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Extraordinary sensitivity in optical microfiber based refractive index sensors near the turning point of turning point of effective group index difference

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Abstract: We show that optical microfiber coupler sensors operating near the dispersion turning point can achieve ultrahigh refractive index (RI) sensitivity at RI around 1.33. It opens up new opportunities to ultra-sensitive biochemical sensing.

OCIS codes: (060.2370) Fiber optics sensors; (260.3160) Interference; (060.2310) Fiber optics

1. Introduction

Optical fiber refractive index (RI) sensors have attracted tremendous research interest in recent years due to their diverse potential applications in the fields of environmental monitoring, food safety and clinical diagnosis. During the past decades, various optical fiber RI sensors have been extensively explored [1-8]. However, most of these sensors exhibit high sensitivity only when the RI of the surrounding medium approaches that of optical fiber[8]. In biochemical sensing, the analyte are given in aqueous solutions whose RI is around 1.33 in most cases. Therefore, it is of great practical significance to develop RI sensors that can achieve high sensitivity in the low RI region.

In this paper, we propose an ultrasensitive optical microfiber coupler (OMC) based RI sensor towards low RI sensing. As a traditional fiber-optic device, OMC has been widely used to either split or combine optical signals in optical fiber systems. Recently, researchers demonstrated optical microfiber couplers' (OMC) ability for various sensing applications including RI sensing[4-6], biosensing[4, 9], salinity sensing[10], current sensing and magnetic field sensing[11, 12]. Most of these sensors are intrinsically RI sensors. However, the RI sensitivity of previous reported OMC sensors are relatively low around RI of 1.33 and what's important, a systematical investigation on the RI sensing performance of OMC based sensors has not been reported[4-6]. Here we propose a sensing model and systematically examine the RI sensitivity of the OMC sensors by numerically calculating the group effective RI difference between the even supermode and odd supermode. Numerical results reveal that there exists a turning point when the group effective RI difference equals zero. By taking advantage of this turning point, the RI sensitivity could be dramatically enhanced. Thus, by carefully design the OMC, we can achieve ultrahigh sensitivity at the low RI range. Experiments are carried out to validate the model and confirmed a good agreement with the expected theoretical performances. Furthermore, an ultrahigh sensitivity of 39541.7 nm/RIU at surrounding RI (SRI) of 1.33 is achieved.

2. Numerical analysis

FIG. 1. Schematic diagram of the microfiber coupler.

A typical optical microfiber coupler is shown in Fig. 1. It comprises two conical transition tapers with four input/output ports and a uniform waist region where two micro-fibers are parallel and next to each other. Based on supermode theory[13], the two parallel microfibers can be regarded as a new waveguide. When light is launched into one input port of the coupler, both even supermode and odd supermode will be excited simultaneously and

coupling between the two modes occurs as they propagate along the waveguide. For the wavelength position of the N th dip λ_N in the transmitted spectra, the phase difference ϕ_N between the two supermodes accumulated along the coupling region satisfies[14]:

$$\phi_N = \frac{2\pi L(n_{\text{eff}}^{\text{even}} - n_{\text{eff}}^{\text{odd}})}{\lambda_N} = (2N - 1)\pi \quad (1)$$

where $n_{\text{eff}}^{\text{even}}$, $n_{\text{eff}}^{\text{odd}}$ are effective RI of the even and odd supermodes. L represents the length of the coupling region and wavelength. N is a positive integer. By taking a small variation from Eq. (1), the spectral sensitivity to the SRI is obtained as[15]:

$$S = \frac{\partial \lambda_N}{\partial n} = \frac{\lambda_N}{\Delta n_{\text{eff}} - \lambda_N \partial(\Delta n_{\text{eff}})/\partial \lambda} \frac{\partial(\Delta n_{\text{eff}})}{\partial n} \quad (2)$$

where Δn_{eff} represents the effective RI difference between the two supermodes and $G = \Delta n_{\text{eff}} - \lambda_N \partial(\Delta n_{\text{eff}})/\partial \lambda$ is defined as effective group index difference between even and odd supermodes.

FIG. 2 (a) Effective group index difference versus fiber diameter with different SRIs of 1.3263, 1.3500, 1.3700, 1.3900 and 1.4100 at wavelength 1550 nm. (b) Calculated RI sensitivities as a function of fiber diameter ranging from 1 to 5 μm with different SRIs at wavelength 1550 nm.

Fig. 2a shows the effective group index difference G for an OMC as a function of fiber diameter D with different SRIs at wavelength 1550 nm. It is clear that by carefully control the diameter of the OMC, $G=0$ could be satisfied for different SRIs. Thus according to Eq. (2), the RI sensitivity can reach infinite. Then we calculate the RI sensitivities of the g OMC sensors. As depicted in Fig. 2b, an extremely high sensitivity can be observed when G approaches zero. When fiber diameter D approaches the turning point diameter from the left side and right side, the sensitivity dramatically increases towards $-\infty$ and $+\infty$. The turning point of the RI sensitivity moves towards larger diameters as SRI increases. According to Fig. 2b, an ultrahigh sensitivity larger than 20000 nm/RIU at low SRI around 1.33 can be obtained when D lies between 1.29 and 1.51 μm , which is of great significance for biosensing and magnetic sensing in which the OMC sensors are placed in aqueous medium.

3. Experimental demonstration

To verify our theoretical findings, OMC sensors with thin diameters around the turning point are fabricated by tapering two twisted standard telecom single mode fibers (SMF-28, Corning, NY, USA) using a flame brushing method. The fabricated OMC has a 2.5 mm long uniform waist region with a diameter of 1.4 μm (see inset in Fig3. a).

