In-fiber polarizer based on a long-period fiber grating written on photonic crystal fiber

Yiping Wang

Department of Electrical Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong, China, and State Key Lab of Advanced Optical Communication Systems and Networks, Shanghai Jiao Tong University, Shanghai 200240, China

Limin Xiao, D. N. Wang, and Wei Jin

Department of Electrical Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong, China

Received November 9, 2006; revised January 13, 2007; accepted January 26, 2007;
posted February 2, 2007 (Doc. ID 76941); published April 3, 2007

A novel in-fiber polarizer based on a long-period fiber grating (LPFG) is written by using a focused CO_2 laser beam to notch a photonic crystal fiber periodically. Such a polarizer exhibits a high polarization extinction ratio of more than 20 dB over a wide wavelength range of ~11 nm near 1550 nm and a very low temperature sensitivity of 3.9 pm/°C, which overcomes the disadvantages of the temperature sensitivity of other in-fiber polarizers created on conventional single-mode fiber.

OCIS codes: 050.2770, 060.2340, 060.4510, 060.2420.

Polarizers and other polarization-related devices are very important in the field of optical fiber communications and sensors. Compared with bulk waveguide polarizers, in-fiber polarizers are desirable devices in all-fiber communication systems because of their low insertion loss and compatibility with optical fiber. Optical fiber polarizers are usually made by polishing the fiber laterally and coating a birefringence crystal[1] or a metal film[2] on the exposed guiding region. Zhou *et al.*[3] reported a 45°C tilted in-fiber polarizer based on fiber Bragg gratings (FBGs). However, the high temperature sensitivity of the polarizer created in conventional single-mode fiber is a disadvantage for its application in optical fiber communications. Clear polarization dependence has been observed in CO_2-laser-induced long-period fiber gratings (LPFGs) due to their asymmetric refractive index profile within the cross section of these gratings.[4–6] Some of us recently reported a novel LPFG fabrication technique based on using a focused CO_2 laser beam to notch a conventional single-mode fiber periodically.[7] Such a technique can write high-quality LPFGs with a low insertion loss and high polarization-dependent loss (PDL).

In this Letter we present an in-fiber polarizer based on the LPFG fabricated by use of a focused CO_2 laser beam to notch a photonic crystal fiber (PCF) periodically. This LPFG polarizer exhibits a high polarization extinction ratio of more than 20 dB over a wide wavelength range of ~11 nm and a low temperature sensitivity of 3.9 pm/°C.

An experimental setup, as shown in Fig. 1 of Ref. 7, was employed to write LPFGs by use of the focused CO_2 laser beam to notch the PCF periodically. A large-mode-area (LMA-10) PCF from BlazePhotonics[8] was employed and situated on the focal plane of the CO_2 laser beam. The cross section of the PCF with a cladding diameter of 124 ± 1 μm and a core diameter of 11 ± 1 μm is illustrated in Fig. 1(a). Following the LPFG fabrication process reported in Ref. 7, the focused CO_2 laser beam scanned repeatedly and periodically at the location corresponding to each grating period of the PCF via a two-dimensional optical scanner under computer control. Focused high-frequency CO_2 laser pulses with enough energy hit repeatedly the side of the PCF. Such repeated hitting induces a local high temperature in the fiber, which not only collapses air holes in the outer cladding of the PCF but actually ablates some of the glass from the side of the fiber. As a result, as shown in Fig. 1, periodic notches with a depth

