High sensitivity curvature sensor with a cascaded fiber interferometer

Shandong Dong*[a,b], Bo Dong[a] and Changyuan Yu[c]
[a]Department of Electrical and Computer Engineering, National University of Singapore, 117583, Singapore; [b]National University of Singapore (Suzhou) Research Institute, China 215123, China; [c]Department of Electronic and Information Engineering, the Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong

ABSTRACT

This paper presents a cascaded fiber interferometer sensor, which is fabricated by fusion splicing of single-mode fibers. The coupling and interference for the CFI were mathematically and experimentally studied. An equal model has been built for the CFI. Furthermore, the curvature sensitivity were explored in sensor application. The curvature sensitivity for the cascaded fiber interferometer is very high, which can achieve 790.18 pm/m^{-1}. Besides, the proposed sensor has advantages like good repeatability, low cost, and simple structure.

Keywords: cascaded fiber interferometer, curvature sensor, modal interferometer

1. INTRODUCTION

Since S. K. Sheem and T. G. Giallorenzi [1] firstly demonstrated the polarization effect in single mode fiber, fiber sensors have got a great development these years. Among various fiber sensor structures, interferometers have its own advantages, such as low cost, simple structure and high sensitivity. Therefore, interferometer structures like Fabory-Perot Interferometer, Sagnac Interferometer and Mach-Zender Interferometer and Modal Interferometer [2-4] have been reported recently. Compared with other three structures, Modal interferometer has attracted much attention and interest for its simple and compact all-fiber structure and good reproducibility. And this type of interferometer has been used in many sensing areas, like: temperature and strain measurement [5], acoustic measurement [6], refractive index (RI) measurement [7], etc.

However, the cascaded fiber interferometer (CFI), which consists of interferometers connected in series, has not been investigated. Hence, in this paper, we proposed a CFI using single mode fiber (SMF). And the cladding mode can be excited by using the abrupt taper method. The basic sensor head is made up of two single interferometers. The coupling between the interferometers is investigated theoretically and experimentally. Furthermore, an equal model has been proposed and verified to calculate the interference of the CFI.

In our experiment, two single interferometers were selected to be connected in series. Each interferometer has two tapers. The distance between two tapers in one single interferometer is set as 2 cm. While the distance between two interferometer is controlled as 8 cm. The transmission response to curvature has been investigated. And the novel sensor presents high curvature sensitivity, which can achieve 790.18 pm/m^{-1}. In conclusion, this novel structure has a lot of advantages such as: strain insensitive, good reproducibility, low cost and really high curvature sensitivity.

2. THEORETICAL MODEL

The schematic diagram of the experimental setup is shown in Fig. 1. The basic structure of the novel sensor consists of four up-tapers. In theory, these four tapers constitute two interferometer structures. Hence, this novel sensor can be considered as two interferometers connected in series. For single interferometer, when light passes a taper, a lot of cladding modes will be excited and re-coupled when passes the second taper. When two interferometers are connected in series, the effect can be seen as the convolution between the two interferometers. Here, to simplify the model, only two dominant modes are taken into consideration.

To facilitate the theoretical analysis, the mathematical model for the fiber is constructed using Jones Matrix. Here, the distance between the first taper and second taper is marked as L_1, the distance between the second taper and third taper is

25th International Conference on Optical Fiber Sensors, edited by Youngjoo Chung, Wei Jin, Byoungho Lee, John Canning, Kentaro Nakamura, Libo Yuan, Proc. of SPIE Vol. 10323, 1032372 · © 2017 SPIE · CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2264779

marked as L_c, the distance between the third taper and fourth taper is marked as L_2. Therefore, the phase of the core mode and cladding mode can be written as [8]:

$$\theta_{co_i} = \frac{2\pi n_{co} L_i}{\lambda}, \theta_{cl_i} = \frac{2\pi n_{cl} L_i}{\lambda} \tag{1}$$

Where θ_{co_i} and θ_{cl_i} are the effective refractive indexes of the core and cladding modes of i-th interferometer. λ is the wavelength and L_i is the interference distance between two tapers of i-th interferometer.

