Ultrahigh sensitivity refractive index sensor based on optical microfiber

Ji, Wen Bin; Liu, Huan Huan; Tjin, Swee Chuan; Chow, Kin Kee; Lim, Anthony

2012

Ji, W. B., Liu, H. H., Tjin, S. C., Chow, K. K., & Lim, A. (2012). Ultrahigh sensitivity refractive index sensor based on optical microfiber. IEEE photonics technology letters, 24(20), 1872-1874.

https://hdl.handle.net/10356/102804

https://doi.org/10.1109/LPT.2012.2217738

Ultra-high sensitivity refractive index sensor based on optical microfiber

Wen Bin Ji, Huan Huan Liu, Swee Chuan Tjin, Kin Kee Chow, Anthony Lim

Abstract— **We demonstrate a nonadiabatic microfiber sensor with a taper diameter of few micrometers. The modal interference caused by the abrupt taper results in a sinusoidal spectral response. The wavelength shift arising from the changes in the external refractive index is found to be significant with a maximum sensitivity of 18681.82nm/RIU achieved. The measured results show a good agreement with the theoretical predictions. The high sensitivity and the simplicity offer the sensor the potential for many real applications.**

***Index Terms*—Optical fiber, refractive index sensor, microfiber, nonadiabatic taper**

I. INTRODUCTION

RECENTLY refractive index (RI) sensors based on optical microfibers have attracted increasing attention since they have large evanescent field, high nonlinearity and low-loss interconnection to single-mode fiber [1]. Meanwhile they normally do not require complicated and expensive experimental set-up. These sensors such as a microfiber coil resonator based sensor [2], a double-pass in-line fiber taper Mazh-Zehnder Interferometer (MZI) sensor [3], the microfiber mode interferometers [4]-[6] and a microfiber probe with micro-cavity as temperature sensor [7] all demonstrate good sensing capability. Other than these, the highly birefringent microfiber sensors [8][9] and the rectangular silica microfiber sensor [10] have exhibited extraordinary sensitivities. The slot-microfiber [9] has both the advantages of birefringence and micro-machining in the fiber.

In this letter, a nonadiabatic microfiber-based refractive index sensor with ultra-high sensitivity is reported using a piece of standard single-mode fiber tapered to around 4.61 μm with large taper slope. With comparison to the microfiber mode interferometer [4]-[6], our sensor has achieved a smaller diameter of the microfiber which makes it performing better in terms of sensitivity and the sharp taper slope causes larger extinction ratio which increases the measurement accuracy. The adoption of the reflection spectrum further increased the extinction ratio. Moreover, our consolidated numerical modal well explained the experimental effects. It is also worth mention that generally the smaller diameter of the microfiber gives a higher sensitivity as more evanescent field will expose to the surrounding of the fiber. For those adiabatic microfiber sensors, the diameter is difficult to approach the scale of a few micrometers since the taper transitions need to be sufficient long to keep the wavelength response nearly without fluctuations that are not caused by light source. The abruptly tapered fiber can be fabricated with a much smaller diameter hence the high sensitivity could be easier to achieve compared with the smoothly tapered fiber.

Manuscript received July 20, 2012. This work was supported by the Ministry of Education via Nanyang Technological University, Singapore.

The authors are with the Photonics Research Center, Nanyang Technological University, Singapore (e-mail: wbji@ntu.edu.sg)

II. NUMERICAL ANALYSIS

For a nonadiabatic biconical fiber taper, it has been shown that most of the light energy from the fundamental mode of the untapered region will couple into the first two modes HE_{11} and HE_{12} in the tapered region [11]. As a result the modal interference spectrum can be expressed as

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\varphi\ , \tag{1}$$

where I_m (m=1,2) is the power coupling between the fundamental mode and the HE_{1m} mode, and φ is the phase difference of the two modes. For a uniform beating region, it takes the form

$$\varphi = \Delta\beta L \tag{2}$$

where L is the length of the beating region, and $\Delta\beta$ is the difference between the propagation constants of the two modes, which can be theoretically represented as [12]

$$\Delta\beta = \frac{\lambda(U_2^{\infty 2} - U_1^{\infty 2})}{4\pi n_{clad}\rho^2}\exp\left(-\frac{2}{V}\right). \tag{3}$$

