Compact three-port optical circulator of W-format

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***Resumo*—Nós apresentamos neste trabalho a possibilidade de projeto de um circulador óptico de três portas com formato de W, sendo mais compacto quando comparado com o circulador conhecido com formato de Y. O circulador em W é mais compacto, entretanto, não possui simetria rotacional como o circulador em Y. Como consequência, o mínimo e o máximo das respostas de isolação e transmissão não são coincidentes na frequência, como mostrados nos resultados de simulação apresentados. Entretanto, o deslocamento de frequência não é crítico.**

***Palavras-Chave*—Circulador óptico compacto de três portas, cristal fotônico, cavidade magneto-óptica.**

***Abstract*—We show in this work a possibility of design a more compact three-port optical circulator wiht W-format as compared to the known one with Y-format. The W-circulator is more compact, but it does not have the rotational symmetry of the Y-circulator. As consequence the minimum of isolation and maximum of transmission responses are not more coincident in frequency, as is shown by the presented simulation results. However the frequency shift is not critical.**

***Keywords*—Compact three-port optical circulator, photonic crystal, magneto-optical cavity.**

I. INTRODUCTION

The great demand for more capacity and efficiency in communication systems is imposing the necessity to increase optical components density by means of components miniaturization and integration. Within the devices of great interest to be integrated down to chip level are the optical isolator and circulator. These non-reciprocal devices are employed for protecting the light source from harmful reflections of non-ideally matched load. The integration of optical components is desired since this improves the robustness of the system by suppressing multi-path reflections between components.

Using a magneto-optical resonator in two dimensional photonic crystal, it was shown in [1] that is possible to produce a compact three-port optical circulator of Y-format, as schematized in Fig. 1. In this work we show a possibility of design a more compact three-port circulator with W-format, as schematized in Fig. 2, consisting of the same magneto-optical cavity designed in [2]. The W-format of the circulator is obtained by changing the position of port 3 of the Y-circulator, i.e., connecting it between port 1 and port 2 at the angles distances of 60°.

The W-circulator is obviously more compact and can be more adequate in cases where it is necessary to have such ports orientation, but it does not have the rotational symmetry of the Y-circulator. As consequence the minimum of isolation and maximum of transmission responses are not more coincident in frequency, which is a desired characteristic for achieving the maximum bandwidth. By introducing some defect in the photonic crystals it is probably possible to tune this curves as the Y-circulator, but this work is limited to the analysis of the W-circulator without any adjustment.

For simulating the W-circulator we used the Commercial software COMSOL, which is based on the finite element method (FEM) [3].

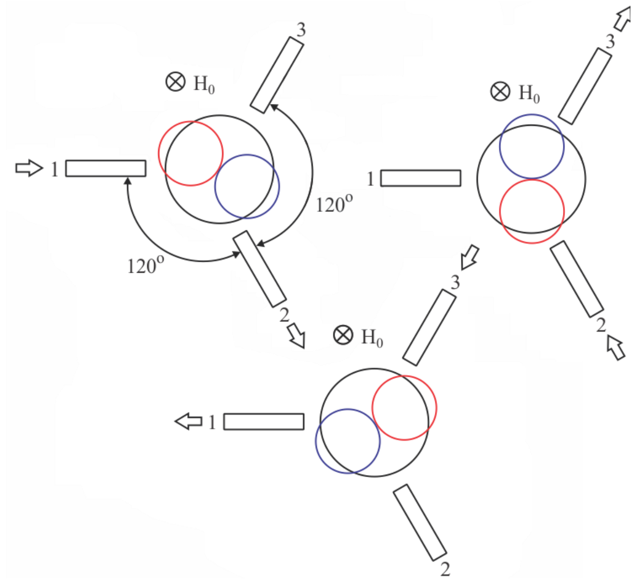

Fig. 1. Schemes of the three-port optical Y-circulator excited at each port with the dipole mode in the cavity. Direction of circulation is 1→2→3→1.

