High-*Q* photonic crystal nanofiber cavity design and application of refractive index sensing

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Abstract: We propose a one dimensional nanofiber photonic crystal dielectric mode micro-cavity with high performance, which can both achieve high sensitivity of 579.3 nm/RIU and high quality over 10^6. Importantly, this design achieves optical coupling automatically.

OCIS codes: (130.3120) Integrated optics devices; (280.4788) Optical sensing and sensors; (230.5298) Photonic crystals, (060.2370) Fiber optics sensors.

1. Introduction

In the past few years, optical resonance has been widely used in optical sensors, which has caused a lot of laboratory interest in the chip to achieve optical sensing. An important factor in limiting the development of photonic crystal sensing devices is that it is difficult to couple using conventional techniques, and even in many cases it is impossible to couple them with ordinary fibers. Hence, it is common to use Single Mode Tapered/ Lensed fibers to achieve optical coupling in most case. We proposed a structure which can achieve optical coupling automatically, expansion of the sensor application scenarios, such as traffic, coal mine safety environment, can reduce costs and improve its practicality.

In this dielectric mode, it is strongly confined to the high-index material which can achieve high quality factor 10^6. In addition, sensitivity to analytes can reach to 579.3 nm/RIU. The motivation for a high quality is related to narrower resonance which allows smaller shifts in the resonance wavelength. Hence, the figure of merit (FOM) of sensors can be defined as FOM= $S{\cdot}Q/\lambda$, where S is the shift of resonance in response to the surrounding index change, Q is the quality factor of the cavity and λ is the cavity resonance. It is said that there is a trade-off between S and Q which limits the FOM demonstrated in the previous works [1-4]. The cavity can achieve high Q and high sensitivity if designed properly. In this paper, we propose a novel optical sensor based on one-dimensional nanofiber photonic crystal model. The sensor FOM will remain high at 4×10^5.

2. The design of nanofiber photonic crystal micro cavity

Fig. 1(a) shows the schematic of the one dimensional nanofiber photonic crystal dielectric mode micro-cavity described in this work. The micro-cavity complies with the deterministic high-Q recipe. We design the nanofiber photonic crystal micro-cavity on a single fiber along its length where it has etched air hole. The diameter of the fiber is w_{nb}=1040 nm and its RI is n=1.45. Furthermore, the periodicity is a=620nm. The nanofiber radius at the center of the cavity is 230nm. To create a Gaussian mirror [5-7], the air hole is parabolically tapered from r_{center}=230 nm in the center to r_{end}=180 nm on both side, i.e., $r_y(i)= r_{center}=230+ i^2(r_{end}- r_{center})/(i_{max})^2$($i$ increases from 0 to i_{max},

i_{max}=30).Here, the radius of air-hole r_{center}=230 nm and r_{end}=180 nm, are chosen from the numerical band diagram simulations shown in Fig.2(a) and (b), respectively. Fig.2(a) shows the TE band diagrams of the single nanofiber photonic crystal micro-cavity with r_{center}=0.37a=230 nm (radius of the central hole) and r_{end}=0.29a=180 nm (radius of the edge hole). Here, the dot in Fig. 2(a) indicates the target resonance frequency of the single nanofiber photonic crystal micro-cavity. Fig.2(b) shows the calculated mirror strength for different filling fraction $f=\pi r^2/aw$, where a is the lattice constant and r is the air hole radius. As seen in Fig. 2(b), when filling fraction f is 0.037 (r=180 nm), the maximum mirror strength obtained [8]. We place 30 taper segments and 25 additional mirror segments at both edges of the Gaussian mirror which have the same hole radius r_{end}=180 nm in order to achieve a radiation-Q-limited cavity. It can achieve Q-factor as high as 10^6at 1437.8 nm through the 3D-FDTD simulation.

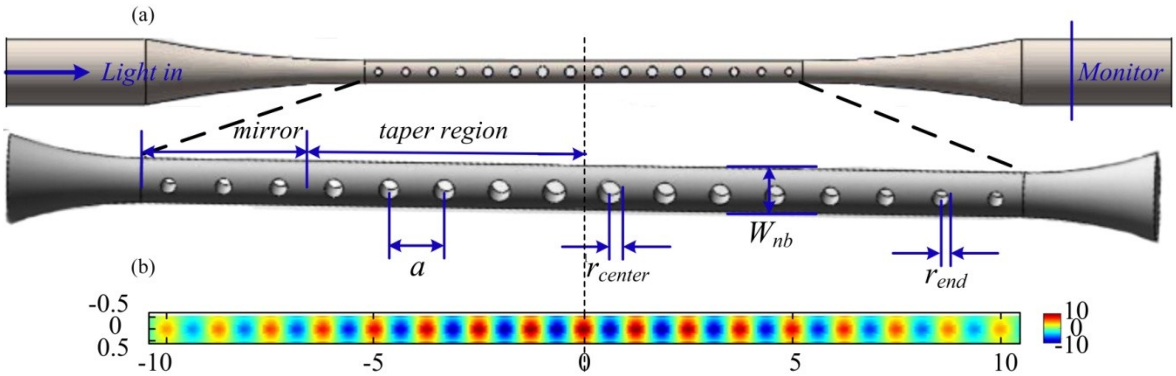

Fig. 1. (a)Schematic of the nanofiber photonic crystal micro-cavity. The structure is symmetric with respect to its center (black dashed line). The periodicity a=620nm and the nanofiber radius is quadratically tapered from r_{center}=230 nm in the center to r_{end}=180 nm on both side, i.e., $r_y(i)= r_{center} + i^2(r_{end} - r_{center})/(i_{max})^2$ (i increases from 0 to i_{max}). (b) 3D FDTD simulation of the major field distribution profile (E_y) in the nanofiber photonic crystal micro-cavity. The number of Gaussian mirror segments i_{max}=30, with 25 additional mirror segments on both ends of the tapering section. A calculated Q as high as $10^6$is obtained. The unit of the x/y axis is micrometers.

