Spectral characterization of helicoidal long-period fiber gratings in photonic crystal fibers

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Abstract

We report a new helicoidal long-period grating by twisting a photonic crystal fiber under CO2 laser irradiation and experimentally investigated its novel transmission characteristics. The fabricated helicoidal PCF-LPG has a relatively short length of ~1.4 cm with a low polarization dependent loss less than 1 dB and thermal shift of ~3.7 pm/°C. The proposed device endows the unique resonant peaks tuning capability more than ~18 nm by applying torsion stress, which has not been achieved in prior PCF-LPGs. From these novel thermo-optic and photo-mechanical properties, the proposed device can be applied for various components, including optical filters, attenuators, and sensors.

1. Introduction

Optical fiber long-period gratings (LPGs) consist of periodic perturbations with a pitch of hundreds of micrometer in the core region of a single mode optical fiber (SMF) [1]. The primary effect of a LPG is to couple light from the core to various cladding modes at certain resonant wavelengths. The coupled light is further leaked into outer jacket during propagating, and series of attenuation bands are developed in the transmission spectrum. Several methods have been developed to fabricate LPGs and the most widely used method is based on UV induced refractive index change in the fiber core. Recently, a new kind of LPG was proposed by homogeneous twisting of a fiber with a non-circular core cross-section [2–5]. The LPGs with helical index structures were also fabricated by rotating the fiber under a continuous single side CO2 laser beam exposure. It was reported that helical LPGs had the relatively lower polarization dependent loss (PDL) along with unique spectral tuning capability by torsional stress [6]. The structurally induced helical LPG based on conventional SMF was proposed and their novel applications were reported by the authors [7,8]. Photonic crystal fibers (PCFs) have been attracted intensive attentions due to their ample potentials in fiber device applications and LPGs based on PCF have been recently reported. It has been shown that LPGs can be produced in non-photosensitive PCF by periodically collapsing the air hole by heat treatment with CO2 laser [9] or by using an electric arc to modify the fiber structure [10]. However, these prior PCF-LPGs could not avoid high polarization dependent loss (PDL) due to inherently non-uniform nature of the induced refractive index perturbation and its fabrication process. The prior PCF-LPGs had a relatively limited mechanical tuning range compared with conventional SMF-LPGs. In this study, we propose a new fabrication technique for helicoidal PCF-LPGs that can provide a low PDL and wide spectral tuning capability by torsional stress, for the first time to the best knowledge of the authors. Novel transmission characteristics of the fabricated helicoidal PCF-LPGs are experimentally investigated.

2. Design and fabrication of helicoidal PCF-LPGs

Compared with conventional LPGs, the proposed LPGs are distinguished in terms of the refractive index modulation in a unique helical structure such as a screw, shown in Fig. 1. The proposed LPGs are based on the periodic eccentricity between the PCF core and the surrounding air-cladding distorted in a helicoidal structure. When a PCF is twisted, its air holes and the central core follow a helical path inside the cladding which produces a significant periodic change in the effective index along the fiber. A helicoidal fiber behaves as a band rejection filter like conventional LPGs and its optical properties are determined by the helicoidal periods.

The spectral property of the proposed helicoidal PCF-LPG is similar to the conventional LPGs and the transmission spectrum of a helicoidal PCF-LPG displays several dips that correspond to coupling between the fundamental core mode and co-propagating cladding modes when the inter-modal beat period equals the propagating pitch that is typically in the range of a few hundred micrometers. Generally, the mode coupling of LPG can be described by four parameters: the effective refractive index of fundamental mode (n_{eff}), the effective refractive index of the ith order cladding mode (n_{cladding}^i), the period of the grating (A_g), and the resonant wavelength of LP_{g}(A_g). The parameters are related to one another by the resonance condition, which is given by...
\[ \lambda_l = (n_{\text{core}} - n_{\text{cladding}}^l) A_g = \Delta n^l A_g, \quad \Delta n^l = n_{\text{core}} - n_{\text{cladding}}^l \]  

