Magneto-optical properties of magnetic photonic crystal fiber of Cerium substituted yttrium iron garnet medium (Ce -YIG) filled with magnetic fluid Fe3O4

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Abstract— **In this work, we propose a photonic crystal fiber based on magneto-photonic crystal (MPC), formed by a triangular ring of circular air holes filled with magnetic fluid (MF) based on magnetic nanoparticle Fe3O4, in a Cerium substituted yttrium iron garnet medium (Ce -YIG), in this fiber, we have theoretically studied the conversion mode, reported and studied the effect of some parameters such as the radius and using a beam propagation method (BPM) in two dimensions. In our proposed structure the maximum conversion modes ratio equal to 98% with low coupling length Lc=15µm is obtained for gyrotropy g=0.35 and Faraday Rotation FR=1900 × 10^4 deg⁄cm.**

Keywords— magneto-photonic crystal fiber, Photonic crystals, optical isolator, mode conversion TE-TM.

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I. INTRODUCTION

This PCF is a kind of fiber based on the properties of photonic crystal, whose significant difference from traditional fiber is the introduction of periodic air-hole structures into the cross section of the fiber. If the refractive index of the core area is higher than the average refractive index of air hole cladding, its guiding mechanism is total internal reflection and it is classified as index guiding fiber. If the refractive index of the core area is lower than the average refractive index of air-hole cladding.

When magneto-optic materials and photonic crystals are combined, new components based on magneto-photonic crystals emerge to exalt the non-reciprocal effects of propagation, during the past few years, some research efforts have been devoted to the investigation of magneto-optical effects in photonic crystals composed of magneto-optical materials [1].

II. MAGNETO-OPTICAL FARADAY EFFECT

The non-reciprocal optical effect of Faraday rotation (FR) is widely exploited in optical isolators, optical circulators and some other magneto-optical (MO) devices [2]. The improvement of Faraday rotation (FR) to reduce the size and cost of magneto-optical devices has been of great interest among researchers [3–6]. As is known, the first design concept of an integrated isolator was based on a non-reciprocal TE - TM mode conversion. In fact, most proposals for waveguide type are based on this [7], [8]. Rare earth elements, such as bismuth and cerium, have been found to increase RF without significantly increasing absorption [9, 10].

It is well-known that the FR effect is caused by a periodic power transfer between the transverse components Ex and Ey [11].

In an isotropic material, three diagonal elements are identical and, in the presence of a magnetic field along the Z axis, there is a non-diagonal element ε, which couples the x and y components of the optical E field [12, 13, 14].

$$\varepsilon = \begin{bmatrix} \varepsilon_{xx} & -\varepsilon_{yx} & 0 \\ \varepsilon_{xy} & \varepsilon_{yy} & 0 \\ 0 & 0 & \varepsilon_{zz} \end{bmatrix}$$

(1)

Where ε represents the diagonal elements of dielectric tensor ε_{xx}, $\varepsilon_{yy}$and ε_{zz}.

Where the magnetooptic permittivity parameters εxx= εyy= εzzare real. In our case, these parametersare given as follows: $\varepsilon = \varepsilon_{xx} = \varepsilon_{yy} = \varepsilon_{zz}$ (2)

The gyrotropy parameter (g), which is responsible for the MO effect, is proportional to Hext in a first approximation, according to the relation: g = ε0χ Hext, (3)

Where ε0 is the permittivity in vacuum and χ is the MO susceptibility in the magnetic field Hext. In absence of Hext, the polarization state of the light wave passing through the wave guide does not change.

However, the complex refractive index of magneto optical matrix is given by N = n + ik, where n is the real partof 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 + iK) 2= ε, (4).

The real and the imaginary parts of dielectric tensor aregiven by: $\begin{cases} \varepsilon' = n^2 - K^2, \\ \varepsilon'' = 2nK, \end{cases}$ (5)

Where K is called the coefficient of extinction and it'sgiven by:

$K = \frac{\alpha\lambda}{4\pi}$ (6)

Where λ is the free space wavelength and α (cm-1) represents the losses inside the matrix, it is linked to intrinsicabsorption of magneto-optical matrix.The specific formula of FR in Deg/cm is given by

$$\theta F = \frac{\pi Re(\varepsilon_{m0})}{n\lambda} \qquad (7)$$

Where n and λ are the refractive index and the wavelength, respectively. Thenon-diagonal term of permittivity tensor can call by the gyrotropy parameter g (εmo = g). This tensor is very often used to study the MO effects, this off diagonal terms lead to a coupling between the TE and TM modes.

