Study of a Photonic Crystal Coupler Doped with Erbium

Elizete R. Sabino[1,2]; Fabio B. de Sousa[1,2]
1 - Postgraduate Program in Electrical Engineering
2 - Federal University of Pará
Belém, Pará, Brazil
elizetesabino@ufpa.br, fabiobarros@unifesspa.edu.br

Fiterlinge M. de Sousa[1,2]; Marcos B. C. Costa[1,3]
3 - Assistent Professor of Faculty of Materials Engineering
Ananindeua, Pará, Brazil
{fiterlinge, marcosta}@ufpa.br

***Abstract*— In the present work is used the nonlinear resonance caused by excitation of Erbium ions located on central row of a Photonic Crystal directional coupler. Such excitement causes the transition of Erbium ions from the ground state to the metastable doing the amplification of the signal when the photons absorb the light emitted by the signal. The simulations occurred in software COMSOL Multiphysics, which uses the Finite Element Method (FEM). A comparative analysis was performance between a directional coupler of Photonic Crystal doped with erbium and another not doped. It was verified the switching performance of both from the variation of normalized frequency and it was verified that the doped coupler was able to operate in the bar and cross states with higher frequency spectrum.**

***Keywords*— coupler; Photonic Crystal; erbium; switching.**

I. INTRODUCTION

Photonic devices have sizes in nanometric scales ideal for the integrated optics system, because of that, Photonic crystal research has been making great strides for the construction of optical switches that operate efficiently with large passing bands [1]. Photonic crystals are periodic structures in dielectric or metallic media in wavelength scale, where it is possible to manipulate electromagnetic waves in these structures, by breaking the periodicity in the lattice of the crystal. From a defect in the structure it is possible to produce photonic devices, such as: circulators, couplers, filters and others.

The directional coupler is a device that allows controlling the exchange of energy between electromagnetic waves, which propagate in structures with different propagation constants. To make this commutation more efficient we provoke a non-linearity, which was done with the insertion of Erbium. This is an internal transition metal belonging to the lanthanide family, which has great light absorption in the optical spectrum, as well as other rare earths. By virtue of this property this metal has been used to decrease the switching threshold power [2].

In this paper, we investigated an erbium-doped triangular network nonlinear optical Photonic Crystal switch in order to analyze the frequency range that this device can operate in an efficient manner. The work is organized as follows: In the second session the materials and methods are discussed, in the third the results and discussions and finally the conclusions and references.

II. MATERIALS AND METHODS

A. Model Teory

There are two theories that explain the behavior of the coupler: the theory of supermodes and the theory of coupled modes. As described by Rahmati and Granpayeh (2010) [3], the supermoder theory focuses on the two waveguides and their normal modes, explaining the interaction of modes in the coupling process. However, the theory of coupled modes considers that the existence of a waveguide close to another causes perturbations, describing the transfer of energy from one waveguide to the other [4].

According to the theories described above, the directional coupler has two waveguides, one as even mode and the other odd mode called supermodes. These supermodes propagate in the structure with different propagation constants. Thus, for switching between the waveguides, you can set the minimum coupling length as [1]:

$$L_C = \frac{\pi}{\beta_{odd} - \beta_{even}} \text{ (cross state)}, \tag{1}$$

were β_{odd} and β_{even} are the odd and even propagation constants of the modes respectively.

When a signal is emitted through the doped guide, the erbium ion is raised to the transition level, producing a resonant nonlinearity which is usually many orders of magnitude larger than the kerr effect [5]. The resonant nonlinearity is produced by the optical transition between $4I_{15/2}$ (fundamental state) and $4I_{13/2}$ (metastable state) of Er^{3+} causing the refractive index of the material to change and also the propagation constants where the real part is related to the change in the refractive index n, since the imaginary part is related to the change in the gain coefficient g. In this way the coupled modes are defined by eq. (2) and (3) [5]:

$$\frac{dA}{dz} = -jk_{ab}B + i\beta_a A + i\frac{2\pi}{\lambda}\Delta nA + \frac{\Delta g}{2}A \tag{2}$$

$$\frac{dB}{dz} = ik_{ba}A + i\beta_b A, \tag{3}$$

were, k_{ab} *and* k_{ba} are the coupling coefficients, Δn is the variation of the refractive index, Δg is the variation of the gain coefficient, β_a *and* β_b constant of propagation of the guided modes, it is worth mentioning that the time-related items were neglected in the above relation.

When a high-intensity signal reaches the non-linear optical switch, only the refractive index of the center bar (coupling region) is changed, as described in eq. (4) [3]:

$$\Delta n = n_0 + n_2 I \,, \tag{4}$$

were n_0 is the index of linear refraction having constant value, n_2 is the nonlinear refractive index that varies with signal strength *I*.

B. Numerical Method Used

The FEM is a precise and flexible method, since it allows to analyze the structure with arbitrary domains, its precision is determined from the size of the mesh, it is advantageous because it decreases the computational time of the simulations [6]. This numerical method is used to generate resolution of partial equations in finite domain. A linear equation is obtained from a discretization of the original continuous domains of the physical problem. This discretization is made from a mesh that can be uniform or adaptive. The adaptive mesh is used for geometries of various shapes, for example, curves. In this device we use an adaptive and refined mesh to determine the intensity of the electromagnetic field in the structure.

