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Silicon on-chip side-coupled high-Q micro-cavities for the multiplexing of high sensitivity photonic crystal integrated sensors array

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ABSTRACT

A novel two-dimensional (2D) silicon (Si) photonic crystal (PC) α-H0-slot micro-cavity with high *Q*-factor and high sensitivity (*S*) is presented. Based on the proposed α-H0-Slot micro-cavities, an optimal design of photonic crystal integrated sensors array (PC-ISA) on monolithic silicon on insulator (SOI) is displayed. By using finite-difference time-domain (FDTD) method, the simulation results demonstrate that both large *S* of 200 nm/RIU (RIU = refractive index unit) and high *Q*-factor $>10^4$ at telecom wavelength range can be achieved simultaneously. And the sensor figure of merit (FOM) > 7000 is featured, an order of magnitude improvement over previous 2D PC sensors array. In addition, for the proposed 2D PC-ISA device, each sensor unit is shown to independently shift its resonance wavelength in response to the changes in refractive index (RI) and does not perturb the others. Thus, it is potentially an ideal platform for realizing ultra-compact lab-on-a-chip applications with dense arrays of functionalized spots for multiplexed sensing, and also can be used as an opto-fluidic architecture for performing highly parallel detection of biochemical interactions in aqueous environments.

1. Introduction

During the last decade, optical sensors based on 2D PC have been widely used in biochemical sensing [1–7], pressure sensing [8–10], and temperature sensing [11–12], and so on. Most of these sensors were designed based on 2D photonic crystal waveguides (PCWs) [13–15] or 2D photonic crystal micro-cavities (PCMs) [16–18]. Particularly, due to the ability to strongly confine light to ultra-small mode volume, numerous PC sensors composed of PC cavities side-coupled to PC waveguides were proposed [19–28]. And various types of PC cavities have been applied to side-couple to waveguide, such as H0-type cavity [29], L3-type cavity [30], ring-type cavity [31], etc. In addition, the ultra-compact size of these PC micro-cavities enable the integration of highly dense PC sensor arrays [32–35] to realize multiplexed sensing applications. Among these sensor devices, the sensor FOM can be defined as follow [36, 37]:

$$\mathrm{FOM}=S\times Q/\lambda_{res}, \tag{1}$$

where λ_{res} represents the resonant wavelength, *S* is the RI sensitivity of the resonant cavity, and Q is the quality factor. However, the trade-off between *S* and *Q* limits the FOM. For example, Mandal et al. [34] demonstrated a high Q-factor ~3000 in a nanoscale optofluidic sensor arrays based on side-coupled one-dimensional (1D) PC cavities. However, *S* was limited to ~130 nm/RIU, and FOM was 250 [34]. Wang et al. demonstrated large *S* of 157.5 nm/RIU in a PC self-collimation sensor with was. However, *Q* was limited to ~130, and FOM was low ~13.3 [35].

Recently, it is found that “nano-slot” structure, the nanosize low index gap between high index waveguides, enable the light field to be strongly confined and guided in a lower-index narrow region (*i.e.* air-slot) surrounded by higher-index materials [38–47], which can greatly enhance *S* due to the strong light-matter interaction while maintaining the same level of high *Q*-factor. Since the “nano-slot” structures can greatly enhance *S* as well as offering an efficient method to confine light in a small mode volume (high-*Q*), so in this work by introducing the “nano-slot” structure into H0-cavity, we display a novel 2D PC α-H0-Slot micro-cavity with high *S* and high-*Q* factor to overcome the design limitations of those sensors array mentioned above. By using FDTD method, the simulation results demonstrated that the high *Q*-factor of the optimized α-H0-Slot micro-cavity of 59,219 and the *S* of 200 nm/RIU can be achieved simultaneously. The calculated *FOM* as high as 7587 is obtained, an order of magnitude improvement over the

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previous sensor arrays [32–35]. In addition, based on a series-connected array of α-H0-Slot micro-cavities side-coupled with PCW, an optimal design of 2D PC-ISA on monolithic substrate is displayed. Moreover, for the proposed Si on-chip PC-ISA, each sensor unit is shown to independently shift its resonance wavelength in response to the RI changes and does not perturb the others. Thus, the PC-ISA is an ideal platform for realizing multiplexed sensing and parallel detection of biochemical interactions.

2. High-*Q* side-coupled 2D PC α-H0-slot micro-cavity design and optimization

In this work, the presented 2D PC structure design is based on Si ($n_{si}=3.48$) with triangular lattice, which consists of a 13 × 27 array of air holes ($n_{air}=1.0$). Fig. 1(a) shows a schematic for 2D PC α-H0-Slot micro-cavity which is side-coupled to a PC-W1 waveguide. The lattice constant of the 2D lattice is $a=420$ nm and the radius of the bulk air-holes is $r=0.31a$. The PC-W1 waveguide consists of a single line defect with the width of $w_1=\sqrt{3}a$. The parameters of the side-coupled α-H0-Slot micro-cavity are: (i) the cavity shifting angle (α), namely the angle between the shifting direction of the green air hole and the x or $-x$ axis; (ii) the cavity lattice shift (L), namely the shift distance of the green air hole along the shifting direction; (iii) the green air hole radius (r_1); and (iv) the slot width (W_s) and length (L_s), respectively. As seen in the inset zoom-in image, there are three "nano-slots" introduced in the center of every two adjacent air holes of H0-cavity. Here, the TE polarized Gaussian-pulse source is used as the incident source. And all simulations are performed by using FDTD commercial software R-Soft and open source software MEEP to calculate the transmittance spectra and the steady state electric filed distribution. A typical band diagram for TE-like polarization in the PCW1 waveguide is shown in Fig. 1(b). As seen, an effective working frequency of the PCW1 waveguide within the photonic band gap (PBG) is between $0.215(2\pi c/a)$ and $0.287(2\pi c/a)$.

