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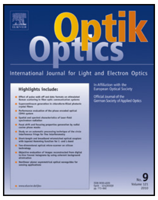

A photonic crystal biosensor with temperature dependency investigation of micro-cavity resonator

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ABSTRACT

A two dimensional photonic crystal biosensor implemented by waveguides and microcavity is theoretically investigated. The designed structure has high quality factor about 15,000 and sensitivity approximately 141.67 nm/RIU, which are important parameters in biosensing applications. Also there is a linear dependency between resonant wavelength shift and refractive index changes. Since water is the main component of human organism, the temperature and wavelength dependence of proposed microcavity is investigated. The results show that the structure has good temperature stability. The temperature sensitivity is about −0.0142 nm/°C.

1. Introduction

Photonic crystal (PC) biosensors have concentrated varying researches because of locally confined optical state into extremely small volume [1,2]. They can be utilized for sensing biomaterials, chemicals and refractive indices [3–6]. Breaking the periodicity of photonic crystal allows to specific modes to arise within band gap. Illuminating the PC with a frequency corresponding to defect mode frequency eventuates to light confinement in defect area [7–11]. The confined light can be sensitive to refractive index variations in defect region. So the device can be as a sensor to detect refractive index changes. Defects such as cavities afforded high quality factor and sensitive sensors which have property to detect high resolution refractive indices and promoting light–analyte interaction [12–14]. In label-free sensing, bio-molecules do not label but target molecules bind to bio-recognition molecules eventuating effective refractive index changes at active sensing area [13,15–18]. Therefore the resonant wavelength peak in transmission spectrum is altered. Homogenous and surface sensing are two types of sensing mechanism. In homogenous and surface sensing the phenomenon of binding mechanism causes covered medium refractive index changes and thickness modification of the sensing hole respectively resulting in effective refractive index (ERI) variation [19].

Di Falco et al. have demonstrated a high sensitive photonic crystal sensor based on cavity resonator for sensing chemicals [20]. A remarkable point in sensors capability is sensitivity of them with respect to ambient variations such as temperature. In this regard Karnutsch et al. have investigated a structure that is insensitive to temperature changes [21]. So in a part of our paper the temperature dependency of the designed cavity is investigated. In this letter, we demonstrate a two-dimensional photonic crystal biosensor based on micro-cavity resonator and waveguides. At first the analyte is flowed through microcavity resonator, then the Gaussian pulse is excited into the structure and the transmitted spectrum is detected. This process can be utilized to determine the properties of analyte. In this paper, the process of physical design for a compact biosensor with parameter optimization is done theoretically. Then bio-sensing characteristics are investigated for proposed structure with optimized quality factor and sensitivity. Also temperature and wavelength dependency is studied for designed microcavity resonator. The sensor characteristics are analyzed by plane wave expansion (PWE) and finite difference time domain (FDTD) methods.

2. Biosensor structure

The structure of photonic crystal is composed of hexagonal lattice of air holes in the slab of silicon. The proposed structure shown in Fig. 1(a) is created by introducing line and point defects which are obtained by eliminating a row of holes and substituting a hole with different radius, respectively. The input and output of waveguide are respectively utilized for applying Gaussian pulse in order to actuate resonant mode of the microcavity and for monitoring trapped mode. The lattice constant ($a = 400$ nm), radius of holes

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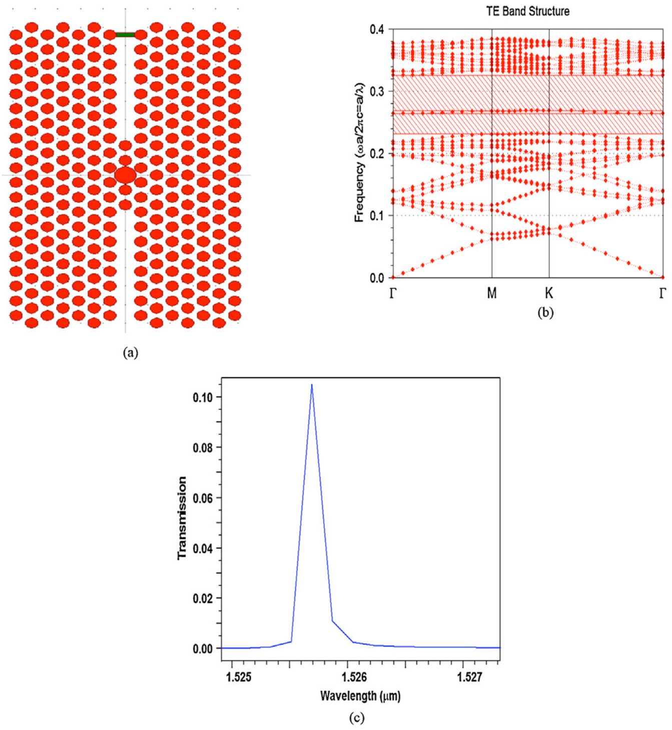

Fig. 1. Two-dimensional photonic crystal biosensor (a) structure, (b) bandgap, and (c) resonant wavelength.

(r = 138 nm) and radius of microcavity (R_c = 240 nm) are considered. The refractive index of dielectric and holes are considered as 3.45 and 1, respectively. Two-dimensional (2D) FDTD and PWE approaches are used for analyzing this sensor.

