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Fabrication and characterization of helical long-period fiber gratings in single-mode fibers

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ABSTRACT

A fabrication method for helical long-period gratings (H-LPGs) in single-mode fibers is experimentally demonstrated. H-LPGs are manufactured by homogenously twisting the melting parts of fibers under indirect CO_2 laser beam irradiation. The resonant wavelength attenuation is controlled by monitoring the real-time transmission spectrum during heating and twisting processes. The torsional and thermal characteristics of the fabricated H-LPGs are systematically investigated in experiments. The achieved torsion sensitivity is 96.4 pm/(rad/m) for twisting angles from −240° to 240°, and the temperature sensitivity is 49.2 pm/° ranging from 20° to 120°. Our experimental results exhibit a highly accurate and reliable fabrication method for H-LPGs in fibers that possess high potentials for torsion and temperature sensing applications.

1. Introduction

In-fiber torsion sensors have been extensively investigated with wide applications in civil engineering, aerospace, and securities [1–11]. A variety of fiber-based torsion sensors have been achieved including traditional long-period fiber gratings (LPGs) [1,2], titled fiber Bragg gratings [3], distributed Bragg reflector (DBR) fiber lasers [4], polarization maintaining fibers [5,6], photonic crystal fibers (PCFs) [7,8], coreless square-fibers [9], as well as other novel structures [10,11]. In general, the resonant wavelengths of LPG-based sensors are much more sensitive to ambient parameter changes compared with other schemes. Nonetheless, most of these in-fiber torsion sensors cannot detect the amount and orientation of torsions simultaneously.

Helical long-period fiber gratings (H-LPGs) has been proposed and demonstrated in recent years [12–16]. Comparing with traditional LPGs, H-LPGs have a larger measurement range and higher sensitivity on torsional parameters because of different formation mechanism and physical characteristics [12]. During measurements of torsional parameters, the resonant wavelength can be shifted due to the effective index change of each transmission mode by the photo-elastic effect [17]. In addition, the index modulation period of H-LPGs can be directly changed by torsional parameters. As simultaneous measurement of torsional amount and orientation is strongly desired for practical fiber sensor applications, H-LPGs thus possess obvious advantages for torsion sensors.

H-LPGs have been fabricated by method of twisting fibers under unilateral CO_2 laser beams; however, laser beams should be precisely irradiated on fibers with tightly focused spots that are very likely to discontinue the molten state

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[14–16]. Another problem arises from the inherently existing core-cladding eccentricity in single mode fibers (SMFs), which is usually fluctuating in a random fashion. Therefore, it becomes difficult to determine the exact length of the fabricated H-LPGs with designed transmission attenuation at the resonant wavelength.

In this paper, we have proposed and demonstrated a homogenous fiber-twisting system, under indirect laser heating, for H-LPG fabrication with in-situ transmission spectrum monitoring. The fabricated H-LPGs are later investigated for torsion and ambient temperature sensing. It has been found that the resonant wavelength shift of H-LPGs has an excellent linear relationship with the amount of torsion and temperature change, respectively. The experimental founding has indicated the fabricated H-LPGs can serve as promising candidates for torsion and temperature sensing applications.

2. Principles of operation

SMFs usually have a small amount of random core–cladding eccentricity due to fabrication imperfection [18], thus, the core index will form a helical periodic modulation after a melting twist process. H-LPGs can couple light from the fundamental core mode to cladding modes at particular wavelengths and cause transmission depletions [14], similar to conventional long-period fiber gratings [19,20]. The resonant peak wavelengths satisfy the phase matching condition that can be described as [15]:

$$\lambda_d = \left(n_{eff}^{co} - n_{eff}^{cl,m}\right) \cdot \Lambda \tag{1}$$

where n_{eff}^{co} and $n_{eff}^{cl,m}$ are the effective refractive indices of the fundamental core mode and mth cladding mode, respectively; Λ is the grating period and λ_d is the resonant wavelength. The resonant wavelength λ_d changes proportionally as the index difference $\left(n_{eff}^{co} - n_{eff}^{cl,m}\right)$ or grating period Λ changes. In particular, when the grating period Λ varies due to the temperature or twisting angle variation, the resonant wavelength shift can be clearly observed in the transmission spectrum. In this paper, positive twist is deemed as the direction of applied twist coinciding with H-LPG's torsion direction; otherwise, it is negative. When the twist is positive, the resonant wavelength shifts towards shorter wavelength, corresponding to a decreased grating period, and vice versa. In addition, the amount of shift strongly depends on the angle of applied torsion. Therefore, H-LPGs can simultaneously detect the twisting angle and orientation, an apparent advantage over ordinary LPGs.

3. Fabrication procedure for H-LPGs

We have built a fabrication and in-situ monitoring system that can write H-LPGs by homogenously twisting a section of SMFs and, at the same time, monitoring the transmission spectrum dynamically. As shown in Fig. 1, H-LPGs are fabricated with the following procedure. The SMFs (G.652) are placed inside a sapphire tube, serving as a miniature oven, and twisted by a rotation motor (Thorlabs, PRM1/MZ8). The sapphire tube is fixated and heated by a CO_2 laser (emission at 10.6 μm) with a continuous-wave output power of 18 W. The SMFs are moving through the sapphire tube at a constant speed of 38 μm/s, by the motorized translation stage 1 (Thorlabs, LTS150/M), and simultaneously twisted at a rate of 25 o/s by the rotation motor. The motorized translation stage 2 (Thorlabs, PT1/M-28) in the setup is utilized to supply a small longitudinal strain to straighten the heated SMFs. During the heating and twisting process, the transmission spectrum is monitored utilizing an amplified spontaneous emission (ASE) light source (1250–1650 nm) and an optical spectrum analyzer (OSA, Anritsu, MS9710C). All procedures are controlled by a computer system with a LabVIEW program.

The sapphire tube is irradiated by the CO_2 laser and served as a miniature oven to heat SMFs inside to molten state. The utilization of the sapphire tube enables indirect and uniform heating of the SMFs, thus alleviating disadvantages associated with tightly focused laser beams. The motorized rotation stage leads the molten parts of SMFs to constant twisting. The moving speeds of stage 1 and 2 are V_1 and V_2, respectively; and the rotation rate is V_r. To note, V_2 is extremely small comparing with V_1. All moving and rotating procedures are controlled by the LabVIEW program to ensure accurate fabrication. The real-

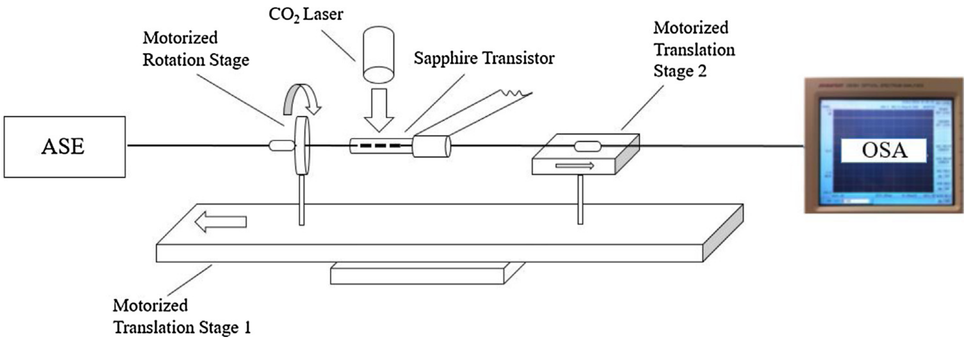

Fig. 1. The experimental setup to fabricate H-LPGs.