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# Design of a Selective Filter based on 2D Photonic Crystals Materials

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**ABSTRACT**

Two dimensional finite differences temporal domain (2D-FDTD) numerical simulations are performed in cartesian coordinate system to determine the dispersion diagrams of transverse electric (TE) of a two-dimension photonic crystal (PC) with triangular lattice. The aim of this work is to design a filter with maximum spectral response close to the frequency 1.55 µm. To achieve this frequency, selective filters PC are formed by combination of three waveguides $W_1^K$ A wherein the air holes have of different normalized radii respectively $r_1/a$=0.44, $r_2/a$=0.288 and $r_3/a$= 0.3292 (*a:* is the periodicity of the lattice with value 0.48 µm). Best response is obtained when we insert three small cylindrical cavities (with normalized radius of 0.17) between the two half-planes of photonic crystal strong lateral confinement.



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## 1. INTRODUCTION

Photonic crystals (PCs) are periodic dielectric nanostructures materials and have many applications: They also have applications in medical imaging field, solar cells and developpment of chemical and biological micro sensors, spectroscopy and electromagnetic shielding [1], [2]. The nanophotonic structures offer exceptional potential for the development of new architectures of photovoltaic solar cells in thin layers and high efficiency. Among the promising applications of PCs, we mentioned selective filter based on 2D CPs [3].

The PCs have a dielectric index which varies across the wavelength that is to be controlled, on one or more spatial directions. Analogous to electrons in semiconductors, the photon propagation can be described using a band structure in which transmission bands are separated by band gaps, energy ranges at which light cannot exist inside the photonic crystals [4]. Most of the research on PCs focuses on the use of band gaps. The insertion of defects is the easiest way to change the properties of photonic crystals and exploit them for the realization of amazing photonic components for integrated optics. Defects cause the appearance of modes within the band gap. Defects are realized by removal, addition or modification of pattern in one or more parallel rows of the crystal in ΓK direction of Brillouin first zone [5]. Hence, can be designed ($W_1^K$ A) waveguide by creating between the two half-planes of photonic crystal strong lateral confinement, when single full row of air cylinders holes is removed in the PCs.

The aim of this work is to design a waveguide with maximum spectral response close to the frequency 1.55 µm. This nanostructure is composed by a superposition of three waveguides $W_1^K$ A with different radii. This kind of filter has been already studied in ref. [6]. The new in this paper is the insertion of a number of defects between the two half-planes of photonic crystal strong lateral confinement, in order to improve the response of the filter.

In this paper, the simulation was based on the method of finite difference time domain (FDTD) [7]. 2-D numerical simulations are performed in Cartesian coordinate system to determine the dispersion diagrams of transverse electric (TE) of two-dimension PC with triangular lattice, operating as filter.

## 2. RESEARCH METHOD

The FDTD is used to numerically modeling a 2D photonic crystal containing air holes with triangular lattice. It is one of the most widely used numerical methods for computing the solution of electromagnetic problems, including photonic structures.

It provides us with a simple way to discretize the Maxwell's equations without requiring a complex mathematical formulation, and it does not require any symmetry in the structure being modelled, moreover FDTD can be used for the inhomogeneous structure materials in two or three dimension forms [7-10]. Furthermore, it computes the solution in the time domain, from which the frequency behaviour of the electromagnetic band gap elements can be extracted over a wide frequency range. The electromagnetic field is represented by Maxwell equations given by the following relations:

$$\begin{cases} \frac{\partial E_x}{\partial t} = \frac{1}{\epsilon}\left(\frac{\partial H_z}{\partial y}\right) \\ \frac{\partial E_y}{\partial t} = \frac{1}{\epsilon}\left(-\frac{\partial H_z}{\partial x}\right) \\ \frac{\partial H_z}{\partial t} = -\frac{1}{\mu}\left(\frac{\partial E_x}{\partial x} - \frac{\partial E_x}{\partial y}\right) \end{cases} \quad (1)$$

ε and μ represent respectively the permittivity and permeability of the material.

The FDTD method is used here to discretize theses equations (1) with time step Δt, spatial steps Δx and Δy which are the distance between two neighboring grid points, respectively along the x and y directions in the xy-coordinate system. For the TE mode, the numerical scheme of the two-dimensional FDTD method [11] is:

