

Research Article

Design, Simulation, and Optimization of Polarization-Independent Four-Port Optical Waveguide Circulator Based on a Ferrite Material

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Received 6 February 2022; Revised 11 March 2022; Accepted 17 March 2022; Published 27 March 2022

Academic Editor: Yuan-Fong Chou Chau

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Optical circulators are used in optical devices such as multiplexers, demultiplexers, and optical routers. Usually, the magnetic material in the center of the circulator conducts light by interacting with the electromagnetic wave. In this research, a polarization-independent four-port optical waveguide circulator with the presence of a rhombus-shaped ferrimagnetic material has been designed, simulated, and optimized in the three-dimensional part of Comsol software. This designed circulator unlike the previous structures has four ports which use the transmission matrix method to conduct waves. By selecting the appropriate size and type of central ferrite, as well as the scale of input and output channels, the most optimal situation is obtained for power transmission with less than 1 dB loss when port 1 is input and port 2 is output.

1. Introduction

Optical circulators play an important role in the development of optical communications and are widely used in routing and data transmission. By examining the suitable materials for magnetic properties, proper circulators can be designed and implemented. In optical circulators, the light entering from each input, after interacting with the magneto-optic material, is directed to the appropriate output. The waveguide Y circulator has been widely used in microwave circuits since the first introduction by Chait and Curry [1]. In 1965, a 120-degree circulator with a ferrite material in the center and its junctions was designed in the range of UHF and low microwave frequencies [2]. With advances in materials science and their combination, new structures of circulators have emerged and, in its design, various materials such as photonic crystals [3, 4], ferrite materials [5], and dielectrics have been used. To achieve an asymmetry, applying the magneto-optical material only on one side of the waveguide is needed [6–8], or by applying strong bending on the waveguide, an asymmetry in the electromagnetic field pattern is achieved [9]. In this research,

a 4-port polarization-independent circulator using ferrite materials was designed with lower losses and higher light efficiency than other similar circulators with 4 ports. This structure can be built with the film deposition method, and because the accuracy of the building film deposition technique is much greater than our size, the possibility of the error is low. Errors that may occur during the manufacturing process can be compensated by applying an offset magnetic field. This designed circulator is made of optical fibers which are available and commonly used in other optical devices. Recently, photonic crystal line defects can also be used to build circulators but the problem of using photonic crystal is that the manufacturing process is difficult to perform [10–13]. In one of the latest structures, Jalas et al. were able to achieve a new model for the design of a three-port circulator by combining photonic crystals and ring resonators [14].

2. Transmission Matrix and Magneto-Optic Effects

In a ferrite circulator, with circular polarity in the same direction as the rotation of the magnetic dipole, the ferrite

environment has a strong interaction with the material, while the interaction of a circular wave of opposite direction is weaker. In other words, the interaction of a circular polarized wave with a magnetically biased ferrite depends on the direction of polarization, because the magnetic field creates an initial rotation that is coordinated with the direction of rotation of the right-hand wave and uncoordinated with the left-hand wave, leading to creation of a nonreciprocal propagation property. The magnetic permeability matrix of ferrites in the presence of DC magnetic permeability can be written as follows [15]:

$$[\mu] = \begin{pmatrix} \mu & jk & 0 \\ -jk & \mu & 0 \\ 0 & 0 & \mu_0 \end{pmatrix}. \quad (1)$$

The presence of nondiagonal elements causes a difference in the refractive index for the two circular waves of right- and left-handed, which causes a difference in Faraday rotation. Ferrite circulators use both permanent magnetic field (DC) and bias field (AC), which we use as the first type in this design. Kerr and Faraday magneto-optic effects are also used. The application of the Kerr effect is in the center of the circulator and the Faraday effect is in the ferrite used in the main arms of the circulator. Using the unit properties of the dispersion matrix and according to the task defined for the circulator, we expect its dispersion matrix to be ideally can be represented as follows:

$$[S] = \begin{pmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}. \quad (2)$$

This matrix describes the right-hand circulator, which can be reversed by taking transpose and have left-hand

rotation. Figure 1 shows the way power is transmitted through different ports of a four-port circulator [16, 17].

