Simulation and experimental verification of off-axis fiber Bragg grating bending sensor with high refractive index modulation*

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Off-axis FBG simulations were performed in this paper using a finite element method in conjunction with the conformal mapping technique to study the bending sensing characteristics of the off-axis FBG with high index modulation. The refractive index (RI) increase of the grating region is taken into consideration for the mode field simulation. The influences of high RI increase and the offset distance of the grating on the bending sensitivity were analyzed. Off-axis FBGs with different offset distances were fabricated using femtosecond laser with phase mask technique in standard single-mode fiber. The simulation results were verified by the experiment. A bending sensitivity of 0.055 dB/m^{-1} was achieved with an offset distance of 4 μm. The simulation and experiment results suggest that the grating offset distance has a greater influence on the sensitivity of the off-axis FBG with high RI modulation than that with low RI modulation. The proposed sensor structure and simulation results can provide suggestion for the design and processing of off-axis FBG bending sensors.
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In the past decades, fiber Bragg grating (FBG) sensors have been developed and widely used in the fields of engineering and scientific research[1-3]. FBG sensors have high accuracy, low cost, and are not susceptible to electromagnetic interference. They are important supplements to traditional electronic sensors. Bending sensors have great application potential in the field of structure monitoring, seismic monitoring and displacement measurement, and therefore have attracted much attention. Optical fiber bending sensors have been realized using various structures including long-period gratings, tilted FBG and off-axis FBG[4-6]. Among them, long-period gratings and tilted FBG bending sensors use the cladding modes to measure fiber bending, which can provide very high sensitivity. But the complex spectrum of the cladding modes is not conducive to the realization of wavelength division multiplexing and the applications in distributed sensing networks. In recent years, bending sensors based on off-axis FBG have been extensively studied[7-9]. The gratings of this type of sensor are written at a position offset from the axis of the fiber core. When the sensor structure is bent, due to the offset of the grating position, the reflected signal or resonant wavelength will change, and realize the bending detection. Due to off-axis FBG is a single-port device using reflected core mode for detection, the signal-to-noise ratio is high, which is beneficial to detection and demodulation, and can provide great flexibility in practical applications[10]. Generally, the sensitivity of the off-axis FBG sensors based on single-mode fiber is not high. Even though higher sensitivity can be achieved by using a thin-core fiber, a tapered fiber, a multi-clad fiber or other special fiber structures to introduce cladding modes, it is still necessary to study bending sensors based on single-mode fiber and fundamental core mode, since they have low temperature-strain crosstalk, and the sensor head is compact and easy to fabricate. Besides, the spectrum of fundamental mode is simple and easy to demodulate, which makes it suitable for wavelength division multiplexing and applications in distributed sensor networks.

The femtosecond laser is a flexible tool for micro processing. With its extremely high peak power density, FBG can be inscribed in optical fibers of various materials[11-13]. Due to the large refractive index (RI) increase induced by the femtosecond laser, the grating structures will cause changes of the mode field distribution in the core, which in turn affects the bending sensing performance of the off-axis FBG. In this paper, the bending sensor characteristics of off-axis FBG bending sensors with high RI modulation are simulated. The influences of

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large RI increase and the offset distance of the grating on the bending sensitivity were analyzed. Using femtosecond laser with phase mask technique, off-axis FBGs were fabricated in standard single-mode fibers with different offset distances, and the simulation results were verified by the experiment. The proposed sensor structure and simulation results can provide suggestion for the design and processing of off-axis FBG bending sensors.

In this paper, off-axis FBG simulations were performed using a finite element method in conjunction with the conformal mapping technique[14,15]. The first step was transforming the circularly curved fiber to an equivalent straight fiber by the process of conformal mapping. When the geometric shape of the fiber waveguide is bent, the equivalent mode field can be analyzed by using the equivalent straight fiber with the RI profile as

$$n_{\mathrm{bent}} \approx n_{\mathrm{fiber}} \times (1 + x/1.3R), \tag{1}$$

where n_{fiber} is the original RI distribution of the fiber cross section, R is the bending radius of the fiber, x is the distance of a point to the center of fiber in the bending plane, and 1.3 is a correction factor when taking the elastic-optical effect of the fiber into consideration. Generally, the correction factor for the conformal mapping method is small, and ranges from 1.28 to 1.31[15]. When the fiber is bent, the mode field will shift to the opposite direction of the curvature center. When the grating structure is inscribed in the fiber with an offset distance to the fiber center, the reflected energy will change with the bending. The change of mode energy within the grating area can be used to evaluate the change of the reflection energy. In the existing reports on intensity demodulated off-axis FBG sensors, the theoretical analysis only considers the deviation of the mode field caused by the bending of the fiber structure alone. The RI modulation of the grating structure and its impact on the mode field were not considered. But for the FBGs with large RI modulation, i.e., FBGs fabricated by femtosecond laser, the high RI of grating region would cause a significant influence on the mode field. In order to further understand the bending sensing characteristics of off-axis FBG with high RI modulation, finite element simulation was used while considering the high RI modulation of the grating region. In the simulation model, the fiber core diameter was set to 8.2 μm, and cladding diameter was set to 120 μm. The cross-section of the grating was set to an elliptical shape with a major axis of 8.5 μm and a minor axis of 1.5 μm. The ellipse was located on the left of fiber core, and the RI increase was set to 0.005 based on previous experiment result and literature research. The RI was adjusted using the conformal mapping theory for different bending radii. Then the mode field simulation and other subsequent analyses were performed.

