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Photonic crystal optoelectronic devices and circuits for student training

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The special properties of the photonic crystals to forbid the electro-magnetic field on all directions in specific spectral optical ranges offer the possibility of creating many viable optoelectronic devices. This paper investigates the properties of photonic crystals trough computer simulations. Using Optiwave FDTD software, computer simulations were made for 2D photonic crystal devices and circuits, having air as basic element ($\varepsilon_{r1}=1$) and a photonic band gap (PBG) cell lattice, square or hexagonal designs, with $\varepsilon_{r2}\approx12$ (SiO_2). As a testing wave for all the studied devices and circuits the IR "eye-safe" 1550 nm wavelength was used. The results confirmed the theoretical data found in literature.

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1. Introduction

The intensive research in photonics – nowadays, one of the most important fields of science and technology – led to the development of different optoelectronic devices and allowed advanced technological contributions in the transmission and optical processing of information.

One of the main drawbacks in telecommunication is the processing nodes that connect the optical fiber nods - nods that are necessary for routing information. Up to now there isn't a cheap and efficient method that makes this process totally optical. On the other hand the energy losses in many optoelectronic devices are quite high. For all these reasons, the photonic crystals could be a good solution.

In this paper our main interest was to verify some theoretical considerations about the mathematical models, which describe the special properties of the photonic crystals. Then, we highlight the utility of Optiwave FDTD software in 2D photonic crystal computer simulations. Considering two different types of lattices, square and hexagonal ones some results of these computer numerical computations are presented for representative optoelectronic devices like waveguides, beam-splitters, turning points, inlets and circuits designed by combining them.

2. Theory

In 1991, E. Yablonovitch highlighted, through theory and experiments, the "photonic band gap" (PBG) materials, later known as photonic crystals.

Photonic crystals are defined as artificial periodic structures capable to forbid the electromagnetic field propagation in certain frequency bands on one, two, or even on all three spatial directions.

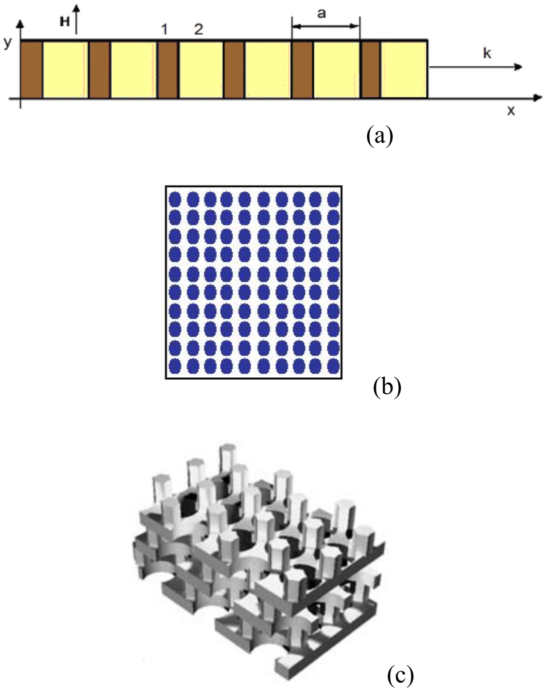

Fig. 1. Photonic crystals (a) 1D (b) 2D (c) 3D.

The most common known photonic crystal is the one made from a basic environment having an ε_{r1} electric relative permittivity, in which is introduced a matrix of cylinders (ε_{r2} electric relative permittivity). Consisting of a periodic succession of materials, the photonic crystals can be analyzed by the interaction between the electromagnetic waves and matter using the Maxwell equations. The equations that are used in determining the dispersion diagrams and the forbidden band gap structure of photonic crystals are:

$$\nabla \times \left(\frac{1}{\varepsilon_r(r)} \nabla \times H(r) \right) = \frac{\omega^2}{c^2} H(r) \tag{2.1}$$

$$\frac{1}{\varepsilon_r(r)} (\nabla \times [\nabla \times E(r)]) = \frac{\omega^2}{c^2} E(r) \tag{2.2}$$

Thus, we established how a certain type of crystal geometry forbids the propagation of light in certain frequency bands.

