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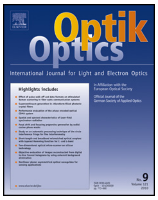

Improved sensitivity of the photonic crystal slab biosensors by using elliptical air holes

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ABSTRACT

We investigate the dependence of sensitivity and quality factor of the resonant mode in photonic crystal H_1 cavity on the slab thickness. Three-dimensional finite difference time domain calculations is performed to study the dependence of quality factor and sensitivity on shape and size of the nearest neighbor holes of the cavity to obtain the optimum structures. For the slab thickness of 0.7a, the sensitivity can achieve 322 nm/RIU (refractive index unit) while the quality factor keeps a relatively high value of 5291 when the refractive index is 1.54.

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1. Introduction

In recent years, photonic sensors have seen a massive development because of the increasing demand of sensing applications in healthcare, defense, security, automotive, aerospace, environment, food quality control, to name a few.

Nowadays, integrated PC-based sensors represent one of the most popular class of photonic sensors, generally employed for physical and chemical/biochemical sensing. In this context, the principal advantages of these intriguing photonic sensor architectures are ultra-high light confinement in very small volumes, high wavelength selectivity, ultra high sensitivity and selectivity in sensing mechanism.

Photonic crystal (PC) microcavity as an optical sensing platform takes advantage of the light confinement in low refractive index air holes where the biological analytes are captured. Therefore a small refractive index change due to bio-molecule infiltration can cause a detectable spectroscopic change [1,2]. The infiltration of PC with fluids or polymers for realizing tunable optical devices or sensors was first suggested a decade ago [3] and experimentally demonstrated in both three dimensional [4] and 2D [5,6] geometries.

Optical microcavities have numerous applications, spanning engineering and science disciplines from designing high-performance optical buffers to studying quantum effects. Recently, these devices have begun to probe biological phenomena, behaving as sensitive and specific chemical and biological sensors. The sensitivity is derived from the long photon life time inside the cavity, and therefore, devices with higher quality factors (Q) are more sensitive.

The photonic crystal sensor arrays make the detection of different analyte simultaneously on a single platform possible. Considering the multiple sensing performance and label-free biomolecular detection, photonic crystal sensor array is a better choice. Examples of such structures include the work of Zhang et al. describe a new photonic crystal sensors array based

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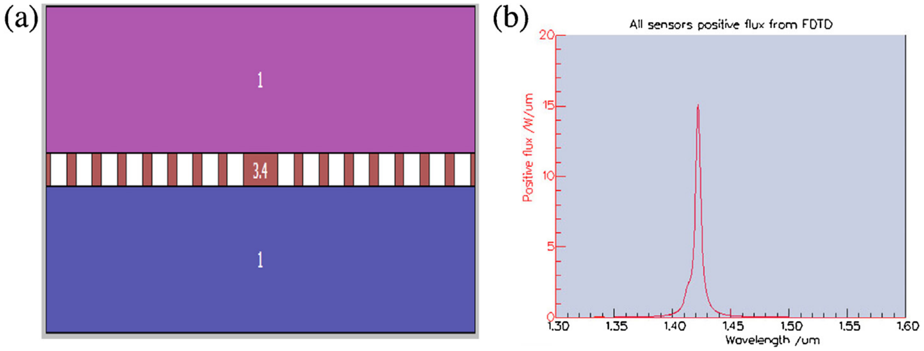

Fig. 1. (a) Side view for a planar photonic crystal H_1 cavity, (b) frequency response of the microcavity inside the complete bandgap of a triangular lattice.