If we assume that a circulator that has a circular symmetry around its three ports is lossless, then the scattering matrix with a propagation constant of β , reflectance constant of Γ , and attenuation coefficient of α can be represented as [18]

$$[S] = \begin{pmatrix} \Gamma & \beta & \alpha \\ \alpha & \Gamma & \beta \\ \beta & \alpha & \Gamma \end{pmatrix}. \quad (3)$$

Since the circulator is assumed lossless, the scattering matrix must be unitary, which implies the following two conditions:

$$\begin{aligned} |\Gamma^2| + |\beta^2| + |\alpha^2| &= 1, \\ \Gamma\beta^* + \alpha\Gamma^* + \beta\alpha^* &= 0. \end{aligned} \quad (4)$$

Whenever the magnetic dipoles of a ferromagnetic material are placed in a magnetic field, the dynamics of the magnetic evolution is obtained from the following equation:

$$\frac{d\bar{M}}{dt} = -\mu_0\gamma\bar{M} \times \bar{H}. \quad (5)$$

As a result, the magnetic susceptibility matrix is in the form of the following equation [19]:

$$\bar{M} = [\chi]\bar{H} = \begin{pmatrix} \chi_{xx} & \chi_{xy} & 0 \\ \chi_{yx} & \chi_{yy} & 0 \\ 0 & 0 & 0 \end{pmatrix} \bar{H}. \quad (6)$$

The elements of the matrix are as follows:

$$\begin{aligned} \chi_{xx} &= \frac{\omega_0\omega_m(\omega_0^2 - \omega^2) + \omega_0\omega_m\omega^2\alpha^2}{(\omega_0^2 - \omega^2(1 + \alpha^2))^2 + 4\omega_0^2\omega^2\alpha^2} - j \frac{\alpha\omega\omega_m(\omega_0^2 - \omega^2(1 + \alpha^2))}{(\omega_0^2 - \omega^2(1 + \alpha^2))^2 + 4\omega_0^2\omega^2\alpha^2}, \\ \chi_{xy} &= \frac{2\omega_0\omega_m\omega^2\alpha}{(\omega_0^2 - \omega^2(1 + \alpha^2))^2 + 4\omega_0^2\omega^2\alpha^2} - j \frac{\omega\omega_m(\omega_0^2 - \omega^2(1 + \alpha^2))}{(\omega_0^2 - \omega^2(1 + \alpha^2))^2 + 4\omega_0^2\omega^2\alpha^2}, \end{aligned} \quad (7)$$

$$\omega_0 = \mu_0\gamma H_0,$$

$$\omega_m = \mu_0\gamma M_s,$$

$$\alpha = \frac{\mu_0\gamma\Delta H}{2\omega}.$$

Therefore, by using following relation:

$$\bar{B} = \mu_0(\bar{M} + \bar{H}) = [\mu]H. \quad (8)$$

And by assuming the magnetic field in the Z direction, the magnetic permeability matrix is obtained as relation (1).

Solving the eigenvalue problem for the permeability matrix in the presence of an external bias magnetic field results in two special vectors of right-handed and left-handed fields with eigenvalues of different values, which make the field response not the same for left-handed and