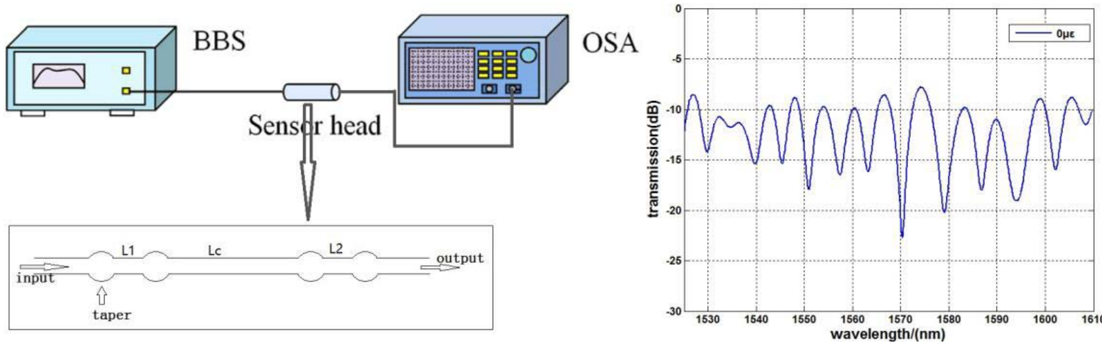

Fig.1. Schematic diagram of the experimental setup (Insets shows the sensing structure and transmission spetrum, respectively).

Consider the function of interferometer is interference, the transmission function of i-th fiber interferometer and transmission matrix of connection period can be written as [9]:

$$\mathrm{T}_i = \begin{bmatrix} \alpha_i e^{j\theta_{co_i}} & 0 \\ 0 & \beta_i e^{j\theta_{cl_i}} \end{bmatrix} \qquad T_c = \begin{bmatrix} \alpha_c e^{j\theta_{co_c}} & 0 \\ 0 & \alpha_c e^{j\theta_{co_c}} \end{bmatrix} \tag{2}$$

So the total transmission matrix of the sensor is:

$$\begin{aligned} \mathrm{T}_{total} &= T_2 \times T_c \times T_1 = \begin{bmatrix} \alpha_2 e^{j\theta_{co_2}} & 0 \\ 0 & \beta_2 e^{j\theta_{cl_2}} \end{bmatrix} \times \begin{bmatrix} \alpha_c e^{j\theta_{co_c}} & 0 \\ 0 & \alpha_c e^{j\theta_{co_c}} \end{bmatrix} \times \begin{bmatrix} \alpha_1 e^{j\theta_{co_1}} & 0 \\ 0 & \beta_1 e^{j\theta_{cl_1}} \end{bmatrix} \\ &= \begin{bmatrix} \alpha_2 \alpha_c \alpha_1 e^{j(\theta_{co_2}+\theta_{co_c}+\theta_{co_1})} & 0 \\ 0 & \beta_2 \alpha_c \beta_1 e^{j(\theta_{cl_2}+\theta_{co_c}+\theta_{cl_1})} \end{bmatrix} \end{aligned} \tag{3}$$

Then the output light field amplitudes can be written as:

$$E_{out} = T \times \begin{bmatrix} E_1 \\ E_2 \end{bmatrix} = \begin{bmatrix} \alpha_2 \alpha_c \alpha_1 e^{j\left(\theta_{co_2}+\theta_{co_c}+\theta_{co_1}\right)} E_1 \\ \beta_2 \alpha_c \beta_1 e^{j\left(\theta_{cl_2}+\theta_{co_c}+\theta_{cl_1}\right)} E_2 \end{bmatrix} = \alpha_2 \alpha_c \alpha_1 e^{j(\theta_{co_2}+\theta_{co_c}+\theta_{co_1})} E_1 + \beta_2 \alpha_c \beta_{1i} e^{j\left(\theta_{cl_2}+\theta_{co_c}+\theta_{cl_1}\right)} E_2 \tag{4}$$

Where E_1 and E_2 are the field distributed in the core mode and the strong cladding mode, respectively. The transmitted light intensity detected at the output then can be written as:

$$\begin{aligned} I_{out} &= E_{out}^{\ *} E_{out} = \alpha^2 E_1^{\ *} E_1 + \beta^2 E_2^{\ *} E_2 + \alpha\beta E_2^{\ *} E_1 e^{j2(\theta_{co}-\theta_{cl})} + \alpha\beta E_1^{\ *} E_2 e^{-j2(\theta_{co}-\theta_{cl})} \\ &= \alpha^2 I_1 + \beta^2 I_2 + 2\alpha\beta\sqrt{I_1 I_2}\cos\left(\frac{2\pi \times 2(n_{co}-n_{cl})L}{\lambda}\right) \end{aligned} \tag{5}$$

