (12) it follows that g depends on the factor of depolarization L. The variation of L leads to the shift of the plasmon resonance, and correspondingly, the wavelength λ, on which the unique index of refraction is observed. Thus, analysis of the transparency conditions is to be taken basing on predefined value of n_{eff}. Here we consider the case $n_{eff} = 1$ ($\varepsilon_{eff} = 1$), when the composite medium is invisible.

The conditions of invisibility of Maxwell-Garnett composite with inclusions of different shapes are presented in Fig. 5. Horizontal axis shows the region of wavelengths, on which the unit
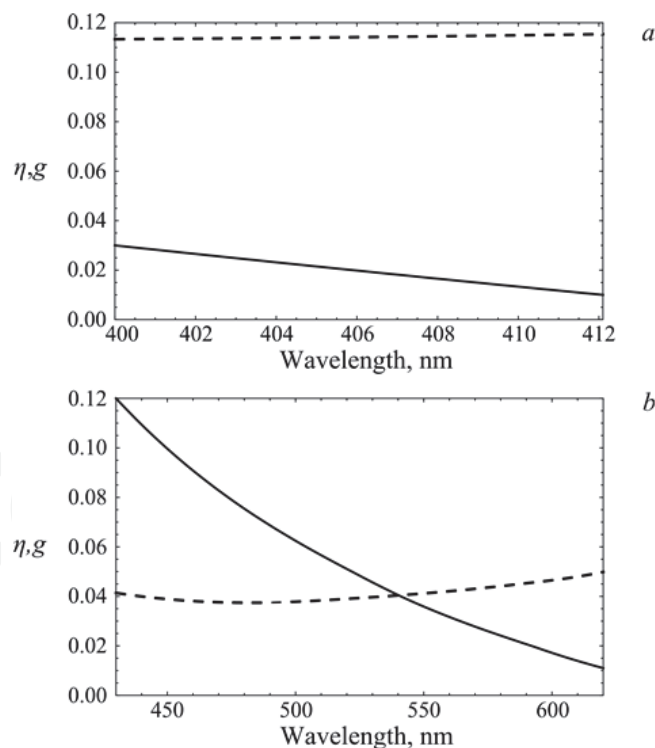
Fig. 5. Gain g of matrix (*dashed lines*) and the volume concentration η (*solid lines*) of spherical (*a*) and needle-like (*b*) nanoparticles are required to produce a transparent composite material with the unit index of refraction. The radius of the spherical particle is equal to 7 nm, the volume of the spheroid with $\xi = 3$ is equal to that of a spherical particle. The external field is oriented parallel to the spheroid revolution.

index of refraction can be obtained. The dependence obtained allows defining the filling factor, whereby the gain required for the transparency of composite medium is minimal. Contrasting parts (*a*) and (*b*) of Fig. 5, the following conclusions can be made. Firstly,composite media with nonspherical nanoparticles require less value of gain of the active component. It can be explained in the following way. In spite of volume of particle being equal the characteristic diameter of the needle-like particle in the direction of the field is bigger, and consequently, the imaginary part of the permittivity *ε* is less than that of spherical nanoparticles. Therefore in the case (*b*) the values of the gain necessary for compensation of absorption are smaller. Secondly, the condition $\varepsilon_{eff} = 1$ can be fulfilled over a wide range of wavelengths covering almost the entire visible spectrum, but exclusively for inclusions of nonspherical forms.

4.3 Heterogeneous medium for anti-reflection coating application

Optical properties of heterogeneous metal-dielectric composites can be efficiently tailored by nanoparticle sizes, shapes, and concentration. As it is shown in Section 4.1, for nonspherical inclusions the effective coefficient of composite extinction is several times smaller than for spherical ones. Let us determine the values of the structural parameters at which a composite slab with nonspherical inclusions can be used as an interference antireflection coating in the visible spectral range.

