

# Bending and Strain Sensitivities in a Helicoidal Long-Period Fiber Gratings

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**Abstract**—In this letter, we report bending and strain sensitivities of helicoidal long-period fiber gratings fabricated by twisting single-mode fibers during CO<sub>2</sub> laser irradiation. Linear spectral shifts of the resonant wavelengths under the bending and tensile strain were observed with the sensitivities of  $-11.7 \text{ nm/m}^{-1}$  and  $-1.1 \text{ pm}/\mu\epsilon$ , respectively. The corresponding transmission power variations at the resonance wavelength were  $4.1 \text{ dB/m}^{-1}$  and  $2.2 \times 10^{-4} \text{ dB}/\mu\epsilon$ , respectively. Detailed measurement techniques and sensor applications are discussed.

**Index Terms**—Bending sensor, CO<sub>2</sub> laser, fiber sensor, helicoidal long-period fiber gratings (HLPGs), strain sensor.

## I. INTRODUCTION

**F**IBER-OPTIC sensors based on long-period gratings (LPGs) have been intensively developed for various physical measurements [1]. Periodic index modulations along the fiber in LPGs provide the coupling between the core mode and the cladding modes to result in band rejection filters, whose transmission spectra shift in a linear manner by the physical perturbations such as bending and strain.

Depending on the types of optical fibers and the ways to inscribe periodic modulations, the sensing capabilities vary in a relatively wide range. Conventional photorefractive LPGs fabricated by UV irradiation have been applied to bending sensors [2] as well as temperature-strain sensors [3]. Parts of optical fiber cladding can be removed in a periodic behavior to result in corrugated LPGs, and their bending, strain, and torsion sensitivities have been reported [4]. Stress in the core can be locally relieved by focused CO<sub>2</sub> laser beam, and stress-relieved LPGs have been reported as a bending sensor in single-mode fibers (SMFs) [5], [6] and photonic-crystal fibers (PCFs) [7], [8].

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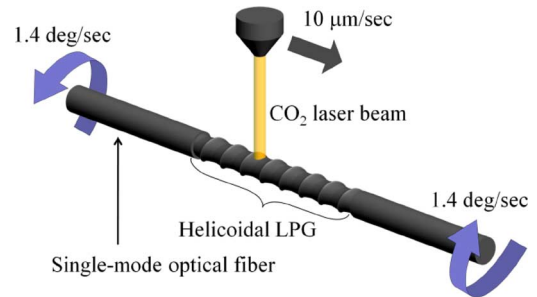


Fig. 1. Schematic fabrication process of helicoidal long-period fiber gratings using CO<sub>2</sub> laser.

Most of the prior LPGs, however, have shown strong dependence on the bending direction due to local anisotropies along the fiber core induced by the grating writing processes. Reduction of bending direction dependence would be highly appreciated in field applications of LPG mechanical sensors.

A new LPG fabrication technique has been proposed by twisting SMF under CO<sub>2</sub> laser irradiation to form helicoidal deformation along the fiber axis [9]. Due to the helical nature of effective index perturbation, helicoidal long-period fiber gratings (HLPGs) have shown remarkably low dependence in bending direction and light polarization. Temperature and torsion dependences on HLPGs have been reported recently [10].

In this letter, we report the bending and strain sensitivities in HLPG, for the first time to the best knowledge of the authors. Spectral shift and power variation of the transmission were characterized in terms of bending and strain perturbations.

## II. EXPERIMENTS AND RESULTS

### A. Helicoidal LPGs Fabrication

HLPGs were fabricated by twisting standard SMF (Corning SMF-28) under CO<sub>2</sub> laser irradiation, and detailed experimental procedures are described elsewhere [10]. Helical period was  $1300 \mu\text{m}$  and twisting rate was  $1.4^\circ/\text{s}$  at both fiber ends to result in the total twisting rate of  $2.8^\circ/\text{s}$ . The helical periodic structure was formed by twisting and moving a fiber at constant transverse speed of  $10 \mu\text{m}/\text{s}$  under CO<sub>2</sub> laser irradiation. When the CO<sub>2</sub> laser beam passes through, the fiber rapidly cools down to shape both core and cladding into helical structure, as shown in Fig. 1.

