High Sensitivity Chiral Long-Period Grating Sensors Written in the Twisted Fiber

Liang Zhang, Yunqi Liu, Xibiao Cao, and Tingyun Wang

***Abstract*— A chiral long-period grating (CLPG) was fabricated successfully by scanning CO_2 laser in a twisted conventional single-mode fiber. The strong mode coupling can be achieved in a short grating length. The sensing characteristics of the CLPGs were investigated experimentally. Compared with the conventional long-period fiber gratings, the CLPGs were found to have the similar temperature and refractive index sensitivities and much higher torsion, bending, and strain sensitivities. The high sensitivity of the CLPG can be attributed to the screw-type waveguide structure induced by the scanning laser in the twisted fiber. The proposed CLPGs could have great potential applications as filters and optical sensors.**

***Index Terms*— Chiral long-period gratings, optical sensor.**

I. Introduction

Long-PERIOD fiber grating (LPFG), which consists of a periodic refractive index modulation along the longitudinal axis of an optical fiber, can couple light from the guided core mode to cladding modes at specific resonance wavelengths. LPFGs have been widely used in optical communications and sensors. In the past decade, many methods have been developed to fabricate LPFGs [1]–[5]. In this letter, we demonstrated the fabrication of the CO_2-laser written chiral long-period gratings (CLPGs), which are firstly proposed by twisting the fiber heated by an oven [6]. The CLPGs are characterized by their helical structures and rotary refractive index change along the fiber axis. Recently, the CLPGs have exhibited wide potential applications in optical communications and sensors, such as filters, polarizers, spatial-mode couplers and sensors [6]–[11].

A few methods have been proposed to fabricate CLPGs. The earliest CLPG was fabricated by winding wire around a two-mode fiber for spatial-mode coupler [7]. However, winding method is hard to operate due to the small size of fiber. Kopp et al fabricated the CLPGs by twisting the soften fibers with a high rate as they pass through a miniature oven [6], [8]. To achieve the polarization-selection, the high birefringence fibers, which have noncircular core cross section and large index difference between the core and cladding, were usually needed in the fabrication. The different mode field diameters of fiber would not match that of conventional single-mode fiber (SMF) so that the gratings have the higher insertion loss and back reflection. A compatible CLPG was fabricated by twisting a conventional SMF [9]. The CO_2 laser can be used to fabricate CLPG thanks to the strong absorption of the fiber at the wavelength of 10.6 μm. Compared with an oven, CO_2 laser is a more efficient and cleaner heating source, whose energy can be more easily and precisely controlled by computer. Therefore the CLPGs with complex refractive index modulation could be written in different specialty fibers by the CO_2 laser. In the previous reports [10], [11], the laser beam is fixed, and the twisted fiber has to be moved when the focused laser is exposing the fiber with a small spot. Therefore, the high stable and precise mechanical stage is usually needed. In this paper, we demonstrate a simple and efficient method to fabricate CLPG in a conventional SMF with scanning CO_2 laser. The sensing characteristics of such gratings were investigated experimentally, and it was found that the CLPGs were more sensitive to the torsion, bending and strain.

II. Fabrication of the CLPG

The fabrication of the CLPGs in conventional SMFs relies on the eccentricity between the fiber core and the cladding. When a SMF is twisted, the core follows a helical path inside the cladding, which is sufficient to produce a periodic-index modulation along the fiber [9]. The experimental setup for the fabrication and measurements of the CLPG is shown in Fig. 1(a). A CO_2 laser (Han' laser CO2-H10) with an output power of $\sim$1 W is used as a heating source. The laser system includes a tuning mirror and an attenuator, which are used to control the scanning orbit and the intensity of laser beam. The fiber holding system consists of a normal fiber holder and a rotating fiber holder, which is linked to the rotation motor and applies the twist stress on the SMF. A CCD vision system is used to observe the shape of fiber, a broadband light source (ASLD-CWDM-5-B-FA, Amonics) with an output covering the wavelength range from 1250 nm to 1650 nm and an optical spectrum analyzer (OSA, AQ6370C, YOKOGAWA) are used to monitor the transmission spectra of the CLPGs. In order to control the fabrication precisely, all parameters in