Assuming that the incident mode is the transverse magnetic (TM), the conversion output R(z) is defined as the intensity ratio of the TE mode at the distance z on the intensity of the TM mode at the start (z = 0):

$$R(z) = \frac{I_{TE(z)}}{I_{TM(0)}} \qquad (3)$$

It can be written then:

$$R(z) = \frac{\theta_F{}^2}{\theta_F{}^2 + (\Delta\beta/2)^2} \sin^2\left[\left(\theta_F{}^2 + \left(\frac{\Delta\beta}{2}\right)^2\right)^{\frac{1}{2}} z\right] \qquad (4)$$

Here we see that the TE-TM mode conversion is affected by the faraday rotation $\theta_F \left(\frac{deg}{cm}\right)$ of the materiel and the phase mismatch $\Delta\beta \left(\frac{deg}{cm}\right)$, When

Δβ= βTE -βTM=(NTE-NTM) (2π/λ) =ΔN(2π/λ) (5)

with NTE and NTM are the effective indexes of the TE and TM modes, respectively, and β is the propagation constant.

In practice, for an efficient mode conversion, the difference between the refractive index TE and TM need to be low as possible. It was obtained for a distance named the couplinglength. When Δβ is not zero, the mode conversion efficiency is limited to value RM obtained at the end of a length of coupling LC, and can be expressed as relation [15]:

$$L_C = \frac{\pi}{(4\theta_F{}^2 + \Delta\beta^2)^{1/2}} \qquad (6)$$

$$R_m = \frac{\theta_F{}^2}{\theta_F{}^2 + (\Delta\beta/2)^2} \qquad (7)$$

One of the most useful properties of CeYIG is the rotation faraday FR which makes it appropriate for the manufacture non-reciprocal devices based on MPC. [16, 17]. Various geometries of waveguides in a PC structure with containing magneto-optic were presented recently, such as the waveguides in a PC structure with triangular and square lattice reported by DEGHDAK et al [18,19] and KAHLOUCHE et al [20,21], and OTMANI et al [22],MounirBouras et al [23], which consists of improvement FRE , and low coupling length.

III. SIMULATION RESULTS AND DISCUSSIONS

As shown in Figure. 1, the XY cross-section of the MPCF has the following variable parameters: nCe YIG = 2.21, nFe3O4 = 1.4102, Λ = 2.52 μm, d = 2.16 μm, where n, Λ and d, are refractive index, period and hole diameter, respectively. Moreover, the refractive indexes of the MF can be changed with the applied external magnetic field, H [24], such as, at H = 89.9 Oe, nFe3O4 = 1.4635 and at H = 271Oe, nFe3O4 = 1.4670.

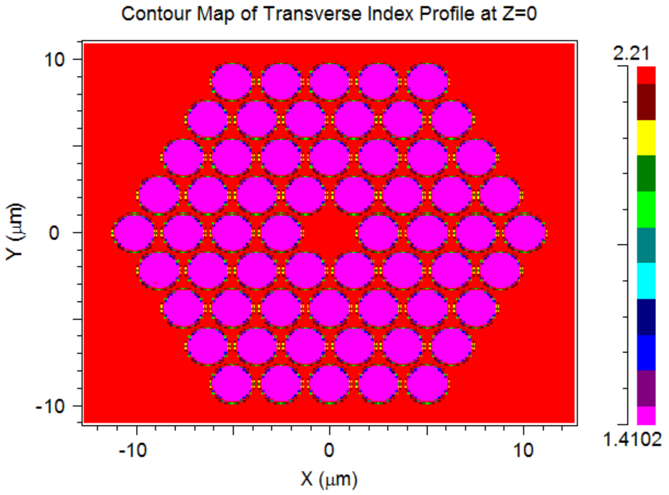


Figure 1 . Index profile of the PCF structure

IV. MODE CONVERSION:

The analysis done in this study has been concentrated on the TE polarization, for which the 2D MPCF. In Figures 2.a and b, the E-field distribution reported inside the fiber and the power run through the fiber (MPCF), the figure 2.a) represents a mode coupling into the MPCF for g=0 there no coupling between the mode. On the contrary, in figure 2.b) once the gyrotropy parameter (g) increases inside 2D magneto-photonic crystal fiber MPCF, so the modes start to couple between them, it starts coupling at value of g=0.11, The Figure 2.b) shows the E-field distribution and the mode conversion obtained with a BeamPROP (BPM) in the case of MO material Cerium-substituted yttrium iron garnet (Ce-YIG) g = 0.27.

