Investigation on a novel fiber-optic sensor based on up-taper-core-offset-up-taper structure

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ABSTRACT

A novel fiber-optic sensor based on all-fiber up-taper-core-offset-up-taper structure is proposed and investigated. The sensor is fabricated by splicing a large core offset between a pair of up tapers in the single mode fiber (SMF). This structure is sensitive to refractive index (RI) and strain with low cost and easy fabrication.

Keywords: fiber-optic sensor, refractive index (RI), strain

1. INTRODUCTION

Recently, fiber-optic in-line Mach-Zehnder interferometers (MZIs) sensors based on miniaturized modal interference (MMI) between core and cladding modes are greatly studied in measurement of various parameters, such as temperature [1], RI [2], strain [3], displacement [4] and humidity [5]. Compared to traditional electrical sensors, optical fiber sensors have many advantages, such as small size, easy fabrication, remote sensing, low expenditure and immunity to electromagnetic interference. So far, a myriad of techniques based on all-fiber MZI have been proposed to monitor the mentioned parameters especially RI and/or strain. Some of them use special fibers to form the modal interferometers. Ref. [6] proposed a MZI which consisting of a perfluorinated graded-index plastic optical fiber fabricated via a heat-and-pull tapering technique. The RI sensitivity and the strain sensitivity is 3.44 nm/RIU and 0.2 pm/με respectively which are relatively low. Ref. [7] presented a RI sensor, which was realized by introducing a normal photonic crystal fiber (PCF)-taper between two waist-broadened SMF-PCF tapers. The sensor achieves a RI sensitivity of 281.6 nm/RIU, while the PCF is needed, which is much more expensive than SMF. Moreover, Ref. [8] designed a thin core fiber (TCF) based MZI by sandwiching a piece of TCF between two adjacent SMF achieving a maximum RI sensitivity of 135 nm/RIU. In Ref. [9] it utilized a structure based on tapered PCF with up-tapered collapsed region for measurement of the strain, and showed a strain sensitivity of 1.6 pm/με. The structures mentioned above have the advantages of small size, easy fabrication and high sensitivity, however, they or employ special fiber or show relatively low sensing sensitivity in RI and/or strain monitoring.

Based on the consideration mentioned above, the MMI only formed by SMF is another promising structure and also extensively studied. A sensor consisting of two adjacent ultra-abrupt fiber tapers with a RI sensitivity of -26.27 nm/RIU was proposed by Li et al. [10], where the RI sensitivity was pretty low. Dong et al. [11] designed a fiber sensor consists of two optimized fiber fusion up-tapers and achieved a strain sensitivity of 0.00113 nm/με, which is just comparable with fiber Bragg grating (FBG)/long period grating (LPG). Yin et al. [12] presented an asymmetrical fiber Mach-Zehnder interferometer realized by concatenating single-mode abrupt taper and core-off section, and the RI sensitivity of the sensor was only 19.1 nm/RIU. Dong et al. [13] proposed a dual thin-taper fiber interferometer fabricated by arc-discharge, which achieves a RI sensitivity of 10.299 nm/RIU. As can be seen, the MMIs only formed by SMF always have a simple structure and low cost but do not have high RI/strain sensitivities.

All of the sensors proposed above have the advantages of compact structure and easy operation. However high sensitivity always accompanies with complex fabrication and high cost, namely, the usage of special fibers or etching

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process, and the sensitivity of SMF formed MMI is accordingly low. In this paper, a novel fiber-optic up-taper-core-offset-up-taper (UCU) structure fabricated in a single SMF is proposed and investigated. Its sensing performances in RI and strain monitoring are conducted. The UCU structure is formed by splicing one large core offset section between a pair of up tapers. The core offset is well controlled by an optical fiber splicer and locates at the middle of SMF between the dual up tapers joints. The fabrication process is only contains cleaving and splicing, which is very easy. The sensor is sensitive to surrounding RI and longitudinal strain. The experiment results show that it can realize simultaneously monitoring the RI and strain with an enhanced RI sensitivity of 102.76 nm/RIU and an enlarged strain sensitivity of 12.4 pm/με respectively. The sensor is only formed of SMF, with easy fabrication and low cost. These inherent characteristics make it possible that the proposed sensor has a potential in practical use and industrialization.

