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Multichannel enhanced Faraday rotations in magnetic heterostructures

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ABSTRACT

Transmittance and Faraday rotation (FR) spectra of one-dimensional magnetic heterostructures are investigated using 4 by 4 transfer matrix method. It is revealed that in a simple magnetic heterostructure the enhanced FR at a desired wavelength can be realized considering a special design of substructures and adjusting the thicknesses of constituent magnetic layers. In addition, a complex magnetic heterostructure with capability of providing the multichannel enhanced FRs at desired wavelengths is introduced. It is shown that such a heterostructure could support high transmittance enhanced FRs at telecommunication wavelengths of 1300 and 1550 nm, simultaneously. The results may have potential applications in designing the multi-function single magneto-optical devices such as multichannel Faraday rotators and wavelength division multiplexing systems.

1. Introduction

Nowadays it is known that the analogous bandgaps of semiconductor crystals can exist when electromagnetic (EM) waves propagate in a spatially periodic dielectric structures [1,2]. Based on the Bragg scattering, EM waves with the frequencies within such a gap cannot propagate inside the structure. Such dielectric crystals have been referred to as photonic crystals (PCs) or photonic bandgap (PBG) materials. After the pioneering papers of E. Yablonovitch and S. John in 1987 [3,4], exponential growth of theoretical and experimental researches on PCs has been started and their potential applications continue to be examined. Periodic one-dimensional PCs (1D-PCs) are composed of an ordered sequence of two different dielectric slabs. One of the most interesting aspects of 1D-PCs is related to the presence of a defect layer in the periodic structure that gives rise to localization of EM wave and creates a resonance transmittance within the gap, allowing the corresponding EM wave with previously forbidden wavelength to propagate inside the structure [4–6].

It has been revealed that the localization of EM waves appears not only in the disordered structures, but also in quasiperiodic systems such as Fibonacci [7] and Thue–Morse [8,9] multilayers. Moreover, kind of particularly attractive disordered structures are heterostructures, formed by combining two or more periodic 1D-PCs with different layer thicknesses or different constituent materials. Since distinct PCs have different optical properties, heterostructures can show many appealing characteristics. For example, extension of the PBG, criterion of omnidirectional reflections, and designing of polarization bandpass filters have been studied in number of literatures [10–13].

On the other hand, in past several years, considerable attention has been paid to magnetophotonic crystals (MPCs) due to their capability of providing unique magneto-optical (MO) properties, such as their drastically enhanced Faraday rotations (FRs) [14–17]. The MPCs are formed when the constitutive materials of the PCs are magnetic, or even only a defect layer in the PC is magnetic [16]. The structures with high MO responses are interesting to use in many MO-devices, such as MO isolators, MO modulators, MO sensors, and MO circulators. Recently, utilizing multicavity MPCs to create multiple passbands inside the PBG has opened a new window to engineer multi-function single MO-devices that show simultaneously high transmittance and enhanced FRs [18–20].

In this paper, we discuss magnetic heterostructures constituted of dielectric and magnetic multilayers. The MO responses of simple and complex heterostructures are studied through 4 by 4 transfer matrix method. We show that the enhanced FRs at desired resonance wavelengths in a wide PBG could be obtained considering special design of heterostructures. Such a capability may have potential applications in multi-function single MO-devices.

The outline of our study is as follows: Section 2 gives a brief description of 4 by 4 transfer matrix method. In Section 3 we have presented our study in two steps. First, for a simple heterostructure

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consisting of two periodic MPCs with different design wavelengths, it is shown that the resonance transmittance would occur at special wavelengths. Second, for a complex magnetic heterostructure constituted of two magnetic microcavity substructures the transmittance and FR spectra are studied. Finally, we summarize the obtained results in Section 4.

2. 4 by 4 transfer matrix formalism

Consider the EM wave propagation through a periodic MPC structure $P=\{A,B\}^m$, where A and B are dielectric and magnetic layers with thicknesses of d_A and d_B. m denotes the repetition number and the whole structure is surrounded by air. To calculate optical and MO responses of magnetic multilayer structures, we use 4 by 4 transfer matrix method and follow the formalism that has been developed by Š. Višňovský [21]. In a medium uniformly magnetized in z-axis, the dielectric permittivity of magnetic layer $\hat{\varepsilon}_B$ has the following form:

$$\hat{\varepsilon}_B = \begin{pmatrix} \varepsilon_{xx} & \varepsilon_{xy} & 0 \\ -\varepsilon_{xy} & \varepsilon_{xx} & 0 \\ 0 & 0 & \varepsilon_{zz} \end{pmatrix}, \tag{1}$$

where the nondiagonal term ε_{xy} corresponds to the magnetic gyration. In linear regime, ε_{xy} is proportional to the magnetization of the medium and can be tuned by external magnetic field $\vec{H}_{ext}$. The dielectric layer is determined by a diagonal tensor $\hat{\varepsilon}_A$ as:

$$\hat{\varepsilon}_A = \begin{pmatrix} \varepsilon_A & 0 & 0 \\ 0 & \varepsilon_A & 0 \\ 0 & 0 & \varepsilon_A \end{pmatrix}. \tag{2}$$