The fundamental mode field distributions of off-axis FBGs with 3 μm offset were simulated and shown in Fig.1. Curvature of +80 m^{-1} (bending to the left) was applied in Fig.1(a) and (c), and −80 m^{-1} (bending to the right) was applied in Fig.1(b) and (d). The RI modulation of the grating region was set to 0 in (a) and (b), and was set to 0.005 in (c) and (d). It shows that after the introduction of large RI modulation in the grating region, the mode field distribution of bending fiber changed significantly.

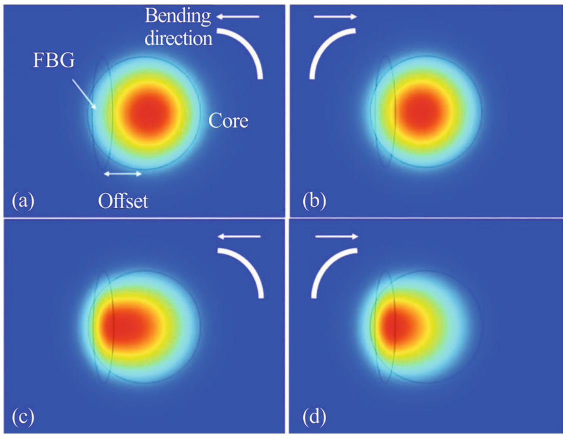

Fig.1 Fundamental mode field distributions of bent off-axis FBGs: (a) and (b) RI modulation is 0; (c) and (d) RI modulation is 0.005

In order to further study the characteristics of the sensor and optimize the structural design of the off-axis FBG, the influence of the offset distance of FBGs on the bending sensitivity of the device was analyzed for FBGs with and without high RI modulation in the grating region. Offset distance of the grating in the simulation was varied from 1.5 μm to 4 μm. The curvature was changed from −80 m^{-1} to +80 m^{-1}. The change of energy within the grating region was calculated for the analysis of the bending sensitivity of the reflection energy. The simulation results are shown in Fig.2.

Fig.2(a) shows that when the RI modulation of gratings region is not considered, the bending sensitivity of the grating decreases slightly as the offset distance of the grating increases from 1.5 μm to 4 μm, which indicates that the sensitivity will not be greatly affected by the offset distance when the RI modulation of the grating region is relatively low. Fig.2(b) shows the results of off-axis FBG with RI modulation of 0.005. The sensitivity shows an opposite trend compared to Fig.2(a). With the increase of offset distance, the bending sensitivity increases rapidly. These results indicate that the sensitivity of the off-axis FBG is greatly affected by the offset distance when there is a large RI modulation of the grating region. When the grating is inscribed at the edge of the core, the sensor can achieve higher bending sensitivity. The simulation results suggest that the grating offset distance has a greater influence on the sensitivity of the off-axis FBG with high RI modulation than that with low RI modulation. Better sensing characteristics can be obtained with large offset distance. However, as the offset of the FBG increases, the reflectivity of the FBG will decrease, and it may cause extra cladding modes related losses. Therefore, a comprehensive consideration is required to determine a suitable offset distance.

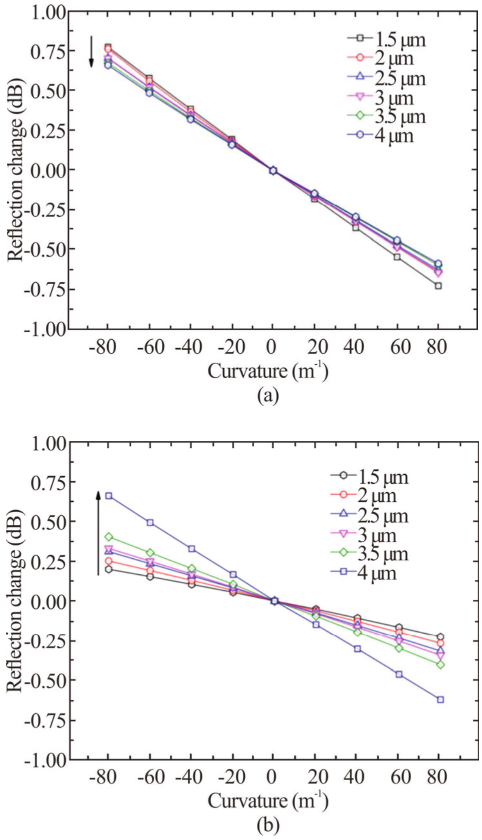

Fig.2 Reflection energy change versus curvature of off-axis FBG with different offsets: (a) RI modulation is 0; (b) RI modulation is 0.005