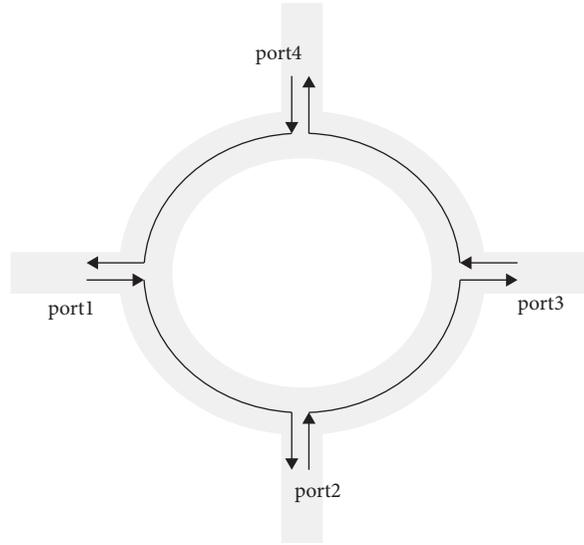


FIGURE 1: Power is propagated by right-handed circulation and transmitted through ports 1 to 2, 2 to 3, 3 to 4, and 4 to 1.

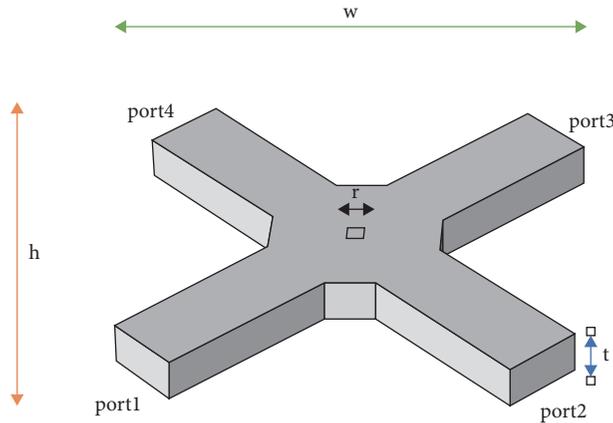


FIGURE 2: 3D geometry of a four-port circulator.

right-handed waves and result Kerr and Faraday magneto-optic effects.

3. Simulation

A ferrite material has a low-order resonance mode before being placed in a magnetic field. When the ferrite is fully magnetized, it turns into two modes with slightly different resonant frequencies. The operating frequency of the circulator is selected so that the sum of the effects of these two modes gathers at the output port and neutralizes each other at the isolated port [2]. The ideal scattering matrix is to describe a four-port circulator as follows:

$$S = \begin{pmatrix} 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix}. \quad (9)$$

The designed structure is shown in Figure 2, which uses air waveguides and a ferrite material called Y-Al in order to

gain double refraction at its center. This simulation was performed in the 3-D section of COMSOL Multiphysics 5.4 with 0.00771 m mesh size and 0.2 m * 0.07 m simulation domain size.

The optimized size of the geometry and the amount of elements of the magnetic matrix of the ferrite material used during the simulation are shown in Table 1.

Figure 3 shows simulation results by which the power is transmitted from ports 1 to 2, 2 to 3, 3 to 4, and 4 to 1 by applying a permanent magnetic field. Loss in this structure does not cause any problems, and power is propagated by right-handed circulation. This designed 4-port circulator has a wide range of applications in optical communication. The proper length of the central ferrite material is 0.0136 (m) length and 3 (GHz) is the best frequency to obtain the ideal situation of right-hand rotation at the ports. Figure 3 shows the simulation results, which were obtained using Comsol software in Electromagnetic Waves, Frequency Domain section.

Figure 4 shows the diagram of power transmission loss in terms of frequency and ferrite size. These diagrams were

TABLE 1: Dimensions of geometry and characteristics of ferrite material.

Variable name	Amount	Description	Variable name	Amount	Description
w	0.18 (m)	Width of waveguide	freq	3 (GHz)	frequency
h	0.066 (m)	Height of waveguide	Ms	5.41E4 (A/m)	Saturation magnetization
r	0.01362 (m)	Size of ferrite material	ϵ_r	14.5	Relative permittivity
t	0.033 (m)	Shape depth size	ΔH	3.18E3 (A/m)	Line width
ϵ_0	8.854E-12	Permittivity of free space	H0	5.5E4 (A/m)	Applied bias field
tdelta	2E-4	Effective loss tangent	γ	1.759E11 (C/Kg)	Electron gyromagnetic ratio

