PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

Investigation on fiber optic curvature sensor based on SMF-FMF-SMF structure with up-taper fusion

Qihang Zeng, Wei Xu, Ying Shen, Changyuan Yu, Fengze Tan

Qihang Zeng, Wei Xu, Ying Shen, Changyuan Yu, Fengze Tan, "Investigation on fiber optic curvature sensor based on SMF-FMF-SMF structure with up-taper fusion," Proc. SPIE 11048, 17th International Conference on Optical Communications and Networks (ICOCN2018), 110484A (14 February 2019); doi: 10.1117/12.2522300

Event: 17th International Conference on Optical Communications and Networks (ICOCN2018), 2018, Zhuhai, China

Downloaded From: https://www.spiedigitallibrary.org/conference-proceedings-of-spie on 2/18/2019 Terms of Use: https://www.spiedigitallibrary.org/terms-of-use

© 2019 SPIE. One print or electronic copy may be made for personal use only. Systematic reproduction and distribution, duplication of any material in this publication for a fee or for commercial purposes, and modification of the contents of the publication are prohibited.

The following publication Qihang Zeng, Wei Xu, Ying Shen, Changyuan Yu, and Fengze Tan "Investigation on fiber optic curvature sensor based on SMF-FMF-SMF structure with up-taper fusion", Proc. SPIE 11048, 17th International Conference on Optical Communications and Networks (ICOCN2018), 110484A (14 February 2019) is available at https://doi.org/10.1117/12.2522300.

Investigation on fiber-optic curvature sensor based on SMF-FMF-SMF structure with up-taper fusion

Qihang Zeng[a,b], Wei Xu[c,*], Ying Shen[b,d], Changyuan Yu[b,e,*], Fengze Tan[e]

[a]Department of Electrical and Computer Engineering, National University of Singapore, Singapore 117583;

[b]National University of Singapore (Suzhou) Research Institute, Suzhou 215123, China;

[c]Anlight Optoelectronic Technology Inc., Suzhou 215123, China;

[d]School of Electronic & Information Engineering, Soochow University, Suzhou 215006, China;

[e]Department of Electronic and Information Engineering, The Hong Kong Polytechnic University, Kowloon, HongKong;

* xuwei_007@163.com, changyuan.yu@polyu.edu.hk

ABSTRACT

A compact fiber-optic curvature sensor based on modal interferometer (MI) in few mode fiber (FMF) is presented and investigated both in theory and experiment. The proposed MI is simply constructed by splicing a 2-centimeter-long FMF between single mode fibers (SMFs) with built-in up-taper fusion mode, i.e., SMF-FMF-SMF structure is fabricated. Both the curvature sensing performance and temperature dependency are addressed, and the result shows that curvature within a range from 0 m^{-1} to 1.87 m^{-1} can be monitored without ambiguity and the temperature sensitivity can reach up to 111 pm/ ℃.

Keywords: Fiber-optic, curvature, few mode fiber

1. INTRODUCTION

With the development of the modern industry, like super high buildings, railways, tunnels, bridges, etc., real-time and long-term curvature monitoring is extremely important, to avoid severe accidents and disasters. Traditional electrical curvature sensors suffer problems including vulnerable to electromagnetic interference, hard to work in harsh environments, etc. [1] As for fiber-based curvature sensor, it intrinsically overcome these drawbacks together with merits of long distance and distributed sensing, compact in size, high sensitivity and low maintenance cost [1]. Therefore, it is a promising technique in curvature sensing, which has been investigated a lot, including multi-core fiber (MCF) based, single/multi-mode fiber (SMF/MMF) based, photonic crystal fiber (PCF), etc. with or without grating inscription.

Y. Wu et al [2] proposed an asymmetrical twin-core fiber based MI utilizing MMF to realize mode excitation and recoupling, achieving a high curvature sensitivity of 103.35 nm/m^{-1} and 0.431 nm/ ℃ within 0.24 ~ 0.6 m^{-1}. S. Wang et al [3] presented a curvature sensor based on three-core fiber with asymmetric core distribution and different core diameters inscribed by two non-orthogonal long period gratings, realizing curvature and temperature sensitivity of 3.234 nm/m^{-1}in a range of 0 m^{-1}~ 0.588 m^{-1} and 56 pm/ ℃. In a similar structure, X. Wang et al [4] utilized a seven core fiber to form the MI obtaining a curvature and temperature sensitivity of 31.54 nm/m^{-1} in 0.45 m^{-1}~ 1.01 m^{-1} and 55.81 pm/ ℃ respectively. One can see that as for MCF-based, the structure is kind of complexity and high fabrication difficulty, especially for grating inscription.