Where $\alpha = \alpha_2 \alpha_c \alpha_1$, $\beta = \beta_1 \alpha_c \beta_2$, $L = L_1 + L_2$, $I_1 = E_1^{\ *} E_1$, $I_2 = E_2^{\ *} E_2$ are the power distributed in the core mode and the strong cladding mode, respectively.

From Equation (5), we can find that the CFI approximates to be a bigger interferometer, where the equivalent effective refractive index doubles. And according to the equivalent model, the period of the sensor can be approximately given by [8]:

$$\mathrm{FSR} = \frac{\lambda^2}{2(n_{co}-n_{cl})L} \tag{6}$$

Theoretically, from Equation. (6), it predicts FSR is about 6nm if wavelength is 1550nm assuming L=4cm. As shown in Fig. 1, the FSR in transmission spectrum is about 5-7nm, which verifies the theory.

For curvature sensitivity, according to [10], the wavelength response to curvature can be written as:

$$\lambda_m = \frac{\Delta n_{eff_0} L}{2m+1} + \frac{kLd}{2m+1} \times \frac{1}{R} \tag{7}$$

From Equations (7), we can conclude that the change of the wavelength dip is relevant with the variations of the effective refractive index. While n_{eff} is proportional to the curvature. Hence, the shift of wavelength is produced by curvature.

3. EXPERIMENTAL RESULTS

The sensing structure can be seen in Fig. 1. In experiment, the CFI is made up of four taper, and the parameters are: 2 cm distance between first and second tapers, 8cm distance between second taper and third taper, 2cm distance between the third taper and fourth taper. So the equal length here is 4cm. The largest extinction ratio reaches 15 dB, as shown in Fig. 2. The transmission spectrum of the sensor was measure by an OSA with a wavelength resolution of 0.02nm. The applied strain was controlled in range of 0-5.135 m^{-1}.

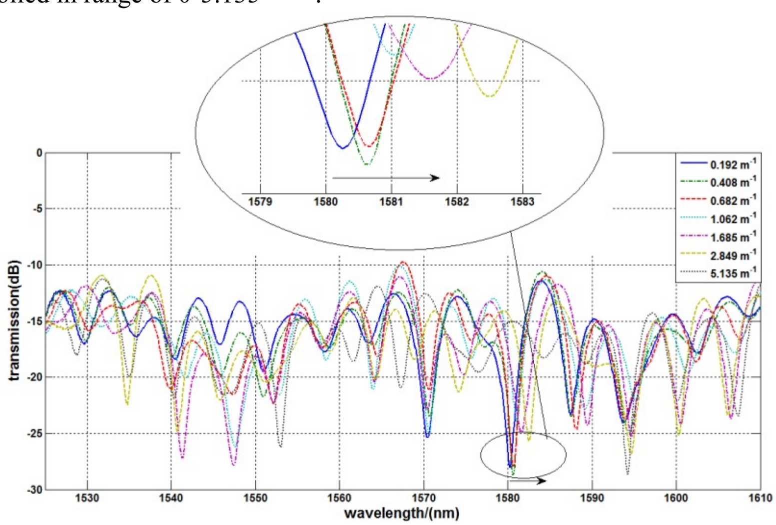

Fig.2. Measured transmission spectrum response to curvature.