$$\begin{aligned} &\frac{E_x\left(x,y,t+\frac{\Delta t}{2}\right)-E_x\left(x,y,t-\frac{\Delta t}{2}\right)}{\Delta t} = \frac{1}{\varepsilon}\left(\frac{H_z\left(x+\frac{\Delta y}{2},y,t\right)-H_z\left(x-\frac{\Delta y}{2},y,t\right)}{\Delta y}\right) \\ &\frac{E_y\left(x,y,t+\frac{\Delta t}{2}\right)-E_y\left(x,y,t-\frac{\Delta t}{2}\right)}{\Delta t} = -\frac{1}{\varepsilon}\left(\frac{H_z\left(x+\frac{\Delta z}{2},y,t\right)-H_z\left(x-\frac{\Delta x}{2},y,t\right)}{\Delta x}\right) \\ &\frac{H_z\left(x,y,t+\frac{\Delta t}{2}\right)-H_z\left(x,y,t-\frac{\Delta t}{2}\right)}{\Delta t} = \frac{1}{\mu}\left(\frac{E_y\left(x+\frac{\Delta x}{2},y,t\right)-E_y\left(x-\frac{\Delta x}{2},y,t\right)}{\Delta x} - \frac{E_x\left(x,y+\frac{\Delta y}{2},t\right)-E_x\left(x,y-\frac{\Delta y}{2},t\right)}{\Delta y}\right) \end{aligned} \quad (2)$$

In order to achieve the numerical stability of the scheme [6], the time step value must satisfy the relation of the following criterion:

$$\Delta t \leq \frac{1}{c\sqrt{\left(\frac{1}{\Delta x}\right)^2+\left(\frac{1}{\Delta y}\right)^2}} \quad (3)$$

Where c: is the velocity of light in free space.Also in our computation, the values of Δx and Δyrespect the relation:

$$\Delta x = \Delta y \leq \frac{\lambda}{10\sqrt{\varepsilon_r}} \quad (4)$$

Where $\varepsilon_r$: is the relative permittivity of the dielectric matrix and $\lambda$ is the wavelength of the desired mode.

The computational domain has a rectangular shape in the x-y plane. The spatial discretization in the FDTD simulation is chosen to be Δx = Δy = 0.04 μm. A modulated Gaussian pulse is used to provide a wide-band excitation at any desired position inside the computational domain comprising the CP.Since the data storage in a computer is limited by the size of its memory, it is not possible to handle an open region problem directly. To mitigate this problem, the perfectly matched layer (PML) technique [12], [13] is widely used in the FDTD simulations; it exhibits an accuracy level that is significantly better than most other absorbing boundary conditions (ABCs) [14], [15]. Here we consider only the conditions of absorption-type wall that simulate a finite domain containing the entire structure study by investigating the lowest reflection digital interfaces.

The adopted two-dimensional finite difference time domain simulation process is shown in Figure 1 in *xyz* coordinate system. According to the Figure 1, two located detectors are used to compute the reflection at the input and transmission at the output of the structure. A Gaussian source is employed for excitation (source). The structure is surrounded by four surrounding absorbing walls.

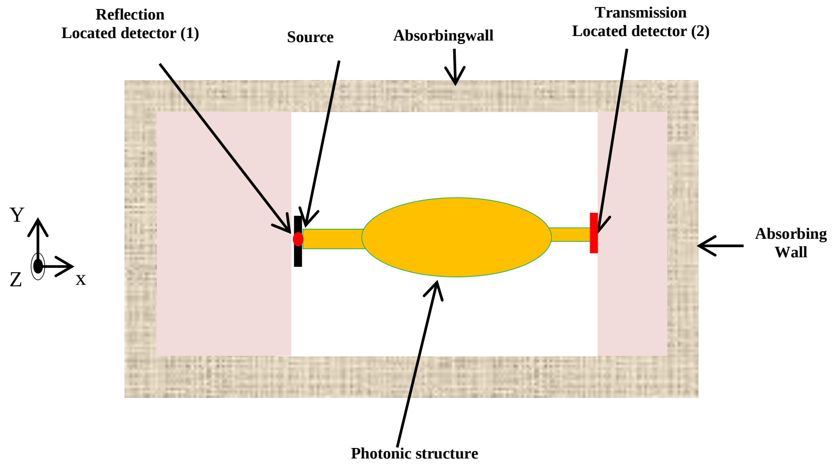



Figure 1. Two dimensional finite difference time domain simulation process

## 3. RESULTS AND ANALYSIS

In the following, numerical simulation is done for the first topology which is the combination of three kinds of waveguides $W_1^K$ A coupled in cascade arrangement within the same cell of PC with triangular lattice and without cavities inside the two half-planes of photonic crystal strong lateral confinement (Figure2).

Each waveguide possesses a number of holes *n*=15 (total number of holes = 45). The normalized size of holes are respectively $r_1/a$ = 0.44, $r_2/a$ = 0.288, $r_3/a$ = 0.3292 and the lattice constant a = 0.48µm. The air cylinders holes having are embedded in a dielectric matrix doped INP/GAINASP/INP; refractive index of matrix is n= 3.24. These air rods are arranged in the x direction and supposed infinitely long in the z direction.

