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Highly sensitive bend sensor with hybrid long-period and tilted fiber Bragg grating

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ABSTRACT

We demonstrate a new type of fiber optic bend sensor with a hybrid structure made up of a long period grating (LPG) and a tilted fiber Bragg grating (TFBG). The sensing mechanism is based on the spectrum of power transfers between the core and cladding modes from a TFBG located downstream from a LPG. We show that the curvature of a beam can be determined by the reflected power difference between the core mode and the recoupled cladding modes. We further provide design rules for the LPG and TFBG to optimize and linearize the sensor response. In addition, the temperature cross-sensitivities of this configuration are also investigated for two different types of fiber.

1. Introduction

Fiber Bragg gratings (FBG) have been used in many configurations for applications in structural health monitoring. For instance, bend sensors have been proposed using two FBGs bonded to opposite sides of a beam [1]. The difference between the two Bragg wavelengths provides a measure of curvature of the beam. Other FBG bend sensors are also demonstrated based on bandwidth broadening due to a chirp in the period of FBGs with curvature [2,3]. It is also well known that the sensitivity of LPGs to bending is superior to that of FBGs and a number of LPG based bend sensors have been proposed recently. The typical mechanisms utilized for LPG bend sensors are based on a bend-induced wavelength shift, on the depth change of the attenuation band, or on the splitting of some attenuation bands [4–6]. Some researchers have also investigated the embedding of LPG sensors in some materials to discriminate the bending from some other measurands [7]. Some disadvantages of LPG sensors are that they operate in transmission and that they have a relatively wide attenuation band which causes difficulty in reading the exact wavelength of the loss dip. Alternatively, Baek et al proposed another kind of bend sensor based on a TFBG [8]. This sensor is based on the transmission loss change of low order cladding modes in a TFBG. Jin et al also used a TFBG for the same purpose but made it work in reflection by inserting a short section of multimode fiber (MMF) upstream of the TFBG written on a single mode fiber (SMF) [9]. The MMF has a larger core diameter compared to SMF and the mismatched interface between the fibers allows some low order cladding modes to recouple back to core mode of the SMF after going through the MMF. In that configuration, the bending changes the amount of power of the recoupled cladding modes but has no effect on the core mode reflection of (the Bragg reflection) of the TFBG. Therefore, the amount of bending can be measured by monitoring the reflected power differences between the core and the cladding modes. The disadvantage of this scheme is that the mode field mismatch at the two splices between MMF and SMF introduces a large insertion loss in the device. The wide bandwidth of reflected cladding mode spectrum is also a problem in signal processing.

In this paper, we demonstrate a hybrid structure consisting of an LPG and a TFBG for bending/curvature measurements. An LPG located upstream from the TFBG only recouples one of the cladding modes excited by the TFBG. Similarly to the above mentioned previous work on TFBG bend sensors, the reflections of core Bragg mode and of the recoupled cladding mode vary in opposite directions when the bending is applied. The differential power change of these two modes provides an efficient measure of bending with enhanced sensitivity. The advantage of the current configuration is that the combined reflection spectrum is relatively narrowband, thereby facilitating the interrogation of the two dominant reflection peaks, and that the introduction of the LPG does not compromises the mechanical integrity of the fiber (by opposition to splices or tapers). Our results further indicate how to properly design the TFBG and LPG spectra to optimize the combined response for the bending application. Finally, the temperature sensitivities of these devices are also studied for two different types of fiber.

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2. Operation principle

An LPG with a typical period of several hundred micrometers can induce co-directional coupling of the core mode and cladding modes in optical fibres. Contrary to the LPG, the TFBG with a much shorter period of several hundred of nanometres couples the incoming core light power into backward propagated core and cladding modes. But normally, the backward-propagating cladding modes in a TFBG are rapidly attenuated by the fibre jacket and cannot be seen in the reflected spectrum. In our proposed hybrid structure, a weak LPG is located upstream of TFBG to realize the cladding mode recoupling. Fig. 1 illustrates the schematic diagram of cladding mode recoupling in the hybrid LPG-TFBG structure. There are two types of cladding mode recouplings. In type 1, the core-guided light coupled to backward cladding mode by the TFBG is recoupled to the fibre core by the LPG. In type 2, the forward propagating cladding mode excited by the LPG is recoupled into the fibre core by the TFBG. As a result, we can see both the recoupled cladding mode and the Bragg mode in the reflection spectrum.

According to the couple-mode theory, the resonance wavelengths of different order cladding modes in a LPG and TFBG are determined by the phase matching condition. The resonance wavelengths of the i-order cladding mode can be expressed as follows for the LPG and TFBG respectively [10]:

$$\lambda_L^{(i)} = \left(N_{\text{eff}}(core) - N_{\text{eff}}^{(i)}(clad)\right) * \Lambda_L \tag{1a}$$

$$\lambda_B^{(i)} = \left(N_{\text{eff}}(core) + N_{\text{eff}}^{(i)}(clad)\right) * \Lambda_B / \cos(\theta) \tag{1b}$$

