A Chemical Sensor Based on Superprism Effects in Photonic Crystals

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Abstract:
The superprism presents one of several methods of detection of the refractive index change. In this paper, we investigate a chemical sensor based on 2D photonic crystal (PC) using a superprism. However, in order to build our sensor, air holes are periodically willing forming a square lattice beside a triangular lattice. It is shown that by appropriately selecting the direction of incidence a strong interaction between the light and analyte is obtained. A high figure of merit (FoM) for the sensitivity of the proposed sensor is achieved.

I. Introduction

Recently, there was a pressing need for miniaturized devices to be used in medicine and communications areas. Several researches are focalized to realize this goal. One of them is based on the use of photonic crystal to build optical sensors. The optimizing of the nanooptical sensor dimensions, which must are less than micrometer [1], gives a solution to these problems. Optical sensors for detecting biological molecules employ fluorescent labels, this technique makes the size of the sensor larger compared to label free ones. Another way to optically detect refractive index changes is based on the local change of the refractive index, which leads to a shift in the transmission spectrum of the sensor [2-5]. However, optical waveguides that employ refractive index changes require large sensing areas, which may pose a challenge towards their integration in lab-on-a-chip systems.

Photonic crystals (PCs) provide a promising candidate to control and manipulate the propagation of light in integrated in subsystems. PCs are periodic structures able to control the propagation of the electromagnetic waves within certain frequency ranges. The band gap in PCs depends on refractive index modulation. Thus there is a growing interest in photonic band gap structures to guide or bend electromagnetic waves through specific directions within the PC lattice. At certain frequencies, the electromagnetic waves are prohibited to propagate within the PC; this may allow the confinement of photon at nanoscale structure based devices. In contrast to that, the propagation of light within the PC has been exploited in many applications, such as optical switch, and directional couplers and light trapping [6]. Such effect is known as the superprism, which is based on the dispersion behavior at the photonic band-edges. Experimental work demonstrated the collimation of light and beam steering at different wavelengths [7]. Mazilu et al. [8] have shown the splitting of light into TE and TM polarizations through a 2-D PC super-prism. It is worth noting that the dispersion of light at different wavelengths may be exploited to design selective nanosensors integrated into a single platform. The dispersion characteristics of such super-prism PC is effectively single-mode at low frequencies. The change in the transmission spectra is a result of the cut-off falling inside the band gap of the PC. Also, the mode cut-off causes a sharp drop of the transmission. The perturbation of the surface film results in the local modification of refractive index allowing a modification in the refractive index contrast between the hole and the slab. This kind of structure may be used to design a sensor, whose principle of operation is based on manipulating the cut-off wavelength shift caused by the local changes in the topology of the surface employed as a sensing region.

In this work, the dispersion characteristics in a 2D-PC superprism are exploited to design a selective chemical sensor. The careful choice of the incidence direction of light is crucial to achieve the superprism effect. The PC superprism is coupled to a curved photonic crystal waveguide (PCW) containing analytes to be detected. The transmitted field is stored in time domain then using the Fourier transformation we determine the transmission spectra. It is observable that this spectrum shows a variation when we change a refractive indices.

II. Analysis

To simulate the proposed sensor, a two dimension finite-difference time-domain (2D-FDTD) method based on Yee's schema is used [9]. The evolution of the electric and magnetic fields along with the transmission spectra are achieved by using the FDTD. The stability condition is fulfilled when the temporal step, Δt verifies the following relation $\Delta t \leq \frac{1}{c}\sqrt{\Delta x^{-2} + \Delta y^{-2}}$, where Δx and Δy present respectively the spatial steps in the *x* and *y*-directions and *c* is the speed of light in a vacuum. The perfect matched layer (PML) [10] is used as absorbing boundaries. For the TM-mode, the Maxwell's equations are given as:

$$\frac{\partial H_x}{\partial t} = \frac{1}{\mu_0}\frac{\partial E_z}{\partial y} \quad (1)$$

$$\frac{\partial H_y}{\partial t} = -\frac{1}{\mu_0}\frac{\partial E_z}{\partial x} \quad (2)$$

$$\frac{\partial E_z}{\partial t} = \frac{1}{\varepsilon_0}\left(\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y}\right) \quad (3)$$

Where H_x, H_y are the x-and y-component of the magnetic field and E_z is the component of the electric field, μ_0 and ε_0 are the permeability and the permittivity in vacuum.