where \( \Delta n^l \) is the effective refractive index difference between the fundamental mode and the cladding mode. However, it is known that the resonance wavelength of a helicoidal LPG is proportional to half of the helical pitch: \( \lambda_l = \Delta n^l (A_g/2) \) [6]. The helicoidal structures can be imbedded in PCF by irradiating CO\(_2\) laser beam while PCF is mechanically twisted and traversing at a constant speed along the optical fiber axis [7]. Fabrication setup is composed of two motorized precision rotating fiber holders, a translation stage, a focusing lens and CO\(_2\) laser. Two fiber holders were simultaneously rotated in the opposite directions at a speed of 6.4/\(^\circ/s\). While the fiber rotates, the actuator translates the PCF along its axis with a speed of 8.8 \(\mu/m/s\). The stabilized CO\(_2\) laser beam was focused on the fiber with a 200 mm focal length lens. The laser power was about 10 W and spot beam diameter was 201 \(\mu/m\). In the fabricated helicoidal PCF-LPGs, the helical period was about 567 \(\mu/m\) and the 25 pitches were constructed along the total length about 14 mm. The length of the helicoidal PCF-LPG is significantly shorter than prior LPGs, which can be an important benefit in packaging process and sensor deployment.

3. The characteristics of helicoidal PCF-LPGs

The magnified cross-section image of PCF and the fabricated helicoidal PCF-LPG are shown in Fig. 2a. The fiber used in the experiments was a large mode area photonic crystal fiber (crystal fiber, LMA-10). The PCF had the center to center distance of \(\sim 6.67 \mu/m\) between air holes and an average air hole diameter of \(\sim 1.8 \mu/m\). The holes were arranged in a hexagonal structure and its diameter is 67 \(\mu/m\). The core and outer diameter were about 10.4 and 124 \(\mu/m\), respectively. In Fig. 2b helically formed periodic structures are clearly shown and the measured helical grating pitch is about 567.01 \(\mu/m\). The cross-section images of fabricated helicoidal PCF-LPG are shown from inset (a) to (c) in Fig. 2b. Inset (a)–(c) of Fig. 2b is a far-, in-, and near-focused cross-section image of fabricated helicoidal PCF-LPG, respectively. By comparing inset (a)–(c) in Fig. 2b, it can be noted that the hexagonal air hole structure is slightly rotated depending on the focused position.

The spectral response of the fabricated helicoidal PCF-LPG was measured with a stabilized white light source and an optical spectrum analyzer. The measured spectral transmission trace in Fig. 3 was similar to that of a conventional LPG. The resonant wavelengths were observed at 876.3 and 999.99 nm. The corresponding peak depths were –7.3, and –4.73 dB, respectively. In comparison to prior LPGs, the fabricated helicoidal PCF-LPG showed a relatively high insertion loss at shorter wavelength. Because of the axial tensile force in twisting process, the macro-bending effects were imbedded in the fabricated LPG, which accounts for over all slant in the transmission spectra toward the shorter wavelength in Fig. 2 [11].

For the analysis of polarization characteristics, the maximum and minimum losses were measured by use of a polarization controller to scan the state of polarization of the input polarized light at each wavelength. The polarization state of broadband white
light source was controlled by changing angle of waveplates of a polarization controller. The polarized light was launched into the helicoidal PCF-LPG and then the output spectra were measured by an optical spectrum analyzer with 0.2 nm spectral resolution according to the polarization state of input light at each wavelength. The PDL was obtained from the difference between the maximum and minimum losses and the measurement result was plotted in Fig. 3. The fabricated LPG showed a significantly lower PDL value less than \( \pm 1 \) dB in comparison to prior PCF-LPGs which have a high PDL value of 5–24 dB [12,13]. It was also slightly lower than helicoidal SMF-LPGs (\( \pm 1 \) dB) [7,8]. The PDL value was uniform over the whole spectral region of interests, 800–1100 nm which was caused by the azimuthally uniform index modulation in the helicoidal PCF-LPG from the helically surrounded air holes of PCF.

