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Lateral force sensor based on a core-offset tilted fiber Bragg grating

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ABSTRACT

A novel lateral force sensor based on a core-offset tilted fiber Bragg grating (TFBG) is proposed and experimentally demonstrated. The lateral force is determined by the differential reflected powers between the cladding mode and Bragg mode in the TFBG. The sensors respond monotonically with the lateral force increasing from 0 to 1.75 N. The sensitivity of such a core-offset TFBG sensor can be tailored by choosing different core-offset values. The simple differential power detection method makes the implementation of the sensor system cost-effective and free of the influence of environmental and system fluctuations.

1. Introduction

Fiber-optic lateral force or pressure sensors have attracted a great deal of interest in many industrial applications because of their distinct advantages over traditional transducers, such as compact size, integrated structure, capability of multiplexing and remote interrogation. Despite the great variety of grating based lateral force sensors that have been demonstrated, they all more or less rely on a sensing mechanism that is based on the change of birefringence of a fiber Bragg grating (FBG). The sensors proposed so far can be divided into two groups using passive and active schemes. The passive lateral force measurement relies on the increase of the birefringence of a FBG in a normal fiber [1] or a polarization maintaining fiber (PMF) [2,3] due to the applied lateral force, resulting in a splitting of the reflection spectrum or a change of the peak separation of two orthogonal polarization modes. Another highly sensitive lateral force sensor has also been demonstrated by the use of a phase-shifted FBG which has a very narrow transmission window in the middle of the reflection band [4]. However, these sensors require a wavelength measurement which can be slow and uses expensive interrogation equipment. For active lateral force sensors, instead of measuring absolute wavelengths they can measure the beat frequency of the two orthogonal polarization laser modes by using cost-effective and high-speed electrical spectrum analyzers. Lateral force sensors based on dual-wavelength fiber lasers [5], distributed-feedback (DFB) lasers [6] and distributed Bragg reflector (DBR) fiber lasers [7] have been reported. However, all of the above birefringence based lateral force sensors have a common issue that the sensitivity is limited by the high Young's modulus of the fiber material. So a core-offset spliced multimode fiber (MMF) interferometer has been proposed to enhance the sensitivity of lateral force measurement [8]. The design is simple but there are several practical issues in implementing the sensors. It needs precise alignment for two SMF/MMF offset splice otherwise the highest sensitivity cannot be obtained. And the SMF–MMF splices introduce so much insertion losses that the signal to noise ratio would decrease significantly.

In this letter, we demonstrate an alternative lateral force sensor implemented by using a core-offset tilted fiber Bragg grating (TFBG). In this sensor, the lateral force applied to the fiber is determined by the difference between the reflected power of the selected cladding modes and that of the core mode of the TFBG. In previous publications we have demonstrated that this structure can be used as a vibration sensor because of its high sensitivity to bending [9]. We use a similar structure here; a weakly tilted fiber Bragg grating that is spliced to single mode fiber with a controllable core-offset. As schematically shown in Fig. 1a, some backward propagating cladding modes excited by the grating are re-coupled into the fiber core via a core-offset splicing junction located upstream of the TFBG. The core offset at the junction also results in loss for the core mode back-reflection. We will now demonstrate the novel phenomenon that a lateral force applied on the core-offset splicing junction will result in an increase of the core mode reflected power and a decrease of the cladding mode re-coupling. By monitoring the difference in the reflected power of these two well-defined mode groups (with the help of suitably chosen fixed

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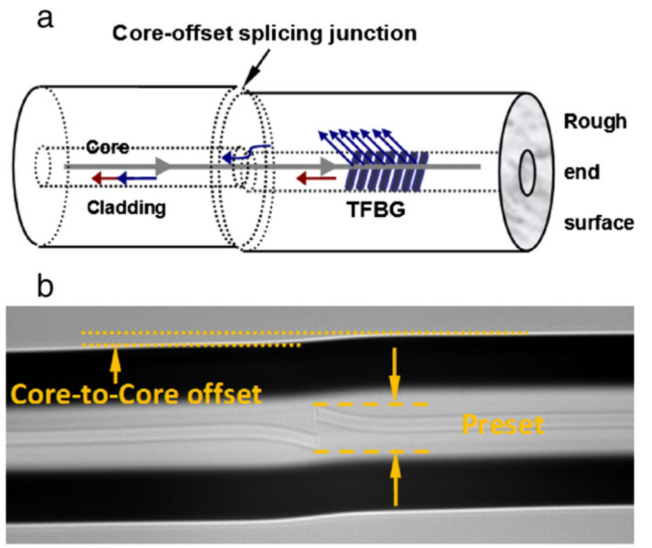

Fig. 1. a) Schematic diagram of the core-offset TFBG b) Microscopy photo of one sample with the core-offset of 8.5 μm.