The special quality of the photonic crystals to forbid the electro-magnetic field on all directions in specific spectral ranges offers the possibility to design different useful optoelectronic devices, like filters, multiplexers, splitters, de-multiplexers, optical guides with 0 losses and so on.

If guides constructed inside photonic crystals by removing an entire row of periodic elements are used, then the field's energy will not be radiated outside the propagation channel, no matter the path followed. The field's existence is impossible in the rest of the crystal, fact determined by the forbidden band gap.

3. Optiwave FDTD computer simulations

The Optiwave FDTD Software has three basic components:

- OptiFDTD_Profile Designer, where the materials used in the simulations are defined
- OptiFDTD_Designer, where crystal structures are constructed, based on the materials defined in the Profile Designer
- OptiFDTD_Analyzer, where the results obtained in the simulations are studied.

3.1. 2D photonic crystal square lattice

In OptiFDTD_Designer we have designed a 2D photonic crystal structure using air as basic element (ε_{r1}=1) and a photonic band gap (PBG) cell lattice with $\varepsilon_{r2}\approx 12$ (electrical permittivity specific for **SiO$_2$**). The materials were previously defined in the Profile Desiger. The designed square lattice has 20x30 µm dimensions. The lattice constant is a=1µm and the diameter of each element is d=2·r = 2·0.3·a = 0.6 µm.

To confine a beam in a created waveguide, we must take in consideration that this device will work only at certain frequencies. These frequencies are determined by the relation:

$$\mathbf{f \approx a / \lambda} \tag{3.1}$$

where a is the lattice constant, and λ represents the desired testing wavelength.

Using the program's Band Solver, the forbidden band gap was in the [0.55 – 0.7] range interval. This permitted the use of an "eye-safe" testing wavelength of 1550, a reference one in the optical engineering.

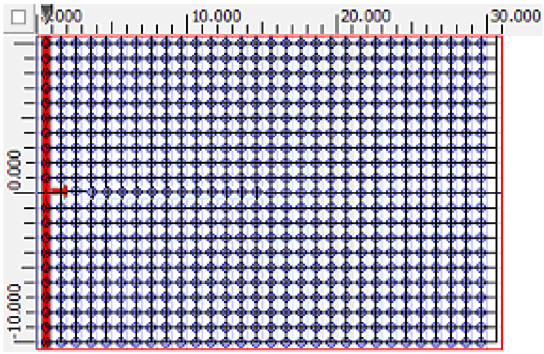

Fig. 2. The 2D photonic crystal square lattice, a=1 µm.

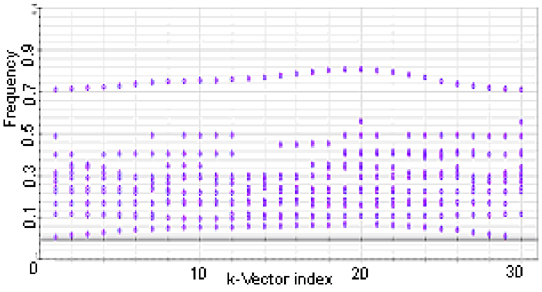

Fig. 3. The TE mode diagramme 2D of the photonic crystal square lattice, a=1 µm.

A waveguide was realized by removing an entire row of periodic elements. Two measuring points where placed at the waveguide's entrance and exit. A testing wave of 1550 nm wavelength was used. The results returned by Opti_FDTD Analyzer showed that the wave goes from entrance to exit with minimal losses, less than 0.5%.

If a crossroad appears on the wave's propagation path, it is desirable that the entire energy to be divided between the two branches. Unlike the classical optical guides, where the energy can escape very easy in the exterior environment if the conditions of total reflection are not satisfied, the photonic ones have the advantage to keep inside the guide the entire energy of the wave that has a wavelength in a specific domain.

