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Photonic Crystal Nanobeam Air-mode Cavity for High-Q and High Sensitivity Refractive Index Sensing

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Abstract: We demonstrate a novel photonic-crystal nanobeam air-mode cavity with high-Q and high-sensitivity for refractive-index sensing. For the air-mode, the light is strongly localized inside the air-region. The high-Q ~5.0×10^6 and high-sensitivity of 537.8nm/RIU are achieved.
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Optical cavities based on a photonic crystal (PhC) platform allow for both high quality factor (Q) and strong field confinement, resulting in enhanced light-mater interaction with an extremely small volume. In recent years, a variety of optical cavity sensors based on PhC waveguides, 2D PhC slabs, and 1D PhC nanobeam cavities have been demonstrated [1-5]. However, in typical PhC sensors, strong light-matter interaction occurs in the high-index material region (dielectric region) where the majority of the optical field is located, making it difficult to overlap efficiently and strongly with the analyte within the hollow part (air region) of the cavity. So, in this case, the high Q-factors ~10^6 can be achieved due to the optical mode (here is dielectric-mode, DM) can be strongly confined in the high-index medium. However, the optimized sensitivities (S) of most geometries are generally around 100~200nm/RIU (RIU= refractive index unit) at telecom wavelength. Because the DM cannot overlap efficiently with the analyte.

In order to overcome this drawback and realize ultra-high sensitivity, the use of PhC slotted waveguides/cavities design were demonstrated [6-8]. In particular, Jagerska *et al.* [7] demonstrated sensitivity of 510nm/RIU in a 2D PhC-slot heterostructure cavity. Wang *et al.* [8] demonstrated sensitivity of 900nm/RIU in PhC slot double-beam waveguides/cavities. However, here the Q-factor is very low, limited to 700 in [8].

Recently, PhC nanobeam cavities have been of great interest for enhancing light-matter interaction, owing to their compact size, ultrahigh Q-factors, and low mode volumes [9,10]. Thus, in this work, to overcome the limitations above and realize a PhC cavity sensor with ultrahigh Q-factor and high sensitivity, a novel silicon PhC sensor based on single nanobeam air-mode (AM) cavity is demonstrated. The schematic of the PhC nanobeam air-mode cavity (NAMC) is shown in Fig. 1(a). As seen, the proposed PhC sensor consists of single nanobeam cavity. The cavity design follows our recently discovered deterministic high-Q recipe [6, 9]. The thickness of the Si-PhC NAMC is 220nm, periodicity a=480nm (n_{si}=3.46). The inset is the unit cell of waveguide used in the band structure calculation. As shown in Fig. 1(b), the band structures of the unit cell with w_y=640nm (blue points line) and w_y=475nm (red points line) are calculated by 3D Finite-difference time-domain (FDTD). The inset is the FDTD simulation of the air-mode major field profile (Ey field in plane, perpendicular to the beam) distribution in the unit cell calculation. As seen, for the air-mode (AM), the light is strongly localized inside the air-region. The optical mode (here is air-mode) can overlap strongly with the analyte within the hollow part of the cavity, resulting in strong light-matter interaction. Thus, the PhC sensor based on the proposed NAMC can be used to achieve high sensitivity.

In this design, the final cavity structure is symmetric to its center (Fig. 1(a)), and on each side, there are 30 gratings (i_{max} =30) in the Gaussian mirror taper region and an additional 15 segments that have the same dimension as the last grating in the mirror region. The nanobeam width at the center of the NAMC is w_{y_center}=640nm, with the hole radii (r) kept constant at 155nm. To create the Gaussian mirror, the nanobeam widths are quadratically tapered from w_{y_center}=640nm to w_{y_end}=475nm, (i.e., $w_y(i) = w_{y\_center} + i^2(w_{y\_end} - w_{y\_center})/i_{max}^2$, i increases from 0 to i_{max}). w_{y_end}=475nm is obtained from band-diagram simulation (Fig. 1(b)), at which produces the maximum mirror strength [6,9]. So, an ultrahigh Q value can be obtained, and the total Q-factor as high as 5.16×10^6 is observed and the resonance is at 1349.58nm. Fig. 1(c) shows the top view of the major field distribution profile (Ey). It is clearly seen that the optical mode (namely, air-mode) is strongly localized in the air region.