As shown in our previous works [29,33], the traditional H0-cavities were designed by shifting the two green holes (in the x direction) outwards slightly in the opposite direction, which means the cavity shifting angle $\alpha=0°$. Firstly, Fig. 2(a) shows the composed transmission spectra as a function of the cavity lattice shift (L) ranging from $L=0.1299a$ to $L=0.3031a$ while the other parameters of $\alpha=0°$, $r=0.31a$, $W_s=0$, and $L_s=0$ are kept fixed. Secondly, when the cavity shifting angle is changed to $\alpha=30°$, while $r=0.31a$, $W_s=0$, and $L_s=0$ are kept fixed, Fig. 2(c) displays the composed transmission spectra as the cavity lattice shift L scanned from $0.15a$ to $0.35a$. As seen from Fig. 2(a) and (c), with the lattice shift L increased, the resonance frequency of the cavity moves towards to low-frequency (red-shift), due to the high-dielectric material increased in the cavity region. Fig. 2(b) and (d) shows the resonance shifts and Q-factor variations as the cavity lattice shift (L) increased, when the cavity shifting angle $\alpha=0°$ and $\alpha=30°$, respectively. Seen from Fig. 2(b) and (d), as the cavity lattice shifts (L) increased, both cavity Q factors firstly increased and then decreased. And the optimized maximum Q factor of 3587 is observed when the cavity shifting angle $\alpha=0°$ in Fig. 2(b), which agrees well with our previous works [29,33]. However, as shown in Fig. 2(d), when the cavity shifting angle is $\alpha=30°$, the optimized maximum Q factor as high as 32,623 can be obtained, an order of magnitude improvement over previous 2D PC H0-cavity [29,33]. Thus, in the following sections, the optimization and investigation of the α-H0-Slot micro-cavity properties (e.g. Q-factors and resonance wavelength) is based on the cavity shifting angle $\alpha=30°$.

Next, to further investigate and optimize the Q-factor of the proposed α-H0-Slot micro-cavity, the composed transmission

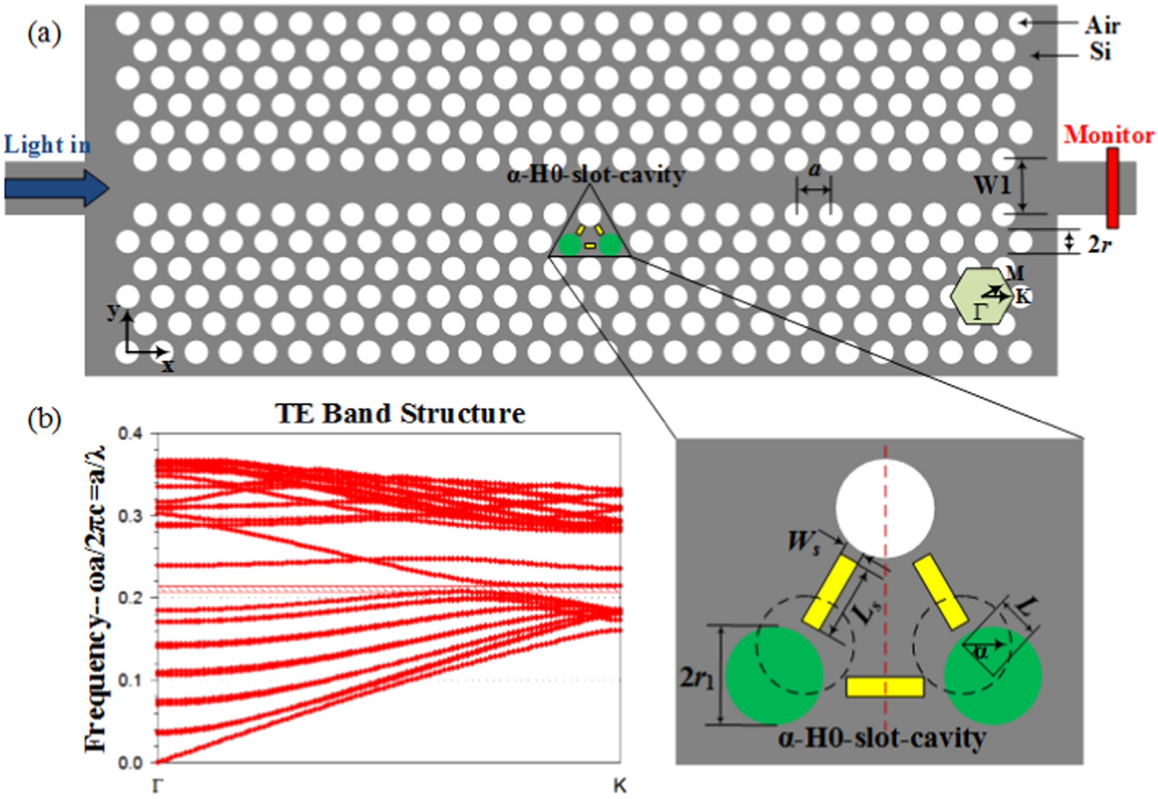

Fig. 1. (a) Schematics for 2D PC α-H0-Slot micro-cavity side-coupled to a PC-W1 waveguide, where $a=420$ nm, $r=0.31a$. Inset: zoom-in of the proposed PC α-H0-Slot cavity area. The α-H0-Slot cavity is symmetric with respect to its center (red dashed line). Here, α is the cavity shifting angle; L is the cavity lattice shift; r_1 is the radius of the green hole; and W_s and L_s are the width and length of the introduced "nano-slots", respectively. (b) The band structure of PCW1 waveguide for the TE-like polarization. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)