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Enhancement and focusing of light in nanostructured quasi-zero-refractive-index films

O.N. Gadomsky, S.N. Stepin, N.M. Ushakov, N.V. Gadomskaya, E.A. Pereskokov*

Ulyanovsk State University, 432017 Ulyanovsk, Russia

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ABSTRACT

We present theoretical and experimental proofs that our synthesized composite material with silver nanoparticles has a quasi-zero refractive index over a wide wavelength range, and the enhanced optical transmission is observed in the material layer. The formulas of the reflectance and transmittance of a layer with a quasi-zero refractive index are consistent with the experimental data. The optical transmission is significantly enhanced by focusing the light that is scattered by the composite film.

1. Introduction

Small metallic particles can only scatter and absorb electromagnetic waves [1]. The effective cross section of this process is given by the ratio between the average dissipated particle energy and the density of the incident energy flux. The average dissipated particle energy is proportional to the imaginary part of the polarizability of the particle. As shown in the radiation theory of metal particles [2,3], certain small particle size can absorb electromagnetic waves and strengthen them. This ability to enhance the electromagnetic waves occurs because the interaction between the external field and the particle in weak fields is nonlinear, when the inversion of the electric dipole quantum transitions of free electrons coincides with its equilibrium value.

It is well known [4–8] that near the surface of metal nanoparticles, the electromagnetic field is enhanced. This effect allows the laser medium to generate a composite of the laser-active molecules at the nanoparticle surface [5]. In this article, in contrast to [4–8], the electromagnetic wave gain treated the metal nanoparticles in the nanoparticles, which are detected in the optical transmission spectra. It will be shown that the addition of silver nanoparticles in the polymer matrix increases the transparency of the matrix. This effect is called the enhanced-optical-transmission effect.

[9] shows the experimental transmission spectra of a layer of acrylic copolymer and the composite layer based on the acrylic copolymer of identical thickness in collimated light, which revealed the enhanced-optical-transmission effect. In this article, we will show that the enhanced-optical-transmission effect significantly increases in the scattered radiation.

Several studies [10–18] theoretically and experimentally developed materials with zero and quasi-zero refractive indices. In these studies, the quasi-zero refractive indices were only obtained in a narrow range of wavelengths. In this paper, we will show that the composite materials that we synthesized have quasi-zero refractive index in a wide wavelength range of at least 450–1100 nm. We will also show that the enhanced-optical-transmission effect directly proves that the synthesized composite materials have quasi-zero refractive index.

In contrast to our previous work, which studied the optical properties of composite layers with quasi-zero refractive index (references to these works are given in the text of this article), this article focuses on theoretically describing the experimental transmission spectra of the composite layers based on real and complex angles of refraction of light in the fiber and a special property of the optical transmission layer when it is irradiated with diffused light. It has been shown that the composite layer with a quasi-zero refractive index has a scattered radiation property because the optical transmittance of the composite layer weakly depends on the angle of incidence of light compared to the optical transmittance of glass.

* Corresponding author. Tel.: +79 372 720 665.
E-mail address: famous_lynx@mail.ru (E.A. Pereskokov).

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2. Experimental reflectance and transmittance spectra of a composite layer with quasi-zero refractive index

One method to synthesize composite materials with quasi-zero refractive index is described in our patent [19]. This article considers thick layers of materials that we obtained, the thickness of which is much greater than the wavelength of the external optical radiation. The silver nanoparticles have radii $a=2.25$–10 nm and are uniformly distributed along the surface as a layer of spherical nanoparticles. There are also other technical conditions: the surface of the nanoparticles is stabilized for missing nanoparticle aggregation stabilizer, and the refractive index of the shell coincides with the refractive index of the polymer matrix.

The distribution of silver nanoparticles on the film surface and its depth was investigated using Auger Microprobe JAMP-9500F and ICP-mass spectrometer Nexion 300D+NWR 213. Diffuse reflectance spectra were measured using a spectrophotometer X-Rite DTP22 with the special software ColorPort 2.0. The films were deposited using HVLP paint-spraying gun in the spray booth. The films were dried at room temperature for 2 to 3 days.

The reflection and transmission spectra of the samples were measured using an integrating sphere, which was directed through the scattering glass with collimated monochromatic light flux. The reflectance and transmittance of the signals were measured using a photodetector.

Fig. 1 shows the reflectance spectra of the samples, which represent a glass substrate with a composite film (PMMA+Ag). According to the location of the interference minima, the refractive index n_2 of the composite film is defined by the formula

$$n_2 = \frac{\lambda_1 \lambda_2}{2d_2(\lambda_1 - \lambda_2)}, \qquad (1)$$

where d_2 is the film thickness, λ_1 and λ_2 are the wavelengths that are adjacent to the interference minima. When $d_2=80\,m$km, $\lambda_1=900$ nm, $\lambda_2=700$ nm, which implies that $n_2=0.0197$. Thus, the light interference in the thick polymer layers is significantly greater than the observed wavelength.

