Design and Optimization of T-shaped Circulator Based on Magneto-Optical Resonator in 2D-Photonic Crystals

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***Abstract*—In this paper, we propose a development of a T-shaped circulator based on a 2D-photonic crystal, which has a simple and compact structure. This structure makes the non-reciprocal transmission of electromagnetic waves. Through a series of adjustments in the crystalline geometry and using the Nelder-Mead optimization method, we achieve a high level of isolation and low insertion losses.**

Keywords–Photonic crystals; Circulators; Optimization.

I. INTRODUCTION

Non-reciprocal components, such as isolators and circulators, are used in communications systems to reduce undesirable reflections that cause instability in generators and amplifiers, as well as loss of performance in these systems.

Different types of circulators based on Photonic Crystal (PhC) technology are known. Among them there are traditional three-port Y-circulators in PhCs with triangular lattice in optical region [1], in THz [2] and W-circulator [3], T-circulator in PhCs with square lattice [4][5]. All of them are based on resonance of the standing dipole mode of a Magneto-Optical (MO) resonator with a complex geometry. The proposed circulator presents a resonant cavity with a very simple structure.

Besides, when compared with the circulators presented by Wang et al. [4] and Jing et al. [5], the proposed one has the splitting factor about five times lower. Therefore, the scaling for operation at higher frequencies is much plausible.

The circulator consists of a square lattice of dielectric cylinders immersed in air. We consider a junction consisting of a resonator with MO material and three waveguides coupled to the resonator. This structure can operate in subTHz and THz frequency range and perform non-reciprocal transmission of electromagnetic waves.

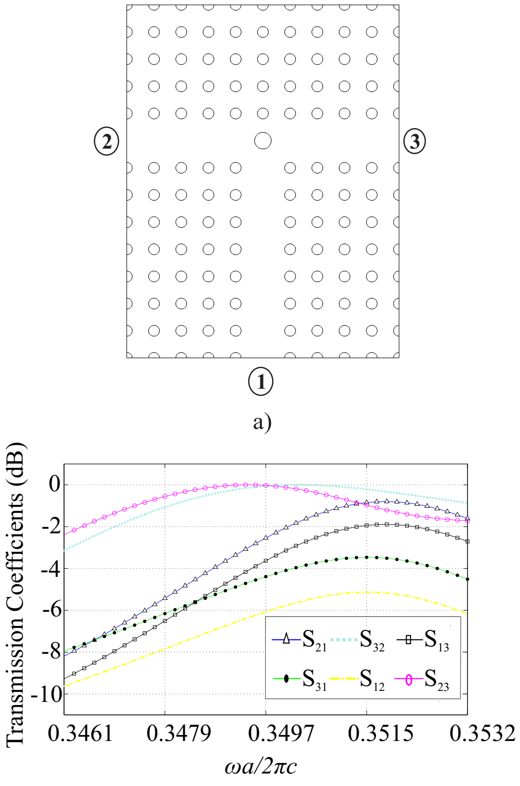
The proposed device based on photonic crystal technology can be built with reduced dimensions, favoring an increase in the component integration density in communications systems. Due to strong dependence of parameters of photonic crystals with respect to geometry, adjustments were made in the crystal structure by using of an optimization technique.

This paper is organized as follows. In Section II, the optimization method is discussed and the optimal design is presented. In Section III, the device performance after using the optimization process is shown. After that, the conclusion is presented.

II. OPTIMIZATION PROCESS

The technique of optimization known as brute force is not appropriate for solution of our problem. The Nelder-Mead method, which is available in COMSOL [6], has been used for the geometry optimization. This algorithm [7] demonstrates a rapid convergence in comparison with other available methods.

Considering excitation in the three ports of the circulator, we look for its good transmission and isolation for a particular frequency band. The objective function was defined as S parameters of the circulator. Thus, optimized values for the radius and the position of the ferrite and dielectric cylinders comprising the resonant were obtained.



a)

b)

Figure 1. Before optimization process: a) Initial design. b) Frequency responses.

In Figure 1a, we show the structure of the crystal before the optimization process. The ferrite cylinder is positioned in the center of the axis between the connecting waveguides. It is noticed that for this geometrical configuration, there is no non-reciprocal transmission, which leads us to seek change in the parameters of the cylinders near the resonator. There are also high losses of the structure for this geometrical arrangement, as it can be seen in Figure 1b. Then one realizes that must be applied to optimization for this problem.

From the values obtained using the optimization module, the final optimal design with the changes made in the crystal structure can be seen in Figure 2. The white cylinders are related to the periodic structure of the employed photonic crystal and each of them has radius equal to $0.2a$, where a is the lattice constant. For frequency $f = 100GHz$, $a = 1.065mm$.