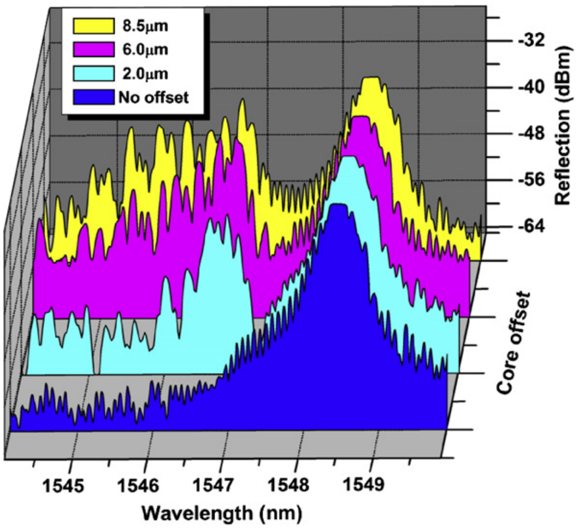

Fig. 2. Reflection spectra evolution against core-offset.

band pass filters), we can measure the applied lateral force without interference from power source fluctuations. We also demonstrate that the sensitivity of the sensor can be tailored by adjusting the amount of the core-offset.

2. SENSOR fabrication

Corning SMF-28 fiber was used to fabricate the gratings. The fiber was soaked in a hydrogen chamber for 12 days at 2500 psi and room temperature of 25 °C to improve its photosensitivity. 1-cm-long TFBGs with a tilt angle of 2° were inscribed in the hydrogen-loaded fibers using a pulsed KrF excimer laser and the phase mask technique. Then they were spliced to another section of single mode fiber (SMF) with different core-offsets by using a Corning Compact fusion set. In general, the cladding modes generated by the TFBG suffer large loss if it propagated for a long distance along the fiber cladding (because they are exposed to the environment and susceptible to bend loss). So we keep the distance between the splicing junction and the TFBG short to 1 cm. In addition, to ensure a robust splicing junction a certain amount of overlap is necessary during the fusion of the SMF to the fiber containing the grating. Here, the push distance was set to 12 μm while the initial distance between the fiber ends was 8 μm. So the overlap was 4 μm as the fibers were heated and melted. Three samples of core-offset TFBGs were prepared for the next experiment of lateral force measurement. Their core to core offsets were 2.0 μm, 6.0 μm and 8.5 μm, respectively. Fig. 1b shows a microscope photo of one example of a TFBG with a lateral fusion offset of 8.5 μm. In order to achieve this offset value, it is necessary to use a pre-fusion alignment offset of 20.3 μm, which is much larger than the core-offset after splicing. We can see that the cores of both fiber ends are deflected at the splicing junction as a result of the aforementioned overlap. The final offset, as measured in the manner shown in Fig. 1b, results from the solidification of the overlapped melted fiber junction and the contribution of the surface tension of the glass to re-align the fibers. Eventually, a mechanically robust splicing junction is obtained with a smooth surface along the fiber cladding.

Fig. 2 shows how the reflection spectra of the TFBGs change with increasing core-offsets. The induced reflection losses for the core modes are 1.5 dB, 4.2 dB and 7.2 dB with core-offsets of 2.0 μm, 6.0 μm and 8.5 μm, respectively. Also, higher order cladding modes (at shorter wavelengths) are recoupled into the fiber core as the offset of the splice increases. The reflection power of the cladding modes in a selected spectral band is going to provide a measure of lateral force.

