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# Mid-infrared Refractive Index Sensor Based on a 2D Photonic Crystal Coupled Cavity-two Waveguides

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**ABSTRACT**

In this paper, a viable design of mid-infrared refractive index sensor based on photonic crystal coupled cavity-two waveguides is proposed. An increasing number of works are dedicated to investigate the behavior of refractive index sensor based on photonic crystal in the mid-infrared range. We define the sensitivity of our sensor by detecting the shift in the resonance wavelength as a function of the refractive index's variations in the region around the cavity. The purpose of this study is to design a highly sensitive mid-infrared photonic crystal sensor. Consequently, an improved sensitivity of 650 nm/RIU (refractive index units) with a detection limit of 0.001 RIU has been obtained. The sensitivity can be improved from 394 nm/RIU to 758 nm/RIU with a detection limit of 0.01 RIU in the wavelength range of 2,97 µm to 3,71 µm by increasing the number of the infiltrated holes. The same design has been used as a liquid sensor and a sensitivity of 550 nm/RIU has been achieved with a detection limit of 0.001 RIU for RI=1.33 and RI=1.331. The properties of the sensor are simulated using the finite-difference time-domain (FDTD) method from the RSoft software package.

## 1. INTRODUCTION

Photonics crystals (PhC) as known today have been defined for the first time by E.Yablonovitch [1] and S. John [2], they have inspired inclusive interest for as far back as decades because of the existence of photonic bandgap (PBG) and the ability to control the propagation of the electromagnetic (EM) waves inside it; which is extremely required for designing PC-based optical devices [3]. PBG in PhC prohibits the propagation of light in the material. Frequencies falling in the bandgap are not permitted to propagate because of the inexistence of the optical modes. Yet, introducing certain defects such as point defects as cavities or line defects as waveguides, and their coupled elements in the structure can adjust the dispersion diagram hence permit to particular modes to propagate in the bandgap [4].

The interaction between a cavity resonator and a waveguide system has been previously demonstrated in [5-8], tremendous research works are done in biosensing [9-14], chemical and gas sensing [15-17], temperature sensing [18], stress sensing [19]. It was also shown that a PhC cavity and waveguides sensor might be used in refractive index (RI) sensing where the detection of an analyte may be done by a local RI shift [20-21].

In the few past years, photonic crystal structure in the mid-infrared (mid-IR) spectral range has gained worldwide attention of scientific community due to the transparency window of silicon for the mid-IR wavelength range (between 1.1 and 8.5 µm) as proposed by Soref [22]. On the other hand, the mid-IR range is highly interesting for chemical and gas sensing, since photon energies here match well with molecular vibrations [23, 24]. However, mid-IR sensors based on photonic crystal are comparatively unexplored when compared to the near-IR and visible sensors, it is therefore of great necessity to provide a mid-IR RI sensor based on PhC coupled cavity-waveguide with high sensitivity.

Herein, a novel mid-IR refractive index sensor based on PhC coupled cavity-two waveguides is designed and described. Sensing technique is established on the change of the refractive index of holes in the range of n=1.01 to n=1.04, and as a result, the detection of the shifted resonance wavelength $\lambda_0$. The comportment of the designed sensor is analyzed using the finite-difference time-domain (FDTD) method from the RSoft software package.

## 2. SENSOR DESIGN

To investigate mid-IR refractive index sensing, a sketch of a two-dimensional RI sensor based on PhC coupled cavity-two waveguides composed by using a hexagonal lattice structure has been proposed in figure 1. In the proposed structure, the size of photonic crystal is (39 × 21), the lattice constant (a) equal to 1 µm, the effective index profile of the silicon slab is $n_{si}$=2.654, the ration of the radii of air holes (r) and lattice constant is 0.3, where the radius of the defected holes is $r_1$=0,45a. The studied sensor is made up of two waveguides couplers and a cavity; the basic two waveguides are a Γ-K directional waveguides formed by removing one row of air holes.