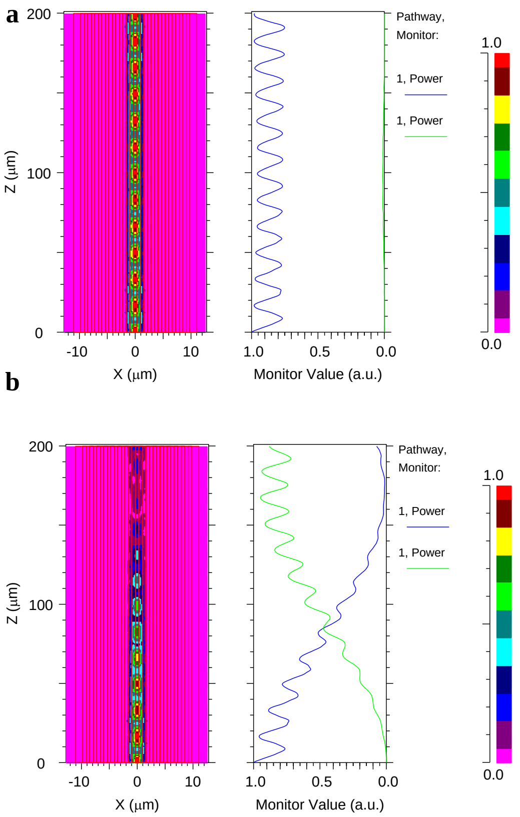


Figure. 2. a) Mode conversion in an isotropic PCF,

b) Mode conversion in 2D magneto-photonic crystal fiber MPCF (g=0,25).

V. THE EFFECT OF RADUIS R ON THE OUTPUT CONVERSION RM:

To examine the effect of the radius of the air holes r on the output conversion Rm, the radius of air holes r is set for different values. Figure 6 a) display variation of conversion output as function radius of air holes r, in this graph show that the modes coupling increase when r increases, with gyrotropy parameter g=0,11 that the coupling is strong between modes, the effect of radius r is proportional on the coupling efficiency, if the is small (r= 1.2 μm) the yield is also small but when it increases, the performance of the conversion increases, thus these results show that the field intensity increases proportionally depending on the radius r. Figure 6.b) shows the output conversion of power Rm for gyrotropy parameter g=0,11,radius r=2.16, Rm increases with the increase of r, such with r=1,20 μm the output is 60% and reached 98% with r=2.16μm.

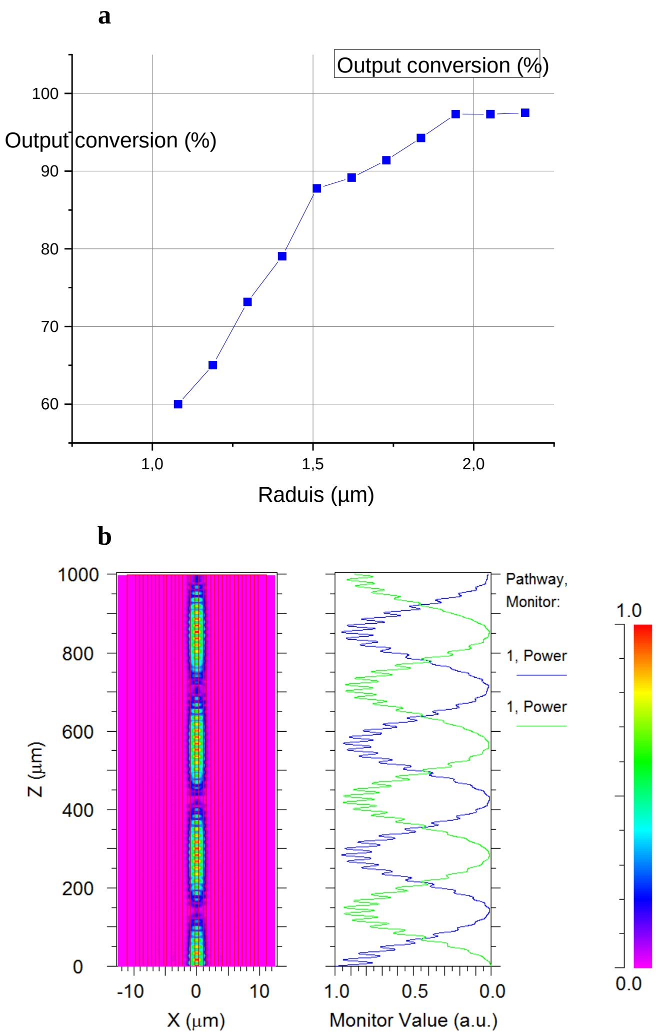


Figure 5. Variations of the power conversion as functions as thickness T, (a=0.73) µm, gyrotropy parameter g=0.45, radius r=0.3a.

