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Photonic crystal nanoslotted parallel quadrabeam integrated cavity for refractive index sensing with high figure of merit

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Abstract

Sensitivities (S) and quality factors (Q) have been trade-offs in optical resonator sensors, and optimal geometry that maximizes both factors is under active development. In this paper, we experimentally demonstrate an optical sensor based on photonic crystal (PhC) nanoslotted parallel quadrabeam integrated cavity (NPQIC) with high figure of merit (FOM). Both high sensitivity (S) of 451 nm/RIU (refractive index unit) and Q-factor >7000 in water at telecom wavelength range have been achieved simultaneously, which features a sensor figure of merit (FOM) >2000, an order of magnitude improvement over previous photonic crystal sensors.

Keywords: Sensitivity; Q-factor; Optical sensors; Photonic crystal; Nanoslot; Integrated cavity; FOM

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1. Introduction

Over the past decades, optical micro-resonators have been widely used in optical sensors, which have attracted considerable interest for lab-on-chip applications [1]. In recent years, significant research has focused on achieving higher sensitivities (S) or higher quality factors (Q) in chip-integrated label-free biosensors [2,3]. So far, many micro-photonic devices or platforms based on photonic crystals (PhCs) [4–18], surface plasmon resonators (SPR)[19–21], interferometers [22–24], and ring resonators [25,26] have been proposed to realize optical sensors. For these sensors mentioned above, the figure of merit can be defined as $\mathrm{FOM} = S \cdot Q/\lambda_{res}$ [27], where $S = \Delta\lambda/\Delta n$ is the refractive index sensitivity, which characterizes the shift of resonant wavelength ($\Delta\lambda$) in response to the surrounding index change (Δn), Q is the quality factor of the resonant cavity, and λ_{res} is the cavity resonant wavelength.

However, sensitivities (S) and quality factors (Q) have been trade-offs in optical resonant sensors [14], which limits the FOM: to achieve high S, the optical mode needs to overlap strongly with the detecting target (i.e. outside of the wave guiding medium), yet in order to achieve a higher Q, the optical mode should be more localized in the wave guiding medium. For example, Lai et al. [12] demonstrated photonic crystal sensors with high Q-factors ~7000. However, S was limited to ~60 nm/RIU (refractive index unit), and resulting in FOM limited ~300. Wang et al. [18] demonstrated

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large *S* of 900 nm/RIU in a slot double-beam waveguides/cavities. However, *Q* was limited to 700, resulting in FOM limited ~400.

In the previous work [14], we proposed and designed a photonic crystal nanoslotted parallel quadrabeam integrated cavity (NPQIC), that can remedy the fundamental trade-off between high sensitivity and high *Q*-factor in optical resonant sensors. In this paper, we experimentally demonstrate an optical sensor based on photonic crystal (PhC) nanoslotted parallel quadrabeam integrated cavity (NPQIC) with high figure of merit (FOM). Both high sensitivity (*S*) of 451 nm/RIU (refractive index unit) and *Q*-factor >7000 in water at telecom wavelength range have been achieved, which features a sensor figure of merit (FOM) >2000, an order of magnitude improvement over previous photonic crystal sensors.

2. Device fabrication

We fabricated and characterized the PhC nanoslotted parallel quadrabeam integrated cavity (PhC-NPQIC) sensor. The PhC-NPQIC sensor devices used in this experiment were fabricated from silicon-on-insulator (SOI) with 220 nm device layer on a 2 μm thick buried oxide layer. Firstly, first electron beam (E-beam) lithography (Elionix ELS-7000) was performed using XR-1541 (6% HSQ) E-beam resist spun at 4000 rpm (~100 nm thick), followed by development in MF-319. Fig. 1(a) shows the scanning electron microscope (SEM) images of PhC-NPQIC sensor device after first E-beam lithography. As seen, the demonstrated NPQIC sensor consists of a PhC nanoslotted parallel quadrabeam integrated cavity with nano-gap separations and two high-efficient in/out couplers on both sides of the NPQIC cavity. Secondly, refractive ion etching (RIE) of the exposed silicon region was performed with C_4F_8, SF_6, and Ar gases. After RIE, the silicon region under the E-beam resist will be retained, while the silicon exposed in the air will be etched and removed. Fig. 1(b) and (c) displays the SEM images of PhC-NPQIC cavity and taper coupler after refractive ion etching (RIE), respectively. As designed in [14], air hole gratings are in rectangular shape (Fig. 1(a) inset), the silicon thickness of the NPQIC sensor is 220 nm, the periodicity (lattice constant) $a = 500$ nm, the single nanobeam width $b = 200$ nm, the slotted gap between adjacent nanobeams is $w = 100$ nm, and the total width of the experimental PhC-NPQIC sensor device is 1.1 μm. The widths of the rectangular gratings are kept the same at 140 nm. The lengths of the gratings are quadratically tapered from cavity center $w_{cen} = 300$ nm to both sides $w_{side} = 225$ nm, i.e. $w_x(i) = w_x(1) + (i\text{-}1)^2(w_x(i_{max}) - w_x(1))/(i_{max} - 1)^2$ (i increases from 1 to i_{max}). The final cavity structure is symmetric to its center, and on each side, there are 40 gratings ($i_{max} = 40$) in the Gaussian mirror region and an additional 20 segments on both ends. Fig. 1(d) shows the field profile obtained from 3D finite-difference-time-domain (3D-FDTD). It is clearly seen that optical field is strongly localized in the slotted region. The interactions between optical mode and analytes will be efficiently enhanced and high refractive index sensitivity can be achieved.

Then, in order to achieve highly efficient coupling between the input/output fiber lens and the NPQIC sensor, a second E-beam lithography was performed with SU8-2002 E-beam resist to fabricate the input/output bus waveguides [28]. The microscope images of the SU8 polymer input/output bus waveguides as shown in Fig. 2.

Finally, to remove the XR-1542 E-beam resist on the sensor, an opening was defined by photolithography with S1818 photoresist. 7:1 buffered oxide etchant (BOE) was applied for 1 min, followed by rinsing in deionized (DI) water. Finally, photoresist was removed with acetone and IPA.

3. Experimental setup and optical characterization

A schematic of the measurement setup is shown in Fig. 3(a). TE-polarized light lunched from a tunable laser (Santec TSL-510) was coupled to the edge of the chip via an optical fiber (OZ optics) through a polarizer controller. The SU8 polymer waveguide couplers fabricated on-chip were designed to match the mode of the tapered fiber. Thus, light can be effectively coupled from the optical input fiber in-to NPQIC sensor device, and out-to the output fiber and finally to the detector. Fig. 3(b) shows the experimental alignment platform used for NPQIC sensor device measurements. Fig. 3(c) are the zoom-in images the experimental sensor device. As seen in Fig. 3(c), NPQIC sensor chip with connected tubes was clamped by home-made clamp and aligned to optical fibers. A microfluidic channel was fabricated with Polydimethylsiloxane (PDMS) by replica molding of a SU8 template, with dimensions 2 mm × 100 μm × 50μm (length, width and height). And two sub-millimeter diameter holes on both sides of microfluidic channel were punched into PDMS as inlet and outlet for sample delivery.

Fig. 4 shows the measured experimental transmission spectrum (top) and 3D finite-difference time-domain simulation (3D-FDTD) (bottom) of the NPQIC sensor device immersed in DI water, respectively. The NPQIC cavity has a resonant wavelength at 1536.30 nm, with

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