The resonant wavelengths  $\lambda^i$  can be expressed as

$$\lambda^i = [n_{\text{core}}(\lambda) - n_{\text{clad}}^i(\lambda)] \Lambda \quad (1)$$

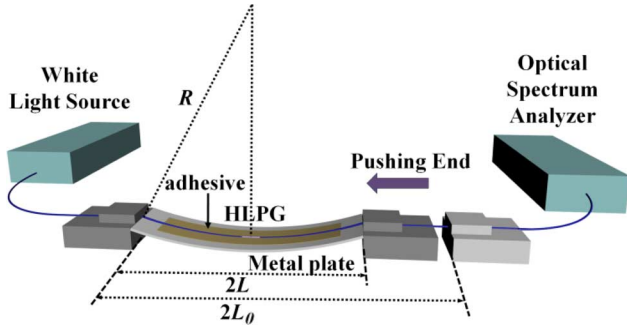


Fig. 2. Experimental setup for two points bending system.

where  $n_{core}(\lambda)$  and  $n_{clad}^i(\lambda)$  are the effective indices of the fundamental core mode and the  $i$ th cladding mode, respectively, and  $\Lambda$  is the grating pitch.

In this investigation, the HPLG was fabricated with maximum band rejection efficiency of 13 dB near 1586 nm measured in the straight fiber without any tension.

**B. Experimental Setup**

In order to measure exact bending radius that requires precise estimation in bending sensitivity, a metal plate was inserted between fiber holders, as shown in Fig. 2 [2], [8]. The sample fiber containing HPLG was attached to the plate with an adhesive. The initial fiber length without bending is  $2L_0$ , which was 88 mm in this study, and the length under the bending reduced to  $2L$ . By pushing one of the two supports, the distance between the supports,  $2L$ , consequently decreases and the plate is deformed with a curvature radius of  $R$ .

The bending radius  $R$  is expressed in (2). By expanding the cosine term up to the fourth order of Taylor series, the curvature could be expressed only in terms of  $L_0$  and  $L$ , as in (3), with a high experimental accuracy

$$R^2 = R^2 \cos^2(L_0/R) + L^2 \tag{2}$$

$$C = \frac{1}{R} \approx \frac{\sqrt{3(L_0^2 - L^2)}}{L_0^2} \tag{3}$$

The axial strain sensitivity was also measured in a similar setup. The strain can be expressed as  $\Delta L/L_0(\epsilon)$ , where  $L_0$  was 10 cm and  $\Delta L$  was within 1 mm in this study.

**C. Results**

The HPLG transmission spectra were measured for various bending curvatures, and the results are summarized in Fig. 3. The primary peak resonance was located at 1586 nm, and the peak shifted to a shorter wavelength with increasing bending curvatures up to  $5 \text{ m}^{-1}$ . The transmission spectra in Fig. 3 were further analyzed for applications in: 1) a spectrum-based sensor tracing the resonant peak positions and 2) an intensity-based sensor monitoring the transmission power at a fixed wavelength, as indicated by horizontal and vertical arrows, respectively, in Fig. 3.

The resonant peak shift measured from (a) in Fig. 3 is summarized as Fig. 4(a), which shows a linear slope of  $-11.7 \text{ nm/m}^{-1}$  in the curvature range from 2.5 to  $5 \text{ m}^{-1}$ . The transmission power change at 1586 nm, from (b) in Fig. 3, is plotted as Fig. 4(b), which shows a linear incline of  $4.1 \text{ dB/m}^{-1}$ .