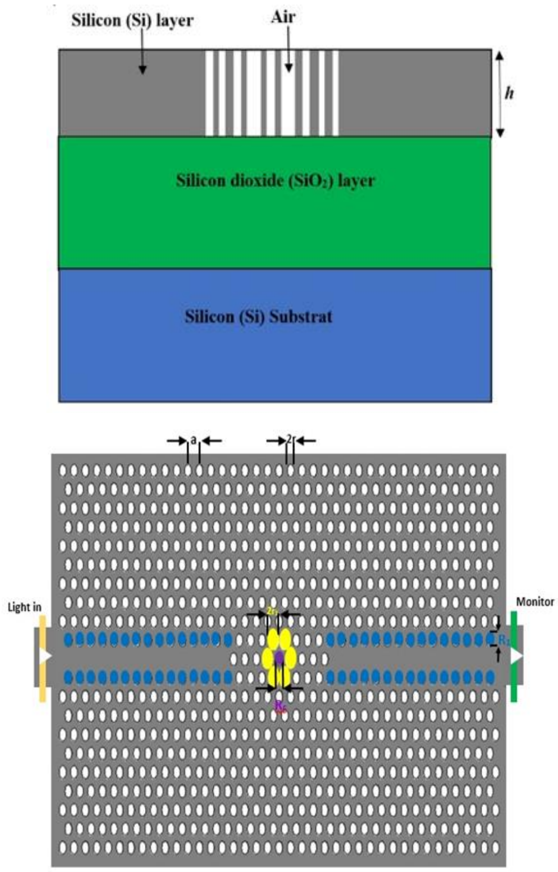



**Figure 1.** Designed photonic crystal coupled cavity-two waveguides sensor

## 3. NUMERICAL RESULTS AND DISCUSSION

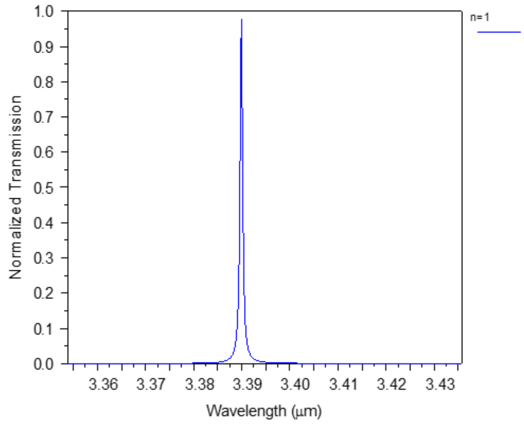
As it was proved by Edwards et al. [25], by using the effective index method the 2D analysis would be close similar to the 3D analysis. The effective index of the proposed structure has been taken equal to 2,654 for a silicon guiding layer with a central wavelength of 3600 nm.

The designed photonic crystal structure having band gap in the wavelength range of 2,9736 µm to 3,7145 µm for TE-polarized wave; which is calculated by 2D Plane Wave Expansion (PWE) method. The photonic band structure principally depends on the radius of holes and the lattice constant of the structure.

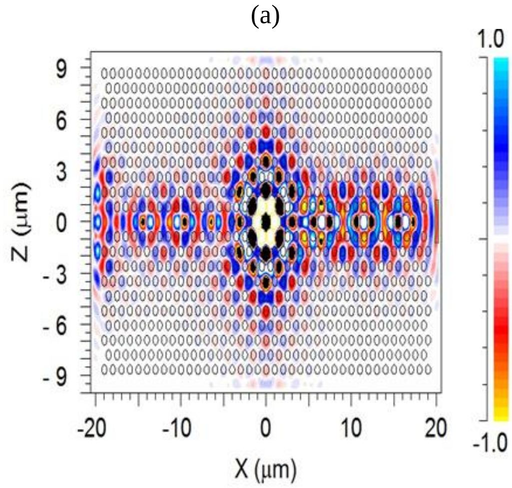
Several approaches are used to create a cavity resonance such as increasing or reducing the radius of particular holes [26]. In the first design A, a microcavity was created within the structure by changing the radius of the holes surrounding the central hole (showing in yellow color in figure 1) to confine light within the cavity, and by separating the microcavity by three holes of the both sides of the waveguides.

In this sensor, we used the input of the waveguide to apply a Gaussian pulse around 3,6 µm to excite the resonant modes of the cavity. In addition, a power monitor was positioned at the end of the waveguide to monitor the trapped mode in order to determine the sensitivity of the proposed sensor [27].

