Highly sensitive long-period fiber-grating strain sensor with low temperature sensitivity

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A long-period fiber-grating sensor with a high strain sensitivity of $-7.6\,\text{pm}/\mu\varepsilon$ and a low temperature sensitivity of $3.91\,\text{pm}/°\text{C}$ is fabricated by use of focused CO_2 laser beam to carve periodic grooves on a large-mode-area photonic crystal fiber. Such a strain sensor can effectively reduce the cross-sensitivity between strain and temperature, and the temperature-induced strain error obtained is only $0.5\,\mu\varepsilon/°\text{C}$ without using temperature compensation. © 2006 Optical Society of America

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During application of long-period fiber-grating (LPFG) strain sensors, one of the main difficulties is the cross sensitivity between the strain and the temperature.[1,2] The common methods for cross-sensitivity reduction are using temperature compensation and simultaneous strain and temperature measurement.[1–3] By use of CO_2 laser radiation, a LPFG with a strain sensitivity of $-0.45\,\text{pm}/\mu\varepsilon$ and a temperature sensitivity of $58\,\text{pm}/°\text{C}$ was written in Corning SMF-28 fiber,[3] and another LPFG with a strain sensitivity of $-0.19\,\text{pm}/\mu\varepsilon$ and a temperature sensitivity of $10.9\,\text{pm}/°\text{C}$ was inscribed in a photonic crystal fiber (PCF).[4] In this Letter, we present a LPFG sensor with a high strain sensitivity and a low temperature sensitivity. Such a LPFG is fabricated by use of focused CO_2 laser beam to carve periodic grooves on a large-mode-area (LMA) PCF and can effectively reduce the cross sensitivity between strain and temperature without using temperature compensation.

As shown in Fig. 1, a CO_2 laser (SYNRAD 48-1) with a maximum output power of 10 W was employed. A broadband light source and an optical spectrum analyzer (HP 70004A) were used to observe the transmission spectrum evolution of LPFG. A LMA-10 PCF was situated at the focal plane of the CO_2 laser beam, with one of the fiber ends fixed. A small weight of ~5 g at the free end of the fiber was employed to avoid the weight-induced macrobend of the fiber and to provide a tensile strain in the fiber. The focused CO_2 laser beam can scan the fiber via a computer-controlled 2D optical scanner. Figure 2(a) illustrates the cross section of the PCF employed. The PCF has a center-to-center distance between the air holes of $\Lambda = 6.1\,\mu\text{m}$ and an average air-hole diameter of $d = 1.8\,\mu\text{m}$. The holes are arranged in a hexagonal pattern, which has a diameter of 65 μm. The core diameter $D_{co} = \Lambda(2 - d/\Lambda) = 10.4\,\mu\text{m}$, and the outer diameter of the PCF is 125 μm.

As shown in Fig. 1, the focused CO_2 laser beam scans repeatedly for M times along the X direction at the location corresponding to the first grating period of the fiber. Then the laser beam is shifted by a grating pitch along the Y direction and scans repeatedly again M times to generate the next grating period. This scanning and shifting process is carried out periodically N times (N is the number of grating periods) along the fiber's axis until the final grating period is produced. The above process may be repeated for K cycles from the first grating period to the final grating period until the high-quality LPFG is produced. The repeated scanning of the focused CO_2 laser beam creates a local high temperature in the fiber, which leads to the gasification of SiO_2 on the surface of the fiber. As a result, periodic grooves with a depth of ~15 μm and a width of ~50 μm are carved on the fiber, as shown in Fig. 2(b). Such grooves can induce periodic refractive index modulations along the fiber axis due to the photoelastic effect, thus creating a LPFG. The groove's depth, which indicates the efficiency of CO_2 laser heating and the refractive index modulation, depends on the fabrication parameters. In our experiments, the diameter of the focused CO_2 laser beam spot is ~35 μm, the line speed of laser beam scanning on the fiber is 2.326 mm/s, the pulse repetition rate is 10 kHz, the pulse width is 4.1 μs, and average output power of the CO_2 laser is ~0.5 W.

As shown in Fig. 3, a high-quality LPFG, i.e., $LPFG_1$, with asymmetric periodic grooves, a low in-

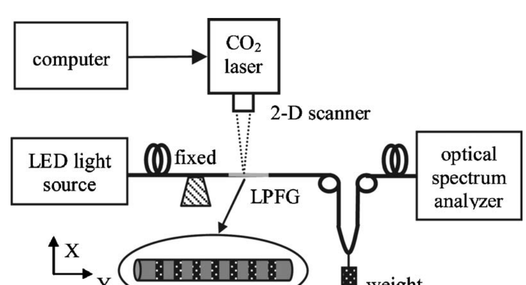

Fig. 1. Experimental setup for LPFG fabrication.