2. FABRICATION OF THE UCU STRUCTURE

An optical fiber splicer (Fujikura FSM-80S) and a fiber cleaver (CT-30) are used to fabricate the UCU structure, the schematic diagram of the UCU structure is sketched in Fig. 1. The distance from the core offset point to the two adjacent up-tapered points is almost the same, and the total sensing length of the sensor is ~4 cm, that is to say, the distance between the two up taper is ~4 cm. It is only the SMF that we use to form the UCU structure. Cleaving and splicing are only need when fabricating the UCU structure, which can be easy controlled by the fiber cleaver and commercial optical fiber splicer.

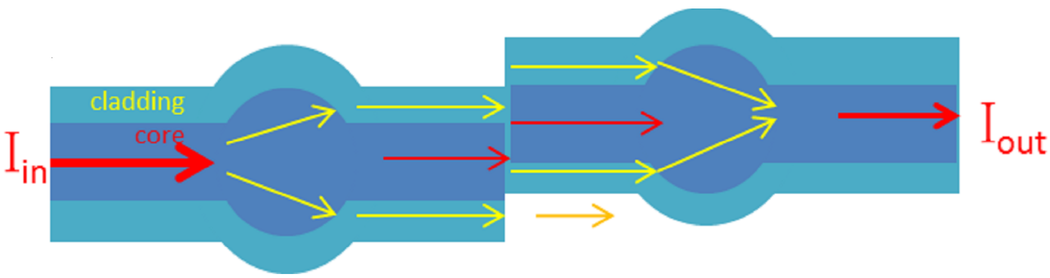

Fig. 1. Schematic diagram of the UCU structure

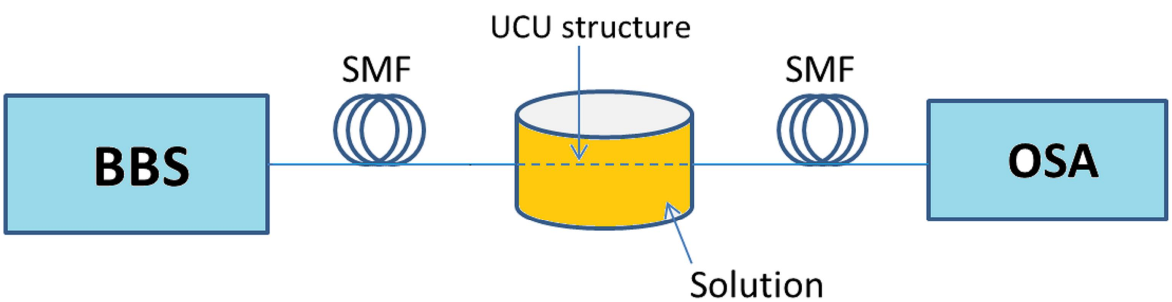

Fig. 2. Schematic configuration of the experimental setup

3. EXPERIMENTAL RESULTS AND DISCUSSION

A C-band broadband source (BBS) is used as the light source whose wavelength ranging from 1525 nm to 1565 nm and an optical spectrum analyzer (OSA, AQ6370C) with a resolution of 0.02 nm is used to monitor the transmission spectra of the UCU structure. The schematic configuration of the experimental setup is shown in Fig. 2. It has to be noted that the coatings of the whole UCU structure are stripped off and the UCU structure is totally immersed in the NaCl (analytically pure, > 99.5%) solutions with different concentrations, which is used to generate environments with different RIs. In addition, a pair of clamps mounted on the optical table is used to keep the fiber straight to avoid undesirable bending or other harmful effects. The transmission of the UCU structure is shown in Fig. 2, and it can be found that there are maximums and minimums which can be utilized to monitor the ambient RI and strain. The spatial frequency spectrum which is given by Fast Fourier Transform (FFT) algorithm is also shown in Fig. 3. As can be seen, except the core mode, other higher order cladding modes are effectively excited as well.

