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Polarization gaps in one-dimensional magnetic photonic crystal

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ABSTRACT

We studied the property of magnetic photonic crystal by using the 4×4-matrix method. The transmittance cures and the corresponding band structures show that this kind of structure possesses significant polarization gaps. We find that application of an external static magnetic field causes the right-hand and left-hand circularly polarized waves to become separated, the polarization gap open up while the absolute photonic band gap disappears.

1. Introduction

The control of the state polarization of light waves is extremely important in a range of applications, including the development of optical sensors, lightwave measurement as well as for the development of optical integrated circuits. The cholesteric liquid crystals, chiral media and artificial chiral-made crystals have been used to modulate circularly polarized light and band structure [1–4]. As the symmetry between the right-hand and left-hand circularly polarized waves is broken by these structures, incident electromagnetic waves of left- and right-circular polarization (LCP and RCP) with different speed, are reflected and transmitted differently in the Bragg and significant polarization gap for circularly polarized electromagnetic (EM) waves can be observed [5].

So far, most of those studies are for structurally chiral periodic structure, in which polarization gaps is generated by introducing spirals structure into a periodic system. Also, it is known that the symmetry between the right-hand and left-hand circularly polarized waves also can be broken by magnetic photonic crystals (MPCs), in which an external static magnetic field is applied to induce magneto-optic (MO) activity [6,7]. Theoretically, just as spirals structure broken symmetry between the right-hand and left-hand circularly polarized waves, magnetic structure play the same role, now its interplay with periodic structure should generate polarization gaps. This question has not been studied adequately.

Magnetic photonic crystals (MPCs) are spatially periodic composite structures with one of the components being a magnetic material, such as a ferromagnet or a ferrite. Some interesting results have been predicted, such as enhancement of Faraday rotation [8,9], nonreciprocity [10,11] and nonlinear optical effect in microwave and infrared regions [12].

During the last years about 15 papers, MPCs based on the family of impurity-doped yttrium-iron garnet (YIG) $Y_3Fe_5O_{12}$ are well theoretically and experimentally investigated and widely using in integrated magneto-optics because they are transparent in the near infrared region [13]. Experiment has confirmed the effect with observation of both Faraday and Kerr rotations in excess of 10° at visible wavelength from stacks of only $\approx 10\ \mu m$ in length [14].

The possibility of using a one-dimensional MPC in magneto-optical isolator devices based on multilayer structures composed of Bi:YIG film and two kinds of dielectric films, SiO_2 andTa_2O_5, was theoretically considered by Kato et al. [15,16] for both transmission and reflection mode operations. The transmission mode one-dimensional MPC was considered as a dual-cavity structure $(Ta_2O_5/SiO_2)^k$/Bi:YIG/$(SiO_2/Ta_2O_5)^k/SiO_2/(Ta_2O_5/SiO_2)^k$/Bi:YIG/$(SiO_2/Ta_2O_5)^k$, where k is the stacking number. For the Bi:YIG with a thickness of 550 nm and total medium thickness of 12.96 μm it was theoretically shown that at $\lambda=1.3$ μm the transmittance $T=99.99\%$. Such multilayer structures can be fabricated by employing a sputtering technique in which yttrium iron garnets is used as physical vapor deposition source to fabricate thin films.

In practice, however, fabrication of such a complex film structure is very difficult. For instance, the film sample always requires a post annealing process at around 700 C° so as to form the magnetic films

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with single garnet phase, which unfavorably results in the destruction of multiplayer structure. For realizing film-based system, then, much simpler film structure is strongly needed.

In this paper, we calculate the transmission spectrum of similar multilayer structures by using the 4×4 matrix method. We find that this kind of structure exhibit a significant polarization gap in the presence of external magnetic fields. It is shown that application of an external static magnetic field causes the right-hand and left-hand circularly polarized waves to become separated, polarization gap open up while the absolute photonic band gap disappears.

Many approaches have been reported to demonstrate tunability of optical filters based on photonic crystal such as the mechanical, electrical, and thermal tuning method [17–23], the slow response of the mechanical, electrical, and thermal tuning method does not meet the requirement of ultrafast information processing. A promising solution may be employing a magnetic-optical photonic crystal to form optical filters. Britun and Danilov [24] have realized periodic metalized ferrite dielectric PBG structure parameters governing via external magnetic field in the real timescale. Thus our study may present an approach to achieve the ultrafast tunability of a photonic filter.

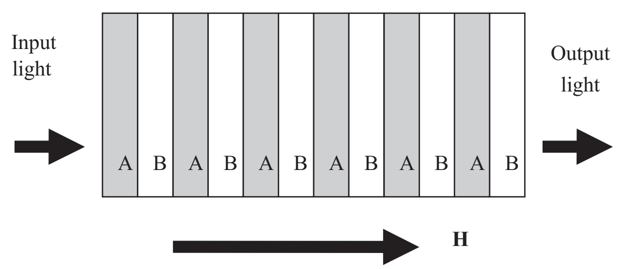

Fig. 1. Typical structure of a magneto-photonic crystal (MPC). A sequence of magnetic (*A*) and non-magnetic (*B*) layers forms a periodic 1-D photonic crystal. Externally applied magnetic field (*H*) directed along the light propagation path allows control of the photonic bandgap properties and polarization state of light transmitted through MPC.