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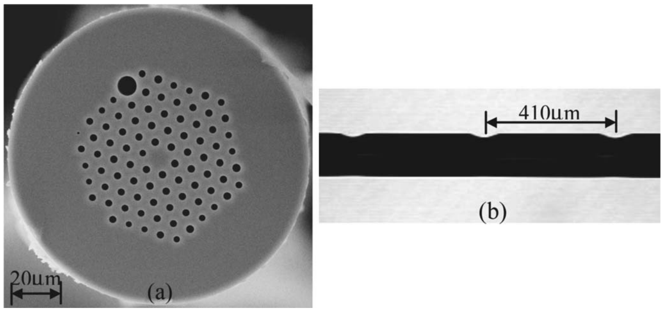

Fig. 2. (a) Scanning electron micrograph of the cross section of the PCF employed. (b) CCD photograph of the LPFG with periodic grooves, obtained via a fiber fusion splicer from ERICSSON.

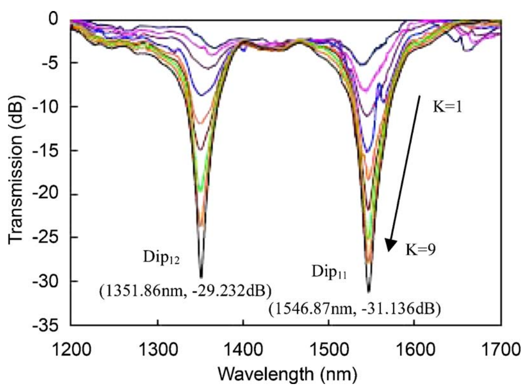

Fig. 3. (Color online) Transmission spectra evolution of the LPFG with the number, K, of scanning cycles increased from 1 to 9, where $N=40$ and $M=5$.

sertion loss of ~2 dB, and two attenuation dips (Dip_{11} and Dip_{12}) is produced after nine scanning cycles, where the resonant wavelengths and the peak transmission attenuations of Dip_{11} and Dip_{12} are $\lambda_{11} = 1546.87$ nm, $A_{11} = -31.136$ dB, $\lambda_{12} = 1351.86$ nm, and $A_{12} = -29.232$ dB, respectively. To observe the difference between the strain characteristics of the LPFGs with and without periodic grooves, another LPFG without periodic grooves, i.e., $LPFG_2$, was written in the same type PCF by decreasing the power of the CO_2 laser and the number of scanning times. The insertion loss of 1.5 dB and two attenuation dips (Dip_{21} and Dip_{22}) were observed in the transmission spectrum of $LPFG_2$, and the resonant wavelengths and the peak transmission attenuations of Dip_{21} and Dip_{22} are $\lambda_{21} = 1548.38$ nm, $A_{21} = -27.142$ dB, $\lambda_{22} = 1352.85$ nm, and $A_{22} = -26.084$ dB, respectively. The grating pitch of both $LPFG_1$ and $LPFG_2$ is 410 μm.

No grooves were observed in the LPFGs fabricated by Zhu *et al.*[5] in the same type of PCF and by Rao *et al.*[3] in standard single-mode fiber. During our LPFG fabrication, however, periodic grooves were carved intentionally on the fiber, as shown in Fig. 2(b). Such periodic grooves have essentially no contribution to the LPFG's insertion loss, which is similar to the case of the corrugated LPFG fabricated by hydrofluoric acid etching.[6] This is because these grooves are totally confined within the outer cladding and have no influence on the light transmission in the core of the fiber. The insertion loss of the LPFG written in the PCF is mainly due to the CO_2-laser-induced collapse of air holes and the nonperiodicity and disorder of the refractive index modulation. During Zhu's[5] fabrication, the CO_2 laser beam was focused to a larger light spot with a diameter of ~180 μm, and the fiber is moved by adjusting a transmission stage, which leads to the difficulty of focusing the laser beam at the desired location of the fiber. As a result, the insertion loss, i.e., ~2 dB, of our LPFGs is much smaller than that, i.e., ~16 dB, of the LPFG written by Zhu *et al.*[5] in the same type of PCF.

