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Three Port Optical Circulator based on Gyromagnetic Property of Photonic Crystals

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ABSTRACT

Optical passive components play a key role in optical communications and computing based on integrated photonic structures. Here a new design of ferrite-based three port optical circulator is suggested and analyzed. This structure of this component consisting of dielectric crystals entrenched in air. The central crystal is magnetized by the DC magnetic field and utilizes the gyromagnetic property of ferrite material to provide the non-reciprocal transmission for 120º of electromagnetic waves. Numerical simulations are demonstrated in order to check the performance of the presented component.

Keywords: Gyromagnetic property; Non-reciprocity; Circulator.

1. INTRODUCTION

Photonic integration is currently an active topic that integrates multiple photonic functions on a single chip.Photonic integrated circuits are widely used in the area of fiber-optic communication and in other fields such as biomedical and photonic computing are also probable [1]. It is used to miniaturize the optical systems and allow them to be higher performance [2]. Photonic crystals are attractive optical materials that affect electromagnetic wave propagation by defining allowed and forbidden photonic bands [3]-4]. Two dimensional photonic crystals are of great interest for both fundamental and applied research to find commercial applications. They have been shown to be a promising platform for creating large-scale optical integrated circuits that are necessary to address the increasing demand of optical information processing for broader communication bandwidth. Defect states of photonic crystal, in particular, provide a mechanism to systematically miniaturize devices down to a single wavelength scale [5-8]. On the other hand, inevitable interferences among waves from different optical elements or devices would change the functions of the systems designed. Therefore, designing optimized and miniaturized optical circuits becomes a key technical issue in developing optical integrated circuits. The use of such devices may reduce the production cost and provide greater functionality in large-scale circuits. Among various photonic crystal devices, non-reciprocal optical elements have been intensely researched [9-10].

In integrated optical systems, passive elements are indispensable devices that eliminate multi-path reflection between components. Non-reciprocal devices, allows light to propagate only along a single direction, and are essential for reducing the multi-path reflection, suppressing the noise and improving stability of the system.To miniaturizing these devices such as circulators down to a single-wavelength scale, nonreciprocal effects in point defects of magneto-optical photonic crystals is introduced [11].

An optical circulator is a distinctive multiport fiber component which is used to separate optical signals that travel in opposite direction in an optical fiber. The operating principle of the circulator is that if light is arrives first port it is released from second port, but if some of the emitted light is reflected back to the device, it does not come out of first port but instead exists from third port [12].

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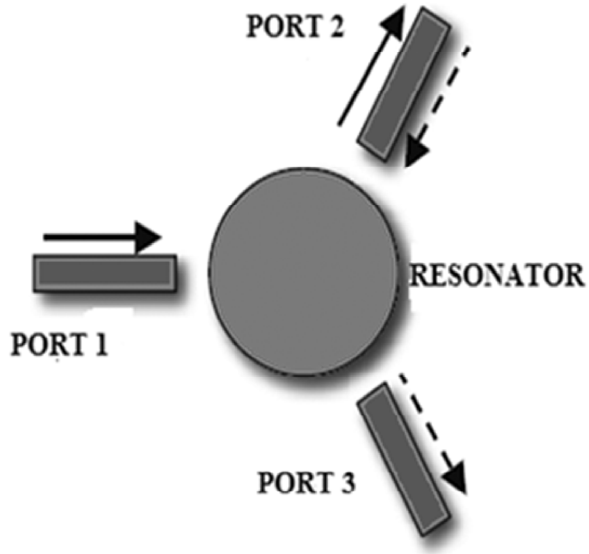

Figure 1: Schematic of an optical circulator

This non-reciprocal transmission can be achieved by three main criteria which are known as defect mode analysis in cavity, application of magnetic field in z-direction and utilization of gyromagnetic property of ferrite crystals.

Because of this non-reciprocal functionality circulators can be used to realize bi-directional transmission systems for eliminating the need of isolators and couplers. Optical circulators are extensively used in advanced communication systems and fiber-optic sensor applications due to the high isolation and low insertion loss of the input and reflected light signals.Photonic crystal circulators have been designed by using the nonreciprocal effect in magneto-optical materials with their sizes on the order of several micrometers, and they can be directly integrated with other photonic crystal devices [13].