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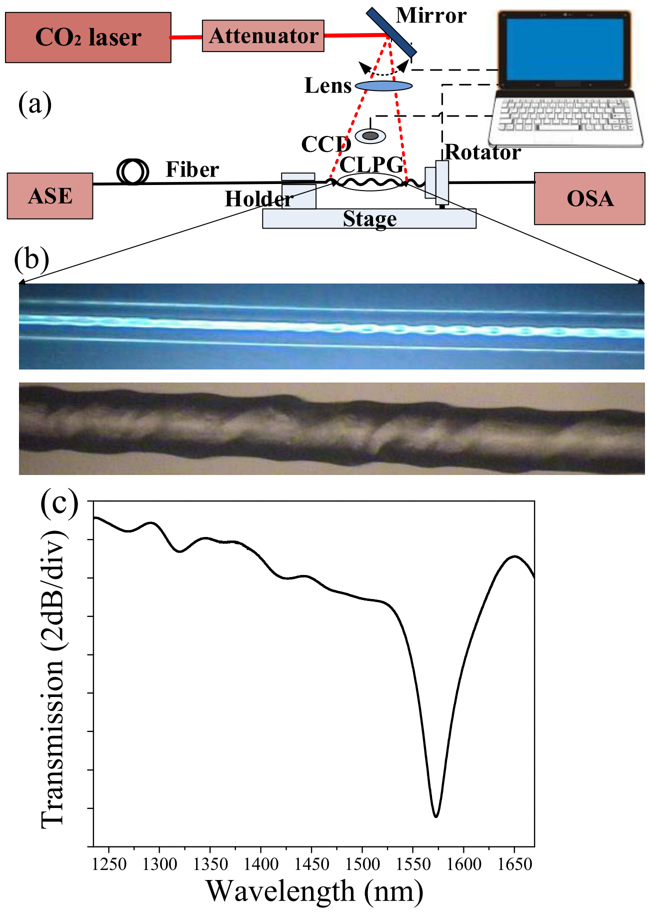

Fig. 1. (a) The experimental setup. (b) The magnified picture of the CLPG. (c) The transmission spectrum of the fabricated CLPG.

the procedure, such as the rotation speed of fiber, the power and the sweeping frequency of CO_2 laser, are controlled by computer.

In our experiments, a conventional SMF was fixed by the holding system, and a stabilized CO_2 laser beam, which was focused by a lens on the fiber on a spot with a diameter of $\sim$50 μm, scanned across the fiber transversely and advance along the fiber axis continuously to form a stable heating field. At the same time, we twisted one end of the fixed fiber at a constant speed of 10°/s with the rotating fiber holder. Fig. 1(b) shows the structure of the fabricated CLPG, which were taken by the microscope with different magnifications, and the focused objects were fiber core and fiber cladding, respectively. In the pictures, the helical structures of the twisted fiber core and fiber cladding can be seen clearly. The bumpy cladding surface could be further optimized, which is believed to be helpful to fabricate the CLPGs with lower extra insertion loss. The period of the CLPG is equal to the pitch of helix, which can be calculated by [9]

$$\Lambda_g = L/N \tag{1}$$

where Λ_g is period of CLPG, L is the length of the twisted fiber section, and N is the number of twist turns. Therefore, the periods of such gratings can be changed flexibly by adjusting the length or the turns of the twisted fiber. Similar to conventional LPFGs, CLPGs couple the guided fundamental mode to forward-propagating cladding modes. For the single-helix CLPG in a conventional SMF, the phase-matching condition can be described as [12]

$$\lambda_i = \left(n_{core} - n^i_{cladding}\right)\Lambda \tag{2}$$

where n_{core} is the effective refractive index of fundamental mode, $n^i_{cladding}$ is effective refractive index of ith-order cladding mode, Λ is the period of the grating, andλ_i is the resonance wavelength of the grating.

In the experiment, the length of the twisted fiber section and the number of turns was 10 mm and 10 turns, respectively. Therefore, the fabricated CLPG had a period of about 1000μm. Fig. 1(c) shows the transmission spectrum of the fabricated CLPG, whose resonance wavelength and contrast are 1572.8 nm and 20.7 dB, respectively. Based on the measurements of the mode pattern using an infrared camera, the cladding mode was identified to be LP_{14} mode. Significantly, more than 20 dB resonance dip can be achieved with a short grating length of $\sim$10 mm, which means the grating has a much stronger coupling strength than that reported previously, where the corresponding grating contrast and length are 11.4 dB and 6cm, respectively [10]. Meanwhile, the spectral width of more than 50 nm is observed in the transmission spectrum. Similar to LPFGs, a CLPG with longer gratings length would have a narrower spectral width. In our experiments, the fabricated CLPG has a short length of $\sim$10mm, thus the grating has a broader spectral width. The bandwidth of a transmission grating, which is the separation between the first zeros on either side of the spectral dip, can be expressed [13]

