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Intensity-modulated Fiber-optic Refractive Index and Strain Sensor based on Miniaturized Modal Interferometer

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ABSTRACT

A novel intensity-modulated fiber-optic refractive index (RI) and strain sensor based on modal interferometer (MMI) is proposed. The sensing mechanism is mainly based on the Mach-Zehnder interferometer (MZI) constructed by one down taper spliced between dual up tapers on the single mode fiber (SMF). High-order cladding modes are efficiently excited owing to the mismatch of the mode filed diameter (MFD). Experimental investigations achieve a RI sensitivity of -22.437dBm/RIU and a strain sensitivity of 0.0008dBm/με with R^2 of 0.9972 and 0.9962 respectively. It has to be noted that this MMI is only made of single SMF and is of low cost and easy fabrication.

Keywords: *miniaturized modal interferometer, Mach-Zehnder interferometer, refractive index, strain*

1. INTRODUCTION

Fiber optic sensors are widely used in temperature, strain, RI sensing, etc., due to their intrinsic advantages like easy to fabricate, small in size and sensitive to a great many physical parameters, including humidity, temperature, magnetic field, RI, strain, etc. So far, a myriad of techniques have been proposed in strain and RI sensing. Some of them only use SMF to form the MMIs, including dual up-tapers [1-2] or down-tapers [3-4], peanut-shape structures [5], core-offsets [6-7], concatenated single-mode abrupt taper and core-off section [8], large lateral offset fusion spliced between two abrupt tapers [9], trench and partially ablated fiber core [10], concatenated two micro-cavities [11], etc. Special fibers are as well employed to be spliced between two adjacent SMFs, like double cladding fiber (DCF) [12], thin-core fiber (TCF) [13], suspended twin-core fiber [14], multi-mode fiber [15-16], photonic-crystal-fiber (PCF) [17], Er/Yb co-doped fiber [18], etc. Besides, fiber Bragg grating (FBG) [19] and long period grating (LPG) [20] are also used to monitor the temperature, strain and RI.

However, in most of the above mentioned techniques, wavelength shifts are always used to detect measurands. In this paper, we propose an intensity-modulated up-taper-down-taper-up-taper (UDU) structure fabricated on a single SMF to realize RI and strain sensing without using the optical spectrum analyzer (OSA). It is of cost-effective, simple operation and fabrication.

The UDU structure is formed by splicing a down-tapered fiber between two up-tapered fibers. The position of the down-tapered point is well-controlled and almost locates at the middle of the dual-up-tapered points. It's sensitive to surrounding RI change and longitudinal strain. Experimental results show that, its sensitivity to RI and strain reaches to -22.437dBm/RIU and 0.0008dBm/με, respectively.

2. PRINCIPLE

The schematic of the UDU is shown in Fig. 1. The distance from the down-tapered point to the two adjacent up-tapered points is equal and denoted by L. The UDU structure is only made of SMF. When the light injects into the first up-taper, due to the mode mismatch of the MFD, the cladding modes are efficiently excited. The injected light is then splitted into two parts, one propagating along the core and the other transmitting towards the cladding. When the lights transmit over the down-taper, the cladding modes and the core mode will be influenced by the surrounding RI. At the second up-tapered junction, the cladding modes are recoupled into the fiber core and interfere with each other.

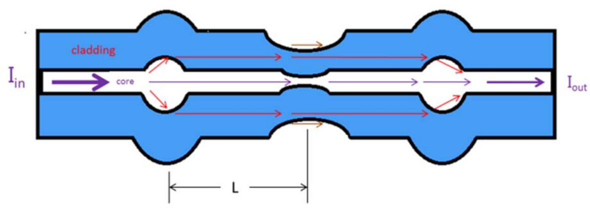

Fig. 1. Schematic diagram of the UDU structure

The transmission spectrum of the UDU with L= 2.5 cm is shown in Fig. 2. We could see that there exist several maximums and minimums which could be used to monitor the RI and strain. The spatial frequency spectrum is demonstrated in Fig. 3. It can be seen that except the strong core mode, other high-order cladding modes are as well effectively excited.