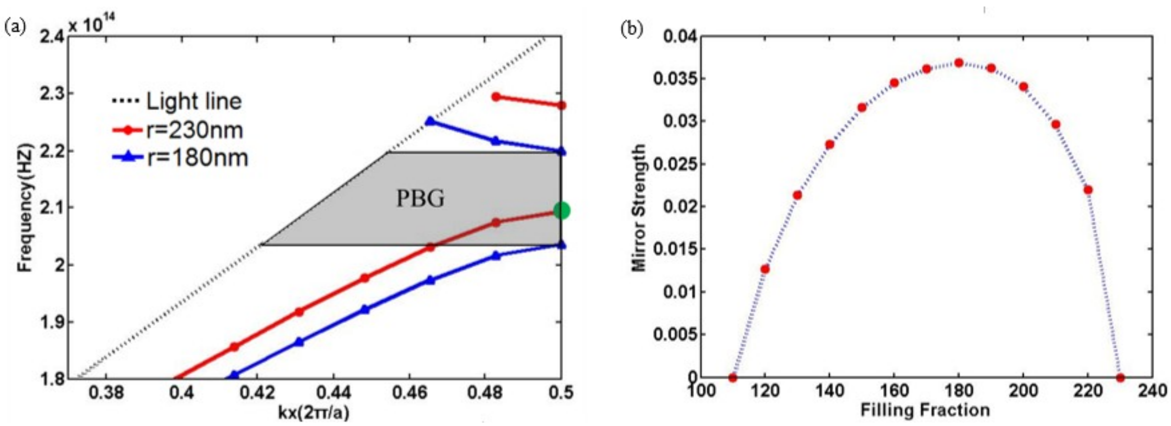

Fig. 2. (a) TE band diagram of the single nanofiber photonic crystal micro-cavity with r=230 nm (red line with dots) and r=180 nm (blue line with small triangles). In both cases, the diameter of the nanofiber is w_{nb}=1040 and the periodicity of the air holes is a=620 nm. The gray region is the photonic bandgap (PBG) for the air hole with r=180nm. The inset green dot indicates the target resonant frequency nanofiber. (b) Mirror strength obtained by using 3D band-diagram simulation for different hole radii and at the same time other parameters are the same as in (a).

3. Simulation results

The fundamental dielectric mode can achieve higher Q compared with other mode. The transmission spectra of the fundamental dielectric mode used for sensing are calculated to calculate the refractive index (RI) sensitivity S of the single one-dimensional nanofiber photonic crystal micro-cavity sensor. As shown in Fig.3(a), the resonant wavelength shift is 86.9 nm when the background index changes from RI=1.0 to RI=1.15 (Δn = 0.15). Therefore, the calculated RI sensitivity is S=$\Delta\lambda/\Delta$n =579.3 nm/RIU at the telecom wavelength ranges. What's more, the liner fit of the resonant wavelength shift along with refractive index increasing shown in Fig.3(b).

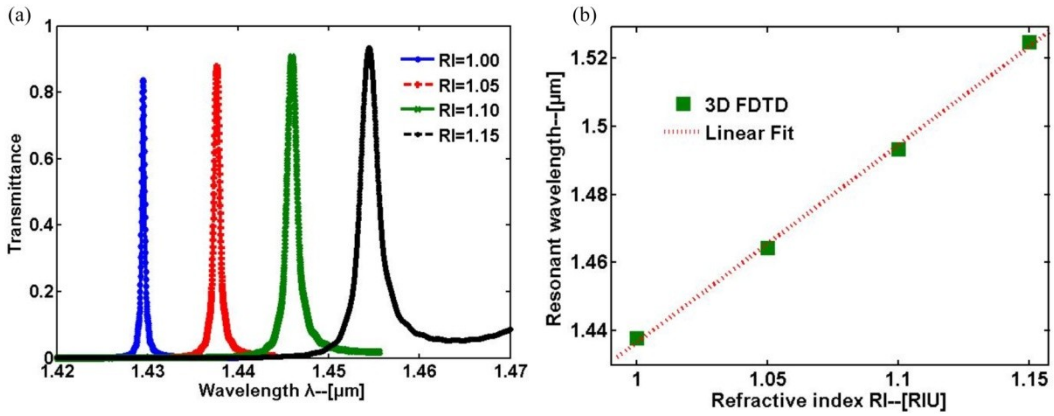

Fig. 3 (a) Transmission spectra of the single 1-D Photonic Crystal Nanofiber Cavity sensor when background refractive index changes from RI=1.00 to RI=1.15. (b) Shift of the cavity resonant wavelength as a function of increased refractive index.

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