When an optical fiber with an asymmetric structure, e.g., periodic grooves on one side of the fiber, is stretched longitudinally, small lateral bends, i.e., periodic microbends, will be induced in the grooved section of the fiber.[7] Thus periodic microbends can be observed when the CO_2-laser-carved LPFG with asymmetric grooves is stretched, as shown in Fig. 4. The refractive index modulation in the CO_2-laser-carved LPFG that is stretched can be expressed as

$$\Delta n = \Delta n_{\text{residual}} + \Delta n_{\text{groove}} + \Delta n_{\text{stretch}}, \tag{1}$$

where $\Delta n_{\text{residual}}$ is the initial refractive index perturbation induced by the residual stress relaxation resulting from the high local temperature, which is similar to the case of the CO_2-laser-induced LPFGs without periodic grooves[3,5]; Δn_{groove} is the initial refractive index perturbation induced by the periodic grooves on the fiber, which is similar to $\Delta n_{\text{corrugated}}$ in the corrugated LPFGs fabricated by hydrofluoric acid etching[6]; $\Delta n_{\text{stretch}}$ is the refractive index perturbation induced by the stretching force and can be expressed as

$$\Delta n_{\text{stretch}} = \Delta n_{\text{strain}} + \Delta n_{\text{microbend}}, \tag{2}$$

where Δn_{strain} is the refractive index perturbation induced by the difference between the stretch-induced tensile strains in the grooved and ungrooved regions via the photoelastic effect[6,7]; $\Delta n_{\text{microbend}}$ is the refractive index perturbation induced by the stretch-induced microbends in the CO_2-laser-carved LPFGs with asymmetric grooves.[7,8] Such stretch-induced microbends effectively enhance refractive index modulation in the CO_2-laser-carved LPFGs, which is similar to the case of the microbend-induced LPFG reported.[8] The amplitude of microbends depends strongly on the stretching force applied and the groove parameters such as the depth and width of

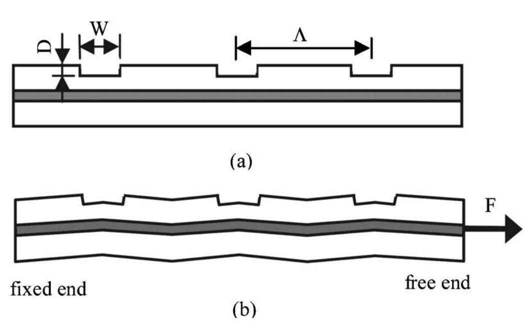

Fig. 4. Schematic of the CO_2-laser-carved LPFG (a) before and (b) after a stretching force, F, is applied, where Λ, D, and W are the grating pitch, the depth, and width of the grooves, respectively.

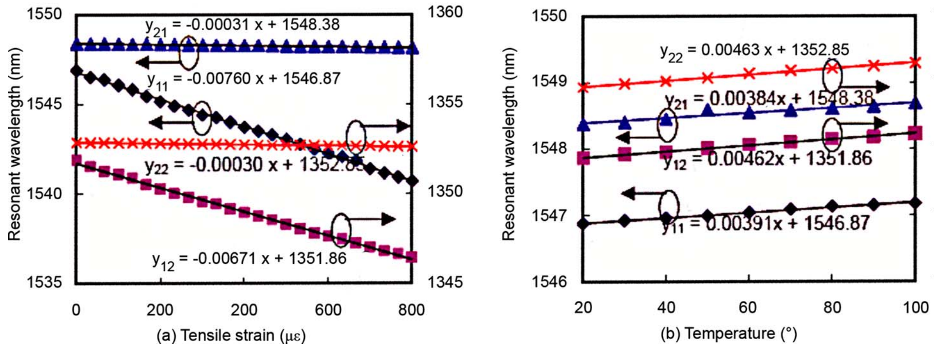

Fig. 5. (Color online) Resonant wavelength of $LPFG_1$ and $LPFG_2$ via (a) the tensile strain and (b) the temperature. ♦, Dip_{11} of $LPFG_1$; ■, Dip_{12} of $LPFG_1$; ▲, Dip_{21} of $LPFG_2$; ×, Dip_{22} of $LPFG_2$.

the groove, the grating pitch, and the critical periodicity of the fiber.[7] Therefore the refractive index modulation efficiency in the CO_2-laser-carved LPFG is higher than that in the CO_2-laser-induced LPFG without periodic grooves.