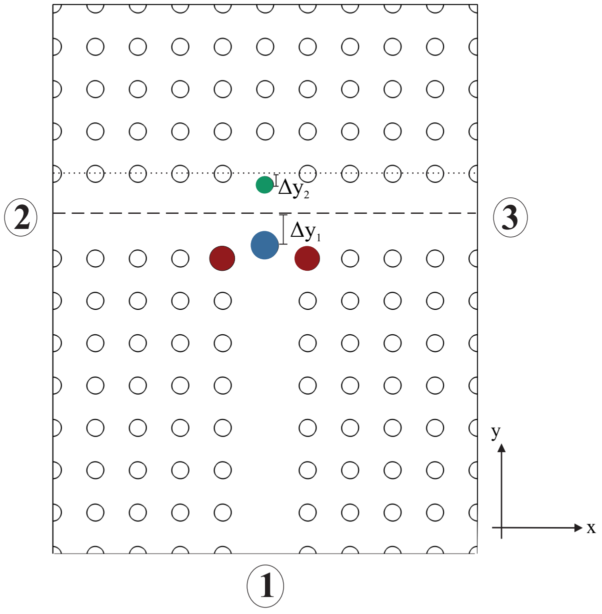


Figure 2. Optimal design.

After the changes made in the central structure, the radius of the blue cylinder remained equal to 0.30562a, but is displaced in relation to the axis of the waveguide between ports 2 and 3 (Δy_1) of 0.69086a. The green cylinder has a reduced radius 0.01249a and was moved vertically to the axis of the upper cylinders (Δy_2) in 0.2563a. The radii of the red cylinders were increased to 0.07439a.

III. OBTAINED RESULTS

The frequency splitting of the rotating modes ω^+ and ω^- versus k/μ is shown in Figure 3. It is apparent that our circulator works with low parameter k/μ = 0.17, i. e. can be projected for THz region.

The resonant cavity is based on a nickel-zinc based ferrite rod inserted in the center of the device and the dipole modes are excited in this rod. The used ferrite is produced by Trans-Tech [8] and its product code is TT2-111. In order to obtain the magnetic permeability and permittivity of the employed ferrite, the following expressions were used in our simulations:

$$[\mu] = \mu_0 \begin{pmatrix} \mu & -ik & 0 \\ ik & \mu & 0 \\ 0 & 0 & \mu \end{pmatrix}; \ \epsilon = 12.5\epsilon_0. \qquad (1)$$

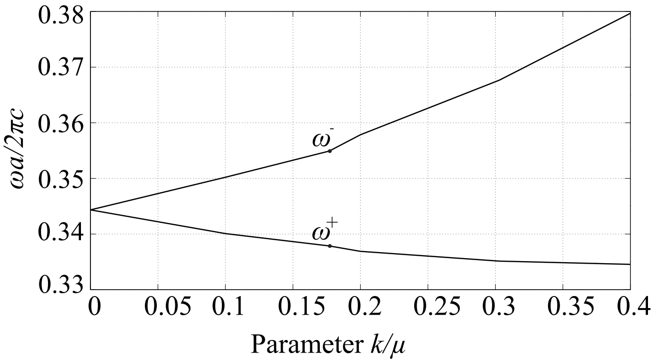


Figure 3. Frequency splitting of dipole modes excited in an MO resonator.

where the on-diagonal term μ and the off-diagonal term k are defined by the following expressions:

$$\mu = 1 + \frac{\omega_m(\omega_i + j\omega\alpha)}{(\omega_i + j\omega\alpha)^2 - \omega^2} \qquad (2)$$

$$k = \frac{\omega_m \omega}{(\omega_i + j\omega\alpha)^2 - \omega^2} \qquad (3)$$

The terms ω_m and ω_i are defined as:

$$\omega_m = \gamma M_0 \qquad (4)$$

$$\omega_i = \gamma H_0 \qquad (5)$$

In (2), (3), (4) and (5), M_0 is the saturation magnetization (398 kA/m), γ is the gyromagnetic ratio (2.33 x 10^5 rad/s per A/m), α is the damping factor (0.03175), ω is the radian frequency (rad/s), μ_0 is the free-space magnetic permeability (4π x 10^{-7} H/m) and $\mathbf{H}_0$ is the applied DC magnetic field (kA/m).

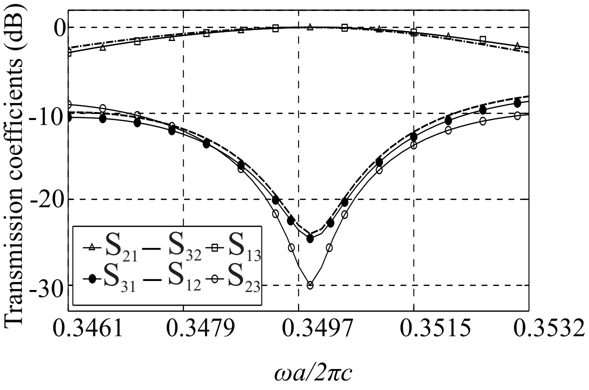


Figure 4. Frequency responses of T-circulator for excitation at ports 1, 2 and 3.