$$\Delta\lambda = \frac{2\Lambda\lambda_i}{L}\sqrt{1-(\frac{\kappa L}{\pi})^2} \tag{3}$$

where $\Delta\lambda$ is the spectrum bandwidth, and κ is coupling coefficient. Therefore, the CLPGs with longer grating length have a narrower bandwidth. For the multiplexing of the CLPGs, the grating with narrow grating bandwidth can be fabricated by writing the gratings with longer grating length. In our fabrication, the fiber need be heated until it is softened enough to be twisted. So, the grating length of the CLPGs relies on the length of the softened fiber, which is determined by the length of scanning area of CO_2 laser along the fiber. Once the scanning area is too large, part of the earlier heated region will be cooled down, which may cause the non-uniform grating period. A maximum grating length of 25 mm can be achieved for the fabrication of uniform gratings. To achieve a longer CLPG, the laser source with a higher scanning frequency can be adopted.

Compared with the previous reported fabrication methods using CO_2 laser [11], the main feature of our setup is the stationary stage and the scanning laser beams, which help to widen the heating and twisting part in fibers. Therefore our method increases the stability of setup, no high precise stage is needed during writing process. By adding the rotator, we can realize the fabrication of CLPGs using the CO_2 laser writing system [14]. In our experiments, the insertion loss of the CLPG is $\sim$2 dB, which is larger than that of the conventional LPFG. It can be attributed to the slight damage of the fiber structure during the heating and twisting processes. To reduce

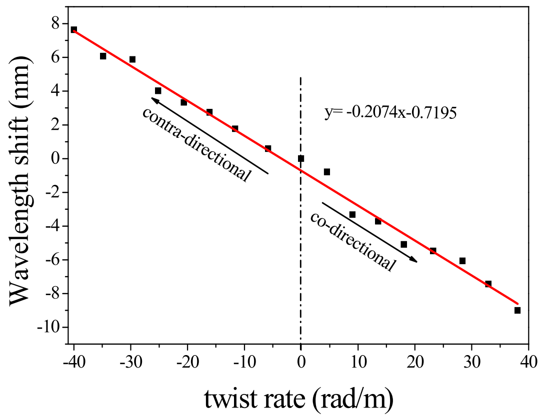

Fig. 2. The dependence of the wavelength shift on the twist rate.

the insertion loss of CLPG, the energy of CO_2 laser beam and the twist speed of ratable holder may be further optimized.

III. Experimental Results and Discussion

The sensing characteristics of the CLPG, including torsion, bending, strain, temperature and surrounding refractive index (SRI) sensitivity are investigated experimentally. For comparison, the similar experiments were performed on a conventional LPFG, whose resonance wavelength is 1550 nm and the coupled cladding mode is identified as LP_{05} mode. To measure the torsion sensitivity of CLPG, one end of the fiber containing CLPG is fixed to a stationary holder, and the other end is fixed to the center of a rotating holder that provides the twist stress to the fiber. The magnitude of twist rate can be defined as $r_{tw} = \theta/L$, where θ is the turning angle of the fiber, and L(=13.5 cm) is the distance between two holders. In our experiments, the same direction to the helix of grating is defined as co-direction, and the opposite twist direction is defined as contra-direction. The torsion of different direction of the CLPG will effectively reduce or enlarge the grating period, thus leads to the wavelength shifts. As the twist angle changed from $-360°$ to $360°$, the transmission spectra of the CLPG were recorded at an interval of 45°. Fig. 2 shows the dependence of the wavelength shift on the twist rate. The resonance wavelength of the CLPG varies monotonically and linearly with a torsion sensitivity of 0.21 nm/(rad/m), which is at least seven times higher than that of a conventional LPFG [15]. By applying the twist stress, the CLPG can be use as tunable band rejection filters.

The bending characteristics were measured by the setup shown in Fig. 3. On the metal experimental platform, two strong magnets were placed at the both end of a thin elastic ruler. The fiber containing CLPG was placed on the ruler, one side of which was fixed by using adhesive tape. To make the fiber straight, a light weight (2 g) was hung along the fiber. The CLPGs were bent when one of the magnets was pushed on the platform. In our experiments, the distance between two magnets is d, the height of the middle point of the ruler beam is h, and the curvature radius of the beam is R. The bending radius R can be calculated by the equation (4), and the curvature C could be expressed only in terms of d and h, as equation (5).