In Eq. (3), V represents the normalized frequency given by

$$V = \frac{2\pi\rho}{\lambda}\sqrt{n_{clad}^2 - n_{ext}^2} \tag{4}$$

where n_{clad} is the refractive index of the fiber cladding, n_{ext} is the refractive index of the external medium, λ is the wavelength of light, ρ is the radius of the taper waist, and U_1^∞ and U_2^∞ are the asymptotic values of the U parameters of the two modes in which U_1^∞ (HE_{11})=2.405 and U_2^∞ (HE_{12})=5.520 in this case [13]. From the above expressions one can predict that the power spectrum is a close-form of sinusoidal function of wavelength. The free spectral range (FSR) can also be locally defined as a function of wavelength as [11]

$$FSR(\lambda) = \frac{2\pi}{\frac{d\varphi}{d\lambda}} = \frac{8\pi^2\rho^2 n_{clad}}{L(U_2^{\infty 2} - U_1^{\infty 2})\exp\left(-\frac{2}{V}\right)\left(1-\frac{2}{V}\right)}. \tag{5}$$

From Eqs. (2) to (4), the wavelength shift due to the change of external refractive index can be derived as

$$\Delta\lambda = \lambda * \left(\exp\left(\frac{2}{V'} - \frac{2}{V}\right) - 1 \right) \qquad (6)$$

where the revised normalized frequency V' follows

$$V' = \frac{2\pi\rho}{\lambda + \Delta\lambda}\sqrt{n_{clad}^2 - (n_{ext} + \Delta n_{ext})^2} \; . \qquad (7)$$

It can be observed that the value $(2/V' - 2/V)$ increases as n_{ext} increases and ρ decreases. In other words, the larger the external refractive index or the smaller the taper diameter, the higher the sensitivity of the sensor. However, the decrease of the taper diameter is limited by the propagating loss induced by light scattering on the surface of the taper waist. Thus, optimization of the taper diameter is required. Due to the reduced effective refractive index in the waist region, the mode of light propagating through the microfiber is broadened. Fig. 1 shows the simulation results on the ratio of optical power coupling out of the microfiber with different taper diameters. In order to obtain effectively sensing without significant propagating loss by the light scattering, microfiber with a diameter of around 4 μm is adopted in our experiment. The inset of Fig. 1 shows the simulated fundamental mode E-field profile of a microfiber with a diameter of 4 μm.

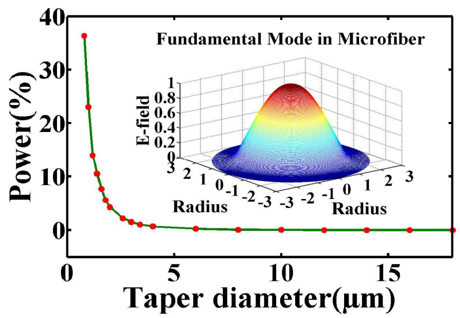
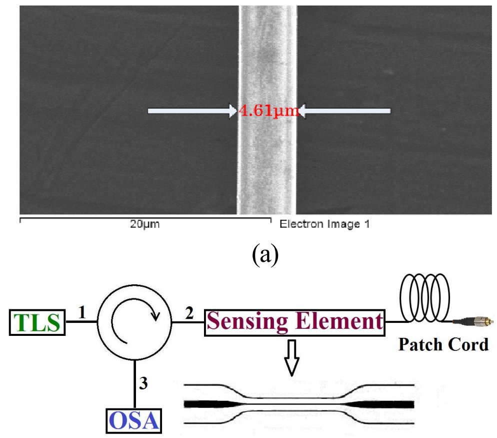


Fig. 1. Plot of optical power coupling out of a microfiber against different taper diameter. The inset shows the E-field profile of fundamental mode of a microfiber with a taper waist diameter of 4 μm.

III. Fabrication and Discussion of Results

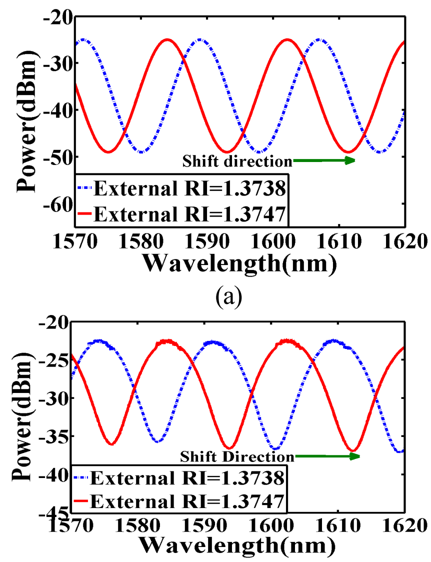
Fabrications of the microfiber are normally done by heating a fiber using a flame, a CO_2 laser, or a fusion splicer together with mechanical pulling. In our work, a fiber drawing machine (Vytran, GPX-3000) with motorized fiber holding stages is utilized to control the taper transition length, waist length, and waist diameter precisely so that the adiabaticity, the free spectral range (FSR) and the sensitivity of the fiber can be manipulated conveniently. The taper waist of the fabricated microfiber is generally uniform as it can be seen from the scanning electron microscope (SEM) image shown in Fig. 2(a). Since the unsymmetrical effect is common in tapering fiber as there is an initial tension to form the first transition and the tension to form the second transition will be much lower because the taper diameter has already been thinned, therefore the transition lengths are set differently to ensure the symmetry of the taper, which are 1 mm in the left side and 5 mm in the right side. The experimental result of transition lengths viewed from the microscope built in the tapering machine are around 2.4 mm for the left and 1.6 mm for the right. The uniform waist length in our work is set as 5 mm.



