Photon mean free path in the metal nanoparticle system

Nikolay S. Panamarev[a], Aleksey A. Zemlyanov[a,b], Ignatiy V. Samokhvalov[a], Anna N. Panamaryova[c]
[a]National Research Tomsk State University, Tomsk, Russia
[b]Siberian Physical-Technical Institute, Tomsk State University, Tomsk, Russia
[c]National Research Tomsk Polytechnic University, Tomsk, Russia
n.panamarev@mail.ru, zeml16@mil.ru, lidar@mail.tsu.ru, mir-annie@ya.ru

ABSTRACT

In the paper comparative evaluation of the photon mean free path in the system of metal nanoparticles and dielectric matrix is performed by means of numerical simulations. As a material of nanoparticles both metals (Ag, Cu) in which the frequency of plasmon resonance falls in the range under study and metals (Al, Ni) in which the plasmon resonance frequency is far from the investigated range have been used. The research has shown that for the studied metals the media based on Al nanoparticles satisfy best the Ioffe-Regel criterion for photons of visible wavelength range.

Keywords: photon, Anderson localization, mean free path.

1. INTRODUCTION

The current state of optoelectronics requires finding materials with laser radiation in different spectral ranges. The dense array of nanoscale lenses placed in the laser-active medium can produce random lasing when at light scattering in an array closed paths of light are randomly generated (Anderson localization). Multiple scattering in random media locates the active radiation in the medium. In this sense, the localization effect replaces the resonator and this fact under the condition of the amplification presence leads to the predominant stimulated active centers emission and forming the spectrum similar to a laser one. Such systems were named random lasers [1].

When a number of random scatterers is quite big, the approach considering the transfer of energy to the scattering medium is justified. In this model the interference of scattered waves is neglected. The fact that a plane wave incident on the medium when passing a distance comparable to the mean free path length becomes almost completely dissipated is taken into account. Then the energy density of the scattered waves obeys the diffusion equation. The condition of applicability of the diffusion approximation is the inequality $l > \lambda$. With increasing a number of scatteres $l < \lambda$, the diffusion slowing down occurs; in this case we can talk about weak localization of light. Finally, when $l \approx \lambda$, light diffusion is stopped, the light is scattered back. In this case Anderson localization of light is discussed. Light scattering is a statistical process in which both the amplitude and phase of the incident wave are subject to random variations. For an ensemble of scatterers such parameter as the mean free path l – the average distance which the photon passes between sequential scattering events – plays an important role [2, 3].

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2. COMPUTING SIMULATION

Numerical simulation was carried out in MATLAB for heterogeneous media based on the dielectric matrix (n = 1,53) and nanoparticles of Al, Ni, Ag, Cu in the visible and near infrared bands when changing the filling factor *f* from 0.02 to 0.6. The impact of the material and the volume fraction of the dispersed phase on the spectral properties of the photon mean free path was analyzed.

For Rayleigh scattering on the spheres of radius *a* for which the filling factor is equal to *f*, the free path is defined by [4]

$$l = \frac{9}{16\, f a^3} \left(\frac{\lambda}{2\pi} \right)^4 \frac{1}{\left| \varepsilon_2 - \varepsilon_1 \right|^2}$$

The dispersion dependence of the dielectric function of Ag, Ni, Al, Cu on the wavelength of the probe radiation is shown in Figure 1 [5, 6].