The device frequency response is shown in Figure 4. In the normalized central frequency $\omega a/2\pi c$ = 0.3499, the insertion losses are smaller than -0.05 dB, where: ω is the angular frequency (in radians per second); c is the speed of light in free space. In the frequency band located around 100 GHz, the bandwidth defined at the level of -15 dB of isolation is equal

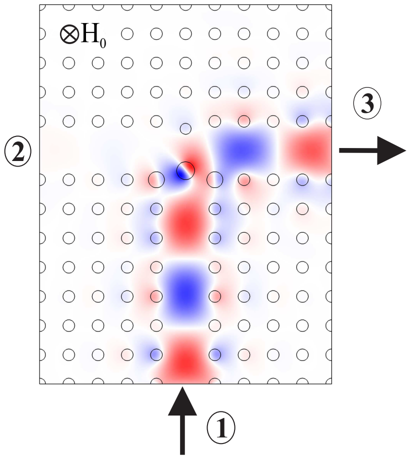


Figure 5. E_z-component of electromagnetic field for T-circulator at central frequency $f = 98.55GHz$ for excitation at port 1.

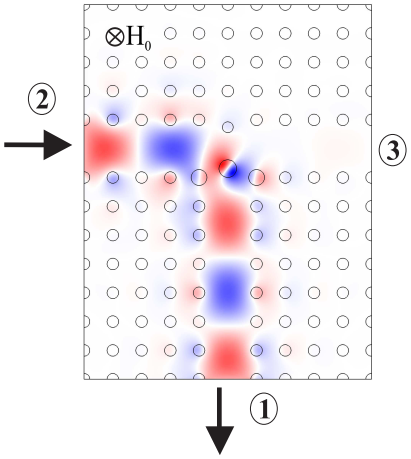


Figure 6. E_z-component of electromagnetic field for T-circulator at central frequency $f = 98.55GHz$ for excitation at port 2.

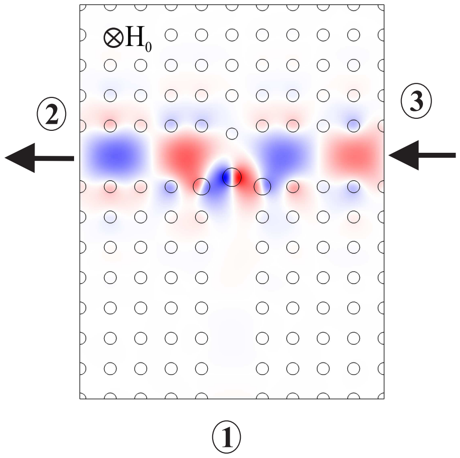


Figure 7. E_z-component of electromagnetic field for T-circulator at central frequency $f = 98.55GHz$ for excitation at port 3.

to 620 MHz for excitation at port 1, 680 MHz for excitation at port 2 and 730 MHz for excitation at the port 3.

The propagation of electromagnetic waves is given as follows: when the excitation is applied at port 1, there is signal transmission from this port to port 3, with isolation of port 2 due to the special alignment of the dipole mode, as can be seen in Figure 5. Similarly, when the input signal is applied in the port 2 (Figure 6), this is transferred to the port 1, with isolation of port 3 and in the port 3 (Figure 7), this is transferred to the port 2, with isolation of port 1. This case corresponds to the propagation in a counterclockwise direction. If the signal of the external DC magnetic field $\mathbf{H}_0$ is reversed, the propagation of signals is clockwise (1 to 2, 2 to 3 and 3 to 1).

In the cases illustrated in Figures 5 and 6, it can be seen that the stationary dipole mode excited in the resonant cavity is rotated by an angle of $45°$, which provides isolation of ports 2 and 3, respectively. On the other hand, in the case illustrated in Figure 7, it is shown that the stationary dipole mode suffers no rotation, making the input signal applied in port 3 is transferred to the port 2 with port 1 isolated.

Analysing intensity of the electric field in the T-junction, one can see that, the resonant cavity is formed by a central ferrite cylinder and two dielectric cylinders with increased diameters compared to other cylinders that comprising the photonic crystal.

IV. CONCLUSION

In this paper, we have presented a T-junction circulator with reduced dimensions. Several changes were made in the device initial design, in order to realize the isolation function. That is, to protect the signal source from stray reflections of not a ideally matched load. By using parameter optimization, we have obtained good characteristics of the circulator, namely, low insertion losses between the input and the output ports, high input isolation levels and a relatively wide operating frequency band.

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