In order to investigate response to external torsion stress, we measured transmission spectra of the helicoidal PCF-LPG under various co-directional or contra-directional rotations. When the external torsional stress is applied along the helix of the helicoidal PCF-LPG, the helical pitch can be effectively reduced or enlarged depending on the rotation direction [14]. As the rotation angle was varied from \(-540^\circ\) to \(540^\circ\) with \(90^\circ\) intervals, the transmission spectra of the LPG were measured and the results are overlaid in Fig. 4a. In the figure, the co-directional rotation made the resonant peaks shift to a shorter wavelength while the peaks shifted to a longer wavelength with the contra-directional rotation. As shown in Fig. 4a, the resonant peaks can be tuned within 18 nm by applying torsional stress on the helicoidal PCF-LPG. The shifts in the spectral locations of the resonant peaks versus the rotation angle are plotted in Fig. 4b. The resonance peak wavelength decreases monotonically and linearly as the rotation angle increases. The spectral shift rate of the first and second peaks near 876.3 and 999.99 nm were estimated as \(-17.45\) and \(-17.23\) pm/ºC, respectively. This novel wavelength tunability by mechanical rotation has not been observed in either prior LPGs or PCF-LPGs. This unique tuning capability of helicoidal PCF-LPG can give potentials in various photonic applications such as optical communication and sensing. In comparison to conventional photorefractive LPGs, the proposed helicoidal PCF-LPG is inherently free from the structural relaxation mechanism at an elevated temperature, which makes the proposed device highly useful for high temperature applications. Temperature dependence of the helicoidal PCF-LPG was characterized in the temperature range of 25–500 ºC by measuring spectral shifts and results are summarized in Fig. 5. It is noted that the spectral shifts are only due to thermo-optical behavior. The transmission peak slightly shifted to the longer wavelength in a monotonic and linear manner and the coefficients of spectral shift were measured to be 2.5–3.7 pm/ºC. This is significantly lower in comparison to conventional photorefractive SMF-LPGs which have a typical temperature dependency of 46–154 pm/ºC [15,16] in the temperature range of 25–250 ºC. In comparison to recent linear PCF-LPGs [17], the thermal shift in the proposed helicoidal PCF-LPG is almost same or less. It is also noted that the full width half maximum (FWHM) of the resonant

![Fig. 4.](image)

**Fig. 4.** (a) The spectral response of fabricated helicoidal PCF-HLPG versus the rotation angle. (b) The spectral shift of the resonant wavelength. The resonant wavelengths and peak depths are 876.3 nm (–7.3 dB) and 999.99 nm (–4.73 dB), respectively.

![Fig. 5.](image)

**Fig. 5.** The shift of the peak wavelength in the helicoidal PCF-LPG in the temperature range of 25–500 ºC. (a) The response of the 1st resonant peak. (b) The response of the 2nd resonant peak.
bands did not vary within experimental measurement error, which also confirm excellent temperature stability of the device. In the temperature range of 25–500 °C, the maximum PDL was measured less than 1 dB over the whole spectral range of interests. Cross-sensitivity in fiber sensors especially between temperature and external mechanical perturbation has been one of core issues in practical sensing applications. Our helicoidal PCF-LPG can provide a fundamental solution to the cross-sensitivity issue between temperature and torsional stress by utilizing its large spectral shift under torsional stress (Fig. 4b) and very small shift in temperature change (Fig. 5).

4. Conclusion

In summary, we successfully fabricated a helicoidal PCF-LPG by twisting a photonic crystal fiber under the CO2 laser irradiation. The propose device was realized with both merit of the helicoidal LPFG and PCF. By introducing the helicoidal structure in PCF, resonant wavelength tunability and low PDL were realized with low temperature dependency originated from the material properties of PCF. The fabricated helicoidal PCF-LPG showed various advantages over prior PCF-LPGs and conventional LPGs in terms of short length of ~1.4 cm, and low PDL less than 1 dB, along with the low thermal shift, and relatively large spectral shift under torsional stress. The temperature dependency of helicoidal PCF-LPG was calculated less than 3.7 pm/°C in the temperature range of 25–500 °C. Under co-directional or contra-directional torsional stress the proposed device shows the resonance wavelength tunability about 17 pm/°C covering 18 nm, which was not achieved in prior PCF-LPGs. From these novel thermo-optic and photo-mechanical properties, we believe that the proposed device can be applied for various components, including optical filters, attenuators, and sensors.

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References