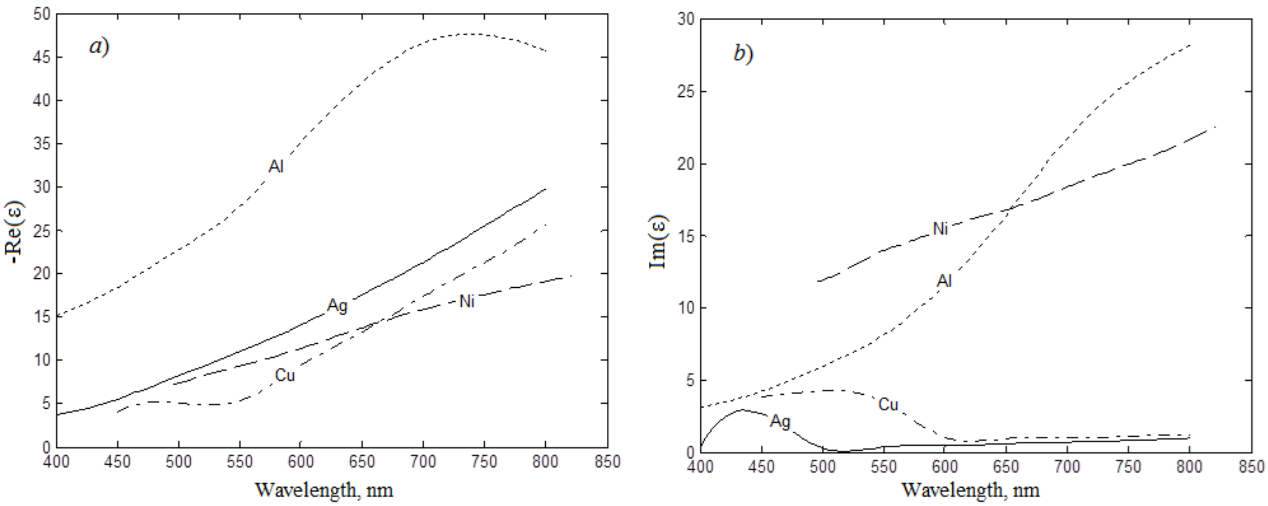

Figure 1. The dispersion dependence of the real (*a*) and imaginary *(b)* part of the dielectric function of Ag, Ni, Al, Cu on the wavelength of the probe radiation (spline interpolation [5, 6]).

The dependence of the photon mean free path on the nanoparticles material, their concentration and morphology and the probe radiation wavelength is shown in Figure 2.

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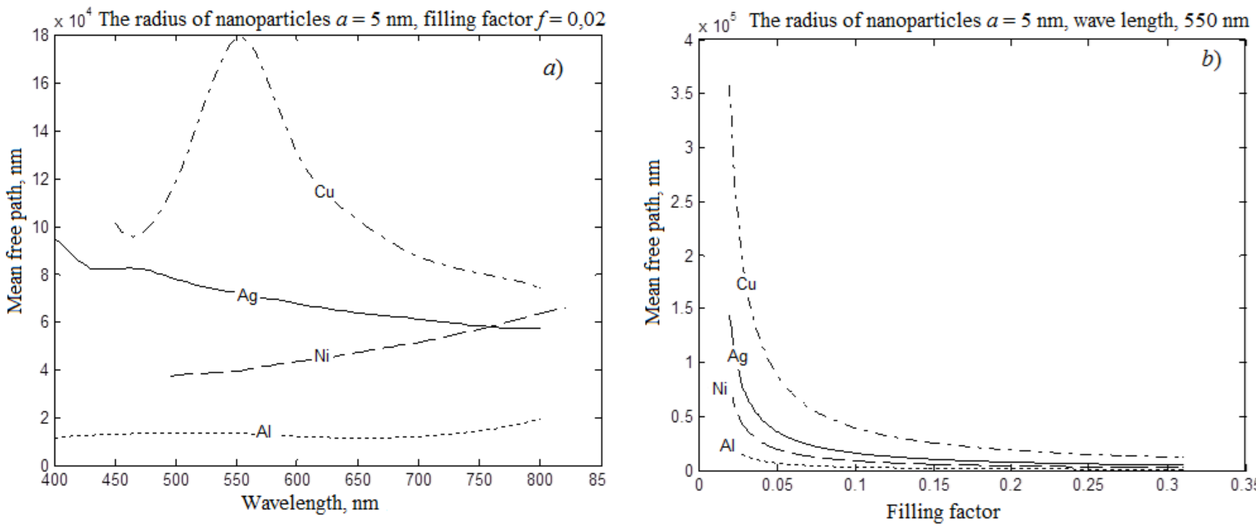

Figure 2. The dependence of the free path of a photon on wavelength radiation *(a)* and the filling factor *(b)*.