C. Doped Non-Linear Photonic Crystal Directional Coupler Structure

The structure of the proposed photonic crystal directional coupler consists of three regions: coupling, input and output.

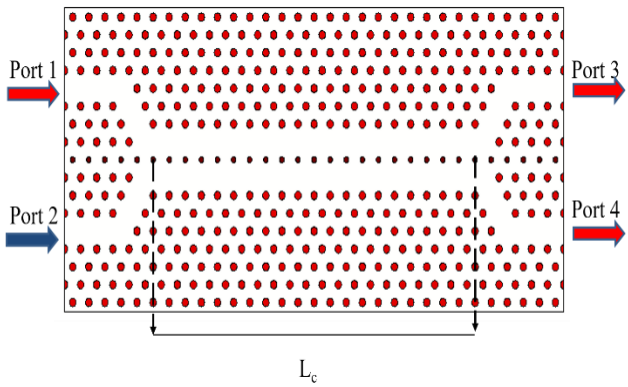

Fig. 1. Geometry of photonic crystal directional coupler of Erbium doped with triangular structure, where the stems highlighted in red are doped with erbium.

The total length of the coupling region is L_c. The coupling is embedded in photonic crystal of triangular structure and Magnetic Transverse (TM) polarization, with bandgap in the range of $0.27<a/\lambda<0.42$. This device is formed by circular columns of silica encased in air. The dielectric rods, with the exception of the central stems, have a refractive index of 3.46, radius 0.2*a*, where a is the net constant. The central stems are doped with erbium with refractive index of 4 and radius 0.14*a*. Fig. 1 shows the structure of the coupler.

III. RESULTS AND DISCUSSIONS

A. Bar State

To demonstrate the switching performance of the photonic crystal directional coupler, the linear state was simulated for the doped with erbium (Fig. 2) and the non-doped state (Fig. 3).

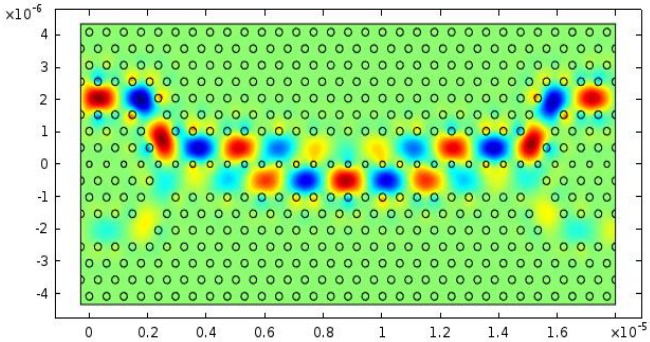

Fig. 2. Distribution of the electric field in relation to the frequency in *z* in photonic crystal directional coupler doped with Erbium operating in linear state (bar).

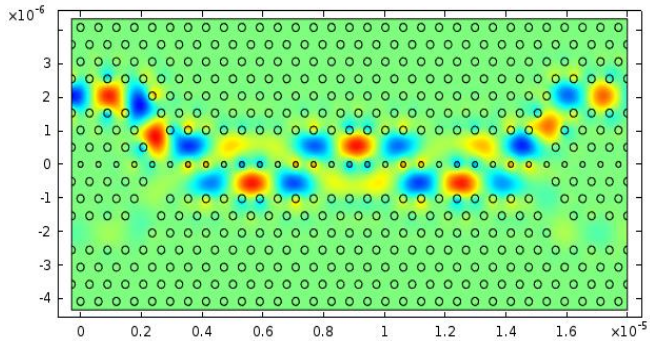

Fig. 3. Distribution of the electric field in relation to the frequency in z in photonic crystal directional coupler without doping operating in linear state (bar).

Through the simulations, it was observed that for the dobutated doped erbium crystal directional coupler, the refractive index of the central stems was not changed by the pump power and the coupler operated in the bar state at a normalized frequency of 0.39 and a wavelength of 1.5 µm. Thus the light was transmitted through port 3 as shown in Fig. 2. In this case the signal was more intense, this was due to the high absorption power of the erbium. For the case of the non-doped coupler, although it also operated in the bar state, there was a difference in both the normalized frequency of 0.38, and the wavelength of 1.54 µm. In this case, due to the lower absorption power of the dielectric used (silica), it caused less field strength when compared to the doped coupler, as can be observed in Fig. 3.

B. *Cross State*

The switching performance of the photonic crystal directional coupler was also simulated for the nonlinear state. Thus the erbium doped coupler (Fig. 4) and the non-doped coupler (Fig. 5) were analyzed.

For the couplers (doped and not doped) operating in the Cross state, the light intensity produces variation in the refractive index of the central rods causing a variation in the coupling coefficient, thus the signal is transmitted by the port 4, as shown in Fig. and 5.