As for SMF/MMF-based, S. Dong et al [5] proposed a cascade MI constructed with dual-up-taper in SMF to monitor the curvature, achieving a curvature sensitivity of 4.362 nm/m^{-1} from 0 to 1.134 m^{-1} and a temperature sensitivity of 108 pm/ ℃. R. Wang et al [6] presented a SMF-MMF-SMF-MMF-SMF structure to form the MI between core mode and cladding mode with a sensitivity of -14.4 nm/m^{-1} in the range of 0 m^{-1} ~ 1.134 m^{-1} and a temperature sensitivity of 63 pm/ ℃. PCF is known for its ultra-low temperature response and H. Gong et al [7] presented a SMF-PCF-SMF based curvature sensing obtaining curvature sensitivity 4.451nm/m^{-1} in a range of 0 m^{-1} ~ 2.14 m^{-1} and temperature sensitivity of 7.78 pm/ ℃.

17th International Conference on Optical Communications and Networks (ICOCN2018), edited by Zhaohui Li, Proc. of SPIE Vol. 11048, 110484A · © 2019 SPIE
CCC code: 0277-786X/19/$18 · doi: 10.1117/12.2522300

Downloaded From: https://www.spiedigitallibrary.org/conference-proceedings-of-spie on 2/18/2019
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use

In this paper, a compact SMF-FMF-SMF with up-taper fusion is proposed and the curvature monitoring performance and temperature dependency are addressed. The length of the FMF is about 2 centimeters supporting LP_{01} and LP_{11} mode and the whole fabrication process is very simple with built-in fusion mode. Besides, compared with PCF or MCF, FMF is more cost-effective and easy to operate.

2. PRINCIPLE

The schematic of the proposed SMF-FMF-SMF structure is sketched in Fig. 1. It mainly consists of a section of FMF sandwiched in SMFs with up-taper connection. When the incident light leaded by the core of the SMF meets the first up-taper junction, high order core modes of FMF mainly including LP_{01} and LP_{11} will be effectively stimulated owing

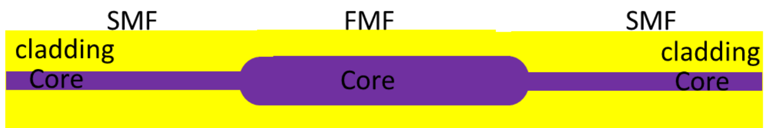

Figure 1. Schematic of the SMF-FMF-SMF structure.

to mismatched mode field distributions. After propagating the FMF, the light meets the second junction and recouples back into the core of the lead out SMF. The output light amplitude E_{out} can be simply described as follows:

$$E_{out} = E_{01}e^{j\varphi_{01}} + E_{11}e^{j\varphi_{11}} . \tag{1}$$

The output intensity I_{out} is calculate by

$$\begin{aligned} I_{out} &= E_{out} \times E_{out} \\ &= E_{01}^2 + E_{11}^2 + 2E_{01}E_{11}\cos(\varphi_{01} - \varphi_{11}) \\ &= E_{01}^2 + E_{11}^2 + 2E_{01}E_{11}\cos(\Delta\varphi) \\ &= E_{01}^2 + E_{11}^2 + 2E_{01}E_{11}\cos(2\pi\Delta nL / \lambda) \end{aligned} , \tag{2}$$

where E_{01}, E_{11} are the amplitude of the exited mode, L is the length of the FMF, λ is the wavelength in vacuum, Δn is the effective index difference. The external curvature will influence the Δn between excited LP_{01} and LP_{11} mode. Assuming the Δn equals to $(2k+1)\pi$, one can obtain that

$$\lambda_{dip} = \frac{2\Delta nL}{2k+1} . \tag{3}$$

Therefore, we can collect the wavelength shift to track the curvature.

3. EXPERIMENT AND DISCUSSION

To investigate its curvature monitoring performance, experimental setup is established as shown in Fig. 2, including a broad band source (BBS), a sensing element, and an optical spectrum analyzer (OSA). The sensing element is arranged as most of the curvature sensing scheme [1]. As shown in Fig. 3, it shows the spectrum of the sensing structure without curvature applied. One can see that there exist two dips denoted with Dip1 and Dip2 respectively. We can track the wavelength shift to study the curvature dependency.

