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Coherent backscattering by discrete random media composed of clusters of spherical particles

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ABSTRACT

The approximate method of accounting for the weak localization effect in discrete random media makes it possible to calculate the intensity and the degree of linear polarization of radiation reflected by a semi-infinite layer containing randomly oriented clusters of identical nonabsorbing spherical particles. The paper is focused on the analysis of the influence of the medium properties – the concentration of the clusters, their structure, the sizes and the number of constituent monomers – on the phase dependence of the characteristics of the interference (coherent) component of radiation. Three types of clusters were chosen for the analysis: a fractal-like cluster and two random clusters with different packing densities of monomers. Three values of the size parameters of monomers were considered: 0.5, 1.0, and 1.5. The chosen values of the refractive index of monomers correspond to that of magnesium oxide in the visible spectral range. This allowed us to compare the theoretical phase curves of the degree of linear polarization of light reflected by the medium with the data of measurements by Lyot. For all of the considered cluster types, starting from some minimal number of constituent monomers, which is typical of the specified cluster's type and the monomer's size, the characteristics of the coherent component were found to be practically independent of the number of constituents. In particular, in the phase-angle range from 0° to 15°, the branch of negative polarization measured for a layer of magnesium oxide by Lyot can be well described with several models of the media containing either the fractal-like clusters or the random clusters with the packing density larger than 30%. In these models, the number and sizes of constituent monomers vary. To select from the whole set of "suitable" clusters those the optical characteristics of which actually correspond to characteristics of an elementary volume of the specified medium, additional information is required. For example, this can be the results of polarization measurements in a wider phase interval that includes a zone of the dominating influence of incoherent (diffuse) scattering.

1. Introduction

The scattering of electromagnetic waves by many discrete media of natural and artificial origin is often accompanied by the weak localization phenomenon. The latter manifests itself as a narrow interference peak of intensity centered exactly at the backscattering direction and as a narrow branch of negative values of the linear polarization degree near opposition. Due to this, the weak localization phenomenon is one of the contributors to the so-called opposition effects in brightness and polarization (e.g., [1–3]). The interference nature of the weak localization phenomenon makes these effects to be strongly dependent on the medium properties, specifically, on size, refractive index, shape, and packing density of the scatterers in the medium. This

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circumstance is of high importance for the interpretation of remote sensing data of different media.

Presently, the weak localization theory is rather well developed for sparse random discrete media. In the theory of multiple scattering by such media, it is assumed that the waves propagating between scatterers in the medium are spherical. Under such assumption, the wave acting on a particle and the secondary spherical wave scattered by this particle propagate in different directions and, therefore, do not interact with each other. As a result, the radiation scattered by such discrete random medium can be represented as a sum of only two parts (see, e.g., [4]). One of them is determined by the diffuse radiative transfer (incoherent scattering), and the second one, by the weak localization phenomenon (coherent scattering). In the diagrammatic representation of the Bethe–Salpeter equation, the first and the second parts correspond to the sums of the ladder diagrams and the cyclical diagrams, respectively. The contribution of the other diagrams (except those corresponding to the radiation extinction in the medium) is assumed to be negligible. The incoherent part of the scattered radiation is described by the classic radiative transfer equation that can be derived, under some assumptions, directly from the Maxwell equations [4]. Under the same assumptions, the weak-localization equation was also obtained [5–7]. The latter turned out to be substantially more complicated than the radiative transfer equation even for a relatively simple case of a plane-parallel layer of a medium. However, for the case of a semi-infinite medium, the approximation providing a rather high accuracy and making the calculations of the weak-localization characteristics to be relatively simple was obtained [8].

