Compact Photonic-Crystals Based Isolator Using Ni–Zn Gyromagnetic Ferrite Posts

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Abstract: A Faraday rotation isolator is conventionally achieved by connecting a matched load to a three-port circulator. It obtains superior performance (isolation > 20 dB) at the inevitable cost of non-ideal size. In order to adapt to the miniaturizations and integrations required for future 5G communication systems, it is particularly important to reduce the size of the devices. This work demonstrates a photonic crystal-based isolator design, comprising a unique reflecting cavity and a built-in fan-shaped coupler, where four Ni–Zn ferrite posts achieve the rotations. The design with the compact size of about 46.6 × 41.6 × 4.32 mm$^3$ obtains excellent forward transmission efficiency and reverse isolation of 0.50 dB and 44.20 dB, respectively.

Keywords: photonic crystals; photonic crystals waveguides; isolator; photonic band gap; 5G communication

1. Introduction

Non-reciprocal devices, such as isolators or circulators, have attracted much attention for their unidirectional transmission property, which play indispensable roles in communication systems [1–7]. With the miniaturization and integration of modern communication systems, magneto-optical isolators and circulators based on photonic crystals (PCs) are widely researched [8–10]. PC devices are praised as the core of future integrated optical communication [11–17], due to their special characteristics such as optical localization and photonic band gap (PBG) [18,19].

When isolators based on photonic crystals transits from the 1-D designs [20] to 2-D [21], their performance makes a great leap. The latter can effectively isolate noise or reflections between elements or modules, thus ameliorating the stability and bit error rate of communication systems. To date, PC isolators have developed into three configurations: chiral edge states (CESs) isolators, resonance isolators and Faraday rotation isolators. A centimeter wave CESs isolator was experimentally realized by inserting two antennas in a 16 × 7 photonic crystal with the lattice constant of 40 mm [22], in which the electromagnetic CESs can travel in only one direction that is fundamentally different from how non-reciprocal isolated operate. In our previous work, a resonance isolator was envisaged by using an ultra-wideband photonic crystal waveguide (PCW) and two magnetized ferrite sheets [23]. Different from the CESs isolator, the operating principle of the resonance isolator is ferromagnetic resonance absorption effect. However, in order to satisfy the conditions of resonance absorption, the ferrite sheets not only require rigorously precise positioning but also need to be magnetized by a strong external magnetic field. To avoid the requirements above, we use Ni–Zn ferrite posts instead of the ferrite sheets to perform the Faraday rotation for the signal isolation. Since the thickness requirement for sheets (0.5 mm) is stringent, the ferrite posts are easier to fabricate in the manufacturing process. Our current design can effectively circumvent the rigorous conditions of resonance absorption, which...
requires lower external magnetic field and provides greater tolerance. In addition, using Faraday rotation for isolation instead of chiral edge states, a more reliable device based on more mature mechanisms is envisaged to save the size of the isolator without two built-in antennas. Our isolator’s input and output ports are designed according to the standard WR34 flanged interface in the 5G millimeter waveband.

In this work, we propose and numerically investigate a compact PCs isolator based on Faraday rotation effect by inserting Ni–Zn gyromagnetic ferrite posts into a T-typed square lattice photonic crystals (SLPCs) defect structure. In the T-typed structure, the forward electromagnetic wave achieved 90° Faraday rotation by coupling two gyromagnetic ferrite posts. Aided with the unique reflecting cavity and built-in fan-shaped coupler, the function of the isolator is realized perfectly in the K waveband. The collinearity of the two isolator ports makes the structure more compact and easier for integration. Therefore, this design provides a convenient solution for using the circulator as an isolator without external matching load.

