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On the dependence of circular Bragg phenomenon of noble metals helicoidally periodic sculptured thin films on visible and IR wavelengths

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Abstract

The concept of local homogenization in the visible and infra-red frequencies is used by estimating the permittivity dyadics of noble metals (Cu, Ag, and Au) in the form of thin film helicoidal bianisotroptic media (TFHBM). Despite the fact that the absorption transitions of dielectric to metal (percolation threshold) in metallic TFHBMs occur at long wavelengths at lower volumetric fraction of metallic particles, at these wavelengths the transition from dielectric to metal in composite relative permittivity scalar occurs at higher volumetric fraction of metallic particles. The latter is responsible for the increase of circular Bragg phenomenon.

Keywords: Helicoidal periodic mediums; Sculptured thin films; Percolation threshold; Circular Bragg phenomenon

1. Introduction

A sculptured thin film's (STF) microstructure is best described as an assembly of parallel columns that all curve in the same way in the thickness direction [1]. Therefore, a STF is locally anisotropic and uni-directionally non-homogeneous and may be considered as a non-homogeneous continuum in the visible and sub-visible frequency regimes [2]. In this work, our aim is to investigate and compare the role of the relative permittivity of noble metals (i.e., Cu, Ag and Au) at visible and infra-red regions on the circular Bragg phenomenon (CBP), which is displayed by the thin film helicoidal bianisotropic media (TFHBM).

It is assumed that the evaporant in its bulk form is isotropic and any sculptured thin film is a composite material consisting of two phases, namely metal and void [3]. The Bruggeman formalism is used to homogenize the composite media of the TFHBM and deduce the effective constitutive properties of dielectric TFHBM [4]. Since the fields decay inside a TFHBM, and real part of the permittivity scalars in metals are high, it is difficult to obtain/calculate the reflection and transmission amplitudes in an even a thick film. In these cases it is recommended that the TFHBM to be considered as a half space, then the reflection from this half space can be obtained for normal incidence [5].

The absorption transitions from dielectric to metal in metal-dielectric composite are described by percolation phenomenon: the percolation threshold (i.e., the insulator to conductor transition) occurs sharply in the permittivity of a homogenized composite material when the volumetric fraction of metallic particles, f_s increases continuously from zero [6]. In general, three transitions occur in a metallic TFHBM with non-circular cross-section [2]. However, only two of them are optically sensitive to normal incident plane waves.

Bruggeman formalism for obtaining the permittivity scalars of composite material is given in Section 2. In Section 3, the formalism of boundary value problem for the reflection of a normally incident plane wave that excites a

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metallic TFHBM half space along its axis of helicoidal periodicity is discussed. The results for Cu, Ag and Au TFHBMs are given in Section 4. Section 5 includes the conclusions drawn from this work.

2. Theory

Assume that the half space ($z \geqslant 0$) is occupied by a metallic helicoidal sculptured thin film, while the half space ($z \leqslant 0$) is vacuum. The linear dielectric properties of the TEHBM are delineated by the non-homogeneous permittivity dyadic [2]:

$$\underline{\underline{\varepsilon}} = \varepsilon_0 \underline{\underline{S}}_z(z,h) \cdot \underline{\underline{S}}_y(\chi) \cdot \underline{\underline{\varepsilon}}^0_{\text{ref}} \cdot \underline{\underline{S}}_y^{-1}(\chi) \cdot \underline{\underline{S}}_z^{-1}(z,h) \quad z \geqslant 0 \tag{1}$$

where

$$\underline{\underline{\varepsilon}}^0_{\text{ref}} = \varepsilon_a \underline{u}_z \underline{u}_z + \varepsilon_b \underline{u}_x \underline{u}_x + \varepsilon_c \underline{u}_y \underline{u}_y \tag{2}$$

is called the local relative permittivity dyadic. The relative permittivity scalars $\varepsilon_{a,b,c}$ are implicit functions of frequency. $\underline{u}_x$, $\underline{u}_y$, $\underline{u}_z$ and are unit vectors in the Cartesian coordinate system. The permittivity and permeability of free space (vacuum) are, $\varepsilon_0 = 8.854 \times 10^{-12}$ F m^{-1} and $\mu_0 = 4\pi \times 10^{-7}$ H m^{-1}, respectively.

The helicoidal periodicity of the chosen TFHBM is obtained by the rotation dyadic [7]:

$$\underline{\underline{S}}_z(z,h) = \underline{u}_z\underline{u}_z + (\underline{u}_x\underline{u}_x + \underline{u}_y\underline{u}_y)\cos pz + h(\underline{u}_y\underline{u}_x - \underline{u}_x\underline{u}_y)\sin pz \tag{3}$$

where $p = \frac{\pi}{\Omega}$. The direction of the non-homogeneity is parallel to the z-axis, with 2Ω as the structural period. The integers $h = +1$ and $h = -1$ are for the structurally right- and left-handed TFHBM, respectively. The tilt dyadic [8]:

$$\underline{\underline{S}}_y(\chi) = \underline{u}_y\underline{u}_y + (\underline{u}_x\underline{u}_x + \underline{u}_z\underline{u}_z)\cos\chi + h(\underline{u}_z\underline{u}_x - \underline{u}_x\underline{u}_z)\sin\chi \tag{4}$$

represents the locally aciculate microstructure of a TFHBM, with $\chi \in \left(0, \frac{\pi}{2}\right]$ being the angle of rise.

