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Mode conversion in magneto photonic crystal fibre

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ABSTRACT

The first concept of an integrated isolator was based on nonreciprocal TE–TM mode conversion, the nonreciprocal coupling between these modes is caused by the Faraday rotation if the magnetization is aligned along the z–axis, parallel to mode propagation.

We propose to study this magneto-optical phenomenon, by the simulation of magneto photonic crystal fibre (MPCF), it consists of a periodic triangular lattice of air-holes filled with magnetic fluid which consists of magnetic nanoparticles into a BIG (Bismuth Iron Garnet) fibre. We simulated the influence of gyrotropy and the wavelength, and calculated Faraday rotation and modal birefringence. In this fibre the light is guided by internal total reflection, like classical fibres. However it was shown that they could function on a mode conversion much stronger than conventional fibres.

1. Introduction

The isolator is key element of photonic integration. Isolators are devices that let light pass through in only one direction. This function allows thus to avoid any risk of damage or of instability of the lasers due to the stray reflections. It is based on the non-reciprocity Faraday rotation of magneto-optical materials (MO). They exhibit large MO effects leading to high isolation ratio and low insertion losses.

The first concept of an integrated isolator was based on nonreciprocal TE–TM mode conversion. However most proposals of the waveguide type isolators are based on nonreciprocal TE–TM mode conversion [1,2]; Ando et al. proposed an optical isolator version which is based on the Faraday Effect for a nonreciprocal mode conversion TE–TM and the Cotton-Mouton effect for a reciprocal conversion [3]. K. Xie shows the isolation effect in the guide with 50% of mode conversion TE–TM [4].

The nonreciprocal coupling between these modes is caused by the Faraday rotation if the magnetization is aligned along the z–axis, parallel to mode propagation [5]. The Faraday Effect results in off diagonal terms of the permittivity tensor of material. If the magnetization is oriented in z–direction along mode propagation, the gyrotropic tensor couples the strong x–component of the quasi TE mode to the strong y–component of the quasi TM mode. This coupling leads to periodical power exchange between these modes. Recently, a new type of structure called magneto photonic crystal (also called magnetic photonic crystal) was proposed by Inoue [6]. The magnetic materials can be inserted in photonic crystals (PC). The photonic crystals are periodic arrangements with 1, 2 or 3 dimensions of several materials of different constant dielectric. For magneto photonic crystals (MPCs), in which the constitutive elements are magnetic (or even only a defect introduced into the periodic structure is magnetic).

Various geometries of optical isolator containing oxides photonic magneto-optic structured in photonic crystals 1D and 2D were presented recently; the waveguide in a photonic crystal with triangular symmetry is presented by N.Kono and M.Koshiba [7]. Among materials of this type the most studied are garnets MO (YIG, BIG, Ce: YIG, etc.) [8–10]. The magneto-optical effect can be increased using photonic crystal structure; indeed Kahl and Grishin fabricated a stack of BIG and YIG layers by pulsed laser deposition (magnetic photonic crystal 1D) [11]. Magdenko et al [12], proposed a 2D photonic crystals formed by triangular lattice of air holes in BIG film, grown on gallium gadolinium garnet (GGG) substrates. In 2005, T. Yoshino realized a theoretical study of the fibre optic Faraday Effect based on the mode theory for the first time [13]. The concept of an effective Verdet constant in a terbium-doped-core phosphate fibre is proposed and experimentally validated by Sun et al [14]. In 2011, M. S. Kang, A. Butsch and P. St. J. Russell realized an opto-acoustic isolators in photonic crystal fibre [15]. A compact all-fibre Faraday isolator and a Faraday mirror are demonstrated by Sun et al [16], At the core of each of these components is an all-fibre Faraday rotator made of a 4-cm-long, 65-wt%-terbium-doped silicate fibre. The effective Verdet constant

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of the terbium-doped fibre is measured to be −32 rad/T.m, which is 27 times larger than that of silica fibre. As well as, a complex Faraday rotation in microstructured magneto-optical fibre waveguides are presented by Schmidt et al [17]. In 2012 a magnetic field sensor based on combination of the magnetic fluid and the tunable photonic bandgap effect of photonic crystal fibre is proposed by Peng Zu et al. The magnetic fluid with higher refractive index (> 1.45) is prepared and filled into the air-holes of photonic crystal fibre to convert the index guiding fibre into photonic bandgap fibre [18]. In addition , Thakur et al. [19]. realized a magnetic field sensor by infiltrating magnetic fluid (MF) into the air-holes of a PM-PCF with a sensitivity of 24.2 pm/Oe. We described a TE–TM mode conversion waveguide optical isolator [20], which in principle is the same as the polarization rotation in a bulk Faraday isolator [21]. In this work we propose a magneto photonic crystal fibre (MPCF); the device consists of a periodic triangular lattice of air-holes filled with MF which consists of magnetic nanoparticles into a BIG (Bismuth Iron Garnet) fibre. We make a numerical study on this structure to determine the parameters which influence on the mode conversion. The computational method used is based on a finite difference beam propagation method (BPM) [22]. BPM is the most widely used propagation technique for modelling integrated and fibre optic photonic devices [23] and most commercial software for such modelling is based on it.