The TE band gaps of the SLPCs are calculated by plane wave expansion method (PWEM). There are three PBGs observed in the different ratios between the dielectric rods’ radius and the lattice constant. The external characteristics of the designed isolator are numerically calculated by finite element method (FEM) in the frequency range from 25 GHz to 27 GHz. The optimal forward insertion loss and reverse isolation of the isolator reach 0.50 dB and 44.20 dB, respectively. The high isolation, low insertion loss and easy integration indicate that our designed PCs isolator has significant advantage in the future communication systems.

2. Materials and Methods

2.1. Design of PCs Isolator

As shown in Figure 1a, the designed PCs isolator includes two SLPCs (white), four ferrite posts (blue) and a built-in fan-shaped coupler (red). The top view of the isolator is described in Figure 1b. In Figure 1c, the SLPCs are formed by Al₂O₃ ceramic rods arrays (white), while the radius and the relative dielectric constant of the rods are \( r_0 \) and 9.2. The lattice constant of SLPCs is represented as \( A \). The distance between the upper and lower arrays is marked by the width \( w \). A list of rods at the central of the lower array is removed to form a T-shaped PCW, whose two collinear arms are expressed as W1 and W2. The third arm of the PCW is closed, in which a fan-shaped PC array structure is introduced, which is also formed by Al₂O₃ ceramic rods with radius \( r_2 \). The area of the fan-shaped PCs is determined by the angle \( \theta \) and the distance \( d \) of the two rods, as shown in Figure 1d. The fan-shaped coupler is exactly located in the middle of the lower arm of the T-shaped PCW. The total length of the fan-shaped coupler is 6 mm with \( d = 0.5A \), where \( A \) is assumed 4 mm long. At the center of the PCW, four ferrite posts (blue) with the radius \( r_1 \) and relative dielectric constant 13.5 are introduced, which are marked F1, F2, F3 and F4.

In our scheme above, two standard WR34 flange interfaces are designed according to the two arms of the PCW, which are the input and output ports of the isolator. The size of the flange interfaces is \( w \times h \), where \( w \) is 8.64 mm and \( h \) is 4.32 mm. The structure has a compact size about of 46.6 × 41.6 × 4.32 mm³ owed to the ingenious design of the built-in fan-shaped coupler. There is no need to use the WR34 matched load alone, which has a comparable size. In our current design analysis, we leave the fan-shape area as it is to obtain the s-parameters and test its bandwidth. For practical fabricated isolators, the bottom of the fan-shape area can be opened with a third connector window, to which a 50 Ohm load can be conveniently attached. In this aspect, our design is no different from existing isolator designs. In addition, some literature has employed wedge type styrofoam to absorb energy inside the device [24].

[24]
2.2. **PBG of the SLPCs**

The PBG of the SLPCs determines the frequency of the electromagnetic waves which can transmit through the SLPCs or be reflected by them. When the lattice constant $A$ is 4 mm, expressed as the distance of the two adjacent $\text{Al}_2\text{O}_3$ rods, the PBGs of the SLPCs mentioned above are calculated by PWEM.

In Figure 2a, there are three band gaps for TE modes with the different radius of the $\text{Al}_2\text{O}_3$ rods. The corresponding gaps' radii with increasing rods' radius are shown in Figure 2b. The interested frequency region is coincidently contained in the first PBG (Gap 1). When the radius of $\text{Al}_2\text{O}_3$ rods $r_0$ takes 0.207$A$, the optimal gap ratio achieves 32.7%, and the corresponding frequency range of the PBG is from 23.36 to 32.45 GHz. Theoretically, the SLPCs forbid the transmission of signals within the frequency range and reflect them back. If certain transmission line surrounded by the SLPCs, the electromagnetic waves with the frequencies in the PBG can transmit stably in the PCW just as mentioned above.

**Figure 1.** (a) The schematic diagram of the PC isolator; (b) the top view of the isolator; (c) the plan view of the isolator; (d) the detailed view of the coupler.