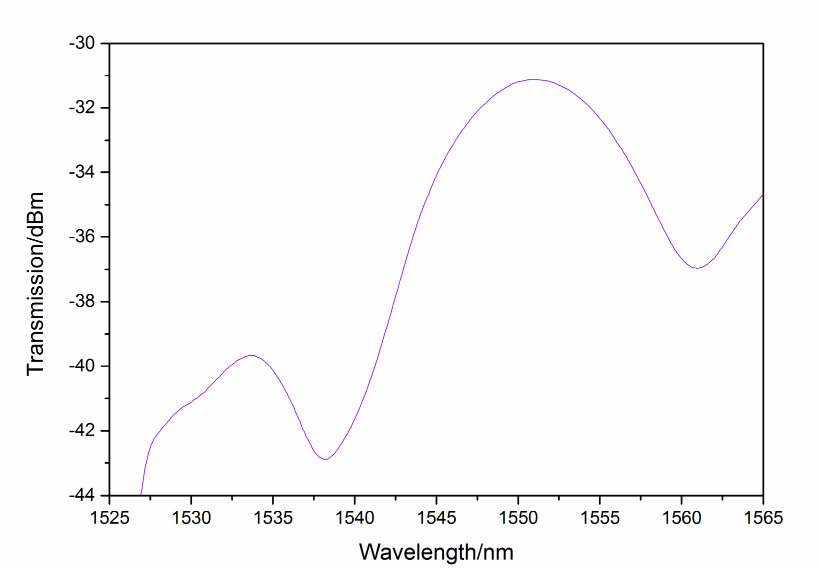

Fig. 3. Transmission spectrum of the UCU structure

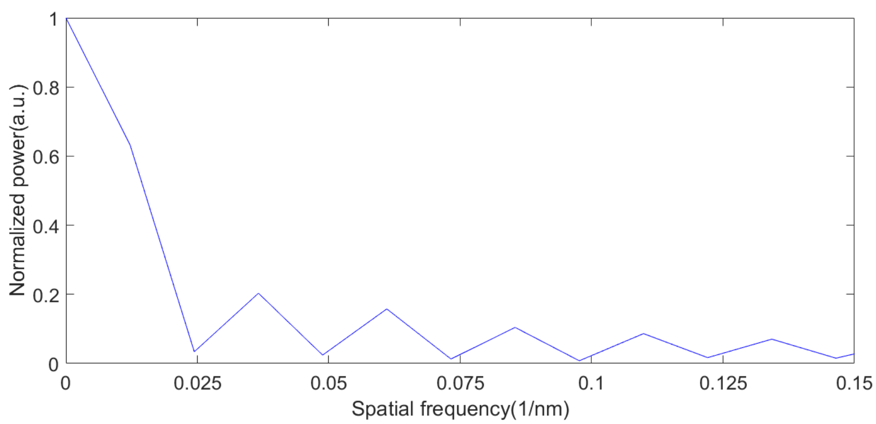

Fig. 4. Spatial frequency spectrum of the UDU structure

3.1 RI experiment

When donging the RI experiment, the NaCl solutions are chosen as the testing solutions. The UCU structure is fully immersed into the testing solutions and a pair of clamps mounted on the optical table is used to keep the fiber straight to avoid undesirable bending or other harmful effects. The RI range was controlled from 1.3195 to 1.3509 by preparing ten NaCl solutions whose concentration ranges from 2% to 20%. The transmission spectra under different RI are shown in Fig. 5, where the dip A and dip B are chosen to trace the RI. It can be seen that a red shift of the spectra happens with the increase of the RI. Fig. 6 gives the spatial frequency spectra by making a FFT to the transmission spectra, which also shows that the intensities of the cladding modes also change versus the RI. Experimental results show that a maximum RI sensitivity of 102.76 nm/RIU at dip B with a value of R^2 = 0.9979 is achieved, as is shown in Fig. 7. The fitting line at dip A also shows excellent linearity with R-square of 0.9911. The introduction of the core-offset effectively excites much more evanescent waves, and as a result brings an enhancement to the RI sensitivity. It makes that the RI sensitivity of the UCU structure is much higher than those MMIs which are only constructed of SMF [10-13], and even comparable to the special-fiber-formed MMIs.