Several researchers predicted and discussed the importance of magnet-optic material and how to incorporate the non-reciprocal transmission of electromagnetic waves in defect contained photonic crystals by utilizing Faraday rotation [14] and magnet-optic effect by designing the passive components [15-21].

In this work, a three-port optical circulator based on magneto-optical cavity on two-dimensional triangular lattice is designed which has simple cavity structure and it is easy to fabricate. Numerous simulations are demonstrated to verify the performance of the designed structure. The device considered here can be realized for the function of splitting and isolation. Miniaturization of the same leads to the micro-chip integration.

2. DESIGNING OF THE OPTICAL CIRCULATOR

2.1. Theoretical Analysis

2.2. Gyro tropic media

Magneto-optic or gyromagnetic media show the change of orientation of the field polarization according to illustrious Faraday rotation effect. These media are characterized by a preferred direction, introduced by an external magnetic field, contributing the medium anisotropic, even though the ambient medium (in the absence of the externally imposed magnetic field) might be isotropic. A general overview of magneto-optical effects in general optically active crystalline or amorphous materials indicates the various effects. In general we have the electromagnetic fields defined in special directions in space, but in addition the externally imposed magnetic field and the crystalline structure define additional preferred directions, contributing the medium to be anisotropic by breaking time reversal symmetry of the system locally which is an essential condition to build passive components such as optical isolators and circulators [22].

The anisotropic permeability of a magneto-optic material magnetized in thez direction is in the following form: [23]

$$[\mu] = \begin{bmatrix} \mu & jk & 0 \\ -jk & \mu & 0 \\ 0 & 0 & \mu_0 \end{bmatrix} \tag{1}$$

The tensor elements μ_r and k are given by the following equations

$$\mu_r = \mu_0(1 + \omega_m (\omega_0 + i\alpha\omega)/[(\omega_0 + i\alpha\omega)^2 - \omega^2] \tag{2}$$

$$k = \mu_0(\omega_m\omega)/[(\omega_0 + i\alpha\omega)^2 - \omega^2] \tag{3}$$

Where,

$$\omega_m = \gamma M_s \tag{4}$$

$$\omega_0 = \gamma H_0 \tag{5}$$

Here μ_0 denotes the permeability of free space; ω is the angular frequency; H_0 is the applied external magnetic bias field; M_s is the saturation magnetization of the ferrite material; and γ is the gyromagnetic ratio.

2.3. Structure of the three port circulator

An alternative photonic crystal circulator is designed by modulating the waveguides along the radial directions of the magneto-optical cavity located at the center, and by introducing defects in the photonic crystals. The

