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Temperature-insensitive polarimetric torsion sensor based on a pair of angularly cascaded LPFGs

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ABSTRACT

A novel torsion sensor is proposed based on the polarization characteristics of a pair of angularly cascaded long period fiber gratings (ALPFG). A set of special designed fiber rings serve as the detached sensor head and the ALPFG provides the polarization filter. The input polarization is continually adjustable through rotating the dial of the fiber rings, which alters the output intensity from ALPFG, and the torsion sensitivity can reach −15.355 dB/rad. We study the periodicity of output intensity theoretically and experimentally and find the angular lag between the fluctuations of the two resonant dips. Through post-proceeding, we break the sensitivity-range limit and double the measuring range by taking advantage of the angular lag. This system design not only theoretically provides a more sensitive sensor head design, but also possesses more flexible, healthy and temperature-insensitive characteristics. Therefore, such sensor can be a good candidate for torsion sensing.

1. Introduction

Torsion sensing is a highly important issue in engineering and has recently aroused considerable research. Unlike the conventional torsion sensors, such as electrical and electromagnetic devices, the fiber-optic sensors are usually lightweight, compact, and immune to electromagnetic interference. These unique characteristics allow fiber-optic sensors to exhibit outstanding performances in the challenging circumstances.

In the last few decades, fiber torsion sensors based on long period fiber grating (LPFG) [1–6], fiber Bragg grating (FBG) [7–9], Mach-Zehnder interferometer (MZI) [10–12], Sagnac loop [13–15], and Michelson interferometer [16,17] have been widely reported. Among these previous reports, the nonuniform refractive index distribution in the cross section of a LPFG fabricated by CO_2 laser irradiation is an excellent candidate for torsion sensing, and it is possible to increase the multiplicity of nonuniformity (MON) by spatial cascading, which may improve the performance of sensor [6,18]. Moreover, with the computer-aided method, the fabrication of CO_2 laser irradiated LPFG is more convenient than the ultraviolet exposure method [19]. For many reported in-fiber torsion sensors, their sensor heads have to undergo twist for obtaining the ambient torsion because their generating part and responding part are integrated. However, a sensor head is usually the most fragile section in the sensing system, because sensors achieve the ambient information from the structural fabrication area, such as splicing, laser irradiating, and tapering, which will easily decrease the mechanical strength of materials. Meanwhile the device aging and detection (e.g. torsion, bend, and strain) further reduce their service life. To solve this problem, the polarimetric method is a considerable way [10]. With the utilization of a special designed polarization ring (15-lap single mode fiber) [20] and polarization-sensitive structures, the conventional sensor head can be separated into two parts: the sensor part (polarization ring) and the polarization filter. The dial of polarization ring rotates instead of twisting the sensor head, and the spectrum will also vary with the polarization state changing. Therefore, torsion sensing is achieved while the vulnerable parts maintain healthy.

In this paper, we propose a set of novel torsion sensors, which consist of a fiber polarization ring and a pair of angularly cascaded LPFGs (ALPFG). ALPFG refers to the structure that two LPFGs with same parameters are cascaded with an angle between their laser-exposed orientations. We theoretically and experimentally test the polarimetric responses of the ALPFGs. Through experiments, we notice the angular lag between the two resonances of ALPFGs, and find that the lagging angle is related to the angle between two cascaded LPFGs. The sensitivity of 90°-LPFG is one order of magnitude higher than that of Ref. [7,12,13], 8 times higher than that of Ref. [2] and 3 times higher than that of Ref. [14]. With a post-processing algorithm, we break the sensitivity-range limit, and the measuring range expands from 35 deg to

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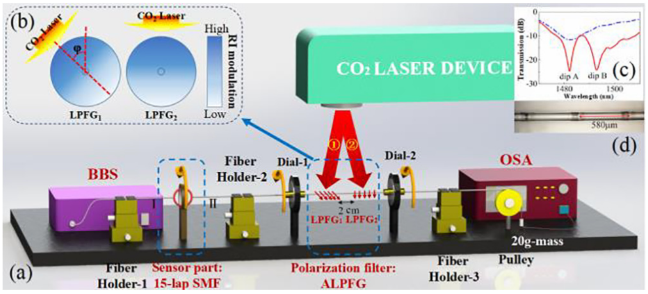

Fig. 1. (a) Schematic diagram of experimental system. (b) Cross sections of $LPFG_1$ and $LPFG_2$ when fabricating ALPFG. (c) Spectra of $LPFG_1$ (dashed-dot) and ALPFG (solid). (d) Microscope picture of LPFG.

85 deg taking advantage of the angular lag. Moreover, the temperature influence on the proposed sensing system is pretty low.

2. Structures and principles

Our experimental setup is shown in Fig. 1(a). A broadband source (China-fiber) emits a linearly polarized light with a wavelength ranging from 1250 to 1650 nm. The laser device (Han's Laser) irradiates CO_2 laser with a maximum power of ~15 W. The exposed orientation of the fiber can be adjusted by rotating the two dials [18] and a 20 g-mass attaches to the fiber to provide a constant tension. After fabricating $LPFG_1$, we rotate the two dials by the angle of φ to change the exposed orientation, and then write $LPFG_2$. The grating pitches of $LPFG_1$ and $LPFG_2$ are both 580 µm, and their grating numbers are both 41. Fig. 1(b) shows the cross section of $LPFG_1$ and $LPFG_2$. We fabricated ALPFGs with φ of 0°, 45° and 90°. The polarization ring consists of 15 laps of the single mode fiber (SMF). From the published experimental results, the polarization rotation angle is linearly dependent on the twisted fiber ring angle but independent of the length of the twisted fiber [20]. The ratio was found to be 0.069. Therefore, rotating the dial by 1 deg corresponds to the polarization rotating 1.035 deg. Moreover, when we rotate the fiber ring, fiber I and fiber II are twisted to opposite orientations with a same angle. The birefringence induced in fiber I and fiber II neutralize each other, therefore, the birefringence have no effect on our experiments. In polarimetric responding tests, the polarization ring serves as a polarization controller, and in torsion sensing property tests, it serves as the sensor part. By using the polarization characteristic of the fiber ring, we separate the conventional sensing structure into two sections, i.e. sensor part (polarization ring) and polarization filter (LPFGs). The torsion sensing can be obtained if one rotates the dial of polarization ring and no torsion is brought to the fragile polarization filter (LPFGs). Therefore, the vulnerable irradiated part is well protected, which enhances the reliability and physical robust of the sensor.