For a J-layered MPC structure the total transfer matrix for noninteracting right- and left-circularly polarized (RCP and LCP) waves,

$$M = \left[D^{(0)}\right]^{-1}\prod_{j=1}^{J} S^{(j)}D^{(j+1)}, \tag{3}$$

relates the EM field amplitudes of incident and transmitted waves through the characteristic (S) and dynamic (D) matrices. For the case of normal incidence and polarization parallel to multilayer surfaces, the block diagonal S and D matrices are given by:

$$D^{(j)} = \begin{bmatrix} 1 & 1 & 0 & 0 \\ N_+^{(j)} & -N_+^{(j)} & 0 & 0 \\ 0 & 0 & 1 & 1 \\ 0 & 0 & N_-^{(j)} & -N_-^{(j)} \end{bmatrix}, \tag{4}$$

$$S^{(j)} = \begin{bmatrix} \cos\beta_+^{(j)} & \dfrac{i}{N_+^{(j)}}\sin\beta_+^{(j)} & 0 & 0 \\ iN_+^{(j)}\sin\beta_+^{(j)} & \cos\beta_+^{(j)} & 0 & 0 \\ 0 & 0 & \cos\beta_-^{(j)} & \dfrac{i}{N_-^{(j)}}\sin\beta_-^{(j)} \\ 0 & 0 & iN_-^{(j)}\sin\beta_-^{(j)} & \cos\beta_-^{(j)} \end{bmatrix}. \tag{5}$$

Here $N_\pm^{(j)} = \sqrt{\varepsilon_{xx}^{(j)} \pm i\varepsilon_{xy}^{(j)}}$ represent the complex refractive indices for RCP and LCP waves in the jth layer. $\beta_\pm^{(j)} = (2\pi/\lambda)N_\pm^{(j)}d^{(j)}$ with $d^{(j)}$ being the thickness of the jth layer and λ is the wavelength of incident wave in the vacuum. For a dielectric layer $N_+^{(j)} = N_-^{(j)}$ and the characteristic and dynamic matrices consist of identical 2 by 2 blocks. In terms of M-matrix components, the complex transmission coefficients of RCP and LCP waves can be obtained by

$$t_+ = \frac{1}{M_{11}}, \quad t_- = \frac{1}{M_{33}}. \tag{6}$$

Finally, the observable transmittance $T(\lambda)$ and Faraday rotation $\Theta_F(\lambda)$ of the MPC can be expressed as follows:

$$T(\lambda) = \frac{1}{2}(|t_+|^2 + |t_-|^2), \tag{7}$$

$$\Theta_F(\lambda) = -\frac{1}{2}(\varphi_+ - \varphi_-), \ with\ \varphi_\pm = arg\,(t_\pm). \tag{8}$$

Note that for normal incidence which the characteristic and dynamic matrices are block diagonal, the total transfer matrix will be block diagonal too. On the other hand, the up-left and down-right 2 by 2 blocks of M-matrix are related to RCP and LCP waves, respectively. Such a feature gives the liberty to calculate the $t_\pm$ using corresponding total transfer matrices with dimensions reduced to 2 by 2.

2.1. A simple magnetic heterostructure

In order to study the MO properties of magnetic heterostructures, firstly, we introduce a simple heterostructure with two substructures. Defining the left substructure as $P_L = \{A_1, B_1\}^{m_1}$ with the thicknesses of d_{A_1} and d_{B_1} and the right substructure as $P_R = \{B_2, A_2\}^{m_2}$ with the thicknesses of d_{A_2} and d_{B_2}, we construct a simple heterostructure SH as:

$$\begin{aligned} SH &= P_L \cup P_R = \{A_1, B_1\}^{m_1}\{B_2, A_2\}^{m_2} \\ &= \{\underbrace{A_1, B_1, \ldots, A_1, B_1}_{m_1 \text{ pair of } A_1, B_1} | \underbrace{B_2, A_2, \ldots, B_2, A_2}_{m_2 \text{ pair of } B_2, A_2}\}. \end{aligned} \tag{9}$$

The SH has $2(m_1+m_2)$ layers and is surrounded by air. The left and right substructures consist of identical dielectric (A) and magnetic materials (B), but with different thicknesses. We utilize SiO_2 and cerium substituted yttrium iron garnet (Ce:YIG) as the dielectric and magnetic layers. Ce:YIG is used because it turns out to be one of the most attractive materials for practical applications due to low absorption in infrared region and large MO response. Also, SiO_2 is chosen to get a transparent structure with high optical contrast ratio. The dielectric permittivity of SiO_2 is $\varepsilon_A=2.19$ and the magnetic Ce:YIG layer has dielectric tensor elements $\varepsilon_{xx}=4.884$ and $\varepsilon_{yy}=0.009i$ at telecommunication wavelength $\lambda=1550$ nm [14]. The specific FR of a single layer Ce:YIG can be calculated by $\theta_F = (\pi/\lambda)\Delta n \cong -0.47$ [deg/μm] at $\lambda=1550$ nm [22]. Here Δn is the difference of the refractive indices of RCP and LCP waves in the magnetic layer.

According to Eq. (3), the total transfer matrix of heterostructure SH can be represented by:

$$\begin{aligned} M_1 = \{&[D^{(0)}]^{-1}S^{(A_1)}S^{(B_1)}\ldots S^{(A_1)}S^{(B_1)}\underbrace{D^{(2m_1+1)}|[D^{(2m_1+1)}]^{-1}}S^{(B_2)}S^{(A_1)} \\ &\ldots S^{(B_2)}S^{(A_1)}[D^{(2(m_1+m_2)+1)}]^{-1}\}. \end{aligned} \tag{10}$$

Looking at the center of M_1, we can easily locate the unit matrix I at the interface of the left and right substructures as:

$$D^{(2m_1+1)}[D^{(2m_1+1)}]^{-1} = I. \tag{11}$$