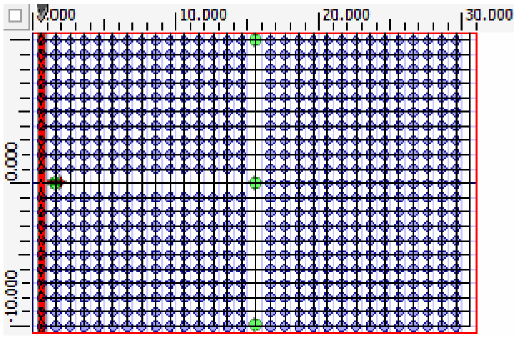

Fig. 4. Beam-splitter.

Using the results returned by the measuring points placed on the device (one at the entrance, two at the exit, one in the ramification zone), we have determined that on each of the ramification there is a 0.45 transmission, that means a total of 9/10 of the initial wave, 1/10 most likely being back reflected. According to the theory, the minimum value that can be obtained for R is 1/9 while the transmission T2 = T3 = 4/9, so the experimental results are quite close.

Next, a 90 degrees turning point and an inlet were designed. The turning point has 71.4% efficiency. The main causes for the losses are back reflections, but also it is very possible to talk about nonlinear phenomena. In the case of the inlet, we have obtained an even lower transmission, of only 42.4%. The inlet is a short optical channel which connects two guides, in this case two perpendicular guides.

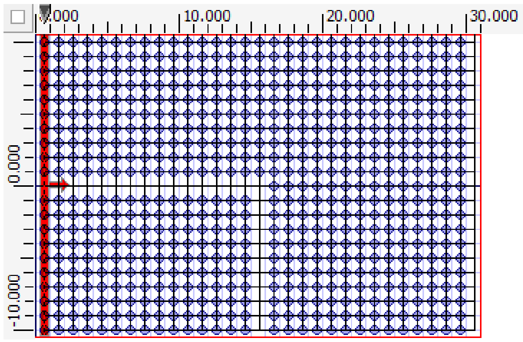

Fig. 5. 90^{o} turning point.

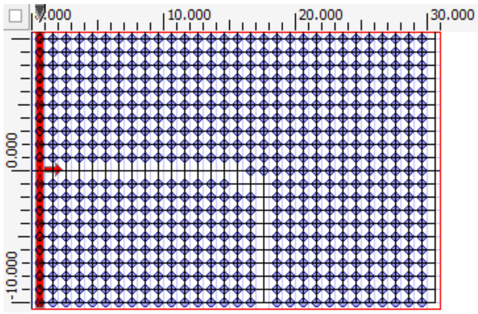

Fig. 6. Inlet.

After that, a guide-inlet-beam splitter circuit was designed. 0.58 of the initial wave was transmitted trough the inlet, the rest being either reflected back or lost because of other phenomena; until the splitting zone there are no significant losses; the remaining wave is transmitted equally, on both branches; practically, the transmission through all the circuit is 0.29.

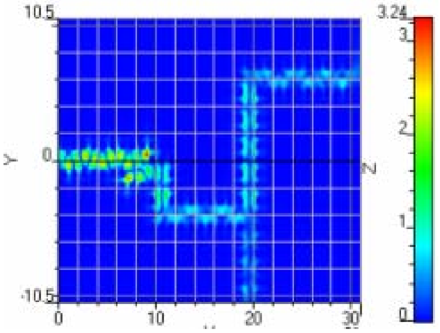

Fig. 7. Map of energy transmission trough the guide-inlet-beam splitter circuit.

Losses of the beam energy are determined by absorption in the material and different various nonlinear effects.

3.1. 2D photonic crystal hexagonal lattice

A photonic crystal structure, having the same materials, same lattice constant, same cell dimension and only two different aspects, the lattice was a 2D hexagonal one, and the array had 20x15 µm dimensions, was designed and studied. The mode diagram is similar with the one of the previously studied lattice. The forbidden band gap is in the frequency band of [0.57 – 0.71] range interval.

Results were very similar with the ones previously obtained, but the losses were a little bit higher in the most studied cases. It seems that the hexagonal geometry increases the losses trough absorption in the material. For the simple, linear waveguide, the losses represented approximately 5%.

