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A novel design of a photonic crystal sensor with improved sensitivity

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ABSTRACT

Biosensors, based on photonic crystal (PC), are emergent subject. The use of PCs in this area brought solutions to both miniaturization and integration challenges that have been facing research groups for long time. We are only recently, by engineering such defects, able to propagate light in complex structures containing molecules of different sizes and shapes. We propose a novel structure containing defects with various sizes. The PC is formed by a dielectric cylinders with permittivity 8.9 (alumina Al_2O_3) and a radius $r = 0.2a$ (a is the square lattice constant), arranged in a square lattice. We use the finite difference time domain to investigate the sensitivity of the proposed sensor to water. The defect based sensing element is introduced in two directions $\langle 0\,1 \rangle$ and $\langle 1\,0 \rangle$. These simulations show a better sensitivity to water than other analytes. It appears in the transmission curves where the peak shifts to high frequency when the refractive index is changed.

1. Introduction

Photonic crystals (PCs) could be defined as periodic dielectric structures that could be placed in one, two or three directions. They are so often described as the optical analogue of the semiconductor materials where the electronic potential is a periodic function depending on the position of atoms in the lattice. The periodicity of the potential defines the electronic band gap. Similar to a semiconductor crystal, photonic crystal (PC) has a periodic dielectric function too. This function is mainly defined by the material forming the PC. This property that is responsible for generating the photonic band gap (PBG) and may be completed when the dielectric contrast has a great value compared to 1. Optical sensors have attracted many research groups worldwide. Compared to their counterpart in electronics, optical sensors present advantages due to their capability to be implemented in complex areas [1].

However, a photonic-crystal waveguide sensor is presented for biosensing. The sensor is applied for refractive index measurements and detection of molecules-concentrations [2]. A highly sensitive method for performing a wide biological and chemical variety has recently been demonstrated [3]. In this theme, we propose a novel PC sensor described in abstract. The analysis of band structure shows that the PC presents a completed PBG. In order to optimize our PC sensor, we produce a waveguide in it, and we research the conditions in which we give a photonic crystal with strong field confinement, small mode volumes, and low extinction losses enabling lower loss interconnects, lower threshold lasers, and higher sensitivity sensors [4]. This operation involves a new defect mode located in the PBG. It imposes accuracy propagation to the light. After implementation, we show a strong field confinement in the waveguide due to the defect mode appearing in the completed photonic band gap. Amongst all of them, the use of PC technology for sensing applications has recently gained much attention [5]. It had an important function in biomedical domain progress because it gives a new technique to pick up all hetero-molecules in some corps. However, by this technique we can detect all diseases in the human body. This may be done by a simple treatment of the human blood by using them as analyte. Also, we can study the sensitivity to water of any PC. This is presently the object of this paper. In this frame, we will demonstrate the nanoscale biosensors through shifts in the localized analyte surface for different refractive indexes.

2. Theory

In order to calculate the band structure, we employed the plane expansion method (PWE). The details of the calculations are reported in [6]. The electromagnetic fields evolution and the transmission spectra are calculated by using the finite difference time domain (FDTD) in Yee schema [7]. The electric and magnetic fields are evaluated at different grids in leapfrog and staggered grid forms. The Maxwell's equations are written as:

$$\frac{\partial H_x}{\partial t} = -\frac{1}{\mu}\frac{\partial E_z}{\partial y} \tag{1}$$

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$$\frac{\partial H_y}{\partial t} = \frac{1}{\mu}\frac{\partial E_z}{\partial x} \quad (2)$$

$$\frac{\partial E_z}{\partial t} = \frac{1}{\varepsilon}\left(\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} - \sigma E_z\right) \quad (3)$$

where μ is the permeability, ε represents the permittivity and σ is the conductivity. In this work, we consider the transverse magnetic (TM) polarization, where the magnetic field is normal to the axis of the rods. The magnetic field components H_x and H_y are in the plane (i.e. $H_z = 0$). The convergence condition is spatial step in x and y directions are similar and fixed to 0.025a [8]. The spatial and temporal steps are related through this equation:

$$\Delta t \le \frac{1}{c}\sqrt{\Delta x^{-2} + \Delta y^{-2}} \quad (4)$$

where c is the speed of light in vacuum, and Δx and Δy are spatial steps in the x- and y-directions, respectively. In order to terminate the computational domain, the perfectly matched layers (PMLs) [9].

3. Results and discussion

3.1. Photonic structure

The photonic crystal sensor presented in this work consists of a square lattice of a spatial period, a = 565 nm. It is formed by a periodic disposition of a cylinders dielectric in the vacuum. The cylinders have a radius r = 0.2a and ε = 8.9 as permittivity. To produce a symmetric waveguide coupled by a cavity, we replace the dielectric cylinder by air holes, then we decrease the cylinders radii above and below the cavity to r = 0.1a (in the direction ⟨1 0⟩) for increasing the passage of light in the top waveguide. Also, we introduce an analyte bending in the cavity which has a radius r = 0.45a and the top waveguide is doped by the same analyte with r = 0.25a.