Based on the designed device, the transmittance spectra corresponding the refractive index n=1 is represented in figure 2.a. The result presents two different resonant peak wavelengths at 3,39 µm and 3,6 µm, A resonant wavelength of 3,39 µm is selected since it has the highest sensitivity. Figure 2.b illustrate the y-component electric field (Ey) distribution of PC cavity in x–y plane. As seen, the TE-like polarized light is strongly confined in the x-direction.




(a)




(b)

**Figure 2.** (a) Transmittance of the designed device for n=1. (b) The y-component electric field (Ey) distribution of PC cavity in x–y plane

The result of the FDTD simulation with a grid size of 0.05 of the proposed structure is shown in figure 3. The normalized transmission spectrum of the resonant mode peak wavelengths for different refractive indices shows a shift in the resonance wavelength of 6.5 nm for Δn =0.001 and a sensitivity of 650 (nm/RIU) is observed (Table 1).

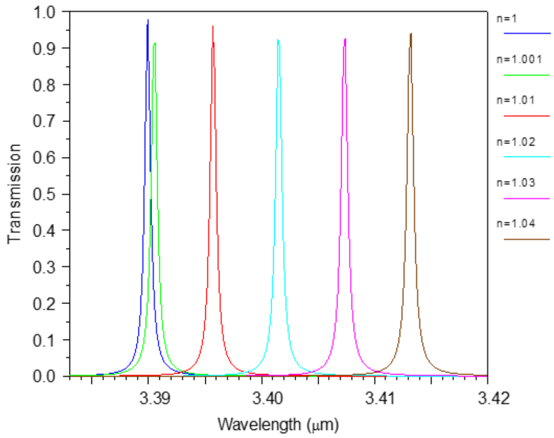



**Figure 3.** Normalized transmission spectrum of the proposed design as a function of wavelength for different refractive indices

**Table 1.** The sensitivity of the sensor for different RI

| Refractive Index | Sensitivity (nm/RIU) | Δn (RIU) |
|---|---|---|
| 1 | - | n0 |
| 1.001 | 650 | 0.001 |
| 1.01 | 575 | 0.01 |
| 1.02 | 576.5 | 0.02 |
| 1.03 | 583 | 0.03 |
| 1.04 | 582.5 | 0.04 |
| 1.33 | 550 | 0.001 |

A microcavity is created in the structure by increasing the central hole's radius ($R_C$) (shown in magenta color in figure.1) for $R_C$ equal to 0.27, 0.28, and 0.29 µm.

The simulation results reveal that sensitivities of 577, 592 and 592 (nm/RIU) are achieved at $R_C$ equal to 0.27, 0.28 µm and 0.29 µm, respectively (figure 4). By increasing the radius of the central hole, an acceptor defect state pulled from the dielectric band into the band-gap, is excited [28].

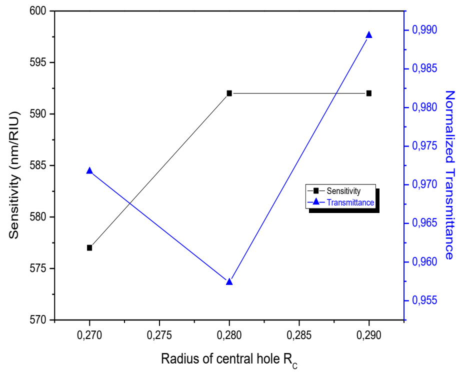



**Figure 4.** Relationships of the sensitivity and the normalized transmittance of our sensor to radius of central hole $R_C$

In order to achieve a better sensitivity, the mentioned above design A was changed to the design B. In design B, the radii of the holes positioned in the vicinity of the two-waveguides (shown in blue color in figure 1) can therefore be enlarged to benefit from an improved light-matter interaction level [18]. As seen in figure 5, the simulation results reveal that a sensitivity of 623 (nm/RIU) is achieved at $R_1$ equal to 0.35 µm.