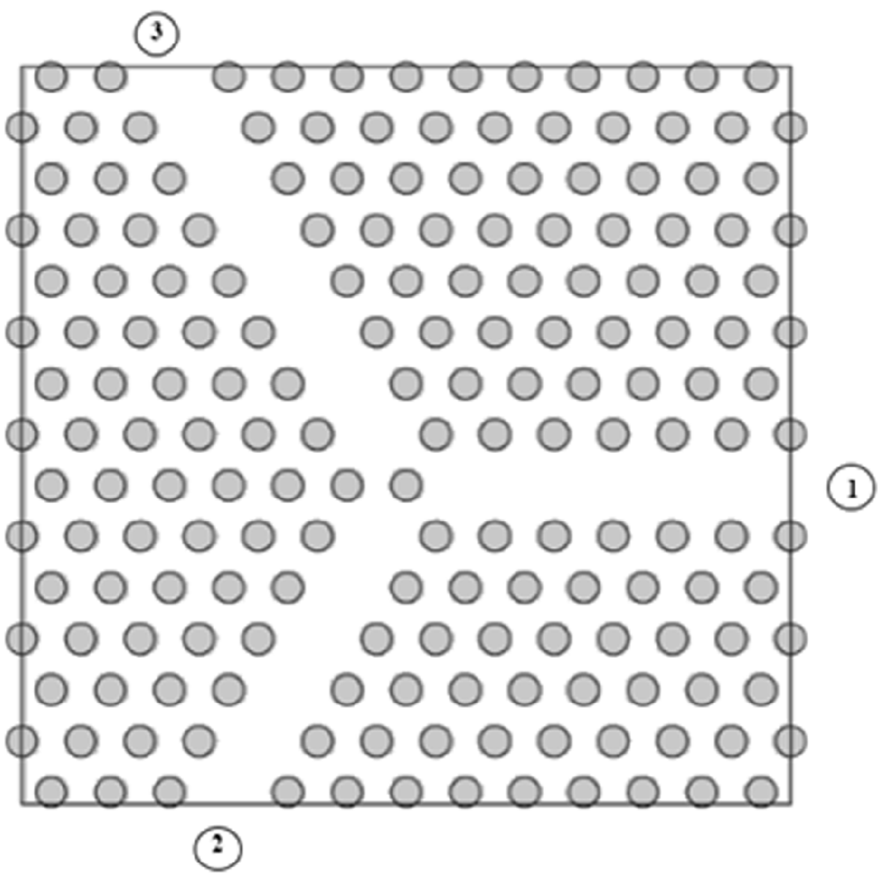

Figure 2: Initial Design

structure of this designed device consisting of dielectric materials which has the refractive index of 3.42 is embedded in air. Initial design of the presented circulator is shown in fig. 2.

Fig. 1, shows the structure of the device before the optimization process where three waveguides are formed by removing the row of dielectric crystals based on line defects. It is noticed that for this geometrical configuration, there is no nonreciprocal transmission, which leads us to seek change in the parameters of the cylinders near the resonator. Then optimization is important to rectify this problem.

The final optimal design with the changes made in the crystal structure can be seen in Fig. 3. The radius of the dielectric crystals is $r_1 = 0.25a$. The cavity is formed by enlarging the dielectric crystals with the radius of $r_2 = 0.247a$ marked in blue color, and the central crystal solid circle marked in black color known as magneto-optic material is in the radius of $r_3 = 0.3a$ where "*a*" is the lattice constant. The crystal structure with three 120º rotational symmetry branches of waveguides coupled at the center of this cavity. The nonreciprocal phase shift occurs when a magnetic field is applied transversely to the beam axis through a magnetically active material. Accordingly dc magnetic field along the z-axis direction is applied in the center area represented by the black solid circle. This material can be characterized by the permeability tensor matrix as in equation (1) and the remaining material parameters are as follows,

Saturation magnetization, Ms = 5.41×10^4 A/m, relative permittivity, $\varepsilon_r = 14.5$, the gyromagnetic ratio is 1.759×10^{11} C/kg, the applied bias field is set to $H_0 = 7.96 \times 10^3$ A/m.

The following equation applies to the electric field vector **E** inside the circulator,

$$\nabla \times \left(\mu r^{-1} \nabla \times E\right) - k_0^2 \left(\varepsilon_r - \frac{j\sigma}{\omega \varepsilon_0}\right) E = 0 \tag{6}$$

