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Temperature- and Phase-Independent Lateral Force Sensor based on a Core-Offset Multi-Mode Fiber Interferometer

Bo Dong
Wilfrid Laurier University

Da-Peng Zhou
University of Waterloo

Li Wei
Wilfrid Laurier University, lwei@wlu.ca

Wing-Ki Liu
University of Waterloo

John W.Y. Lit
Wilfrid Laurier University, jlit@wlu.ca

Temperature- and phase-independent lateral force sensor based on a core-offset multi-mode fiber interferometer

Bo Dong,[1,*] Da-Peng Zhou,[2] Li Wei,[1] Wing-Ki Liu,[2] and John W. Y. Lit[1]

[1] *Department of Physics and Computer Science, Wilfrid Laurier University, Waterloo, Ontario, N2L 3C5, Canada*
[2] *Department of Physics and Astronomy, Guelph-Waterloo Physics Institute, University of Waterloo, Waterloo, Ontario N2L 3G1, Canada*
[*] *Corresponding author: dbo1978@163.com*

Abstract: A novel lateral force sensor based on a core-offset multi-mode fiber (MMF) interferometer is reported. High extinction ratio can be obtained by misaligning a fused cross section between the single-mode fiber (SMF) and MMF. With the variation of the lateral force applied to a short section of the MMF, the extinction ratio changes while the interference phase remains almost constant. The change of the extinction ratio is independent of temperature variations. The proposed force sensor has the advantages of temperature- and phase-independency, high extinction ratio sensitivity, good repeatability, low cost, and simple structure. Moreover, the core-offset MMF interferometer is expected to have applications in fiber filters and tunable phase-independent attenuators.

OCIS codes: (060.2310) Fiber optics ; (060.2370) Fiber optics sensors.

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1. Introduction

Different types of force sensors based on fiber Bragg grating (FBG), Mach-Zehnder (M-Z) interferometer, high-birefringence fiber, etc have been developed. Among them, the use of an FBG has to adopt the specially designed beam to realize the temperature and force discrimination [1-3], which leads to a complicated sensing structure. In addition, the force sensors with two FBGs [4, 5] to realize the temperature and force discrimination result not only in measurement errors due to the temperature-strain cross effect of the FBG sensor, but also a complicated structure and high price. Moreover, FBG is very fragile. The force sensor with M-Z interferometer [6] has to adopt a complicated sensing structure to tune the reference arm. Moreover, the fabrication of M-Z interferometer is complicated. High-birefringence fiber-based sensor [7] realized the distributed force measurement, but they did not consider the temperature influence. Compared to the above fiber sensors, the multi-mode fiber (MMF) interference sensors based on modal interference [8] have the advantages of low cost and simple structure, which have attracted much attention. Reported MMF interference sensors were focused on the strain and temperature measurement [9~14]. However, most of the MMF interference strain sensors did not consider the temperature influence [9,13]. One method to overcome the temperature influence on the MMF interference sensor has been presented by our group [14]. By connecting a fiber Bragg grating (FBG) to the MMF interferometer, simultaneous measurement of strain and temperature can be realized. However, the sensor needs to be connected to another fiber sensor such as an FBG, which makes the sensing structure more complex and increases the cost. Moreover, the temperature-strain cross effect of the sensor can not be completely eliminated, which leads to measurement errors.

In this paper, we presented a novel temperature- and phase-independent lateral force sensor based on a core-offset MMF interferometer. By misaligning a fused cross section between the SMF and MMF, a core-offset MMF interferometer with high optical intensity extinction ratio can be obtained. This extinction ratio will change with the variations of the lateral force applied to a short section of the MMF, while the interference phase will remain almost constant. Moreover, it is independent of temperature variations. Experimental results show that the extinction ratio varies quadratically with the applied force. This type of sensor has the advantages of temperature- and phase-independency, good repeatability, high extinction ratio sensitivity, low cost, and simple structure. Moreover, it is expected to be applicable to fiber filters and tunable phase-independent attenuators.

