Abstract—a novel structure of the pure macro-bending sensor based on the tilted fiber Bragg grating (TFBG) is proposed. The TFBG located in the half circle with the different diameters is bent at a constant angle with respect to the tilted grating planes. With the variations of the curvature, the core-mode resonance is unchanged and the transmission power of cladding modes detected by the photodiodes varies linearly with curvature, while the ghost mode changes by the form of two-order polynomial. So we can use the transmission power of ghost mode or other cladding modes to detect bending curvature as shape sensor. From a practical point of view, the sensor proposed here is simple, low cost and easy to implement. Moreover, it is possible to make a temperature-insensitive shape sensor due to the same temperature characteristic between the core mode and the cladding modes.

Index Terms—Half circle, optical fiber sensing, pure bending sensor, tilted fiber Bragg grating.

1. Introduction

At present, in structure quality monitoring, the assessment of the deformation of structural elements is important. Knowledge of deformation can not only provide shape information on flexible structures in aircrafts or ships, but also verify the security status and improve the structural diagnostics. There are a lot of bending sensors based on the long-period gratings (LPG). There have been many reports about the technique of using LPGs for curvature measurement, based on either cladding-mode resonance increasing with bending curvature\(^1\), or resonant mode splitting\(^2\). But when the conventional LPG is used as a bending sensor, the constant reinforcement in mode coupling will be destroyed as the fiber is bent. Therefore, a large bending curvature may completely wash out the grating properties, causing the resonant loss to be attenuated and the resonance wavelength to be hard to distinguish\(^3\),\(^4\).

In this letter, we propose and present experimentally a new structure for the curvature measurement based on the tilted fiber Bragg grating (TFBG). The transmission power of the TFBG is diminished by different degrees with an increase of the curvature of the TFBG. The curvature can be measured with the changes of transmission power in all cladding modes or the ghost mode, as the transmission power is directly proportional to the variation in the curvature. Transmission power can be detected by the photo-detectors, which enormously decreases the sensor cost and increases the practical value.

2. Theory

TFBG is a special kind of fiber grating. It consists of a refractive index modulation that is purposely tilted relative to the fiber axis in order to enhance coupling between the forward-propagating core mode and the contra-propagating cladding modes as Fig. 1 shows, which was first reported in 1990 by Meltz et al., and has been demonstrated for applications such as refractometers\(^5\),\(^6\). The contra-propagating cladding modes attenuate rapidly and are therefore not observable in reflection but are observed as numerous resonances in the transmission spectrum of the TFBG. There are two kinds of couple in the TFBG\(^7\), which result in the core modes and a lot of cladding modes existing as Fig. 2 shows. The resonant wavelengths for these mode couplings depend differently on external perturbations. This has several advantages. While the core mode is only sensitive to axial strain and temperature, the cladding modes are sensitive to the external perturbations (strain, temperature, bending, refractive index, etc.)\(^6\),\(^8\)-\(^10\). At the same time, an important feature of the low tilt angle results in the presence of a strong ‘ghost mode’ resonance, which corresponds the lower-order cladding mode and locates immediately to the left of the Bragg (core mode) resonance. The spectral response of the TFBG is governed by the phase matching condition:

\[
\lambda_{\text{core}} = 2n_{\text{eff,core}}\Lambda\cos \theta \\
\lambda_{\text{clad}} = (n_{\text{eff,core}} + n_{\text{eff,clad}})\Lambda\cos \theta
\]
where $\theta$ is the tilt angle, $n_{\text{eff,core}}$ and $n'_{\text{eff,clad}}$ are the effective refractive index of the core mode and the $i$th cladding mode, respectively. $\Lambda$ corresponds to the nominal grating period and such that $\Lambda = \Lambda_0 \cos \theta$. In this relationship, $\Lambda_0$ denotes the grating period along the axis of the fiber.

