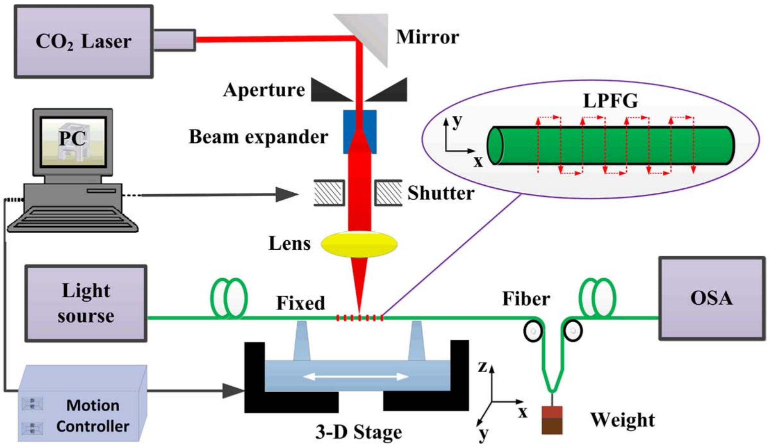
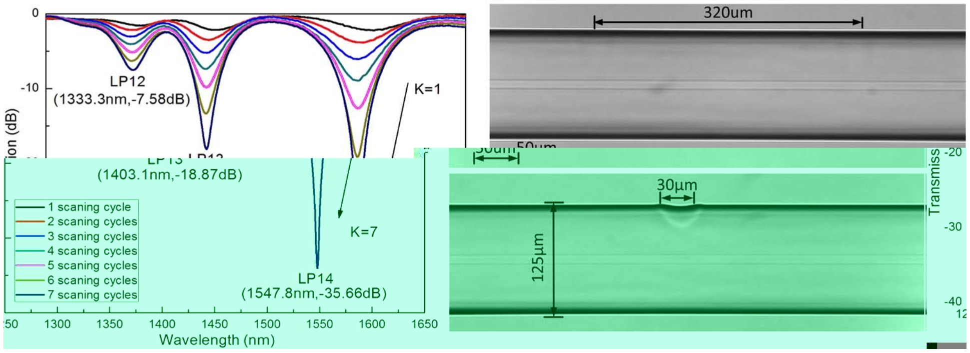
IEEE Photonics Journal
An IEEE Photonics Society Publication

Long Period Fiber Gratings Inscribed With an Improved Two-Dimensional Scanning Technique

Volume 6, Number 4, August 2014

Xiaoyong Zhong
Yiping Wang, Senior Member, IEEE
Changrui Liao
Guolu Yin
Jiangtao Zhou
Guanjun Wang
Bing Sun
Jian Tang





DOI: 10.1109/JPHOT.2014.2337875

Long Period Fiber Gratings Inscribed With an Improved Two-Dimensional Scanning Technique

**Xiaoyong Zhong, Yiping Wang, *Senior Member, IEEE*, Changrui Liao,
Guolu Yin, Jiangtao Zhou, Guanjun Wang, Bing Sun, and Jian Tang**

Key Laboratory of Optoelectronic Devices and Systems of the Ministry of Education and Guangdong
Province, College of Optoelectronic Engineering, Shenzhen University, Shenzhen 518060, China

DOI: 10.1109/JPHOT.2014.2337875

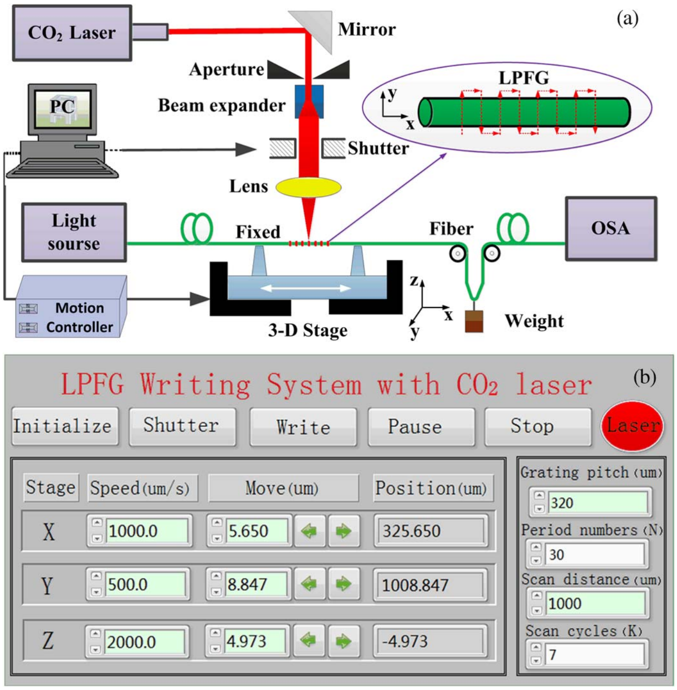
Manuscript received May 23, 2014; revised June 27, 2014; accepted July 1, 2014. Date of publication July 10, 2014; date of current version August 11, 2014. This work was supported in part by the National Science Foundation of China under Grants 61308027, 61377090, and 11174064; by the Science & Technology Innovation Commission of Shenzhen under Grants KQCX20120815161444632 and JCYJ20130329140017262; and by the Distinguished Professors Funding from Shenzhen University and Guangdong Province Pearl River Scholars. Corresponding author: Y. Wang (e-mail: ypwang@szu.edu.cn).