Fig. 2 shows the transmission spectra of the glass structure (PMMA+Ag) / glass. The coordinate axis represents the voltage in volts on the photodetector. Fig. 2 shows that the structure of the optical transmittance increases by approximately 20% on average compared with the transmittance of glass.

In all experimental results, the transmission spectrum of the sample was estimated as the ratio between the signal of the photodetector when light passes through the sample and the signal without the sample.

Fig. 3 shows the relative spectral transmission function of the polymer thick-film nanostructure composite Ag (3 wt%)+PMMA and the glass transmittance of the polymer film of pure PMMA on glass. The film thickness was 50 microns. The relative spectral function is the ratio of the photodetector signals that are recorded after light passes through the sample. The relative spectral features throughout the measured spectral range exceed unity, which indicates a significant increase in bandwidth when the administered polymethylmethacrylate film in a silver nanoparticle has a mass fraction of 3%. The transparency of the composite polymer-based thick film of silver nanoparticles in a matrix of polymethyl methacrylate increases from 15% to 40%.

Fig. 4 shows the transmission spectra of the sample in the form of a thick film based on the composite nanomaterial

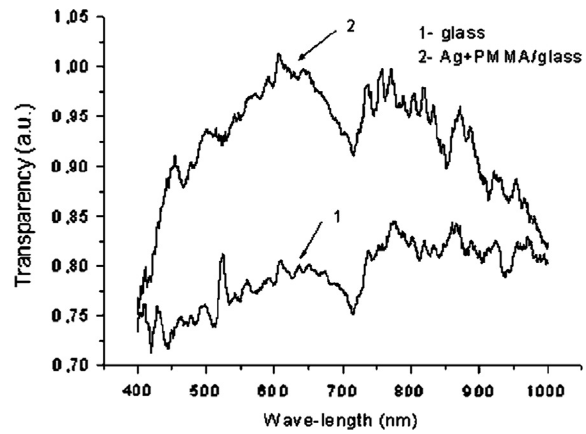

Fig. 2. The optical transparency of the glass thickness of 1 mm (curve 1) and the structure of the polymer nanocomposite 3wt. % Ag + PMMA film thickness of 50 microns on glass (curve 2).

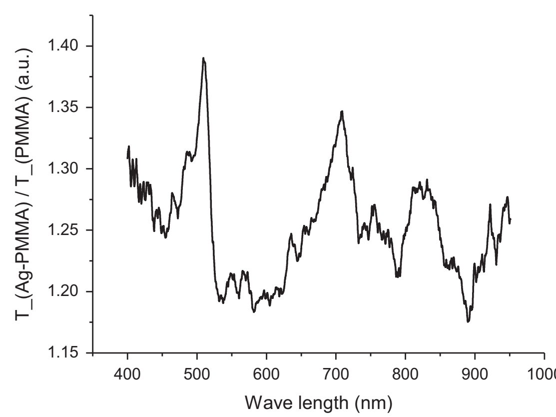

Fig. 3. Relative spectral transmission function of polymer thick film Ag (3 wt. %) + PMMA composite nanostructures on glass and polymer film transmittance of pure PMMA on glass. Film thickness equal to 50 microns.

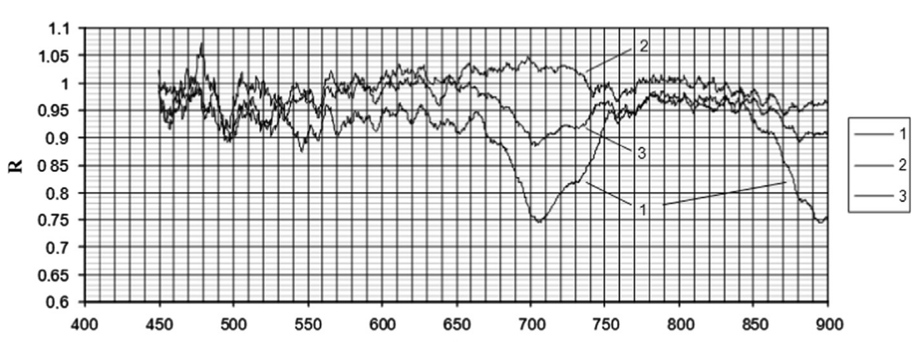

Fig. 1. The reflectivity of the composite films PMMA+Ag of silver nanoparticles R_film on glass relative to the reflectance of the glass R_glass. 1 - the thickness of the composite film d_2=90 mkm, 2 - thickness of the composite film d_2=55 mkm, 3 - the thickness of the composite film d_2=55 mkm. The weight content of silver in the composite films of uniform and equal to 5% and the conditions of synthesis differ.