Assuming that the collected light power equals I, it can be simply expressed as

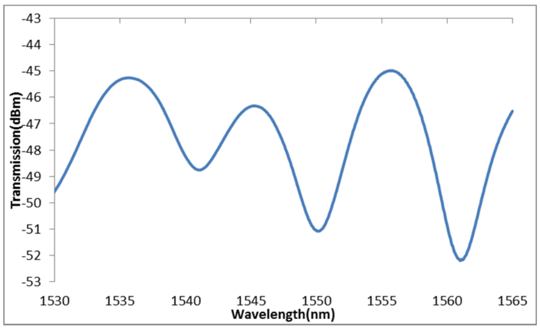

Fig. 2. Transmission spectrum of the UDU structure

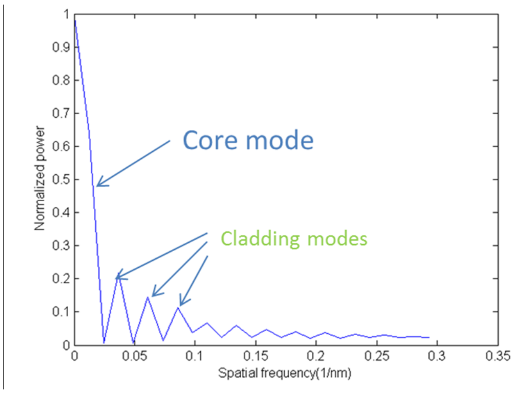

Fig. 3. Spatial frequency spectrum of the UDU

$$I = I_{core} + I_{cladding} + 2\sqrt{I_{core} I_{cladding}} \cos(\delta)$$

where I is the intensity of the interference signal, I_{core} and $I_{cladding}$ are the intensities of the core and cladding modes respectively, and δ is the phase difference between the core mode and the cladding modes. Due to that δ is a function of L and RI, we can monitor the L and RI by observing the transmission spectra of the proposed UDU structure.

3. EXPERIMENT

A fusion splicer (Fujikura FSM-80s) is used to make the UDU structure. The two up-tapers almost have the same diameter of ~160μm, and the length of the down-taper is ~250μm which can be controlled by the splicer. A C-band broadband source (BBS) is used as the light source. Here we use an optical spectrum analyzer (OSA) to facilitate the data acquisition by observing the spectrum shifts. The schematic configuration of the experimental setup is shown in the Fig. 4. The UDU structure is totally immersed in solutions to be measured.

3.1 RI sensing

To measure the sensitivity to RI of the UDU, we chose the dip around 1560nm. Different concentrations of the NaCl solutions are chosen as the testing environments and the RI range is controlled from 1.3262 to 1.3527[21].

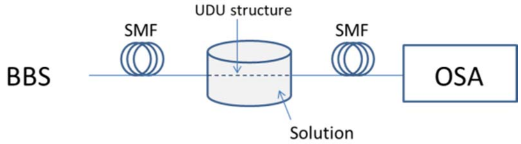

Fig. 4. Schematic configuration of the experimental set-up

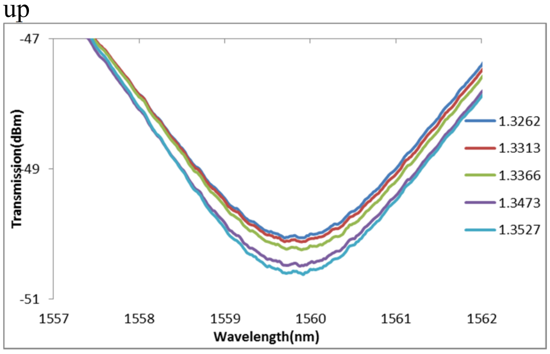

Fig. 5. The transmission spectra of the UDU with different RIs of the solutions

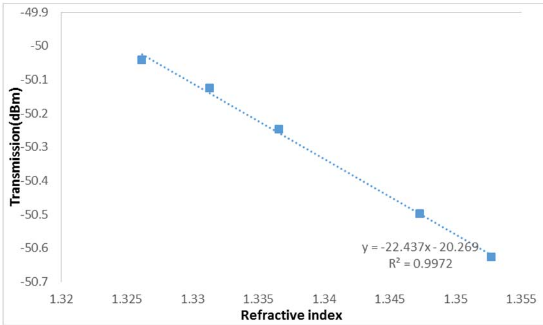

Fig. 6. Transmission light intensity versus the RI around 1560 nm

When doing the RI sensing experiment, the total UDU structure is fully immersed into the solutions. The transmission spectra of the UDU at different RIs around 1560nm are shown in figure Fig. 5. Experimental results show quasi-linear relationship between the RI and light intensity, with linear R-squares of 0.9972 and RI sensitivity of -22.437dBm/ RIU, as is shown in Fig. 6.