Abstract: We demonstrated a promising CO_2 laser irradiation system based on an improved 2-D scanning technique. Such a system could be used to inscribe high-quality long period fiber gratings (LPFGs) with good reproducibility of grating inscription, which attributes to the fact that our system includes a CO_2 laser with an excellent power stability of less than ±2% and a 3-D ultraprecision motorized translation stages with an excellent bidirectional repeatability value of 80 nm. Moreover, a control program with an easy-to-use operation interface was developed in our system so that a high-quality LPFG could be achieved as soon as grating parameters, such as grating pitch and number of grating periods, are entered, which has a widespread commercial value and prospects for development. Additionally, near mode fields of the CO_2-laser-induced LPFG were observed and simulated to investigate mode coupling in the gratings.

Index Terms: Long period fiber gratings (LPFGs), optical fiber sensors, CO_2 laser 2-D scanning, fiber optics components.

1. Introduction

Long period fiber gratings (LPFGs) have been widely used in the field of optical fiber sensors, communications, and lasers. A few inscription methods, such as UV laser exposure [1], CO_2 laser irradiation [2]–[5], electric arc discharge [6], femtosecond laser exposure [7], [8], mechanical microbends [9], etched corrugations [10], [11], and ion beam implantation [12], [13], have been demonstrated to inscribe LPFGs in different types of optical fibers. Among these methods, the CO_2 laser irradiation method is particularly flexible and low cost, as it could be applied to inscribe LPFG in almost all type of fibers without using a phase mask [14], [15]. Since Davis *et al.* reported the first CO_2-laser-induced LPFG in a conventional glass fiber in 1998 [16], various CO_2 laser irradiation techniques have been demonstrated and/or improved to inscribe LPFGs in different types of optical fibers such as SMFs [17], [18], PCFs [19], [20], and PBFs [21]. In 2003, Rao *et al.*, reported a typical CO_2 laser inscribing system in which an industrial 2-D optical scanner with a poor bi-directional repeatability was employed so that the precision of grating



Stage	Speed(um/s)	Move(um)	Position(um)
X	1000.0	5.650	325.650
Y	500.0	8.847	1008.847
Z	2000.0	4.973	-4.973

Grating pitch (um): 320
Period numbers (N): 30
Scan distance (um): 1000
Scan cycles (K): 7

Fig. 1. (a) Schematic diagram of the LPFG inscribing system based on a 2-D scanning technique employing a CO_2 laser. (b) Easy-to-use operation interface of the control program. Z-dimension of the 3-D stage is used to focus the laser beam on the fiber, and X- and Y-dimensions are used to realize the 2-D scanning of the laser beam.

pitch was not good [22]. In addition, in the CO_2 laser irradiation systems reported, an industrial CO_2 laser with a maximum output power of 10 W usually was employed to inscribe LPFGs. However, such a CO_2 laser has a poor power stability of ±10% so that the reproducibility of LPFGs is not good. In other words, the output power of the CO_2 laser employed has to be finely adjusted to achieve a high-quality LPFG during each grating inscription.

In this letter, we demonstrated a promising CO_2 laser irradiation system based on an improved 2-D scanning technique for inscribing high-quality LPFGs. Such a system employs a 3-D ultra-precision motorized translation stages with an excellent bi-directional repeatability of 80 nm, a CO_2 laser with an excellent power stability of less than ±2%, and a control program with a easy-to-use operation interface to inscribe high-quality LPFGs. Moreover, near mode fields of the achieved LPFGs was observed to investigate their mode coupling.