The source is located at the input of the structure; the measurements are realized at the ending section on the top (output).

This description is depicted in Fig. 1.

The defects introduced in this structure will be used as sensing regions, in fact when those defects are filled with analytes, their refractive indices change, which results in local modification of surrounding medium of the defect. This modification affects the properties of the electric field.

The defect mode frequency is located at f = 0.366 $wa/2\pi c$ as defined in bands structure (Fig. 2).

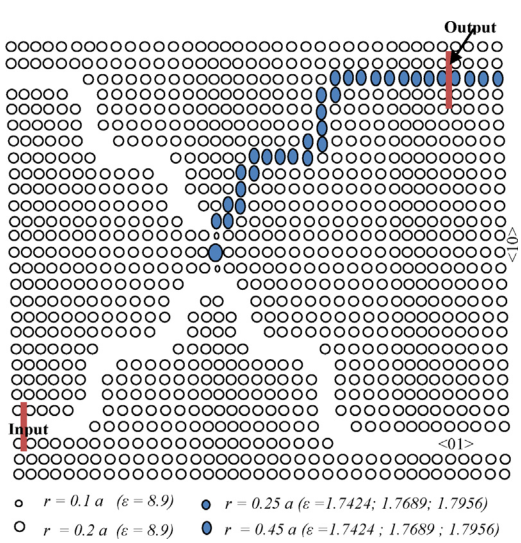

Fig. 1. The photonic structure with line of defects based sensor.

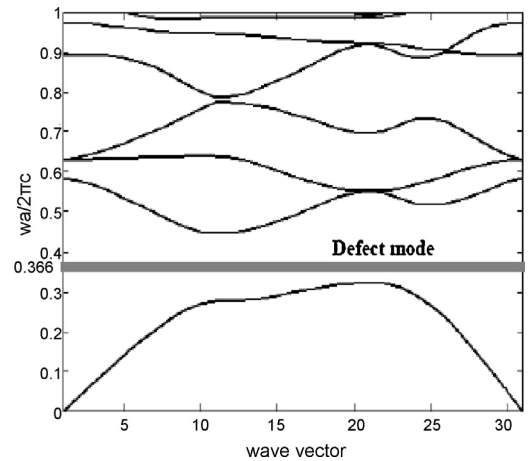

Fig. 2. Band structure of the crystal for TM polarization.

3.2. Optimization of the radius of the analyte cylinder bending in the cavity

As first step for the implementation, we proceed by optimizing the cylinder radii of the analyte existing in the cavity. The transmission curve determination for different radii as, described in Fig. 4, gives an idea about the best radius founding (r = 0.45a).

Fig. 2a–c depicts the snapshot field for versus radii of cylinders analyte. It is shown that the field looks the same for different radii value.

As a second step, we move to the determination of the transmission spectra in goal to find the best choice of the cylinder analyte radius bending in the cavity which fact the tow waveguide coupling.

Fig. 3 shows the change of the radii cylinder entrains variation in transmission spectra in terms intensity and resonance frequency. Also, It is clear that the maxima relative to r = 0.45a is located at the normalized frequency f = 0.366 $wa/2\pi c$ which presents the source frequency excitation. This value will be used in our next simulations.

3.3. Influence of refractive indexes

After defining the optimum dimension of the analyte bending in the cavity, the next step is to optimize the radii cylinders doping the top waveguide. The radii r = 0.25a is determined as best choice.

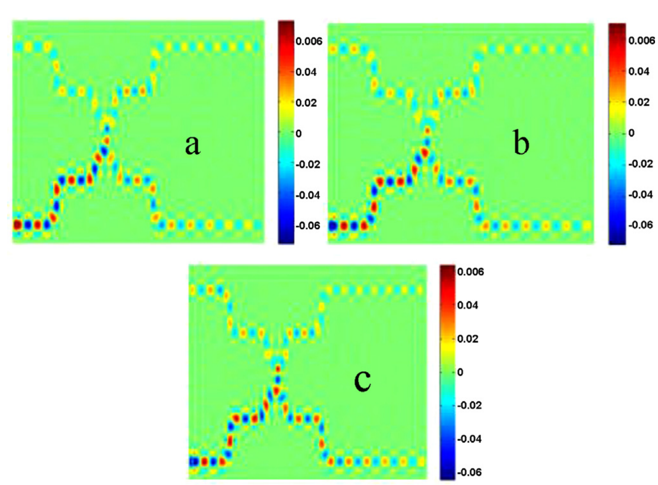

Fig. 3. Snapshots of the electric field when: (a) r = 0.35a; (b) r = 0.4a; (c) r = 0.45a.