III. Numerical results

The proposed design scheme integrates the operation of a superprism and a waveguide based sensor on the same chip. This design shows a proof of the photonic integrated circuit principle. A 2D photonic crystal (2D-PC) composed of air holes arranged in the silicon ($\varepsilon = 11.56$) forming a square lattice. The radius of air hole is $r = 0.26a$, where *a* is the lattice constant. The PC is used to generate the superprism effect. As reported in [11] the asymmetry in the first band is the main cause of superprism effect. The integrated sensor is presented in figure 1.

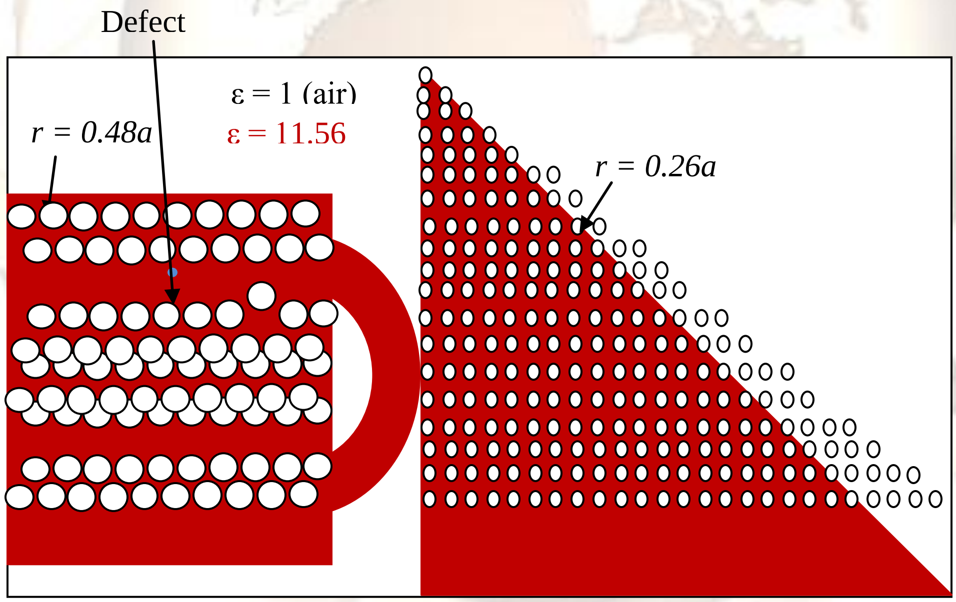

Figure 1: Schematic of the combined photonic system of a 2-D PhC superprism

The principle of operation of the sensor is as follows, the 2D-PC is coupled through a curved waveguide of a refractive index n_{arc}, into a photonic crystal waveguide (PCW) which is composed of air holes of radius $r = 0.48a$ arranged in a triangular lattice. A line of defects is introduced along the PCW that will be filled with different analytes. We begin our study by investigating and determining the performances of the proposed sensor by employing a 2D FDTD. The excitation source is a TM plane-wave with the magnetic field vector normal to the axes of the air holes, the frequency of the source is $f = 0.219\ a/\lambda$.

This work is begun to optimize the field concentration in the waveguide, so some implementations are doing for various dielectric constants. We begin the analysis by using n_{arc}= 3.16 as refractive index of the curved PCW. It shows that the field is more concentrated in lower channel of the PC (figure 2a). Next we increase the refractive index value to 3.24: in this case the field is divided into the lower and upper channels; the result is depicted in figure 2b. The ended simulation has been realized for n_{arc}= 3.31: it gives the same distribution as the first case which presents a high concentration field in the upper channel (figure 2c).