2. LPFG Inscription Setup

A promising LPFG inscribing system based on an improved 2-D scanning technique was demonstrated by use of a focused CO_2 laser beam, as shown in Fig. 1(a). This system consisted of an industrial CO_2 laser with a maximum power of 10 W (SYNRAD 48-1) and a power stability of ±10%, an electric shutter for turning on/off the laser beam, an infrared ZNSE PO/CX lens with a focused length of 63.5 mm, a four-times beam expander for decreasing the diameter of the focused laser spot, and a 3-D ultra-precision motorized stage (Newport XMS50, VP-25X and GTS30V) with a minimum incremental motion of 10 nm and a bi-directional repeatability of 80 nm. A closed loop control system was, for the first time, employed to improve the power stability of the CO_2 laser to ±2%, which is a huge advantage of our LPFG inscribing system Our experiment results showed that the power stability (±2%) of the CO_2 laser improved effectively the stability and reproducibility of grating inscription. For example, the success rate of grating inscription is almost 100% in our current experiments. In contrast, the success rate was about

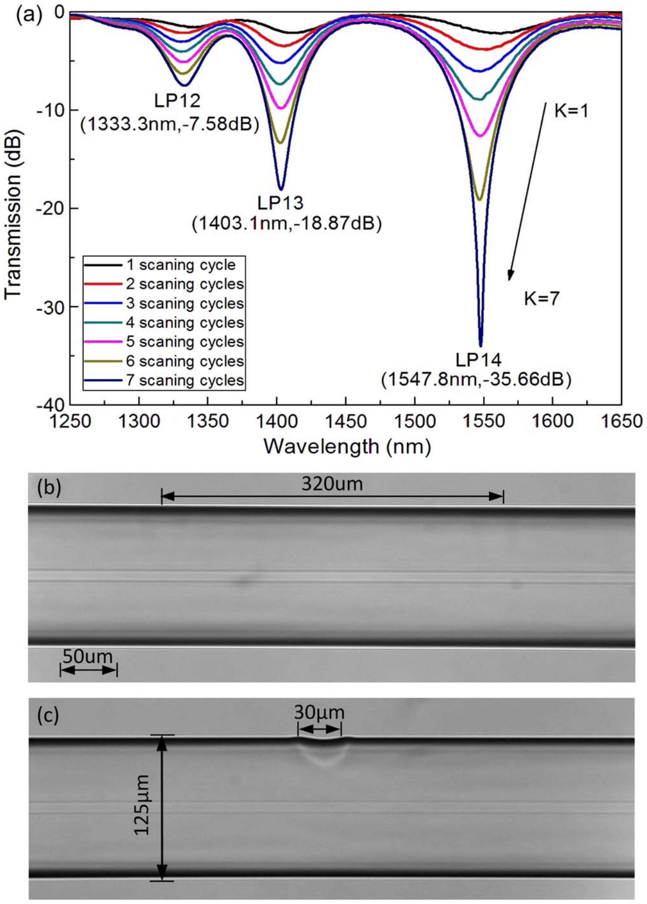


Fig. 2. (a) Transmission spectrum evolution of a CO_2-laser-inscribed LPFG with 30 grating periods and a grating pitch of 320 μm while the number of scanning cycles (K) increases from 1 to 7. (b) Microscope image of the CO_2-laser-inscribed LPFG. (c) CO_2-laser-ablated zone on the surface of the fiber.

30% in our previous experiments with a CO_2 laser with a power stability of ±10% [22], [23]. A supercontinuum light source (NKT Photonics SuperK Compact) and an optical spectrum analyzer (YOKOGAWA AQ6370C) were employed to monitor the transmission spectrum of the CO_2-laser-inscribed LPFG during grating inscription.

A control program with a easy-to-use operation interface was developed by use of LabVIEW software in order to control every devices in the system and to inscribe high-quality LPFGs. As soon as the grating parameters, such as grating pitch, number of grating periods, number of scanning cycles, are entered via the operation interface illustrated in Fig. 1(b) and the “Write” button is clicked, a high-quality LPFG could be achieved. Of course, the grating inscribing process could be paused or stopped at any time by means of clicking the “Pause” button or the “Stop” button. Hence, such an improved LPFG inscription system could potentially be integrated with a fiber drawing tower to inscribe continuously a large number of LPFGs during drawing a fiber, which has the widespread commercial value and the prospects for development.

