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Temperature-independent bending sensor with tilted fiber Bragg grating interacting with multimode fiber

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ABSTRACT

A new type fiber bending sensor based on a tilted fiber Bragg grating (TFBG) interacting with a multimode fiber (MMF) is presented. The sensing head is formed by insertion of a small section of MMF between a single-mode fiber (SMF) and the TFBG. The average reflective power in the cladding modes decreases with the increase of curvature. The measurement range of the curvature from 0 to 2.5 m^{-1} with a measurement sensitivity of -802.4 $\mathrm{nW/m}^{-1}$ is achieved. The proposed sensor is also proved as temperature-independent from the experimental investigation.

1. Introduction

Fiber Bragg gratings (FBGs) are attractive in sensing areas due to many advantages, such as immunity to electromagnetic interferences, compact size, fast response and long lifetime. Recently, bending sensors based on fiber gratings, such as fiber Bragg gratings, long-period gratings, and photonic crystal fiber have been widely investigated [1–6]. Tilted fiber Bragg gratings (TFBGs) are one of members of the short-period grating family. Their grating planes are blazed by an angle in relation to the longitudinal fiber axis. This asymmetry configuration enhances the couplings of the light circularly and non-circularly symmetric to backward-propagating cladding modes at shorter wavelength range than its own Bragg wavelength, which is caused by mode coupling between the core mode and backward-propagating cladding modes inside the fiber. Recently, TFBGs have been proposed for many sensing applications, ranging from external refractive index, bending, modern biological analysis, and others [7–9].

In this paper, a novel sensor for curvature measurement based on a TFBG interacting with a MMF is proposed and demonstrated. The sensor can be used for bending measurement by detecting of the change of the optical power. The working principle and fabrication of the sensor are presented in Section 2. The experiment results are discussed in Section 3 and a conclusion is given in Section 4.

2. Sensor fabrication and working principle

The proposed fiber bending sensor is shown in Fig. 1. A section of 2 mm MMF is spliced between the SMF and the TFBG. The MMF used in our experiment has a core diameter of 105 μm. The TFBG had been manufactured by using a hydrogen-loaded SMF which was exposed on a frequency-doubled argon laser emitting at 244 nm through a 1066 nm uniform phase mask. The tilt angle was set to 5° and the length of the TFBG was 2 cm. The measured transmission spectrum of the TFBG is shown in Fig. 2. The right dip, on the long-wavelength side, corresponds to the Bragg resonance wavelength. The other dips are due to coupling between the core mode and counter-propagating cladding modes of the fiber. The counter-propagating cladding modes emitted from the tilted grating planes cannot propagate through a long distance along the fiber cladding due to the absorption coefficient of the high refractive index jacket material. Therefore these peaks of cladding modes are not observable in reflection spectra.

The working principle of the proposed sensor can be explained as follows, when the TFBG is kept in straight and the cladding is not

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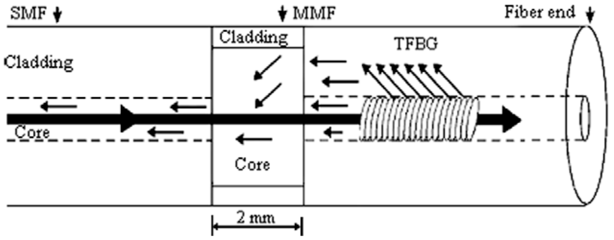

Fig. 1. Schematic diagram and principle of operation (SMF: single-mode fiber; MMF: multimode fiber; TFBG: tilted fiber Bragg grating.)

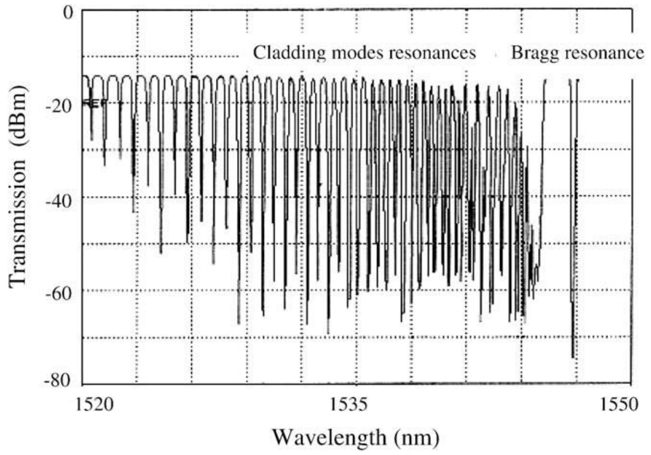

Fig. 2. Measured transmission spectrum.