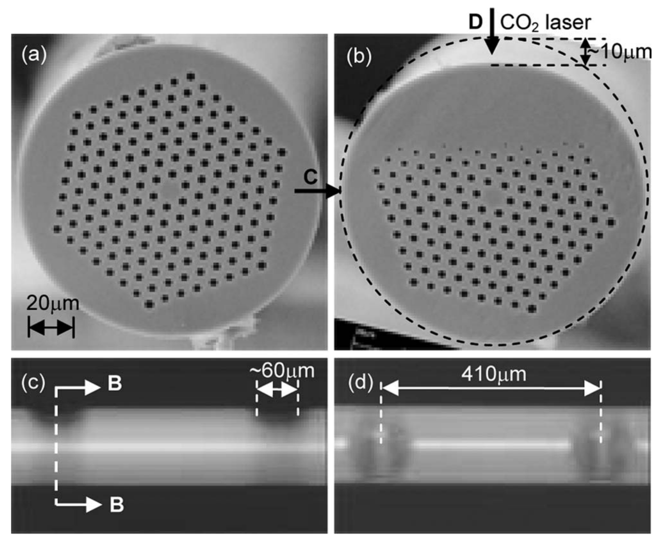

Fig. 1. Scanning electron micrographs for the cross sections of the PCF employed (a) before and (b) after CO_2 laser irradiation, where the PCF is cut off at the $B-B$ plane; (c), (d) micrographs, observed from the C and D directions, respectively, with a microscope image (IM 713, Atto Instruments Ltd.), of the PCF with periodic notches (the CO_2-laser-notched LPFG). The CO_2 laser irradiates from the D direction, and the dashed circle in (b) outlines the cross section of the PCF before the CO_2 laser irradiation. The grating pitch of the LPFG with 40 grating periods is 410 μm.

0146-9592/07/091035-3/$15.00

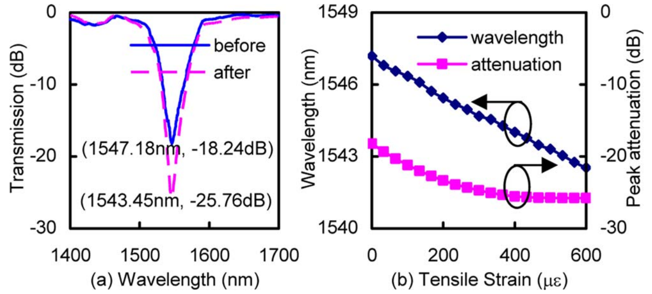

Fig. 2. (Color online) (a) Transmission spectra of the CO_2-laser-notched LPFG before and after a stretch strain of 500 $\mu\epsilon$ is applied; (b) resonant wavelength and peak transmission attenuation of the LPFG as function of the stretch strain.

of ~10 μm and a width of ~60 μm were created on the fiber surface along the axis of the PCF due to the ablation of glass and the collapse of air holes. Such notches induce periodic refractive index modulation along the axis of the PCF, thus creating a LPFG. The real curve in Fig. 2(a) illustrates the transmission spectrum of the obtained LPFG with a resonant wavelength of 1547.18 nm, a peak transmission attenuation of −18.24 dB, and a low insertion loss of ~1 dB.

Refractive index modulation in the CO_2-laser-notched LPFG in the strain-free state may be expressed as[7]

$$\Delta n = \Delta n_{\text{residual}} + \Delta n_{\text{notch}}, \quad (1)$$

where $\Delta n_{\text{residual}}$ is a refractive index perturbation induced by the residual stress relaxation resulting from the local high temperature, which is similar to the case of CO_2-laser-induced LPFGs without periodic notches[4–6]; Δn_{notch} is a refractive index perturbation induced by the notches due to the photoelastic effect and its results; Δn_{notch} results essentially from the new stress field induced by the ablation of glass and the collapse of air holes near the notched regions. It can be seen from Fig. 1(b) that, although the outer four ring air holes in the cladding, facing the CO_2 laser irradiation, collapsed, the air holes near the core are not affected. The mode field diameter of the PCF employed is ~8.5 μm.[8] Thus the insertion loss of our LPFG is only ~1 dB because most of the energy of the input light is transmitted in the core and the inner cladding of the PCF.

When a tensile stain was applied to the LPFG, the resonant wavelength was linearly shifted toward the short wavelength with a sensitivity of −7.6 pm/$\mu\epsilon$, and the absolute value of the peak transmission attenuation was gradually increased, as shown in Fig. 2(b). The peak transmission attenuation was hardly changed with an increase of the tensile stain of more than 500 $\mu\epsilon$. The dashed curve in Fig. 2(a) illustrates the transmission spectrum of the LPFG with a tensile strain of 500 $\mu\epsilon$, where the resonant wavelength was shifted to 1543.45 nm and the peak transmission attenuation was increased to −25.76 dB.

The PDL of the CO_2-laser-notched LPFG was measured by an Agilent 81910A photonic all-parameter analyzer. Figure 3 illustrates the maximum loss, the minimum loss, and the PDL of the CO_2-laser-notched LPFG before and after a tensile strain of 500 $\mu\epsilon$ is applied to the LPFG. 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 PDL obtained is the difference between the maximum and minimum losses measured. As shown in Fig. 3(a), after the tensile strain is applied to the LPFG, the maximum loss is observably increased, whereas the minimum loss is hardly changed. Thus the maximum PDL of the LPFG is increased from 16.240 dB at 1543.80 nm to 27.27 dB at 1544.60 nm, as shown in Fig. 3(b).