Our LPFG inscription could be described as follow. First of all, one end of a standard single mode fiber (YOF Inc) is fixed on the 3-D motorized stage by use of a pair of fiber holders, and another end of the fiber is attached by a small weight to provide a constant pre-strain in the fiber, thus enhancing the efficiency of inscribing LPFGs [24], [25]. The CO_2 laser beam propagates through the beam expander and the lens and then is focused on the fiber by means of adjusting Z-dimension of the 3-D stage. We achieved the diameter of the focused spot by means of observing the CO_2-laser-ablated zone on the surface of the fiber. As shown in Fig. 2(c), a

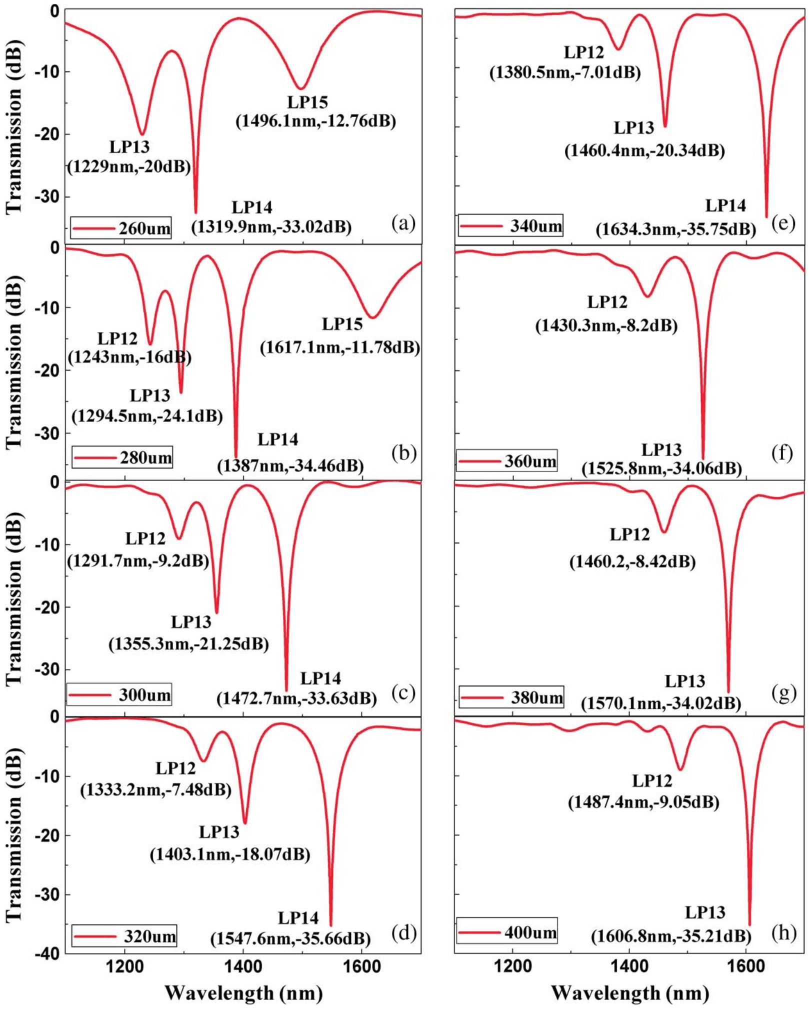


Fig. 3. Measured transmission spectrum of the CO_2-laser-inscribed LPFGs with 30 grating periods and different grating pitches of (a) 260 μm, (b) 280 μm, (c) 300 μm, (d) 320 μm, (e) 340 μm, (f) 360 μm, (g) 380 μm, and (h) 400 μm.

groove was carved on one side of the optical fiber by repeated scanning of a focused CO_2 laser beam with a higher power of 5 W. The width of the groove was measured to be 30 μm. So the diameter of the focused laser spot is about 30 μm. To the best of knowledge, this is the smallest focused spot in the LPFG inscribing system employing a CO_2 laser so far [22]. Second, the motorized stage is moved by 1 mm with a speed of 0.5 mm/s along the “Y” direction, i.e., the vertical orientation of the fiber axis, in order that the focused CO_2 laser beam scans/irradiates cross the fiber. Therefore, the first period of LPFG is created. Thirdly, the motorized stage is shifted by a grating pitch, e.g., 320 μm, along the “X” direction, i.e., the fiber axis, and then moved by 1 mm along the “-Y” direction in order that the focused CO_2 laser beam scans/irradiates cross the fiber again. Therefore, the second period of LPFG is created. This scanning and shifting processes are periodically carried out N times (N is the number of grating periods) until the last grating period is created. The process above may be repeated for K cycles from the first grating period to the last grating period until a desired LPFG is achieved.

