Enhancement of magneto-optical properties in magnetic photonic crystal slab waveguide based on yttrium iron garnet

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Abstract. In this work, a polarization-independent waveguide based on magnetic photonic crystal (MPC) with a triangular lattice of air holes in Yttrium Iron Garnet (YIG) slab grown on alumina (Al₂O₃) substrate is proposed, where both TE-like and TM-like periodic band gaps overlap. YIG is well known for its attracting magneto-optical (MO) properties and used to produce a coupling between the TE and TM modes. Thus, a nonreciprocal effect can be obtained by applying an external magnetic field parallel to the direction of propagation. At 1550 nm, the complete photonic band gap is simulated and optimized using the three dimensional plane-wave expansion method. The aim of this study is to enhance Faraday rotation (FR) while maintaining a low modal birefringence. A numerical analysis in function of magnetic gyration ($g$) has been reported, using the BeamProp software. The results reveal a proportional relation between FR, $\Delta n$ and $g$, such for $g = 0.5$, a large FR of $26.11 \times 10^4$ °/cm with $\Delta n = 7 \times 10^{-6}$. The results show a real improvement of this MPC structure based on YIG with larger FR, lower modal birefringence and minimal losses. The notable enhancement in the MO behaviour could improve the performance of optical isolators, and makes it suitable for nonreciprocal devices.

1. Introduction
Photonic crystals have been implemented in many integrated optical devices due to their unique property of light confinement [1]. The key element of these structures is the photonic band gap (PBG) representing the prohibition of the light propagation with the certain wave vectors inside photonic crystals, which helps to develop magnetic photonic crystals (MPCs) combining magnetic constituents with photonic crystals [2]. Therefore, the optical signal is modulated via external magnetic fields through magneto-optical (MO) effects, which improve the MO properties, such as Faraday rotation and minimize the optical losses. These interesting properties are widely applied for high-sensitive biosensors, magnetic field detectors, MO isolators and develop the growth of smaller and cheaper isolators and circulators than currently likely [3, 4]. At the telecommunications wavelengths, from 1300 to 1550 nm, in the near infrared, iron garnets, such as Yttrium iron garnet (Y₃Fe₅O₁₂, YIG), have the highest figures of merit of any known material by several orders of magnitude [5]. YIG is one of the most important ferrimagnetic materials, that has been studied during the last four decade for the realization of MO applications [1], [6–13], due to its excellent electromagnetic properties, including, low dielectric loss, adjustable saturation magnetization, good temperature and chemical resistance [14].
Furthermore, MPC waveguides have attracted considerable interest due to their promising application in optical isolators, circulators, and switch, essential building blocks for all photonic circuit [10]. In the presence of external magnetic field, Faraday Effect inside the magnetic material change the polarization state along the waveguide length, after a certain distance, the TE-like polarized lightwave become a TM-like polarized lightwave. To guarantee this operation, a polarization-independent waveguide that imposes a complete PBG is required in which both even and odd modes overlap. As a result, the lightwave is confined inside the waveguide and thus minimizes the losses [12]. Several studies have been performed on YIG photonic crystal slabs using alumina. Mondal et al [9] have designed a photonic crystal slab waveguides based on YIG with an Al₂O₃ substrate. Thus, He et al have proposed a MPC waveguide splitter with tunable one-way propagating properties. The MO slab is constructed by inserting air background with YIG rod and alumina as cladding [10].

In this work, we suggested a polarization-independent waveguide based on MPC slab with a triangular lattice of air holes in YIG slab grown on Al₂O₃ substrate. The structure parameters have been numerically optimized to obtain the complete PBG in the near infrared. The nonreciprocal phenomenon is analyzed by studying the influence of the magnetic gyration on the MO properties of the proposed device. The method employed here is essentially the same as used by Deghdak et al [12] and Otmani et al [15]. Therefore, our structure shows a clear improvement regarding the width of the complete PBG, and the MO properties of the MPC waveguide based on yttrium iron garnet.