The band diagram of the structure is illustrated in Fig. 1(b). According to the results, a defect mode is identified in the defect band diagram. The forbidden frequency range is 0.23185–0.32539. This photonic band gap range is obtained for TE mode. In the main structure, the resonant wavelength is as shown in Fig. 1(c). The resonant wavelength and $\Delta\lambda_{\mathrm{FWHM}}$ are 1525.7 nm and 0.1 nm, respectively. So the quality factor is computed as 15,257 which shows an improvement resulting from reduced group velocity in resonator.

3. Evaluation of biosensing characteristics

In this section, the structure analysis for biosensing applications is demonstrated. In biosensing application, it is important to emphasize that the device is utilized to measure local refractive index variations [22]. Changing the RI of the microcavity is provided by trapping antigen to antibody molecules [12]. Consecutively spectral shifting is afforded due to ERI variations of defect.

At first we assume that the analyte with refractive index of n = 1.33 is flown inside microcavity. Then the refractive index of analyte with increment of 0.02 until n = 1.45 (DNA molecule) has been varied. In each stage the Gaussian pulse is applied and the output is recorded. The transmission spectra are depicted in Fig. 2(a). The resonant wavelength with the increment of refractive index of the microcavity shifts to longer wavelength. The shift in resonant wavelength is due to the binding of molecules in the sensing region. The results are obtained by two-dimensional FDTD method. Also the resonant wavelength shifts in range of refractive index variations are illustrated in Fig. 2(b). Therefore, we can calculate the sensitivity that is defined as the wavelength shift per refractive index unit ($\Delta\lambda/\Delta n$). The value of sensitivity for refractive indices between n = 1.33 and n = 1.45 is equal to 141.67 nm/RIU.

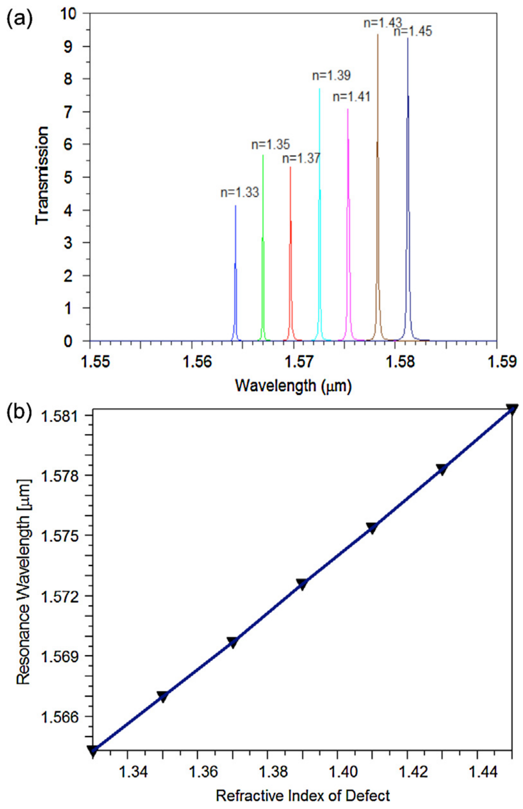

Fig. 2. (a) Transmission spectra and (b) the resonant wavelength shift as a function of refractive index in the range of 1.33–1.45 for structure.

4. Evaluation of temperature dependency of structure

The photonic structures have response to the environmental index changes, however, this does not mean the structures may be applied in practical sensor devices. Some practical factors should be taken into account in the design and in the description of the properties.

Biochemical optics problem of water in the human body seems to be necessary, because water is a most important biological fluid. Water is the main component of interstitial fluid, blood plasma, and so on. Since the refractive index of water is dependent on temperature, in this section we tried to investigate the temperature dependence of the water molecules for our designed structure. According to research done in previous, the wavelength dependence of the water in the visible and near-infrared spectral range for temperature 20 °C is obtained according to Eq. (1). But the temperature of interstitial fluid is approximately 37 °C [23]:

$$n(\lambda) = 1.3199 + \frac{6878}{\lambda^2} - \frac{1.132 \times 10^9}{\lambda^4} + \frac{1.11 \times 10^{14}}{\lambda^6} \quad (1)$$

where, λ is the wavelength in nm unit.

To determine the refractive index of the water with considering temperature and wavelength dependence for different temperatures, we have utilized Cauchy formula with temperature-dependent coefficients (Eq. (2)), that the approximated Cauchy coefficients are presented in Eqs. (3)–(6) [23]:

$$n(\lambda, t) = A(t) + \frac{B(t)}{\lambda^2} + \frac{C(t)}{\lambda^4} + \frac{D(t)}{\lambda^6} \quad (2)$$

$$A(t) = 1.3208 - 1.2325 \times 10^{-5} t - 1.8674 \times 10^{-6} t^2 + 5.0233 \times 10^{-9} t^3 \quad (3)$$

$$B(t) = 5208.2413 - 0.5179 t - 2.284 \times 10^{-2} t^2 + 6.9608 \times 10^{-5} t^3 \quad (4)$$

$$C(t) = -2.5551 \times 10^8 - 18341.336 t - 917.2319 t^2 + 2.7729 t^3 \quad (5)$$