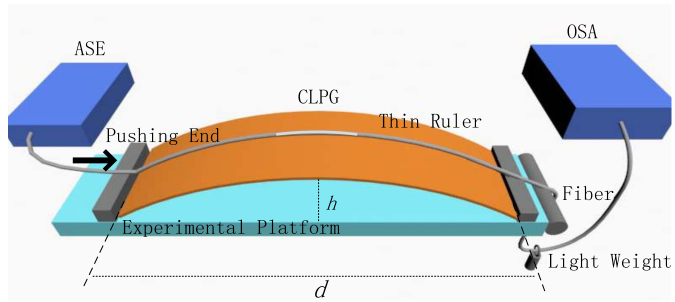

Fig. 3. Experimental setup for bending measurements.

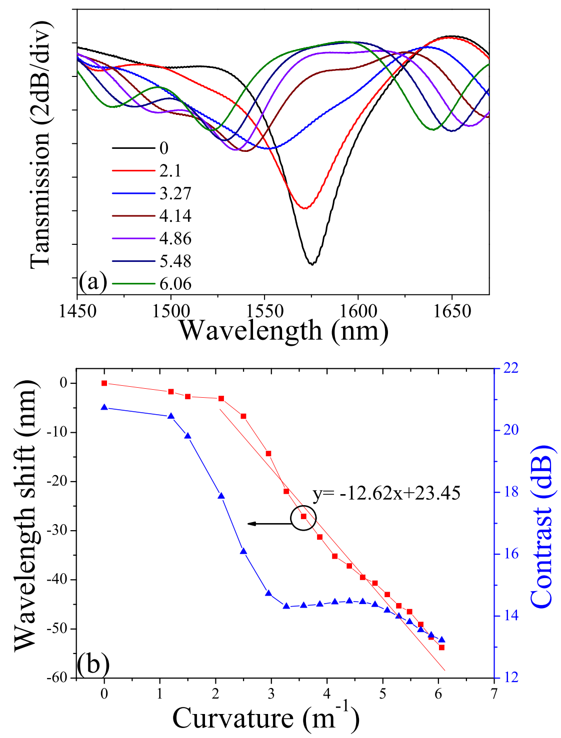

Fig. 4. (a) The transmission spectra of the CLPG with different curvature. (b) The dependence of resonance wavelength and grating contrast on the curvature.

$$R^2 = \left(\frac{d}{2}\right)^2 + (R-h)^2 \tag{4}$$

$$C = \frac{1}{R} = \frac{8h}{d^2+4h^2} \tag{5}$$

The transmission spectra of the CLPGs were recorded when bending curvatures increase. Fig. 4(a) shows the transmission spectra of the CLPG, and Fig. 4(b) shows the dependence of resonance wavelength and grating contrast on the curvature. The transmission dip was found to shift to a shorter wavelength when the bending curvature increases. The higher bending sensitivity can be achieved when the curvature is larger than 2.10 m^{-1}, and the measured sensitivity is 12.62 nm/m^{-1}, which is similar to that of helical LPFG [16], and almost twice higher than that of conventional LPFGs [17].

The sensitivity of the gratings to axial strain was also investigated experimentally. One end of the CLPG was fixed on a translation stages by fiber holder, and the other end was

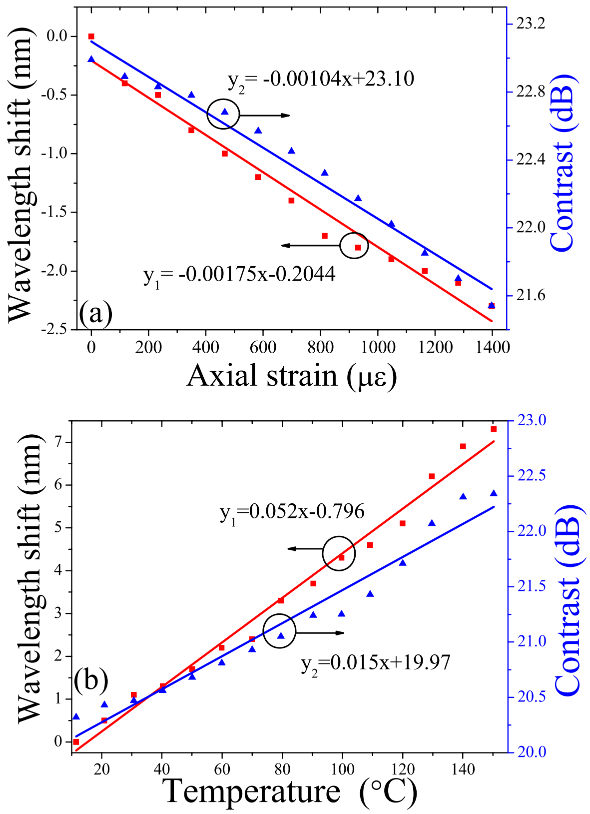

Fig. 5. Dependence of resonance wavelength and grating contrast on (a) axial strain variation and (b) temperature.