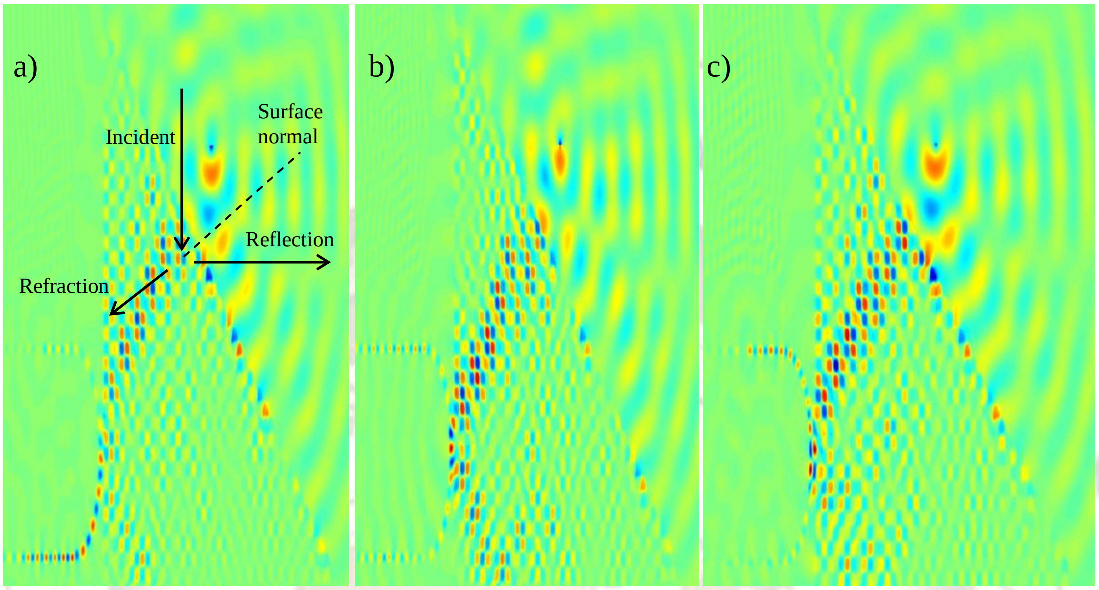

Figure 2: Snapshot of E_z for a) n_{arc}= 3.16; b) n_{arc}= 3.24; c) n_{arc}= 3.31

After determining the best choice of the curved PCW index, we pass to study the sensitivity of this photonic structure to water (n=1.33). So a single defect, having a different dielectric constant, is placed in the wave guide produced in the proposed structure. In first part, an optimizing of cylinder analyte radius is doing by studying of a transmission curve for different analyte radii. This operation is to know the best radii giving the intense transmission wich is calculated in the upper channel of the PCW coupled to the 2-D PC superprism through the curved waveguide.

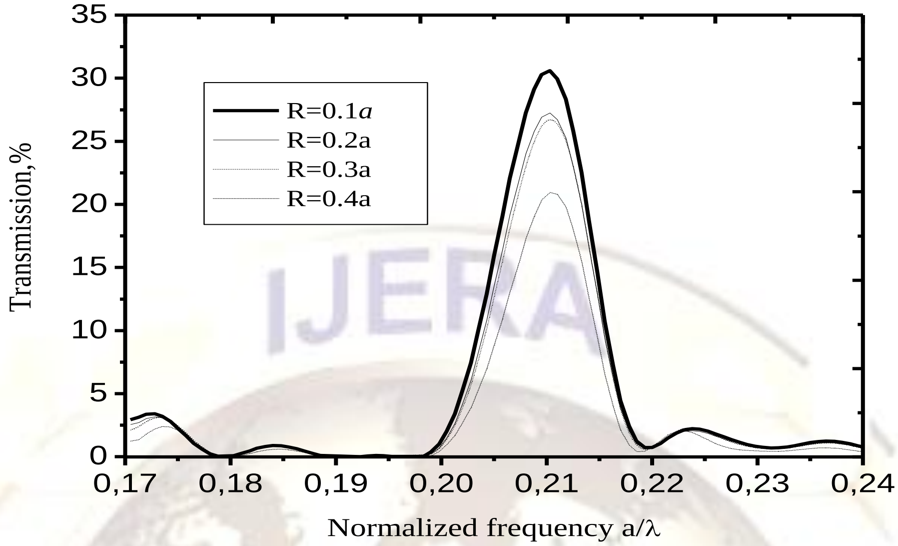

Figure 3: Transmission with frequency for various radii of the defect

The transmission is calculated for various values of the radius of the defect, the result is reported in Figure 3. It is clear that the transmission reaches its maximum between 0.2 a/λ and 0.22 a/λ. The largest value in the transmission, which is about 0.3 is obtained when the radius of the defect R = 0.1*a*. This value decreases to 0.2 when R is increased to 0.4*a*. From these investigations, one can conclude that the optimum value of the radius is $R = 0.1a$, therefore the different analytes will be introduced in the defect with the optimized radius.

The goal of the second part is demonstrate the structure sensitivity to water. In this axes we concentrate our work to watch the response of the light comportment when we change the analyte binding in the defect cylinder. This is may be doing by calculate and trace the transmission curve for different analyte, the result is depicted in figure 4.