The transmission coefficient versus wavelength for the TE polarization, derived from the FDTD simulation corresponding to the first topology is plotted in Figure 3(a). We observe that the response of the filter is peaked around 1.55 µm. The maximal quantity of transmission computed is 77%. Others peaks appear very close of this frequency with coefficient of transmission of value 80% ranged in the frequency band [1.54-1.57] µm (Figure 3(b)).

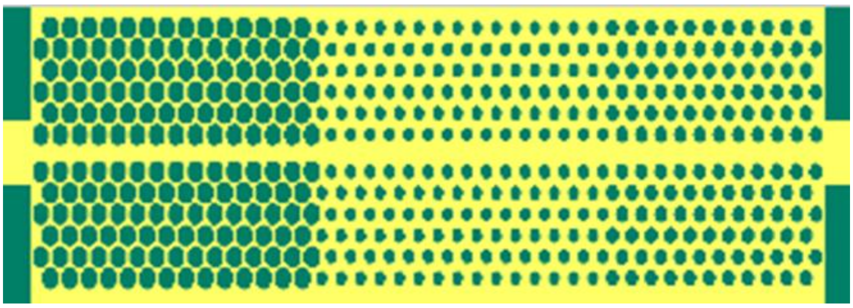
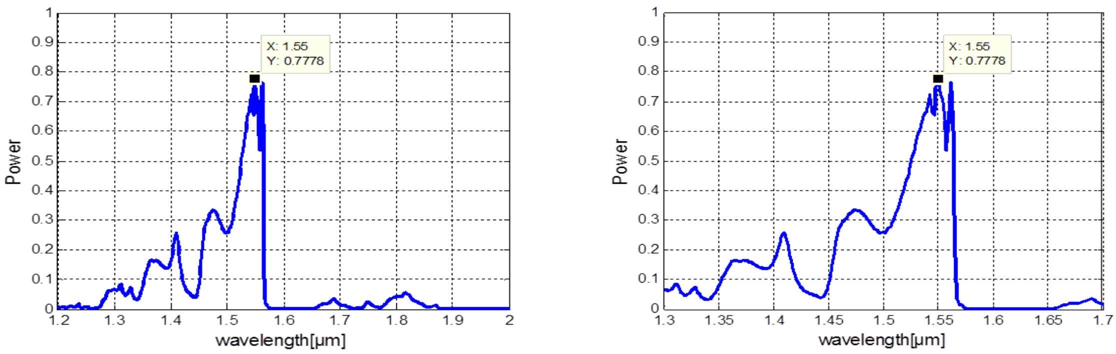


Figure 2. Modeling scheme of PC with combination of three guides $W_1^K$ A with triangular lattice and without cavities




(a) (b)

Figure 3. Computed transmission coefficients for the three simulated selective filter (without cavities). $r_1/a$=0.44, $r_2$/a=0.288 and $r_3/a$= 0.3292 (*a*: is the periodic lattice of value 0.48 µm)

Another two-dimensional PC filter is simulated in order to eliminate unwanted peaks and filter the desired frequency, based on the same first topology with the three $W_1^K$ A but we add three small cylindrical holes with normalized radius of 0.17 between the two half-planes of photonic crystal strong lateral confinement. All the previous geometrical parameters are unchanged (Figure 4). We report in the Figure 5 the transmission coefficient versus wavelength for the TE polarization. According to this plot, it can be seen apparently that maximum spectral response (80%) occurs close to the frequency 1.55 µm. A significant improvement was observed regarding the disappearance of unwanted peaks around the desired frequency but a slight decrease occurs in the amplitude of appearing modes.

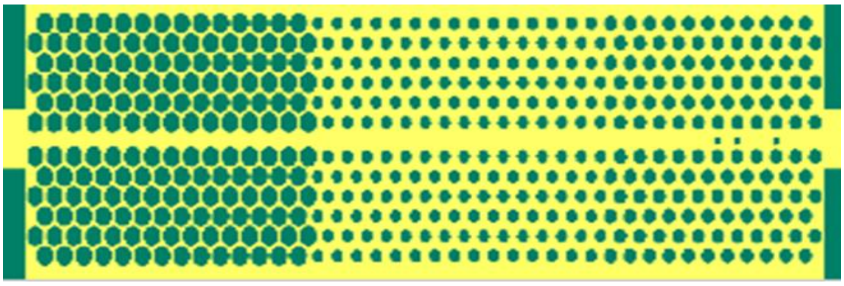


Figure 4. Modelling scheme of PC with combination of three guides $W_1^K$ A with triangular lattice and having three cavities

