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RESEARCH ARTICLE - PHYSICS

Improved Sensitivity of the Refractive Index Sensor Based on a Photonic Crystal Waveguide

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Abstract In this paper, we used the finite-difference time domain method to analyze the wavelength spectrum as detected at the end of two-dimensional photonic crystal waveguide that contains circle- and ring-shaped silicon rods distributed in an air wafer. A shift of 0.0758 μm in the wavelength position of the upper band edge, corresponding to a sensitivity of 758 nm/RIU, was observed. A local defect has been introduced, which produces a very high shift in the cutoff wavelength corresponding to a higher sensitivity of 1490 nm/RIU.

Keywords Photonic crystals · Waveguide · Sensor · Sensitivity

1 Introduction

Optofluidics, the marriage of nano-photonics and microfluidics, refers to a class of optical systems that integrate optical and fluidic devices. The compact optofluidic devices have been widely investigated for a number of applications. One of the most exciting optofluidic applications is to realize sensors, which can be used to detect, manipulate and sort cells, virus and biomolecules in fluidics [1–5].

The interest in the optical sensor research is driven by the increasing need for specific sensors to enable fast routine measurements in many fields of analysis in health care, defense, security, automotive, aerospace, environment and food quality control [6–10].

Much attention has been drawn to the photonic crystal sensors because of their high sensitivity and biocompatibility traits. The changes inside and around the photonic crystal provide the method of sensing by measuring the power output, wavelength and band gap shifts [11].

The PCs in which the light is guided along defects, such as missing rows of holes or rods, can be designed to obtain a very high and spatially selective sensitivity to changes in RI superior to bulk devices [12].

The performance of this device is based on the guided mode light interaction with the liquid matter at the waveguide surface. The sensor sensitivity is an important parameter to be considered. The sensitivity can be defined as the magnitude of sensor signal with respect to the magnitude of binding event or refractive index change occurring at the sensor surface. It is mainly determined by the light–matter interactions [13].

The researchers will struggle to improve the sensitivity of their sensors because of the positive meaning of the word; high sensitivity will be regarded as desirable regardless of the exact meaning of the concept. Therefore, the meaning of the word should be such that sensors with higher sensitivity actually do give better sensor performance [14].

The development of sensor designs that enhance sensitivity is especially important because it allows detection of lower concentrations of analytes and nondestructive analysis. Many optical sensors operate by measuring the change in refractive index at the surface of the sensor with the method of, for example, surface plasmon resonance, colorimetric resonances and interferometry in porous silicon. However, these methods require large-area beams and relatively large sensing area. Recently, there have been advances in the development of fully integrated microfluidic and photonic platforms [12].

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Table 1 Designs parameters

Parameters	Ring-shaped photonic crystal waveguide	Circle-shaped photonic crystal waveguide
Lattice constant (a)	0.42	0.42
Refractive index of rodes (Si)	3.47	3.74
Refractive index of wafer (Air)	1	1
Distribution	Hexagonal	Hexagonal
Radius	Inner radius $(R') = 0.375 * a$ Outer radius $(r) = 0.6 * R'$	$R = 0.375 * a$