With the stretching force applied, the curvature of the stretch-induced microbends and the stretch-induced tensile strain difference between the grooved and the ungrooved regions increase, which leads to the increase of Δn_{strain} and $\Delta n_{\text{microbend}}$. As shown in Fig. 5(a), with the increase of the tensile strain, the resonant wavelengths of $LPFG_1$ with periodic grooves shift rapidly toward the shorter wavelength and a good linearity is observed, whereas that of $LPFG_2$ without periodic grooves shifts slowly toward the shorter wavelength. The strain sensitivities of the resonant wavelengths for Dip_{11}, Dip_{12}, Dip_{21}, and Dip_{22} are −7.60, −6.71, −0.31, and −0.30 pm/$\mu\varepsilon$, respectively. It is obvious that the strain sensitivity of resonant wavelength, e.g., Dip_{11} and Dip_{21}, of the LPFGs written by CO_2 laser in the same fiber (the LMA PCF) is increased by 25 times by means of carving periodic grooves on one side of the fiber. The strain sensitivity of our LPFG is much higher than that of other CO_2-laser-induced LPFGs without periodic grooves.[3,4] The resonant wavelengths of the corrugated LPFG with symmetric grooves is insensitive to the tensile strain,[6] which is because no periodic microbend is induced in the LPFG with symmetric grooves. Therefore asymmetric grooves, instead of symmetric grooves, should be created in order to increase the strain sensitivity of the LPFGs fabricated, and the strain sensitivity of the LPFG depends strongly on the depth and width of the grooves, as can be seen in Ref. 7.

As shown in Fig. 5(b), both resonant wavelength and peak transmission attenuation of $LPFG_1$ and $LPFG_2$ hardly change when the temperature increases from 20°C to 100°C. The temperature sensitivities of resonant wavelengths for Dip_{11}, Dip_{12}, Dip_{21}, and Dip_{22} are only 3.91, 4.62, 3.84, and 4.63 pm/°C, respectively. Thus, compared with the temperature sensitivity of the LPFG written in standard single-mode fiber,[3] e.g., 58 pm/°C, the resonant wavelength of our LPFGs written by CO_2 laser in the large-mode-area PCF is insensitive to the temperature, and the periodic grooves have no influence on temperature sensitivity. The reduction of the temperature sensitivity of the LPFGs obtained is due to the air-hole structure of the pure silica PCF. According to the strain and temperature sensitivity of the resonant wavelength for Dip_{11}, the temperature-induced strain measurement error is only 0.5 $\mu\varepsilon$/°C without using temperature compensation. Therefore our LPFG strain sensors can effectively reduce the cross sensitivity between strain and temperature.

In conclusion, an LPFG strain sensor with a high strain sensitivity of −7.6 pm/$\mu\varepsilon$ was achieved, and the temperature-induced strain measurement error is only 0.5 $\mu\varepsilon$/°C in the case of no temperature compensation. Such an LPFG is fabricated by use of focused CO_2 laser beam to carve periodic grooves on a large-mode-area PCF, and the strain sensitivity of the LPFG obtained is increased by 25 times compared with that of the LPFG without periodic grooves.

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References

1. V. Bhatia, D. K. Campbell, D. Sherr, T. G. DAlberto, N. A. Zabaronick, G. A. TenEyck, K. A. Murphy, and R. O. Claus, Opt. Eng. **36**, 1872 (1997).
2. Y. P. Wang, Y. J. Rao, Z. L. Ran, T. Zhu, and A. Z. Hu, IEEE Photon. Technol. Lett. **15**, 251 (2003).
3. Y. J. Rao, Y. P. Wang, Z. L. Ran, and T. Zhu, J. Lightwave Technol. **21**, 1320 (2003).
4. Y. Zhu, P. Shum, H. W. Bay, M. Yan, X. Yu, and J. Hu, Opt. Lett. **30**, 367 (2005).
5. Y. Zhu, P. Shum, J. H. Chong, M. K. Rao, and C. Lu, Opt. Lett. **28**, 2467 (2003).
6. C. Y. Lin, L. A. Wang, and G. W. Chern, J. Lightwave Technol. **19**, 1159 (2001).
7. M. Vaziri and C. L. Chen, Appl. Opt. **32**, 6399 (1993).
8. C. H. Lin, Q. Li, A. A. Au, Y. Jiang, E. B. Wu, and H. P. Lee, J. Lightwave Technol. **22**, 1818 (2004).