High Resolution and Wide Dynamic Range Pressure Sensor Based on Two-Dimensional Photonic Crystal

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Abstract: The authors present a new design of high resolution and wide dynamic range photonic crystal pressure sensor. This sensor is based on two-dimensional photonic crystal with square array of silicon rods surrounded by air. The sensor consists of a photonic crystal waveguide which is coupled to a photonic crystal nanocavity. The waveguide is configured by removing one row of Si rods and nanocavity is formed by modifying the radius of one Si rod. The sensor is designed for 1300 nm–1400 nm wavelengths. Simulation results show that resonant wavelength of nanocavity is linearly shifted to larger wavelengths by increasing the pressure. The designed sensor has a linear behavior between 0.1 GPa to 10 GPa of applied pressure and 8 nm/GPa of pressure sensitivity.

Keywords: Photonic crystal, waveguide, nanocavity, pressure sensor

1. Introduction

Since the last decade, photonic crystals (PhCs) have been attractive optional structures for controlling and manipulating the light. The PhCs are the periodic microstructures with a period in order of optical wavelength that the refractive index of material changes in one, two, or three directions. Their inherent properties, such as photonic band gap (PBG), reflectance-transmittance, high design flexibility, and possibility to be made in nanometer range, make it possible to utilize these structures in many applications such as waveguides, nano-resonators, photonic crystal fibers [1–5]. The research fields of PBG structures are explosively growing, with numerous novel applications being introduced every day [6].

Their application as sensor is a new research field that seems to be applicable in nano-electro-mechanical systems (NEMS). Xu *et al.* have proposed and analyzed a micro-displacement sensor with a large dynamic range based on a two-dimensional (2D) PhC co-directional coupler, by which the sensing range can be as large as tens of lattice constant or even more [7]. Shi *et al.* have reported an optical humidity sensor based on a nano-porous polymeric PhC that have excellent reversibility and reproducibility [8]. Other works such as refractive index sensor [9], chemical sensor, and oil sensor [10] have been also reported.

The PhC pressure sensor can be constructed by coupling a waveguide and a nanocavity. A waveguide is made by introducing line defect in 2D PhC structure, and a nanocavity is made by introducing point defect in PhC structure.

The resonant wavelength of nanocavity is a function of shape, dimension, and surface state of defects. This point is a fundamental work of pressure sensor. When pressure is applied to the nanocavity, its characteristics change, and therefore

the linear relation between pressure and resonant wavelength shift can be observed [11, 12]. In this paper, we propose a novel, linear, and high resolution pressure sensor.

2. Principle of the pressure sensor

The effect of hydrostatic pressure on the electronic and optical properties of material such as energy gap and refractive index can be considered for sensing applications. When a crystal is compressed by the pressure, the band gap is increased. The refractive index of Si is modified when optical coefficients such as photoelastic, piezoelectric, and permittivity change in different strains. In PhC structure, PBG is dependent on refractive index, lattice constant, and radius-to-lattice constant ratio $\left(\dfrac{r}{a}\right)$. By applying the pressure to the PhC, the refractive index of material, the geometrical shape of PhC, and the PBG of structure change. In the PhC waveguide coupled to the nanocavity output, the spectrum of waveguide changes with different strains. On the other hand, resonant wavelength of nanocavity is dependent on the geometrical shape of defect that makes the cavity. By applying certain pressure to the structure, the resonant wavelength and resonant wavelength shift of nanocavity can be measured as a function of pressure. This point is a fundamental idea for PhC pressure sensor. In this section, we calculate the refractive index modulation resulted from the applied pressure. To determine the refractive index of the stressed structure, we utilize optical tensor coefficients for silicon characterized by the stress-optical tensor equation [6, 13]:

$$
\begin{bmatrix} n_{xx} \\ n_{yy} \\ n_{zz} \\ n_{yz} \\ n_{xz} \\ n_{xy} \end{bmatrix} = \begin{bmatrix} n_0 \\ n_0 \\ n_0 \\ 0 \\ 0 \\ 0 \end{bmatrix} - \begin{bmatrix} c_1 & c_2 & c_2 & 0 & 0 & 0 \\ c_2 & c_1 & c_2 & 0 & 0 & 0 \\ c_2 & c_2 & c_1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \sigma_{yz} \\ \sigma_{xz} \\ \sigma_{xy} \end{bmatrix} \quad (1)
$$

where n_{ij} denotes the refractive index along ij

direction, n_0 is the refractive index in zero-pressure, and σ_{ij} is the pressure along ij direction. We assume that pressure is applied in one direction, therefore:

$$\sigma_{xy} = \sigma_{xz} = \sigma_{yz} = 0 \quad (2)$$

$$\sigma_{xx} = \sigma_{yy} = \sigma_{zz} = \sigma . \quad (3)$$

Thus pressure-modified refractive index value reduces to:

