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Magneto-optical characteristics of layered Epsilon-Near-Zero metamaterials

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ABSTRACT

The transmittance magneto-optical (MO) characteristics of Epsilon-Near-Zero (ENZ) metamaterials are studied, using 4 by 4 transfer matrix method. The considered structures are a free standing ENZ-MO slab, and a microcavity type multi-layer structure containing an ENZ-MO layer. The transmittance coefficients of the right- and left-handed circular polarizations for the slab are analytically obtained and numerically investigated. Furthermore, these characteristics are numerically studied for the multi-layer structure. In addition, the Faraday rotations of both structures are investigated. The results reveal the circular polarization filtering effects.

1. Introduction

Metamaterials as the artificial structures with some unusual electromagnetic properties have become one of the most intriguing and important subjects of researches in the past decade [1–5]. Recently, Epsilon-Near-Zero (ENZ) metamaterials with permittivity near zero are introduced [6–19]. The ENZ metamaterials offer unprecedented electromagnetic properties which enable applications such as subwavelength imaging [6–8], manipulation the wave-front [9–11], constructing subwavelength channels and bends [12–14], creating the nano-circuit boards [15–17] and many others [18,19].

On the other hand, the magneto-optical (MO) effects, such as Faraday and Kerr rotations are produced through interaction of light and magnetized materials [20,21]. The most important property of these effects is the non-reciprocity or time-reversal symmetry breaking [22,23]. Moreover, during the past decade, it is revealed that including MO materials into periodic or defective photonic crystals can extremely enhances the MO effects, and make it more appropriate for utilization in miniaturized one-way optical elements [Refs. [24,25], and references therein]. Such structures, named magnetophotonic crystals, are capable of providing unique MO characteristics by exploiting properties of band gaps and defects. Miniaturized MO isolators [26,27] and MO circulators [28,29] are the examples of optical devices which are introduced by utilization of magnetophotonic crystals.

The purpose of this work is the study of the single- and multi-layer structures which contains the ENZ and MO characteristics, simultaneously. For this purpose, at first we consider a free standing ENZ-MO slab in Faraday geometry and investigate the circular polarization (CP) transmittance coefficients and Faraday rotation angle of the system, analytically and numerically. At the second step, we insert the ENZ-MO slab in between the two mirror symmetric dielectric Bragg reflectors to combine the ENZ-MO properties and photonic band gap effects. The considered quantities are studied in this structure, too.

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The obtained results of both structures demonstrate the CP filtering effects, but with different enhancing conditions and under certain circumstances.

2. Model and method

In this section we provide a brief description of 4 by 4 transfer matrix method which can be applied to the MO single- and multi-layer structures. This method was introduced by P. Yeh [30] for anisotropic layered structures and developed by S. Visnovsky for MO multilayers in Faraday geometry [31].

At first, we consider a free standing MO slab in Faraday geometry. The slab thickness is d and its interfaces are in the x-y planes. The z-direction is perpendicular to the slab, as shown in Fig. 1(a).

The slab is subjected to an external static magnetic field along the z-direction. Then, in this geometry the permittivity tensor of the slab is represented by

$$\varepsilon_{MO} = \begin{pmatrix} \varepsilon_{xx} & i\alpha & 0 \\ -i\alpha & \varepsilon_{xx} & 0 \\ 0 & 0 & \varepsilon_{zz} \end{pmatrix}, \tag{1}$$

where the ε_{xx} is diagonal element and the α is off-diagonal element (which is proportional to the external magnetic field) of the permittivity tensor. The magnetic permeability of the slab in the optical wavelengths is assumed to be its vacuum value.

Consider a linearly polarized plane-wave light which is incident normally on the slab. The electric field of the light inside the slab can be expressed as

$$\vec{E}\left(\vec{r},t\right) = \vec{E}_0 \exp\left[i\left(\omega t - \vec{k}\cdot\vec{r}\right)\right], \tag{2}$$

in which the $\vec{E}_0$ is the electric field amplitude with the Cartesian components of (E_{0x}, E_{0y}, E_{0z}). The ω and $\vec{k}$ denote the angular frequency of the light in vacuum and wave-vector in the medium, respectively. Solving the wave equation inside the slab gives

$$\begin{bmatrix} N^2 - \varepsilon_{xx} & -i\alpha & 0 \\ i\alpha & N^2 - \varepsilon_{xx} & 0 \\ 0 & 0 & \varepsilon_{zz} \end{bmatrix} \begin{bmatrix} E_{0x} \\ E_{0y} \\ E_{0z} \end{bmatrix} = 0, \tag{3}$$

in which the N represents the complex refractive index of the slab. Through solving Eq. (3), four eigen values of the wave-vector and corresponding polarization eigen modes are obtained. These quantities are as

$$\vec{k}_{1,2} = \pm\frac{\omega}{c}N_+\,\hat{z}, \quad \vec{k}_{3,4} = \pm\frac{\omega}{c}N_-\,\hat{z}, \tag{4}$$

$$\hat{e}_1 = \hat{e}_2 = \frac{1}{\sqrt{2}}\left(\hat{x} + i\hat{y}\right) = \hat{R}, \quad \hat{e}_3 = \hat{e}_4 = \frac{1}{\sqrt{2}}\left(\hat{x} - i\hat{y}\right) = \hat{L}, \tag{5}$$

where $N_\pm = \sqrt{\varepsilon_{xx}\pm\alpha}$ and the c stands for the speed of light in vacuum. The polarization eigen modes $\hat{e}_\ell$, $(\ell = 1,2,3,4)$ imply that the polarization eigen states of traveling light inside a MO slab are right- and left-handed circular polarizations (RCP and

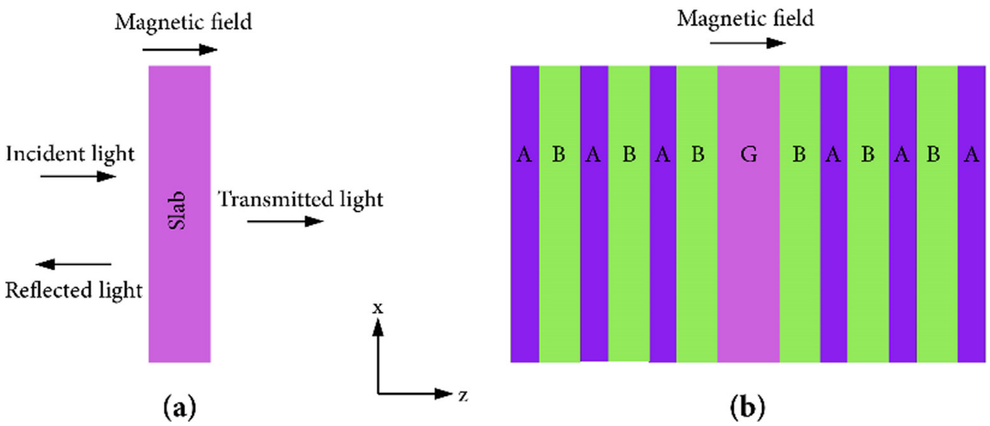

Fig. 1. (a) Schematic of a slab in Faraday geometry, (b) schematic of the multilayer structure with arrangement of $(A/B)^3$ G $(B/A)^3$.