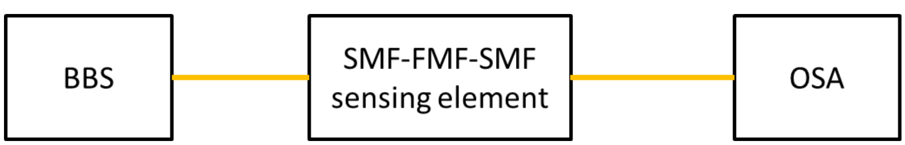

Figure 2. Experimental setup.

Downloaded From: https://www.spiedigitallibrary.org/conference-proceedings-of-spie on 2/18/2019
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use

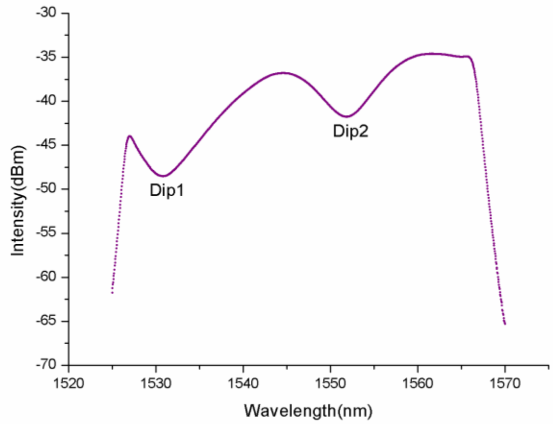

Figure 3. Spectrum of the sensing element without curvature applied.

As shown in Fig. 4, Dip2 is used to track the curvature change within a range of 0 m^{-1} ~ 1.87 m^{-1}. Here, we use polynomial fitting line to fit the data, which has a high R^2 more than 0.99. The nonlinearity mainly results from the different mode excitations, i.e., with the increasing curvature, the excited mode could be changed. Therefore, it shows piecewise linear characteristics. Besides, the estimated linear sensitivity is about -6.7 nm/m^{-1} with R^2 of 0.96.

Fig. 5 shows the temperature dependency within a range of 25.9 ℃ ~ 67.9 ℃ for Dip1 and Dip2 respectively. The linearity of the fitting lines for both two Dips are 0.999 and 0.997 with similar sensitivity of 127.2 pm/ ℃ and 116.9 pm/ ℃, respectively.

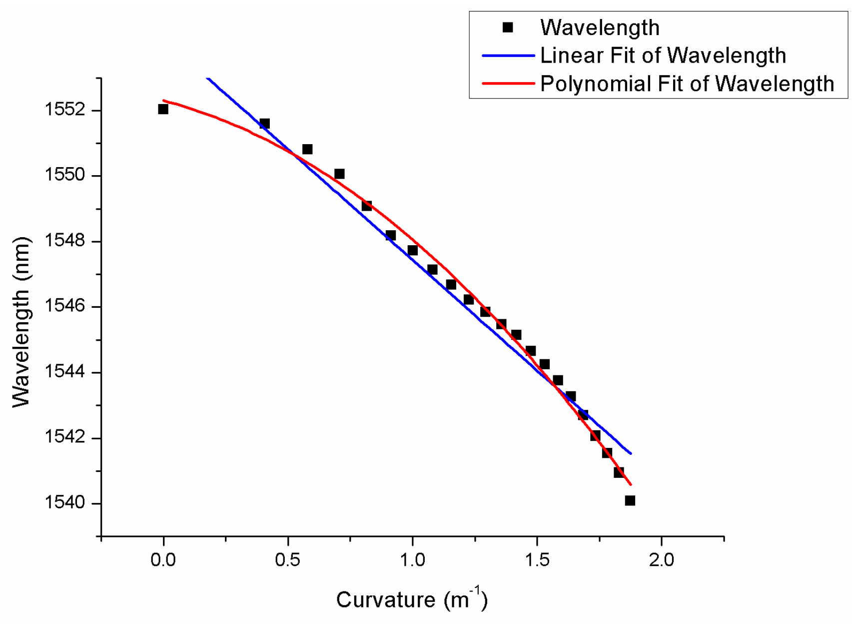

Figure 4. Wavelength shift versus curvature of Dip2.