The use of the effective-medium model significantly simplifies the study of the dispersion characteristics of composite coating: disregarding the discrete-continuous structure of the composite, one can calculate the reflectance and transmittance using the Airy formulas (Born & Wolf, 1999). According to these formulas, for normal incidence of light the reflection from dielectric is completely suppressed by a layer of material with a complex refractive index $n_{eff} + ik_{eff}$ if its imaginary part $k_{eff} \ll 1$, the refractive index n_{eff} and thickness h satisfy the conditions

$$n_{eff} \approx \sqrt{n_s}\left(1 - \frac{\pi(n_s-1)}{4n_s}k_{eff}\right), \tag{13}$$

$$h \approx \frac{\lambda}{4\sqrt{n_s}}\left(1 + \frac{4}{\pi(n_s-1)}k_{eff}\right), \tag{14}$$

where n_s is the refractive index of substrate. The values of the composite parameters at which condition (13) is satisfied simultaneously with the inequality $k_{eff} \ll 1$ can be determined from relation (3), taking into account (2), (4), and (5).

The anisotropy of optical properties of ordered composite imposes certain limitations on the antireflection coating design. To make the composite coating reflectance and transmittance independent of the light vector orientation for normal incidence of light, the optical axis of the composite must be perpendicular to the interfaces, i.e., the equatorial plane of spheroids must be parallel to the plane of composite plate. With allowance for this circumstance, we will consider the optical properties of the composite only for an ordinary ray. For definiteness, we consider a transparent dielectric with a refractive index $n_m = \sqrt{\varepsilon_m} = 1.5$ as a matrix (light glass, polycarbonate, and other widespread optical materials have similar refractive indices).

Figure 6 shows the spectral dependencies of the effective refractive index and extinction coefficient of the composite, calculated from (3). The peaks in the curve $k_{eff}(\lambda)$ correspond to plasmon resonances of nanoparticles. The resonances for $\xi > 1$ and $\xi < 1$ are always at different sides from the plasmon resonance of spherical particles (the plasmon resonance in Fig. 6(b) blueshifts). Therefore, oblate silver nanospheroids (nanodisks) are most appropriate for our purposes: due to the redshift of the plasmon resonance, the range of small refractive index $n_{eff} < 1.3$ is in the visible spectral range at a relatively low extinction coefficient $k_{eff} \ll 1$.
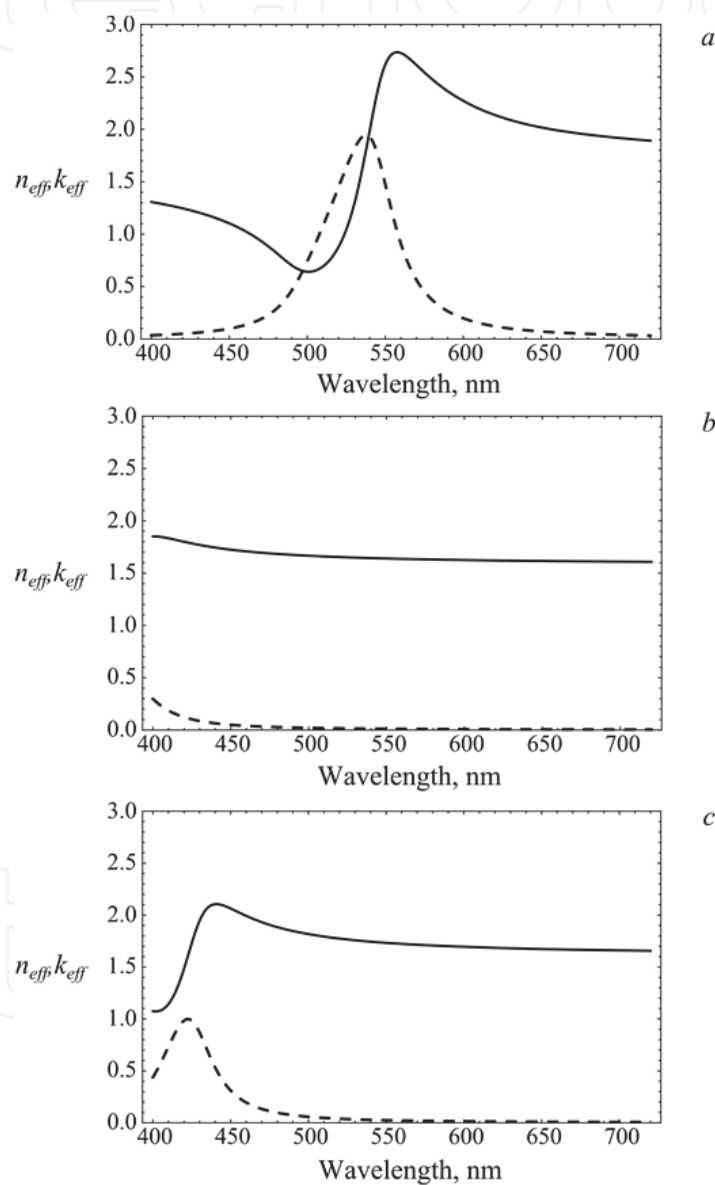
Fig. 6. Dispersion relations of the refractive index n_{eff} (*solid lines*) and extinction coefficient k_{eff} (*dashed lines*) for a composite with (*a*) spherical inclusions and (*b, c*) inclusions in form of (*b*) elongated and (*c*) oblate spheroids. The radius of spherical particles is 7 nm, and each spheroid has a volume equal to that of spherical particle. The volume fraction of silver nanoparticles is 0.05.

