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High quality factor and high sensitivity photonic crystal rectangular holes slot nanobeam cavity with parabolic modulated lattice constant for refractive index sensing

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ABSTRACT

In this paper, we present a novel optical sensor based on photonic crystal slot nanobeam cavity (PCSNC) with rectangular air holes. By introducing a continuous slot and quadratically modulated hole spacing (lattice constant a) structure, the majority of the optical field is localized in the slot region, which enhances the light-matter interaction. With applying the three dimensional finite-difference time-domain (3D-FDTD) simulations, three key geometric parameters (hole width w_x, slot width w_s and the number of the holes N) are optimized to achieve a high sensitivity (S) while keeping a high quality (Q) factor. The highest S over 1000 nm/RIU (refractive index unit) is achieved when the slot width equals to 200 nm. The highest Q-factor of 2.15×10^7 is obtained when 30 holes are placed on both sides of the host waveguide with the slot width of 80 nm. Considering the transmission efficiency and the trade-off between S and Q-factor, the slot width and the number of the tapered region are chosen as 80 nm and 20, respectively. A high S approximately 835 nm/RIU and a Q-factor about 5.50×10^5 with small effective mode volume of $0.03(\lambda/n_{air})^3$ are achieved simultaneously, resulting in an ultra-high figure-of-merit (FOM) above 2.92×10^5. Furthermore, the active sensing region of the optimized structure occupies only about 12 μm×0.08 μm, which makes the device attractive for realizing on-chip integrated sensor arrays.

1. Introduction

In recent years, photonic crystal nanobeam cavities (PCNCs) have been widely and intensely researched as an excellent platform for optical sensing, owing to their ultra-high quality (Q) factor, small mode volume (V), and compact size [1–17]. The sensing fundamental is mainly based on the analyte-induced resonant wavelength shift either globally or locally. Therefore, in order to enhance sensitivity (S) of sensors, the optical resonant field needs to be strongly localized and overlapping with the analyte. Currently, there are mainly two ways to improve S. One way is to design air-mode PCNC to confine light into the air holes (circular [7,8], elliptical [9]). Apparently, compared with the dielectric-mode PCNC sensors [3–6], the S of the air-mode PCNC sensor can be significantly improved. However, the effective mode volume of air-mode PCNC is much larger than the dielectric-mode PCNC [18]. The other way is to confine the optical field in the air-slot region by introducing a nano-slot into the dielectric-mode PCNC [10–17]. Among them, the single photonic crystal slot nanobeam cavity (PCSNC) sensor [15–17] can achieve much higher S, Q-factor and lower effective V compared with air-mode PCNC sensor [7–9] and parallel PCSNC sensor [10–14].

In this paper, we propose a novel high Q-factor and high sensitivity optical sensor based on a single PCSNC with rectangular-shaped air holes. By implementing a continuous slot and quadratically increasing lattice constant from the center of the cavity to either sides, the majority of the optical field is localized in the slot region, which enhances the light-matter interaction. When the slot width and the number of tapered holes are equal to 100 nm and 20, respectively, the calculated S and Q-factor of the sensor are 875 nm/RIU and 2.32×10^5, respectively, resulting in a FOM above 1.32×10^5. Compared with previously reported sensor with slot PCNC [15] with radius tapered circular holes, apparently our device has a higher Q and S. In addition, the device possesses an ultrahigh S up to 1030 nm/RIU and a Q-factor of 830 when the slot width equals to 200 nm and the number of holes on either side is 20, which has better performance than ever reported double PCSNC with S~900 nm/RIU and Q~700 [10]. Considering the transmission efficiency and the trade-off between S and Q-factor, the slot width and the number of the tapered holes are chosen as 80 nm

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and 20, respectively. A high S approximately 835 nm/RIU and a Q-factor about 5.50×10^5 with small effective mode volume of $0.03(\lambda/n_{air})^3$ are achieved simultaneously, resulting in an ultra-high FOM above 2.92×10^5. To make a clear comparison, the sensing performance obtained in our paper and some previously published papers have been presented in Table 1. It can be seen that high performance is achieved here. Additionally, previous studies have shown that the hole position can be changed much more accurately (< 1 nm) [19] than the hole size (2–4 nm) [20], which indicates that our structure is easier to fabricate compared with the hole size change structure. Moreover, an ultra-compact active sensing region of 12 μm×0.08 μm makes the device attractive for realizing on-chip integrated sensor arrays.

Table 1
Sensitivity, Q-Factor, and FOM compared with different references.

	Sensing Structure	Q-factor in air	Sensitivity-nm/RIU	FOM
Ref. [4]	Dielectric mode PCNC	3.50×10^4 (in water)	58	1281
Ref. [6]	Air mode PCNC	10^4	537.8	4000
Ref. [10]	Parallel PCSNC	700 (in water)	900	419
Ref. [14]	Parallel PCSNC	1.54×10^4	415	4122
Ref. [15]	PCSNC	1.74×10^5	851	9.65×10^4
The present work rectangular holes PCSNC	slot width 80 nm	5.50×10^5	835	2.92×10^5
	slot width 100 nm	2.32×10^5	875	1.32×10^5
	slot width 200 nm	830	1030	614

2. Device structures and designs

The schematic of the proposed air-bridged PCSNC surrounding by air is shown in Fig. 1(a). It is formed by introducing a nano-slot with a width of w_s in the middle of PCNC. The proposed PCNC consists of an array of rectangular air holes etched into a silicon (n_{si}=3.48) strip waveguide with a width w of 650 nm and a thickness h of 220 nm. The width and length of the air holes are w_x and w_y, respectively. The background index is set to be 1.00. The structure is symmetric with respect to the red dashed line in Fig. 1(a). The cavity was optimized using the deterministic high-Q design method introduced by Quan et al. [17]. Here we create the Gaussian field attenuation by quadratically increasing the lattice constant (a) of the holes from the center to both sides ($a(i)=a_{center}+i^2(a_{end}$ - $a_{center})/\ i_{\max}^2$, i increases from 0 to i_{max}), while other parameters of the structure (w_s, w_x, w_y, w, h) remain unchanged. The simulation is performed with commercial finite-difference time-domain (FDTD) software (Lumerical FDTD Solutions) [21].

