Temperature-Independent Fiber Bending Sensor Based on a Superimposed Grating

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***Abstract*—A compact fiber bending sensor has been presented by superimposing a uniform fiber Bragg grating (FBG) into a tilted fiber Bragg grating (TFBG). The reflection of FBG is modulated by the same bandwidth of the cladding modes of TFBG, which is sensitive to the bending of fiber. By monitoring the differential Bragg reflection between FBG and TFBG, the sensor is insensitive to ambient temperature changes and power fluctuations from light source or fiber link during the measurement. The sensitivity of the sensor is also doubled because the signal from FBG passes through the TFBG twice.**

***Index Terms*—Bending measurement, fiber-optic sensor, superimposed grating, tilted fiber Bragg grating (TFBG).**

I. INTRODUCTION

BENDING measurement is one of the important techniques which can be extended to develop diversity of sensing systems such as micro displacement sensor, pressure sensor, accelerometer, etc., [1], [2]. Optical fiber bending sensors have been widely studied, which mainly take use of special optical fibers [3], [4], long-period gratings (LPGs) [5]–[7], and tilted fiber Bragg gratings (TFBGs) [8]. LPGs and TFBGs provide higher sensitivity and ease to be configured in the sensing systems. The LPG-based sensors offer higher bending sensitivity benefit from its relatively long grating period but it is really challenged to distinguish the bending from other surrounding parameters (like temperature and refractive index) which affect the stability and accuracy of bending measurement. In contrast, TFBG has a lower cross-sensitivity to other external conditions and its Bragg wavelength may act as an inherited reference signal in the measurement. Recently, some techniques have been put forward to realize intensity-demodulation for fiber bend sensing including recoupling the counter-propagating cladding modes back to the fiber core with a section of multimode fiber (MMF) or a LPG located upstream [9], [10]. However, the MMF scheme introduces too much loss to the sensor and the LPG one still subjects to the problem of cross-sensitivity to external environment.

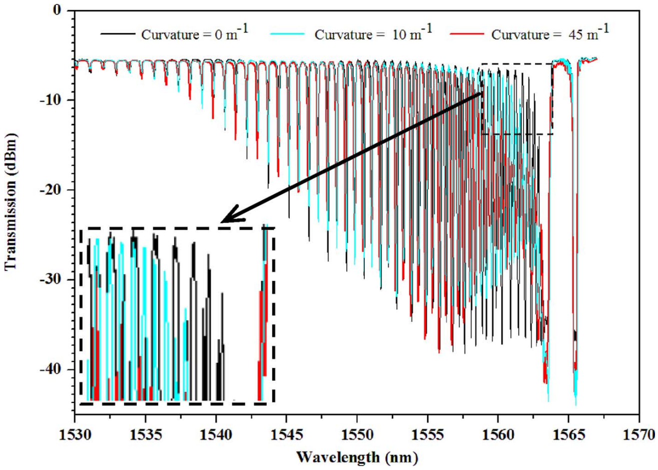

Fig. 1. Transmission spectra of the sensing TFBG under different bending.

In this paper, we propose an intensity-modulated fiber sensor for bending measurement. The sensor head consists of a uniform FBG superimposed in the rear of a strong TFBG. The transmission of TFBG is modulated by the fiber bending which affects the coupling strength between the core mode and cladding modes [11], [12]. The superimposed FBG acts as a wavelength bandpass filter and allows the sensor to work in reflection mode. The reflected light from FBG passing through TFBG twice is modulated by the transmission of the TFBG and doubles the sensitivity of bending measurement. The power difference between reflections from FBG and Bragg resonance of the TFBG is employed to determine the applied bending, which eliminate the affection of ambient temperature changes and power fluctuation from light source or fiber link during the measurement (a common issue of intensity-demodulated sensor).