2. Operation principle

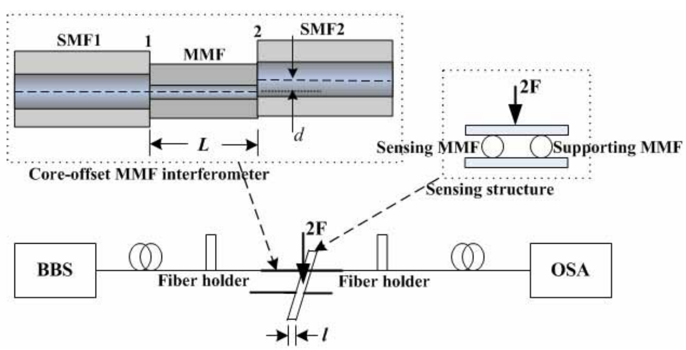

Fig. 1. Schematic diagram of the experimental setup (Insets show the interferometer structure and the sensing structure, respectively).

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As shown in Fig. 1, the core-offset MMF interferometer is a three-segment fiber structure, where a segment of MMF of length L is connected to two standard communication SMFs. The MMF was originally designed for dispersion compensation applications, with a large dispersion parameter of −270 ps/nm/km at 1550 nm and a cutoff wavelength of 1663 nm. The core/cladding diameter of the MMF is 1.9μm/115.7μm. The SMF-MMF-SMF structure can act as an M-Z interferometer, based on intermodal interference. Many modes with different effective refractive indices can be excited when the light is coupled into the MMF from SMF1. When these modes are re-coupled back into the SMF2, they will interfere with each other. If only considering two dominant modes, the transmission spectrum is approximately a periodic function, given by

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos[\frac{2\pi(n_2 - n_1)L}{\lambda}], \tag{1}$$

where I_1 and I_2 are the power distributed in the lower-order and higher-order dominant modes, respectively, with $I_2 < I_1$; n_2 and n_1 are the effective refractive indices of the two modes respectively, and λ is the wavelength of light in vacuum. The extinction ratio ER of the interferometer can be given by $ER = 10\lg(\frac{1+\sqrt{I_2/I_1}}{1-\sqrt{I_2/I_1}})^2$. Figure 2 shows the extinction ratio as a function of the power ratio I_2/I_1 of the two interference modes. It can be seen that bigger power ratio of I_2/I_1 gives rise to higher extinction ratio. The extinction ratio for the

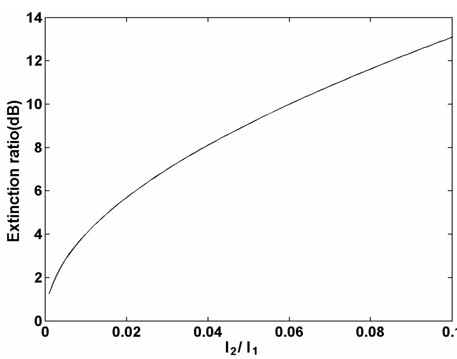

Fig. 2. Extinction ratio as a function of the power ratio I_2/I_1 of the two interference modes

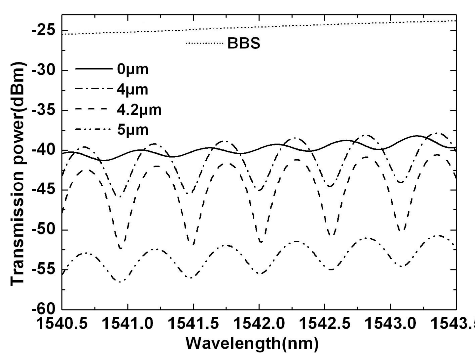

Fig. 3. Transmission power spectra of the BBS and the MMF interferometer with core-offset *d* about 0, 4μm, 4.2μm and 5μm, respectively

directly fused 1.9μm/115.7μm MMF interferometer without core-offset is generally lower than 4 dB, corresponding to a power ratio of 0.01. In order to obtain a high extinction ratio, we have to increase the power ratio I_2/I_1, which can be realized by manually offsetting the cores between the SMF2 and MMF at splicing section 2. The core-offset splicing is an effective method to control the modes coupling [15]. The offset dependent loss characteristic was firstly studied with a MMF about 24cm in length. The splicing section 1 is fused automatically without core-offset. Using a broadband source (BBS) with the transmission power spectrum shown as the dotted line in Fig. 3, the transmission power spectra of the interferometer are shown in Fig. 3 for different core-offset distances of *d* at splicing section 2. It can be seen that there is a best offset position to obtain maximum extinction ratio. The homogeneous spectra in Fig. 3 confirm that the interference is mainly produced by two

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dominant modes. Because other higher-order modes are very weak, they have little influence on the interference.

