Modeling and optimization of nonreciprocal transmission through 2D magnetophotonic crystal

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Abstract. A combination of unique magneto-optic (MO) non-reciprocity and photonic band gap in periodic structures is promising for efficient enhancement of optical isolation and integrated isolator applications [M. Vanwolleghem et al., Phys. Rev. B 80 (2009) 121102(R)]. In this paper we model and optimize a novel magneto-photonic crystal structure consisting air holes in transparent magneto-optic material in transverse geometry (Bismuth iron garnet ($\varepsilon_{xx} = 6.25$ and $\varepsilon_{yy} = 0.1$) at wavelength $\lambda = 1300$ nm). Such a system with reduced symmetry shows an unidirectional bandgap. The model is based on plane wave Fourier expansion of the field inside the periodic system using RCWA. While in the forward direction the structure transmit the light in the backward direction it shows a band gap and transmission is almost forbidden.

1. Introduction

The need for an integrated and miniaturised version of an optical isolator is making itself increasingly felt. The drive towards ever higher degrees of all optical on-chip integration is often hindered by the absence of an element that induces a one-way sense in the long optical path of the signal in such an integrated circuit. Without such an isolating element, long path interferences can lead to large changes somewhere in the circuit due to small amplitude oscillations at a remote distance. A competitive integrated optical isolator is still not available today despite many years of intense research effort by several groups worldwide [1]. Among other reasons this is mainly due to the limited magneto-optical strength of the common magnetic material in the infrared part of the spectrum, leading to large integrated devices with important sensitivity to fabrication errors. Over the past decade increasing attention has therefore been devoted to artificial enhancement of MO effects using photonic crystal layouts [2]. One very interesting concept that appears by combining magneto-optics and photonic crystal (PhC) effects is the possibility to obtain one-way band gaps. We have recently theoretically proven the existence of such unidirectional regimes for TE modes in 2D integrated uniformly transversely magnetized magneto-optic photonic crystals [3]. In this communication we present a numerical optimization study of one flexible type of such a 2D photonic crystal.

2. Structure of photonic crystal

In Ref. [4] it is proven that the necessary condition for band structure asymmetry (of which local one way band gaps are an extreme manifestation) is the absence of any symmetry operation...
Figure 1. (left panel) Schematic representation of the $cm'$ hexagonal crystal and the resulting symmetries in the Brillouin zone. The black crosses indicate equivalent points in the BZ. The red cross shows the time reversed point. (right panel) The isofrequency contour at a reduced frequency of $f^* = \frac{a}{\lambda} = 0.4545$ of the uniformly magnetized MO PhC of the left panel (material parameters and geometrical details as below). A one-way forbidden gap around the $K$-points is clearly observed. Incident plane waves with $k_y = k_y(K)$ would be totally reflected at this frequency. Those with the opposite $k_y$ would be transmitted.

inside the magnetic space group describing the MOPhC that transforms an arbitrary reciprocal space vector $\mathbf{k}$ into its opposite. We have derived in [3] the 5 plane magnetic Shubnikov groups (out of 80 possible ones [5]) that fulfill this condition under uniform magnetization and derived the recipe to identify the location of the high nonreciprocity regions in the Brillouin zone. By appropriately reducing the symmetry of the motif of the crystal lattice, one can in this way artificially create strong band structure asymmetry close to “crystallographic” directions of the PhC. Fig. 1 shows a possible layout that corresponds to the $cm'$ plane group. This precise motif symmetry with its purely rectangular features is perfectly adapted for RCWA modelling. Other symmetries (e.g. $p3m'1$) might lead to stronger effects. Its Brillouin zone along with its irreducible part is given in Fig. 1. It can be seen that due the axial character of the (uniform) magnetization and the reduced symmetry, the only symmetry present, besides the unity operator, is $m_y'$ ($\equiv m_x$), or thus the combination of time reversal and the mirror operation perpendicular to the $y$-axis. As a result the irreducible part of the Brillouin zone of this hexagonal Bravais lattice is extended to half of the hexagon. For this reason the $K$ ans $K'$ are not equivalent anymore. The only remaining reciprocal direction is $\Gamma - M$, i.e. the $k_x$ axis.

The right panel of Fig. 1 shows the impact of the symmetry reduction on the resulting isofrequency contours in the Brillouin zone. These have been calculated using a standard plane wave expansion technique taking into account the anisotropic nonreciprocal character of the permittivity [6]. The material and geometrical details of the crystal are detailed in a following paragraph. We have plotted a single isofrequency contour (reduced frequency $f^* = \frac{a}{\lambda} = 0.4545$) of the second photonic band at a frequency halfway those of the now non-degenerate $K$ and $K'$ points. As expected from the symmetry arguments elaborated in the left panel of the Figure, a local interior gap without inversion symmetry in the reciprocal space opens up. A TE plane wave at this frequency and incident under the appropriate angle ($k_y = \frac{2\pi}{3\alpha} = \frac{2\pi}{\lambda} \frac{1}{3f^*}$) on this crystal
cut along a $\Gamma - K$ direction will be totally reflected in one sense while partially transmitted in the other. This makes for an extremely compact one-way mirror that can be used as for instance a novel integrated isolator.

