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Photonic crystal microcavity as a highly sensitive platform for RI detection

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ABSTRACT

In this paper, we propose a new design principle of two-dimensional photonic crystal refractive index sensors with high transmission and sensitivity simultaneously. The proposed sensor is made of two waveguide couplers and one microcavity which is obtained by varying the radius of one air hole in the center of PC structure. The microcavity is separated from the input and output waveguides by many holes of the PC. It is shown that by injecting an analyte such as gas or a liquid into a sensing hole, and thus changing its refractive index, a shift in the resonant wavelength may occur. The transmission spectra, quality factor and sensitivity of the sensor have been analyzed numerically by the finite difference time domain (FDTD) method. The sensitivity value of the sensor has been found to be 668 nm/(RIU with minimum detection limit of 0.002 RIU), which proves the ability of the structure to produce biosensor PhC.

1. Introduction

Photonic crystals PCs are materials that possess a periodic refractive index variance and have become a subject of high interest within the materials science community [1,2]. Due to the periodicity in dielectric materials, PC materials have a photonic band gap (PBG), forbidding certain wavelengths of light located in the PBG from transmission through the material [3]. According to variations in the refractive index and period in space, PCs can be classified as one-dimensional (1D), two-dimensional (2D) and three-dimensional (3D).They have been intensively used in the area of waveguides, cavities, optical fibers, photovoltaic devices and Bragg mirrors [1,2,4,5].

In recent years, various devices based on Photonic Crystal material is designed and fabricated such as Multiplexers, Filters and Sensors etc. Optical Sensors based on a Photonic principle have also a wide range of applications in the field of health care, defense, security, automotive, aerospace, environment and food quality control [6,7].

Photonic crystals with one-and two-dimensional band gaps have been studied for a variety of refractive index sensing applications. Below, we give some of the most recent and important examples. A new design based on a 2D photonic crystal slab with a triangular lattice pattern has been used for optofluidic sensing with sensitivity ($\Delta\lambda/\Delta n$) of 636 nm/RIU [8]. A 2D photonic crystal L7 cavity has been studied for refractive sensing of water and ethanol solutions [9]. Another design of biosensor based on PhC waveguides incorporated with microcavities led to a sensitivity of 425 nm/RIU with a detection limit of 0.00 1RIU [10]. In this paper, a two-dimensional (2D) PhC refractive index sensor is proposed which is based on two waveguides and a cavity with a hexagonal lattice of air holes in a silicon slab. Using the finite difference time domain (FDTD) method, the results of our analysis indicate that

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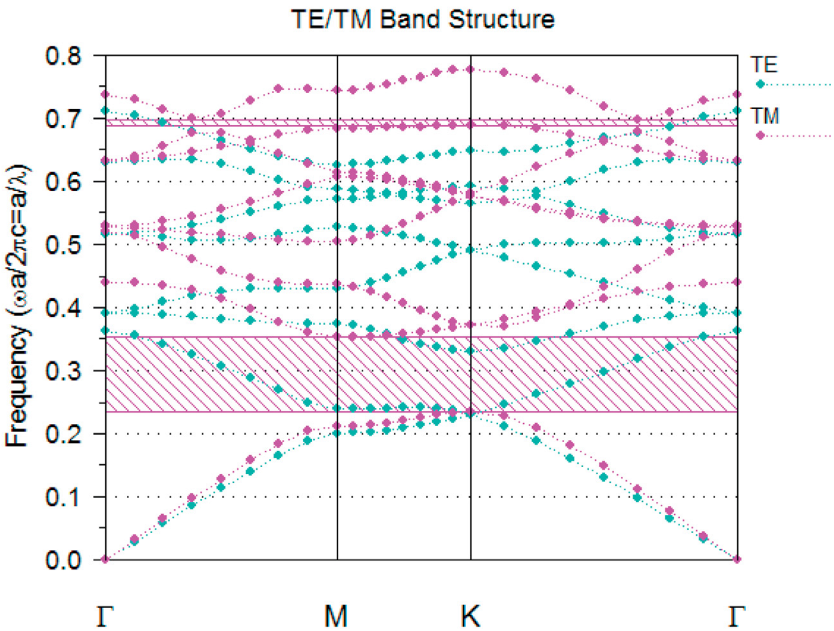

Fig. 1. Dispersion curves and band gaps for TM polarizations for the 2D lattice without defects.

the transmission spectrum shows the shift of resonance wavelength, which occurs due to the change in RI of air holes ($n = 1$ to $n = 1.020$ with a step $\Delta n = 0.004$). The Sensitivity, the most important biosensor parameter, was studied and found to be approximately equal to 668 nm/refractive index units (RIU).

2. Design of the photonic crystal structure

The 2D photonic crystal structure designed in this work consists of a triangular lattice of air holes etched in silicon slab. The PC structure has a lattice constant $a = 440$ nm and a bulk air holes radius of $0.36a$. The refractive index of Si is approximately 3.32 at a wavelength of 1.55 µm. Using the triangular PCs is practically important as they have a large transverse electric band gap and it is expected to serve as a good platform for photonic integrated circuits and ultra-compact optical sensors [11].

To find the band gap using 2D band solver package of the software (RSoft CAD), the 2D plane wave expansion (PWE) method is applied. The band diagrams show a photonic band gap (PBG) for transverse magnetic modes TM, which have no magnetic field in the direction of propagation. The PBG properties of the regular PC structure have a large band gap, between 1245 and 1876 nm, for TM polarization, the device also shows a smaller band gap for TM polarization as shown in Fig. 1.

3. Optimization of photonic crystal sensing

The structure design under consideration in this paper is based on two waveguide couplers and one cavity. The two waveguides are obtained by removing one row of air holes in the x direction, as shown in Fig. 2. They are used to couple light in and out of the PC cavity. The microcavity is obtained by varying the radius of one air hole in the center of PC structure $R_0 = 0.55a$, and it is separated from the input and output waveguides by many holes of the PC. The presence of a microcavity in the periodicity creates transmission resonance in the band gap associated with a trapped state [12,13]. Indeed, the H_1 microcavity has emerged as one of the most important platforms used to design a high transmission and high quality factor. This enhancement can be applied to improve the performance of optical sensor.

In this paper, the two-dimensional finite difference time domain (2D FDTD) method is used to calculate their transmission spectra. We set the light source at the head of the input W_1 waveguide and the monitor is located at the end of the output W_2 waveguide. In our simulations, the boundary conditions at the spatial edges of the computational domain must be carefully considered. One-spatial unit thick PML which surrounds the simulated area absorbs the fields leaving the simulated region to implement reflections.

Here the calculation field consists of a 25 × 19 matrix of air pores and the grid spacing is chosen to $a/20$, where a represents the lattice constant (that is, we set the resolution to 20), and all the simulations are implemented at the same resolution in order to obtain consistent comparison results. The time step Δt must satisfy the Courant stability condition given by the inequality:

$$\Delta t \leq \frac{1}{c}\sqrt{\Delta x^{-2} + \Delta y^{-2}} \tag{1}$$

where c is the speed of light in vacuum, and Δx and Δy are spatial steps in the x- and y-directions, respectively. The time step is chosen to be 0.01.