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A Novel Nanoslotted Quadrabeam Photonic Crystal Cavity Sensor with High Sensitivity and High *Q*-factor

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Abstract: We experimentally demonstrate a sensor based on a novel nanoslotted quadrabeam photonic-crystal cavity (NQPC). The NQPC possesses both high-sensitivity and high-*Q* factor. We achieved sensitivity of 451nm/RIU and *Q*-factor >7000 in water at telecom-wavelength range.

OCIS codes: (130.3120) Integrated optics devices; (280.4788) Optical sensing and sensors; (160.5298) Photonic crystals; (230.5750) Resonators; (130.6010) Sensors; (130.5296) Photonic crystal waveguides.

Over the past several years, significant research has focused on achieving higher sensitivities or higher *Q*-factors in chip-integrated label-free biosensors based on different optical resonators [1-5]. The figure of merit (FOM) of these sensors can be defined as FOM = $S \bullet Q/\lambda_{res}$ [6], where $S = \Delta\lambda/\Delta n$ characterizes the shift of resonance ($\Delta\lambda$) in response to the surrounding index change (Δn) and λ_{res} is the cavity resonance wavelength and Q is the quality factor. However, sensitivities (S) and quality factors (Q) have been trade-offs in label-free optical resonator sensors. For example, Lai *et al.* [7] demonstrated photonic crystal sensors with high *Q*-factors ~7000. However, S was limited to ~60nm/RIU (refractive index unit), and FOM was ~300. Wang *et al.* [8] demonstrated large S of 900nm/RIU in a slot double-beam waveguides/cavities. However, *Q*-factor was limited to 700, and FOM was ~400. In the previous work [9], we proposed and designed nanoslotted quadrabeam photonic crystal cavity (NQPC), that can remedy the fundamental trade-off between high sensitivity and high *Q*-factor in cavity sensors. In this work, we report an experiment demonstration of sensitivity (S) of 451nm/RIU, and *Q*-factor of 7015 in water at telecom wavelength range. This features FOM of 2060, an order of magnitude improvement over previous photonic crystal sensors [7,8].

Fig. 1(a) shows the scanning electron microscope (SEM) images of NQPC. It consists of four parallel photonic crystal nanobeam cavities with nano-gap separations. As designed in [9], gratings are in rectangular shape (Fig. 1(a) inset), the thickness of the cavity is 220nm, the periodicity a =500nm, the nanobeam width b =200nm, the gap w between adjacent nanobeams is 100nm, and the total width of the NQPC is 1.1μm. The widths of the rectangular gratings are kept the same at 140nm. The lengths of the gratings are quadratically tapered from cavity center w_{center} =300nm to both sides w_{side} =225nm, (i.e. $w(i) = w_{center} + i^2(w_{end} - w_{center})/i_{max}^2$, i increases from 0 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(b) shows the field profile. It is clearly seen that optical field is strongly localized in the slotted region.

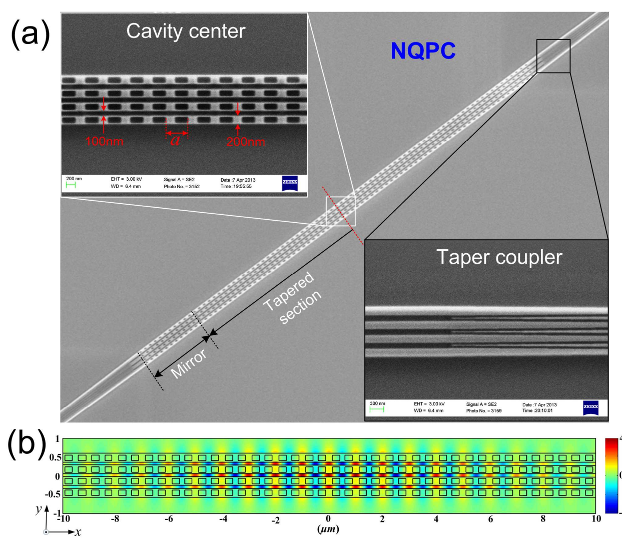

Fig. 1 (a) SEM images of the proposed Si-PhC NQPC cavity with the designed parameters: periodicity a=500nm, the nanobeam width b=200nm, the slot width w between adjacent nanobeams w=100nm. The structure is symmetric with respect to its center (red dashed line). Inset: zoom in of the NQPC cavity center and taper couplers. (b) 3D FDTD simulation of the major field distribution profile (Ey) in the NQPC.

Fig. 2(a) shows the experimental transmission spectrum of the NQPC in DI water. The cavity has a resonance at 1536.30nm (marked with red dash oval), with Q factor of 7015, obtained from Lorenztian fitting (Fig. 2(a) inset). The experimental Q is lower than its theoretical prediction, primarily because of the surface roughness and parameter discrepancy between the designed structure and final structure after Ebeam lithography and reactive ion etching processes. In addition, due to water absorption at telecom wavelength range, Q of the cavity is bounded to the order of 10^4 [10]. Next, NQPC sensor was calibrated with liquids of known refraction indices to characterize its response to bulk refractive index change. Different concentrations of ethanol/water solution were injected into the microfluidic channel. Fig. 2(b) shows the resonance shifts as a function of the refractive indices controlled by different volume ratio of ethanol and water. The volume ratios (v/v) used in our measurement are 0% (DI-water), 10%, 20%, 30%, 40%, 50%, 60%, 80%, respectively. As seen from Fig. 2(d), the dependence of the resonant shift on the refractive indices is linear and yields the experimental bulk refractive index sensitivity S=Δλ/Δn =451nm/RIU, which is close to the FDTD simulation result (540nm/RIU). Therefore, FOM is 2060. In addition, the sensitivity can be even increased by suspending the cavity off the substrate.