Femtosecond laser pulses with 150 fs duration were generated by an amplified Ti: sapphire laser at a center wavelength of 800 nm and 1 kHz repetition rate. The maximum output energy is about 1 mJ. The 10-mm-diameter Gaussian beam was focused with a 25 mm cylindrical lens through a zero-order nulled phase mask with a period of Λ_m=2.14 μm into the standard single mode fiber core. According to free space Gaussian beam optics, the width of the focal spot size is 1.75 μm, the laser pulse energy was set to 600 μJ, and the energy density in the focal spot was about 0.926×10^{13} W/cm^2. The offset distance was controlled with a translation stage position and the exposure time was set to 10 s. Considering the simulation results and the reflectivity of the fabricated FBGs, two off-axis FBGs with 2.5 μm and 4 μm grating offset were fabricated respectively for the bending sensitivity verification.

The microscope image of an off-axis FBG is shown in Fig.3. The grating area exhibits a cylindrical lens effect due to the increase of RI. Fig.4 shows the reflection spectra of the fabricated off-axis FBG with 4 μm offset.

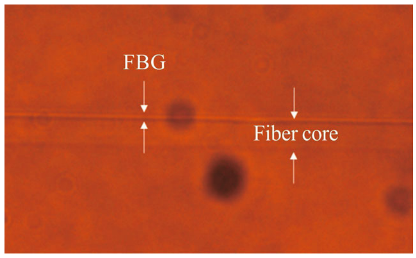

Fig.3 Optical micro scope image of the fabricated off-axis FBG

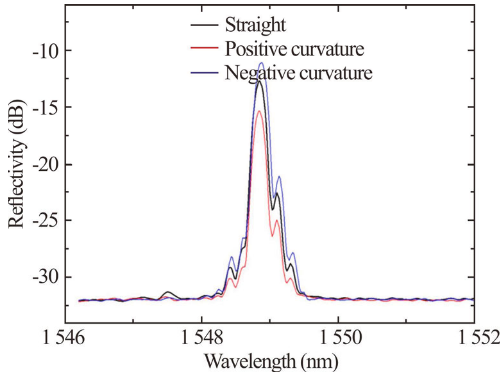

Fig.4 Reflection spectrum variation of the fabricated off-axis FBG bending sensors

The configuration shown in Fig.5 was used for the curvature measurement. To avoid strain along the fiber, only one end of the fabricated sensor was fixed by an optical fiber holder, and the sensitive grating area was curved by using standard cylinders. The curvature measurements were achieved using cylinders with diameters of 25 mm, 35 mm, 50 mm and 100 mm, respectively, and the reflection spectra were measured and recorded by a spectrometer. The peak reflectivity changes versus curvature are shown in Fig.6. The bending sensitivity of FBG with 4 μm offset is about 0.055 dB/m^{-1}, and the FBG with 2.5 μm offset shows a sensitivity of 0.029 dB/m^{-1}. The experimental results are in good agreement with the simulation, which can verify the conclusion that for off-axis FBG with high RI modulation, better bending sensitivity can be obtained with larger offset distance.

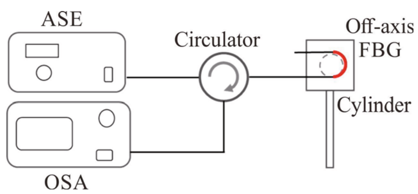

Fig.5 Configuration for curvature measurement

In this paper, finite element method combined with conformal mapping technique was used to simulate the bending sensing characteristics of off-axis FBG bending sensor with high RI modulation. The influence of the RI increase of the grating region was taken into consideration

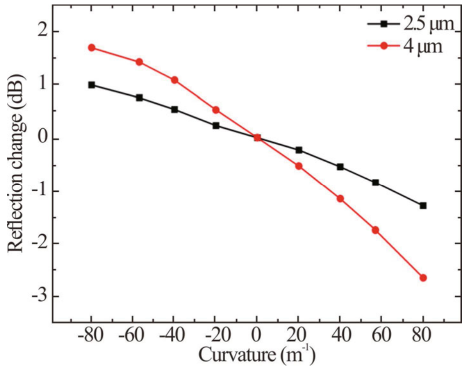

Fig.6 Reflection change versus curvature of off-axis FBG with 2.5 μm and 4 μm offset, respectively

and analyzed. The influences of high RI modulation and the offset distance of the grating on the sensitivity were analyzed. The simulation results were verified experimentally. Off-axis FBGs with different offset distances were fabricated using femtosecond laser with phase mask technique in standard single-mode fiber. A bending sensitivity of 0.055 dB/m^{-1} was achieved with an offset distance of 4 μm. The simulation and experiment results suggest that the grating offset distance has a greater influence on the sensitivity of the off-axis FBG with high RI modulation than that with low RI modulation. For off-axis FBG with high RI modulation, better bending sensitivity can be obtained with larger offset distance. The proposed sensor structure and simulation results can provide suggestion for the design and processing of off-axis FBG bending sensors.

Statements and Declarations

The authors declare that there are no conflicts of interest related to this article.

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