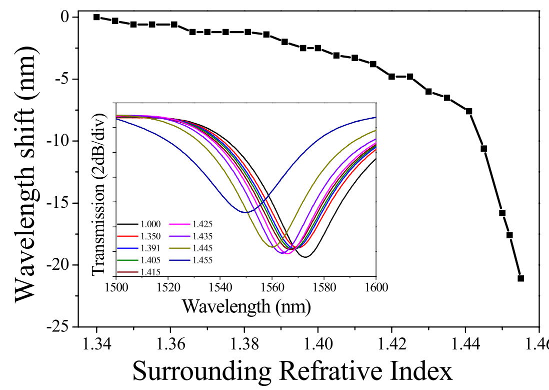

Fig. 6. The dependence of the wavelength shift on the SRI. The inset shows spectral response of the fabricated CLPG with different SRI in the index range of 1.000–1.446.

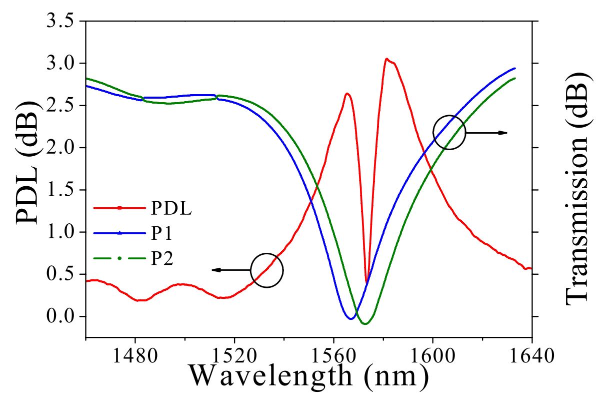

Fig. 7. The transmission spectra corresponding to the two orthogonal polarizations and PDL of the CLPG.

fixed to a strain sensor. The transmission spectra were recorded at a strain interval of 0.1 N and summarized in Fig. 5(a). The resonance wavelength shifted to the shorter wavelength with increase of the axial strain. The measured strain sensitivity of the CLPG is 1.75 pm/$\mu\varepsilon$, which is four times higher than that of conventional LPFGs [5], [18]. In addition, to study the thermal characteristics of CLPGs, we placed the fabricated CLPG in a thermostat, whose temperature varies from 10°C to 150°C, and recorded its transmission spectra at a temperature interval of 10°C. The experimental results are summarized as Fig. 5(b). With the increase of temperature, the resonance wavelength of the CLPG shifts to longer wavelengths. The temperature sensitivity is 52 pm/°C, which is similar to that of conventional LPFGs [5], [18].

We measured the sensing characteristics of the CLPGs on the surrounding refractive index. The fabricated CLPG was placed in the different index matching liquid in the range of 1.000∼1.446. As the SRI increased, the resonance wavelength of CLPG shifted to shorter wavelength, as shown in Fig. 6. The inset shows its spectral response to different SRI in the index range of 1.000-1.446. The measured index sensitivity is 995 nm/RIU in the range of 1.441∼1.446, which is roughly the same as that of a conventional LPFG.

The polarization-dependent loss (PDL) of the fabricated CLPG was measured using an optical component analyzer (N7788BD, Agilent). Fig. 7 shows the measured transmission spectra corresponding to the two orthogonal polarizations and PDL of the CLPG. The maximum PDL is 3.0 dB, which indicate that the CLPG has higher polarization dependence.

In our experiments, the sensitivities of CLPG on temperature and SRI are roughly the same amount as that of conventional LPFGs. The sensitivities of the CLPG on torsion, bending and strain are 0.21 nm/(rad/m), 12.62 nm/m^{-1} and 1.75 pm/$\mu\varepsilon$, respectively, which are much higher than that of most LPFGs. The high sensitivity of the CLPG can be attributed to the screw-type waveguide structure of the gratings, which is induced by the scanning CO_2 laser in the twisted SMF.

IV. Conclusion

In summary, a CLPG was fabricated successfully by CO_2 laser in the twisted conventional SMF. The grating has a strong coupling strength and its sensing characteristics of torsion, bending, strain, temperature and SRI were investigated experimentally. The proposed CLPG is found to have great potential applications as filter and sensors.

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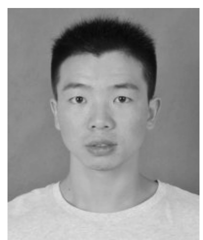

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