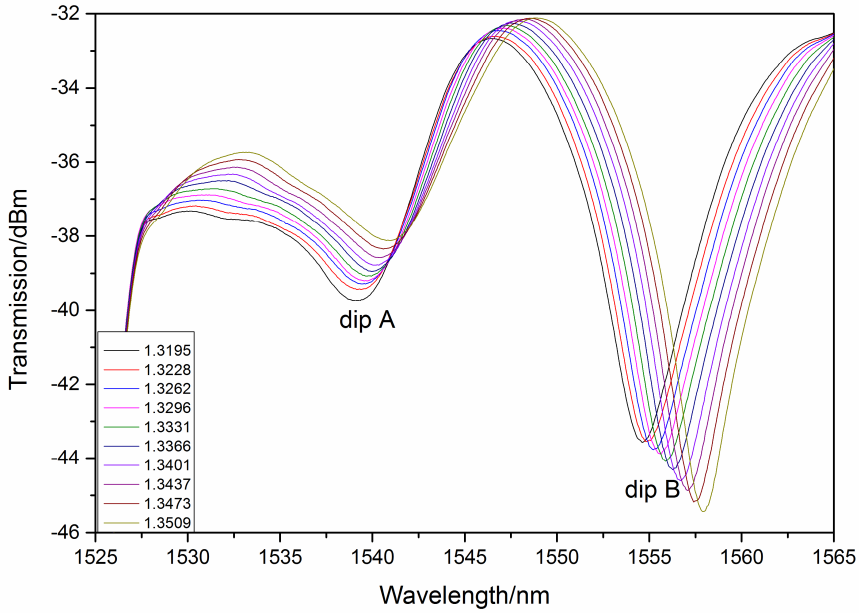

Fig. 5. The spectra of UCU structure under different RI

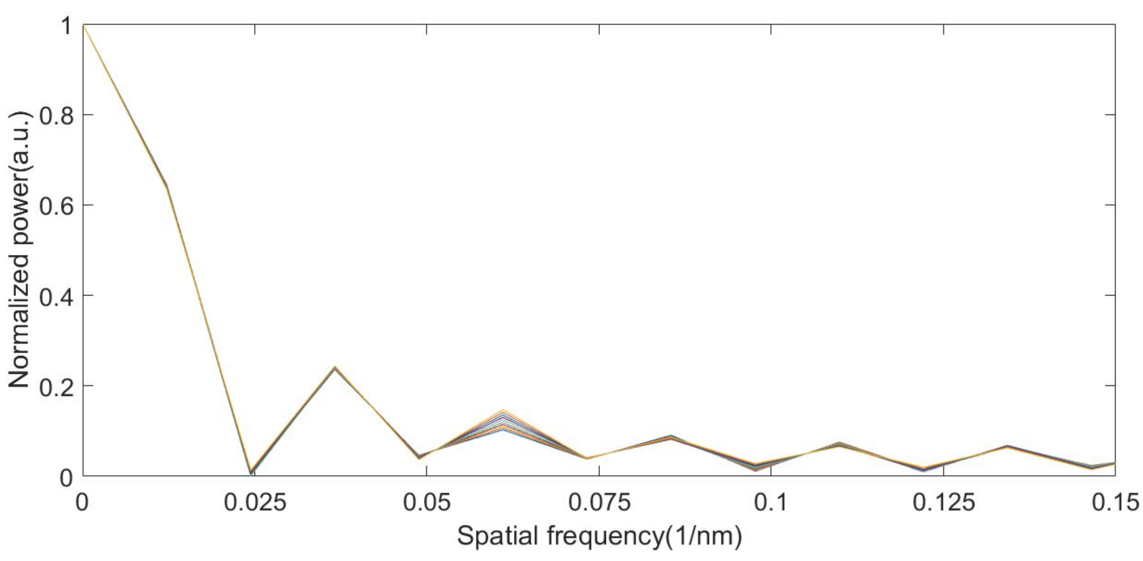

Fig. 6. Spatial frequency spectra of the UDU structure under different RI

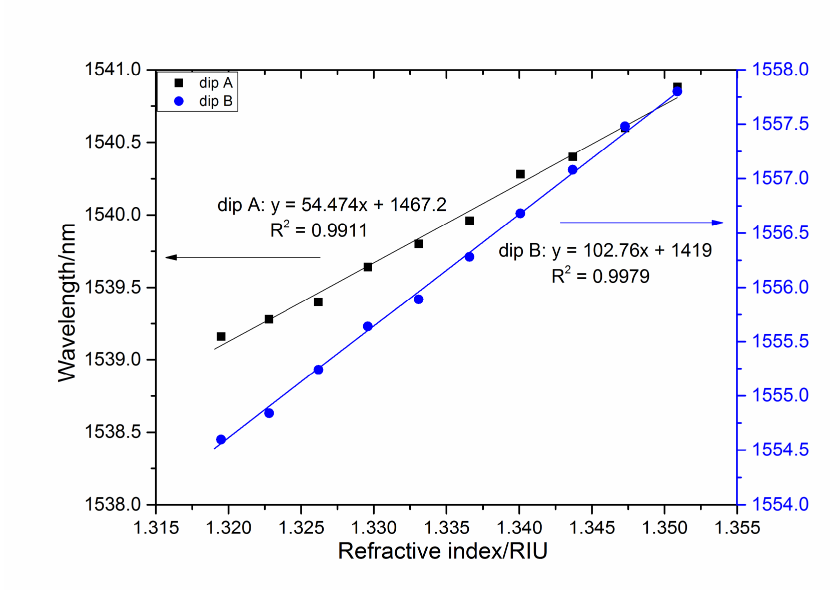

Fig. 7. The RI sensitivity of different dips.

3.2 Strain experiment

The strain sensing experiment is carried out on an optical table. A micro-displacement platform is utilized to induce different longitudinal strains. The range of the strain is controlled from 0 to 423.529 με with a step of 70.588 με. The spectra show a blue shift with the increase of the strain, as is shown in Fig. 8. FFT algorithms are made to the spectra and the corresponding spatial frequency spectra are shown in Fig. 9. As is shown in Fig. 10, a maximum strain sensitivity of 12.4 pm/με at dip A with a value of R^2 = 0.9974 is achieved, while at dip B a good linearity of 0.9908 is achieved as well. Compared with other proposed sensor and the traditional FBG/LPG [14-16], it has a big enhancement, and it is much higher than other proposed sensors.