Figure 4 illustrates the losses, corresponding to the s- and p-polarized input light, and the polarization extinction ratio of the CO_2-laser-notched LPFG before and after a tensile strain of 500 $\mu\epsilon$ is applied to the LPFG. The polarization extinction ratio is an absolute value of the difference between the losses corresponding to the s- and p-polarized input light. As shown in Fig. 4(a), after the tensile strain is applied to the LPFG, the loss of the p-polarized input light is observably increased, whereas that of the s-polarized light is hardly changed. Thus the maximum polarization extinction ratio of the LPFG is increased from 13.72 dB at 1546.65 nm to 22.83 dB at 1548.35 nm after the tensile strain is applied to the LPFG.

Single-side irradiation with the CO_2 laser beam induces an asymmetric index profile within the cross section of the CO_2-laser-notched LPFG on the PCF due to the asymmetric residual stress relaxation, which is similar to the case of the CO_2-laser-induced LPFG without periodic notches in a conventional

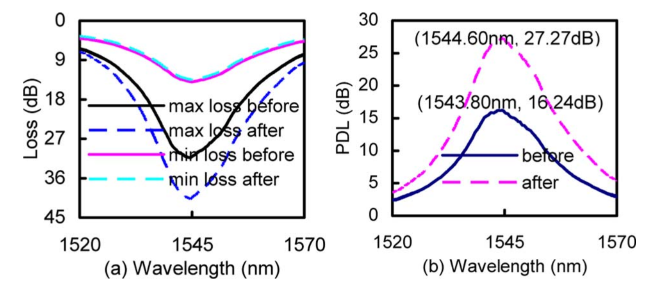

Fig. 3. (Color online) (a) Maximum and minimum losses; (b) PDL of the CO_2-laser-notched LPFG before and after a stretch strain of 500 $\mu\epsilon$ is applied.

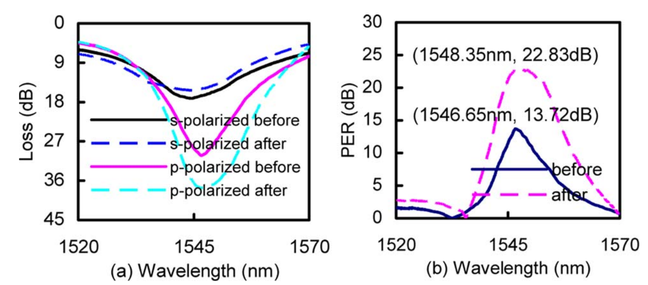

Fig. 4. (Color online) (a) Loss corresponding to s- and p-polarized light; (b) polarization extinction ratio (PER) of the CO_2-laser-notched LPFG before and after a stretch strain of 500 $\mu\epsilon$ is applied.

single-mode fiber.[4,6,7] Furthermore, the ablation of glass and the collapse of air holes in the cladding facing the CO_2 laser irradiation effectively enhance the asymmetry of the index profile within the cross section of the LPFG, which induces a large birefringence in the LPFG. As a result, a high PDL of 16.24 dB and a high polarization extinction ratio of 13.72 dB are observed when the LPFG is in the strain-free state (before stretch strain is applied to the LPFG), as shown in Figs. 3(b) and 4(b), respectively. It is obvious that the maximum PDL of 16.24 dB in the CO_2-laser-notched LPFG on the PCF is much larger than the maximum PDL of ~1.2 dB in the CO_2-laser-induced LPFGs in the conventional single-mode fiber,[6,7] which is because of the collapse of air holes in the PCF.

When a CO_2-laser-notched LPFG on the Corning SFM-28 fiber was stretched longitudinally, as shown in Fig. 6 in Ref. 7, wrinkles, i.e., periodic microbends, were induced in the notched section of the fiber due to asymmetric notches. The same phenomenon was also observed when a CO_2-laser-notched LPFG on the PCF was stretched longitudinally. Such wrinkles induce periodic refractive index perturbations in the LPFG, which lead to the transmission spectrum evolution of the LPFG[7,9] as shown in Fig. 2. On the other hand, when the CO_2-laser-notched LPFG is stretched, an asymmetric strain field is induced within the cross section of the notched regions because of the asymmetric structure, which enhances the asymmetry of the index profile within the cross section of the LPFG as a result of the photoelastic effect.[9] Consequently, a higher PDL was observed after our LPFG was stretched longitudinally, as shown in Figs. 3 and 4. It can also be seen from Fig. 4(b) that, after a tensile strain of 500 $\mu\epsilon$ is applied to our LPFG, the polarization extinction ratio is more than 20 dB over a wide wavelength range of ~11 nm near 1550 nm. This indicates that the CO_2-laser-notched LPFG could be used as a promising in-fiber polarizer with a high polarization extinction ratio.