For the data shown in Figure 2, the average distance between nanoparticles ≈ $a\cdot(4/f)^{1/3}$ ≈ 1500 nm what corresponds to the concentration of nanoparticles $N \approx 3\cdot10^{8}$ cm^{-3}.

In the case when the scattering of photons at each of the scatters occurs independently, i.e. when the concentration of the scatters c is low enough, the mean free path will be connected with their concentration and the scattering cross-section σ by the ratio [3] $l = (c\sigma)^{-1}$.

Figure 3 shows the dependence of the free path of a photon in the system of silver and aluminum nanoparticles aggregates for various values of their filling factor. The aggregates concentration c = 10^{12} $cм^{-3}$, the average size is 300 nm. The average distance between the aggregates centers ≈ 1000 nm. It is assumed that the aggregates are distributed uniformly in the dielectric matrix.

Figures 2 and 3 show that the mean free path of a photon in the system of uniformly distributed nanoparticles-monomers depends essentially on the nanoparticle material within the investigated range. In the system of aggregated nanoparticles the mean free path of a photon almost does not depend on the material of nanoparticles.

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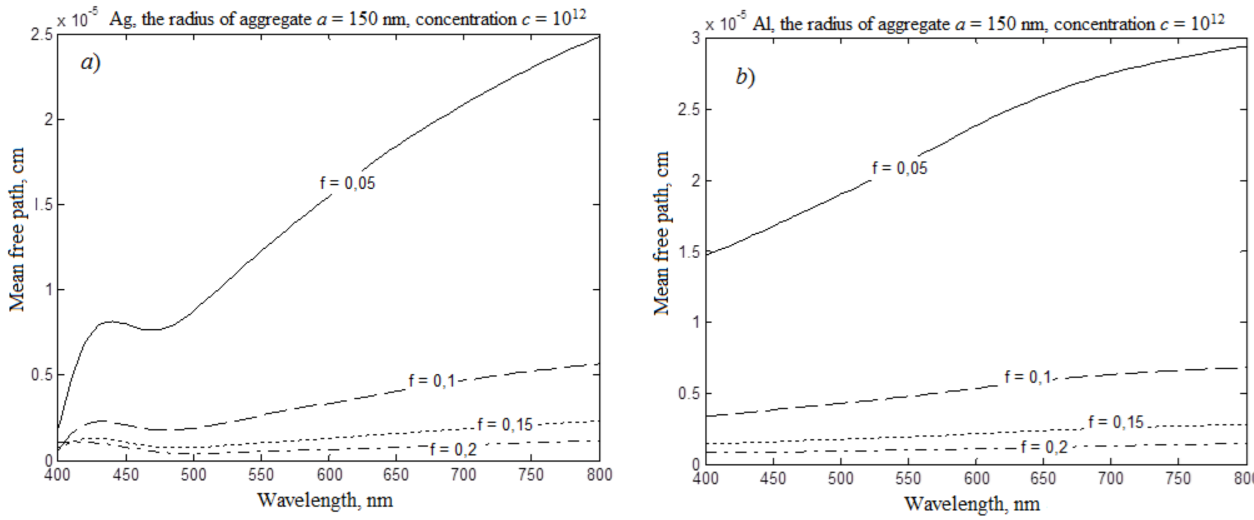

Figure 3. The dependence of the mean free path of a photon on radiation wavelength for silver *(a)* and aluminum *(b)* aggregates when the values of the filling factor *f* are different.

3. CONCLUSION

Thus, the comparative analysis by numerical simulation of the photon mean free path in the composite media based on nanoparticles Ag, Cu, Al, Ni and dielectric matrix has shown that the media based on Al nanoparticles satisfy best Ioffe-Regel criterion for photons in the visible range of wavelengths.

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