on the radius vertical graded structure. This design contains five resonant cavities (three H_1 cavities and two L_2 cavities) interlaced coupled along W_1 waveguide, which makes it more suitable to ultra-compact optical mono lithic integration. With three-dimensional finite-difference time-domain (3D FDTD) method, simulation results demonstrate that the quality factors of microcavities are over 10^4. Besides, the refractive index sensitivity is 100 nm/RIU with the detection limit approximately of 5.63×10^{-4} [7]. Dorfner et al. [8] have presented the fabrication and experimental investigation of nanocavities coupled to photonic crystal waveguides for their use as biosensors. The evolution of the cavity mode wavelength and optical finesse of a local width modulated cavity design were studied as a function of the ambient refractive index and as a function of adsorbed proteins (bovine serum albumin) on the sensor surface. Liu et al. [9] have proposed a novel nano-scale photonic crystal biosensor arrays platform with a three dimensional radius-graded photonic crystal structure. The simulation results demonstrate the refractive index sensitivity of sensor array varies from 66.67 to 136.67 nm/RIU corresponding to the number of functionalized air holes around the resonant microcavity ranged from 4 to 21.

The shape alteration from the regular circle to ellipse offers a great structural freedom to tune the optical properties of the nanocavities. PC cavity with elliptical air holes have been studies by several papers. Examples of such structures contain the work of Gopal et al. [10] studied the effect of the size, shape and refractive index of the central hole and the neighboring holes on the *Q*-value. The authors used the elliptical holes to improve the in-plane *Q* value by about 10%. Kang et al. [11] present tunable air-slot mode-gap nanocavities in two dimensional (2D) silicon photonic crystals by varying the shape of air holes from the usual circle to ellipse which offers a great structural freedom to tune the optical properties of the nanocavities. In Ref. [12] the proposed PC fiber structures are designed with supplementary elliptical air holes in the core region vertically-shaped and horizontally-shaped. The authors report a design of high sensitivity Photonic Crystal Fiber (PCF) sensor with high birefringence and low confinement losses for liquid analyte sensing applications.

In this paper we report the design and simulations of a biosensing characteristics of two-dimensional PC microcavity by using 3D finite-difference time domain (FDTD) method using a commercial software photon design (crystalwave) [13]. This structure is optimized to maximize the *Q* factor and the sensitivity with very high transmission. For that we act on several parameters such as the thickness of the slab, shape and size of the nearest neighbor holes of the cavity.

2. Design of the PC microcavity

Fig. 1a shows schematically the basic structure of the two-dimensional (2D) PC microcavity in silicon-on-insulator (SOI) devices under consideration. The device layer has a triangular array of air holes in a 0.7a thick silicon (Si) slab. The PC has a lattice constant “a” and a pore radius of 0.32a. The refractive index of Si is approximately 3.4 at a wavelength of 1.55 μm. The structure is simulated by plane wave expansion (PWE) and has a photonic bandgap (PBG) for transverse-electric modes, which have no electric field in the direction of propagation. The PBG extends from 0.2550 (a/λ) to 0.3224 (a/λ), where λ is the wavelength of light in free space. The H_1 cavity consists of an omitted air cylinder from a triangular lattice photonic crystal (PC) slab in the ΓK direction.

We note the appearance of one peak which presents the position of a resonant mode for the wavelength $\lambda_0 = 1.42$ μm (see Fig. 1b). The quality factor is calculated using the 3D finite-difference time-domain (FDTD) method. The *Q* factor is defined as $\lambda_0/\Delta\lambda$, where $\Delta\lambda$ is the full width at half-maximum (FWHM) of the resonator's Lorentzian response and λ_0 is the resonance wavelength. The full width at half-maximum (FWHM) of the single resonance peak yield the cavity quality factor $Q = 269$.

We have performed three-dimensional finite-difference time-domain (3D FDTD) calculations of a H_1 cavity in a slab with variable thickness to obtain the wavelength of the cavity modes. The perfectly matched boundary layers (PMLs) are surrounded the whole structure as absorbing boundary condition, and the number of PMLs is set to be 8. The FDTD mesh size used in this paper is: $\Delta x = \Delta y = a/20$. In order to make the solution of differential equations discretized is convergence and stability, the time step Δt must satisfy with courant stability condition that is $\Delta t \le 1/c$, where c is speed of light in free space. The results are shown in Fig. 2a. As the slab thickness increases from $d = 0.5a$ to $d = 0.8a$, the resonant wavelength of the PC H_1 microcavity also increases, and hence, the resonant frequency decreases substantially.

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