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Design and simulation of high sensitive photonic crystal waveguide sensor

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ABSTRACT

Photonic crystal waveguide, formed by local line defect in a perfect periodic structure, is generally used for sensing. In this paper, we have proposed a very high sensitive photonic crystal waveguide (PCW) based sensor in silicon-on-insulator (SOI) material after optimisation of etch-depth of the circular holes up to a finite depth underneath the buried oxide layer. Properties of the sensor are analysed by 3-D finite difference time domain (FDTD) method. Output transmission and sensitivity of the proposed sensor is analysed by varying the defect radius and etch depth. Optimised structure shows an average value of sensitivity as 386 nm/RIU over a range of refractive index of 1.0 and 1.5.

1. Introduction

Photonic crystal structures, which are regarded as an optical analogue of semiconductors, has attracted considerable interest among researchers due to their ability of controlling and manipulating the flow of light or photon [1]. During last decade, a lot of attention is focused on to photonic crystals for various applications such as coupler [2], resonator [3], waveguide [4], fibre [5], filters [6] etc. Photonic crystal fibres (PCFs) have been demonstrated for sensing, antibodies [7] and DNA [8] whereas photonic crystal waveguides (PCWs) have been utilised for refractive index measurements [9], and other various sensing applications. A simple structure of photonic crystal is shown in Fig. 1(a), which is designed by placing circular array of holes on top of silicon layer, in a triangular lattice arrangement in an SOI substrate. Band gap of this photonic structure depends on the filling factor and the lattice constant of the structure. A photonic crystal waveguide (PCW) structure thereafter can be realised by creating a line defect on this structure simply by removing a single row of holes, as shown in Fig. 1(b), where light is guided through this waveguide effectively.

Various types of compact photonic devices and components like coupled cavity, filter, resonator, directional coupler, splitter, etc., have been realised by utilising this structure. PCW based sensors have also been widely studied in past few years due to their high sensing abilities. Recently, a PCW sensor having sensitivity of 260 nm/RIU has been reported by Dutta and Pal [10], using photonic crystal waveguide platform for refractive index based bio-sensing. Bagci and Akaoglu [11] have reported sensitivity of 282.4 nm/RIU using selective infiltration in photonic crystal waveguide. Photonic crystal waveguide based liquid sensor of sensitivity 200 nm/RIU and 174.8 nm/RIU have also been demonstrated [12,13]. The above-mentioned sensitivity values are relatively low and therefore needs improvement in order to achieve its better performance with enhanced sensitivity and output signal strength.

In this paper, we have proposed a simple PCW structure for sensor application in silicon-on-insulator (SOI) material with significantly high sensitivity by optimising the etch-depth of the circular holes up to a finite depth underneath the buried oxide layer. The structure is analysed by 3D FDTD method. Sensitivity of the sensor is estimated by infiltrating liquids of different refractive index and calculating corresponding shift in cut off wavelength. In order to achieve the best possible sensitivity, the structure is optimised by varying the defect hole diameter and etch depth.

2. Designed structure and working principle

Photonic crystal is considered an optical analogue to semiconductor, which shows band gap for certain range of frequency. This band gap can be tailored by changing various parameters such as lattice constant, hole radius, and slab thickness etc. Due to its unique properties photonic crystal is used in various applications as sensors, filters and couplers etc. A simple structure of photonic

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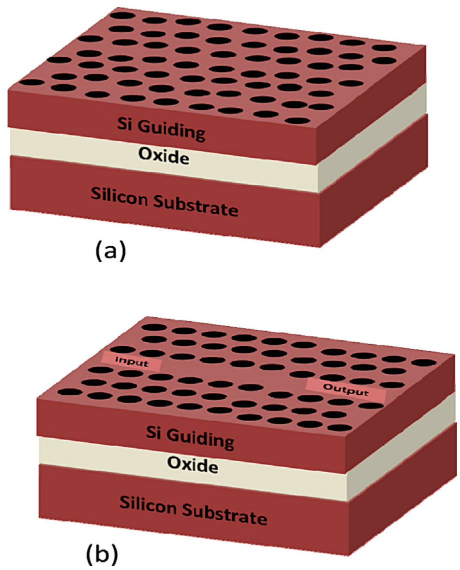

Fig. 1. (a) Schematic of a simple structure of photonic crystal made of triangular array of holes in silicon (b) Photonic crystal waveguide made of removing a single row of holes.

crystal is shown in Fig. 1(a), which is designed by placing circular array of holes on top of silicon layer, in a triangular lattice arrangement over a SOI substrate. Other optical devices can also be made by utilising this structure, such as a PCW is made by removing a single row of holes as shown in Fig. 1(b) where light is guided through this waveguide effectively.

