Twist Sensor Based on Long Period Grating and Tilted Bragg Grating Written in Few-mode Fibers

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Abstract: A twist sensor based on a few-mode long period grating (LPG) and a tilted fiber Bragg grating (TFBG) is proposed and demonstrated. The LPG, inscribed in a step index few-mode fiber by a CO2 laser, is utilized to excite the LP11 core mode. The followed tilted few-mode fiber Bragg grating (TFBG) written in graded index few mode fiber (GI-FMF) with the LP11 core mode as exciting light is served as sensing element. By analyzing transmitted intensity difference of two dips in transmission spectrum of the TFBG induced by the mode couplings from forward-propagating LP11 core mode to backward-propagating LP11 and LP21 core modes, a twist sensitivity of 1.074 dB/(rad/m) from -5.23 rad/m to 5.23 rad/m is achieved. The proposed sensor has advantages of easy operation and simple structure.

Index Terms: Fiber optics, twist sensor, tilted fiber Bragg grating, long period grating.

1. Introduction

Recently optical fiber-based torsion sensors have attracted widely attention [1, 2] due to the advantages such as anti-electromagnetic interference, compact structure and light weight. The operating mechanism of torsion sensors mainly based on interference [3-5] and optical grating. The interferometric sensors usually present temperature dependence and relatively complex signal demodulation which limit their potential application. Compared with interference-based torsion sensors, optical grating-based torsion sensors attracted more attention due to their compaction, reliability and stability. Various fiber twist sensors based on fiber long period grating (LPG) were realized such as using helical LPG in two-mode fiber [6], LPG in birefringent fiber [7], LPG in asymmetrical thin-core fiber [8], ultra-long-period fiber grating [9]. However, the fiber LPG based twist sensors are faced with difficulty of broad spectral width, which restrict their application in high resolution twist sensing [10]. The fiber grating bandwidth is wider, the resolution of the grating-based sensor is lower which results in poor sensitivity [11]. Fiber Bragg gratings (FBGs) compensate this weakness in fiber LPGs, possess smaller size and narrower linewidth.

FBGs based twist sensors have been studied for many years. Generally, the FBGs were written in SMF and the two polarizations of fundamental mode are used to realize twist sensing. The twist sensor based on dual-polarization distributed Bragg reflector (DBR) FBG laser had been reported by J. H. Wo et. al [12]. Y. P. Wang et. al [13] improved the sensitivity by using polarization dependent loss (PDL) multimeter with the sensitivity of 0.955 dB/deg. Twist effect and sensing of few mode polymer fiber Bragg gratings had been demonstrated by B. B. Yan et.al [14]. But as POF itself has geometry asymmetry (core off-center), there is a large loss when splicing with SMF in optical links.

As for the tilted FBGs (TFBGs), it enhances the coupling of light from fundamental core mode
to higher order modes which are much more sensitive to polarization and torsion. Researches on TFBG based sensor are focused on cladding modes in single mode fiber (SMF) [15-19]. L. Y. Shao et al. [10] demonstrated a fiber optic bend sensor with a hybrid structure of LPG and TFBG, which were written in SMF and photonic crystal fiber (PCF) respectively in order to eliminate the temperature cross-sensitivity. A curvature sensitivity of 2.36 dB/m\(^{-1}\) in the range from 0 m\(^{-1}\) to 7.2 m\(^{-1}\) was achieved. This kind of sensor scheme shows high refractive index dependence [20] and requires additional recoupling device to couple cladding modes back to core modes using offset splicing [21] or fiber tapering [22] methods. These methods introduce extra loss into the fiber twist sensor system, and thus it is valuable to transfer cladding modes to core modes smoothly with less loss consumption. T. Guo et al. [20] proposed a twist sensor based on TFBG in multimode fiber (MMF). They utilized a 4° TFBG written in multimode fiber to transfer sensing characteristics from cladding modes to core modes and achieved a sensitivity of 0.075 dB/deg in the twist range from -90° to 90°. To the best of our acknowledge, the reported works on TFBGs based twist sensors were all focused on fundamental core mode coupling to high-order core or cladding modes, which need polarizer and polarization controller (PC) to adjust the polarization states of the input light in order to obtain a high fringe visibility [20].

