Design of photonic crystal microcavity side-coupler to a waveguide based pressure sensor

Chayma Mosbah¹, Ahlem Benmerkhi¹, Mohamed Bouchemat¹, and Touraya Bouchemat¹

¹Frères Mentouri Constantine1 University, Department of electronics, Laboratory L.M.I Constantine, Algeria

Abstract

A novel design of two-dimensional photonic crystal pressure sensor based on microcavity coupled to waveguide is proposed. This sensor consists of photonic crystal microcavity side-coupler to a waveguide. The complex of microcavity and waveguide are formed by removing one hole, and eliminating the central row of holes, respectively. The radius of the holes localized in next alternating holes along the waveguide is changed, in order to enhance the quality factor and sensitivity. Then we applied the different pressures from 1 to 6 GPa by 1 GPa increment at each step. By using finite difference time domain method method, the simulation results demonstrate that when the pressure change the resonant wavelength shifts, the transmission efficiency is varied and quality factor increase.

Keywords: Photonic crystal, microcavity, waveguide, pressure sensor, sensitivity

Introduction

Photonic crystals (PhCs) have very important properties for realization of future and active optical devices [1], such as: optical filters [2], optical switches [3], multiplexers [4], demultiplexers [5] sensors [6] and fibers [7]. Photonic crystal (PhC) is a periodically arranged dielectric material. The periodic variation of the refractive index gives rise to a unique band structure, and may have a Photonic Band Gap (PBG) [1,8]. PBG have properties to control and guide the electromagnetic wave at the scale of optical wavelength [9].

Among the optical devices, PhC based sensors are more attractive in research and scientific community due to their ultra-compact size, high sensitivity [10]. Sensor devices is employed for several sensing application such as: refractive index [11], temperature

[12], pressure [13], and gas [14], etc. In literature, there is various sensor based on PhC realized by microcavity coupled with waveguide, as two-dimensional (2D) PhC pressure sensor [15], biosensing application [16], refractive index sensing [17].

In this paper, a 2D PhC pressure sensor is proposed to detect the range of pressure from 0 GPa to 6 GPa. The sensing principle is based on the shift of resonant wavelength when the refractive index of the sensor is changed by the application of pressure. Our sensor design is based on 2D PhC microcavity side-coupler to a waveguide. Firstly, we create the waveguide by removing the central row of air holes. The microcavity is formed by removing only one hole. After that, we optimized the sensor structure in order to obtain high quality factor (Q) and light confinement. The modification applied to the structure is produced by enlarging the radius (R) of holes localized in next alternating holes along the waveguide. After simulation, we can take as an optimal result $R = 0.37a$ corresponding to $Q = 13211$. By applying the pressure to the structure, the sensitivity is about 9 nm/GPa.

Principle of the pressure sensor

The application of pressure to the PhC structure, leads to various modifications. When the crystal is compressed by the pressure, the geometric shape of PhC, the PBG of the structure changes and the refractive index of the material modifies, due to the photo-elastic effect. We can determine a novel refractive index of the stressed structure, by the relationship given as [18].

$$n = n_0 - (c_1 + 2c_2)\sigma \quad (1)$$

where c_1 and c_2 are defined as

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

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

n_0 is the refractive index at 0 GPa

σ is the applied hydrostatic pressure

E is Young's modulus

V is Poisson's ratio

$$P_{11} = -0.101, P_{12} = 0.0094 \quad (4)$$

Structure design and optimization

Our proposed sensor designed is based on a 2D PhC with triangular array of air holes ($n = 1$) patterned perpendicularly to a silicon substrate ($n = 3.52$). The lattice of a spacial period is $a = 428$ nm and the radius of the holes is $r = 0.35a$. The 2D finite difference time domain (FDTD) method is used in order to reduce the computer memory and simulation time for 3D calculation, using effective refractive index approximation method for the fundamental TE guided mode.

The dispersion properties of the regular PhC structure have been analyzed using two dimensional plane-wave expansion (2D-PWE) method of BandsOLVE software. The band diagram of the proposed sensor is shown in Fig. 1(b). From this figure, we observed that one frequency band gap for TE polarization mode but no gap for TM modes with this RI contrast and relatively small r/a . The PBG extends from $\omega_1 = 0.25611$ (a/λ) to $\omega_2 = 0.36433$ (a/λ), equivalent to the wavelength range of 1170–1670 nm.

The structure design of our proposed sensor is formed with microcavity side-coupler to a waveguide. The microcavity is created by removing only one hole. The waveguide is obtained by removing row of air holes in the Γ –K direction as shown in Fig. 1(a).

With this structure, the resonant wavelength located at $\lambda = 1.4857$ μm corresponding to a quality factor equal to 10789.

(a)

(b)

Fig. 1. a Structure design of our sensor based on microcavity side-coupler to waveguide, **b** Dispersions curves and bandgaps.

To realize a high quality factor and sensitivity, we modified the shape of waveguide. The radius of holes situated in next alternating holes along the waveguide (blue holes in Fig. 1(a)) is changed from $R = 0.36a$ to $0.40a$ for provide a better coupling between the W1 and the defect and improve the quality factor (Q). Fig. 2(a) and (b) shown the transmission spectrum with different value of R , the quality factor and resonant wavelength as function of radius variation. From this figure, we can take as an optimal results the radius $R = 0.37a$, equivalent to a quality factor equal to 13211. We take into on consideration this value because it has the highest quality factor. (a)

(b)

Fig. 2. a Transmission spectrum with different value of R, **b** quality factor and resonant wavelength variations according to the change of R.

To analyze pressure effect on the structure, we applied to the structure a range of pressure from 0 GPa to 6 GPa by 1 GPa increment at each step. The transmission spectrum with different value of pressure is depicted in Fig. 3. We can see that the resonant wavelength shifts to higher wavelength region while the applied pressure increasing. The applied pressure with its refractive index, resonant wavelength, and Q-factor of the sensor for the range from 0 GPa to 6 GPa are summarized in Table 1. From Table. 1, it can be noted that, when the value of pressure increases, the resonant mode shifts to higher range, the transmittance changes slightly and the quality factor increases from 13211 to 15782.

To estimate the sensor sensitivity S as the ratio of the resonant wavelength variation to the applied pressure variation:

$$S = \frac{\Delta\lambda}{\Delta P} \quad (5)$$

The simulation results shown that, the sensitivity of our proposed pressure sensor is around 9 nm/GPa.

Fig. 3. The transmission spectrum with the range of pressure from 0 GPa to 6 GPa.

Table 1. The corresponding refractive index, resonant wavelength, and quality factor for different pressures.

level of pressure	Refractive index	Resonant wavelength (μm)	Quality factor
0 GPa	2.98	1.4760	13211
1 GPa	3	1.4850	13632
2 GPa	3.02	1.4936	14010
3 GPa	3.04	1.5025	14439
4 GPa	3.06	1.5113	14858
5 GPa	3.08	1.5200	15282
6 GPa	3.1	1.5300	15782

Conclusion

In this paper, we present a novel design of pressure sensor with his structure is based on triangular lattice of air holes patterned to an silicon substrate. The sensor consists of a 2D photonic crystal microcavity side-coupled to a waveguide. We optimized our structure in order to improve the sensitivity and quality factor, $Q = 13211.7$ for $R = 0.37a$. The refractive index of the silicon changes with applied pressure. From the results of simulation, we show that when the pressure is applied the resonant wavelength is shifted to higher wavelength range, the transmittance changes slightly and quality factor increase.

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