II. OPERATION PRINCIPLE AND FABRICATION OF SENSOR

As analyzed in [11], the fiber bending changes the mode profile of cladding modes and thus the coupling strength between the core mode and cladding modes. The transmission spectrum is modulated by the applied bending subsequently. In order to verify the concept, we have characterized a TFBG with tilt angle of 8° under different curvature of bending. As shown in Fig. 1, when the bending increases, the envelope of low-order cladding modes (close to the ghost mode) changes significantly. Meanwhile, those high-order cladding modes (at shorter wavelength) only change little in the coupling strength. So, the low-order

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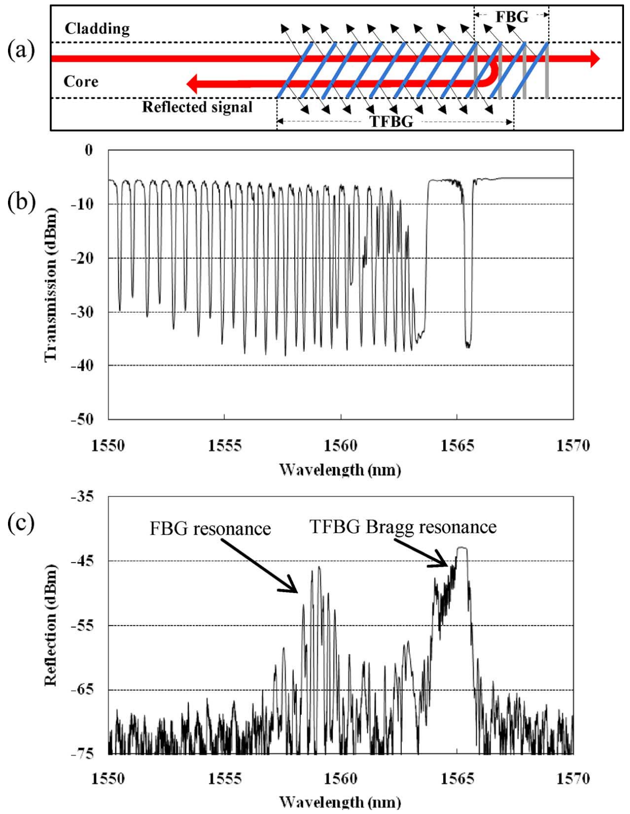

Fig. 2. (a) Schematic diagram of the superimposed fiber Bragg grating. (b) Transmission spectrum of the TFBG. (c) Reflection spectrum of the superimposed grating.

cladding modes with highly bending dependency are of interests and employed to determine the applied bending.

The proposed sensor configuration and corresponding spectra are illustrated in Fig. 2. The uniform FBG is superimposed in the rear of the TFBG. Both the uniform FBG and TFBG were manufactured by phase mask method in a hydrogen-loaded Germanium-doped single-mode fiber (SMF). The UV laser source in our grating fabrication system is a frequency-doubled Argon ion laser emitting at 244 nm. To realize strong cladding modes couplings, the tilt angle of the TFBG was set to 8° by placing the phase mask on a rotating stage. The period of phase mask for writing TFBG is 1080 nm and the length of the TFBG is 2 cm. The transmission spectrum of the TFBG is shown in Fig. 2(b). In order to locate within the sensitive wavelength area of the TFBG for bending, the central wavelength of the FBG was set to about 6 nm away from the Bragg resonance of the TFBG, as shown in Fig. 2(c). The length of uniform FBG was set to 3 mm to make sure that more cladding-mode resonances of interests can be included within the reflection window of the FBG and increase the stability of the measurement. The fabricated FBG has a 3 dB bandwidth of over 1 nm and high reflectivity (more than 99%) so that higher intensity of the detected signal can be obtained.

The working principle of the proposed sensor is described as follows: the TFBG enables coupling between co-propagating core-mode and counter-propagating cladding-modes. Lower order cladding modes are especially sensitive to the fiber bending, which present distinct overlaps under different bending curvature. Due to the existence of the uniform FBG, part of the incident light is reflected and modulated by the TFBG twice. Fig. 2(c) shows the reflection spectrum of the superimposed grating at straight state. It can be seen that the Bragg resonance of the FBG was modulated by the cladding-mode couplings of the TFBG, resulting in some dips in its reflection peak. When the sensor is applied by different bending, the transmission loss of cladding mode resonances in TFBG changes and thus the reflected power from FBG varies accordingly. Meanwhile, the power of Bragg resonance of TFBG is unaffected by the bending so it can act as a power reference to eliminate the influence of optical source instability. The same temperature sensitivities of Bragg wavelengths of FBG and TFBG make the output of the sensor insensitive to ambient temperature changes.

