

Mode Conversion in SiO₂/ZrO₂ Layer Doped with Magnetic CoFe₂O₄ Nanoparticles

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This paper describes the TE-TM mode conversion in a magneto-optical layer made by a SiO₂/ZrO₂ layer doped with magnetic CoFe₂O₄ nanoparticles. The mode conversion is caused by the Faraday rotation if the magnetization is aligned along the z -axis, parallel to mode propagation. The properties of this phenomenon are simulated using the full-vectorial beam propagation method (BPM). The simulation results show clearly the influence of two parameters in such devices, the first one is the off-diagonal component of tensor that enhances the rotation and the second one, the imaginary diagonal tensor (parameters K) which makes it suffering from absorption. This result of simulation is an important step to achieve a monolithic integration of optical isolators.

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1. Introduction

Magneto optic effects are divided into three main categories, related to transmission, reflection, and absorption of light by magnetic material, the first category deals with the interaction of the internal magnetization of matter with the electromagnetic wave propagating through it. When linearly polarized light travels through a magnetized sample, the plane of polarization is rotated. The second category of magneto optic effects deals with reflected light from the surface of a magnetized material. It is labeled, in all its different configurations, as the Kerr effect. The last magneto optic effect to be mentioned is the circular magnetic dichroism. This effect is the difference in the absorption coefficient for right or left circularly polarized light. This difference changes slightly the spectrum of absorption of a sample magnetized in the beam direction [1, 2]. A magneto-optical layer can be used with glassy integrated circuits in order to realize a mode converter. In magneto-optical waveguides the problem of thin-film modal birefringence between TE and TM modes ($\Delta\beta = \beta_{TE} - \beta_{TM} = 2\pi\Delta Nm/\lambda$, where ΔNm is the modal birefringence, λ is the wavelength) affects the Faraday rotation and the conversion efficiency in these films. TE-TM waveguide mode conversion ratio R is given by:

$$R = \frac{\theta_F^2}{\theta_F^2 + (\Delta\beta/2)^2}. \quad (1)$$

θ_F (°/cm) is the specific Faraday rotation of the material constituting the waveguide. Glass has unprecedented properties that make it the material of choice for many optical applications. It provides minimal optical attenuation and is rugged against a diversity of atmospheric, thermal and mechanical strains. This is crucial for a

long-term stability of optical waveguides. The material is magnetized along the Z -direction. The magneto-optical materials Faraday rotation response is determined by off-diagonal components in the dielectric tensor. In this paper, we study the TE-TM mode conversion in magneto-optical planar waveguides integrated on glass substrate with an operating wavelength of 1550 nm. This device is constituted by a SiO₂/ZrO₂ layer doped with magnetic nanoparticles CoFe₂O₄ with volume fraction $\Phi = 1\%$, the refractive index of the material is 1.5. This flexibility of the refractive index will be helpful to suit the optical characteristics of the magneto-optical film with requirements of the desired application [2–5].

2. Design

The structure of magneto-optic plan waveguides as shown in Fig. 1, is defined in the (x, y, z) . It consists of a stack of three different environments. We will denote refractive indices respectively n_s , n_f and n_c . The index of the thin film n_f , is greater than that of the substrate n_s , and air n_c index. First, it is assumed that the waveguides are prepared in an anisotropic dielectric material and their electromagnetic modal fields are calculated by beam propagation methods. They lead to nonreciprocal mode conversion and nonreciprocal phase shifts [6].

Different methods have been developed to solve the partial differential equations of E and H . Analytical approximations can be applied to obtain a quick overview. More rigorous techniques apply Vector Finite Difference (VFD), beam propagation method (BPM), finite-difference, or rigorous planar eigenmode expansion (film mode matching). However we use the BPM method which is a quick and easy method of solving for fields in integrated optical devices. It is typically used only in solving for intensity and modes within shaped waveguide structures, as opposed to scattering problems. These structures typically consist of isotropic optical materials, but the BPM has also been extended to be applicable to simulate the propagation of light in general anisotropic