$$n = n_0 - (c_1 + 2c_2)\sigma \quad (4)$$

where c_1 and c_2 are defined as

$$c_1 = \frac{n_0^3 (P_{11} - 2VP_{12})}{2E} \quad (5)$$

$$c_2 = \frac{n_0^3 [(P_{12} - V(P_{11} + P_{12})]}{2E} \quad (6)$$

where E is Young's modulus, V is Poisson's ratio, and P_{ij} denotes strain-optic constant. For silicon at $\lambda = 1.3\ \mu m$ we have

$$P_{11} = -0.101, P_{12} = -0.0094 . \quad (7)$$

3. Design of PhC sensor structure

Waveguide is an important element in optical circuit to conduct light between components. The researches mainly focus on the waveguides with only a few resonant electromagnetic modes, because of drastically reducing the size of photonic components. In 2D PhC waveguide, a linear defect is introduced into the crystal, creating a localized band that falls within and is guided by the photonic band gap [14]. The waveguide can be made by removing one row of air holes or by eliminating one row of dielectric rods. The wave propagates in Si for the first case and propagates in air for the second case, and consequently, the loss can be ignored. This waveguide is constructed in silicon-on-insulator (SOI) wafer. In SOI wafer having Si rods, Si and SiO$_2$ are the substrate (n=3.5) and the insulator (n=1.45), respectively, and Si rods are configured in Si top layer [15]. The PhC nanocavity resonator with a high quality factor (Q) can be used in many applications. The Q value of nanocavity can be improved by changing the number of crystal periods between the nanocavity and the waveguide.

In this research, the designed photonic crystal

structure consists of a square array of Si rods with n=3.5 surrounded by air with n=1. The lattice constant and radius of Si rods are respectively considered as $\alpha = 450$ nm and r=0.2a. By performing plane wave expansion (PWE) approach, the PhC indicates normalized frequency of photonic band gap for TE mode between 0.2795 eV and 0.4154 eV that is equal to wavelengths between 1083 nm and 1610 nm.

Figure 1 shows the layout of the designed photonic crystal sensor. In this paper, we optimize the PhC waveguide and nanocavity to be applied in near infrared from 1300 nm to 1400 nm. The PhC waveguide is formed by removing one row of Si rods in the PhC, and nanocavity is formed by modifying the radius of one Si rod to R_c=0.077a. In this study, there are two crystal rods between nanocavity and waveguide that results in a good quality factor for nanocavity. The length and width of this sample are respectively designed as l=9.2 μm and w=4.7 μm.
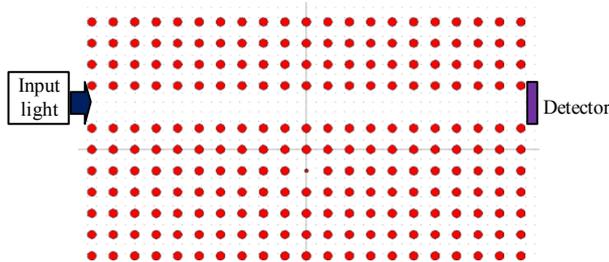
Fig. 1 Layout of sensor structure consisting of a square array of Si rod in air with a=450 nm and r=0.2a.

4. Simulation results

The two-dimensional finite-difference time-domain (2D-FDTD) method is applied to simulate propagation of electromagnetism wave in waveguide. The structure is excited by Gussian pulse and by applying appropriate boundary condition (perfectly matched layer, PML). As shown in Fig. 2, in absence of pressure, the nanocavity shows resonant wavelength at λ=1316 nm. The quality factor for nanocavity is Q=1470. The structure is excited by continuous wave (CW) to simulate the field pattern in the waveguide. Figure 3 illustrates the simulation result of light propagation through the pressure sensor. The interaction between the wave propagated in the waveguide and field localized in the nanocavity results in the change in the transmission spectrum from the cavity to the end of waveguide, and the field intensity passing through the nanocavity reduces.
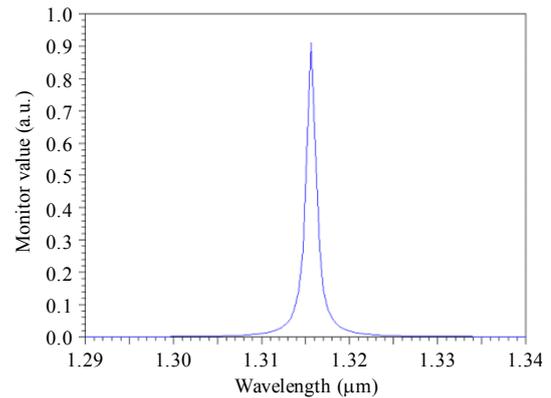
Fig. 2 Transmission spectrum of the cavity without applied pressure (the resonant wavelength is λ=1316 nm).
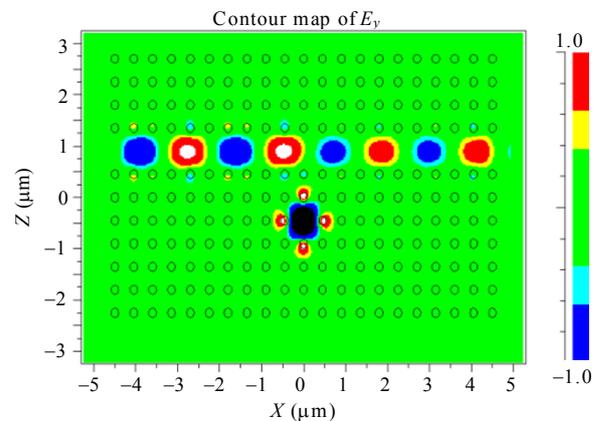
Fig. 3 Simulation result of light propagation in the structure.