Thus, the antireflection coating design is determined by the features of composite optical properties. According to the results obtained, the composite coating for natural light must be formed by nanoparticles in the form of oblate spheroids, whose polar axis is oriented perpendicular to the surface of underlying medium.

The calculation shows that a composite with a moderate volume fraction of inclusions ($\eta\sim0.01-0.1$) satisfies all necessary conditions for the visible spectral range. Figure 7 shows the reflectance and transmittance of the antireflection composite layer with the following parameters: $\xi = 0.1$ and $\eta = 0.05$. The layer thickness, calculated from formula (14), is $h = 93$ nm.
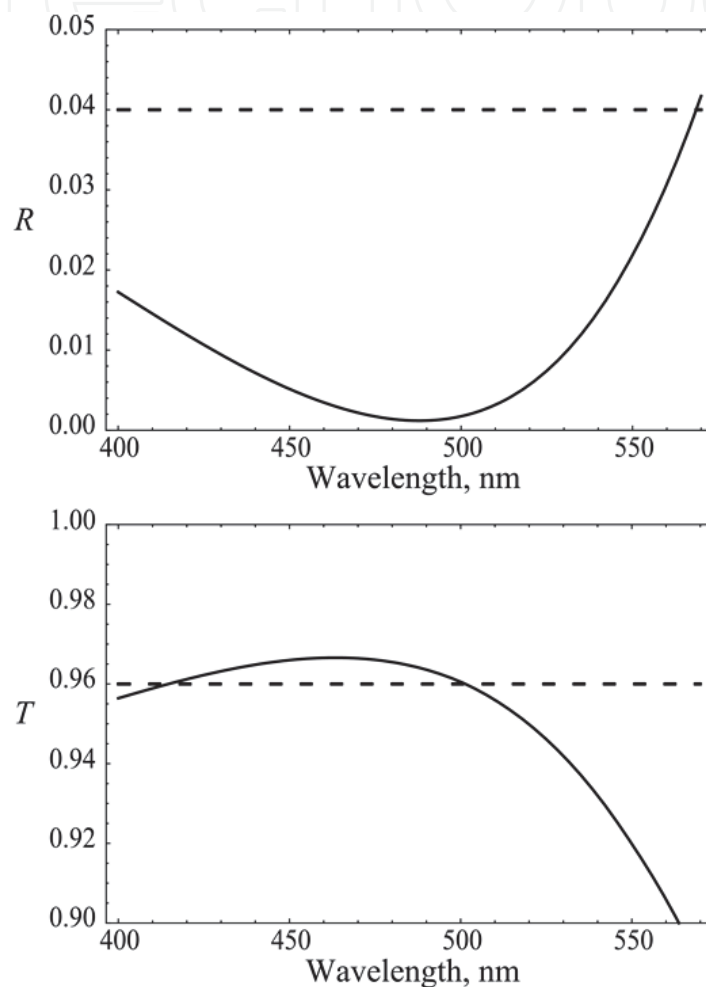
Fig. 7. Reflectance R and transmittance T of a composite slab with silver nanoparticles for normal incidence of light, calculated within the effective-medium model. The reflectance and transmittance of the clean dielectric surface are shown for comparison by dashed lines.

