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High Sensitivity Fiber Refractometer Based on an Optical Microfiber Coupler

Lin Bo, Pengfei Wang, Yuliya Semenova, and Gerald Farrell

***Abstract*— An optical microfiber coupler-based refractive index sensor is proposed and experimentally demonstrated in this letter. A microfiber coupler with a minimum diameter of 2.5 μm and a uniform waist with a length of 2 mm is fabricated and used for sensing surrounding refractive index. Both theoretical and experimental results have shown that the spectral response of the proposed microfiber coupler is highly sensitive to the surrounding refractive index over the range from 1.3340 to 1.3800. An average sensitivity of 2723 nm/RIU over this entire refractive index range has been achieved experimentally. Furthermore, for the refractive index range from 1.3340 to 1.3515, this sensor has demonstrated high sensitivity of 4155 nm/RIU.**

***Index Terms*— Fiber coupler, optical microfiber, refractive index sensor.**

I. Introduction

SINCE the first demonstration of silica subwavelength-diameter optical fibers in 2003 [1], increasing research interest has been given to optical microfiber and nanowire related photonic devices. While maintaining the same useful attributes as conventional optical fibers, microfibers have several extra advantages such as micro-scale size, large evanescent field, strong light confinement and great configurability [2]. Those unique properties give microfiber based photonic devices the potential to form the basis of novel sensors offering high sensitivity, small footprint, compact size, low cost and fast response.

To date several types of microfiber based RI sensors have been proposed. Examples include microfiber loop resonators [3], microsphere resonators [4], and microfiber coil resonators [5]. However they have either relatively low sensitivity, typically 40–800 nm/RIU, or they need complex manipulation of the microfibers to form the sensing structure. Recently, a twisted optical microfiber refractometer utilizing evanescent fields coupling between tapered microfiber sections has been proposed [6] which allows for the measurement of RI with a sensitivity of 2735 nm/RIU. As an alternative to the existing microfiber refractometers, a refractometer using the reflection spectra of a non-adiabatically tapered single-mode fiber has been proposed. A maximum sensitivity of 18681.82 nm/RIU has been achieved [7].

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Recently the authors of [8] have presented a broadband bi-conical 2×2 optical microfiber coupler (MFC) made from conventional telecom single-mode fibers that effectively suppresses any higher-order modes present at the input fiber and provides efficient power splitting between the two output ports. This microfiber coupler has many potential applications, for example in high performance fiber lasers, fiber sensors and optical coherence tomography systems. Furthermore MFC based thermometers [9], [10] and ultra-broadband 3 dB coupler [11] have also been demonstrated recently. Earlier research on the dependence of the coupling coefficient of traditional fused bi-conical tapered couplers on the external RI has been presented and it has been shown that it is possible to use such a structure to develop a fiber based refractometer [12], [13].

In this letter, we report for the first time the application of an MFC structure, with a diameter of 2.5 μm, as a high sensitivity refractometric sensor. We experimentally demonstrate that the sensor is capable of an RI sensitivity of 2723 nm/ RIU over the RI range of 1.3340 to 1.3800, with a maximum sensitivity circa 4155 nm/RIU within the RI range of 1.3340 to 1.3515. The resolution of this microfiber coupler based RI sensor is circa 3.67×10^{-5} RIU.

II. Theory

The coupled wave equations for the microfiber coupling have been derived in [14] and [15]. However, a simple analytical method has been chosen for an initial approximate theoretical analysis in this letter.

Traditionally when an optical fiber is tapered down to a scale such that the diameter of the fiber is comparable with the wavelength of the transmitted light, the fiber becomes a micro-scale diameter waveguide with an air cladding. Under these conditions, for a weakly fused MFC, the coupling coefficient can be approximated by [16]:

$$C(\lambda)=\frac{\pi\sqrt{n_1^2-n_2^2}}{2an_1}e^{-2.3026(A+B\tau+C\tau^2)} \tag{1}$$

$$\begin{array}{ll}
A=a_1+a_2V+a_3V^2 & a_1=2.2926\\
B=b_1+b_2V+b_3V^2 & b_1=-0.3374\\
C=c_1+c_2V+c_3V^2 & c_1=-0.0076\\
a_2=-1.591 & a_3=-0.1668\\
b_2=0.5321 & b_3=-0.0066\\
c_2=-0.0028 & c_3=0.0004
\end{array}$$

where λ is the wavelength, n_1 and n_2 are the RIs of the silica fiber cladding and the surrounding medium, a is the radius of

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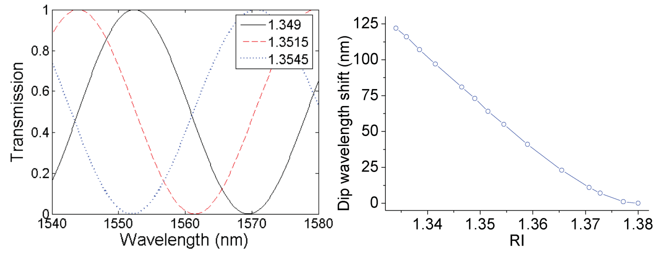


(a) (b)

Fig. 1. (a) Calculated spectral response of the proposed MFC in different RI media. (b) Calculated dip wavelength shift versus medium RI.