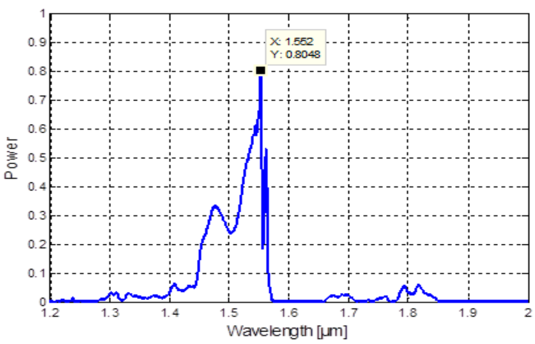
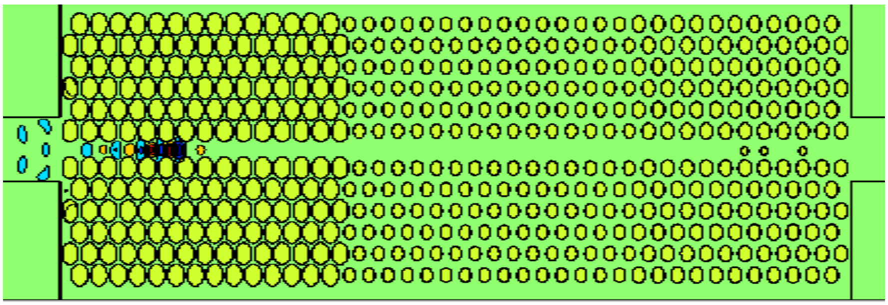
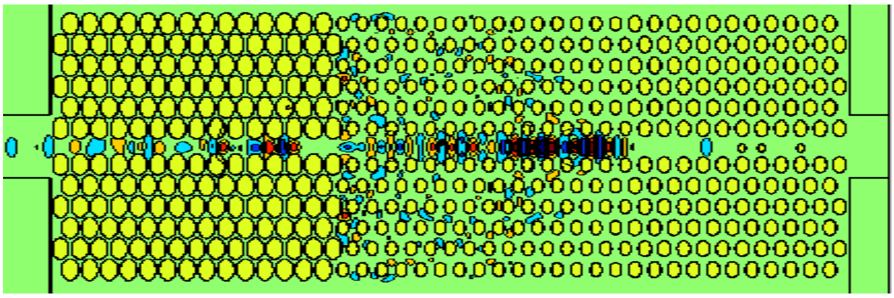



Figure 5. Computed transmission coefficients for the three simulated selective filter with three cavities having normalized radius of 0.17. $r_1/a$=0.44, $r_2$/a=0.288 and $r_3/a$= 0.3292 (*a* is the periodic lattice of value 0.48 µm)

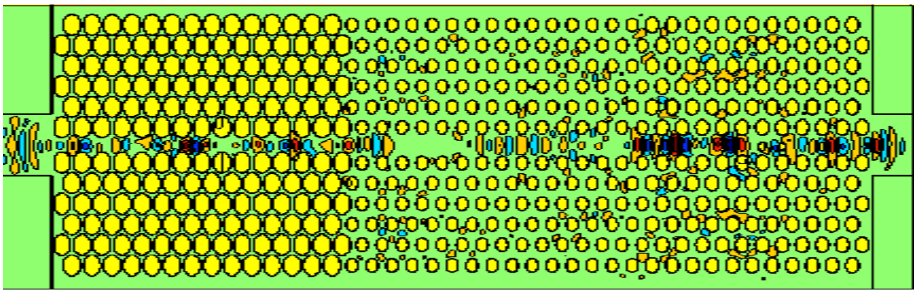
The magnetic field pattern inside the selective filter corresponding to the second topology with a spectral response close to frequency of 1.55μm is reported in Figure 6(a-c) for different step time iterations 1500, 4500 and 6500. These figures show the light-guiding propagation of the electromagnetic field inside the empty row along the waveguide (confinement). We can observe that one part of electromagnetic energy is transmitted intil the end of PC with a frequency belonguing the gap, and the other part of energy with no allowed frequency is reflected by the added inclusions embedded in dielectric matrix in empty row.



(a)



(b)



(c)

Figure 6. Simulated distribution of a magnetic field. (a) 1500, (b) 4500, (c) 6500 step time iterations

## 4. CONCLUSION

A novel selective filters based on a two-dimensional photonic crystal with a triangular lattice with air holes in a dielectric substrate was proposed. This device consists of three waveguides $W_1^K$ A placed in cascade with different road of radii respectively $r_1/a$=0.44, $r_2/a$=0.288 and $r_3/a$= 0.3292. An improvement is observed when we add a number defects in the empty row. From our computation this CP can be conceived for achieving frequency of 1.55 μm which is suitable optical devices with a transmission maximum in order to 80%.

In order to improve more the selectivity of this filter, others simulations with new design will be done later. This study will be completed when comparison with experimental data is done.

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