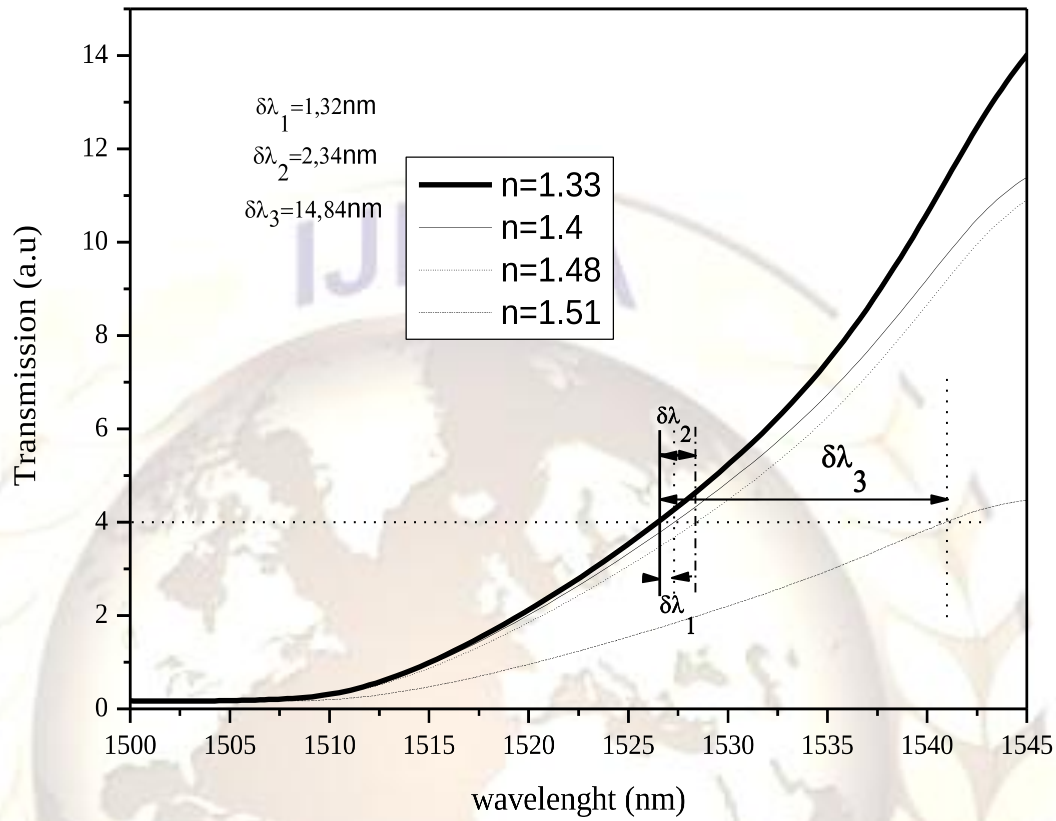

Figure 4: transmission curves versus indexes refraction.

The transmission is calculated as a function of the wavelength. It is shown in figure 4 that the increasing of the refractive index value causes a variation in the transmission curves. This is due to the absorption/adsorption phenomena of the light by the molecular binding in the defect cylinder. The different interaction of defect analytes introducing with light appears in field intensity which have the greatest value when n=1.33, then it decreases when we introduce the others anlytes and it shifts to the high wavelength. The sensitivity of this structure is determined for the value 4 of the transmission, however we consider n=1.33 as a reference and we respectively manipulate with the three others anlytes (n=1.4; n=1.48 and n=1.51). We obtain the following shift wavelength $\delta\lambda_1$ = 1.32 nm, $\delta\lambda_2$ = 2.34 nm and $\delta\lambda_3$ = 14.84 nm. It is clear that increasing of the shift is proportional to the refractive index difference $\Delta n = n - n_{ref}$ where n define the refractive index of one of the three analyte used.

Conclusion

A novel chemical sensor has been proposed in this paper. The sensor is based on the exploitation of the superprism effect of a 2D photonic crystal. It is has been shown that the direction of incidence of light is an important factor to generate the strong dispersion of light. The change in the refractive index of the region surrounding the nanocavity results in a shift in the wavelength. It is shown that in case of oil1, the mode is strongly confined in the nanocavity, yielding to a sharpness of the resonance and a small shift in wavelength.

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