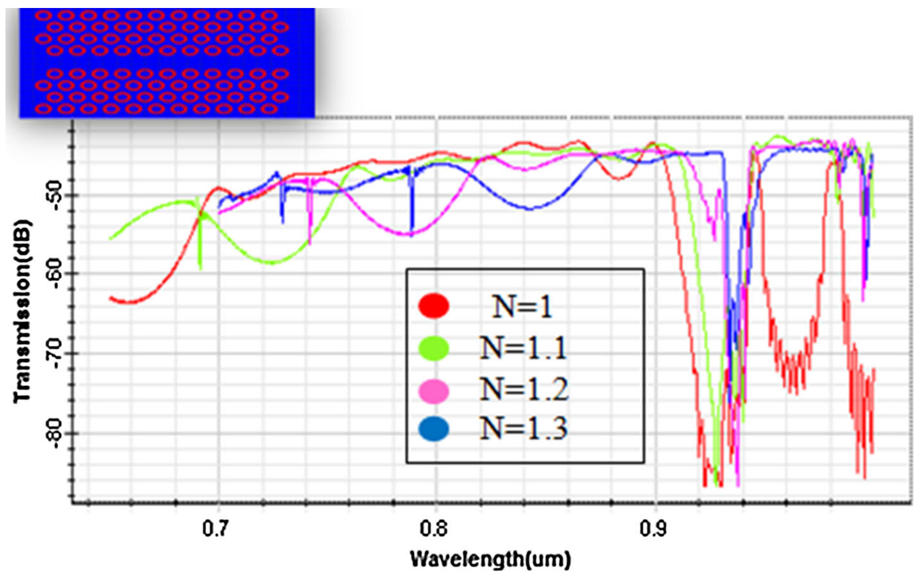

Fig. 1 The output transmission spectrum for ring-shaped rods PCW for different refractive index

For instance, the RI sensing techniques detect an analyte by a local RI shift [6]. This can be an advantage in biosensing as it typically involves an aqueous cover medium containing biological molecules and detection of specific biological molecules is primarily done by immobilizing molecules at the surface (creating an adlayer of biological molecules), resulting in an RI change in the close vicinity of the Si surface [12].

Recently, the proposed sensor of Derbali et al. [15] shows a sensitivity of $s = 7.36$ nm/RIU, where Pu has presented an integrated refractive index sensor based on a ring-shaped photonic crystal waveguide. He measured the shift in cutoff wavelength for different ambient refractive indices, and he observed a sensitivity of $\Delta\lambda\Delta n = 110$ nm/RIU [16].

In another study applied with an ultra-compact RI sensor based on PC waveguide with a triangle lattice of air holes, a 80 nm cutoff shift was observed corresponding to a sensitivity of 240 nm/RIU [16].

Moreover, Bougriou et al. have reported an optofluidic sensor design based on 2D photonic crystal slab with a triangular lattice pattern of ring-shaped holes. The achieved sensitivity is of 636 nm per refractive index unit (RIU) [12]. In a very recent work where Benelarbi et al. have proposed a photonic crystal waveguide with a ring-shaped structure of holes, the proposed structure shows a 200 nm shift in the cutoff wavelength, corresponding to a sensitivity of 606 nm/RIU [2].

In this work, a sensitivity of 758 nm/RIU has been reached with a design combining a circle- and a ring-shaped photonic crystal waveguide. The results have been obtaining with OptiFDTD software where the finite deference time domain has been applied. Introducing a defect in the same design to create a cavity increases the sensitivity to 1490 nm/RIU.

2 Structure and Model

For further comparison, we went to study the sensitivity of photonic crystal waveguide composed by silicon rods with hexagonal distribution on air wafer in two cases: circle-shaped rods and ring- shaped rods. The parameters of these two designs are summarized in Table 1.

The light enters from the left of the waveguide. A photodetector at the end of the waveguide detects the light. When the liquid analyte is filed in the dielectric slab, a change in refractive index of the wafer takes place, so that the nature of the electromagnetic waves is altered.

The finite-difference time domain method using OptiFDTD simulator is used to obtain the transmission spectrum of both circle- and ring- shaped rods photonic crystal waveguide