**Figure 2.** (a) The TE band gaps of the SLPCs with the $\text{Al}_2\text{O}_3$ rods' radius; (b) the gaps' ratios with the radius of the $\text{Al}_2\text{O}_3$ rods.
3. Photonic-Crystals Isolator

3.1. Operating Principle of Faraday Rotation Isolator

In the K waveband, if a ferrite post is magnetized in z-direction, its magneto-optical effect is usually described in terms of the tensor permeability [25]:

\[
[\mu_r] = \mu_0 \begin{bmatrix}
\mu & j\kappa & 0 \\
-j\kappa & \mu & 0 \\
0 & 0 & 1
\end{bmatrix}
\]  

(1)

where \( \mu = 1 + \omega_m(\omega_0 + i\alpha\omega)/[\omega_0 + i\alpha\omega]^2 - \omega^2 \) and \( \kappa = \omega_m\omega/[\omega_0 + i\alpha\omega]^2 - \omega^2 \) with \( \omega_0 = \mu_0\gamma H_0, \omega_m = \mu_0\gamma M_s \) and \( \gamma = 1.759 \times 10^{11} \text{ C/kg} \). Here, \( \alpha = 3 \times 10^{-3} \) and \( M_s = 2.39 \times 10^5 \text{ A/m} \) depend on material parameters. The external DC field is \( H_0 = 3.15 \times 10^5 \text{ A/m} \), which is reduced twofold compared with that in [23]. The symbol of the off-diagonal element \( \kappa \) is decided by the direction of external DC magnetic field and the strength of Faraday rotation effect is determined by the quality factor \( Q = \kappa/\mu \).

Isolators based on the Faraday rotation effect have been discussed in infrared, terahertz and optical waveband [26,27]. The principle of our designed isolator is similar to a T-shaped Faraday rotation circulator with one port shorted. Based on the Faraday rotation effect, the electromagnetic wave splits a pair of rotary degenerate modes, which it transmits into the magnetized ferrite post. The speeds of the two modes are different from each other. Thus, the composite wave of the two modes takes place a Faraday rotation angle when these deviate from each ferrite area. In this simulation, there is a pair of degenerate modes in the ferrite post such as Figure 3 in [28] with \( H_0 = 0 \). When the ferrite posts are fully magnetized, the two modes are coupled, which leads to a Faraday rotation of the wave front in the area of ferrite posts. Here, a 45° rotation of electromagnetic wave can be realized with appropriate operating conditions through each ferrite post. The propagation direction of the electromagnetic waves is deflected in the ferrite area, which mainly attributed to the Faraday rotation effect.

![Figure 3](image)

**Figure 3.** (a) The path of electromagnetic wave incoming from W1; (b) the path of electromagnetic wave incoming from W2.

In Figure 3, the operating principle of the designed PC isolator is introduced by describing two transmission paths. The electromagnetic wave incoming from W1 takes place a 90° rotation by the cooperation of the ferrite posts F1 and F4 and is totally reflected by the cavity. The reflecting cavity consists of the ferrite post F4 and the five Al₂O₃ rods in the orange dotted box as shown in Figure 1c. Then, the electromagnetic wave rotates with an angle of 90° again when it transmits through the ferrite posts F4 and F3 sequentially. Finally, the signal exactly travels to W2 as shown in Figure 3a. It can be seen that the electromagnetic wave transmission along a straight line is realized by bending twice of 90° with the three ferrite posts and the aid of the reflecting cavity.

Similarly, Figure 3b illustrates the path of electromagnetic waves incoming from W2. The electromagnetic wave is firstly rotated by an angle of 45° through the ferrite post F3 and then another angle of 45° through the ferrite post F2. Then a 90° bend of electromagnetic wave is obtained by the cooperation of the two ferrite posts. Finally, the electromagnetic
wave travels into the fan-shaped coupler shown in Figure 1d and is almost all confined in it, thus the W1 is isolating. Here, the built-in fan-shaped coupler works similar to a matched load, whose PBG is different from that of the SLPCs, so the input electromagnetic wave can diffuse in the coupler but is confined in the third arm of the T-shaped PCW. In microwave circuits, the modified port is usually deemed to have ‘short-circuited’. Furthermore, we can adjust the angle \( \theta \) mentioned above in order to achieve the superior isolation for W1 of the isolator.