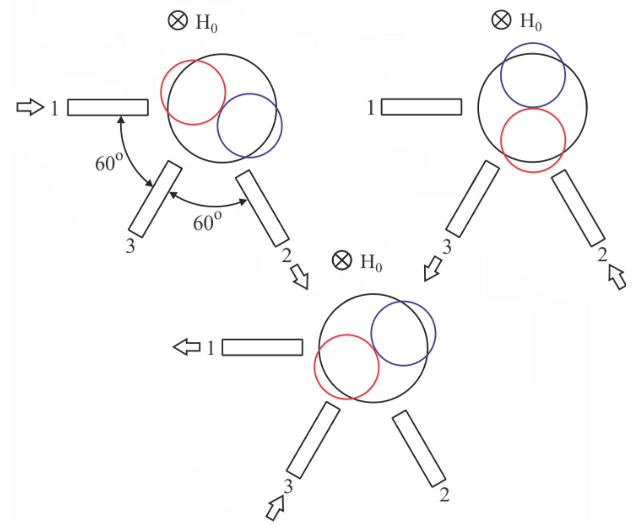

Fig. 2. Schemes of the three-port optical W-circulator excited at each port with the dipole mode in the cavity. Direction of circulation is 1→2→3→1.

II. SYMMETRY ANALYSIS

The Y-circulator has the symmetry $C_{3v}(C_3)$ (in Schoenflies notations [4]). The magnetic group $C_{3v}(C_3)$ contains the 3-fold rotational axis and 3 vertical anti-planes of symmetry. The scattering matrix has the structure

$$[S]_Y = \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{13} & S_{11} & S_{12} \\ S_{12} & S_{13} & S_{11} \end{bmatrix} \quad (1)$$

with 3 independent complex parameters. The transmissions for all 3 ports are equals: $P_{21} = P_{32} = P_{13}$ (Fig. 1), the isolations are also equals: $P_{12} = P_{23} = P_{31}$, and also $S_{11} = S_{22} = S_{33}$. These equalities are valid for any frequency.

For W-circulator, we can have a reduced symmetry which is defined by only one element, namely the vertical anti-plane of symmetry Tσ which passes the port 3 (Fig. 2). The calculated scattering matrix for the W-circulator is

$$[S]_W = \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{11} & S_{23} \\ S_{23} & S_{13} & S_{33} \end{bmatrix} \quad (2)$$

with 6 independent complex parameters. Here we have only the equalities $P_{31} = P_{23}$, $P_{32} = P_{13}$ and $S_{11} = S_{22}$.

III. DESCRIPTION OF THE OPTICAL CIRCULATOR OF W-FORMAT

The presented W-circulator, as schematized in Fig. 2, is based on a magneto-optical (MO) cavity in a two dimensional photonic crystal (PC) of lattice constant *a*. The PC is a triangular lattice of air holes of radius 0.3*a* in bismuth iron garnet (BIG) material. The BIG is described by the following common expressions for the permittivity and permeability

$$\varepsilon = \varepsilon_0 \begin{bmatrix} \varepsilon_r & ig & 0 \\ -ig & \varepsilon_r & 0 \\ 0 & 0 & \varepsilon_r \end{bmatrix}; \mu = \mu_0 \quad (3)$$

with $\varepsilon_r = 6.25$ and $g = 0.3$. The parameter g can be assumed to be constant when the applied static external magnetic field (SEMF) is large enough to ensure magnetic saturation of the BIG.

The MO cavity is the same used in [2]. Without external magnetic field this cavity supports two degenerated localized modes, namely, even and odd modes. The SEMF makes the modes to couple forming two rotating modes, i.e., right and left-rotating modes with frequencies ω_- and ω_+, respectively. This cavity was designed so as to increase the coupling strength (V) between the even and odd modes of the cavity. Since the frequency splitting $\Delta\omega = |\omega_- - \omega_+|$ is related to V by $\Delta\omega = 2V$, this MO cavity was designed to improve its operational bandwidth.

The two small circles in Figs. 1 and 2 show the distribution of the z-component of the magnetic field (H_z) of the standing waves (dipole modes) in the resonators when the SEMF is applied. Notice that each case corresponds to a different port excitation. From the dipole orientation we can determine the transmission and isolation ports.

IV. SIMULATION RESULTS

For showing the operation of the W-circulator we excited it at each port and calculated the transmission and isolation responses at the others ports in accordance with the schemes shown in Fig. 2. For example, when the excitation is applied at port 1, the transmission and isolation responses are calculated at ports 3 and 2, respectively.