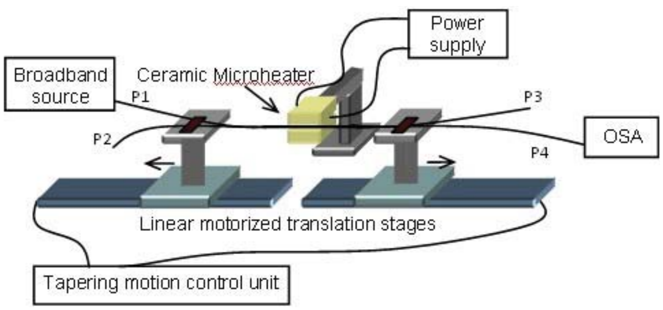


Fig. 2. Microfiber coupler fabrication setup.

the microfiber, $\tau = d/a$, d is the distance between the axes of the fused microfibers, V is the normalized frequency where $V = \left[(2\pi a)/\lambda\right] \cdot \left(n_1^2 - n_2^2\right)^{1/2}$.

The output power of the coupled port of the MFC is given by

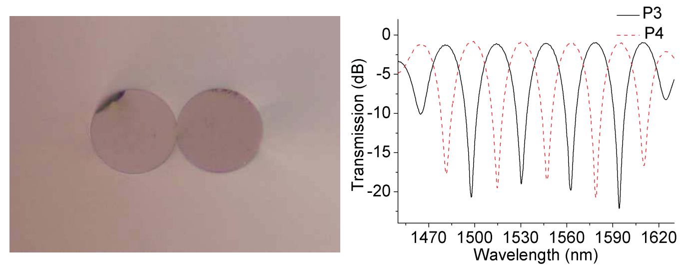
$$P(\lambda) = P_0 \cos^2\left(C L_{eff}\right) \tag{2}$$

where P_0 and P are the input power and the output power and L_{eff} is the effective coupling length.

The RI of silica microfiber estimated in the model is 1.45. For an MFC with a radius of 1.25 μm, an effective coupling length of 2 mm and $\tau = 2$, Fig. 1(a) shows the calculated transmission spectra when the surrounding RI is 1.3490, 1.3515 and 1.3545, respectively. From the figure, one can see that an increase in the surrounding RI causes a significant blue shift of the dip wavelength. The relationship between the surrounding medium RI and the dip wavelength shift is shown in Fig. 1(b). The calculated result shows that an average sensitivity of circa 2609 nm/RIU over an RI range between 1.3340 and 1.3800 is expected for the proposed MFC RI sensor.

III. Microfiber Coupler Fabrication

To verify the theoretical estimates presented in the previous section, the MFC was fabricated by tapering and fusing two standard telecom single-mode optical fibers (SMF-28, Corning) together at the same time using a method known as the microheater brushing technique [17]. Fig. 2 shows the fabrication setup. The fibers were placed in close proximity before being fixed on two linear motorized translation stages. The fibers were also slightly twisted together to ensure the fibers remained in contact during fabrication. A ceramic microheater (CMH-7019, NTT-AT) was used to heat up the fibers to circa 1300°C, making the silica fibers soft enough for tapering and fusing. The translation stages were precisely controlled by a motion control unit connected to a personal computer (PC). A customized program on the PC made it possible to control the diameter, the length and the shape of the fabricated tapers [18].



(a) (b)

Fig. 3. (a) Microscope image showing the cross section of the MFC cut in the middle of the waist, indicating that the MFC is weakly fused. (b) Spectral responses of the two output ports (P3 and P4) of the MFC in the air at room temperature.

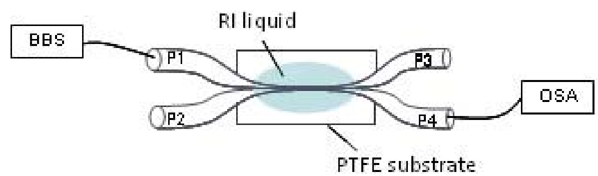


Fig. 4. Schematic diagram of the experimental setup.