The dependencies in Fig. 7 show that coating of dielectric surface by a composite layer gives a positive effect. In a wide (>100 nm) spectral range the total intensity of reflected light decreases by a factor of more than two, and the minimum reflectance of the composite coating is lower than that of the dielectric by a factor of 20. Unfortunately, the refracted wave intensity increases only slightly in this case, and even decreases in comparison with the initial dielectric at $\lambda > 500$ nm. The latter circumstance can be explained as follows: some part of the light wave energy spent on excitation of free-electron oscillations in composite

nanoparticles is transformed into heat. Thus, the light wave energy is partially absorbed by the dispersed subsystem of the composite coating, as a result of which the surface of transparent material cannot be made totally antireflective.

4.4 Thin-film composite polarizing splitter

As it is shown in Section 3, the absorption of the composite medium incorporating metallic nanoparticles can be controlled by careful selection of geometric parameters of nanoparticles. Here we investigate the possibility to realize a thin-film plasmonic polarizing splitter in the visible region. For definiteness, we consider a transparent dielectric with a refractive index $n_m = 1.5$ as a matrix. In our design, the high polarization contrast of composite film is obtained by using uniformly oriented silver nanoparticles of ellipsoidal shape.

The shape of nanoparticles can be selected so as to observe only one plasmon resonance in the visible region of light. According to Fig. 2, this condition complies with $\xi < 0.85$ or $\xi > 1.5$. In this paper, we consider the case of prolate particles of aspect ratio $\xi = 3$. In this case, the plasmon resonance in the visible region corresponds to the field component polarized parallel to the polar semi-axis of the spheroid.

Let us assume that a layer of the composite material with uniformly oriented prolate silver spheroids has been deposited on surface of transparent medium. Let light be incident normally on this layer from vacuum. To provide maximum optical anisotropy, nanoparticles have to be oriented parallel to the plane interface between media. Using the relation (3) and Airy equation (Born & Wolf, 1999), the reflectance and transmittance can be calculated for arbitrary values of filling factor η and layer thickness h.
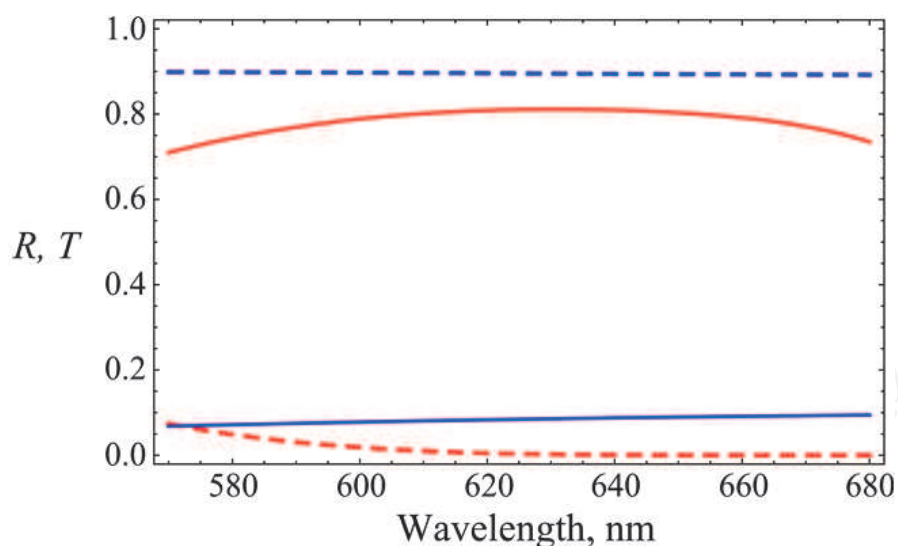