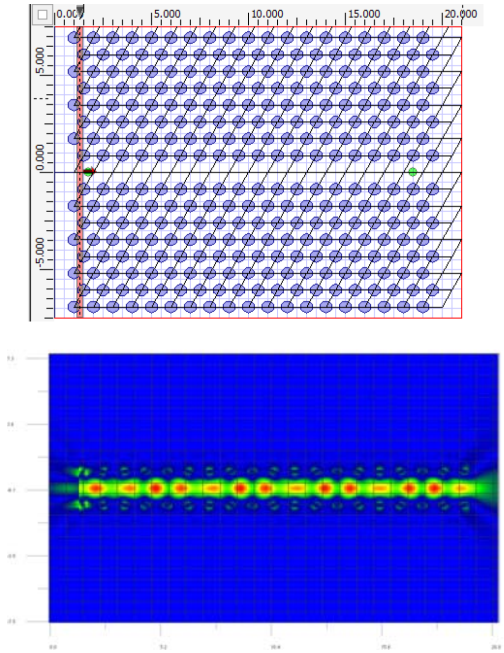

Fig. 8. Waveguide realized in a 2D photonic crystal hexagonal lattice.

A photonic resonator is made by modifying the crystal's structure in a specific region. In the development of a resonant cavity, we have to take in consideration the fact that it must admit modes with frequencies taken from the forbidden band of interest. There isn't a simple mathematical method to realize this thing, but we can repeatedly modify the cavity's geometry until we reach the desired result.

A device made out of two waveguides connected through a resonator was made. A 19% transmission was recorded through the left waveguide.

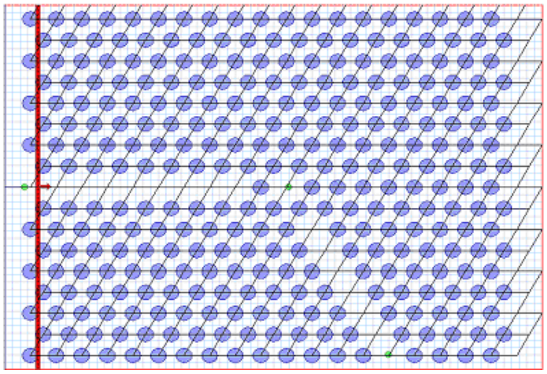

Fig. 9. Waveguides connected trough resonator.

In many applications, it is preferable that the power of the wave that reaches the intersection zone between waveguides to be fully transmitted, in a larger spectral band as possible.

By removing the resonator, it is obvious that the transmission is much higher, because by coupling the two waveguides directly, there is a better energy transfer. Indeed, a 90% value was obtained, the rest of the wave being either back reflected or absorbed in the material.

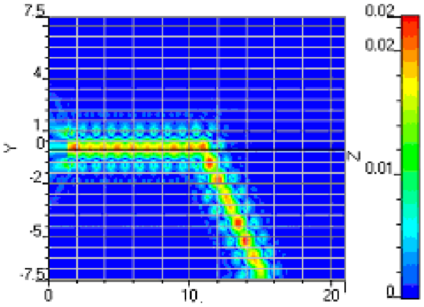

Fig. 10. Transmission map of directly coupled waveguides.

4. Conclusions

The computer simulations realized on 2D photonic crystal devices and circuits designs, having air as basic element ($\varepsilon_{r1}=1$) and a photonic band gap (PBG) cell lattice, square and hexagonal, with $\varepsilon_{r2}\approx 12$ (**SiO_2** permittivity) showed interesting results: a photonic waveguide made in a square crystal lattice is more efficient that one made from a hexagonal lattice. The situation is reversed in the case of turning points or inlets, in which the hexagonal lattice is showing better results.

Results confirm the theoretical data found in literature and can be used for the development and implementation of complex photonic crystal devices and circuits. [2]

The photonic crystals have a high application potential. If mass produced, they can become reliable materials in communications and many other applications.

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