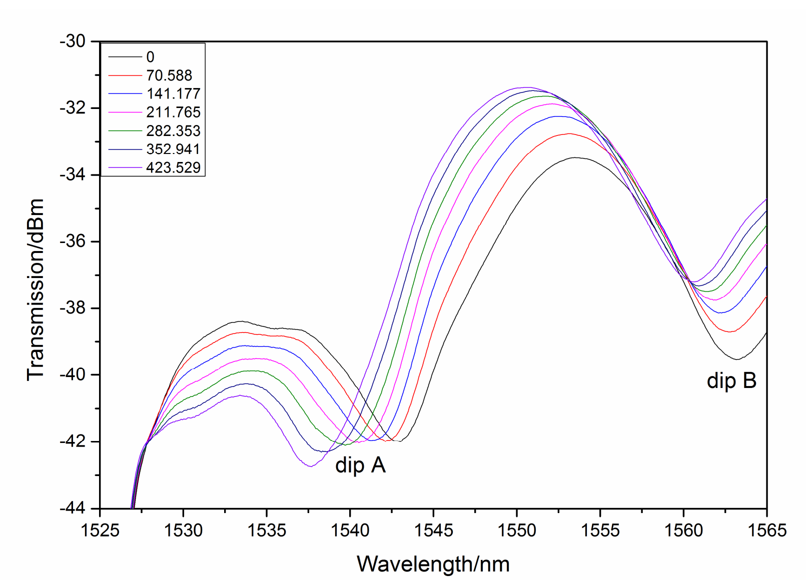

Fig. 8. The spectra of UCU structure under different strain

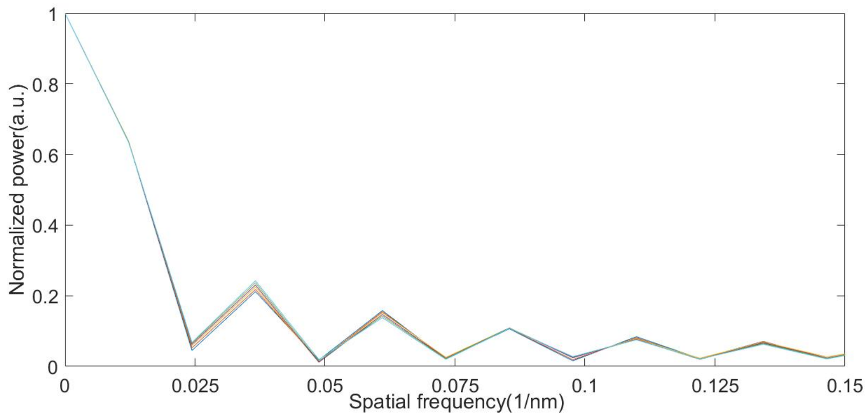

Fig. 9. Spatial frequency spectra of the UDU structure under different strain

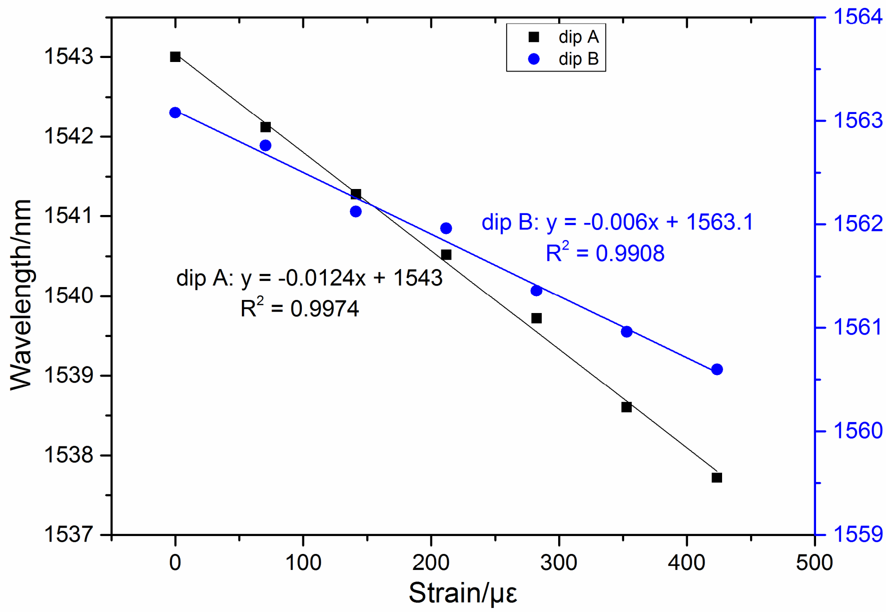

Fig. 10. The strain sensitivity of different dips of the UCU structure

3.3 Simultaneous RI and strain measurement

Considering the experimental results given in Fig. 7 and Fig. 10, it is possible to realize simultaneous RI and strain measurement. And the RI Δn and strain $\Delta\varepsilon$ measurement matrix for dip A and dip B could be given by

$$\begin{bmatrix} \Delta\lambda_A \\ \Delta\lambda_B \end{bmatrix} = \begin{bmatrix} 54.474 & -0.0124 \\ 102.76 & -0.006 \end{bmatrix} \begin{bmatrix} \Delta n \\ \Delta\varepsilon \end{bmatrix}.$$

4. CONCLUSION

In conclusion, a novel MZI-based UDU structure which is realized by introducing a large core offset between a pair of up tapers in a SMF is proposed and investigated. It is only the SMF that used to form the UCU structure and the manufacture process only contains cleaving and splicing which is very simple and can be well controlled by a fiber cleaver and a commercial fiber splicer. The performances of the proposed structure in RI and strain sensing are considerately addressed. Experimental results shows that the sensor achieves a maximum RI sensitivity of 102.76 nm/RIU with a value of R^2 = 0.9979 and a maximum strain sensitivity of 12.4 pm/με with a value of R^2 = 0.9974 respectively. In addition, this all-fiber SMF-MZI-based sensor could monitor RI and strain simultaneously without complex operations or other fiber devices. These characteristics confer the proposed UCU structure wide applicability.