2. Theoretical study
For magnetization directed along the z-axis and parallel to direction of light propagation and in the absence of external magnetic field, the material is assumed to be isotropic. The permittivity tensor for a magnetic material is written as follows [16]:

\[
\varepsilon = \begin{pmatrix}
\varepsilon_{xx} & i\varepsilon_{xy} & 0 \\
-i\varepsilon_{yx} & \varepsilon_{yy} & 0 \\
0 & 0 & \varepsilon_{yy}
\end{pmatrix},
\]

(1)

where, the magnetic gyration is defined by the non-diagonal tensor elements \(\varepsilon_{xy} = -\varepsilon_{yx} = g\), and has a linear dependence on the magnetization. Assuming that the attenuation coefficient is zero, the diagonal term is defined as \(\varepsilon_{xx} = \varepsilon_{yy} = \varepsilon_{zz} = \varepsilon_{\text{material}}\). The specific FR parameter \(\theta_f (°/\text{cm})\) is related to the tensor components of the effective dielectric permittivity as follows [16]:

\[
\theta_f = \frac{\pi\text{Re}(g)}{n\lambda},
\]

(2)

where \(\text{Re}(g)\), \(n\) and \(\lambda\) are real part of the MO permittivity, refractive index and the wavelength, respectively. The isolation ratio variation with wavelength can be understood by considering its dependence on the linear birefringence \(\Delta_n\) and FR parameters. From the familiar expression for the maximum mode conversion efficiency \(R_m\), in terms of the \(\Delta\beta\) and \(\theta_f\) [17]:

\[
R_m = \frac{\theta_f^2}{2(\theta_f^2 + (\Delta\beta / 2)^2)},
\]

(3)

where \(\Delta\beta \,(°/\text{cm})\) is the phase mismatch between TE and TM modes: \(\Delta\beta = 2\pi\Delta_{\text{m}}/\lambda\), where \(\Delta_{\text{m}}\) is defined by \(\Delta_n = n_{TE} - n_{TM}\) for mode number \(m\) [18].
3. Structure design and simulation results

3.1. Device configuration

The investigated MPC slab waveguide shown in figure 1, consists of a triangular array of a spatial period, \( a = 0.61 \, \mu \text{m} \), formed by a periodic disposition of air holes in a YIG slab with a refractive index \( n_{\text{YIG}} = 2.28 \), grown on \( \text{Al}_2\text{O}_3 \) substrate with refractive index \( n_{\text{Al}_2\text{O}_3} = 1.6 \) [9]. To simulate the propagation in the MPC waveguide and to study the mode conversion, we used the Beam Propagation Method [19]. Thus, the waveguide (W1) is obtained by removing a single row of holes in the \( \Gamma'\text{-K} \) direction of the 2D MPC slab structure.

![Figure 1. Schematic of the MPC slab waveguide formed by triangular lattice of air holes in YIG film deposited on Al\(_2\)O\(_3\) substrate.](image)

3.2. Optimization of the complete PBG

For 2D photonic crystal structures, polarization independent transmission in a linear defect requires a full band gap in which the TE and TM band gaps overlap [20]. The influence of both air holes radius \( (r) \) and layer thickness \( (T) \) on the variation of the width and PBG position are examined in figure 2, where \( r \) and \( T \) are varied from 0.32\( a \) to 0.38\( a \) and 1 to 1.4 with 0.1 increment, respectively.

![Figure 2. Effect of the radius/period ratio (\( r/a \)) on the width (a) and the central wavelength (b) of the complete PBG.](image)
As known, iron garnets possess highest figures of merit at the telecommunications wavelengths in the near infrared, hence, the position of PBG must lie within this bandwidth with a central wavelength \( \lambda_c = 1550 \text{ nm} \). As shown figure 2(a), the largest PBG of 0.1683 is obtained for \( r = 0.345a \) and \( T = 1.1a \). However, because of the tradeoff between the largest PBG and the central wavelength, we set the slab thickness and the air holes radius to \( T = 1.2a \) and \( r = 0.355a \) with \( \lambda_c = 1551 \text{ nm} \) (figure 2(b)). The complete PBG width is then equal to 0.1521 \( \mu \text{m} \), which is wider compared to other similar structure [12].