Next, NQPC sensor was used to detect streptavidin and quantify its affinity to biotin. In this work, streptavidin of varying concentrations were prepared by serially diluting streptavidin from 100 pg/ml down to1ag/ml in 1×PBS. The pure PBS solution was first injected by syringe pump into the sensor and a reference spectrum was taken as baseline. Streptavidin solutions were then injected from low-concentration to high-concentration. Measurements of the NQPC resonance were taken every 10 seconds, for 20 min, before the next concentration was introduced. In between two different concentrations, pure PBS solution was flushed for 4 min (PBS-wash). The resonance shift during the entire experiment is shown in real-time in Fig. 2(c). Inset of Fig. 2(c) shows the resonance shift vs. streptavidin concentration, both experiment data, and the fitting curve with Langmuir equation [11] $\Delta\lambda = C \cdot K_a \cdot \Delta\lambda_{max}/(1+C \cdot K_a)$. C is the streptavidin concentration and K_a is the affinity constant. From fitting, we obtained $K_a = 2.50\times10^{18} M^{-1}$. As seen, The lowest detected concentration in our experiment was ~200zM (10ag/mL).

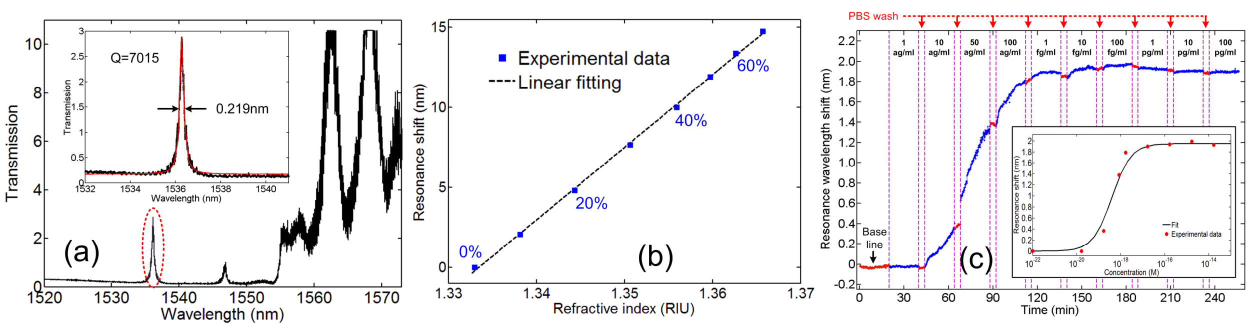

Fig. 2 (a) Experimental transmission spectrum of the silicon NQPC with the infiltration of distilled water. Inset: a close up of the resonance peak of fundamental mode (marked with red dash oval) at 1536.30nm with a Lorentzian fit indicating an experimentally measured Q-factor 7015 in water. (b) Resonant wavelength shifts as a function of the variations in refractive indices of different concentrations ethanol/water solutions (v/v). (c) Real time measurement of streptavidin/biotin binding showing shifts in cavity resonance wavelength (based on Lorentzian fit). Inset: resonance shift as a function of streptavidin concentration in PBS.

In summary, we experimentally demonstrated a novel nanoslotted quadrabeam photonic-crystal cavity (NQPC) sensor with high sensitivity (451nm/RIU) and high Q-factor (7,015) at the same time, improving the sensor FOM (2,060) by an order of magnitude over previous photonic crystal sensors. We also reported the detection of streptavidin at ultra-low concentrations (10ag/mL). In addition, the device structure is very simple and easily fabricated. Thus, we believe that the results presented here may widen the high sensing performance of PhC nanobeam sensors. Here, this research was supported by NSFC (No.61372038), National 973 Program (No.2012CB315705), National 863 Program (No.2011AA010305), and BUPT Excellent Ph. D. Students Foundation (CX201212, CX201331), P. R. China. D. Yang thanks the China Scholarship Council (CSC) (NO. 201206470026) for fellowship support. Device fabrication is performed at the Center for Nanoscale Systems (CNS) at Harvard. Thanks for the great help.

References

[1] X. Fan, I. M. White, S. I. Shopova, H. Zhu, J. D. Suter, and Y. Sun, Anal. Chim. Acta **620**, 8–26 (2008).
[2] F Vollmer, L Yang, Nanophotonics **1**, 267–291 (2012).
[3] D. Yang, H. Tian and Y. Ji, Sensors and Actuators A: Physical **171**, 146-451 (2011).
[4] D. Yang, H. Tian, and Y. Ji, Opt. Express **19**, 20023-20034 (2011).
[5] D. Yang, H. Tian, J. Huang, and Y. Ji, **CM3B.7**, CLEO:2012.
[6] L. J. Sherry, S. Chang, G. C. Schatz, and R. P. Van Duyne, Nano Lett. **5**, 2034-2038 (2005).
[7] W. Lai, S. Chakravarty, Y. Zou, Y. Guo, and R. T. Chen, Appl. Phys. Lett. **102**, 041111 (2013).
[8] B. Wang, M. A. Dündar, R. Nötzel, F. Karouta, S. He, and R. W. van der Heijden, Appl. Phys. Lett. **97**, 151105 (2010).
[9] D. Yang, H. Tian, Y. Ji, and Q. Quan, JOSA B, **30**, 2027-2031 (2013).
[10] A. M. Armani and K. J. Vahala, Opt. Lett. **31**, 1896-1898 (2006).
[11] S. Zlatanovic, L. W. Mirkarimi, M. M. Sigalas, M. A. Bynum, E. Chow, K. M. Robotti, G. W. Burr, S. Esener, and A. Grot, Sensors and Actuators B: Chemical **141**, 13-19 (2009).