3. Experimental results and discussion

Fig. 3 illustrates the schematic diagram of our lateral force measurement system. The light from a broadband source (BBS: C + L band ASE source from JDSU Corporation) goes through a 3 dB coupler and into the core-offset TFBG from the splicing junction side. The sensing TFBG is clamped between two rotatable holders, which can rotate the fiber and hence adjust the direction of the applied lateral force on the sensor. The light reflected from the device is further divided into two parts by another 3 dB coupler: one half is used to monitor the spectrum with an optical spectrum analyzer (OSA: AQ6317B from Anristu); the other half is used for power measurement with a power meter (PM). A tunable bandpass filter with 1-nm bandwidth is employed to distinguish the power reflected by the cladding modes relative to the reflection from the core mode. The dotted frame in Fig. 3 shows how the lateral force is applied using two glass plates with smooth surfaces. Because of the short distance between the splicing junction and TFBG (1 cm), the widths of the top and ground glass plates are chosen to be 1 cm and 2 cm respectively so that the force is only applied to the core-offset splicing junction and no force to the TFBG

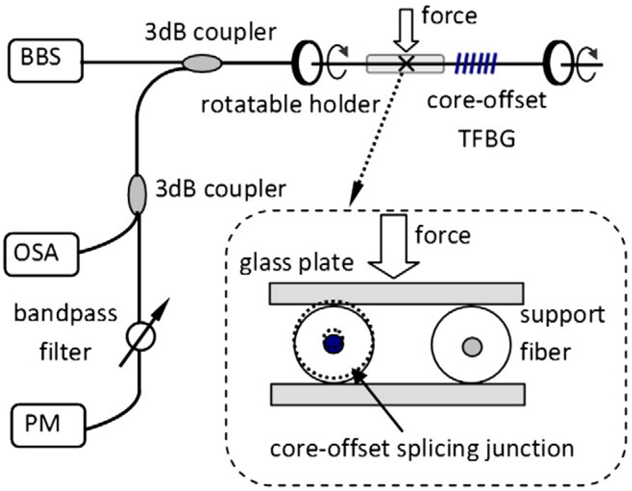

Fig. 3. Schematic diagram of lateral force measurement system. The dotted frame shows how the lateral force is applied.

itself. Another section of uncoated SMF with the same cladding diameter of 125 μm was put between the plates and parallel to the sensing TFBG so that the lateral force applied on the top glass plate transfers precisely across the diameter of the device under test. A set of standard weights (corresponding to forces from 0.25 N to 1.75 N) are used to quantify the applied force. Because the top glass plate is much lighter compared to the weights, it can be neglected in the following analysis.

Before the lateral force measurement, we have marked the direction of offset splice. It is noticeable that the sensor has the maximum sensitivity to the applied lateral force through this direction. And the response is negligible if the lateral force applied at 90° to the direction of the offset splice. So in the following experiments, three sensors with different offsets were investigated at the direction of the off-set splice (with maximum sensitivity). Fig. 4 depicts the relative change in the total reflected power of the core mode band (P_B) and the cladding mode band (P_C) for three different core-offset TFBGs against applied lateral force. The center wavelength of the tunable filter (with a bandwidth of 1 nm) is set to 1548.58 nm for P_B and to 1546 nm for P_C (where the power of cladding modes has the best sensitivity), respectively. We can see that the reflected power of the core mode increases with the applied lateral force while the power reflected in the cladding mode band decreases. This behavior can be explained easily: a properly oriented lateral force will deform the core-offset splice and tend to "re-align" the two cores, resulting in increased core mode transmission and reduced cladding mode re-coupling. Quantitatively, the reflection powers of the core mode for the TFBG with the largest offsets (P_{B3}) have a highest lateral force sensitivity of 0.86 dB/N, which is much higher than that of the 2.0 μm core-offset TFBG (the force sensitivity is 0.08 dB/N). Meanwhile, the responses of the re-coupled power of the cladding modes are still monotonic but not linear anymore. This phenomenon is likely caused by the non-uniform power distribution of the cladding modes in the cross-section of the fiber cladding. However, we note that the sensitivity of the cladding mode response also increases with the amount of the core offset in the range of 0 to 8.5 μm. We will not use higher core-offset because it introduces too big insertion loss to the device. Furthermore, as the fiber cores are deflected at the offset splicing junction (see the microscopy photo in Fig. 1b), we cannot quantify the effect of the core-offset on the recoupled power by directly using the mode overlap integral. Theoretical analysis of mode recoupling mechanism for the core-offset TFBG under lateral force is our future work to optimize the sensor's performance.