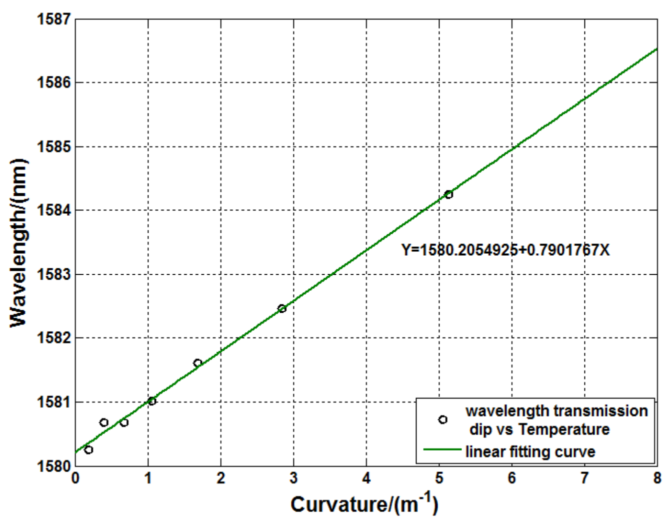

Fig.3. Relationship between Measured Wavelength and Curvature

Fig.2. shows the measured transmission spectrum shift for different curvatures. It can be seen that with the increase of curvature, the inter-modal interference changes a lot, especially for the extinction ratio at each wavelength. This is because when the interferometer is bended, the interference mode between two tapers will be greatly influenced.

In addition, dips around 1580nm were taken to be analyzed. As exhibited in Fig. 3, the transmission dips get a red shift with the increasement of curvature. The resonant wavelength for different curvatures can be determined accurately by using a linear fit to the spectra. The correlation coefficient square and curvature sensitivity in 1580nm of the sensor are 0.9962 and 790.18pm/ m^{-1} . Therefore, wavelength dips presents good linearity to curvature.

4. CONCLUSION

A novel high curvature sensitive fiber based on the cascaded interferometers has been proposed in this paper. The coupling between each interferometer in the CFI has been proved mathematically and experimentally. And an equal model to calculate the FSR has been proved. For the sensor application, curvature property has been investigated. And the curvature sensitivity can achieve 790.18pm/ m^{-1} . Besides, this novel sensor has the advantages like simple and compact structure, low cost.

5. ACKNOWLEDGEMENT

The authors would like to thank for the financial support of AcRF Tier 2 Grant MOE2013-T2-2-135 from MOE Singapore, Grants 61501313, 61471253 and 61571316 from the National Natural Science Foundation of China, and Grant 1-ZE5K from HKPU.

REFERENCES

[1] Sheem S K, Giallorenzi T G. Polarization effects on single-mode optical fiber sensors[J]. Applied Physics Letters, 1979, 35(12): 914-917.
[2] Wang C, Zhang W, Ruan J, et al. Characteristic analysis of a novel FP interferometer based on a pair of FBGs with built-in LPFGs[J]. Optoelectronics Letters, 2012, 8: 84-88.
[3] X. Y. Dong, H. Y. Tam, and P. Shum, "Temperature-insensitive strain sensor with polarization-maintaining photonic crystal fiber based Sagnac interferometer," Appl. Phys. Lett., vol. 90, p. 151113, 2007.
[4] Lu P, Men L, Sooley K, et al. Tapered fiber Mach–Zehnder interferometer for simultaneous measurement of refractive index and temperature[J]. Applied Physics Letters, 2009, 94(13): 131110.
[5] Dong B, Hao J, Liaw C, et al. Simultaneous strain and temperature measurement using a compact photonic crystal fiber inter-modal interferometer and a fiber Bragg grating[J]. Applied optics, 2010, 49(32): 6232-6235.
[6] van Dijk M A, Lippitz M, Orrit M. Detection of acoustic oscillations of single gold nanospheres by time-resolved interferometry[J]. Physical review letters, 2005, 95(26): 267406.
[7] Jung Y, Kim S, Lee D, et al. Compact three segmented multimode fibre modal interferometer for high sensitivity refractive-index measurement[J]. Measurement Science and Technology, 2006, 17(5): 1129.
[8] Dong B, Zhou D P, Wei L. Temperature insensitive all-fiber compact polarization-maintaining photonic crystal fiber based interferometer and its applications in fiber sensors[J]. Journal of Lightwave Technology, 2010, 28(7): 1011-1015.
[9] Leandro D, Bravo M, Lopez-Amo M. High resolution polarization-independent high-birefringence fiber loop mirror sensor[J]. Optics express, 2015, 23(24): 30985-30990.
[10] Niu L, Zhao C L, Gong H, et al. Curvature sensor based on two cascading abrupt-tapers modal interferometer in single mode fiber[J]. Optics Communications, 2014, 333: 11-15.