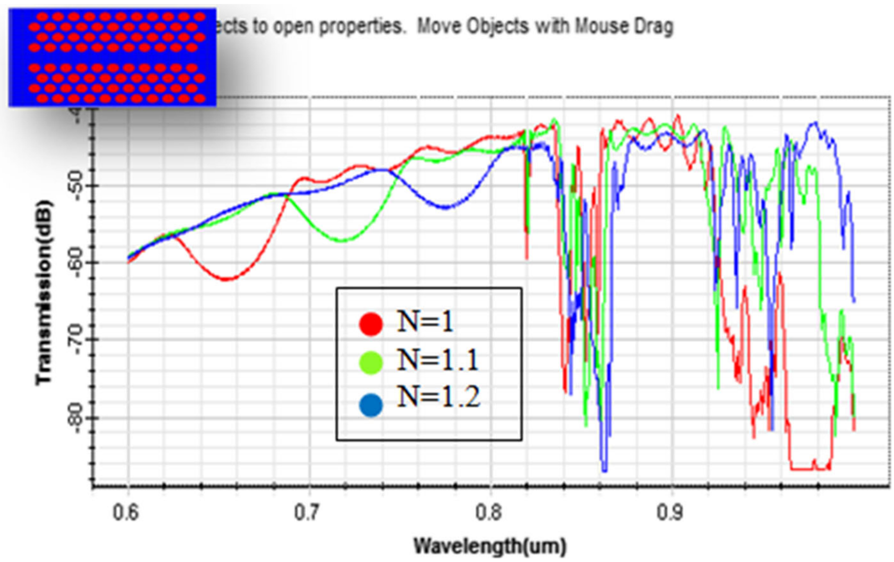

Fig. 2 The output transmission spectrum of circle-shaped rods of PCW for different refractive index

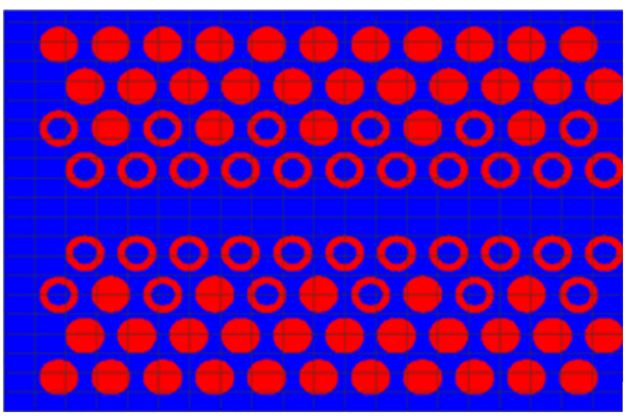

Fig. 3 Structure of the proposed model

where the refractive index is varied from 1 to 1.2. Figures 1 and 2 represent the response spectrum for ring-shaped rods and circle-shaped rods, respectively. The achieved sensitivity is of about 588 and 578 nm/RIU, respectively.

In order to improve the sensitivity, the mixing circle- and ring- shaped rods in the same design is realized. So, let us turn now to our proposed model that is composed of both circle- and ring-shaped rods. But any radius we choose to make this model up to the high sensitivity?

Firstly, the lattice constant was fixed at 0.42 µm, the relation between the inner and outer radius of annular rods at $R'/r = 0.6$, and the radius of circle rods at $0.3 * a = 0.126$ µm. The reason of choosing this parameter is demonstrated in [17].

We have a single variable that is the outer radius of ring-shaped rods, which it is assumed to be varied in this manner ($R' = 1.3 * R$, $R' = 1.2 * R$, $R' = 1.1 * R \ldots$). We must calculate the sensitivity at each value and take in consideration to avoid radius when rods overlapping and radius when PBG is closed. The proposed design is represented in Fig. 3.