where Λ_L and Λ_B are the grating periods of LPG and TFBG, θ the tilt angle of the grating planes, $N_{\text{eff}}(core)$ and $N_{\text{eff}}^{(i)}(clad)$ are the effective index of the core mode and i-order cladding mode. Combining Eqs. (1a) and (1b), the wavelength of the recoupled cladding mode λ_C can be calculated as

$$\lambda_C = \lambda_B\left(1 - \frac{\Lambda_B / \cos(\theta)}{\Lambda_L + \Lambda_B / \cos(\theta)}\right) \tag{2}$$

where $\lambda_B = 2N_{\text{eff}}(core)\Lambda_B/\cos(\theta)$ is the Bragg wavelength of the TFBG. Considering the broad transmission bandwidth of the LPG, only one cladding mode reflected by TFBG can satisfy the phase matching condition and recoupled into the core by the LPG. The reflected power of recoupled cladding mode and Bragg mode (P_c,P_b) in this hybrid grating device can be written as [11]

$$P_c = 2T_L^{(i)}\left(1 - T_L^{(i)}\right)R_B^{(i)} \tag{3a}$$

$$P_b = \left[T_L^{(i)}\right]^2 R_B^{(0)} \tag{3b}$$

where $T_L^{(i)}$ is the transmission of the LPG at the wavelength at which the i-order cladding mode is recoupled. $R_B^{(0)}$ and $R_B^{(i)}$ denote the reflectivity of Bragg mode and recoupled i-order cladding mode in the TFBG. The maximum value of P_c is $R_B^{(i)}/2$ when $T_L^{(i)} = 1/2$.

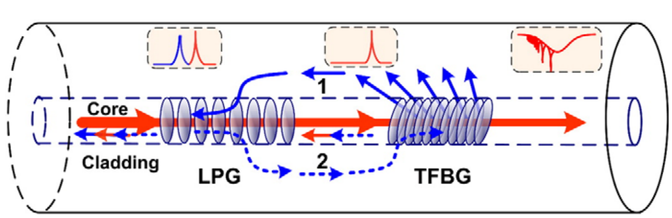

Fig. 1. Schematic diagram of cladding mode recoupling mechanism in the hybrid LPG-TFBG structure.

As the hybrid grating is bent, the transmission of the LPG and the reflectivity of the cladding modes of the TFBG will change. The curvature can be determined by monitoring the reflected powers of the Bragg mode and of the recoupled cladding mode. Furthermore, the differential power ($P_b - P_c$) of these two reflected modes is employed to eliminate the power fluctuations of the light source and enhance the sensitivity to curvature.

3. Experiments

3.1. Fabrication and experimental setup

TFBGs and LPGs were fabricated by using the phase mask technique and the amplitude mask technique respectively. In order to study the effect of the transmission loss of the LPG on the sensor's curvature sensitivity, two LPGs were made in two segments of photosensitive fiber (PS1250/1500 from Fibercore, Ltd) with different transmission losses of 5.2 dB and 18.0 dB, respectively. They have the same length of 20 mm and different periods of 375 μm and 377 μm. Their resonance wavelengths (for coupling to the 9th order cladding mode) are near 1557 nm and 1561 nm respectively. Another LPG with attenuation of 5 dB was fabricated in a standard single mode fiber (Corning SMF-28) with a resonance wavelength of 1557 nm for the investigation of the temperature cross-sensitivity. After the inscription of the LPGs, three TFBGs were inscribed in the same segment of fiber at a distance of 5 mm from each LPG. The TFBGs have the same tilt angle of 2° and Bragg wavelength of 1548.6 nm. Fig. 2 schematically shows the experimental setup for the curvature measurement. A broadband source (BBS: C+L band ASE source from JDSU Corporation) was used to interrogate the grating from LPG side. The reflected light was extracted by an optical circulator and monitored by using an optical spectrum analyzer (OSA). The hybrid grating sensor was inserted into a polymer capillary with the inner diameter of 280 μm and outer diameter of 900 μm. The capillary was bonded to a steel beam with dimensions of 150 × 12 × 0.5 mm. The beam was laid on two movable supports located 116 mm apart and bent with a micrometer driver in the middle. One end of the steel beam was clamped on the support. The position of the hybrid gratings with respect to the center of bending could be varied by shifting the fiber in the capillary fixed on the steel beam. In our experiment, the sensor was located in the middle of the beam. To avoid the introduction of axial strain on the sensor, only one end of the fiber was fixed on the beam.

The bent fiber is normally approximated as an arc of circle. So the sensor's curvature C is given by [12]

$$C = \frac{2 \cdot d}{l^2 + d^2} \tag{4}$$

where d is the central deflection of the steel beam and l is the half distance between the edges of the two supports.

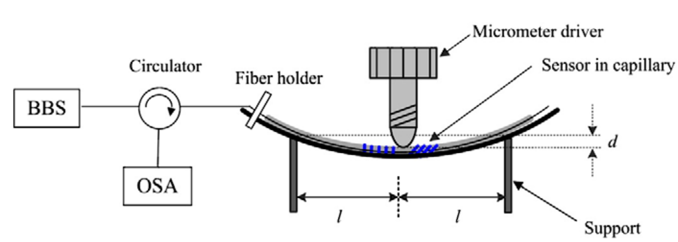

Fig. 2. Schematic diagram of the experimental setup for curvature measurement.