(a)

(b)

Fig. 2. (a) SEM image of the taper waist with a diameter of 4.61μm and (b) experimental set-up of the refractive index sensor.



(a)

(b)

Fig. 3. (a) Calculated results and (b) experimental results of wavelength response of the microfiber sensor surrounded by different concentration of the salt solutions.

Fig. 2(b) shows the schematic diagram of the experimental setup of the microfiber sensor. Output light from a tunable laser source (Ando TLS AQ4321D, 1520-1620 nm) is coupled into port 1 of the circulator through port 2 towards the microfiber. The microfiber is surrounded by a few droplets of salt solution. The salt solutions with different refractive index were prepared by diluting the saturated NaCl solution using distilled water. The refractive index was measured by a refractometer (KEM RA-130) with a resolution of 0.0001. Another end of fiber is terminated by a fiber patch cord. The effect of using the patch cord in this work is similar to coating a layer of gold on the end facet with the only difference being the lower reflectivity but more cost-effective. The reflected light from the microfiber is coupled via port 3 of the circulator to an optical spectrum analyzer (Ando OSA AQ6317B). The reason of investigating the reflection spectrum instead of the transmission spectrum is similar to the double-pass in-line fiber taper MZI sensor [3]. The extinction ratio of the received power is larger in the reflection spectrum thus the accuracy of reading the resonance wavelength dip value will be larger, while the sensitivity is the same in both reflection and transmission spectra.

From our experimental results (Fig. 3(b)), it is observed that an increase in external refractive index, a decrease in taper waist length, or an increase in wavelength will result in an increase in FSR which agrees with Eqs. (4) and Eqs. (5). More importantly, Fig. 3(a) and Fig. 3(b) depict the calculated results and the measured results of the wavelength response of the fabricated sensor respectively, which show good agreement with the simulated results. A tiny difference between the refractive index of the solution (around 0.0009) results in a resonance wavelength shift of over 10 nm.

Fig. 4 illustrates the wavelength shift as a function of RI ranging from 1.33 to 1.37. Note that the wavelength shift from 0 to 200 nm is not referencing one single resonant dip, instead the graph should be analyzed by looking into adjacent points. The small measuring range of RI reflects high sensitivity but is also a common drawback of such modal interferometers and MZI based sensors since the spectra have periodic responses. The possible ways to improve this are making the taper waist length shorter so that the FSR will be larger or alternatively, using asymmetrical taper such as the S shape taper [14] without compromising sensitivity. Fig. 5 shows the wavelength shift as a function of RI for two different fiber taper waist diameters, 4.61 μm (square data points) and 5.11 μm (circular data points). The fiber with smaller diameter shows a steeper slope suggesting that the fiber sensor has a higher sensitivity. In the RI range from 1.3707 to 1.3769, the measured average sensitivity for sensor with a diameter of 4.61 μm is 15532.24 nm/RIU and the maximum sensitivity achieved is 18681.82 nm/RIU. With our OSA's resolution of 10 pm, the detection limit for RI is 5.35×10^{-7}.

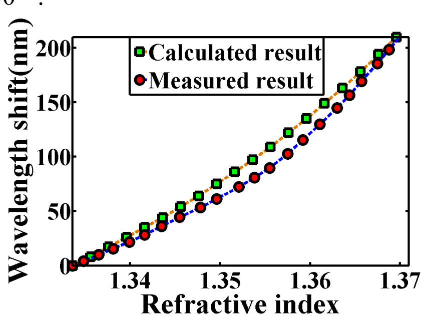


Fig. 4. Resonant wavelength shift as a function of RI: theoretical prediction and measured result for waist diameter ~5.11 μm .