The fabricated MFC has a 2 mm long uniform waist region formed by two weakly fused microfibers each with a 2.5 μm diameter. 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 27 mm. The fabricated tapers should be adiabatic for the LP01 mode as the profile of the transition region falls within the adiabatic regime demonstrated in [8].

A microscope image of the cross-section of the MFC cut at the uniform waist region is shown in Fig. 3(a). From the shape of the cross section one can see that the microfibers are weakly fused together. Fig. 3(b) shows the measured transmission spectral responses of the output ports P3 and P4 in air over a wavelength range of 1450 nm to 1630 nm.

IV. Refractive Index Sensing Measurements and Discussion

In order to experimentally investigate the RI sensitivity of the MFC, we immersed the coupling region of the MFC in a series of dimethyl sulfoxide/water solutions with different calibrated RIs ranging from 1.3340 to 1.3800 with an interval of circa 0.0030. The schematic of the experimental setup is shown in Fig. 4. As shown in the figure, the MFC was placed on a PTFE flat panel (Teflon) which has a relatively low RI since materials with a high RI will absorb the transmitted light due to the large evanescent field of the microfibers. Subsequently the different RI liquids were placed as a drop around the coupling section to create a surrounding medium with different RIs.

In the experiments the RI of the set of liquids was calibrated using a commercial refractometer (ABBE5,

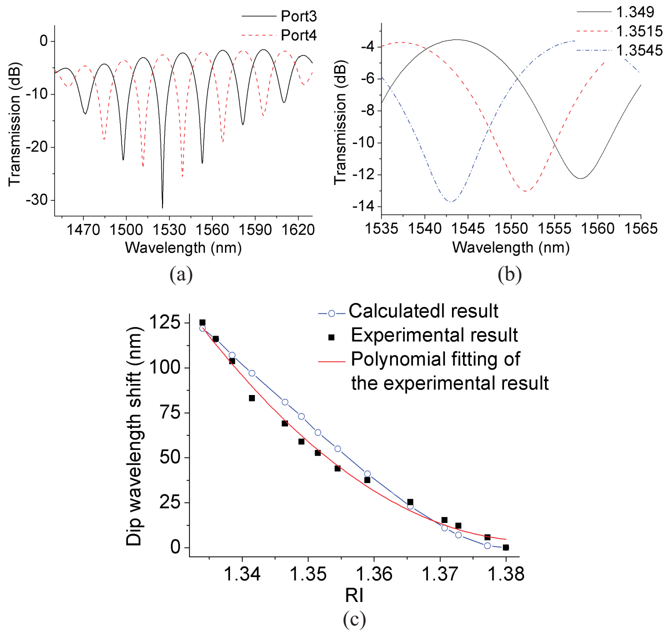


Fig. 5. (a) Spectral response of the two output ports (P3 and P4) in a liquid (RI = 1.3340). (b) Examples of spectral responses of the MFC surrounded by liquids with different RI (1.3490, 1.3515, and 1.3545). (c) Dip wavelength shift versus medium RI change.

Bellingham +Stanley). Radiation from a broadband source (SLD-6597, COVEGA) covering an output wavelength range of 1450 to 1630 nm was launched into P1 and the output light was collected from P4 using an optical spectrum analyzer (Q8384, ADVANTEST).

When the coupling region is immersed in the liquid, the MFC maintains a good coupling symmetry as in air. The transmission spectral responses measured at P3 and P4 when the MFC is immersed in liquid are shown in Fig. 5(a). Fig. 5(b) shows the measured spectral responses of the MFC for three surrounding medium RI values used in the previous calculations shown in Fig. 1(a). As one can see the experimental results show a good match with the calculated results in Fig. 1. When the external RI increases, the selected dip wavelength of the spectrum experiences a blue shift within the measured RI range. The experimental and the calculated results for the relationship between the dip wavelength shift and the surrounding medium RI are compared in Fig. 5(c). The experimental results show that the fabricated sensor has an average sensitivity of circa 2723 nm/RIU over the entire measured RI range from 1.3340 to 1.3800. Furthermore a high sensitivity of 4155 nm/RIU is obtained for the RI range from 1.3340 to 1.3515.

One can also see from Fig. 5(c) that the measured result is in good agreement with the calculated result. The perceptible discrepancy between the experimental and theoretical results may be caused by (1) the limitation of the theoretical model which has only considered the coupling between two parallel fibers with a uniform diameter and an ideal cylindrical shape. However the fabricated MFC has a considerable transition region length of transition region which is tapered in shape and where the fibers are not strictly parallel; (2) as illustrated in Fig. 4, the mechanical stability of the MFC may be disturbed by the dropping and removing of the RI liquids during the measurements; (3) the MFC is highly sensitive to the temperature change [10] and the RI of the liquid is also temperature dependent; (4) finally, the limited physical accuracy of the achieved diameter of the uniform waist of the fabricated MFC.