With 3D-FDTD simulation, we obtained the transmission of the proposed PhC NAMC sensor, as light is launched from the bus waveguide (fundamental TE-likemode) coupled into the NAMC and finally collected from the output bus waveguide. In order to save the simulation time of the transmission calculation, we used a high transmission but low Q geometry: the number of gratings in the Gaussian mirror taper region was chosen to be i_{max}=10, and there were no additional mirrors outside of the taper region. The total transmission spectrum is shown in Fig. 2(a) when the background refractive index is RI=1.00. The modes at wavelengths lower than 1330nm and higher than 1800nm are the band edge modes. Fig. 2(b) shows the composed transmission spectra when the refractive index changes from RI=1.300 to RI=1.345. Fig. 2(c) shows the resonant wavelength shifts (red-shift) as the function of the refractive index increases. The refractive index sensitivity as high as 537.8nm/RIU is observed.

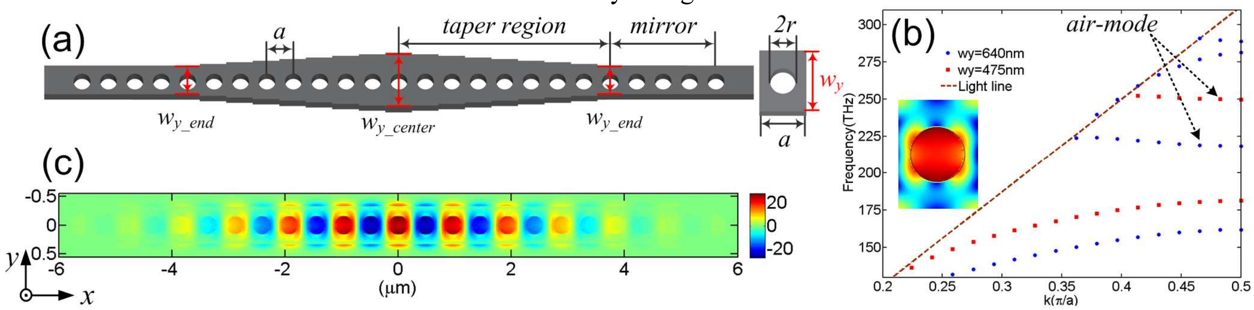

Fig. 1 (a) Schematic of silicon PhC nanobeam air-mode cavity (NAMC). The structure is symmetric with respect to its center. The inset is the unit cell of waveguide used in the band structure calculation. (b) 3D-FDTD calculation of the band structures of the unit cell with w_y=640nm (blue points line) and w_y=475nm (red points line), respectively. The inset is the FDTD simulation of the air-mode major field profile (Ey field in plane, perpendicular to the beam) distribution in the unit cell calculation. (c) 3D FDTD simulation of the major field distribution profile (Ey) in the NAMC. Here the number of Gaussian mirror segments i_{max} =30, with an additional 15 mirrors on both ends of the tapering section. The calculated Q-factor as high as 5.16×10^6 is observed.

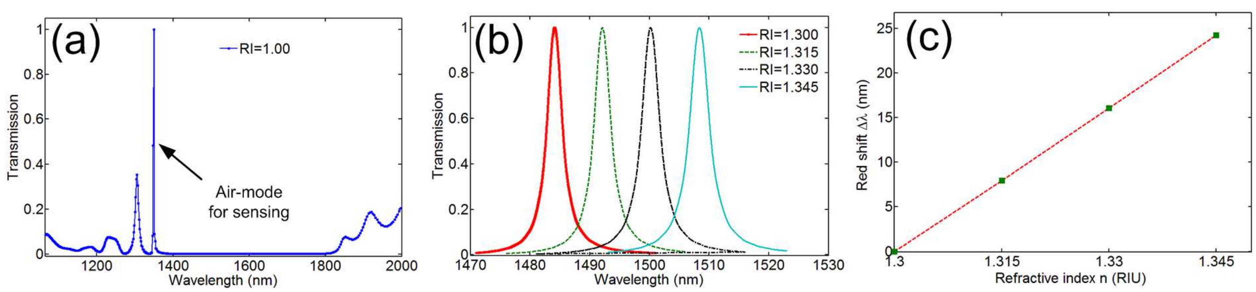

Fig. 2 (a) Transmission spectrum of the NPMC sensor from 3D-FDTD simulation. The number of gratings in the taper region was chosen to be i_{max}=10, and there were no additional mirrors. (b) Composed transmission spectra of the PhC NAMC sensor when the RI changes from RI=1.300 to RI=1.345. (c) Resonant wavelength shift (red-shift) as the function of the RI increases.

It is important to point out that the demodulation of the proposed PhC nanobeam air-mode cavity sensor is straightforward. 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. Thanks for the great help.

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