Development of 3mm three-port Y-junction magnetic optical circulator with two-dimensional magneto-photonic crystals

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Abstract: Two kinds of defect structures of two-dimensional (2D) magnetic-photonic crystal (MPCs) are envisaged to realize circulators in millimeter wave band. The band gaps of the two kinds of photonic crystals are calculated by the plane wave expansion method. The function of the circulator is simulated by finite element method. The calculated excellent external characteristics of the circulator show that MPCs is a promising way for generating an optical circulator.

1. Introduction

In recent decades, photonic crystals (PCs), a new class of artificial materials [1, 2], have attracted a lot of attention, because they can be used for the light flow control. With the special characteristics of photonic localization and band gap (PBG), PCs have found comprehensive applications in sensors [3], mirrors [4], waveguides [5, 6], lasers and cavities [7, 8], filters [10, 11], splitters [12], circulators [13-16] and other important components for optical integrated systems.

Circulators suppress multiple reflections between components and thereby improve tolerance with respect to fabrication imperfections and environmental fluctuations. In this paper, two kinds of defect structures of two-dimensional (2D) magnetic photonic crystals (MPCs) are designed to realize 3mm Y-junction circulators. The MPCs are formed by distributing air holes in bismuth iron garnet (BIG) or introducing gyrotropic ferrite post in the Al2O₃ rods array. In the millimeter wave region, Faraday rotation effect of the circulator is expressed as tensor permeability. The band gaps of the PCs are calculated by the plane wave expansion method (PWEM). The function is simulated by the FEM. The calculated excellent external characteristics of the circulator show that MPCs is a promising way for generating an optical circulator.

2. Air hole Y-shaped MPCs circulator

Several kinds of 2D MPCs design schemes have been envisaged to realize three-port circulators in [11, 13, 14]. A windmill-typed circulator formed by air holes array is shown in figure 1(a). An air hole Y-shaped circulator is shown in figure 1(b). A T-typed circulator composed by dielectric posts is shown in Figure1(c).

The first two 2D MPCs defect structures shown in figure 1(a) and figure 1(b) are composed of triangular lattice 2D MPCs, which is made of air holes array distributed in BIG. A point defect is introduced in the central position of the defect structures and a micro resonant cavity is constituted by the adjacent six holes around the central defect. The three line defects composed of air holes with different radius form three optical waveguides labeled Port A, B, and C. Under external DC magnetic field, light wave launched from input port spread into micro resonator by the coupling between waveguide and micro-cavity. Due to Faraday rotation effect, the mode generates frequency division in the micro-cavity, and the wave front occur an angle deflection.
Finally, light wave go output to the corresponding waveguide and achieve the desired ring function.

Figure 1. Three kinds of circulators: (a) A windmill-shaped circulator; (b) Three ports Y-shaped circulator; (3) Three ports T-shaped circulator.

Figure 2. Triangular lattice 2D MPCs with air hole array.

2.1. Defect structure with air holes
Due to the scaling theory of Maxwell’s equations, 2D MPCs defect structure of air holes with optical band in [14] will be scaled to the size of millimeter-wave band. Actually, the structure shown in figure 2 is used to achieve a 3mm three-port Y-junction magnetic optical circulator.

As shown in figure 2, a 2D MPCs defect structure is composed of 2D triangular lattice air holes array distributed in BIG, where the white circles (radius is \( r_w \)) represent air holes and the three rows of air holes with smaller radius (\( r_i = 0.4r_w \)) form three line defect waveguides marked as Port A, B, and C. A bigger point defect with radius of \( r_i = 1.39r_w \) is lead into the central location of the designed structure and a micro-resonator is taken shape at the central area. The micro-cavity can be treated as a cylindrical cavity approximatively and the radius is \( R = a - r_c \). In Figure2, the lattice constant \( a \) is 1mm, which is amplified from the corresponding lattice constant 1 \( \mu \text{m} \) in [14]. When the circular area (red) is biased DC magnetic field, the Y-typed structure composed of air holes array has excellent external characteristics as a single circulator. As compared to the structure of [12], this design seems more simple and compact.

2.2. Photonic band gap and mode field analysis of point defect
As shown in Figure3, the band gap of TM mode for 2D triangular lattice PCs is calculated by PWEM without external DC magnetic field. It is expressed as a normalized frequency range \( 0.2903(2\pi/a) \sim 0.3728(2\pi/a) \), where \( c \) is speed of light.

In order to obtain a circulator with the specified operating frequency (\( \lambda = 3\text{mm} \)), the radius of resonant cavity in figure 2 will be precisely adjusted. The radius of micro-resonator is determined by the lattice constants \( a \) and the air hole radius \( r_i \). When the lattice constant \( a = 1\text{mm} \) is fixed, the center frequency of resonant cavity versus with the radius \( r_i \) of air holes is shown in figure 4. As the radius of air pore increasing,
the corresponding wavelength progressively decreases. Exactly, when the radius of the air holes is \( r = 0.321689 \text{mm} \), the wavelength of circulator is \( \lambda = 3 \text{mm} \).

![Figure 3. PBG for triangular lattice PCs.](image)

![Figure 4. The relationship between the radius of air hole and the center frequency of micro-cavity.](image)

![Figure 5. Hz field distribution of modes in micro resonator cavity: (a) odd mode; (b) even mode.](image)

Numerical results show that the cylindrical resonant cavity can support a pair of dipole degenerate modes at the central normalized frequency of \( 0.333333(2\pi/a) \), which are represented respectively as even
mode $|e\rangle$ and odd mode $|o\rangle$. The distribution of magnetic field intensity $H_z$ is shown in figures 5(a) and 5(b).