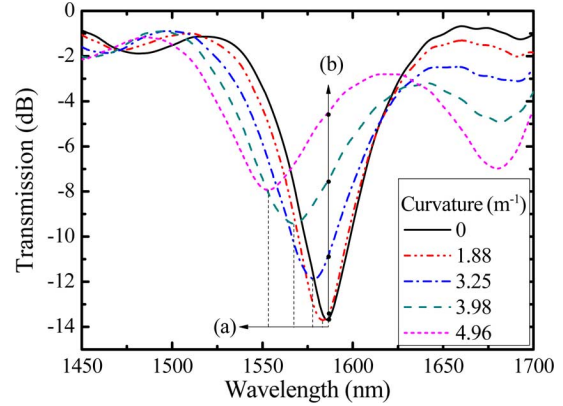


Fig. 3. Transmission spectra of HPLG for various bending curvatures. (a) Resonant peak wavelength shift toward a shorter wavelength. (b) Transmission power variation at the first resonance position of 1586 nm.

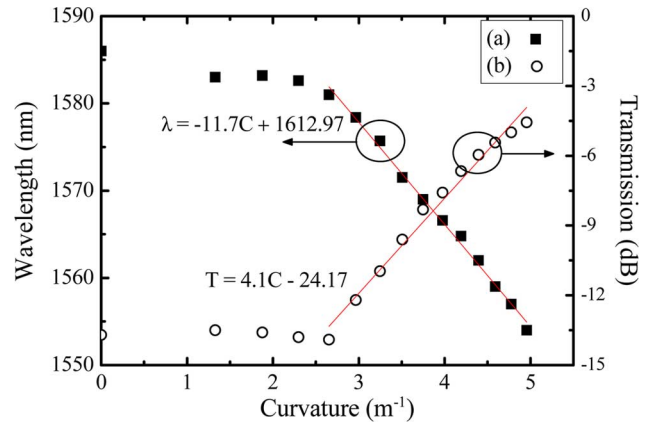


Fig. 4. (a) Resonant peak wavelength shift. (b) Transmission power change at the original resonant wavelength 1586 nm as a function of bending curvatures. The corresponding data were taken from the measurement points along the arrows (a) and (b) in Fig. 3 .

In a similar setup, we measured the transmission spectra for various strains in the range of 0–8000  $\mu\epsilon$ . Fig. 5 shows the spectral shifts of the strain, where the resonant wavelength moves to the shorter region. In contrast to bending, the strain did not significantly change the maximum band rejection efficiency. The linear fitting results of the spectral shift and corresponding power variation at initial resonant wavelength as a function of bending curvature are plotted in Fig. 6. The wavelength shift rate was  $-1.1 \text{ pm}/\mu\epsilon$  and the increasing rate of the transmission power was  $2.2 \times 10^{-4} \text{ dB}/\mu\epsilon$ .

The polarization-dependent loss (PDL) was also measured at the peak resonant wavelength at each curvature. The PDL of the device slightly varied from 0.1 to 0.8 dB in the bending curvature range from 0 to  $5 \text{ m}^{-1}$ . In prior LPGs in [5], the PDL without bending was less than 0.5 dB, and we could confirm that our proposed device shows better or equivalent performance in PDL.

The spectral shift caused by temperature changes has been reported in [10], and its slope was  $0.053 \text{ nm}/^\circ\text{C}$ .

In Table I, we compared the aforementioned HPLG with previous LPGs. HPLG showed almost same temperature-dependent spectral shift as other SMF-based LPGs. The bending

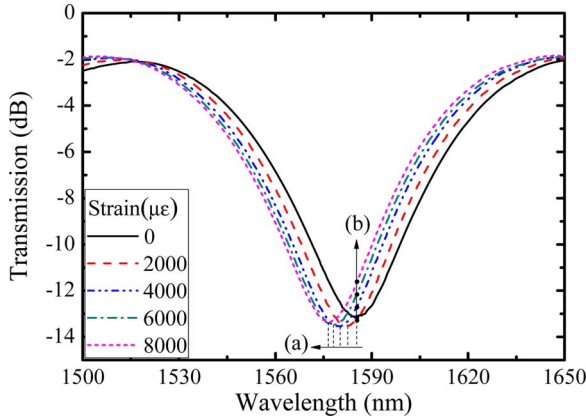


Fig. 5. Transmission spectral changes under various strain levels. (a) Resonant peak wavelength shift. (b) Transmission power variation at the early resonant position of 1586 nm.