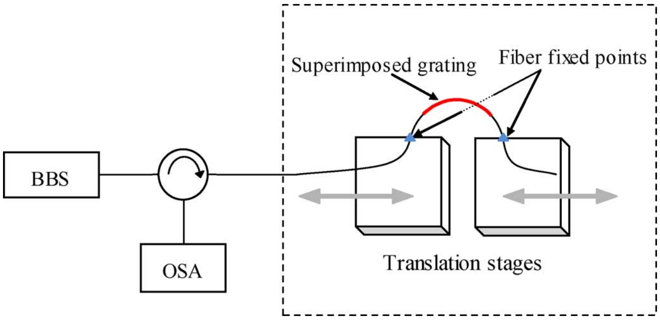

Fig. 3. Schematic diagram of the experimental setup for bending measurement.

III. EXPERIMENTAL IMPLEMENTATION

Fig. 3 shows the schematic diagram of the experimental setup for bending measurement. The two ends of fiber were mounted on two translation stages. By moving the translation stages along the direction indicated by the gray arrows, different curvature radius (R) can be applied on the fiber sensor as well. In the experiment, the broadband light source (BBS) from an erbium doped fiber amplifier was launched into the fabricated sensor through a three ports optical circulator (OC). The reflected light from the sensor was measured using an optical spectrum analyzer (OSA: YOKOGAWA AQ6370).

Bending test was carried out by moving the translation stages. As the two points of the fiber adjacent to the edge of the translation stages were fixed, the whole tunable length of the fiber with the superimposed grating was constant during moving the translation stages. A certain relationship can be expressed between the curvature radius of the fiber and the distances between the stages as follows:

$$\sin\frac{L}{2R} - \frac{D}{2R} = 0 \tag{1}$$

where L is the arc length of the fiber between the two fixed points, R is the curvature radius of the sensing configuration, and D is the linear distance between the two fixed points.

Fig. 4 shows the evolution of the reflection spectra with curvature. As expected, the reflection from the FBG decreases with the increasing curvature, while the Bragg resonance of the

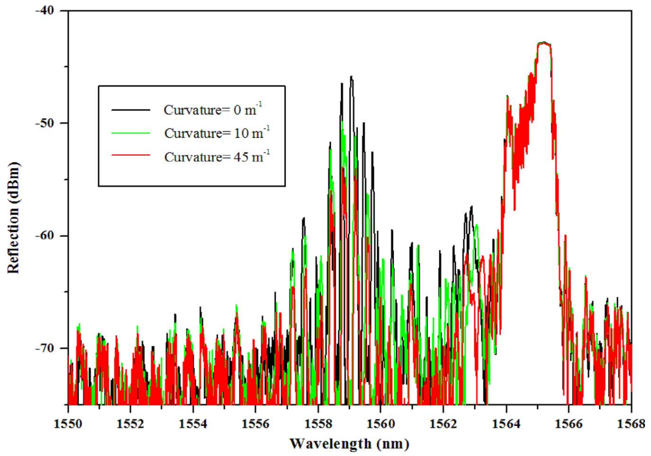

Fig. 4. The evolution of the reflection spectra of the superimposed grating with curvature.

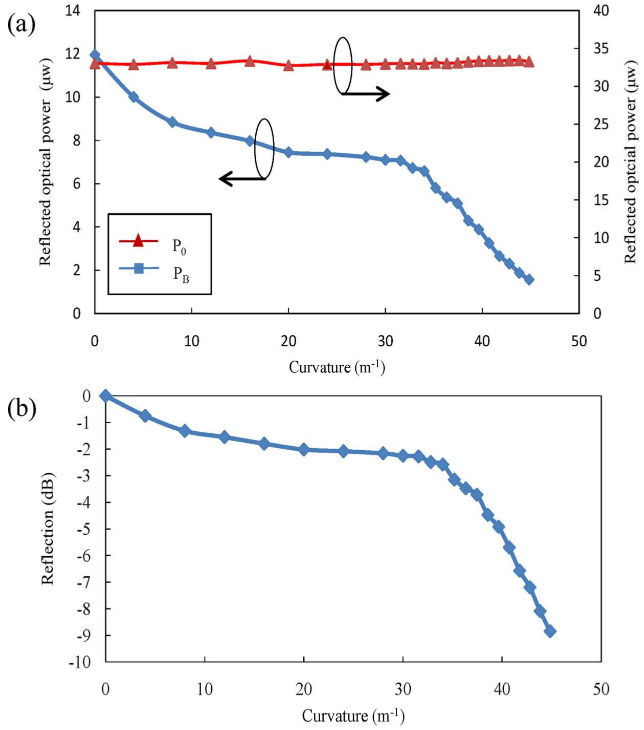

Fig. 5. (a) Reflected optical power for the FBG and TFBG Bragg resonance versus curvature. (b) Normalized reflection of the FBG against curvature.