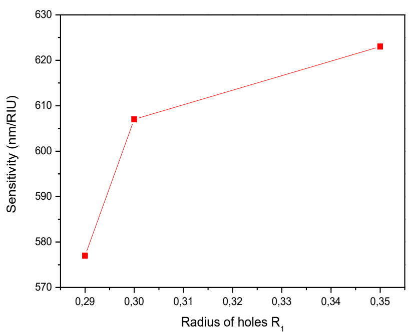
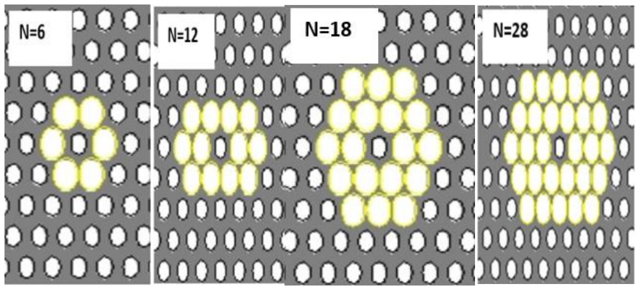
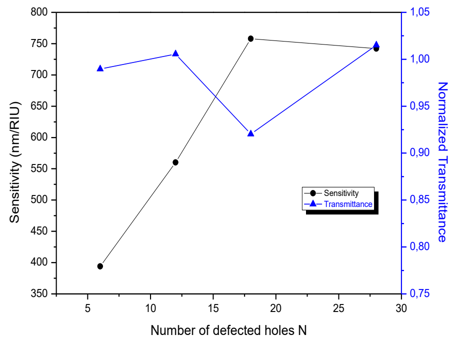



**Figure 5.** Variation of sensitivity as a function of the different radiuses of the first row of holes R1

As mentioned, previous, our main goal is to design a new mid-IR refractive index sensor based on PhC coupled cavity-two waveguides with the highest possible sensitivity. In this section, as seen in figure 6.a, the sensing properties of the studied sensor were investigated by changing the number of functionalized holes N (6, 12, 18 and 28) when $r_1$=0,45a.




(a)




(b)

**Figure 6.** (a) Schematic diagrams of defected holes when N=6, 12, 18 and 28 (holes in yellow color refers to the sensing region filled with analyte), (b) Relationships of the sensitivity and the normalized transmittance of our improved sensor to number of defected holes N

**Table 2.** Comparison of the proposed sensor with several similar PhC designs

| Sensing structure | Sensitivity (nm/RIU) | detection limit (RIU) | Year |
|---|---|---|---|
| [30] RI biosensor formed by two waveguides and one microcavity. | 330 | 0.001 | 2008 |
| [31] RI sensor formed by Two types of defect nanocavities L3 and H1−r embedded between two W1 photonic crystal waveguides | 70-200 | 0.018 | 2008 |
| [17] RI sensor formed by PhC microcavity | 500 | 0.05 | 2016 |
| [32] PhCW based RI sensor | 260 | 0.001 | 2013 |
| [13] RI biosensor formed by two waveguides and one microcavity | 425 | 0.001 | 2015 |
| The proposed sensor | 650 | 0.001 | - |

As it can be expected, a sensitivity of 758 nm/RIU has been achieved, the sensitivity increases rapidly to a greater number of functionalized holes (figure 6.b). this can be explained by the reduced effective refractive index between the infiltrated holes and the semiconductor membrane [14, 29]. Consequently, a local infiltration guarantees a better sensitivity.

A brief comparison between our results and some of the results already published in scientific research papers is illustrated in Table 2.

These results display that the proposed sensor possesses a better sensing property and well apply to RI sensing in mid-IR.

## 4. CONCLUSIONS

To conclude, we have effectively designed and simulated in this paper a novel mid-IR 2D photonic crystal coupled cavity-two waveguides platform for RI-based sensing application nearby $\lambda_0$=3.6 μm and the extensive simulation results show that the proposed sensor is highly sensitive to a small change in refractive index, a high sensitivity of 758 nm/RIU in the RI range of 1.01-1.04 was accomplished. Due to the improvement in the limit of detection with high sensitivity, the high transmittance and the small size, our improved sensor is well matched for applications in mid-IR sensing and it would be a great potential platform in other on-chip photonic circuits. Improving the achieved sensitivity by using slotted waveguide coupled cavity sensor will be subject of future studies.

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