The resonant frequency of the dielectric-mode cavity is determined by the dielectric band-edge frequency of the center mirror segment. To keep the resonance of the cavity mode near 1550 nm, we choose a_{center}=600 nm when w_x=360 nm, w_y=450 nm, w=650 nm, w_s=80 nm, N=20 and h=220 nm. The TE band diagram with lattice constant a_{center}=600 nm and a_{end}=664 nm simulated by 3D-FDTD method with Bloch boundary conditions is given in Fig. 1(c). Here, a_{end} is chosen to realize a maximum mirror strength (γ), as shown in Fig. 1(d). The mirror strength γ for different lattice constant is calculated by $\sqrt{(w_2-w_1)^2/(w_2+w_1)^2-(w_{res}-w_0)^2/w_0^2}$, where w_{res} is the proposed target resonance, and w_2, w_1, and w_0 are the air band edge, dielectric

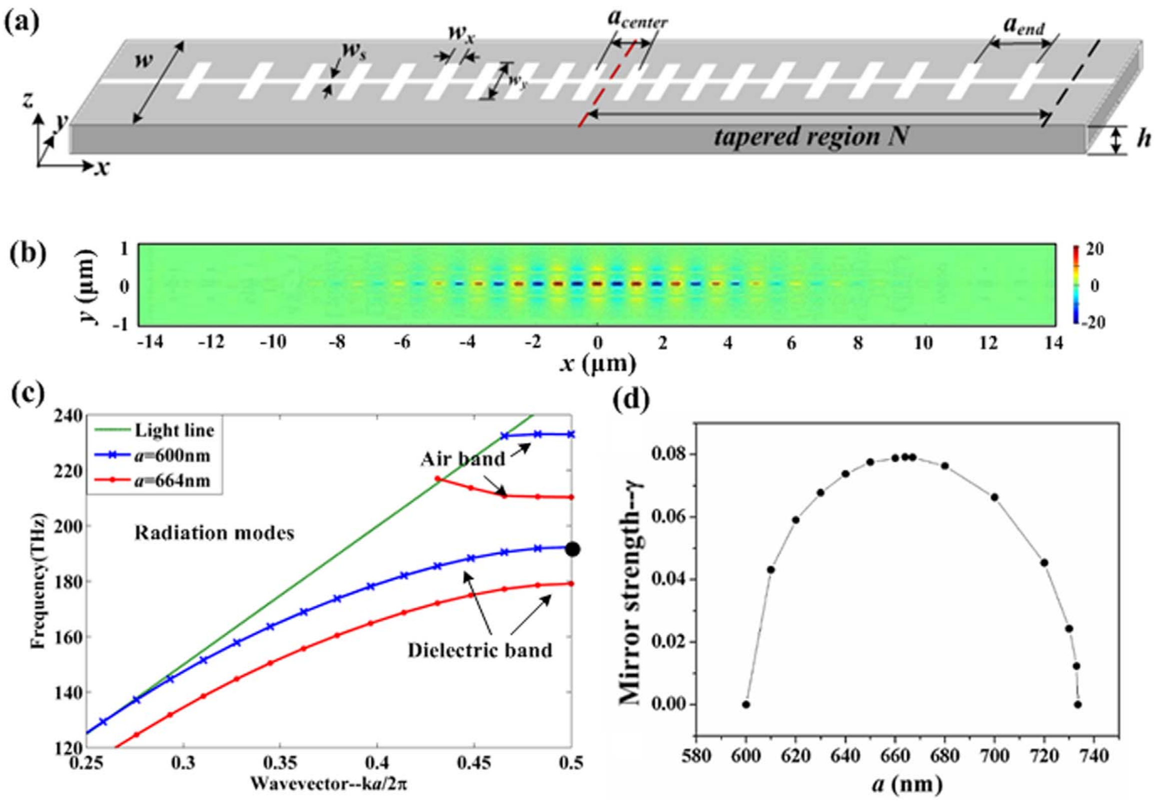

Fig. 1. (a) Schematics of the proposed 1-D PCSNC. The structure is symmetric with respect to its center (red dashed line). w and w_s are the width of the 1-D PC nanobeam and slot, respectively. The air holes have dimension $w_x\times w_y$, and are kept constant. The lattice constant (center to center distance between the gratings) are quadratically modulated from a_{center} to a_{end} on both sides. (b) Electric field intensity (E_y) of the resonant mode calculated by 3D-FDTD method for the cavity with N=20, w=650 nm, w_s=80 nm, w_x=360 nm, w_y=450 nm and a parabolically modulated from a_{center}=600 nm in the center to a_{end}=664 nm on either side. (c) TE band diagram of the PCSNC with a=600 nm (blue line) and a=664 nm (red line). The black dot indicates the target resonant frequency. (d) Mirror strengths at different lattice constant from the 3D band diagram simulation.

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