TFBG remains unchanged. In addition, no obvious wavelength shift of the TFBG Bragg mode was observed in the whole bending process. Thus, the reflection of the TFBG Bragg mode can plays as a power reference and its wavelength can offer a multiparameter sensing for temperature, strain, etc.

Fig. 5(a) shows the reflected optical power changes for curvature ranging between 0 and 45 m^{-1} (the measuring ranges are from 1556 to 1562 nm and 1564.5 to 1566 nm for the FBG and TFBG Bragg resonance, respectively). When the curvature increases, the reflected power of the FBG ($\mathrm{P_B}$) decreases with an increasing bending sensitivity at large curvature radii and the Bragg resonance of the TFBG ($\mathrm{P_0}$) varies slightly resulting from the volatility of the optical power. Therefore, the normalized $\mathrm{P_0}$ can be used to eliminate the interference of the optical power

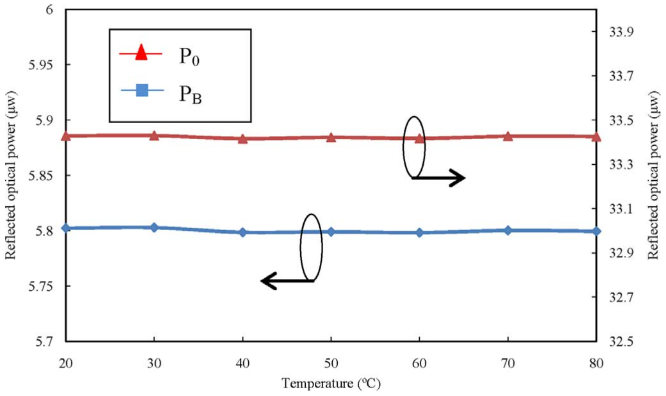

Fig. 6. Reflected optical power versus temperature.

and the reflection of the FBG normalized to the case curvature is 0 m^{-1} is shown in Fig. 5(b). It can be seen that the reflection of the FBG decreases almost linearly with the curvature ranging from 33 to 45 m^{-1}. The curvature sensitivity is about 0.6 $\mathrm{dB}/\mathrm{m}^{-1}$ with the curvature varying within the linear range of the sensor.

The working principle of the sensor determines that keeping relative spectral location between the FBG peak and the cladding-modes of the TFBG unchanged is critical for the stability of the measurement. On one hand, during different bending conditions, no obvious wavelength shifts have been observed for both the FBG and the TFBG so that the impact from wavelength matching of two gratings can be ignored.

On the other hand, as the FBG is superimposed with the TFBG, there is the same temperature sensitivity for both the two gratings. Thus, there are almost no relative wavelength shifts between the Bragg resonance of the FBG and selected cladding mode resonances of the TFBG under different temperature environments. Fig. 4 shows the reflected power against temperature variation at the curvature of 35 m^{-1}. As expected, no obvious optical power variations have been detected. Furthermore, when the bending effect was moved away from the sensor, the reflection power returned to its initial value, showing a good repeatability.

IV. CONCLUSION

A superimposed grating structure (FBG and TFBG) for bending sensing has been proposed and demonstrated experimentally. The reflection power from uniform FBG was modulated by the TFBG and sensitive to the applied bending. The experimental results show that the reflected power decreases with the increase of curvature. In the quasi-linearly changing area, curvature sensitivity is achieved to about 0.6 $\mathrm{dB}/\mathrm{m}^{-1}$. Furthermore, the measured optical power keeps unchanged when temperature varies, proving the proposed sensor of insensitivity to temperature. Besides, since the exact wavelength measurement of the signals is not required but only the reflected powers in limited spectral bands are measured, high-resolution spectral measurement equipments (like an OSA) are not necessary. A real interrogation system for our sensor would work with lower cost photodetectors associated with bandpass filters [13].

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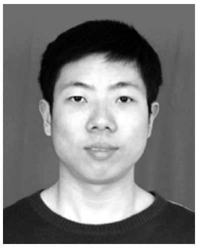

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