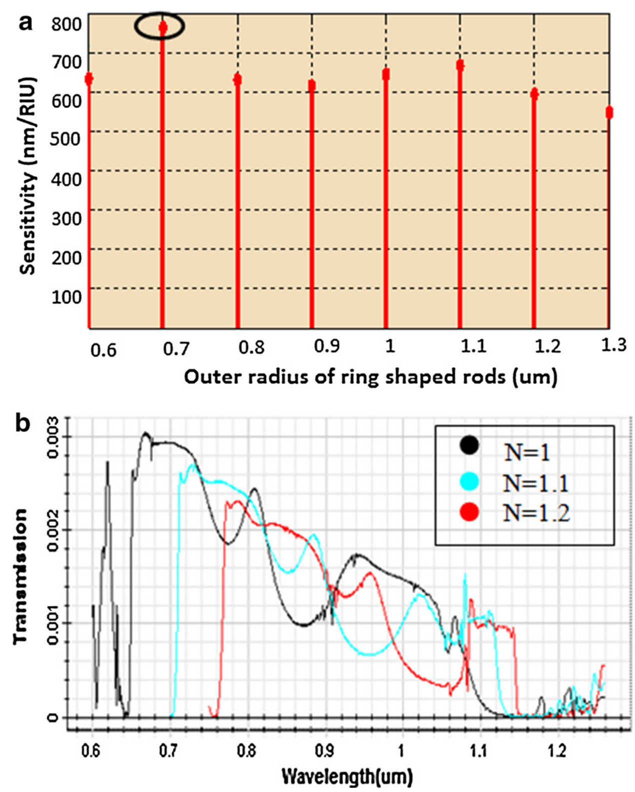

Fig. 4 **a** Sensitivity value for different outer radius of ring-shaped rods. **b** The transmission spectrum when the outer radius of ring-shaped rod becomes 0.0882 µm

3 Results and Discussions

We used MATLAB to obtain the diagram that represents the dependence of the sensitivity with the variation of the outer radius of ring-shaped rods, which is illustrated in Fig. 4a.

We observed that when the outer radius becomes $0.7 * 0.126 = 0.0882$ µm we reach the higher sensitivity, which

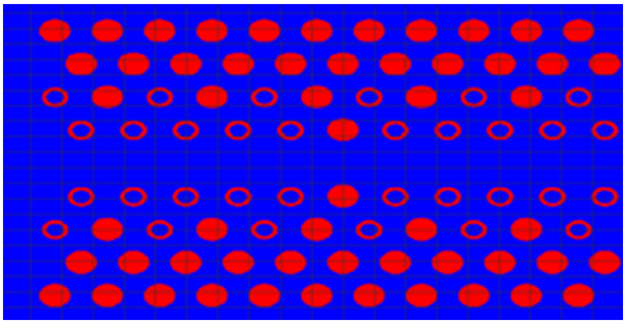

Fig. 5 Structure of the second proposed design

is 765 nm/RIU. Figure 4b represents the transmission spectrum when the outer radius of ring-shaped rod becomes 0.0882 µm.

In this area, it is argued that the sensitivity of the sensor is improved by using an optofluidic waveguide, while the sensitivity of the improved optofluidic sensor is higher than most reported results for other PCW sensors, for example Bougriou et al. [12] where she has reported an optofluidic sensor design based on 2D photonic crystal slab with a triangular lattice pattern of ring-shaped holes. The achieved sensitivity is of 636 nm per refractive index unit (RIU), Benelarbi et al. [2] where he found a sensitivity of about 606 nm/RIU and other works as Dutta and Pal [18] with 260 nm/RIU and Benmerkhi et al. [10] with 322 nm/RIU.

We can say that mixing the circle- and the ring-shaped rods in the same design the sensitivity will be higher than when using each pure one separately.

4 Proposed Model2

By creating a defect in the previous design, the periodicity is broken and the light can be localized at the defect region, which is replacing two rings shaped rods by two circle one with the same radius of outer radius of ring-shaped rods, which is 0.126 µm [19].The new design is represented in Fig. 5.

We infiltrated our model by liquids where $n = 1$ and $n = 1.1$ and we have noticed at each infiltration the transmission spectrum at the end of the medium; Fig. 6 represents the transmission spectrum in the two cases.

5 Results and Discussions

A shift in the cutoff wavelength of about 924 nm has been observed corresponding to the sensitivity of 924 nm/RIU. This sensitivity is higher than the sensitivity obtained in the previous model and even higher than the most reported results for other PCW cavity sensors as Kwon et al. where he found 512 nm/RIU in ref [1]. The sensitivity is derived from the long photon lifetime inside the cavity [10]. It provides high field localization, which increases the interaction between the light and the matter, that's why the sensitivity increases also.

Can we increase the value of sensitivity more and more? Let us vary the radius of the two defect rods in this manner (0.126∗1.3 0.126∗1.2 0.126∗1.1 0.126 0.126∗0.9. . ..). And calculate the sensitivity at each variation without forgot to take into consideration to ovoid radius when rods overlapping and radius when PBG closed or radius when sensitivity is too low.

