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2016

Li, K., Zhang, T., Liu, G., Zhang, N., Zhang, M., & Wei, L. (2016). Ultrasensitive optical microfiber coupler based sensors operating near the turning point of effective group index difference. *Applied Physics Letters*, 109(10), 101101-.

<https://hdl.handle.net/10356/83935>

<https://doi.org/10.1063/1.4961981>

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Ultrasensitive optical microfiber coupler based sensors operating near the turning point of effective group index difference

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(Received 21 May 2016; accepted 28 July 2016; published online 6 September 2016)

We propose and study an optical microfiber coupler (OMC) sensor working near the turning point of effective group index difference between the even supermode and odd supermode to achieve high refractive index (RI) sensitivity. Theoretical calculations reveal that infinite sensitivity can be obtained when the measured RI is close to the turning point value. This diameter-dependent turning point corresponds to the condition that the effective group index difference equals zero. To validate our proposed sensing mechanism, we experimentally demonstrate an ultrahigh sensitivity of 39541.7 nm/RIU at a low ambient RI of 1.3334 based on an OMC with the diameter of 1.4 μm . An even higher sensitivity can be achieved by carrying out the measurements at RI closer to the turning point. The resulting ultrasensitive RI sensing platform offers a substantial impact on a variety of applications from high performance trace analyte detection to small molecule sensing. Published by AIP Publishing. [<http://dx.doi.org/10.1063/1.4961981>]

Recent advances in optical fiber refractive index (RI) sensors have enabled a large number of studies and applications, especially in environmental monitoring, food safety, and biomedical diagnosis. Compared with conventional bulk optics or planar waveguide approaches, optical fiber sensors offer unique advantages including small size, long interaction length between analytes and light, easy alignment, industry-scalable fabrication, and low cost. To date, comprehensive investigations have been made on optical fiber RI sensors with the configurations ranging from a simple form of tapered fiber^{1,2} to a variety of new ones, including fiber grating sensors,^{3,4} optical couplers,⁵⁻⁹ photonic crystal fiber sensors,^{10,11} fiber-optic surface plasmonic sensors,^{12,13} as well as nanoparticle enhanced fiber-optic sensors.^{14,15} However, most of these sensors exhibit high sensitivity only when the RI of the surrounding medium approaches that of the optical fiber (~ 1.44). This is due to the fact that evanescent field becomes prominent when the ambient refractive index (ARI) is close to that of the optical fiber, thus enhancing light-matter interaction. In practice, biomolecules under detection are virtually prepared in the form of solutions which have a RI quite close to that of water (~ 1.33); thus, to achieve high sensitivity in detection of trace analytes and small molecules still remains fundamentally challenging for fiber-based sensors.

Yu and Fan proposed a concept of multi-mode sensing, which in principle could achieve extremely high spectral sensitivity by designing the dispersion relation of the probing wave.¹⁶ In this paper, we propose an optical microfiber coupler (OMC) based RI sensor which can achieve ultrahigh sensitivity at low ARI around 1.33 by taking advantage of the turning point of the effective group index difference

between the even supermode and odd supermode. OMC based RI sensors have been previously studied⁵⁻⁷ and various sensing applications can be found from biosensing,^{5,17} salinity sensing¹⁸ to magnetic field sensing.^{19,20} However, a systematical investigation on the IR sensing performance of OMC based sensors has not been reported. Here, we first lay a theoretical foundation of the OMC, and then through numerical calculations we discover a turning point where the effective group index difference equals zero. By taking advantage of this turning point, the RI sensitivity could be dramatically enhanced and approaches infinity as the effective group index difference comes close to zero. Thus, by carefully designing the OMC, we can achieve ultrahigh sensitivity at low RI range. Furthermore, we experimentally validate the sensing mechanism and confirm a good agreement with the expected theoretical results. By fabricating an OMC with a diameter of 1.4 μm which possesses a turning point around RI of 1.33, we achieve an ultrahigh sensitivity of 39541.7 nm/RIU at a low ARI of 1.3334.

Figure 1(a) is a schematic showing a typical OMC. The device comprises two parallel and closely packed microfibers

FIG. 1. (a) Schematic diagram of the microfiber coupler. (b) Modal field profiles of the even supermode and odd supermode for TE polarization with fiber diameter $D = 1.4 \mu\text{m}$ and ARI = 1.3325.