In the following paragraph we will numerically validate these qualitative band structure arguments using a RCWA method.

Figure 2 shows a crosssection of the photonic crystal structure and its parametrization. We consider two-dimensional structure consisting of magnetic garnet with the refractive index of $n = 2.25$ for the wavelength $\lambda = 1.3\, \mu\text{m}$ with T-shaped air holes. The centers of the holes constitute a hexagonal lattice with the period $\Lambda$. $\Delta$ denotes the spacing between T-shaped elements, $s_p$ is the thickness of separation layer between gratings layers, and $a$ and $x$ are the scale and the shape parameters of the element, respectively. In our notation one period of photonic crystal consists of two layers of the air holes in magnetic garnet shifted by $\Lambda/2$ and separated by the thickness $s_p$. The filling factor, defined as the surface fraction of the air holes, can be obtained from the geometrical parameters $f = (1 + \sqrt{3}/2 + 2/\sqrt{3})a^2/\Lambda^2$.

We expect that the magnetic garnet is homogeneously magnetized in $x$ direction (perpendicular to the 2D crosssection plane) and the permittivity tensor of the magnetic garnet is in the form

$$
\hat{\varepsilon} = \begin{bmatrix}
n^2 & 0 & 0 \\
0 & n^2 & i\varepsilon_1 \\
0 & -i\varepsilon_1 & n^2
\end{bmatrix},
$$

where $\varepsilon_1 = 0.1$ denotes the off-diagonal magneto-optic parameter. The periodic structure is surrounded by nonmagnetic garnet (in $\varepsilon_1 = 0$) in our model.

3. Modeling of photonic-crystal structure

Transmission through the finite magneto-photic crystal was modeled using Rigorous Coupled Wave Analysis (RCWA). Optical field in the anisotropic structures containing a periodic grating can be on the basis of Bloch theorem expressed using a Fourier expansion into plane waves [7, 8, 9]. The Maxwell’s equations are converted into the eigenvalue problem [7, 10, 11, 12]. Improvement of the convergence speed can be achieved by appropriate application of boundary conditions also for the permittivity tensor elements representations. This improvement for the lamellar gratings is denoted as the Li factorization rules [13, 14] or Fourier factorization [7, 8]. We found that the Fourier expansion can be truncated without loss of required precision for $N = 30$ Fourier harmonics.

In the following we consider the structure with the period of $\Lambda = 590.85\, \text{nm}$ ($f^* = \Lambda/\lambda = 0.4545$), the angle of incidence $\varphi = 17.94\, (N_y = n \sin \varphi = 0.693)$, and the filling factor of the air holes $f = 0.4$. 

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure2}
\caption{Scheme of photonics crystal structure.}
\end{figure}
Figure 3. Transmission of the magneto-photonic crystal as a function of number of periods. Solid (blue) and dashed (red) lines show the transmission of $p$-polarized light in forward and backward direction, respectively. Right subplot shows transmission in logarithmic scale. The period $\Lambda = 590.85$ nm, the wavelength $\lambda = 1.3$ $\mu$m, and the angle of incidence of $\varphi = 17.94^\circ$ (corresponding $N_y = n \sin \varphi$) were used in the calculation.

Figure 3 (left panel) shows the forward (solid blue line) and backward (dashed red line) transmission as a function of the number of periods in the photonic crystal corresponding to increased thickness of the stack. Forward transmission shows oscillatory behavior similar to Fabry-Perot resonances. However, in the backward direction, the transmission rapidly decreases. Right subplot shows linear decrease of the transmission in the logarithmic scale, which corresponds to exponential decay of optical field and photonic bandgap behavior. The first maximum of the transmission in forward direction is around 22 periods.

Figure 4 shows dependence of the forward and backward transmission for 22 periods of air holes as a function of $N_y$. The backward transmission is blocked in the interval from about $N_y = 0.67$ to 0.72 corresponding to photonic bandgap. However the structure is transparent in the forward direction and transmission of 30% is obtained.

Figure 5 shows calculated field (the $x$-component of the magnetic field $H_x$) inside the structure. Left subplot shows the complete structure of 22 periods in forward and backward regime. Note that the color scale is logarithmic to visualize strong decrease of the field in backward direction. In the forward direction (structure is illuminated from the top) the optical field is amplified in the structure and the structure is partially transparent (orange color on the bottom). However, in backward direction (illumination from the bottom) the field is exponentially decreasing and the photonic structure block the transmission (blue color on the top). Right subplot shows a detail of the field distribution in the central area of the structure. It is clearly visible that the field is concentrated in between air holes.

4. Conclusions
Nonreciprocal photonic crystal mirror was designed and modeled. Due to unique behavior of transverse magneto-optic effect, the photonic bandgap was obtained only in backward direction, while in the forward direction the device is transparent.
Figure 4. Transmittance of the $p$-polarized light through the photonic crystal structure as a function of $N_y = n \sin \varphi$ for 22 periods. Solid (blue) and dashed (red) lines show the transmission in forward and backward direction, respectively. In the bandgap ranging from about $N_y = 0.67$ to 0.72 the transmission in backward direction is almost blocked, while the forward transmission reach more than 30%.

Figure 5. Field in the photonic-crystal structure
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