The phase-matching condition for an ideal LPFG can be described as [21]

$$\lambda_{res} = \Lambda(n_{01} - n_{mn}) = \Lambda(\Delta n), \tag{1}$$

where λ_{res} is the wavelength of resonant dip, n_{01} and n_{mn} are the effective refractive indexes (ERIs) of LP_{01} fundamental mode and LP_{mn} high-order cladding mode, Λ is the grating period of the LPFG, and Δn is the ERI difference between LP_{01} and LP_{mn} mode. However, due to the nonuniformity of CO_2-laser-induced refractive index modulation in the cross section of fiber, the grating properties (such as transmission spectrum, resonance, and coupling strength) depend on the state of polarization (SOP) of incident light. As a result, if the SOP of incident light periodically changes, the resonant wavelength and light intensity will also vary accordingly.

For the cascaded LPFG pair irradiated by CO_2 laser, n_{01} and n_{mn} vary with the SOP of input. When the input is linearly polarized, Δn is given by

$$\Delta n = \Gamma(\theta, \phi)\sqrt{(\Delta n_x \cos\theta)^2 + (\Delta n_y \sin\theta)^2}, \tag{2}$$

where Δn_x and Δn_y stand for the ERI differences between LP_{01} mode and LP_{mn} mode when the input electric fields are parallel or perpendicular to the CO_2 laser irradiating direction. $\Gamma(\theta,\varphi)$ is defined as the modulating function, which relates to the angle between the actual input electric field and the CO_2 laser irradiating direction of $LPFG_1$ (θ), and the angle between the exposure directions of two LPFGs (φ).

On the basis of the Mach-Zehnder interference principle, the light transmission is given by

$$I = E_1^2 + E_2^2 + 2E_1E_2\cos(2\pi\Delta nl/\lambda), \tag{3}$$

where E_1 and E_2 are the electronic complex amplitudes of LP_{01} mode and LP_{mn} mode, respectively. ($\Delta n \times l$) is the optical path difference between the two modes, and λ is the wavelength.

To analyze the grating transmission varying with the light polarization, we set $\Lambda = 580\,\mu m$, $\Delta n_x = 3 \times 10^{-3}$, $\Delta n_y = 2.99 \times 10^{-3}$, $\lambda = 1550$ nm, $E_1{}^2 = E_2{}^2 = 1/2$, the grating number $k = 41$, and the space between two LPFGs $d = 2$ cm. Therefore, $l = (k-1)\Lambda + d = 4.32$ cm. To simplify the calculation, $\Gamma(\theta,\varphi)$ is set as 1 in the scenario of 0°-ALPFG. The simulation result is shown in Fig. 2(a) and four dips appear within 360 deg rotation of input light.

To verify our simulation, the polarimetric response of 0°-ALPFG is firstly tested. During experiments, the dial of polarization ring is rotated from 0 to 400 deg, and the spectra are recorded in every 5 deg. The spectra are plotted in Fig. 2(b) and it is obvious that the transmission varies with the rotating angle, while four dips appear within the rotating angle range, which confirms our theoretic result in Fig. 2(a). This trend is also reflected in the polarimetric responses of 45°-ALPFG and 90°-ALPFG.

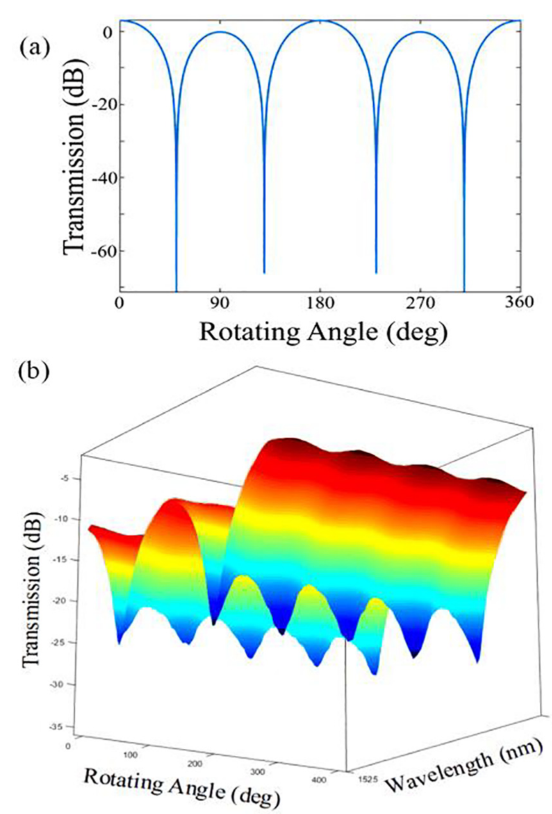

Fig. 2. (a) Simulated transmission (I) varying with rotating angle (θ) for cascaded LPFG pair. (b) Experimental output intensity of 0°-ALPFG.