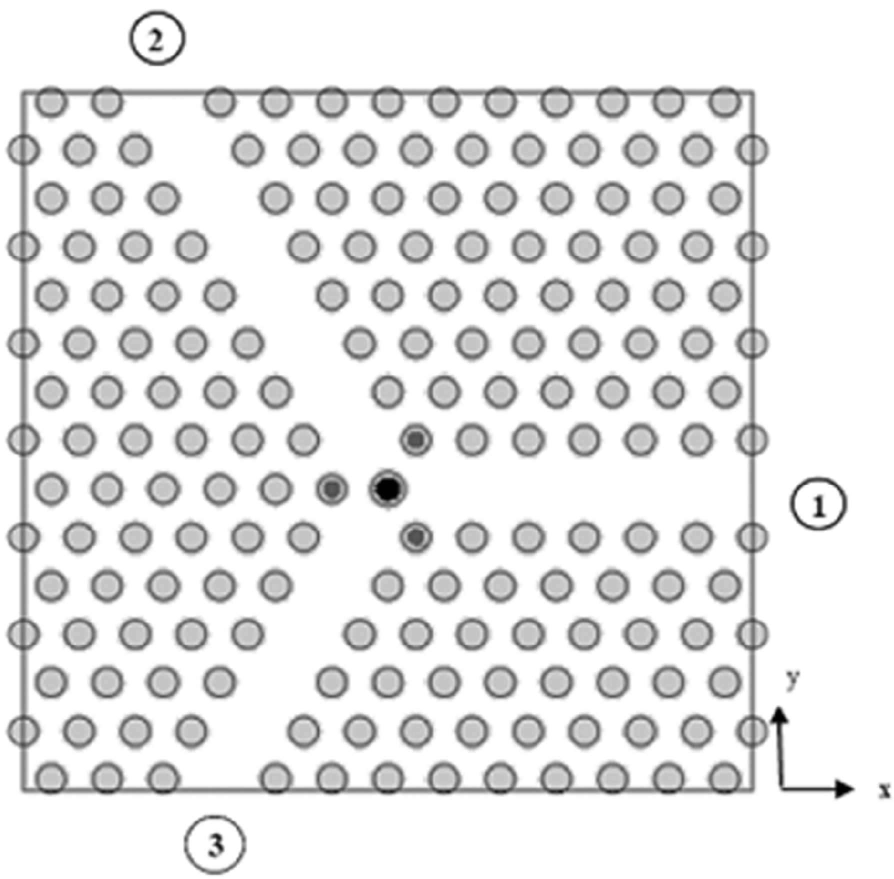

Figure 3: Optimal Design

Where, μ_r denotes the relative permeability tensor, ω is the angular frequency, σ is the conductivity tensor, ε_0 is the permittivity of vacuum, ε_r is the relative permittivity tensor, and k_0 is the free space wave number. In this particular model, the conductivity is zero everywhere. Losses in the ferrite are introduced as complex-valued permittivity and permeability tensors. The magnetic permeability is of key importance as it is the anisotropy of this parameter that is responsible for the nonreciprocal behavior of the circulator.

3. SIMULATION AND OBTAINED RESULTS

The presented results were obtained by numerical simulations. Calculated band structure of the main lattice is displayed in Fig. 4. The desirable TE band gap takes place in the in the frequency range of 0.47765(c/a) to 0.5835(c/a). The mesh diagram of the designed structure is shown in fig. 5. Mesh settings aim for a good resolution of all curved boundaries to get a decently accurate solution with fewer elements.

In order to manifest the attainability of the pretended circulator, it is excited at each port and shown the transmission and isolation at the other two ports in accordance with the base of photonic crystal based circulator. The electric field pattern of the designed device is shown in the fig. 6. The arrow indicates direction of the excited light input. The propagation of electromagnetic waves as follows: when the input wave is applied at port 1 for the case without magneto-optical effect, it is found that the symmetry axis of the E_{z-}field distribution in the cavity area is along the symmetry axis of Ports 2 and 3. Fig. 6a. Shows that the light is divided into two parts which go toward Ports 2 and 3, respectively.

When the excitation is applied at port 1, in the presence of magnetic field there is signal transmission from this port to port 2, with isolation of port 3 due to magneto-optical material, as can be seen in Fig. 6b. Similarly, when the input signal is excited in the port 2 (Fig. 6c), this is transferred to the ‘port 3, with isolation of port 1 and in the port 3, the applied signal is transferred to the port 1 with isolation of port 2

