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Mode Conversion in 2D Magneto Photonic Crystals Made of SiO_2/ZrO_2 Matrix Doped With Magnetic Nanoparticles

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In this work, we theoretically study the use of magneto-photonic crystal for amplification of the magneto-optical effects, to improve the merit factor. A two dimensional magneto-photonic waveguide device, formed by a triangular lattice of air holes, embedded in SiO_2/ZrO_2 matrix doped with magnetic nanoparticles, is used to study the influence of the volume fraction (VF %) on the mode conversion. We have used the beam propagation method (BPM) to simulate the efficiency coefficient in a planar 2D magneto-photonic waveguide. The influence of VF % on propagation length is studied, and an enhancement in Faraday rotation in 2D magneto photonic crystal is achieved, which proves the ability of the structure to produce magneto-photonic crystal isolator.

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1. Introduction

Magneto-optical (MO) devices, such as optical isolator and optical circulator are the main non-reciprocal components which are used in system telecommunications. These elements are based on the Faraday rotation effect of magneto-optical materials and its non-reciprocal behavior [1, 2]. Magneto-optical isolator consists of a slab of a MO material sandwiched between two polarizers, rotated by 45° with respect to each other [3]. This component allows the transmission of light in only one direction, while preventing the propagation in undesired directions. Because of this behavior, the optical isolator is essential for protection of other optical active devices, such as amplifiers and laser source, from the reflected light [4, 5].

However, magneto optical isolator is the only element which has not been integrated yet. Several years ago, to fabricate bulk optical isolators the ferromagnetic garnet oxide crystal, yttrium iron garnet (YIG), or bismuth-substituted yttrium iron garnet (Bi:YIG), deposited on a gadolinium gallium garnet substrate (GGG) [6] were widely used. However this class of material cannot be easily embedded by classical technologies to realize magneto optical integrated devices, because of the annealing temperature needed for the crystallization of magnetic iron garnet, which is as high as 700 °C [7]. On the other hand, the use of gadolinium gallium garnet (GGG) as a substrate is not commonly used to realize integrated functions based on III-V semiconductors, silica, silicon or polymer [8].

To overcome these problems, lots of researches have been focused on a novel approach based on a composite magneto-optical matrix doped with magnetic nanoparticles. Sol-gel processing can be used to prepare a large variety of thin films, obtained on several substrates (glass, silicon), having a low refractive index (≈ 1.5), compatible with classical technologies and compatible with semiconductor substrate [9, 10].

The magneto optical material made of SiO_2/ZrO_2 matrix doped with 1.5% of cobalt ferrite nanoparticles shows an interesting Faraday rotation of about 310 °/cm at 1.55 μm. However this material is suffering from low merit factor, which is the quality ratio between the Faraday rotation and the absorption, it is about 10° at 1.55 μm for a planar waveguide [11]. This value is still too low to consider this material as a good candidate for integrated applications.

Based on our previous paper [12], the present paper describes a new kind of artificial magneto optical materials, called magneto-photonic crystals, which are used for amplification of the magneto-optical effects, to improve the merit factor $F = \theta_{\mathrm{F}}$ $(^\circ\,\mathrm{cm}^{-1})/\alpha$ (cm^{-1}). Using beam propagation method (BPM), we look to study the influence of the volume fraction on the mode conversion in 2D magneto-photonic waveguide formed by a triangular lattice of air holes.

2. 2D magneto waveguide design

Magneto-optical waveguides are the key elements of non-reciprocal devices which perform guiding, isolation, modeling, and circulation of optical signal [13, 14]. The SiO_2/ZrO_2 matrix, doped with magnetic nanoparticles, is used to fabricate a planar waveguide. Planar waveguides have been widely used in integrated optical devices due to their low optical losses and high temperature stability [15].

In this work, the physical design, that we analyze and simulate, is a two-dimensional magneto-photonic waveguide, consisting of a triangular array of air holes embedded in SiO_2/ZrO_2 matrix, characterized by a relative radius $r/a = 0.36$ and with the permittivity tensor given by:

$$\hat{\varepsilon} = \begin{bmatrix} \varepsilon & \varepsilon_{xy} & 0 \\ -\varepsilon_{yx} & \varepsilon & 0 \\ 0 & 0 & \varepsilon \end{bmatrix}, \qquad (1)$$