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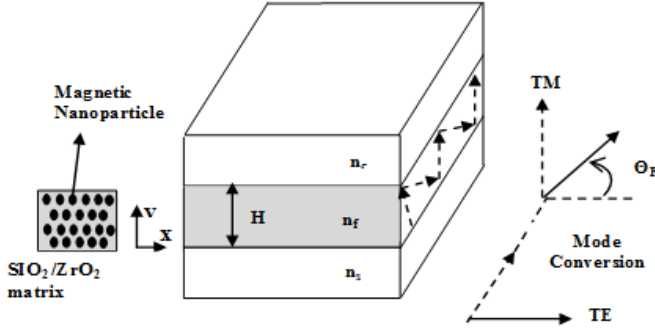


Fig. 1. Schematic representation of a planar waveguide, the nanoparticles used to dope the silica/zirconia are made of cobalt ferrite (CoFe_2O_4), x and y denote the cross section coordinate axes, with the z -direction of propagation.

materials. This allows us to analyze the polarization rotation of light in anisotropic materials [7–11].

3. Magneto-optic effects and the dielectric tensor

With magnetization perpendicular to the direction of light propagation, the permittivity tensor in magneto-optical multi-mode waveguides can be given as [12]:

$$\hat{\epsilon} = \begin{bmatrix} \epsilon_i & +i\epsilon_{m0} & 0 \\ -i\epsilon_{m0} & \epsilon_i & 0 \\ 0 & 0 & \epsilon_i \end{bmatrix}, \quad (2)$$

where each element of tensor $\epsilon_i = \epsilon'_i + i\epsilon''_i$ has real and imaginary parts where $i = xx$ or xy . The diagonal part represents the permittivity tensor of isotropic medium:

$$\epsilon'_{xx} = n^2 - k^2, \quad \epsilon''_i = 2nk \quad \text{and} \quad \epsilon_{m0} = n\lambda\theta_F/\pi,$$

where n is the refractive index of material and k is the extinction coefficient. However, the application of the magnetic field to a material with a direction, parallel to the light beam (Oz), produces an off-diagonal elements, where the magnitude depends on the kind of material (on the Faraday rotation θ_F and ellipticity ϵ_F) [13].

$$\epsilon'_{xy} = \frac{\lambda}{\pi}(n\theta_F - k\epsilon_F), \quad (3)$$

$$\epsilon''_{xy} = \frac{\lambda}{\pi}(n\theta_F + k\epsilon_F). \quad (4)$$

The complex ϵ_{xx} of thin-film were determined by spectroscopic ellipsometry; then ϵ_{xy} was determined by analyzing Faraday rotation and ellipticity data using the determined ϵ_{xy} data [14]. As an example, Fig. 2 shows the profiles of the TE_0 and TM_0 mode of a typical plane waveguide. These profiles are calculated by the full-vectorial beam propagation method. The parameters are listed in the figure caption. Note the discontinuity of the electric field at the vertical boundaries.

3.1. Faraday rotation

Faraday rotation is a Magneto-optical phenomenon, that is an interaction between light and a magnetic field

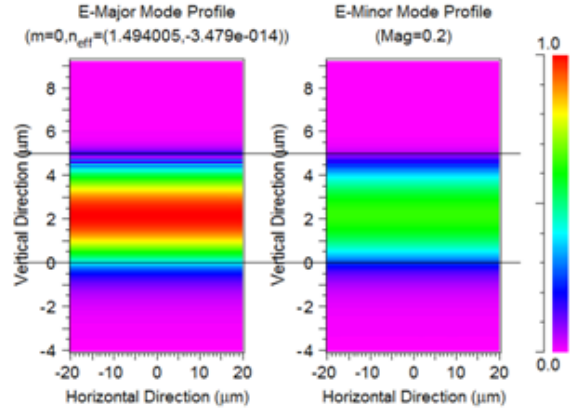


Fig. 2. Contour plots of the main field components $|EY|$ (left) and $|EX|$ (right) of the fundamental TE_0 and TM_0 modes, respectively. The waveguide parameters for $H = 5 \mu\text{m}$, and the respective refractive indices are $n_s = 1.45$, $n_f = 1.51$, and $n_c = 1.0$.

in a medium. A nonreciprocal effect can be achieved in planar waveguide by the TE - TM mode conversion under a longitudinal magnetic field. Figure 3 reports the rotation of polarization in the structure under study, without taking in consideration the parameter K ($K = 0$). The obtained curve has a nonreciprocal behavior typical of the Faraday effect in $\text{SiO}_2/\text{ZrO}_2$ layer doped with magnetic CoFe_2O_4 nanoparticles at $\lambda = 1550 \text{ nm}$.