In this paper, the torsion characteristics of a TFBG written in a graded index few-mode fiber (GI-FMF) with LP\(_{11}\) core mode as exciting input light is experimentally demonstrated and investigated. Orientation-recognized torsion sensing from -5.23 rad/m to 5.23 rad/m with 1.074 dB/(rad/m) sensitivity is achieved. Thanks to the few-mode fiber LPG before the TFBG, the TFBG incident mode is LP\(_{11}\) core mode instead of fundamental core mode. As LP\(_{11}\) has polarization dependent property, there is no polarizer in optical link. Furthermore, the mode transformation efficiency of LPG from LP\(_{01}\) mode to LP\(_{11}\) mode achieved 96.8% in the proposed structure. The high transformation efficiency reduces the effect of LP\(_{01}\) which purify the mode content in each resonance wavelength. The modes participate in twist sensing are LP\(_{11}\) and LP\(_{21}\) core modes transferred from LP\(_{11}\) which have opposite variation tendency. As the TFBG is fabricated in GI-FMF, there is no additional recoupling device to coupling cladding modes back to core modes. So, the motivation of the design is to realize a twist sensor with simpler structure and lower insertion loss.

### 2. Twist sensor fabrication and operation principle

The schematic diagram of the proposed twist sensing system based on a few-mode LPG and a TFBG is illustrated in Fig. 1. The two fiber holders are used to hold on the polarization of the LPG and avoid the change during rotation process. The splices among SMF, SI-FMF and GI-FMF are core to core fusion with no lateral offsets to avoid energy loss. As the twist angles are different in different points along the distance between fiber holder 2 and Rotator, thus we quantify the twist rate \(\gamma\) by

\[
\gamma = \frac{\theta}{L}.
\]

where \(\theta\) and \(L\) denote twist angle and twist length respectively.

Fig. 1 Schematic diagram of the twist sensing system.

The LPG in step index few-mode fiber (SI-FMF) was fabricated by CO\(_2\) laser radiation method [23]. The periods of LPG were accurately designed to ensure fundamental core mode couple to
LP$_{11}$ core mode. Coupling resonance wavelength between the fundamental and LP$_{11}$ core mode can be described as fellow:

$$\lambda_{LP01\rightarrow LP11} = \left( n_{eff\rightarrow LP01} - n_{eff\rightarrow LP11} \right) \cdot \Lambda.$$  \hspace{1cm} (2)

where $n_{eff\rightarrow LP01}$, $n_{eff\rightarrow LP11}$ are the effective refractive index of the forward-propagating fundamental core mode and forward-propagating LP$_{11}$ core mode respectively, and $\Lambda$ is the grating period.

TFBG was manufactured by using the phase-mask technique with a 193 nm UV excimer laser as the writing source. The TFBG was written in a GI-FMF. The expression of refractive index in graded-index fiber is [24]:

$$n^2(r) = \begin{cases} n^2(0)[1 - 2\Delta \left( \frac{r}{a} \right)^g] & 0 \leq r \leq a \\ n^2(0)(1 - 2\Delta) & r > a \end{cases}.$$  \hspace{1cm} (3)

$\Delta$ is the relative refractive index,

$$\Delta = \frac{n^2(0) - n^2(a)}{2n^2(0)}.$$  \hspace{1cm} (4)

where $n(0)$ is the refractive index at fiber core center, $a$ is the core radius, and $n(a)$ is the cladding index. When $g \rightarrow \infty$, the fiber is going to be a step-index fiber. The optimum parameter $g \rightarrow 4$ in the simulations for obtaining a better match with experiment results.

Bragg reflection resonance at $\lambda_i$ is determined by core modes phase matching condition [25]:

$$\lambda_i = \left( n_{eff\rightarrow LP11} + n_v \right) \cdot \Lambda'.$$  \hspace{1cm} (5)

where $n_{eff\rightarrow LP11}$, $n_v$ are the effective refractive index of the forward-propagating LP$_{11}$ mode and $v^{th}$ backward-propagating high order core modes respectively. $\Lambda' = \Lambda / \cos \alpha$, where $\Lambda$ is the period of phase mask and $\alpha$ is the tilt angle between phase mask and fiber.