VI. THE EFFECT OF GYROTROPY G ON COUPLING MODE:

Figure 3 represents a mode coupling in an MPC fiber, for gyrotropy parameter g = 0,06, g=0,08, and g = 0,1. In this figure, when the non-diagonal terms in the permittivity tensor are zero, the modes are separated; by the existence of these terms induce a coupling mode, which increase proportionally with the increase of these terms, thus a study of the effect of g on mode conversion Faraday rotation is taken in figure.3.

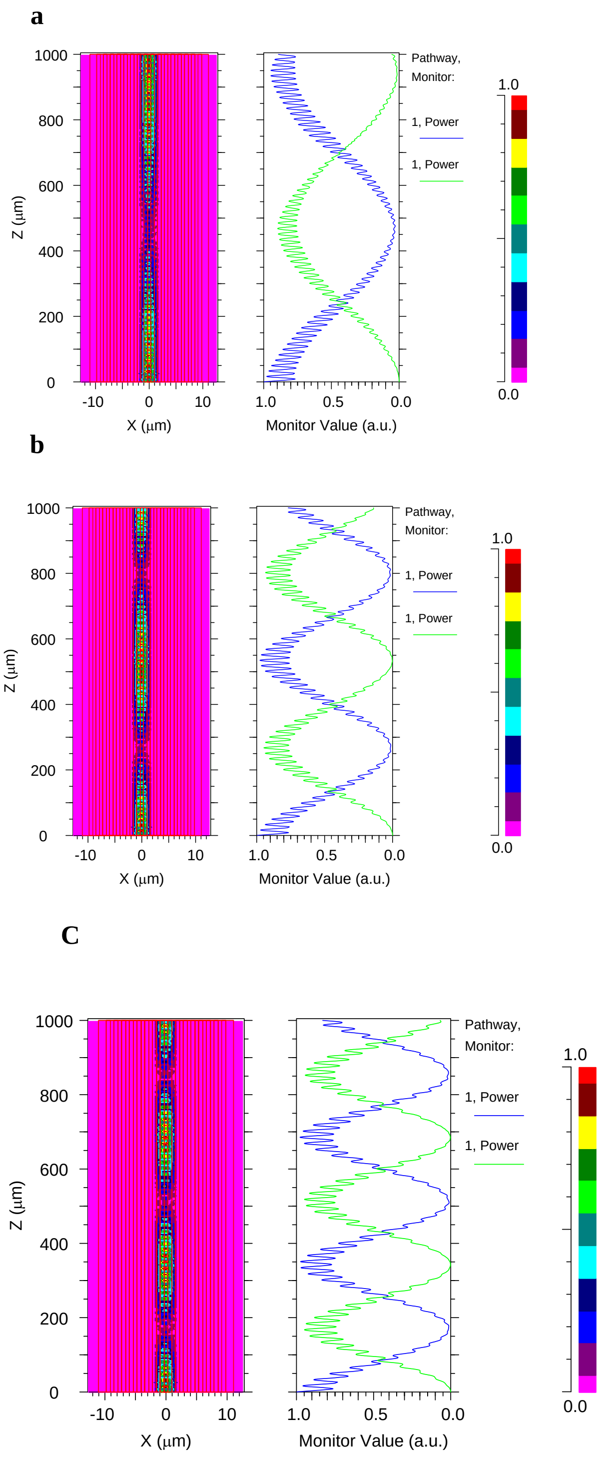


Figure 3- Mode conversion in an MPC Fiber formed by a triangular lattice of air holes: (a) g = 0,06, (b) g =0,08, and,(c) g = 0,1.

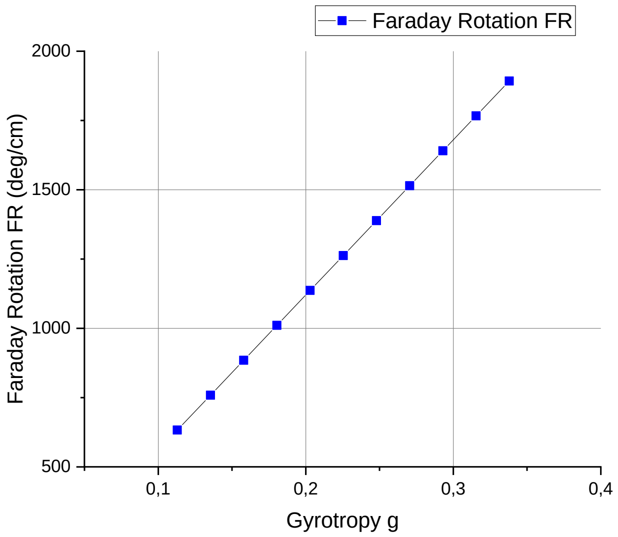
VII. The effect of gyrotropy(g) and radius r on the Faraday Rotation FR:

Figure 4 a) shows the influence of gyrotropy parameter (g) on Faraday rotation (FR). The existence of the off-diagonal parameters in ε allows the coupling between the TE and TM modes in a periodic way, and the variation of these parameters influences much more on the conversion.