Downloaded From: https://www.spiedigitallibrary.org/conference-proceedings-of-spie on 2/18/2019
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use

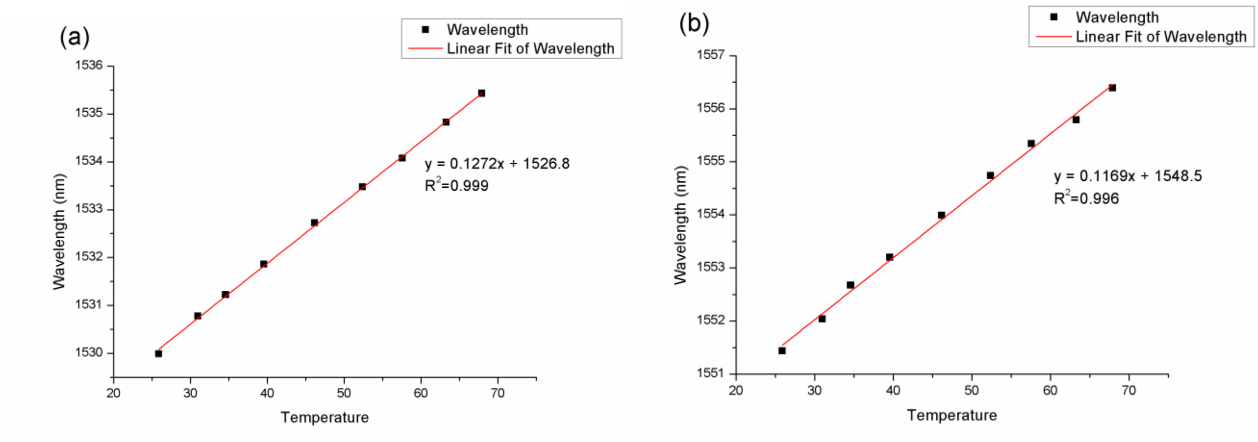

Figure 5. Temperature dependency of the SMF-FMF-SMF structure for Dip1(a) and Dip2(b).

4. CONCLUSION

In conclusion, a simple SMF-FMF-SMF with up-taper fusion is investigated and the curvature can be monitored from 0 m^{-1} ~ 1.87 m^{-1} with high R^2 exceeding 0.99. The proposed sensor's temperature sensitivity can reach up to 127.2 pm/ ℃.

Acknowledgements

This work is supported by National Natural Science Foundation of China (Grant No. 61501313 and 61471253), The Hong Kong Polytechnic University (Grant No. 1-ZVHA and 1-ZVGB).

REFERENCES

[1] Q. Wang, Y. Liu, "Review of optical fiber bending/curvature sensor," Measurement, vol. 130, pp. 161-176, 2018.

[2] Y. Wu, L. Pei, W. Jin, Y. Jiang, Y. Yang, Y. Shen and S. Jian, "Highly sensitive curvature sensor based on asymmetrical twin core fiber and multimode fiber," Optics & Laser Technology, vol. 92, pp. 74-79, 2017.

[3] S. Wang, W. Zhang, L. Chen, Y. Zhang, P. Geng, Y. Zhang, T. Yan, L. Yu, W. Hu, and Y. Li, "Two-dimensional microbend sensor based on long-period fiber gratings in an isosceles triangle arrangement three-core fiber," Optics Letters. vol. 42, pp. 4938-4941, 2017.

[4] X. Wang, D. Chen, H. Li, G. Feng and J. Yang, "In-Line Mach–Zehnder Interferometric Sensor Based on a Seven-Core Optical Fiber," IEEE Sensors Journal, vol. 17, no. 1, pp. 100-104, 2017.

[5] S. Dong, B. Dong, C. Yu and Y. Guo, "High Sensitivity Optical Fiber Curvature Sensor Based on Cascaded Fiber Interferometer," Journal of Lightwave Technology, vol. 36, no. 4, pp. 1125-1130, 2018.

[6] R. Wang et al., "Highly Sensitive Curvature Sensor Using an In-Fiber Mach–Zehnder Interferometer," IEEE Sensors Journal, vol. 13, no. 5, pp. 1766-1770, May 2013.

[7] H. Gong, H. Song, X. Li, J. Wang, X. Dong, "An optical fiber curvature sensor based on photonic crystal fiber modal interferometer," Sensors and Actuators A: Physical, vol. 195, pp. 139-141, 2013.

Downloaded From: https://www.spiedigitallibrary.org/conference-proceedings-of-spie on 2/18/2019
Terms of Use: https://www.spiedigitallibrary.org/terms-of-use