For our in-fiber polarizer based on the CO_2-laser-notched LPFG, the required tensile strain can be applied, in advance, to the LPFG during the packaging of the grating. Thus a compact in-fiber polarizer is obtained after a CO_2-laser-notched LPFG is packaged. Although the maximum loss of ~15 dB for the desired polarization light, e.g., the *s*-polarized light, will be induced when our LPFG polarizer is employed in the communication system, such a loss can be easily compensated by an erbium-doped fiber amplifier.

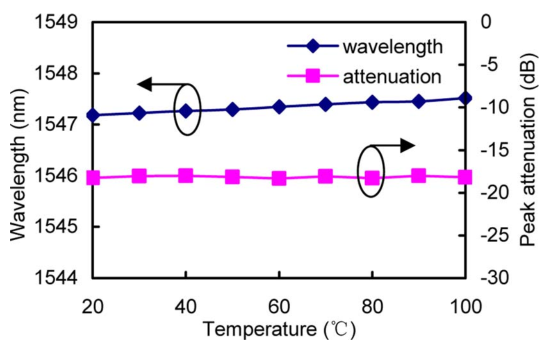

Fig. 5. (Color online) Resonant wavelength and peak transmission attenuation of the CO_2-laser-notched LPFG as function of the temperature.

As shown in Fig. 5, the temperature sensitivity of the resonant wavelength of the CO_2-laser-notched on the PCF is only 3.9 pm/°C, and the peak transmission attenuation is hardly changed with temperature. Compared with the temperature sensitivity, e.g., 58 pm/°C, of other CO_2-laser-induced LPFGs in conventional single-mode fiber,[4,7] the resonant wavelength of the CO_2-laser-notched LPFGs on the PCF is insensitive to temperature, which is due to the air-hole structure of the pure silica PCF.[10] Thus our in-fiber polarizer resolves the temperature sensitivity problem of other in-fiber polarizers fabricated in the conventional single-mode fiber.

In conclusion, a novel LPFG is written by use of a focused CO_2 laser beam to notch a PCF periodically. Clear polarization dependence is observed in the LPFG due to the collapse of air holes. The maximum PDL and the maximum polarization extinction ratio of our LPFG can be increased to 27.27 and 22.83 dB, respectively, by application of tensile strain. Such a CO_2-laser-notched LPFG could be used as a promising in-fiber polarizer with a high polarization extinction ratio of more than 20 dB over a wide wavelength range of ~11 nm near 1550 nm and a very low temperature sensitivity of 3.9 pm/°C.

This work was supported by the research grants of the Hong Kong Polytechnic University in a Postdoctoral Research Fellowship Scheme (G-YX51) and the National Science Foundation of China (60507013). Y. Wang's e-mail is ypwang@china.com; D. N. Wang's, eednwang@polyu.edu.hk; W. Jin's, eewjin@polyu.edu.hl.

References

1. R. A. Bergh, H. C. Lefevre, and H. J. Shaw, Opt. Lett. **5**, 479 (1980).
2. R. B. Dyott, J. Bello, and V. A. Handerek, Opt. Lett. **12**, 287 (1987).
3. K. M. Zhou, G. Simpson, X. F. Chen, L. Zhang, and I. Bennion, Opt. Lett. **30**, 1285 (2005).
4. Y. J. Rao, Y. P. Wang, Z. L. Ran, and T. Zhu, J. Lightwave Technol. **21**, 1320 (2003).
5. Y. P. Wang and Y. J. Rao, IEEE Sens. J. **5**, 839 (2005).
6. H. S. Ryu, Y. Park, S. T. Oh, Y. J. Chung, and D. Y. Kim, Opt. Lett. **28**, 155 (2003).
7. Y.-P. Wang, D. N. Wang, W. Jin, Y.-J. Rao, and G.-D. Peng, Appl. Phys. Lett. **89**, 151105-3 (2005).
8. Large Mode Area Photonic Crystal Fiber (LMA-10) from BlazePhotonics, http://www.blazephotonics.com.
9. Y. P. Wang, W. Jin, and D. N. Wang, IEEE J. Quantum Electron. **43**, 101 (2007).
10. Y. N. Zhu, P. Shum, H. W. Bay, X. Y. Chen, C. H. Tan, and C. Lu, Opt. Lett. **29**, 2608 (2004).