An increase in FR is observed with the increase of gyrotropy parameter (g): for g = 0,1, the value of FR is 600 × 104deg ⁄cm and for g = 0,3, FR reaches 1900 × 104deg ⁄cm,

In the figure 4 b), we represent the variation of faraday rotation according to the gyrotropy (g) and radius r, in fact, the faraday rotation remains constant as long as the value radius r varies, such as, it is equal to 0,6 104 approximately. Then the radius r values do not influence on the rotation faraday in this structure.

a



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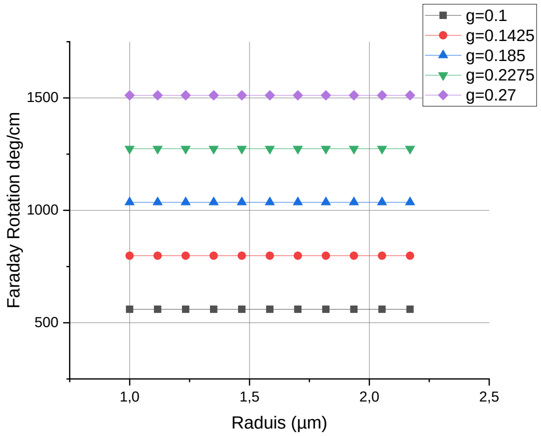
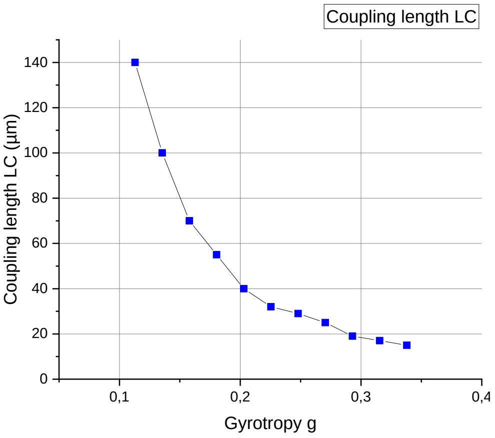


Figure 4 a) variation faraday rotation (FR) versus gyrotropy parameter (g)

b) Influence of the radius of air holes on the Faraday rotation FR with different value of gyrotropy parameter g at λ = 1.55 µm,

VIII. The effect of gyrotropy (g) on coupling length Lc

The existence of the off-diagonal parameters in ε allows the coupling between the TE and TM modes in a periodic way, and the variation of these parameters influences much more on. In figure 5 we see that the coupling length decreases with the increase of the gyrotropy such as, in g=0.12, the coupling length Lc =140µm, if g increases to g=0.34 the coupling length decrease to Lc=15µm)



Figure(5)Variationcoupling length (LC) versus gyrotropy parameter (g) .

IX. CONCLUSION

During the last two decades, the simulation and technical modeling of magneto photonic fiber MPCF have been considerably developed. this work, presented a study of our proposed MPCF, filled with magnetic fluid (MF) based on magnetic nanoparticle Fe3O4 (1.4102), in a Cerium substituted yttrium iron garnet medium Ce-YIG (n = 2,21), arranged on a triangular lattice constant a =2.52 µm, embedded in Ce-YIG (n = 2,21), grown on a silica SiO2 substrate(n=1,45).

We have optimized our proposed structure based on Ce:YIG/Fe3O4 at the telecommunications wavelength λt = 1,55 µm, for an optimal radius r = 2.16µm.

We have studied also the improvement of the conversion efficiency of the polarization modes in this fiber. A conversion rate of 98% is observed for the optimized geometrical structure.

The results show that the radius variation is proportional to the modes conversion efficiency and when the gyrotropy parameter g increases to 0.3, the FR increases and the coupling length can decrease to 15µm. These simulation results represent an important step in the design of magneto optical devices, which are useful for fabricating MPhCs isolator with decreasing propagation losses and low size, to integrate it with other optical functionality.

Acknowledgments

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