Figure 3 represents the dispersion diagram for the complete PBG of the optimized MPC waveguide, it has been calculated by employing a 3D plane wave expansion method. The complete PBG extends from normalized frequency \( u = 0.36857 \) to 0.40654 which corresponds to wavelength range \( \lambda = 1475.8 \) - 1627.9 nm.

4. Discussion
Next, in order to analyze the effect of the non-diagonal term in the permittivity tensor on the MO properties of the MPC slab waveguide, the influence of the magnetic gyration (\( g \)) values is performed.
The mode conversion variation in function of the $g$ parameter is displayed in figure 4. It can be seen that $g$ affects the conversion mode, such for $g = 0$, the modes are separated. The existence of this term produces a coupling between the modes and increases comparably from $g = 0.1$. Besides, the maximum power transfer in the waveguide, which represents the mode conversion efficiency, is observed and no significant losses are evidenced.

As it has been well explained by Dissanayake [21], guided modes in a waveguide-geometry are characterized by their propagation constants $\beta' = k_0 n_{\text{eff}}$, where $k_0 = 2\pi/\lambda$ and $n_{\text{eff}}$ is the effective index. The number of modes supported by the waveguide depends on the film thickness, the wavelength and the indices of the layers. For given wavelength and waveguide structure, only the fundamental mode can exist right above the cut off thickness. If the thickness is increased, more than one mode is allowed [21].
For the single mode propagation $m = 0$, the variation of $n_{\text{eff}}$ versus $g$ for TE-mode is plotted in figure 5. As shown, $n_{\text{eff}}$ is linearly proportional to the increase of $g$; it is equal to 2.16788 and 2.223934 for $g = 0.2$ and 0.5, respectively.

Meanwhile, due to the coupling between the odd and even modes, as shown in equation (2), the variation of FR depends on both, $g$ and the $n_{\text{eff}}$ [22]. This variation is represented in figure 5, where a linear relation between $g$ and $\theta_F$ is confirmed. For $g = 0.2$, $\theta_F = 10.72 \times 10^4 \, ^\circ/\text{cm}$ and for $g = 0.5$ it is equal to $26.11 \times 10^4 \, ^\circ/\text{cm}$.

![Figure 5](image-url)

**Figure 6.** Influence of the magnetic gyration on the modal birefringence.

The difference between the effective indices of TE and TM modes gives $\Delta n$, which plays an important role in the evaluation of the structure MO properties. As shown in equation (3), the maximum rate of mode conversion imposes the reduction of modal birefringence. So in MO waveguides, one needs to reduce this birefringence [18]. Therefore, $\Delta n$ has been calculated for each $g$ value and the results are reported in figure 6. We can notice that $\Delta n$ is directly linked to $g$; when $g$ increases such as with $g = 0.2$, $\Delta n$ is equal to $-9 \times 10^{-6}$ and for $g = 0.5$, it increases to $7 \times 10^{-6}$. This results demonstrate that polarization independent waveguide minimize the optical losses at telecommunication wavelength $\lambda = 1550$ nm and improve the MO performance, such as increasing FR and $\Delta n$, regarding to those reported in [15], [18].

5. Conclusion
In this work, we have presented the conversion mode in a magnetic photonic crystal waveguide in YIG slab grown on Al$_2$O$_3$ substrate. The complete PBG is simulated and optimized in the near infrared, therefore, an analysis of the magneto optical properties versus the magnetic gyration have been presented, using Beamprop software, such for $g = 0.5$, Faraday rotation reaches 26.11×10$^4 \, ^\circ/\text{cm}$, and modal birefringence of 7×10$^{-6}$ are achieved. The results show a significant enhancement in the magneto-optical properties, which improve photonic devices performance such as one-way filters, optical isolators, circulators, and optical switches.

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