Sensing principle is based on measurement of cut-off wavelength shift by changing analytes refractive index because change in analytes refractive index will lead to change in effective index of the slab [14]. In order to sense different gases, this change in cut off wavelength is measured. Because sensitivity is normally given by

$$S = \frac{\Delta\lambda}{\Delta n} = F\frac{\lambda}{n}$$

where $\Delta\lambda$ is change in cut-off wavelength, Δn is change in refractive index of gas, n is slabs refractive index, λ is optical wavelength transmitted inside the photonic crystal and F is filling factor.

3. Simulation results and analysis

Initially a photonic crystal waveguide structure (shown in Fig. 2) is designed by etching circular array of holes in triangular lattice arrangement over SOI substrate. The structure is designed to have TE band gap centred on ~1.55 μm (1.38–1.74 μm). But an additional dip is obtained within the band gap range which is due to anti-crossing of different modes within formed waveguide structure [15]. To design this structure lattice constant is taken to be

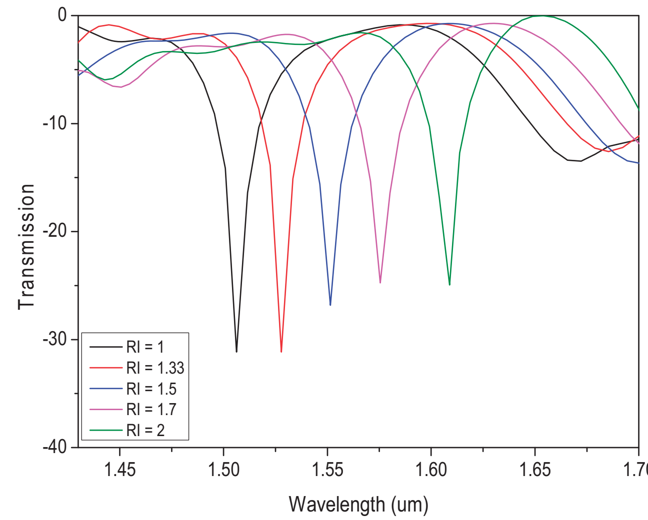

Fig. 3. Effect of changing refractive index of analytes on minimum wavelength of dip.

0.42 μm with filling factor of 0.3 and thickness of slab is taken to be 0.260 μm. To measure sensitivity different analytes are infiltrated and corresponding shift in minimum wavelength of dip is analysed. Fig. 3 shows output response of designed sensor structure. By analysing the minimum wavelength shift in dip in accordance with change in refractive index a sensitivity of 100 nm/RIU is obtained.

Although designed structure provides very simple mean to analyse sensitivity (by measuring minimum wavelength) it provides very low value of sensitivity. To enhance the sensitivity further a new photonic crystal waveguide based structure is designed using different parameters. For that, again circular air holes are etched in triangular lattice arrangement over a SOI substrate and response of structure is analysed using crystal wave 3D FDTD software. A waveguide is obtained by removing a single row of holes in Γ-K direction as shown in Fig. 4, which shows a TE band gap around 0.2855–0.408 a/λ centred at 1.55 μm. The waveguide comprises silicon (n = 3.45) as guiding layer, silicon dioxide (n = 1.45) as lower cladding and air (n = 1) as upper cladding layer. The lattice constant is taken as 0.5 μm with a fill factor of 0.4 and thickness of the slab (h) is taken to be 0.260 μm. A broadband light source is applied at the input of the waveguide such that light effectively guides through the waveguide and is detected at the output by output sensor.

To calculate the sensitivity of this unperturbed PCW structure, holes are infiltered with different analytes and corresponding cut off wavelength shift is measured. The cut off wavelength shifts by 11 nm as refractive index of the analytes changes from 1 to 1.2 giving a sensitivity ($\Delta\lambda_{cutoff}/\Delta n$) of 55 nm/RIU. Since sensitivity mainly depends on the filling factor and effective refractive index near the waveguide, sensitivity can be further enhanced by varying

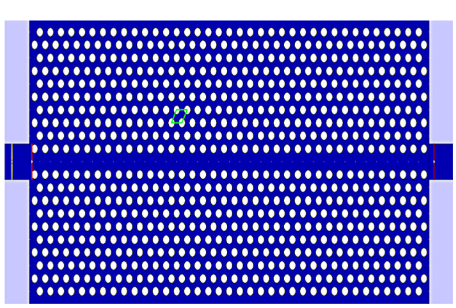

Fig. 2. Simple photonic crystal waveguide structure made in SOI wafer, lattice constant = 420 nm, holes diameter = 250 nm.

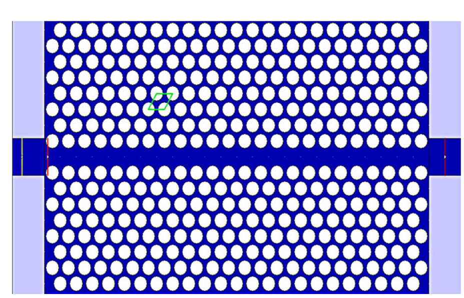

Fig. 4. Photonic crystal waveguide structure made in SOI wafer, lattice constant = 500 nm, holes diameter = 400 nm.