3. Experimental results and discussions

As LPG is the device to transfer fundamental core mode to LP$_{11}$ core mode, LPG needs to be carefully designed to ensure that LP$_{11}$ mode stimulates the TFBG.

The FMF used to fabricate LPG is a commercial two-mode step index fiber (OFS). The mode field diameters of LP$_{01}$ and LP$_{11}$ are 15.6 um and 13.6 um, respectively. The cladding refractive index is 1.444 and the refraction index difference between core and cladding is 0.005. The FMF was spliced to the SMF in both ends with no core offset. The LPG was fabricated by irradiating the few-mode fiber from one side with a CO$_2$ laser (CO$_2$-H30, Han’s Laser). The writing period was 1730 $\mu$m and the number of period was 29. The transmission spectrum of the LPG is presented in Fig. 2. The transmittance in the wavelength range from 1547.18 nm to 1556.89 nm, which covers the span of TFBG resonance wavelengths, is more than 15 dB. This indicates the mode transformation efficiency from LP$_{01}$ mode to LP$_{11}$ mode achieves 96.8%.

Although the splices between the two-mode step index fiber and SMF have no lateral off-set, the mismatch of the core diameters and mode field diameters between the two-mode fiber and SMF lead to about 5dB total loss obtained by OSA as shown in Fig. 2. The light from a continuous wave source (1250-1650 nm) was launched into the SMF and the output transmission spectrum is measured by OSA with the highest resolution of 0.02 nm. The LPG is accurately designed to ensure fundamental core mode couple to LP$_{11}$ core mode in certain wavelength (~1550 nm). The mode fields were observed by tunable laser at wavelengths A, B and C. The mode on wavelengths A and C are only LP$_{01}$ which indicates the mode coupling are not happened on these wavelengths. The mode on wavelength B is LP$_{11}$ which indicates the mode coupling is occurs on ~1550 nm. The perturbs in Fig. 2 are caused by the interference between different core modes.
The TFBG was written in a commercial four-mode graded index fiber (OFS). The refractive index distribution was mentioned in equation (3). The refractive index at fiber core center is 1.457 and the cladding refractive index is 1.444. The mode field diameters of LP_{01} and LP_{11} are 10.7 µm and 10.8µm, respectively.

The four-mode graded-index fiber is chosen to fabricating TFBG based on two important reasons. One is the matched mode field diameters and the fiber diameters between the few-mode LPG and the TFBG can reduce the splicing loss. The other reason is the GI-FMF with parabolic refractive index profile makes the transmission spectrum of the TFBG have much larger and equal wavelength spacing as illustrated in Fig. 3(b) and Fig. 3(c).

In experiment, the radial axis alignment issues should be considered as the asymmetrical gratings writing in both LPG and TFBG. The splicing point between the LPG and the TFBG should be carefully designed to ensure the two gratings are spliced core to core. Besides, the PC which on the left of LPG as shown in Fig. 1 is used to control the polarization of the fundamental mode. Tuning the PC and optimizing splicing process until the intensities of the TFBG dips achieve the biggest before twisting. Furthermore, as the transmission modes in LPG and TFBG are core modes, there is few influence on radial axis alignment when they are spliced core to core.

The graded-index FMF was spliced to SMF in one end and connected with optical spectrum analyzer (OSA) in the other end. The angle between FMF and the phase mask was adjusted to 1.5°. The period of the phase mask is 1068.79 nm and the length of grating is 10 mm. When the tilted angle θ is 1.5°, the period of TFBG is 534.6 nm according to equation (5). The energy and repeated frequency of the excimer laser was 1.5 mJ and 100 Hz respectively.

Using finite element method (FEM), the grating pitches against wavelength for different mode couplings in the graded-index FMF is calculated and shown in Fig. 3(a). Figure 3(b) illustrates the transmission spectrum of the TFBG with LP_{01} mode as incident light. Based on the calculated results in Fig. 3(a), we deduce that the right three resonant dips at 1555.332 nm, 1553.662 nm and 1552.036 nm originate from the couplings from the forward-propagating LP_{01} mode to the backward-propagating LP_{01}, LP_{11} and LP_{21} modes, respectively, as shown in the inset on the right of Fig. 3(b). The insets on the left in Fig. 3(b) represent the schematic mode coupling process of the TFBG. The transmission spectrum of the LPG cascaded with TFBG is shown in Fig. 3(c). The inset on the left in Fig. 3(c) represent the schematic mode coupling process of the TFBG cascade with the LPG. As the incident mode of the TFBG is mainly LP_{11}
mode, the longest resonance wavelength at 1555.332 nm almost disappeared and the right three resonant dips at 1553.907 nm, 1552.272 nm and 1550.595 nm in Fig. 3(c) are deduced to originate from the couplings from the forward-propagating LP_{11} mode to the backward-propagating LP_{01}, LP_{11} and LP_{21} modes, respectively, from the calculated results in Fig. 3(a).