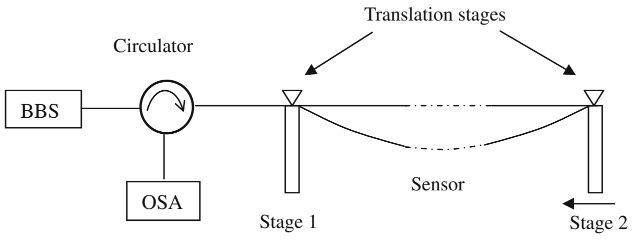

Fig. 3. Schematic diagram of the experimental setup (BBS: broadband source; OSA: optical spectrum analyzer.)

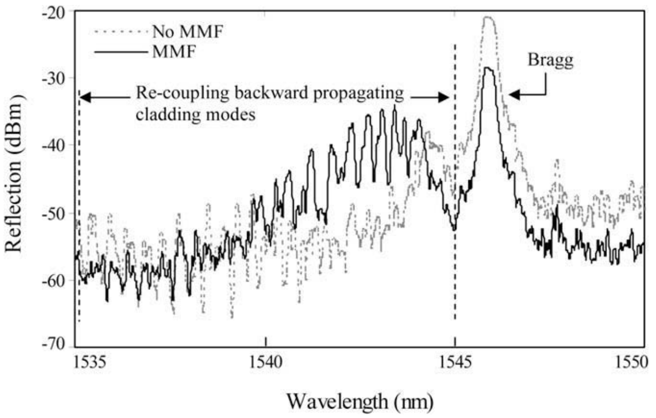

Fig. 4. TFBG reflection spectrum before and after spliced with MMF.

covered by a jacket, such cladding modes can propagate for several meters without much attenuation. The MMF is used to couple back the counter-propagating cladding modes of the TFBG into the core at the splicing point between the MMF and the SMF. At the MMF–TFBG splicing point, the counter-propagating cladding modes can be coupled back into the guided modes of the MMF, consequently coupled back into the fundamental mode of the SMF at the splicing point between the MMF and the SMF. The average power of the cladding modes has different optical power levels when the sensor is bent, while the power of the reflected Bragg mode keeps unchanged. Therefore, the power of the reflected Bragg mode can be used as a reference to compensate any possible fluctuation of the light source power [9–15].

The TFBG sensors based on cladding-core recoupling with an offset splicing have been reported [10,11]. However, it requires a very accurate control of the splice process to maintain repeatability of the results. By using a short section of MMF to perform the recoupling, the reproducibility of the effect can be enhanced. Furthermore, the modes, which are reflected from the TFBG, are guided by the core-cladding interface of the MMF and hence immune to refractive index of the outside medium. Therefore a protective coating can be put on to enhance the device reliability.

3. Experimental results and discussion

The proposed sensor was operated in reflection mode, as shown in Fig. 1. The sensor was fabricated by splicing a 2 mm long MMF with a core diameter of 105 μm and cladding diameter of 125 μm to a TFBG by normal fusion splicing. The two ends of the sensor head were clamped between two stages without applied twist. The stage one was fixed while the stage two was moved towards to the stage one for inducing bending on the sensor. The curvature could be obtained for a given displacement by assuming the bent fiber as an arc of a circle.

The schematic diagram of the experimental setup is shown in Fig. 3. In the experiment, the light from an erbium doped fiber based amplified spontaneous emission broadband source (L + C band ASE source) was launched into the fabricated sensor through a three-port optical circulator (OC), the reflection light from the sensor was measured by using a YOKOGAWA AQ6370 optical spectrum analyzer (OSA).

The reflection spectra of the proposed sensor compared with that standalone TFBG are shown in Fig. 4. It can be seen that the reflection spectra are different due to the existence of the small section of MMF between the SMF and the TFBG of the proposed sensor. For the standalone TFBG, the Bragg resonance peak predominated in the reflection spectrum. When the 2 mm long MMF was spliced to the TFBG, there were several cladding modes between 1535 and 1545 nm emerging in the reflection spectrum, because the counter-propagating cladding modes were being coupled into the core due to the mode field mismatch. The reflection core mode was decreased by about 8-dB, as shown in Fig. 4, because the large core diameter mismatch between the SMF and MMF caused large insertion losses. The length of the MMF segment also affects the recoupling coefficient. Therefore, the optimization of the length of MMF can help to minimize the power loss of the counter-propagating cladding modes [16–18]. As multimode interference (MMI) occurs in the MMF section, the increase of length of the MMF segment introduces the modulation effect on the reflection spectrum and reduces the number of the counter-propagating cladding modes. Therefore the sensitivity of device is reduced [19]. Furthermore, the increase of length of the MMF segment also enhances the temperature sensitivity [20], so the bending sensitivity of our proposed sensor will decrease.