To analyze pressure effect on the structure, we perform comprehensive simulation study. The simulations have been performed in different pressures from 0 to 10 GPa by 1-GPa increment at each step, and corresponding resonant wavelengths obtained with different curves are shown in Fig. 4. It has been observed that with increment in the refractive index, the resonant wavelength shifts to larger wavelength region. For example, in 1-GPa pressure, the refractive index of Si changes from

3.50 at zero pressure to 3.5398, and consequently the resonant wavelength shifts from 1316 nm to 1324 nm. In 2-GPa pressure, the refractive index is calculated as 3.5797, and nanocavity resonant wavelength is obtained to be 1332 nm.
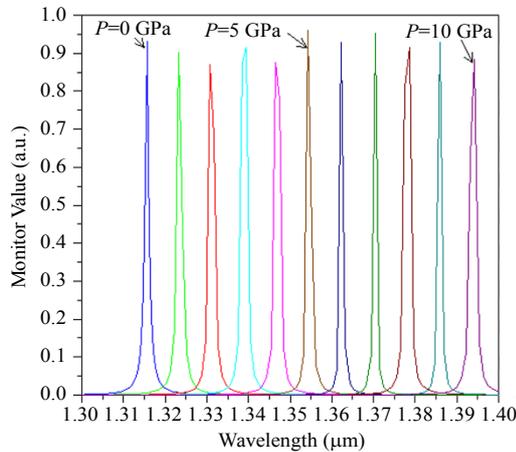

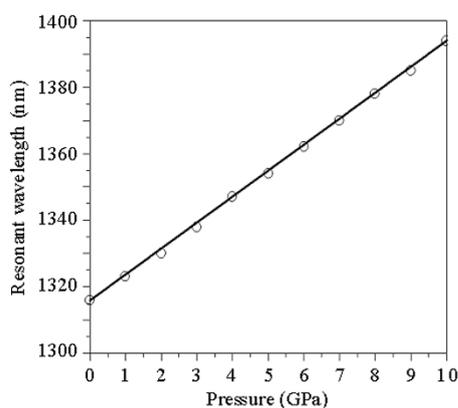Fig. 4 Transmission spectra for different pressures from 0 to 10 GPa.

Fig. 5 Linear relationship between resonant wavelength and pressure in the range of 0 to 10 GPa.

By analyzing the results of Fig. 4, it can be shown that there is a linear relationship between applied pressure and resonant wavelength. Therefore, we can estimate the sensitivity of sensor equal to 8 nm/GPa, which shows better result compared to well-known researches, e. g. in [11]. Since the resonant peak has a very narrow linewidth, the resolution can be quite high. Figure 5 indicates an excellent linear relationship between pressure and resonant wavelength shift. This curve also indicates a wide dynamic range for this sensor from 0 to 10-GPa pressure. By numerical analysis, the

minimum detectable pressure with this structure is 3 mN. With 0.1-GPa incremental pressure, nanocavity shows 0.9-nm increment in resonant wavelength, as shown in Fig. 6.
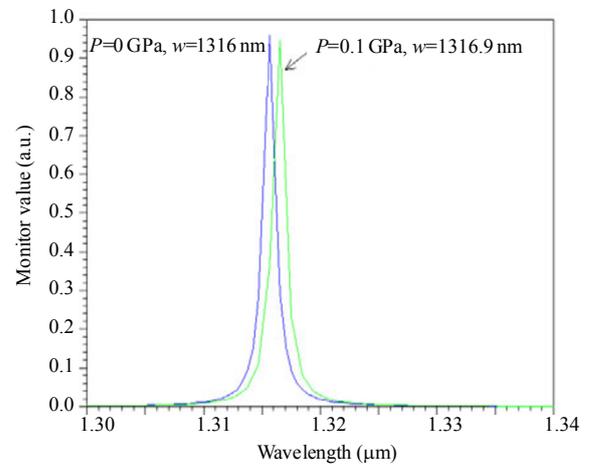

Fig. 6 Resonant wavelength for nanocavity by 0.1-GPa increment in pressure.

5. Conclusions

In this paper, a novel photonic crystal pressure sensor has been designed and presented. This sensor is constructed with two-dimensional photonic crystal waveguide which is coupled to the nanocavity. By changing optical properties of Si, the refractive index changes, and therefore, resonant wavelength of nanocavity shifts. With emphasis on this point, the sensor can be calibrated to measure applied pressure. The designed sensor has a good resolution in mN range, quality factor equal to 1470, and wide linearity range between 0 to 10 GPa. By applying similar scheme and improving quality factor of nanocavity, the resolution of senor can be improved. This sample can be utilized in nanotechnology and NEMS industry.

Acknowledgment

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