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with two input (P1 and P2) and two output ports (P3 and P4), two transition tapers, and a central uniform waist region. The modal fields injected from the input ports are often referred to as supermodes, which include even and odd distributions as shown in Fig. 1(a). Power exchange occurs as the even and odd supermodes propagate along the OMC and thus an interferometric spectrum is obtained at the output ports. The spectral interference pattern is dependent on the surrounding RI, and thus by tracking the peak or valley wavelengths the measured RI can be inferred. According to the hybrid mode theory,²¹ in a coupler with small excess loss, only the even supermode and odd supermode can be excited if the adiabatic condition is satisfied. Therefore, in our analysis below, only the coupling between the two lowest-order supermodes is considered. Fig. 1(b) shows typical modal field profiles of the even supermode and odd supermode for TE polarization supported by an OMC with fiber diameter $D = 1.4 \mu\text{m}$ and ARI = 1.3325.

According to the supermode theory,²² the two parallel and clingly microfibers are regarded as a new waveguide. When light in TE/TM polarization is launched into input port P₁, both the even supermode and the odd supermode are excited equally and simultaneously. The beating between these two modes provides the coupling of power along the coupler. The output powers at through port P₃ and cross port P₄ are then given by²³

$$P_3 = P_1 \cos^2\left(\frac{1}{2}\phi\right), \quad (1)$$

$$P_4 = P_1 \sin^2\left(\frac{1}{2}\phi\right), \quad (2)$$

where ϕ represents the phase difference between the two supermodes accumulated along the coupling region for TE/TM polarization. In fact, the phase difference induced in the transition regions is much lower than that in the waist region because of the larger geometric size. Thereby, we can approximately express the phase term ϕ as that of a uniform microfiber coupler²³

$$\phi = (\beta_{\text{even}} - \beta_{\text{odd}})L = \frac{2\pi L(n_{\text{eff}}^{\text{even}} - n_{\text{eff}}^{\text{odd}})}{\lambda}, \quad (3)$$

where β_{even} , β_{odd} and $n_{\text{eff}}^{\text{even}}$, $n_{\text{eff}}^{\text{odd}}$ are propagation constants and effective RI of the even and odd supermodes for TE/TM polarization, respectively. L and λ represent the length of the coupling region and wavelength, respectively. The wavelength position of the N th dip λ_N in the transmitted spectrum of the through port satisfies

$$\phi_N = \frac{2\pi L(n_{\text{eff}}^{\text{even}} - n_{\text{eff}}^{\text{odd}})}{\lambda_N} = (2N - 1)\pi, \quad (4)$$

where ϕ_N is the phase difference of the N th dip and N is a positive integer.

We numerically calculate the effective RI (n_{eff}) and the power proportion of the evanescent field (η) using a FEM method (COMSOL Multiphysics 4.4). The RIs of the coupler and surrounding medium are 1.4362 and 1.3325, respectively, and the wavelength is 1550 nm. From Fig. 2, we can

FIG. 2. Calculated effective refractive index and evanescent power fraction of the TE/TM even mode and odd mode at wavelength $1.55 \mu\text{m}$ with respect to the microfiber diameter.

find that n_{eff} decreases and η increases as the fiber diameter decreases, owing to the fact that a larger portion of optical power converts into evanescent field as the diameter gets smaller. Furthermore, both even and odd supermodes have cut-off diameters. We can infer that when the diameter lies between the cut-off point of the even mode and odd mode, only the even mode can be supported; thus, the optical power is equally divided into the two output ports, which is useful for designing ultra-broadband single mode fiber couplers.²⁴ Whereas for sensing applications, the diameter should be larger than the odd mode cut-off diameter in order to introduce the odd mode that would interfere with the even mode.

By taking a small variation from Eq. (4), the spectral dependency on the external RI is obtained as²⁵

$$S = \frac{\partial \lambda_N}{\partial n} = \frac{\lambda_N}{\Delta n_{\text{eff}} - \lambda_N \partial(\Delta n_{\text{eff}})/\partial \lambda} \frac{\partial(\Delta n_{\text{eff}})}{\partial n}, \quad (5)$$

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 the effective group index difference between even and odd supermodes for TE/TM polarization. For simplicity, we focus on TE polarization in the following calculations and experiments. The results for TM polarization are similar, as illustrated in Fig. 2.

Figure 3 shows the calculated effective group index difference G for an OMC as a function of fiber diameter D with different ARIs of 1.3263, 1.3500, 1.3700, 1.3900, and 1.4100 at wavelength 1550 nm. It is clear that the curve for G consists of two regions (i.e., $G > 0$ and $G < 0$). For $G > 0$, when D increases from the cut-off point to the turning point, G is a positive value and it decreases rapidly towards 0. On the other side, G increases rapidly from a negative value towards 0 as D decreases. According to Eq. (5), the RI sensitivity can reach infinity when $G = 0$. On both sides of the turning point, ultrahigh sensitivity could be achieved when D approaches the turning point value. Moreover, the variation trends of G are similar for different ARIs of 1.3263, 1.3500, 1.3700, 1.3900, and 1.4100, while the diameters corresponding to the turning point gradually increase from 1.4 to $2.8 \mu\text{m}$, which means that the turning point shifts to larger diameters as the ARI increases.