The reflection spectra of the fiber bending sensor with an increasing curvature are shown in Fig. 5. It can be seen that bending leads to attenuation in average cladding modes power but

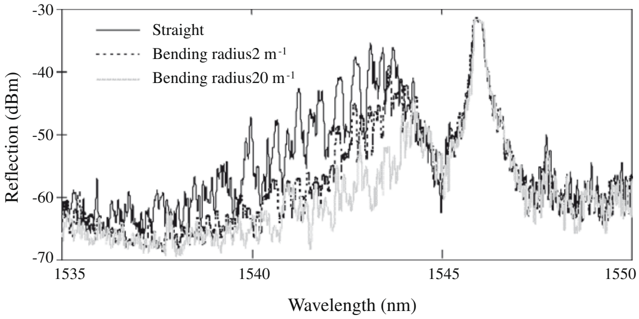

Fig. 5. Spectrum response of cladding modes and Bragg mode resonances vs. curvature.

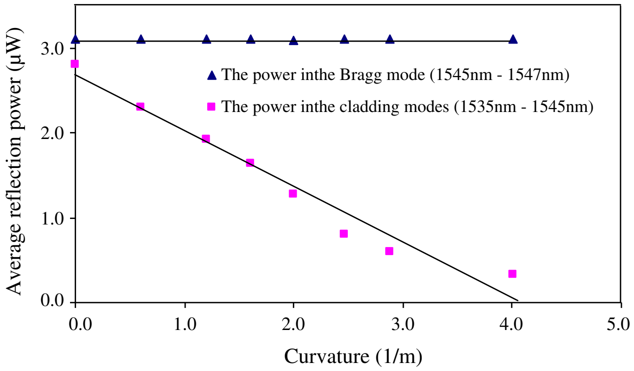

Fig. 6. Average reflection power cladding modes vs. curvature.

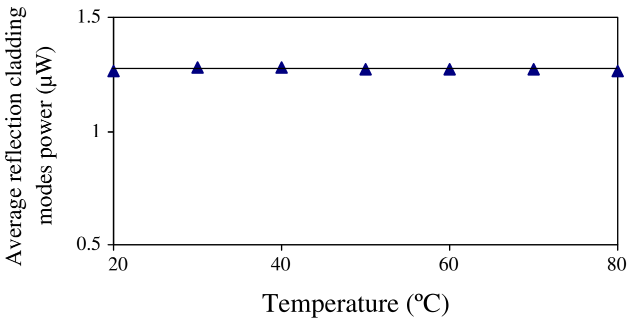

Fig. 7. Average reflection cladding modes power vs. temperature.

there is no apparent change in the Bragg reflection peak power, and its spectrum shape is well-maintained. Changing the curvature from 0 to 20 m^{-1} resulted in more than 15-dB reduction of the average cladding modes power. When the bending effect was moved away from the sensor, the reflection spectrum returned to its initial state, showing that it had good stability and repeatability.

The average reflection power of the cladding modes decreases with the increase of curvature, as shown in Fig. 6. The power in the reflected Bragg wavelength reflected core mode was measured from 1545 to 1547 nm, while the average power in the cladding modes was measured from 1535 to 1545 nm. The power levels in these two wavelength bands, as a function of the bending curvature, are plotted. From the experimental results, show that the average power of the cladding modes decreases linearly with the increase of bending curvature. When the curvature of the sensor was changed from 0 to 2.5 m^{-1}, the average reflection cladding power decreased from 2802 to 796 nW, with a sensitivity of -802.4 nW/m^{-1}. Because of the power reflected from the Bragg core mode unchanged, so it could be used to compensate any possible variation of light source power. When the curvature was over 2.5 m^{-1}, the average power of the cladding modes became very low so that the measurement was limited by the sensitivity of the power meter. From the resolution of power meter of the sensing system (10 nW), the minimum bending measurement of 0.0125 m^{-1} was achieved. Fig. 7 shows the power of the reflected cladding modes against temperature variation at the curvature of 2 m^{-1}. The root mean square (RMS) detection error of the average power was 6.33 nW, i.e. 0.008 m^{-1} in curvature, within the temperature range from 20 to 80 °C. That was similar to the core mode power at the longer wavelength side. Moreover, this error is smaller than the sensitivity of the proposed sensor. Therefore, the experiment testified that it is a temperature-independent bending sensor.

4. Conclusion

A simple sensor design for curvature measurement has been presented and demonstrated experimentally. The sensor is composed by inserting a small section of MMF by fusion splicing between a TFBG and a SMF. The experimental results show that the average reflection power of the cladding modes decreases with the increase of curvature, while the average power of the Bragg mode keeps unchanged while providing power reference to eliminate the possible fluctuation of the light source. The detection sensitivity and the RMS detection error of the curvature of 0.0125 and 0.008 m^{-1} are achieved, respectively. This proves that the proposed sensor is temperature insensitive.

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