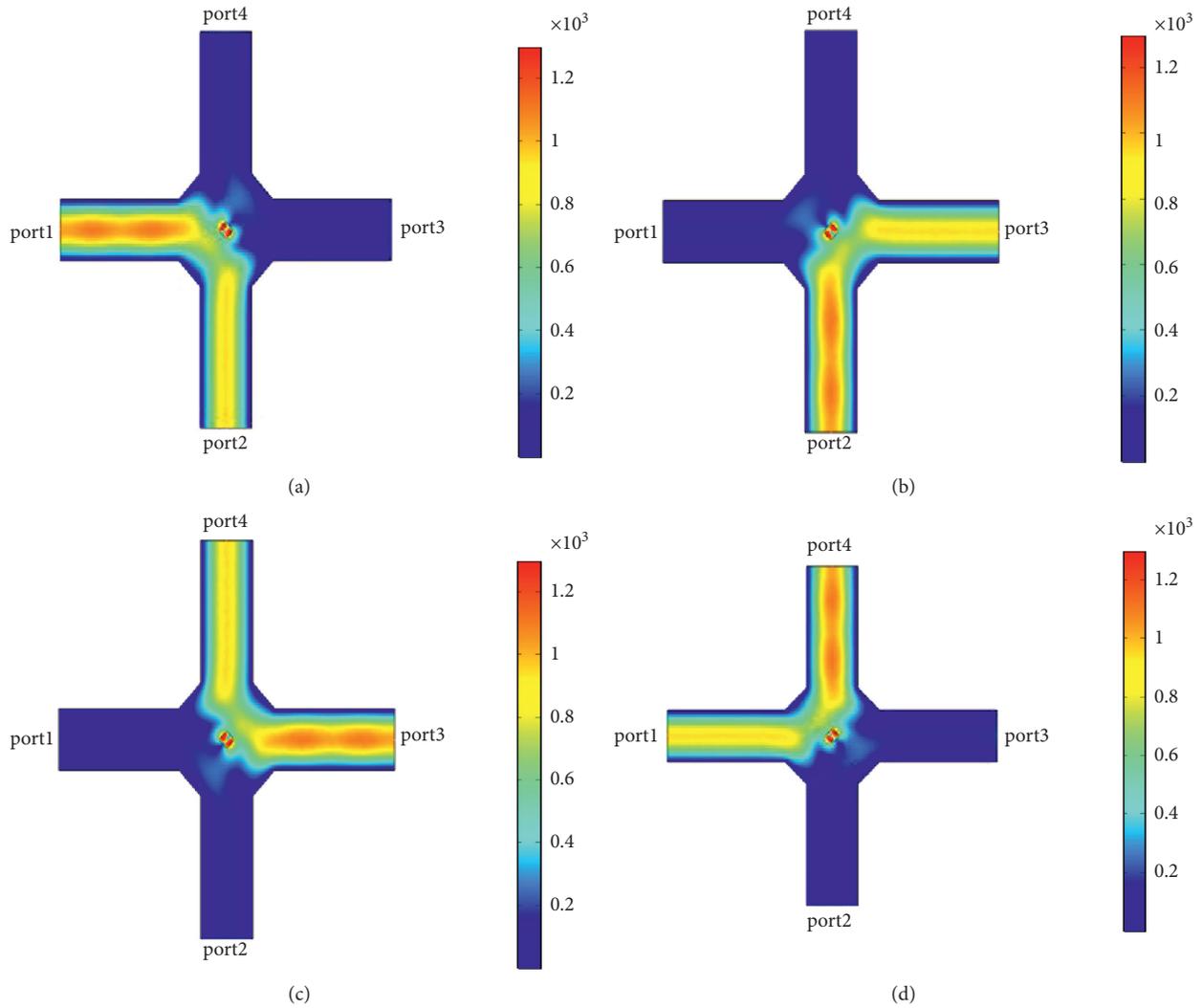


FIGURE 3: Four-port circulator: (a) enters from port 1 and exits to port 2, (b) enters from port 2 and exits to port 3, (c) enters from port 3 and exits to port 4, and (d) enters from port 4 and exits to port 1.

obtained when port 1 is input and port 2 is output. S-parameters describe the response of an N-port network to signal(s) incident to any or all of the ports. The first number in the subscript refers to the responding port, while the

second number refers to the incident port. Thus, S21 means the response at port 2 due to a signal at port 1.