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where ε represents the diagonal elements of dielectric tensor ε_{xx}, ε_{yy} and ε_{zz}. In our case, these elements are equal and are given as follows:

$$\varepsilon = \varepsilon_{xx} = \varepsilon_{yy} = \varepsilon_{zz} = \varepsilon' + i\varepsilon''. \tag{2}$$

However, the complex refractive index of magneto optical matrix is given by $N = n + ik$, where n is the real part of complex refractive index for diagonal tensor elements and k is the imaginary part of complex refractive index. The complex dielectric permittivity of diagonal elements is given by:

$$(n + \mathrm{i}K)^2 = \varepsilon. \tag{3}$$

The real and the imaginary parts of dielectric tensor are given by:

$$\begin{cases} \varepsilon' = n^2 - K^2, \\ \varepsilon'' = 2nK, \end{cases} \tag{4}$$

where K is called the coefficient of extinction and it's given by:

$$K = \frac{\alpha\lambda}{4\pi}, \tag{5}$$

whereλ is the free space wavelength and α (cm^{-1}) represents the losses inside the matrix, it is linked to intrinsic absorption of magneto-optical matrix.

Application to a material of magnetic field with direction parallel to the direction of light beam ($\boldsymbol{M}\|$Oz) produces off-diagonal elements, the magnitudes of which depend on the properties of material (on the Faraday rotation θ_{F} and ellipticity η_{F}) [16, 17].

$$\varepsilon_{xy} = -\varepsilon_{yx} = \varepsilon'_{\mathrm{mo}} + i\varepsilon''_{\mathrm{mo}}. \tag{6}$$

The real and the imaginary parts of $\varepsilon_{\mathrm{mo}}$ are strongly depending on the Faraday rotation θ_{F}, which is proportional to the concentration of magnetic nanoparticles VF. These elements are given by:

$$\begin{cases} \varepsilon'_{\mathrm{mo}} = \frac{\lambda}{\pi}\left(n\theta_{\mathrm{F}} - K\eta_F\right), \\ \varepsilon''_{\mathrm{mo}} = \frac{\lambda}{\pi}\left(n\theta_F + K\eta_F\right). \end{cases} \tag{7}$$

In the limit of small off-diagonal components: $|i\varepsilon_{\mathrm{mo}}| << |\varepsilon|$ and small absorption, an approximate expression for the imaginary part of $\varepsilon_{\mathrm{mo}}$ is obtained [17, 18]:

$$\varepsilon''_{\mathrm{mo}} = \frac{\theta_{\mathrm{F}}\lambda\sqrt{E}}{\pi}. \tag{8}$$

Figure 1 shows a $W3^K_A$ waveguide. The concept for our magneto photonic crystal waveguide consists of a linear waveguide, obtained by removing three rows of air holes along the ΓK direction (waveguide of type K) and by keeping the air holes on both sides of the guide symmetric (waveguide of type A). The considered structure is called air-bridge structure which is surrounded by air (substrate and cover).

3. Dispersion diagram of 2D photonic crystal

In this section we first investigate the band diagram of a two dimensional magneto photonic crystals (2D-MPC). We consider the structure described in the previous section (Fig. 1) without defects. It is made by circular air holes of $r = 0.27$ μm, arranged in a triangular lattice of period $a = 0.75$ μm and embedded in SiO_2/ZrO_2 matrix. The matrix has a permittivity $\varepsilon = 2.2801$ and the magnitude of the off-diagonal elements of $\varepsilon_{\mathrm{mo}} = 0$, corresponding to the SiO_2/ZrO_2 at optical communication wavelength $\lambda_0 = 1550$ nm [19, 20].

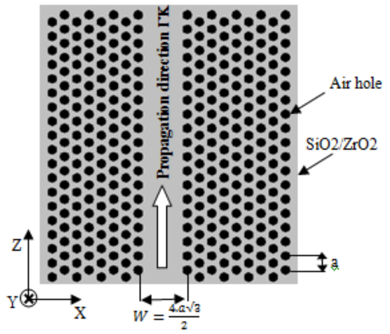

Fig. 1. Representation of a $W3^K_A$ waveguide in a two-dimensional triangular lattice of air holes formed by removing three rows of holes along the ΓK direction.

Figure 2, shows the band diagrams of non-magnetic structure of 2D photonic crystal (with $\varepsilon_{\mathrm{mo}} = 0$) for TE (blue) and TM (red) modes of the polarization.

The band-structure calculation was performed with the plane-wave expansion method. The band diagrams show a frequency band gap for TM-polarized modes but no gap for TE modes with these parameters. It is clear that the TM band gap extends between a normalized frequency $0.482 < a/\lambda < 0.503$ in all plane directions.