V. Conclusion

In summary, a highly-sensitive RI sensor based on an optical MFC has been proposed and investigated. The MFC is highly sensitive to the surrounding RI. The experimentally measured sensitivity of the proposed MFC reached on average 2723 nm/RIU and a maximum sensitivity was as high as 4155 nm/RIU at an RI = 1.3340. Compared with the conventional fused fiber coupler-based refractometer, our device has shown not only a high sensitivity. Furthermore, the compact dimensions of our device allow for very good spatial resolution, in applications where RI can change over miniscule distances.

References

[1] L. M. Tong, *et al.*, “Subwavelength-diameter silica wires for low-loss optical wave guiding,” *Nature*, vol. 426, pp. 816–819, Dec. 2003.
[2] G. Brambilla, *et al.*, “Optical fiber nanowires and microwires: Fabrication and applications,” *Adv. Opt. Photon.*, vol. 1, pp. 107–161, Jan. 2009.
[3] X. Guo and L. M. Tong, “Supported microfiber loops for optical sensing,” *Opt. Express*, vol. 16, pp. 14429–14434, Sep. 2008.
[4] N. M. Hanumegowda, C. J. Stica, B. C. Patel, I. White, and X. Fan, “Refractometric sensors based on microsphere resonators,” *Appl. Phys. Lett.*, vol. 87, pp. 201107-1–201107-3, Nov. 2005.
[5] F. Xu and G. Brambilla, “Demonstration of a refractometric sensor based on optical microfiber coil resonator,” *Appl. Phys. Lett.*, vol. 92, pp. 101126-1–101126-3, Mar. 2008.
[6] C. R. Liao, D. N. Wang, X. He, and M. W. Yang, “Twisted optical microfibers for refractive index sensing,” *IEEE Photon. Technol. Lett.*, vol. 23, no. 13, pp. 848–850, Jul. 1, 2011.
[7] W. B. Ji, H. H. Liu, K. K. Chow, S. C. Tjin, and A. Lim, “Ultrahigh sensitivity refractive index sensor based on optical microfiber,” *IEEE Photon. Technol. Lett.*, vol. 24, no. 20, pp. 1872–1874, Oct. 15, 2012.
[8] Y. Jung, G. Brambilla, and D. J. Richardson, “Optical microfiber coupler for broadband single-mode operation,” *Opt. Express*, vol. 17, no. 7, pp. 5273–5278, Mar. 2009.
[9] M. Ding, P. Wang, and G. Brambilla, “A microfiber coupler tip thermometer,” *Opt. Express*, vol. 20, no. 5, pp. 5402–5408, Feb. 2012.
[10] P. Wang, M. Ding, G. Brambilla, Y. Semenova, Q. Wu, and G. Farrell, “High temperature performance of an optical microfiber coupler and its potential use as a sensor,” *Electron. Lett.*, vol. 48, no. 5, pp. 283–284, Mar. 2012.
[11] M. Ding, P. Wang, T. Lee, and G. Brambillla, “A microfiber cavity with minimal-volume confinement,” *Appl. Phys. Lett.*, vol. 99, pp. 051105-1–051105-3, Aug. 2011.
[12] R. G. Lamont, D. C. Johnson, and K. O. Hill, “Power transfer in fused biconical-taper single-mode fiber couplers: Dependence on external refractive index,” *Appl. Opt.*, vol. 24, pp. 327–332, Feb. 1985.
[13] F. P. Payne, R. Finegan, M. S. Yataki, R. J. Mears, and C. D. Hussey, “Dependence of fused taper couplers on external refractive index,” *Electron. Lett.*, vol. 22, no. 22, pp. 1207–1209, Oct. 1986.
[14] F. Xu, P. Horak, and G. Brambilla, “Optimized design of microcoil resonators,” *J. Lightw. Technol.*, vol. 25, no. 6, pp. 1561–1567, Jun. 2007.
[15] M. Sumetsky, “Optical fiber microcoil resonator,” *Opt. Express*, vol. 12, pp. 2303–2316, May 2004.
[16] R. Tewari and K. Thyagarajan, “Analysis of tunable single-mode fiber directional couplers using simple and accurate relations,” *J. Lightw. Technol.*, vol. 4, no. 4, pp. 386–390, Apr. 1986.
[17] G. Brambilla, V. Finazzi, and D. Richardson, “Ultra-low-loss optical fiber nanotapers,” *Opt. Express*, vol. 12, pp. 2258–2263, May 2004.
[18] T. A. Birks and Y. W. Li, “The shape of fiber tapers,” *J. Lightw. Technol.*, vol. 10, no. 4, pp. 432–438, Apr. 1992.