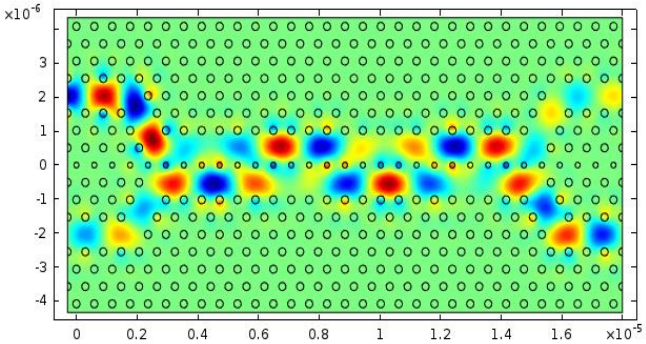

Fig. 4. Distribution of the electric field in relation to the frequency in z in photonic crystal directional coupler doped with Erbium operating in non-linear state (cross).

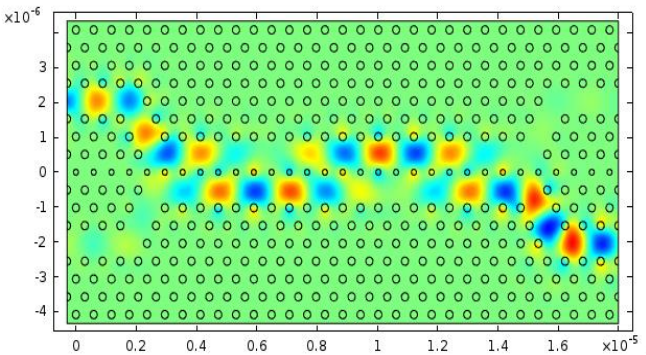

Fig. 5. Distribution of the electric field in relation to the frequency in z in photonic crystal directional coupler not doped operating in non-linear state (cross).

Similarly to the case of linear state operation we observe that the signal is more intense in the doped coupler, this is due to the previously mentioned properties of the erbium. This coupler operated at a cross-state at a normalized frequency of 0.38 and a wavelength of 1.54 µm, while the coupler not doped the transmission occurred at a normalized frequency of 0.385 and a wavelength of 1.52 µm and also with low field strength.

C. *Analysis of the Couplers Based on Output Power*

The results with respect to the output powers of the couplers in relation to the frequency are shown in Figs. 6 and 7. The simulations were performed using the frequency range from 1.9 to 2.2 THz.

It has been observed that the output power at ports 3 and 4 are equal to 0.5 for the normalized frequencies 0.378, 0.387 and 0.404, for both couplers.

For the normalized frequencies 0.38 and 0.45 the doped device presented switching between the guides and the signal was transmitted on port 4, characterizing the cross state, already for the normalized frequency 0.395 the signal was transmitted by the port 3, operating in the state bar as shown in Fig. 6.

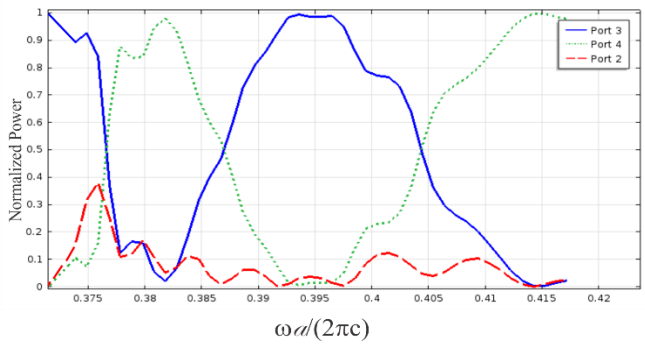

Fig. 6. Spectrum of frequencies in relation to output powers for erbium-doped coupler.

For the non-doped device the transmission in the cross state (port 4) was obtained from the normalized frequencies 0.375, 0.385 and 0.392. However for the transmission of state bar (port 3) was obtained for the normalized frequency 0.38 and 0.405 as can be observed in Fig. 7.

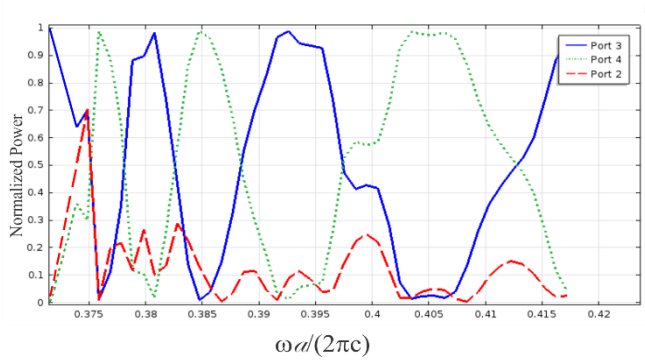

Fig. 7. Frequency spectrum in relation to potential output to a coupler not doped.

IV. CONCLUSION

In this work a photonic crystal directional coupler with triangle network doped with erbium was proposed to induce resonant nonlinearity. For the erbium doped coupler the frequency spectrum to operate in the cross and bar states was higher than those of the non-doped device, it was possible to observe that this occurred due to the absorption power of the erbium. Thus, the doped device obtained better performance with respect to frequency. Future work will aim to work with the reduction of switching threshold power in relation to input power and non-linear effects.

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