In Figs. 3, 4 and 5 are shown the power transmission and isolation curves of the W-circulator for excitation at ports 1, 2 and 3, respectively. These curves were obtained neglecting the waveguide and cavity loss, i.e., normalizing the curves by the maximum value of transmission. As can be seen, the maximum of transmission and the minimum of the isolation responses for excitation at port 1 are not coincident in frequency, but the shift is not critical. The transmission remains very near 0 dB for an isolation of 20 dB.

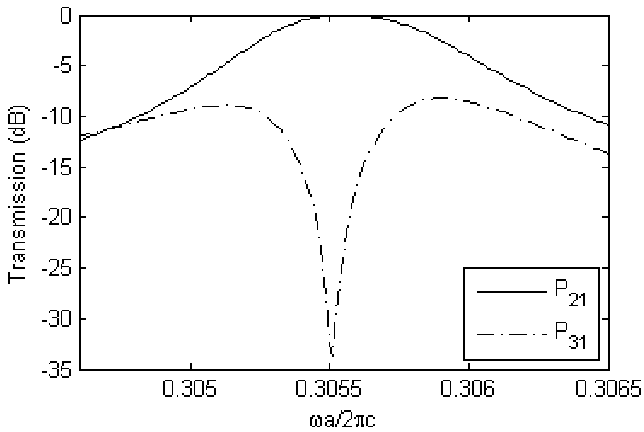

Fig. 3. Power transmission and isolation curves for excitation at port 1.

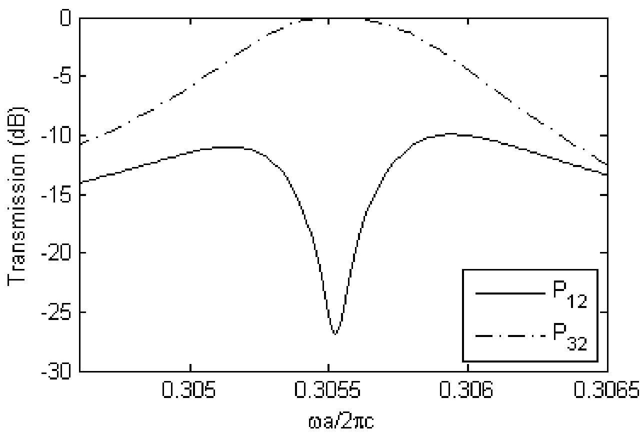

Fig. 4. Power transmission and isolation curves for excitation at port 2.

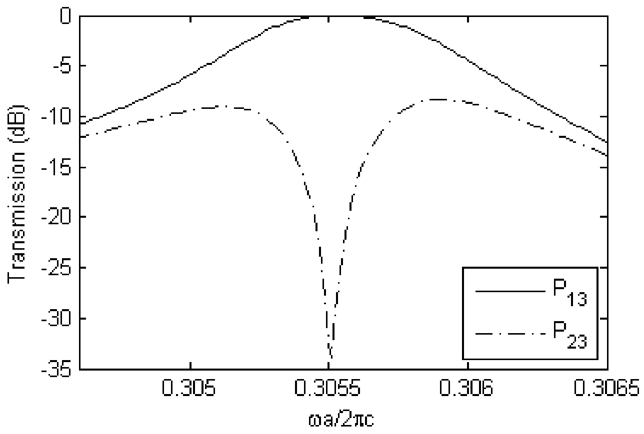

Fig. 5. Power transmission and isolation curves for excitation at port 3.

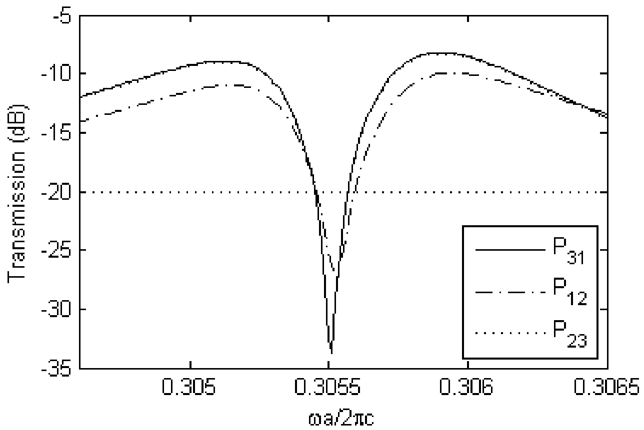

Fig. 6. Isolation curves for excitation at ports 1, 2 and 3.