In our case, the use of the photonic crystal structure helps not only to confine the light in the central core but also improves optical performance, such as increasing Faraday rotation and mode conversion as well as decreasing modal birefringence and losses with a miniature structure .

2. Magneto photonic crystal fibre

We propose to study a magneto photonic crystal fibre (MPCF); it consists of a periodic triangular lattice of air-holes filled with MF (Fe_3O_4) which consists of magnetic nanoparticles into a BIG (Bismuth Iron Garnet) fibre. We have considered magneto-optical structure in bismuth iron garnet (BIG) fibre because of the high magneto-optical effects of this material [12].

The magnetic nanoparticle concentration dependent refractive indice of a kerosene-based magnetite (Fe_3O_4) MF are taken from Ref [24]. (ambient temperature T=24.3 °C). In this work the magnetic nanoparticle volume fraction concentration within the MF is 1.5%.

The light will be guided in a defect within the periodic crystal structure which in this case is formed by removing the centre hole. The computational method used is based on a finite difference beam propagation method (BPM) [22].

The XY cross-section of the MPCF is shown (Fig. 1). It has the following variables: $n_{BIG}=2.51$, $n_{Fe3O4}=1.5384$, $\Lambda=2.52$ μm, $d=2.16$ μm. Where n, Λ and d, are refractive index, period and hole diameter respectively.

When the magnetization is aligned along the z–axis, parallel to mode propagation, the coupling between the modes TE and TM of a guide is obtained; this coupling comes from the terms off diagonal

($\varepsilon_2 = \varepsilon_{mo}$) of the permittivity tensor of magneto-optical material subjected to a magnetic field [25]:

$$\begin{pmatrix} \varepsilon_1 & -i\varepsilon_2 & 0 \\ i\varepsilon_2 & \varepsilon_1 & 0 \\ 0 & 0 & \varepsilon_1 \end{pmatrix} \quad (1)$$

Where εmo is proportional to magnetization reigning within material:

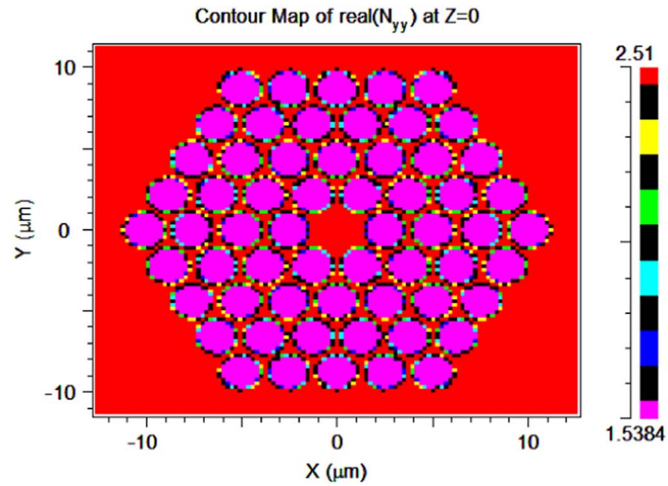

Fig. 1. Index profile of the MPCF structure.

$$\varepsilon_{mo} = \gamma M. \quad (2)$$

Specific Faraday rotation is written:

$$\theta_F = \frac{\pi \mathrm{Re}(\varepsilon_{mo})}{n\lambda} \quad (3)$$

With n and λ respectively the refractive index and the wavelength, we call also the off diagonal term by the gyrotropy g ($\varepsilon_{mo}=g$) [26], this tensor is very often used to study the magneto-optical effects, this off diagonal terms lead to a coupling between the modes TE and TM.

By supposing that the incidental mode is TM,

The conversion output $R(z)$ is defined like the intensity ratio of the mode TE at distance Z on the intensity of the mode TM at the beginning:

$$R(z) = I_{TE(z)}/I_{TM(0)} \quad (4)$$

He is written then:

$$R(z) = \left(\theta_F^2/\left(\theta_F^2 + (\Delta\beta/2)^2\right)\right)*\sin^2\left[\left(\left(\theta_F^2 + (\Delta\beta/2)^2\right)^{1/2} z\right]\right. \quad (5)$$

$$\text{When } \Delta\beta = \beta_{TE} - \beta_{TM} = (N_{TE} - N_{TM})*(2\pi/\lambda) = \Delta N*(2\pi/\lambda) \quad (6)$$

Where NTE and NTM are the effective indexes of the TE and TM modes, respectively, and β is the propagation constant. This last relation highlights which conversion is complete only if $\Delta\beta=0$.

In this case, it is obtained for a distance from propagation

$$L_C = \pi/(2*|K|), \quad (7)$$

called coupling length (Fig. 2), where k is the coupling coefficient.

Since each orthogonal mode acts independently, any input polarization state can lead to an efficient mode conversion. Indeed, owing to the independent operation of these modes, a TE–TM phase matching condition must be reached. In practice, as for an efficient mode conversion, the difference between NTE and NTM needs to be as low as possible.

If the difference of phase $\Delta\beta$ is not null, the conversion output is limited to value R_M obtained at the end of a distance [27] :

$$Lc = \pi/(4\theta_F^2 + \Delta\beta^2)^{1/2} \quad (8)$$