An additional improvement consists of using the difference between the core mode and cladding modes ($P_B - P_C$) reflected powers as a measure of the applied lateral force. The corresponding results are shown in Fig. 5. This simple computation not only improves the sensitivity of the sensor by taking the advantages of the two complementary but independent measurements available, but also eliminates the power source fluctuations automatically. The response of the 8.5 μm core-offset TFBG is particularly interesting because of its near-linearity at high applied lateral force (from 0.75 to 1.75 N) with an average sensitivity of 3.90 dB/N. The corresponding resolution of the lateral force measurement is ~0.003 N if the precision of the optical power meter is 0.01 dB.

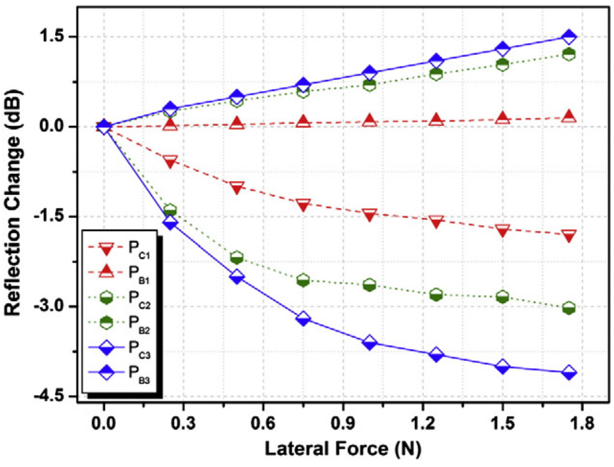

Fig. 4. Reflection changes of the core and cladding modes ($P_{Bi\ and}$ P_{Ci}) for three different core-offset TFBGs against applied lateral force. The subscript i = 1,2,3 stand for the sensors with offset of 2.0 μm, 6.0 μm and 8.5 μm, respectively.

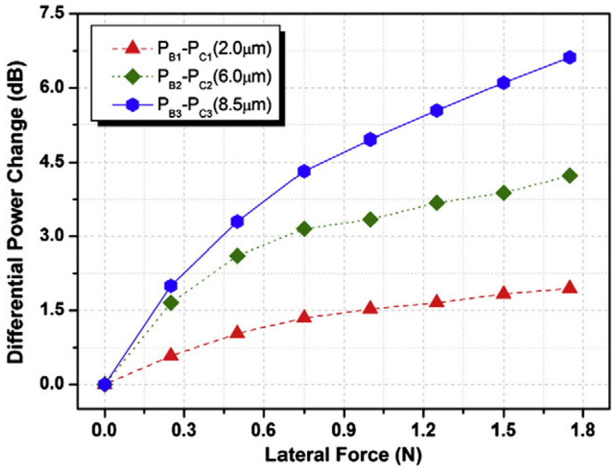

Fig. 5. Differential power changes against applied lateral force.

Finally, the effect of temperature changes on the proposed sensor can be minimized with a suitable choice of the central wavelength and bandwidth of the passband filters used since the core mode and cladding mode resonances all shift at the same small rate of 10 pm/°C. With a 0.5 nm wide core mode resonance and a 1 nm wide bandpass filter, fairly temperature variations of a few degrees would not result in changes in the measured power. For applications where larger temperature variation might occur, we could also adjust the work wavelength of tunable bandpass filters actively.

4. Conclusions

A lateral force sensor is implemented by using a core-offset TFBG. The differential reflected power of the core mode and cladding modes is used to determine the applied lateral force. The sensitivity can be tailored by changing the core-offset. The sensor with bigger core-offset has a higher sensitivity of lateral force measurement. To enhance the reliability of the lateral force configuration, the sensor can be recoated or even glued in a plate with V-groove since only low order cladding modes are used, and these are almost completely insensitive to the outer refractive index. The proposed sensor is a potential candidate for practical applications because of its small temperature cross-sensitivity, simple operation and interrogation, and ruggedness (once packaged).

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