When a lateral force is applied to a short section of the MMF, deformation is produced in the MMF, which will lead to power loss of the two modes. For a given applied lateral force, the higher-order mode with power I_2 has more power loss than that of the lower-order mode. Moreover, the power of the higher-order mode decreases much faster than that of the lower-order mode when the force increases. Thus, the power ratio of the two interference modes I_2 / I_1 decreases accordingly with the increase of the lateral force, which will lead to a reduction of the extinction ratio (See Fig. 2). With a same lateral force applied to the MMF, the core-offset interferometer with higher extinction ratio will have a larger reduction in extinction ratio. The above phenomena can be applied to the measurement of the lateral force.

When the lateral force is applied to a short section l of the MMF, the elongated length Δl of the section is far less than L, producing negligible longitudinal strain ($\Delta l / L \approx 0$). Thus the phase in Eq. (1) is only determined by the difference of the two effective mode indices at a given value of λ. The birefringence variation Δn per unit length of the core refractive index under the lateral force can be expressed as [16]

$$\Delta n = \frac{4kF}{\pi r l E} \tag{2}$$

where k is strain optical coefficient, F is the force acting on fiber of length l, and r, E are the outer radius and Young's Modulus of the fiber, respectively. Under the lateral force, the two interference modes approximately experience the same amount of variation according to Eq. (2). Thus the difference between two effective mode indices of $n_2 - n_1$ almost remains constant. As a result, the interference phase is independent of the lateral force, which can be applied to phase-independent force measurement.

When the ambient temperature changes, the transmission spectrum of the MMF interferometer will shift, which is related to the thermal expansion and thermo-optic coefficients of the MMF material [9,11]. Although the extinction ratio varies with the applied lateral force, it does not change with the temperature variation. This feature can be applied to temperature-independent force measurement.

3. Experimental results and discussions

The sensing structure is shown in Fig. 1. With the above fabrication method, a core-offset MMF interferometer sensor with the MMF length about 22 cm is fabricated. The extinction ratio reaches 8 dB, as shown in Fig. 4. A section of MMF identical to the sensing MMF is used as a supporting fiber. Rotation of the MMF will lead to inhomogeneous interference spectrum mainly because part of the power in the dominant interference modes is coupled into other higher-order modes. In order to avoid the rotation of the MMF, the interferometer is supported by two fiber holders placed on an optical table, and the supporting MMF and sensing MMF are fixed between two aluminum flakes with smooth surfaces. The width of the aluminum flake is about 1 cm. The transmission spectrum of the sensor is monitored by an optical spectrum analyzer (OSA). With different forces applied to the MMF, the extinction ratio changes accordingly, while the interference phase remains constant, as shown in Fig. 5. This can also be used as a tunable phase independent attenuator.

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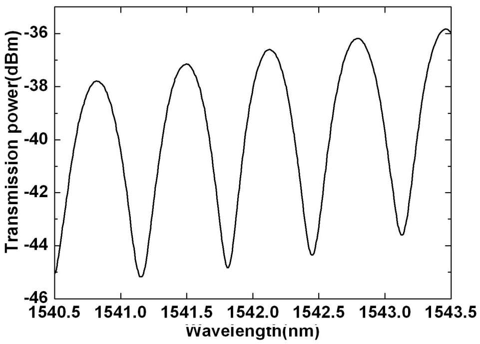