Each column in the TFHBM structure is considered as a string of identical long ellipsoids. The surface of each ellipsoid in relation to its centroid may be considered in Cartesian coordinate by [4]:

$$x^2 + \left(\frac{y}{\gamma_b}\right)^2 + \left(\frac{z}{\gamma_\tau}\right)^2 = \delta^2, \tag{5}$$

where δ is a linear measure of absolute size of an ellipsoid, while the factors γ_τ and γ_b relate the lengths of the principal semi-axis. In addition, without losing the generality, it is assumed that the cross-section of the ellipsoids is circular (i.e., $\varepsilon_a = \varepsilon_c$ and $\gamma_b = 1$).

In order to obtain the relative permittivity scalars, the Bruggeman formalism was used:

$$f_s \underline{\underline{A}}_s + (1 - f_s)\underline{\underline{A}}_\upsilon = \underline{\underline{0}}, \tag{6}$$

where ($0 \leqslant f_s \leqslant 1$) is the volume fraction of the ellipsoidal inclusions. The polarizability density dyadic of an ellipsoidal inclusion, $\underline{\underline{A}}_s$ embedded in the homogenized composite medium is denoted, on a per unit volume basis, by:

$$\underline{\underline{A}}_{s,\upsilon} = \varepsilon_0(\varepsilon_{s,\upsilon}\underline{\underline{I}} - \varepsilon^0_{\text{ref}}) \cdot [\underline{\underline{I}} + i\omega\varepsilon_0 \underline{\underline{D}}_{s,\upsilon}.(\varepsilon_{s,\upsilon}\underline{\underline{I}} - \varepsilon^0_{\text{ref}})]^{-1} \tag{7}$$

where $\underline{\underline{0}}$ and $\underline{\underline{I}}$ are null and unit dyadics, respectively and ε_s and ε_υ are the bulk metal and vacuum permittivities, respectively. The depolarization dyadic of an ellipsoidal region in the homogenized composite medium is given by:

$$\underline{\underline{D}}_{s,\upsilon} = \frac{2}{i\pi\omega\varepsilon_0} \int_{\phi=0}^{\pi/2} \int_{\theta=0}^{\pi/2} \sin\theta \times \frac{(\sin\theta\cos\phi)^2 u_z u_z + \left(\frac{\cos\theta}{\gamma_\tau^{s,\upsilon}}\right)^2 u_x u_x + \left(\frac{\sin\theta\sin\phi}{\gamma_b^{s,\upsilon}}\right)^2 u_y u_y}{(\sin\theta\cos\phi)^2 \varepsilon_a + \left(\frac{\cos\theta}{\gamma_\tau^{s,\upsilon}}\right)^2 \varepsilon_b + \left(\frac{\sin\theta\sin\phi}{\gamma_b^{s,\upsilon}}\right)^2 \varepsilon_c} \mathrm{d}\theta \mathrm{d}\phi \tag{8}$$

In order to obtain the relative permittivity scalars $\varepsilon_{a,b,c}$, Eq. (6) should be solved numerically. The solution can be readily obtained, using the iterative methods such as Jacobian technique [9].

3. Boundary value problem

Suppose an arbitrary polarized plane wave is normally incident on the TFHBM half space from the lower half space $Z \leqslant 0$. Owing to the axial excitation of the upper half space ($Z \geqslant 0$), a plane wave is reflected into the lower half space. The electromagnetic field phasors associated with the two plane waves in the lower half space are [2,10]:

$$\underline{E}(z) = \left(a_{\mathrm{L}} \frac{\underline{u}_x + i\underline{u}_y}{\sqrt{2}} + a_{\mathrm{R}} \frac{\underline{u}_x - i\underline{u}_y}{\sqrt{2}}\right) \mathrm{e}^{ik_0 z} + \left(r_{\mathrm{L}} \frac{\underline{u}_x - i\underline{u}_y}{\sqrt{2}} + r_{\mathrm{R}} \frac{\underline{u}_x + i\underline{u}_y}{\sqrt{2}}\right) \mathrm{e}^{-ik_0 z}, z \leqslant 0 \tag{9}$$

$$\underline{H}(z) = -\frac{i}{\eta_0} \left\{ \left(a_{\mathrm{L}} \frac{\underline{u}_x + i\underline{u}_y}{\sqrt{2}} - a_{\mathrm{R}} \frac{\underline{u}_x - i\underline{u}_y}{\sqrt{2}}\right) \mathrm{e}^{ik_0 z} + \left(r_{\mathrm{L}} \frac{\underline{u}_x - i\underline{u}_y}{\sqrt{2}} - r_{\mathrm{R}} \frac{\underline{u}_x + i\underline{u}_y}{\sqrt{2}}\right) \mathrm{e}^{-ik_0 z} \right\}, z \leqslant 0 \tag{10}$$

where a_{L} and a_{R} are the known amplitudes of the left- and right-circularly polarized (LCP and RCP) components of the incident plane wave, respectively, and r_{L} and r_{R} are the unknown amplitudes of the reflected plane wave components.

Table 1
The relative permittivity of noble metals at chosen visible and infra red wavelengths

	λ_0 (nm)	ε_s
Copper	590.38	−7.67+2.63i
	1239.8	−71.8+7.38i
Silver	619.6	−15.03+1.01i
	1240	−71.97+5.58i
Gold	563.54	−8.2+1.76i
	1239.8	−76.77+6.52i