FIG. 3 (a) Transmission spectral responses to different SRI of 1.3325, 1.3329, 1.3334 and 1.3339. Black arrows are to guide the shift of resonant dips as SRI increases. Inset: SEM image of the waist part of an OMC sensor with diameter $D=1.4\ \mu\text{m}$. (b) Modeled (solid curves) and measured wavelengths (points) at transmission dips versus SRI.

The sensing spectrum of the OMC sensor is shown in Fig. 3a. The resonant dips tend to redshift dramatically when SRI increases from 1.3325 to 1.3339. The RI sensitivity is higher for long wavelength than short wavelength. Moreover, an ultrahigh RI sensitivity of 39541.7 nm/RIU is achieved at wavelength around 1400 nm, which is so far the highest sensitivity for OMC sensor at low RI around 1.33. We plot the wavelengths for different dips in our experiment together with numerical simulation results in Fig. 3b, and our experimental results agree well with the theoretical results. The small discrepancy could be attributed to the fact that the actual OMC geometry is not a perfect uniform parallel cylinder compared with the theoretical model. We also observe a large power drop at wavelengths above 1400 nm. This is due to the strong vibrational absorption of water molecules that lies right between 1400 nm and 1500 nm[16].

In conclusion, we present a comprehensive study on the RI sensing performance of OMC based sensors working around the turning point of effective group index difference. Both theoretical and experimental results demonstrate an ultrahigh sensitivity of 39541.7 nm/RIU at a low SRI around 1.33. The ultrasensitive sensing platform opens up opportunities to a wide range of applications in chemical and biological sensing fields.

4. References

- [1] S. Lacroix, R. J. Black, C. Veilleux, and J. Lapierre, "Tapered single-mode fibers: external refractive-index dependence," *Appl. Opt.* **25**, 2468-2469 (1986).
- [2] K. S. Chiang, Y. Q. Liu, M. N. Ng, and X. Y. Dong, "Analysis of etched long-period fibre grating and its response to external refractive index," *Electron. Lett.* **36**, 966-967 (2000).
- [3] G. G. Liu, K. W. Li, P. Hao, W. C. Zhou, Y. H. Wu, and M. Xuan, "Bent optical fiber taper for refractive index detection with a high sensitivity," *Sensor Actuat. A-Phys* **201**, 352-356 (2013).
- [4] H. Tazawa, T. Kanie, and M. Katayama, "Fiber-optic coupler based refractive index sensor and its application to biosensing," *Appl. Phys. Lett.* **91**, 113901 (2007).
- [5] K. T. Kim, K. J. Cho, K. Im, S. J. Baik, C. H. Lee, and J. Lee, "High Sensitivity Refractive Index Sensor Based on a Wet-Etched Fused Fiber Coupler," *IEEE Sens. J.* **11**, 1568-1572 (2011).
- [6] L. Bo, P. F. Wang, Y. Semenova, and G. Farrell, "High Sensitivity Fiber Refractometer Based on an Optical Microfiber Coupler," *IEEE Photonic Tech. L.* **25**, 228-230 (2013).
- [7] D. Monzon-Hernandez, J. Villatoro, D. Talavera, and D. Luna-Moreno, "Optical-fiber surface-plasmon resonance sensor with multiple resonance peaks," *Appl. Opt.* **43**, 1216-1220 (2004).
- [8] G. G. Liu, Y. H. Wu, K. W. Li, P. Hao, P. Zhang, and M. Xuan, "Mie Scattering-Enhanced Fiber-Optic Refractometer," *IEEE Photonic Tech. L.* **24**, 658-660 (2012).
- [9] L. Bo, C. C. O'Mahony, Y. Semenova, N. Gilmartin, P. Wang, and G. Farrell, "Microfiber coupler based label-free immunosensor," *Opt. Express* **22**, 8150-8155 (2014).
- [10] S. Wang, Y. Liao, H. Yang, X. Wang, and J. Wang, "Modeling seawater salinity and temperature sensing based on directional coupler assembled by polyimide-coated micro/nanofibers," *Appl. Opt.* **54**, 10283-10289 (2015).
- [11] S. C. Yan, Y. Chen, C. Li, F. Xu, and Y. Q. Lu, "Differential twin receiving fiber-optic magnetic field and electric current sensor utilizing a microfiber coupler," *Opt. Express* **23**, 9407-9414 (2015).
- [12] L. F. Luo, S. L. Pu, J. L. Tang, X. L. Zeng, and M. Lahoubi, "Highly sensitive magnetic field sensor based on microfiber coupler with magnetic fluid," *Appl. Phys. Lett.* **106**, 193507 (2015).
- [13] A. Yariv and P. Yeh, *Photonics: optical electronics in modern communications* (Oxford University Press, Inc., 1997), Vol. p.526-531.
- [14] S. W. Yang, T. L. Wu, C. W. Wu, and H. C. Chang, "Numerical modeling of weakly fused fiber-optic polarization beamsplitters - Part II: The three-dimensional electromagnetic model," *J. Lightwave Technol.* **16**, 691-696 (1998).
- [15] J. Li, L. P. Sun, S. Gao, Z. Quan, Y. L. Chang, Y. Ran, L. Jin, and B. O. Guan, "Ultrasensitive refractive-index sensors based on rectangular silica microfibers," *Opt. Lett.* **36**, 3593-3595 (2011).
- [16] K. F. Palmer and D. Williams, "Optical properties of water in the near infrared," *J. Opt. Soc. Am.* **64**, 1107-1110 (1974).