Fig. 4. Transmission spectrum of the core-offset MMF interferometer sensor

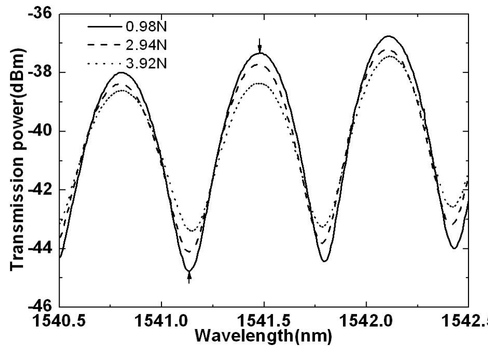

Fig. 5. Measured transmission power spectra under different lateral forces

Figure 6 shows the responses of the extinction ratio (See the extinction ratio between the two arrow marks in Fig. 5) to different lateral forces. It can be seen that there is a good quadratic relationship between the extinction ratio and the force for the 1.9μm/115.7μm MMF-based sensor, and the correlation coefficient square reaches 0.9944. In addition, another gradient index MMF of length 150 cm and core/cladding diameter of 50.7μm/125.3μm was used to measure the lateral force with the same sensing mechanism. Again, a good quadratic relationship between the extinction ratio and the applied force is found, and the correlation coefficient square reaches 0.999, as shown in Fig. 6. The extinction ratio of the 50.7μm/125.3μm MMF-based sensor is more sensitive to the force than that of the 1.9μm/115.7μm MMF-based sensor. However, the interferometer based on the 50.7μm/125.3μm MMF needs a longer fiber, which is vulnerable to the influence of the ambient disturbance and is not suitable for smart sensing in actual measurement environment. The interferometer based on the 1.9μm/115.7μm MMF with shorter length is more suitable for the smart sensing in actual measurement environment.

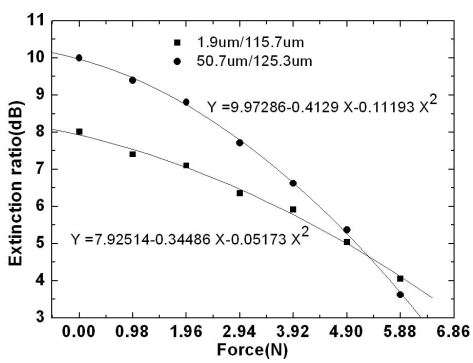

Fig. 6. Extinction ratio responses to different lateral forces

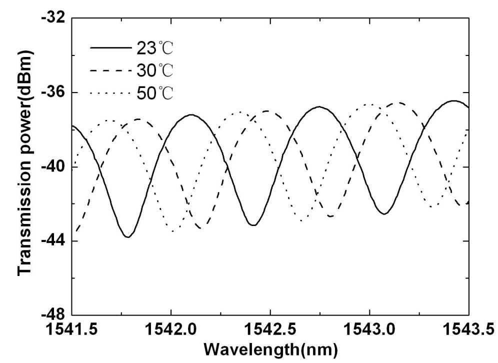

Fig. 7. Measured transmission power spectra under different temperatures at a fixed force of 2.94 N

Figure 7 shows the transmission power spectra of the 1.9μm/115.7μm MMF-based sensor under different temperatures at a fixed force of 2.94 N. When the temperature increases, the spectrum has a red shift; a wavelength shift of 1.516 nm is observed when the temperature varies from 23°C to 50°C. However, the extinction ratio is unaffected when the ambient

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temperature changes. The above experimental results agree with the theoretical prediction of the temperature- and phase-independent features of the force sensor. Additional experimental results show that in the temperature range of 23°C ~ 60°C, the variation of the extinction ratio with the applied force can be well described by a quadratic relation. However, when the temperature is over 60°C, the extinction ratio and phase responses to temperature start to change erratically, which is attributed to the limitation of the thermal property of the MMF and aluminum flake materials. The operational temperature range may be extended by encapsulating temperature compensation materials with negative temperature coefficient to the sensor. In order to avoid breaking the MMF, the force is controlled in the range of 0~ 5.88N. The operational force range of the sensor can be increased by encapsulating the MMF sensing head in materials with high Young's modulus for practical applications. In addition, in order to avoid the rotation influence of the MMF on the interference spectrum of the sensor, the encapsulating model can adopt shape of a cuboid with a given force direction.

4. Conclusion

A novel and simple core-offset MMF interferometer force sensing mechanism has been presented and demonstrated experimentally. The MMF-based interferometer can be obtained by misaligning a fused cross section between the SMF and MMF. The advantages of the sensor include temperature- and phase-independency, high extinction ratio sensitivity, good repeatability, low cost, and simple structure. Moreover, the sensing mechanism shows that core-offset MMF-based interferometer can be applied to tunable phase-independent attenuators. Hence the core-offset MMF interferometer not only has the potential applications in fiber sensing but also in fiber filters and tunable phase-independent attenuators.

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