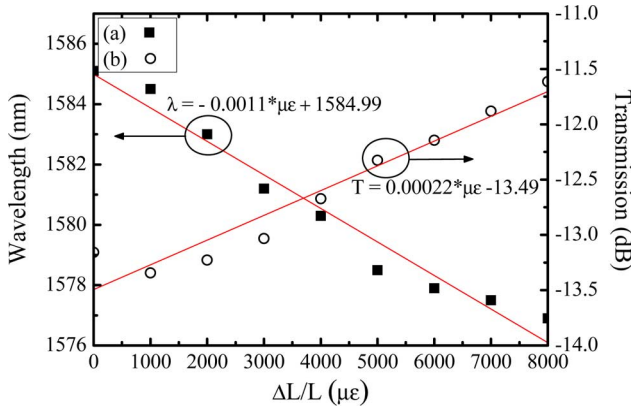


Fig. 6. (a) Resonant peak wavelength shift. (b) Transmission power variation at the primary resonant wavelength 1586 nm as a function of the applied strain. The corresponding data were taken from the measurement points along the arrows (a) and (b) in Fig. 5.

TABLE I  
BENDING, STRAIN, AND TEMPERATURE SENSITIVITIES

Types of LPG	Bending	Strain	Temperature
Helicoidal LPG	-11.7 nm/m <sup>-1</sup> 4.1 dB/m <sup>-1</sup>	-1.1 × 10 <sup>-3</sup> nm/με 2.2 × 10 <sup>-4</sup> dB/με	0.053 nm/°C [10]
UV induced LPG [2]	5 nm/m <sup>-1</sup>	-1.5 × 10 <sup>-4</sup> nm/με	0.054 nm/°C
Corrugated LPG [4]	-18.48 nm/m <sup>-1</sup>	-5.75 × 10 <sup>-3</sup> /με <sup>a</sup>	0.05 nm/°C
CO <sub>2</sub> laser used with SMF LPG [5]	-7 nm/m <sup>-1</sup>	-4 × 10 <sup>-4</sup> nm/με	0.058 nm/°C
CO <sub>2</sub> laser used with PCF <sup>b</sup> LPG [7]	16.4 nm/m <sup>-1</sup>	-9.5 × 10 <sup>-4</sup> nm/με	0.009 nm/°C

<sup>a</sup>This unit means the ratio of the transmission power with the microstrain.

<sup>b</sup>PCF is the photonic-crystal optical fiber.

and strain sensitivities of HLPG belonged to higher sensitivity group.

Despite of high sensitivities, the corrugated LPGs could suffer from mechanical reliability problems, and PCF would be an economic burden. Furthermore, prior LPGs were fabricated by side illumination of grating writing lasers, and they have inherent directional dependence with respect to the illuminated

side in the bending responses. In comparison to side-illuminated LPGs, HLPG is fabricated by rotating SMF during laser illumination, which removes the anisotropy in the periodic structure. We did measure the directional dependence in the bending, but the experimental data equivalent to Figs. 3–6 did not show any perceptible changes within experimental errors. Therefore, the proposed conventional SMF-based HLPG would provide substantial advantages over prior LPGs in robust structure, cost effectiveness, and high-temperature-viable fiber optic sensing capability along with low PDL and bending direction dependence.

### III. CONCLUSION

We characterized the bending and strain sensitivities of HLPGs fabricated by twisting SMF during CO<sub>2</sub> laser irradiation in terms of both spectral shift and transmission power variation. For the bending curvature up to 5 m<sup>-1</sup>, the resonant peak shift showed a linear slope of -11.7 nm/m<sup>-1</sup>, and transmission power change at the initial peak position of 1586 nm also showed a linear incline of 4.1 dB/m<sup>-1</sup>. In the strain sensitivity, the resonant wavelength shift showed -1.1 pm/με, and the transmission power changing rate was 2.2 × 10<sup>-4</sup> dB/με at 1586 nm. Bending the fiber up to 5 m<sup>-1</sup>, the polarization-dependent loss was kept below 0.8 dB. These experimental results showed better or equivalent sensing performance than prior LPGs, which confirms high potential of HLPGs in robust mechanical fiber-optic sensor applications.

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