5. ACKNOWLEDGEMENT

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REFERENCES

[1] B. Dong, C. Yu, Y. Wang, "Thermal characteristics of the ethanol-filled hollow-core photonic-crystal-fiber modal interferometer," 14th International Conference on Optical Communications and Networks (ICOCN) 2015, Nanjing, China, July 3-5 (2015).

[2] D. K. C. Wu, B. T. Kuhlmey, B. J. Eggleton, "Ultrasensitive photonic crystal fiber refractive index sensor," Opt. Lett., 34(3), 322-324 (2009).

[3] B. Dong, Y. Peng, Y. Wang, C. Yu, "Mode Division Multiplexing in a Fiber Modal Interferometer for Dual-Parameters Measurement," IEEE Photonic. Technol. Lett., 28(2), 143-146 (2016).

[4] A. Mehta, W. Mohammed, E. G. Johnson, "Multimode interference-based fiber-optic displacement sensor," IEEE Photonic. Technol. Lett., 15(8), 1129-1131 (2003).

[5] M. Shao, X. Qiao, H. Fu, H. Li, J. Zhao, Y. Li, "A Mach-Zehnder interferometric humidity sensor based on waist-enlarged tapers," Opt. &Lasers in Eng., 52(1), 86-90, (2014).

[6] A. A. Jasim, N. Hayashi, S. W. Harun, H. Ahmad, R. Penny, Y. Mizuno, K. Nakamura, "Refractive index and strain sensing using inline Mach-Zehnder interferometer comprising perfluorinated graded-index plastic optical fiber," Sens. & Actuators A Phys., 219, 94-99 (2014).

[7] Y. Zhao, F. Xia, J. Li, "Sensitivity-Enhanced Photonic Crystal Fiber Refractive Index Sensor With Two Waist-Broadened Tapers," J. Lightwave Technol., 34(4), 1373-1379 (2016).

[8] T. H. Xia, A. P. Zhang, B. Gu, "Fiber-optic refractive-index sensors based on transmissive and reflective thin-core fiber modal interferometers," Opt. Commun., 283(10), 2136-2139 (2010).

[9] J. N. Dash, R. Jha, "Mach–Zehnder interferometer based on tapered PCF with an up-tapered joint for curvature, strain and temperature interrogation," J. Opt. 18 (2016).

[10] B. Li, L. Jiang, S. Wang, L. Zhou, H. Xiao, H. L. Tsai, "Ultra-abrupt tapered fiber Mach-Zehnder interferometer sensors," Sens., 11, 5729-5739 (2011).

[11] B. Dong, B. Zhang, J. Ng, Y. Wang, C. Yu, "Ultra-high-sensitivity fiber acoustic sensor with a dual cladding modes fiber up-taper interferometer," IEEE Photonic. Technol. Lett., 27(21), 2234-2237 (2015).

[12] G. Yin, S. Lou, H. Zou, "Refractive index sensor with asymmetrical fiber Mach-Zehnder interferometer based on concatenating single-mode abrupt taper and core-offset section," Opt. Laser Technol., 45, 294-300 (2013).

[13] B. Dong, Y. Ge, Y. Wang, C. Y. Yu, "High extinction-ratio dual thin-taper fiber interferometer fabricated by arc-discharge and its performance as sensors," Opt. Commun., 355, 225-229 (2015).

[14] N J Alberto, C. A. Marques, J. L. Pinto, R. N. Nogueira, "Simultaneous strain and refractive index sensor based on a TFBG" Fourth European Workshop on Optical Fibre Sensors. International Society for Optics and Photonics (2010).

[15] V. Bhatia, T. D'Alberto, N. Zabaronick, R. O. Claus, "Temperature-insensitive long-period gratings for strain and refractive index sensing," SPIE Proc. Smart Mater. Struct., 1997, 194-202(1997).

[16] Q. Huang, Y. Yu, Z. Ou, X. Chen, J. Wang, P. Yan, C. Du, "Refractive Index and Strain Sensitivities of a Long Period Fiber Grating," Photonic. Sens., 4(1), 92-96 (2014).