![Fig. 1. Schematic diagram of TFBG.](image)

**3. Experiment**

In the experiment, the TFBG structures were home-made, inscribed by means of a 248 nm KrF laser in H2-load standard single mode photosensitive fiber with rotating the phase mask at a certain angle in the plane of fiber. Here, the effective length and the tilted angle of the TFBG are 1 cm and 3° respectively. The TFBG is placed in the half-circle shaped V groove on the PMMA. Both ends of the TFBG are in the free condition and the TFBG is purely curved at a constant angle with respect to the tilted grating planes. The diameters of nine concentric half-circles are 13.55 cm, 11.5 cm, 8.4 cm, 6.95 cm, 5.65 cm, 4.25 cm, 3.25 cm, 2.50 cm, and 1.85 cm. The light is shot into the TFBG using a broadband source (BBS); the transmission spectrums of the TFBG are detected by an optical spectrum analyzer (OSA) with a resolution of 0.01 nm and the transmitted power is measured by the photo-detector.

![Fig. 3. Experimental setup of TFBG with bending characteristic.](image)

**4. Experiment Result and Discussion**

Fig. 4 presents the effect of the curvature on the transmitted spectrum of TFBG. With diminishing of the radius, i.e. increasing of the curvature, the transmission spectrum will change obviously and all modes in the transmission spectrum present different variation trends. When the fiber is bent, the tilt angle of the TFBG varies effectively; thus the incident ray experiences different tilt angles in accordance with bending. The variation in the tilt angle gives rise to changes in the coupling ratios for both the core mode and the cladding modes.

The transmitted power of the core mode resonance changes hardly in the experimental range of macro-bending radius, the curvature which changes between 0 and 1.081 cm$^{-1}$ influences mainly the cladding modes near the ghost-mode region and the ghost mode. Thus we can focus on the variations in the coupling ratio of the ghost mode and the cladding modes.

The ghost mode experiences variations in the coupling wavelength and transmitted power, but the coupling wavelength change is small, and thus the detection of the wavelength shift of the ghost mode is not suitable for macro-bending detection. Hence we can detect macro bending by measuring the transmitted power of the ghost mode.

The transmitted power of the cladding modes gradually reduce from the lower-order cladding mode. It shows that the intensity of some low-order cladding modes will fade away and vanish finally fit to a smooth line while the higher-order cladding modes are not influenced by the perturbation. The maximal and minimum detectable range of the method was determined to be 6.775 cm and 0.925 cm in terms of the bending radius.

![Fig. 4. Transmission spectrum under different curvatures.](image)
obvious liner relation between the transmitted power $y$ (form 1.825 mw to 1.769 mw) and the radius of curvature $x$. The equation can be demonstrated as: $y=1.82998-0.0561x$, and the linear relevance $R^2$ reaches 0.9981.

Fig. 5. Transmitted power of all cladding modes vs. the curvatures of TFBG.

Fig. 6 plots the change of the transmitted power of the ghost mode when different curvatures are applied to the TFBG. The variation of the ghost mode is evident. The relationship between the transmitted power of the ghost mode and the curvature can be expressed as the two-order polynomial: $y=-10.506x^2+20.955x-48.93$ and the linear relevance $R^2$ reaches 0.99519.

Fig. 6. Transmitted power measurement of the ghost mode with the variation in the curvature of the bent TFBG.

5. Conclusions

In this letter, the pure bending characteristic of TFBG is investigated. The maximal and minimum detectable range of the method was determined to be 6.775 cm and 0.925 cm in terms of the radius of the bending curvature. The results show that the different modes of this sensor have different transmission characteristics with respect to the different curvatures. The core-mode resonance is unchanged and the transmission power of cladding modes detected by the photodiodes varies linearly with curvature, while the ghost mode changes by the form of two-order polynomial. So it can be used as a shape sensor. The curvature can be measured with the changes of transmission power in all cladding modes or the ghost mode, as the transmission power is directly proportional to the variation in the curvature. Transmission power can be detected by the photo-detectors, which enormously decreases the sensor cost and increases the practical value. If the TFBGs with different ghost mode resonance can be in cascaded, they can be used to detected multipoint macro-bending. From a practical point of view, the sensor proposed here is simple, low cost and easy of implement. Due to the cladding modes and core mode possess the same temperature sensitivity, it is potential in structure inspecting as a temperature-insensitivity macro-bending sensor. This method is proposed to be more cost effective as compared to more complex spectroscopic methods based on wavelength detection.

All conclusions from this study is carried out and based on the condition that the TFBG located in the half circle is bent at a constant angle with respect to the tilted grating planes, while another condition of different angle between them is under investigating.

References


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