The torsion experiments were carried out at room temperature 25 °C. The opposite direction resonance dips located at 1552.272 nm and 1550.595 nm were selected as the monitoring wavelengths. Figure 4 shows the variation of the transmission spectra with different twist rates from -5.23 rad/m to 5.23 rad/m (or twist angles range from -30° to 30°). The transmitted intensity changes of the resonance dips (corresponding to the two resonances colored in purple and pink in Fig. 4), originated from the mode couplings from forward-propagating LP_{11} core mode to backward-propagating LP_{11} and LP_{21} core modes respectively, always had opposite response direction. The phenomenon can be clearly seen in Fig. 5(a). But the resonance wavelengths almost have no shift with the increment of twist rate which is illustrated in Fig. 5(b). As the twist rate is increased from -5.23 rad/m to 5.23 rad/m, the transmitted intensity of resonance from LP_{11} mode to LP_{11} mode increases gradually while the transmitted intensity of resonance from LP_{11} mode to LP_{21} mode decreases because of different polarization properties of the two high-order core modes.
Fig. 4 Spectrum with different twist rate from -5.23 rad/m to 5.23 rad/m.

(a) LP_{11}, LP_{21} Transmission, LP_{11}, LP_{21} Transmission, Differential Intensity

Transmission (dB)

-18
-20
-22
-24
-26
-28
-30

Twist rate (rad/m)

-6
-4
-2
0
2
4
6

Differential Intensity (dB)

0
2
4
6

Slop = 1.074 dB/(rad/m)
Linear response for both clockwise and anticlockwise rotation from -5.23 rad/m to 5.23 rad/m can be achieved. The torsion angle can be monitored by observing the transmitted intensity difference of the two modes. Based on the relationship between twist rate and the transmitted intensity difference (blue line) as shown in Fig. 5(a), the torsion sensitivity of TFBG cascaded with LPG is 1.074 dB/(rad/m) from -5.23 rad/m to 5.23 rad/m or 0.187 dB/deg when the twist length is 10 cm.

It is worth noting that the phenomenon of spectral integral shift in Fig. 4 when the TFBG is twisted. That’s owing to the change of the fiber birefringence caused by the torsion. The coupling coefficient from LP01 to LP11 modes alters during that process, thus the intensity of output light from LPG is also changed. Figure 6 shows the spectral change process when only the fiber out of LPG without TFBG is twisted. As shown in Fig. 6, the transmitted spectral intensity of the LPG overall shifts in wavelength range from 1548 nm to 1555 nm when the fiber is rotated from -5.23 rad/m to 5.23 rad/m. As the twist rate increased, the fiber birefringence is changed and the total intensity of LPG spectrum from 1548 to 1555 nm become more and more weaker. The coupling from LP01 to LP11 core modes grows inefficiency as shown in Fig. 6. The spectrum from 1548 to 1555 nm covers the span of TFBG.
4. Conclusion

In conclusion, the torsion characteristics of a TFBG in GI-FMF have been analyzed and experimentally demonstrated when LP11 core mode acts as stimulation light. A LPG written in a two-mode fiber is used to transfer fundamental mode to LP11 core mode which is polarization dependent. The motivation of the design is to realize a twist sensor with simpler structure and lower insertion loss. A high torsion sensitivity of 1.074 dB/(rad/m) or 0.187 dB/deg is achieved. As the sensing modes are all core modes, there is no additional recoupling device to couple cladding modes back to core modes, which introduce less extra loss. The proposed sensor has also advantages of easy operation, simple structure and can be potentially used in optical fiber sensing systems.

Reference