FIG. 3. (a) Effective group index difference versus fiber diameter with different ARIs 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 ARIs at wavelength 1550 nm.

Then, we calculate the RI sensitivities of the resulting OMC based sensors as a function of diameter ranging from 1 to 5 μm for different ARIs at wavelength 1550 nm. As depicted in Fig. 3(b), an extremely high sensitivity can be achieved when G approaches zero. When fiber diameter D is smaller than the turning point diameter, the sensitivity dramatically increases towards $-\infty$ as the diameter increases. While on the other side, when the diameter is larger than the turning point diameter, the sensitivity is significantly enhanced towards $+\infty$ as the diameter approaches the turning point. The turning point of the RI sensitivity moves towards larger diameters as ARI increases. According to Fig. 3(b), an ultrahigh sensitivity above 20 000 nm/RIU at low ARI 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. It should be noted that, however, when the diameter is relatively large, e.g., when D exceeds 2.41 μm , the OMC has a relatively low negative sensitivity of below 3000 nm/RIU , which is consistent with published results.⁷

To experimentally examine our theoretical findings, we fabricate OMC sensors with thin diameters around the turning point by tapering two twisted standard telecom single mode fibers (SMF-28, Corning, NY, USA) using a flame brushing method. Then, we fix the OMC in a specially designed fluid cell to keep it stable for RI sensing. The

fabricated OMC has a 2.5 mm long uniform waist region formed by two weakly fused microfibers each with a 1.4 μm diameter (see the inset in Fig. 4(a)). The uniform region is connected to the input ports (P1 and P2) and the output ports (P3 and P4) through two transition regions with a length of 12 mm and should be adiabatic for the even and odd supermodes. To eliminate the influence of temperature, the sensing experiments are carried out in a clean room environment where the temperature is kept at $24.50 \pm 0.15^\circ\text{C}$. All the RI solutions are stored at the same room temperature to eliminate the temperature difference. The whole sensing experiment is finished within 1 h to minimize the influence from the environment.

We test the RI sensing performance by sequentially injecting sucrose solutions with different RIs of 1.3325, 1.3329, 1.3334, and 1.3339 into the fluid cell. Fig. 4(a) shows the typical transmitted spectral response of the OMC for RI sensing. The interference dips tend to redshift dramatically when ARI increases slightly. The RI sensitivity is higher for long wavelength than for 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 based sensors at low RI around 1.33. We plot the wavelengths for different dips in our experiment together with numerical simulation results in Fig. 4(b), and our experimental results agree well with the theoretical

FIG. 4. (a) Transmission spectral responses to different ARIs of 1.3325, 1.3329, 1.3334, and 1.3339. Black arrows are to guide the shift of interference dips as ARI 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 ARI.

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. From the numerical results, we infer that higher sensitivity can be obtained for interference dips at longer wavelengths. We can also expect a negative sensitivity for interference dips at even longer wavelengths. However, in our experiments, similar responses are not observed. We believe this is caused by that the intervals between two adjacent interference dips increase dramatically as wavelength increases, and thus the dips for longer wavelengths shift beyond the cut-off wavelength of the odd mode. 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 around 1450 nm.^{25,26} Although the sensitivity of our sensor is very high, the dynamic range is relatively narrow, as shown in Fig. 4(a). A feasible method to broaden the dynamic range is to reduce the coupling length L , which eventually would enlarge the period of oscillation in the output spectrum. However, it will also lead to a decrease to the quality factor of the interference dips. The trade-off between the quality factor and dynamic range should be considered when the OMC based RI sensor is applied to different occasions.

In conclusion, we present a comprehensive study on the RI sensing performance of OMC based sensors around the turning point of the effective group index difference between even and odd supermodes. Both theoretical and experimental results demonstrate an ultrahigh sensitivity, and a sensitivity of 39541.7 nm/RIU at a low ARI of 1.3334 using a 1.4 μm -thick OMC is experimentally achieved. The resulting ultrasensitive mechanism not only opens up opportunities to a wide range of applications in chemical and biological sensing fields but also broadens the repertoire of other interferometric fiber-optic sensors and even acoustic sensors.

This work was supported in part by the Singapore Ministry of Education Academic Research Fund Tier 2

(MOE2015-T2-1-066) and Nanyang Technological University (Start-up grant: Lei Wei).

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