3.2 Strain sensing

A micro-displacement platform mounted on an optical table is used to induce different longitudinal strains to the UDU structure. The range of the strain is controlled from 0 to 400με with a step of 66.67με. To measure the sensitivity to strain of the UDU, we chose the dip around 1550nm. The transmission spectra of the MMI at different strains are shown as Fig. 7. Fig. 8 shows that there exists quasi-linear relationship between the strain and light intensity, with linear R-squares of 0.9962 and strain sensitivity of 0.0008dBm/με.

4. CONCLUSION

In conclusion, a novel intensity-modulated fiber-optic RI and strain sensor based on modal interferometer (MMI) is proposed. We only use light intensity to realize RI and strain sensing. In the coming days, more experiments should be carried to investigate the simultaneous monitoring of RI, strain and temperature with increased sensitivity.

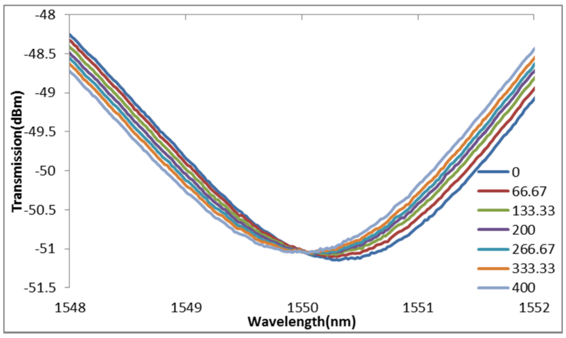

Fig. 7. The transmission spectra of the UDU at different strain.

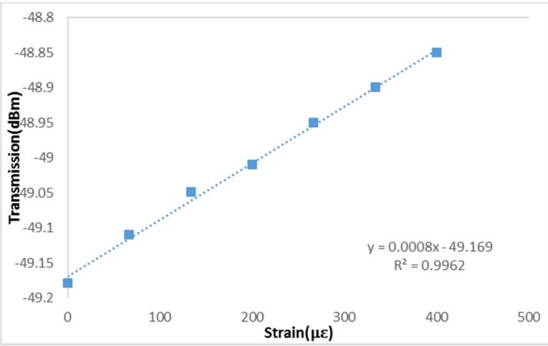

Fig. 8. Transmission light intensity versus strain around 1550 nm.

5. ACKNOWLEDGMENT

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6. REFERENCES

[1] B. Dong, Y. Peng, Y. Wang, C. Yu, "Modal division multiplexing in a fiber modal interferometer for dual parameters measurement," IEEE Photon. Technol. Lett, vol. 28, No. 2, pp. 143-146, 2015.

[2] 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 Photon. Technol. Lett, vol.27, No.21, pp. 2234-2237, 2015.

[3] Z. B. Tian, S. S. H. Yam, "In-line abrupt taper optical fiber Mach-Zehnder interferometric strain sensor," IEEE Photon. Technol. Lett, vol. 21, No. 3, pp.161–163, 2009.

[4] B.Y Li, L. Jiang, S.M. Wang, L.Y. Zhou, H. Xiao, H.L. Tsai, "Ultra-abrupt tapered fiber Mach-Zehnder interferometer sensors," Sensors, vol.11, pp.5729-5739, 2011.

[5] D. Wu, T. Zhu, K.S. Chiang, M. Deng, "All single-mode fiber Mach-Zehnder interferometer based on two peanut-shape structures," IEEE J. Lightw. Technol, vol. 30, No. 5, pp. 805-810, 2012.