In densely packed media, the assumption of the sphericity of secondary waves does not obey. In such media, the scatterers are in the near-field zones of each other. The incident and scattered fields in the vicinity of a scatterer are not independent, and the contribution of the diagrams corresponding, for example, to the interference of singly and multiply scattered waves may be substantial (see [7] and the references therein). This is of high importance especially for absorbing media, the scattering characteristics of which are determined by several first orders of scattering. The theoretical consideration of multiple scattering by such media becomes extremely complicated. To avoid these difficulties, it was suggested that the incoherent part of the scattered radiation be calculated from the radiative transfer equation, where the phase function of an elementary (differential) volume element and the extinction in the medium are found under some assumptions accounting for a high packing density of particles [9,10]. This approach is close to that suggested in [11], where the scattering characteristics of chaotically oriented clusters of spherical particles were used as the scattering characteristics of an elementary volume element to solve the radiative transfer equation. With such a model of a closely packed medium, the coherent part of radiation reflected by a medium can be also calculated.

In the present paper, we report the results of calculations of the intensity and the degree of linear polarization of radiation reflected by a semi-infinite medium composed of randomly oriented clusters of non-absorbing identical spherical particles (monomers). We restrict ourselves by these characteristics of radiation, intensity and linear polarization, since they are most often used in experimental and theoretical studies. The incident radiation is assumed to propagate normally to the boundary of the medium. Three types of clusters are considered. One of them is a fractal-like cluster, and two others are random with different packing densities of the constituents. The size parameters of the clusters' constituents are $x=0.5$, 1.0, and 1.5 ($x=2\pi r/\lambda$, where r is the radius of the constituent monomers and λ is the wavelength). Their refractive index has no imaginary part and approximately corresponds to that of magnesium oxide in the visible spectral range. This will allow us to compare the results of our modeling with the available laboratory measurements of the degree of linear polarization of light reflected by the smoked MgO coating [12,1].

2. Computational aspects

There were three steps in our calculations of the scattering characteristics of a semi-infinite medium. At the first step, the scattering matrix of chaotically oriented clusters was calculated with the computer code available online [13]. This code was adapted in order to produce the file containing the expansion coefficients of the scattering matrix into the generalized spherical function series. This file is required in the following procedures to solve the radiative transfer equation and to calculate the coherent component of radiation reflected by the medium composed of these clusters. To solve the radiative transfer equation, the online available computer code [14] was used, while to calculate the coherent component, we applied the approximation described in [7,8].

Since the methods to calculate the single-scattering characteristics of clusters and the diffuse radiative transfer component have been widely discussed and used before, we will focus here only on the retrieving procedure for the coherent component of radiation reflected by a medium. Let a homogeneous isotropic and non-chiral semi-infinite particulate medium be illuminated by a plane electromagnetic wave propagating perpendicularly to the boundary of the medium. In this case, the matrix corresponding to the sum of cyclical diagrams $\mathbf{S}^{(C)}$ in the circular-polarization (CP) presentation is

$$S^{(C)}_{pn\nu\mu} = \frac{\pi\eta^2}{k_0^4 \mathrm{Re}(\varepsilon)} \sum_{qq_1LM} (-1)^L \Theta^{*(q_1\mu)(qp)}_{LM} \gamma^{(qn)(q_1\nu)}_{LM} \tag{1}$$

where n, p, μ, ν, q, $q_1=\pm 1$, η is the number density of scatterers in the medium, $k_0=2\pi/\lambda$,

$$\varepsilon = \mathrm{Im}(m_{eff})\left(1-\frac{1}{\cos\,\vartheta}\right) + i(1+\cos\,\vartheta)\left(\frac{\mathrm{Re}(m_{eff})-1}{\cos\,\vartheta}+1\right), \tag{2}$$

m_{eff} is the complex effective refractive index of the medium, and ϑ is the scattering angle ($\vartheta=\pi-\alpha$, where α is the phase angle). The coefficient γ in Eq. (1) is determined from the following system of equations

$$\gamma^{(pn)(\mu\nu)}_{LM} = Q^{(pn)(\mu\nu)}_{LM} + \frac{2\pi\eta}{k_0^3} \sum_{qq_1lm} \chi_l^{(pq)(\mu q_1)} \gamma^{(qn)(q_1\nu)}_{lm} G^{(No)}_{LMlm}, \tag{3}$$