IV. Conclusion

In conclusion, an RI sensor is fabricated by tapering a single-mode fiber into a few micrometers with abrupt taper transitions. The microfiber sensor has shown remarkable sensitivity and the maximum achieved is 18681.82 nm/RIU. The high sensitivity in the RI ranging from 1.3337 to 1.37 could be useful in detecting contamination of water, monitoring leakage for oil companies and so on. Moreover, the fabrication process is simple and the sensor is generally compact and robust.

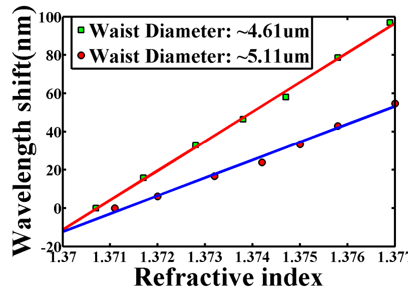


Fig. 5. Resonant wavelength shift as a function of RI: comparison for two different taper diameters.

References

[1] L. Tong, R. R. Gattass, J. B. Ashcom, S. He, J. Lou, M. Shen, I. Maxwell, E. Mazur, "Subwavelength-diameter silica wires for low-loss optical wave guiding," *Nature*, vol. 426, no. 6968, pp. 816-819, Dec. 2003.

[2] F. Xu, P. Horak, and G. Brambilla, "Optical microfiber coil resonator refractometric sensor," *Opt. Express*, vol. 15, no. 12, pp. 7888-7893, Jun. 2007.

[3] L. Yi, Liang, Chen, E. Harris, Xiaoyi, Bao, "Double-Pass In-line Fiber Taper Mach-Zehnder Interferometer Sensor," *IEEE Photon. Technol. Lett.*, vol. 22, no. 23, Dec. 1, 2010.

[4] K. Q. Kieu and M. Mansuripur, "Biconical fiber taper sensors," *IEEE Photon. Technol. Lett.*, vol. 18, no. 20, pp. 2239-2241, Nov. 1, 2006.

[5] P. F. Wang, G. Brambilla, M. Ding, Y. Semenova, Q. Wu, G. Farrell, "High-sensitivity, evanescent field refractometric sensor based on a tapered, multimode fiber interference," *Opt. Lett.*, vol. 36, no. 12, pp. 2233-2235, Jun. 2011.

[6] G. Salceda-Delgado, D. Monzon-Hernandez, A. Martinez-Rios, G. A. Cardenas- Sevilla, and J. Villatoro, "Optical microfiber mode interferometer for temperature-independent refractometric sensing," *Opt. Lett.*, vol. 37, no. 11, pp. 1974-1976, Jun. 2012.

[7] J. L. Kou, J. Feng, L. Ye, F. Xu, and Y. Q. Lu, "Miniaturized fiber taper reflective interferometer for high temperature measurement", *Opt. Express,* vol. 18, no. 13, pp. 14245-14250, Jun. 2010.

[8] L. P. Sun, J. Li, Y. Z. Tan, X. Shen, X. D. Xie, S. Gao, and B. O. Guan, "Miniature highly-birefringent microfiber loop with extremely-high refractive index sensitivity," *Opt. Express*, vol. 20, no. 9, pp. 10180-10185, Apr. 2012.

[9] J. L. Kou, F. Xu, Y. Q. Lu, "Highly birefringent slot-microfiber," *IEEE Photon. Technol. Lett.,* vol. 23, no. 15, pp. 1034-1036, Aug. 1, 2011.

[10] 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.*, vol. 36, no. 18, pp. 3593-3595, Sep. 2011.

[11] S. Lacroix, F. Gonthier, R. J. Black, J. Bures, "Tapered-fiber interferometric wavelength response: the achromatic fringe," *Opt. Lett.*, vol. 13, no. 5, pp. 395-397, May. 1988.

[12] D. T. Cassidy, D. C. Johnson, and K. O. Hill, "Wavelength-dependent transmission of monomode optical fiber tapers," *Appl. Optics*, vol. 24, no. 7, pp. 945-950, Apr. 1985.

[13] A. W. Snyder and J. D. Love, *Optical waveguide theory.* London : Chapman & Hall, 1983.

[14] R. Yang, Y. S. Yu, Y. Xue, C. Chen, Q. D. Chen, and H. B. Sun, "Single S-tapered fiber Mach-Zehnder interferometers," *Opt. Lett.*, vol. 36, no. 23, pp. 4482-4482, Dec. 2011.