[6] X. Hao, Z. Tong, W. Zhang, Y. Cao , "A fiber laser temperature sensor based on SMF core-offset structure," Opt. Commun," vol. 335, pp. 78-81, 2015.

[7] D. W. Duan, Y. J. Rao, L. C. Xu, T. Zhu, D. Wu, J. Yao, "In-fiber Mach-Zehnder interferometer formed by large lateral offset fusion splicing for gases refractive index measurement with high sensitivity," Sens. Actuat. B, vol. 160, pp. 1198-1202. 2011.

[8] 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., vol.45, pp. 294-300, 2013.

[9] Q. Zhang, J. Zhou, J. Chen, and X. l. Tan, "Single-mode fiber refractive index sensor with large lateral offset fusion splicing between two abrupt tapers," Opt. Eng, vol.51, No. 9, pp. 1487-1489, 2012.

[10] L. J. Zhao, S. M. Wang, H. Xiao, Y. F. Lu, H. L. Tsai, "A high-quality Mach-Zehnder interferometer fiber sensor by femtosecond laser one-step processing," Sensors, vol. 11, pp. 54–61, 2011.

[11] L. Jiang, J. Yang, J. S. Wang, B. Li, M. Wang, "Fiber Mach-Zehnder interferometer based on micro cavities for high-temperature sensing with high sensitivity," Opt. Lett, vol. 36, No. 9, pp. 3753-3755, 2011.

[12] F. Pang, H. Liu, H. Guo, Y. Liu, X. Zeng, N. Chen, Z. Chen, T. Wang, "In-fiber Mach-Zehnder interferometer based on double cladding fibers for refractive index sensor," IEEE Sens. J, vol. 11, No. 10, pp. 2395-2400, 2011.

[13] J. J. Zhu, A. P. Zhang, T. H. Xia, S. L. He, W. Xue, "Fiber-optic high-temperature sensor based on thin -core fiber modal interferometer," IEEE Sens. J, vol. 10, No. 9, pp. 1415-1418, 2010.

[14]O. Frazao, S. F. O. Silva, J. Viegas, J. M. Baptista, J. L. SantosKobelke, K. Schuster, "All fiber Mach-Zehnder interferometer based on suspended twin-core fiber," IEEE Photon. Technol. Lett, vol. 22, No. 17, pp.1300-1302, 2010.

[15] L. V. Nguyen, D. Hwang, S. Moon, D. S. Moon, Y. Chung, "High temperature fiber sensor with high sensitivity based on core diameter mismatch," Opt. Express, vol. 16, No. 15, pp. 11369-11375, 2008.

[16] H. Xue, H. Meng, W. Wang, R. Xiong, Q. Yao, B. Huang, "Single-Mode-Multimode Fiber Structure Based Sensor for Simultaneous Measurement of Refractive Index and Temperature," IEEE Sen. J, vol. 13, NO. 11, pp. 4220-4223, 2013

[17] Q. Wang, L. Kong, Y. Dang, F. Xia, Y. Zhang, H. Hu, J. Li , "High sensitivity refractive index sensor based on splicing points tapered SMF-PCF-SMF structure Mach-Zehnder mode interferometer," Sens. Actuat. B, vol. 225, pp. 213-220, 2016.

[18] N. K. Chen, Y. H. Hsieh, Y. K. Lee, "Tapered fiber Mach-Zehnder interferometers for vibration and elasticity sensing applications," Opt. Express, Vol. 21, No. 9, pp. 11209-11204, 2013.

[19] Y. Ma, X. Qiao, T. Guo, R. Wang, J. Zhang, Y. Wen, Q. Rong, Manli Hu, Z. Feng, "Reflective fiber-optic refractometer based on a thin-core fiber tailored Bragg grating reflection," Opt. Lett, vol.37, No.3, pp. 323-325, 2012.

[20] Y. J. He, "Investigation of LPG-SPR sensors using the finite element method and eigenmode expansion method," Opt. Express, vol. 21, No. 12, pp. 13875-13895, 2013.

[21] J. E. Saunders, C. Sanders, H. Chen, H.P. Loock, "Refractive indices of common solvents and solutions at 1550 nm," Appl. Opt, vol.55, No.4, pp.947-953, 2016.