In the diagrams of Figure 4, the red line indicates the transmission of light from port 1 to 2. Highest light

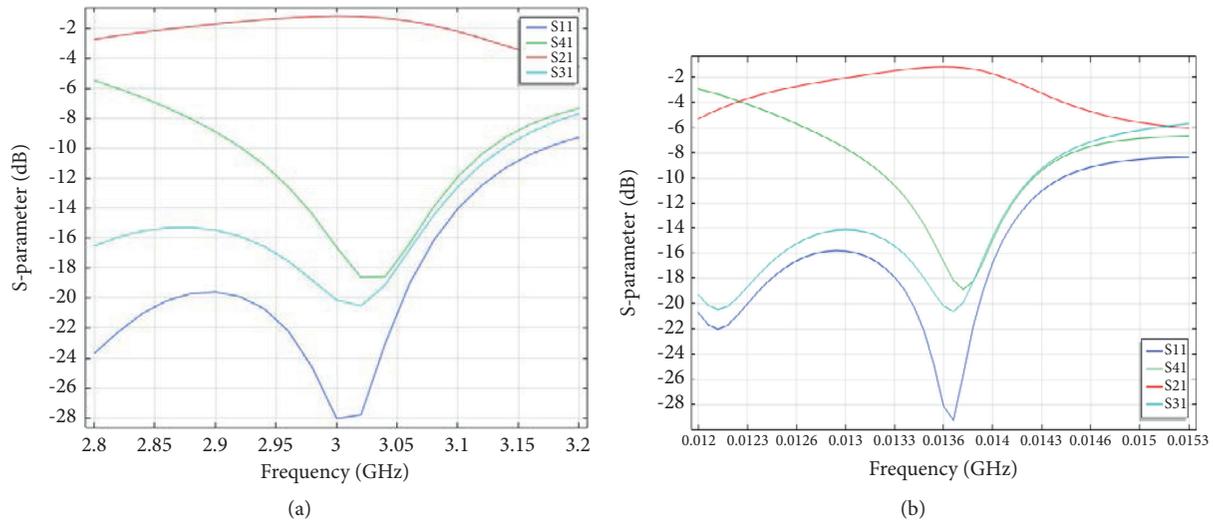


FIGURE 4: Power diagram in terms of (a) frequency (GHz) and (b) ferrite size (m).

transmission occurs when the frequency is 3 GHz and a ferrite material size is 0.0136 m with the light losses less than 1 dB, which is better than the previously designed 4-port circulators [20–22]. Also, at these two points, the lowest reflection and light transmission from port 1 to ports 3 and 4 occurred at 30 dB, 19 dB, and 21 dB, respectively. Therefore, by choosing the best working frequency and ferrite material size, a 4-port waveguide circulator is designed, simulated, and optimized with notable results.

4. Conclusion

In this research, an attempt has been made to design, simulate, and optimize a four-port polarization-independent waveguide circulator. By properly selecting the size of the input and output ports, as well as the size of the connection area and the shape and dimensions of the ferrite material in the center of the circulator, it is seen that the electromagnetic wave is directed in the appropriate direction in the four-port ferrite optical circulator. In this simulation, it was observed that electromagnetic wave radiation is transmitted from ports 1 to 2, 2 to 3, 3 to 4, and 4 to 1. By examining the appropriate frequency and length of the central ferrite at frequency 3 GHz and length 0.0136 m, we obtained the ideal state for right-handed rotation in all ports with less than 1 dB loss.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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