2. Materials and theoretical model

As either uniaxial or isotropic magnetic material placed in a magnetic field parallel to the *z*-axis, circular birefringence (or MO activity) is induced, and the off-diagonal elements appear in the dielectric permittivity tensor [25,26]. Therefore the dielectric permittivity tensor of the magnetic media can be written as

$$\hat{\varepsilon} = \begin{pmatrix} \varepsilon_{xx} & i\varepsilon_{xy} & 0 \\ -i\varepsilon_{xy} & \varepsilon_{xx} & 0 \\ 0 & 0 & \varepsilon_{zz} \end{pmatrix} \quad (1)$$

In Eq. (1) ε_{xy} represents circular birefringence, which is proportional to the strength of the external magnetic field. In the optical wavelength regime, the magnetic permeability in most of the practice cases is reduced to a scalar which is the permeability of free space μ_0. Note that the application of an external magnetic field that induces MO activity does not only affect the off-diagonal elements of the permittivity, but in general it can also modify the diagonal elements of the permittivity. However, we neglect this latter effect since it is known that it is usually much smaller than the diagonal terms.

The structure under consideration is built from alternating magnetic and non-magnetic layers (Fig. 1). Each layer is characterized by the dielectric tensor but they all have different dielectric constants. To form the band structure, the dielectric permittivity is assumed to be $\varepsilon_A \rangle \varepsilon_B$. The dielectric permittivity of non-magnetic layers *A* is assumed to be $\varepsilon_A = 9$, and the corresponding thickness is $d_A = 0.403\ \mu m$. For magneto-optic material, we assume the $\varepsilon_{xx} = 3$, $\varepsilon_{zz} = 9$ and

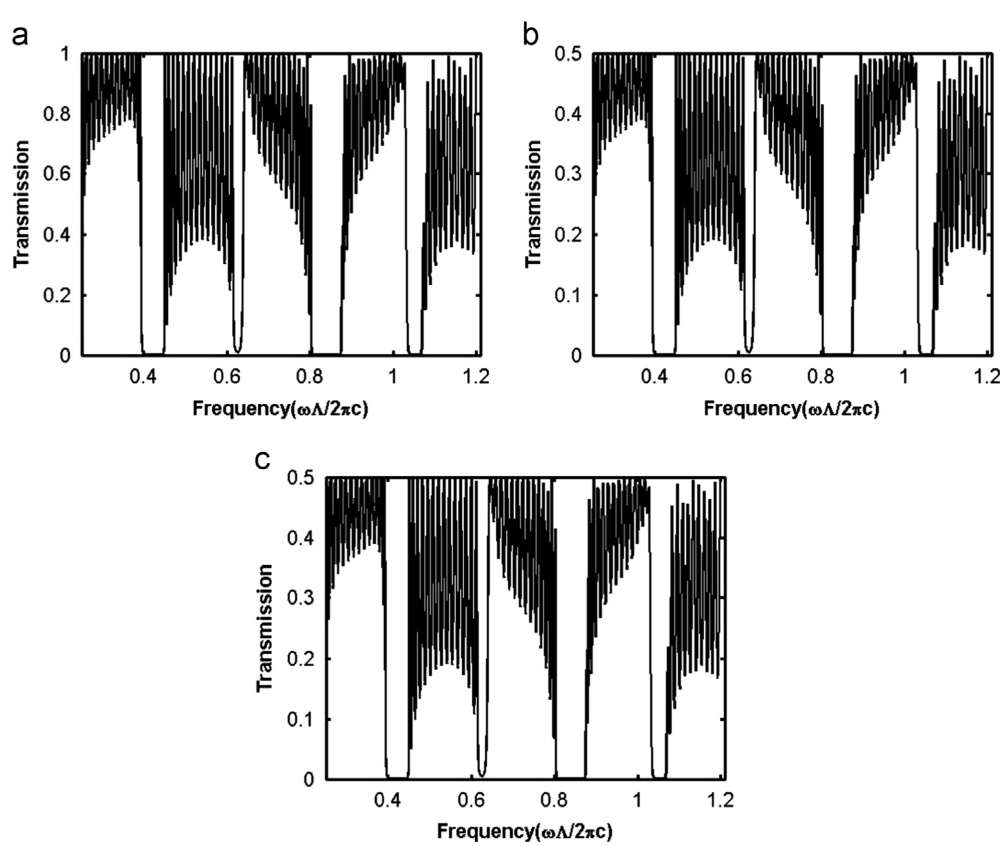

Fig. 2. Transmission spectra for (a) linearly polarized wave (TE), (b) left circular polarized wave and (c) right circular polarized wave without external magnetic fields $\varepsilon_{xy} = 0$ and the number of periods, $N = 14$.