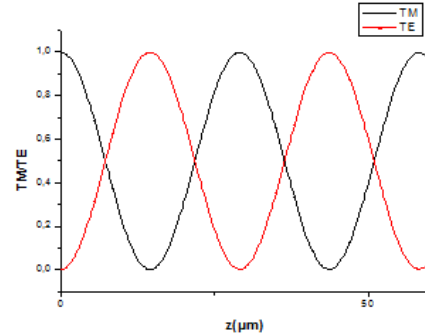


Fig. 3. TM - TE mode conversion ratio in $\text{SiO}_2/\text{ZrO}_2$ layer doped with magnetic CoFe_2O_4 nanoparticles at $\lambda = 1550 \text{ nm}$.

3.2. Waveguides absorption

Absorption in optical waveguides is an important parameter in terms of the performance of waveguides based devices. In a waveguide, absorption loss stems from dissipation or conversion of electromagnetic energy into other forms of energy as a result of its interaction with a material medium [15]. The corresponding electrical field is given by:

$$\mathbf{E}(x, y, z) = \mathbf{E}(x) e^{-i\beta z}, \quad (5)$$

where β is the propagation constant.

In effect, the problem is much more complex because of the different phenomena that can affect the propagation of light in a waveguide. This is the absorption by the

material constituting the thin layer, imperfections in the interface layer and the radiation and at the substrate and the superstrate. Taking into account all these factors, the propagation constant is expressed as follows:

$$\beta = \beta' + i\beta'' \quad (6)$$

The imaginary part of this constant, β'' which contains the various contributions relating to the preceding phenomena, is causing an exponential decay of the amplitude of the light intensity I :

$$I(z) = |\mathbf{E}(x, y, z)|^2 \alpha I_0 e^{-\alpha z}, \quad (7)$$

α ($\alpha = 2\beta''$) is the attenuation coefficient in intensity, it is expressed in dB cm⁻¹.

A previous study on the Faraday rotation behavior of these nanoparticles versus wavelength shows two resonances peaks around 820 and 1550 nm [2–3]. Moreover, this large effect at 1550 nm is located in the optical transparency domain of the cobalt ferrite nanoparticles. A SiO₂/ZrO₂ layer doped with magnetic CoFe₂O₄ nanoparticles with $\Phi = 1\%$, which has Faraday effect of 310 °/cm at 1550 nm, is close to that of YIG (200 °/cm at 1550 nm). Of course, substituted YIG would give a larger effect (≈ 500 °/cm at 1550 nm) [16]. To complete this comparison, we calculate the figure of merit of our material: $F(^{\circ}) = \theta_F(\text{deg cm}^{-1})/\alpha(\text{cm}^{-1})$. The attenuation coefficient α is around 120 cm⁻¹ at 820 nm and around 30 cm⁻¹ at 1550 nm [1]. Thus, the figure of merit is around 2 ° at 820 nm and 10 ° at 1550 nm. These values are less than those of YIG and substituted-YIG material (≈ 40 °/cm at 1550 nm, but they are located in the middle range of the figure of merit of the materials used in magneto-optical applications: between 0.1° and 150° for a wavelength in the range (1300, 1550 nm) [1, 16–17].

4. The mode conversion in the structure

In this section, we study the TM-TE mode conversion in magneto optical planar waveguide, and we analyze how light propagates in straight planar waveguide and what is the influence of the absorption (the diagonal and off-diagonal element of the tensor). Then we interpret the results obtained by simulation of different characteristic parameters of the devices using Rsoft CAD software (module Beamprop).

Figure 4 shows the profile of the propagation of light in the anisotropic structure under study. This allows us to analyze the polarization rotation of light in magneto optical layer in two cases, the first one without taking in consideration the parameter K (Fig. 4a), and the second one with taking in consideration the parameter K (Fig. 4b.)