Fig. 8. Reflectance R (*solid lines*) and transmittance T (*dashed lines*) of parallel (*red lines*) and perpendicular (*blue lines*) polarized light of composite slab with uniformly oriented prolate silver spheroids on glass substrate.

Results of calculation show that for $600\,\text{nm} < \lambda < 650\,\text{nm}$, values of $\eta \sim 0.1$ and $h \approx 100 - 150$ nm are optimal from the point of view of the posed problem. Indeed, as one can see from Fig. 8, for $\eta = 0.1$ and $h = 130$ nm composite layer exhibits high polarization contrast. For radiation of the region from 570 nm to 680 nm, this composite slab reflects the

parallel polarized light, and for the perpendicular polarized light this coating is transparent. From the practical point of view it is interesting that high reflectance corresponds with low transmittance and vice versa. According to the results shown in Fig. 8, the reflectance and transmittance of this composite slab possess the values either more than 0.7 or less than 0.1. So, such composite structure can be used as a polarizing beam splitter with high performance in transmission and reflection. By selecting the proper shape of the nanoparticles or choosing matrices with different refractive indexes it is possible to achieve the polarization contrast at specified spectral regions.

5. Conclusion

We explore the utility of effective medium representation to simplify the electromagnetic analysis of composite system, and demonstrate the use of this simplification in solving of the boundary problem under consideration. This approach allows us to easily control the parameters of a system and predictably change its optical properties, expressing the necessary conditions in an analytical form. The data obtained with the help of formula (3) show that a heterogeneous medium with plasmonic impurities, such as silver nanoparticles with a concentration of 10^{-2}–10^{-1} per unit volume, is new and interesting object of research with many perspectives for applications. Such plasmonic medium can be used as a transparent anti-reflection coating, weakly reflecting light-absorbing filter, or polarizing beam splitter with high performance in transmission and reflection. It is shown also that an extraordinary refractive index $n_{eff} = 1$ in a heterogeneous medium with metal nanoparticles at transparency can be reached with the compensation of absorption at metal nanoparticles by the amplification in the matrix, and in the case of nonspherical nanoparticles the values of the gain necessary for compensation of absorption are smaller. Provided that silver nanoparticles are located not on the surface but in the bulk of glass or some other sufficiently strong and chemically stable optical material, proposed nanocomposite devices would have high operating qualities, in particular, high stability to contaminations, mechanical effects, and corrosive media.

6. Acknowledgments

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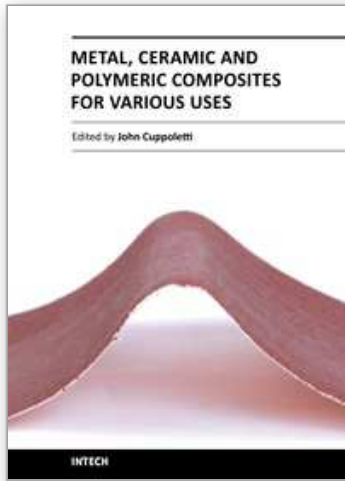
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Edited by Dr. John Cuppoletti

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