With MATLAB, we obtained the diagram, which represents the dependence of the sensitivity with the variation of the radius of defect rods. In Fig. 7a, it can be seen that when the outer radius becomes $0.7 * 0.126 = 0.0882$ µm, the higher sensitivity is reached. A shift in cutoff wavelength of about 1490 nm is observed in Fig. 7b, corresponding to the sensitivity of 1490 nm/RIU.

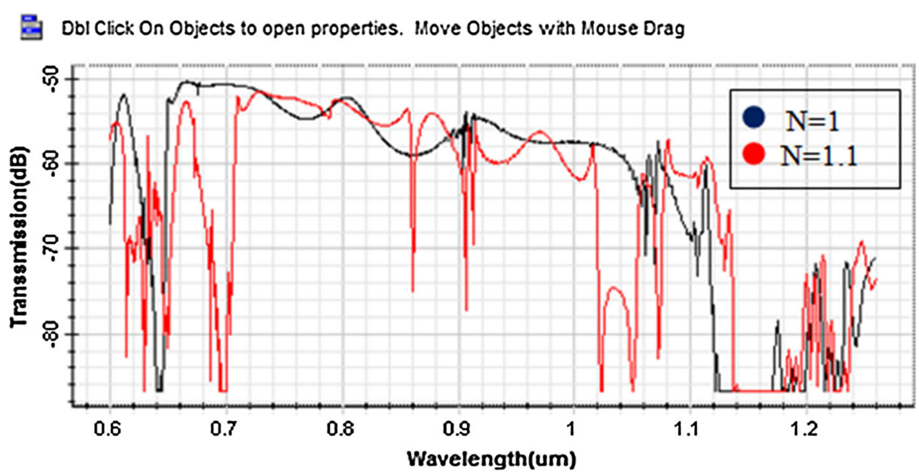

Fig. 6 Transmission spectrum for different refractive index

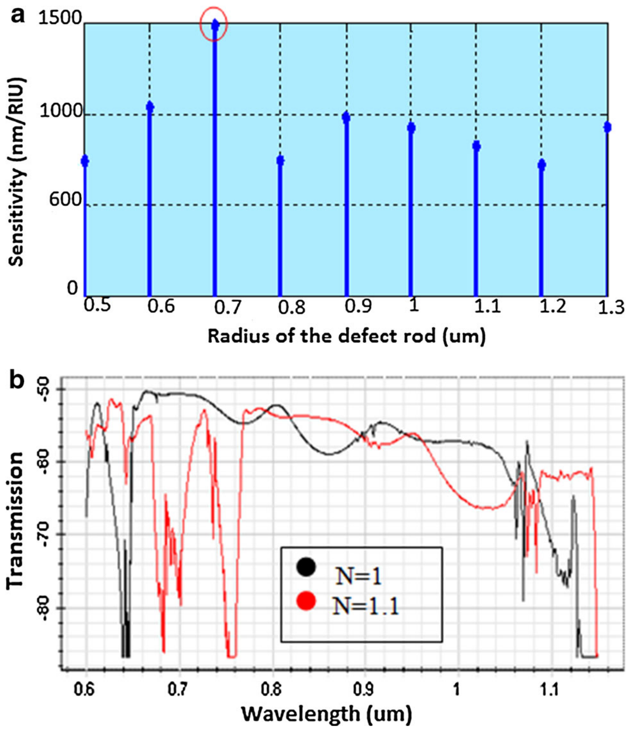

Fig. 7 **a** Sensitivity value for different radius of the defect rods. **b** Transmission spectrum for different refractive index

6 Conclusion

We have presented two structure designs: a Si photonic crystal waveguide and Si photonic crystal waveguide cavity for refractive index sensing, where we studied the effect of the size and the shape of silicon rods on the sensitivity. By FDTD simulation, we showed that the sensitivity of 765 and 1490 nm/RIU, respectively, is achieved knowing that the development of sensor designs that enhance sensitivity is especially important because it allows detection of lower concentrations of analytes and the nondestructive analysis and detection of small molecules [12].

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