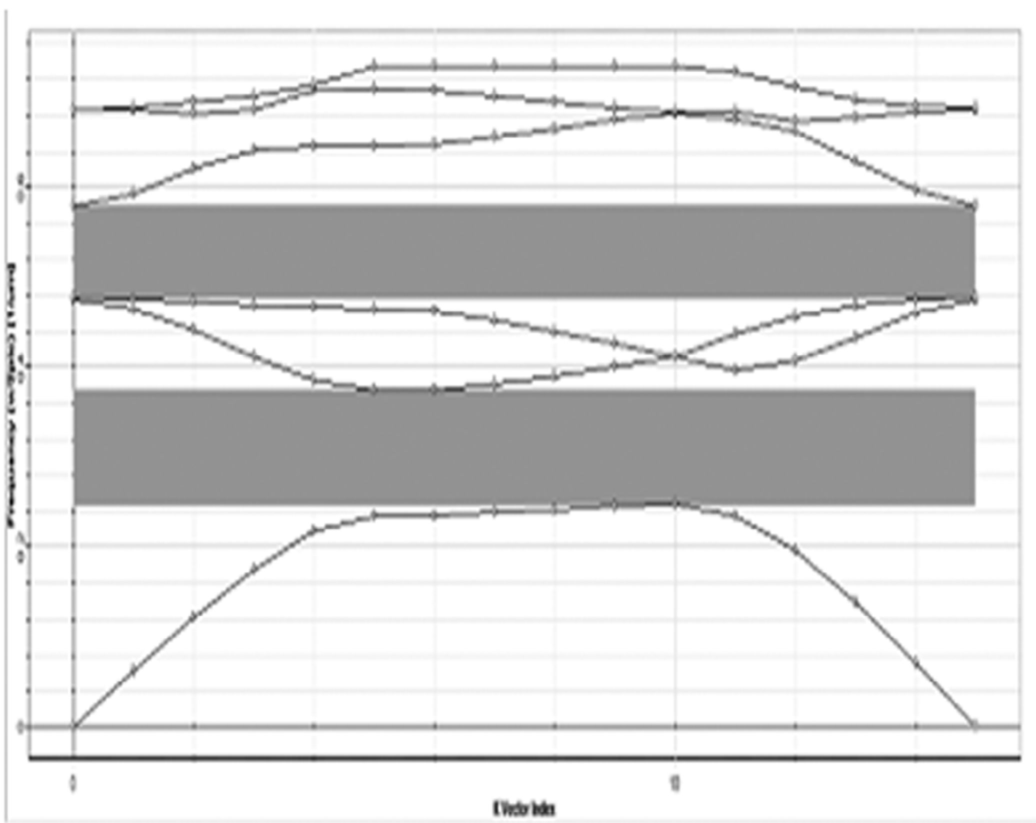

Figure 4: Band structure for the designed structure and its first band gap

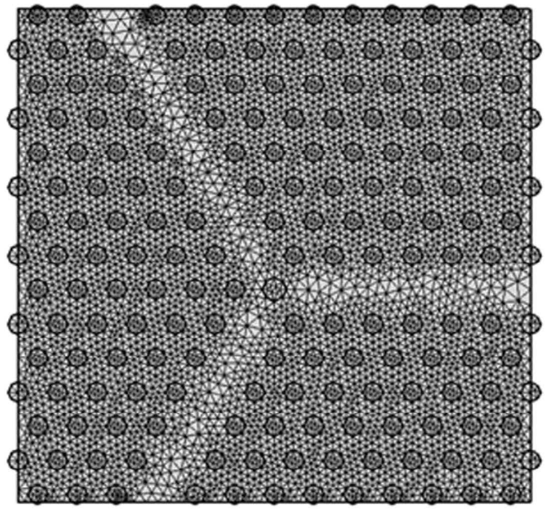

Figure 5: Mesh diagram of the designed structure

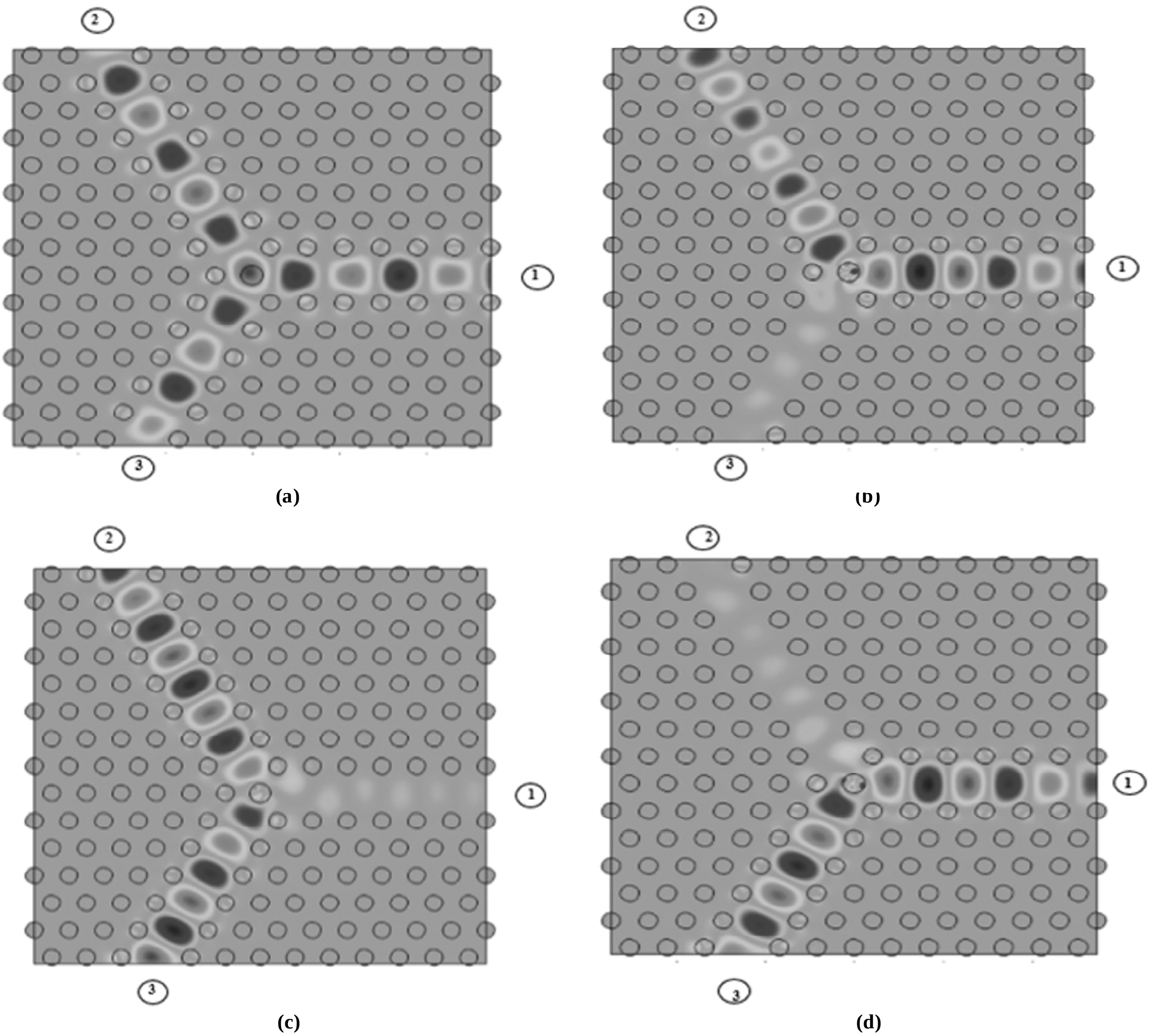

Figure 6: Ez-components of electromagnetic field of the designed device (a) incident at port 1 for the case without magnetic field, (b), (c), (d) propagation pattern of light for the case of magnetic field excited at port 1, port 2, port 3, respectively at normalized frequency.

(Fig. 6c). An input wave is launched from one of the three ports, signals are collected at the transmitting waveguide and the isolated waveguide and compared them with the input signal.

In the cases illustrated in Fig. 6.(b), (c) and (d), it can be seen that the stationary dipole mode excited at the normalized central frequency 0.5612(c/a) in the resonant cavity is rotated by an angle of 120°, which provides isolation of ports 2 and 3, respectively. Similarly for the excitation cases of ports 2 and 3 respectively. To demonstrate the effect of magneto-optical coupling on the central photonic crystal, dc magnetic field along the z-axis direction is applied and this ferrite crystal is characterized by the permeability tensor matrix as in the equation (1) by utilizing the gyromagnetic properties to obtain the non-reciprocal transmission.

The results designate that, at the operating frequency of 0.5612(c/a), the highest normalized transmission from the input port to the output port and lowest reflection to isolated ports can be realized.

4. CONCLUSION

In summary, a novel three port optical circulator based on gyromagnetic properties of ferrite photonic crystals is proposed and investigated. Several optimization processes were made in the device initial design, in order to realize the non-reciprocal transmission of electromagnetic waves for 120º. The magnet-optic or gyromagnetic property of ferrite photonic crystal is discussed. Furthermore, the operating principle of the circulator is examined to have a high transmission from the input to the output port and almost complete isolation among the isolated ports. The results indicate that the performance of the circulators can be improved in the cascaded systems. This type of structure can be used to optimize optical circuits in designing large-scale photonic crystal microchips.

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