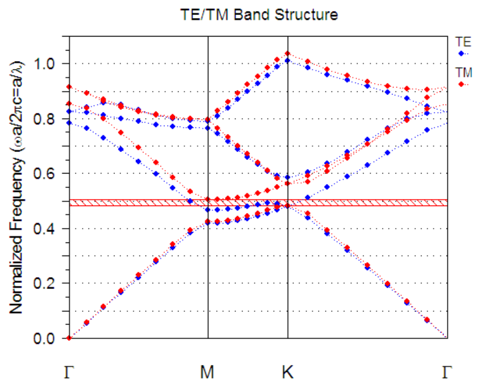

Fig. 2. Dispersion diagram for triangular lattice of 2D photonic crystal embedded in SiO_2/ZrO_2 matrix with filling factor of ff = 47%.

4. Effect of the volume fraction on the mode conversion

Beam propagation method (BPM) in the Rsoft CAD is a powerful technique, used generally for modeling of different aspects of photonic devices or circuits, such as waveguide devices, lasers, filters, isolators, circulators and modulators.

In this section, we look to study the mode conversion in 2D magneto photonic waveguide component and we simulate the influence of different volume fractions VF on the propagation length in the planar waveguide device.

Therefore, in the following we study the effects of VF of magnetic nanoparticles, introduced in the SiO_2/ZrO_2 matrix.

To model the beam propagation through our waveguide, we used a 2.60 μm wide Gaussian beam and directed it along the guide from the input of the guide (Z_{min}). The width, height and length of the guide are 2.6 μm, 2.6 μm and 1200 μm, respectively. Figure 3a shows the E-field distribution inside the guide. Figure 3b illustrates the conversion efficiency as a function of propagation length for a sample doped with VF = 18%, with dielectric tensor elements of the SiO_2/ZrO_2 matrix; $\varepsilon = 2.2801$ and $\varepsilon_{\text{mo}} = 4 \times 10^{-3}$ at $\lambda = 1.55$ μm. From results, it is clear that the coupling length (L_C) is about 0.041 cm.

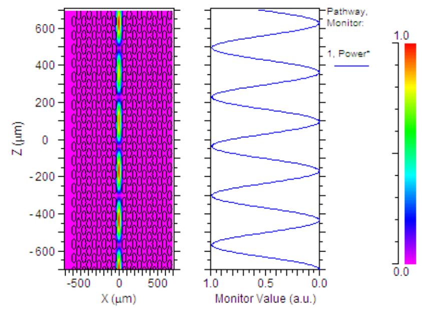

Fig. 3. (a) E-field distribution inside the guide, (b) conversion efficiency as a function of propagation length for a sample doped with VF = 18%.

To explore the effect of Faraday rotation due to off-diagonal elements, we are modeling the beam propagation of light through the MO waveguide for different values of volume fraction. From Fig. 4, it is clear that coupling length is widely linked to volume fraction. The coupling length (L_C) decreases from 0.056 cm for 1% to 0.024 cm for 39%. It is clear that as the VF increases, the coupling length L_C decreases, which leads to an enhancement in Faraday rotation.

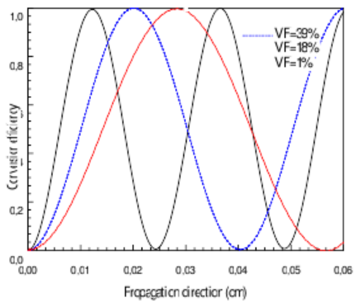

Fig. 4. Conversion efficiency as a function of propagation length for three values of volume fraction (1%, 18% and 39%).

5. Conclusions

The present paper provides an analysis of 2D magneto photonic crystals based on SiO_2/ZrO_2 matrix, doped with different volume fraction of magnetic nanoparticles in order to enhance Faraday rotation. The simulations are based on the propagation of light through a linear waveguide device ($W3_A^K$), designed by removing three rows of air holes along the ΓK direction. The obtained results show clearly that important enhancement in Faraday rotation is achieved in magneto photonic crystals. Furthermore, the coupling length of light decreases with volume fraction, which is strongly linked with off-diagonal elements of the complex tensor.

These simulation results represent an important step in the design of magneto-optical optoelectronic devices. In future work the absorption coefficient in the SiO_2/ZrO_2 matrix doped with different volume fraction of magnetic nanoparticles will be considered.

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