### 2.3 2D MPCs circulator with air holes array

When external magnetic field is applied along $z$-direction in the central position, the electromagnetic field propagation in the circulator is numerically simulated by FEM at the operating frequency of $0.333333(2\pi/a)$, as shown in figure 6. Figure 6(a) shows that the light wave launched from the input port (A) is almost totally and averagely transmitted to the output port (B) and the isolated port (C) without any external DC magnetic field ($\varepsilon_c = 0$). In the case of external DC magnetic field ($\varepsilon_c = 0.6$), figure 6(b) exhibits that the doubly degenerate modes take place coupling in the central position and the wave front occur a 120° Faraday deflection angle, so light wave launched from Port A is transmitted to Port B and isolating to Port C, analogously also shown in figures 6(c) and 6(d).

![Figure 6](image)

**Figure 6.** Light wave transmission in 2D MPCs circulator: (a) Light wave transmission without any external DC magnetic field; (b)(c)(d) Light wave transmission with external DC magnetic fields.

The insertion loss and isolation of the circulator are then studied by changing the frequency of incident light wave. When light wave is launched from one of the three ports, the power of light wave at the other two ports is measured. Isolation and insertion loss of the circulator changing with frequency are shown in figure 7.

![Figure 7](image)

**Figure 7.** Numerical insertion loss and isolation

The numerical results show that at the center frequency of $\lambda = 3\text{mm}$ or the normalized frequency is $0.333333(2\pi/a)$, circulator has highest isolation of 15.53dB and lowest insertion loss of 0.12dB. When the
frequency of the input light wave diverges from the central frequency, transmission efficiency of the circulator gradually decreases. With the increasing frequency offset, the transmission characteristic of the circulator sharply deteriorate for the constantly reducing isolation and the increasing insertion loss.

3. Dielectric cylinder Y-shaped MPCs circulator

3.1 Defect structure with dielectric rods

As shown in figure 8(a), a T-shaped three-port [13] circulator has been designed based on square lattice photonic crystals (SLPCs) with posts array. The numerical isolation of this design reaches 25dB, but the bandwidth is still narrow. Based on SLPCs, a four-port cross-typed circulator is designed in [16].

Summarizing the former several designs, a novel simpler 2D MPCs defect structure is envisaged and a more compact Y-typed circulator is numerically studied. By introducing a ferrite post ((ε = 12.9) in the central position of the triangular lattice PCs with dielectric rods array, the circulator is shown in figure 8(b). The ferrite post with bigger radius plays a role of resonator. When the central ferrite post is longitudinal magnetization, the light wave takes place a 120° Faraday rotation in the central area.

![Figure 8. Rods array 2D-MPCs circulator: (a) T-shaped; (b) Y-shaped](image)

3.2 Low-loss 2D MPCs circulator

Photonic band gap structure for TE mode and point defect micro-cavity of two-dimensional triangular lattice rods array have been analyzed in [15]. Similar to the previous section, the structural parameters of circulator will be set in the millimeter wave band and lattice constants take $a = 1.125\text{mm}$ and the radius of dielectric post is $r_0 = 0.18a$. This time the dielectric post is chosen low-loss ceramics material with refractive index $n_0 = 3.4$ [17]. The PBG of TE mode for 2D triangular lattice PCs is also calculated by PWEM. The normalized frequency range of the PBG is $0.2385 - 0.4216(2\pi/a)$. By changing the radius $r_1$ of the central ferrite post to $0.27a$, the operating wavelength of circulator can achieve 3mm, at this moment, the normalized frequency is $0.375(2\pi/a)$.

When the external DC magnetic field is $H_e = 2.85 \times 10^5 \text{ A/m}$, and loss coefficient is $\alpha = 3 \times 10^{-4}$, the elements of tensor permeability are represented by following equations [16]:

$$\mu_1 = 1 + \omega \kappa (\omega_0 + \omega_0) / \left[ (\omega_0 + \omega_0)^2 - \omega^2 \right]$$  \hspace{1cm} (1)

$$\kappa = \omega_0 \alpha / \left[ (\omega_0 + \omega_0)^2 - \omega^2 \right]$$  \hspace{1cm} (2)

$$\omega_0 = \mu_0 H_e$$  \hspace{1cm} (3)

$$\omega_0 = \mu_0 M_s$$  \hspace{1cm} (4)

where $\gamma = |e/m| = 1.759 \times 10^7 \text{ C/kg}$ is gyromagnetic ratio and saturation magnetization is $M_s = 2.39 \times 10^3 \text{ A/m}$. In
different situations, the electromagnetic field propagations in circulator are simulated at the central frequency of $0.375(2\pi/a)$ by FEM, as shown in figure 9.

\[ \text{Figure 9. Light wave transmission in 2D MPCs circulator. (a) Light wave transmission without any external magnetic field; (b)(c)(d) Light wave transmission with external magnetic field.} \]

The numerical results show that the variations trend with frequency for isolation and insert loss in this paper perfectly conform to those numerical results of [13], as shown in figure 10. The maximum isolation is by nearly 26.36dB higher than the optimal result in [13]. Furthermore, the lowest insertion loss of 0.064dB has a significant improvement. In [13], four ferrite rods were used as the central defect, which undoubtedly will bring more energy loss.

4. Conclusions
Two kinds of defect structures of 2D MPCs are envisaged to realize circulators in the millimeter wave band. The band gaps of the two kinds of PCs are calculated by PWEM. The function of the circulator is simulated by FEM. The excellent performance of insertion loss 0.064dB and isolation 26.36dB for the circulator show that MPCs is a promising way for generating an optical circulator.
Acknowledgments

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