Figure 4 shows the Magneto-optical TM-TE mode conversion in the planar structure of SiO₂/ZrO₂ layer doped with magnetic CoFe₂O₄ nanoparticles with $\Phi = 1\%$ at $\lambda = 1550$ nm, and normalized intensity of light streak along propagation distance for TE-TM polarization. The same process is illustrated in Fig. 5 with, this time, taking into account the parameter K . The real part of the off-diagonal parameters has a great influence on the performance, and is responsible for the remarkable increase

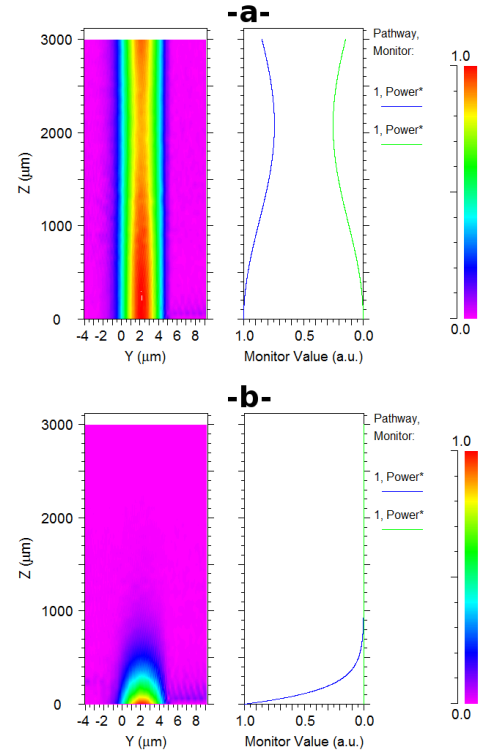


Fig. 4. Magneto-optical TM-TE mode conversion in the planar structure of SiO₂/ZrO₂ layer doped with magnetic CoFe₂O₄ nanoparticles with $\Phi = 1\%$ at $\lambda = 1550$ nm a) with $K = 0$ b) with $K \neq 0$.

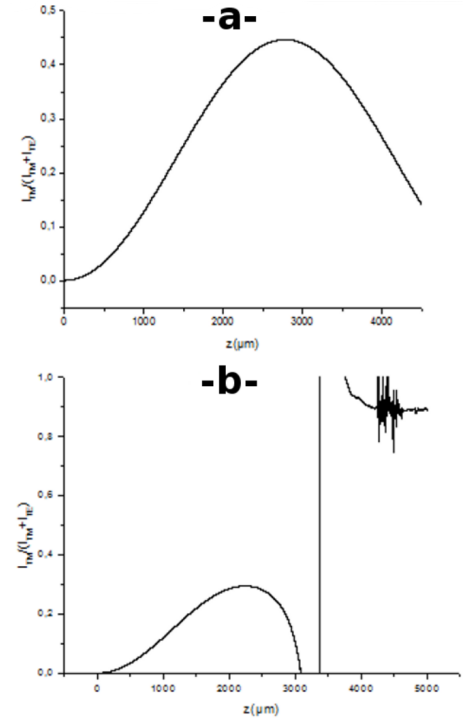


Fig. 5. Normalized intensity of light streak along propagation distance for TE-TM polarized.

of the Faraday rotation (Fig. 5a). It is clear that when we took into consideration the parameter k (Fig. 5b), the absorption increases and the energy tends to zero. We note that the problem with magneto-optical waveguide is that along with Faraday rotation, the absorption and linear birefringence can affect dramatically the merit factor, compromising the device performance.

5. Conclusion

We have reported on a simulation study of the mode conversion in $\text{SiO}_2/\text{ZrO}_2$ layer doped with magnetic CoFe_2O_4 nanoparticles with $\Phi = 1\%$ using the full-vectorial beam propagation method. We study the influence of diagonal and off-diagonal elements of the complex dielectric tensor of the mode conversion of the magneto-optical material. It is clear that the absorption affects drastically the merit factor, compromising the device performance. This study is an important step to achieve a monolithic integration of optical isolators and circulators with other magneto-optical based optoelectronic devices. In future, this material can find wide applications in magneto-photonics crystals that enhance Faraday rotation.

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