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Surface-induced optical anisotropy of inhomogeneous media

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Abstract

We demonstrate that the presence of interfaces induces anisotropy in the optical properties of thin inhomogeneous layers. Several mechanisms are discussed that can control the properties of this surface-induced anisotropy. We found that the effective refractive indices for *s*- and *p*-polarized fields are different and depend on the thickness of the layer, concentration and optical properties of inclusions in the layer, and the angle of incidence.

Keywords: Random media; Inhomogeneous and anisotropic thin films; Surface effects; Effective material parameters; Material modeling

1. Introduction

Effective optical properties can be attributed to inhomogeneous media containing inclusions much smaller than the wavelength. In the simplest case, these properties are described with Maxwell-Garnett or Bruggeman theories [1,2]. According to these theories, the bulk properties of media consisting of isotropic and spherically symmetric inclusions embedded into optically isotropic host materials are always isotropic. There are situations however where, even in this highly symmetric situation, the inhomogeneous media can manifest certain anisotropic properties.

In reference [3], it was demonstrated that in the geometrical optics limit smoothly inhomogeneous and isotropic materials can be weakly anisotropic in the sense that refractive indices are noticeably different for right-hand and left-hand circular polarized light. The difference in the phase velocities is caused by accumulation of the Berry phase with the interference of two modes also leading to the Rytov law for the rotation of the polarization plane of a wave. The refractive index contains the correction, which is proportional to the Berry geometric phase.

Another possible source of optical anisotropy is the inevitable surface of materials. The transmission and reflection of light was recently investigated in the case of a slab containing a dilute system of randomly located spherical particles with dimensions comparable to the wavelength of incident radiation [4]. It was found that this system must possess both effective anisotropic electric permittivity and magnetic permeability and that these optical parameters are functions of the angle of incidence and the polarization of the incident wave. However, although the effective permittivity and permeability of the system described in [4] are highly anisotropic and polarization dependent, the effective

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refractive index does not depend on incident wave polarization.

In the present paper we introduce and discuss different mechanisms that can lead to the surface induced anisotropy of isotropic composite media consisting of small spherical inclusions. Here we will focus our attention on thin layers of composite materials having randomly inhomogeneous optical properties. We show that, unlike the bulk materials discussed in [3], such thin inhomogeneous layers possess different effective refractive indices for *s*- and *p*-polarized incident light.

2. Mechanisms for surface-induced anisotropy

One can single out several mechanisms that can contribute to surface induced anisotropy in randomly inhomogeneous media having macroscopically isotropic properties.

The first mechanism relates to the fact that inclusions cannot penetrate the surface. As a result, the concentration of inclusions in the vicinity of the surface will be smaller than that in the bulk as illustrated in Fig. 1a. According to effective medium theories, a change in the concentration of inclusions leads to a change in the effective refractive index. Thus, a thin layer situated near the interfaces of an inhomogeneous slab will have slightly different refractive indices. It is known that such multilayer structure will manifest anisotropic effective properties [5–7]. However, because the thickness of the regions having different refractive indices is of the order of the size of inclusions, only small changes are induced in the magnitude of the refractive index of the slab and one cannot expect sensible effects due to this mechanism.

We note that the surface penetrating inclusions can be sectioned along that surface and, in this case, the concentration of inclusions can be constant across the entire volume. However, the truncated inclusions will now lose their spherical symmetry and their anisotropic shape will again induce surface anisotropy.

Another mechanism that could lead to surface-induced anisotropy relates to the change in local fields near the surface [8,9]. The local field at the position of some inclusion is determined by surrounding inclusions located within the so-called Lorentz sphere drawn around the observation point as shown in Fig. 1b [8]. When the observation point is close to an interface, the Lorentz sphere is truncated and the distribution of local fields inside the sphere changes. The magnitude of local field inside the truncated sphere will depend on polarization of incident wave and this determines the anisotropic behavior of the surface layer. Also, this means that the effective refractive indices for thin slabs of inhomogeneous materials will be different for *s*- and *p*-polarized incident wave. We should mention that the anisotropy of dielectric permittivity caused by finite size of particles and retardation effects (Drude transition layer) was discussed previously in the case of plasmonic metamaterials with periodically arranged metallic inclusions [10–12]. The authors of these papers note that the presence of surface does require a more careful description of the metamaterial slab's optical properties.

A third mechanism for the surface-induced anisotropy can be simply explained by the interaction between the inclusions and their own images with respect to the surface as illustrated in Fig. 1c. This interaction changes the polarizability of inclusions located near the surface and, consequently, modifies the effective properties of the medium near the surface. We expect this effect to be significant for metallic inclusions.

3. Local field changes near the surface

A simple analytical theory for surface layers of inhomogeneous media that takes into account local field change near the surface is described in Ref. [13] where the effective permittivity of a medium containing small spherical inclusions arranged in a cubic lattice was

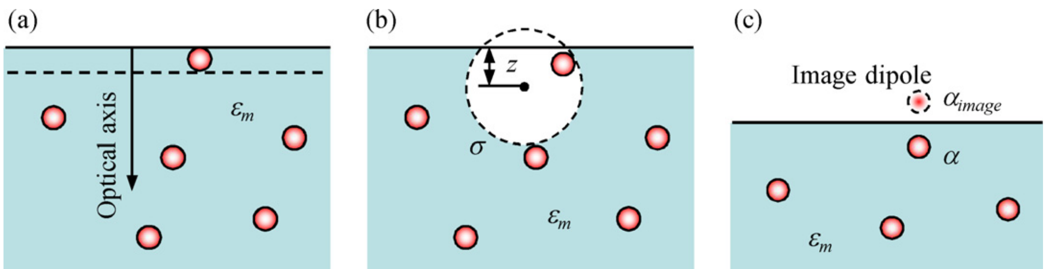

Fig. 1. Surface induced anisotropy can be attributed to (a) change in the concentration of inclusions, (b) modification of local field, (c) inclusion–surface interaction.