3.2. Numerical Simulation of the PCs Isolator

In this section, the function and transmission characteristics of the PCs isolator are numerically simulated by the software COMSOL Multiphysics like [10], based on the following equation:

\[
\epsilon^{-1} \nabla \times \left( [\mu_r]^{-1} \nabla \times \vec{E} \right) = \frac{\omega^2}{c^2} \vec{E}
\]

(2)

where \( \epsilon \) is the relative dielectric constant of the materials, \( \omega \) is the frequency of incident signal, \( c \) is the speed of the light and \( \vec{E} \) is the electric field intensity. The parameters of the designed PCs isolator are \( A = 4 \text{ mm}, r_0 = 0.207A, r_1 = 1.28 \text{ mm}, r_2 = 0.5r_0, d = 0.5A, \theta = 6^\circ, w = 8.64 \text{ mm} \) and \( h = 4.32 \text{ mm} \). At 26 GHz, the power distribution of the signal in the PCs isolator is shown in Figure 4.

![Figure 4. The power distribution in the PCs isolator at 26 GHz.](image)

As shown in Figure 4a, the signal incoming from Port 1 is transmitted stably to Port 2. Nonreciprocally, the signal incoming from Port 2 totally travels into the fan-shaped coupler, thus Port 1 is isolated, as in Figure 4b. Consequently, it perfectly realizes the function of the PC isolator, and its external properties are also numerically calculated as shown in Figure 5.

In Figure 5a, the numerical results suggest that the optimal isolation of the PCs isolator is 44.20 dB at 25.81 GHz, and the isolation remains above 15 dB within the range of 25.66 to 25.95 GHz. In addition, the insertion loss is low to 0.50 dB at 26.06 GHz with the transmission efficiency of above 50% (3 dB) over a wide frequency range from 25.03 to 26.92 GHz, revealing an excellent forward transmission characteristic of the proposed PCs isolator. The curves of the forward and backward reflected powers of the PCs isolator with frequency are basically coincident, as shown in Figure 5b. It means that the return losses of the two ports are almost the same, which are reflected by the symmetrical structure. The peaks of the S parameters S11 and S22 respectively are −21.87 dB and −21.83 dB at 26.02 GHz. The S parameters play important roles in describing the performance of the devices, which are the ratios between the powers of waves between these ports. In our design, the parameters S11 and S22 represent the ratio of the reflected power to the input power of the Port 1 and Port 2, respectively. The parameter S21 represents the insertion loss of the isolator, which is the logarithmic value of the ratio of the transmission power of the Port 2 from the input power of the Port 1. Moreover, the parameter S12 is used to measure the isolation performance of the isolator, which is described in detail in [10].
Moreover, the parameter $S_{12}$ is used to measure the isolation performance of the isolator, which is described in detail in [10].

Figure 5. (a) The curves of isolation and insertion loss of the PC isolator with frequency; (b) the curves of the forward and backward reflected powers of the PC isolator with frequency.

4. Conclusions

In conclusion, a new compact PC isolator based on the Faraday rotation effect is demonstrated numerically by inserting Ni–Zn gyromagnetic ferrite posts into a T-typed SLPCs defect structure. As the radius of SLPCs’ rods $r_0$ takes 0.207 A, the optimal gap ratio of 32.7% achieves an ultra-wideband level, and the corresponding frequency range of the PBG is from 23.36 to 32.45 GHz. The optimal forward transmission efficiency and reverse isolation of the isolator reach 0.50 dB and 44.20 dB, respectively. With the unique reflecting cavity and built-in fan-shaped coupler, the structure of the designed isolator is more compact for integration. Our designed PCs isolator with high isolation and low insertion loss shows potential applications in future 5G communication systems.

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