In Fig. 6 it is shown simultaneously the isolations curves from Figs. 3, 4 and 5. As predicted from the symmetry analysis, the power isolation curves P_{31} and P_{23} are coincident, but P_{12} has a little displacement in frequency with respect to the others. For that reason, the W-circulator bandwidth is a little degraded. At an operation wavelength of 1.5 μm the calculated bandwidth is around 120 GHz at the level of 20 dB of isolation.

In Figs. 7, 8 and 9 is plotted the amplitude of the perpendicular component of the magnetic field at the normalized frequency of 0.30554(ωa/2πc) for excitation at ports 1, 2 and 3, respectively. As it can be seen, the field amplitude is greatly amplified on the MO cavity and the orientation of the dipole is in accordance with that illustrated in Fig. 2.

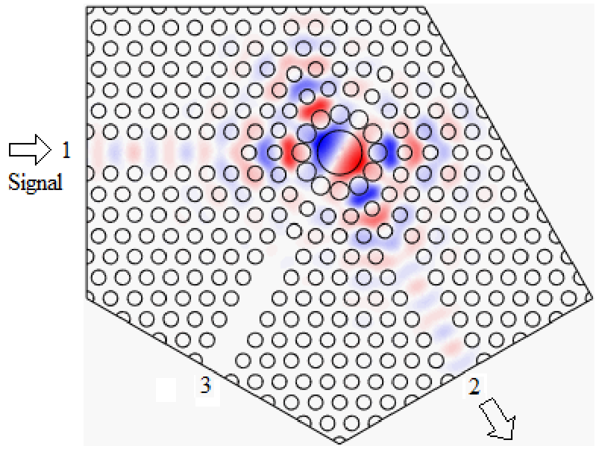

Fig. 7. Simulated H_z amplitude of the W-circulator for excitation at port 1.

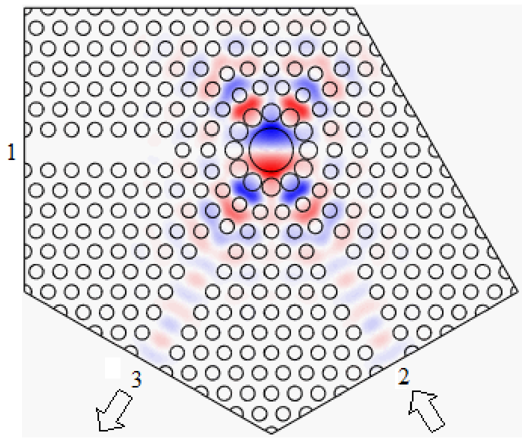

Fig. 8. Simulated H_z amplitude of the W-circulator for excitation at port 2.

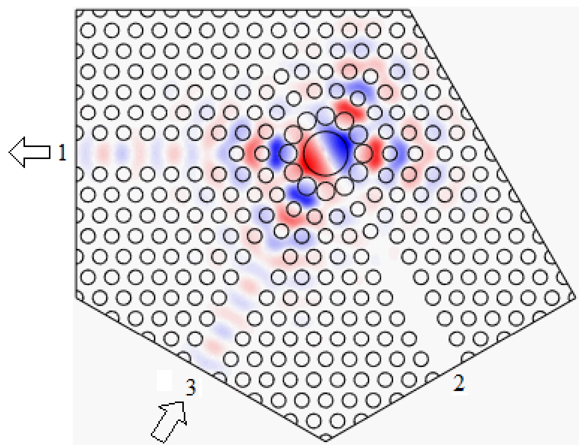

Fig. 9. Simulated H_z amplitude of the W-circulator for excitation at port 3.

V. Conclusions

In general, the characteristics of the W-circulator are similar to that of the Y-circulator, including the bandwidth which at 1.5 μm is about 120 GHz. The main difference is not coincidence in frequency of the maximum of the transmission and minimum of the isolation responses. However due to very high Q-factor of the resonator, the influence of nonsymmetrical connection of the ports to the resonator is not very large and results in a small reduction of the circulator bandwidth. It can be adjusted by a small modification of the circulator geometry.

Acknowledgments

This work was supported by the Brazilian agencies CAPES and CNPq.

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