3. Experiment Results

As shown in Fig. 2(a), with the increase of the number of scanning cycles, the resonant wavelength of the LPFG shifts toward the shorter wavelength, the resonant attenuation is increased,

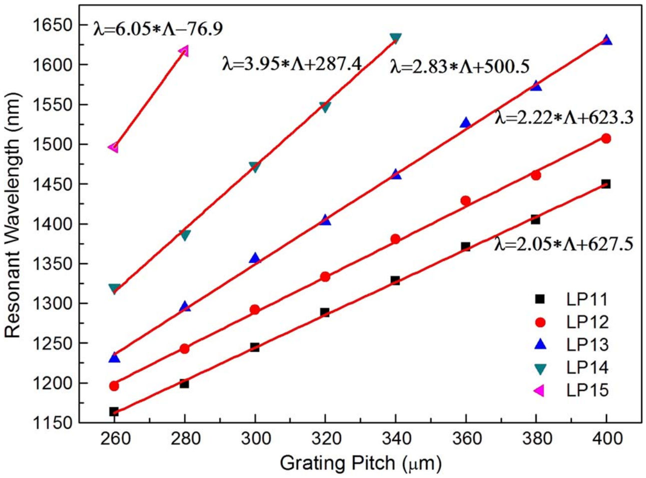


Fig. 4. The measured resonant wavelengths versus the grating pitches of the CO_2-laser-inscribed LPFGs illustrated in Fig. 3.

and the 3 dB bandwidth of the resonant dip is decreased. One high-quality LPFG with a large dip attenuation of -35.66 dB at the resonant wavelength of 1547.8 nm and a low insertion loss of less than 0.3 dB was achieved in a standard single mode fiber after only seven scanning cycles were done. As shown in Fig. 2(b), no obvious physics deformation was observed on the surface of the grating. This is due to the fact that, during the grating inscription, the CO_2 laser power was decreased to 0.5 W in order to avoid to induce physics deformation (i.e. groves) on the surface of the fiber. So residual stress relaxation and glass densification are the possible mechanisms for refractive index modulation in our CO_2-laser-induced LPFGs [2]. In contrast, physical deformation is the dominant mechanism for refractive index modulation in the asymmetric LPFGs with periodic grooves (i.e. physical deformation).

In our system, the CO_2 laser beam is immovable, and the employed fiber is periodically moved/shifted along the “X” and “Y” directions via the 2-D ultra-precision motorized stage with an excellent bi-directional repeatability of 80 nm and a minimum incremental motion of 10 nm. In contrast, in the system reported in reference [22], the fiber is fixed, and the CO_2 laser beam periodically scans the fiber via an industrial 2-D optical scanner with a poor bi-directional repeatability. Compared with our 2-D scanning technique, providing a common point-to-point technique is used to inscribe a LPFG, the CO_2 laser beam has to be aligned with and focused on the fiber core during each inscription of grating period, which is a very difficult work and is of disadvantage to the stability and repeatability of grating inscription.

To investigate the phase matching condition as function of a resonant wavelength, eight LPFGs with the same number of grating periods $(N = 30)$ and different pitches of 260, 280, ..., and 400 μm were inscribed in the standard SMF by use of the improved CO_2 laser system above. As shown in Fig. 3, each LPFG has a large dip attenuation of more than -33 dB at the resonant wavelength and a low insertion loss of less than 0.5 dB, as well as more than three attenuation dips for each LPFG are observed from 1100 to 1700 nm, indicating that the fundamental mode is coupled to different cladding modes. As shown in Fig. 4, the CO_2-laser-inscribed LPFG with a longer grating pitch has a longer resonant wavelength corresponding to the same order cladding mode, which is the same as the phase matching condition of the UV-laser-inscribed LPFGs illustrated in Fig. 8 reported in reference [1]. Therefore, we can inscribe a high-quality LPFG with a desired resonant wavelength by mean of determining a suitable grating pitch from the curve illustrated in Fig. 4.

As shown in Fig. 5, another four LPFGs, i.e. $LPFG_1$, $LPFG_2$, $LPFG_3$, $LPFG_4$, with different grating pitch of 420, 380, 320, and 280 μm, respectively, were inscribed in a standard SMF in order to investigate mode coupling in the CO_2-laser-inscribed gratings. A single-wavelength light from

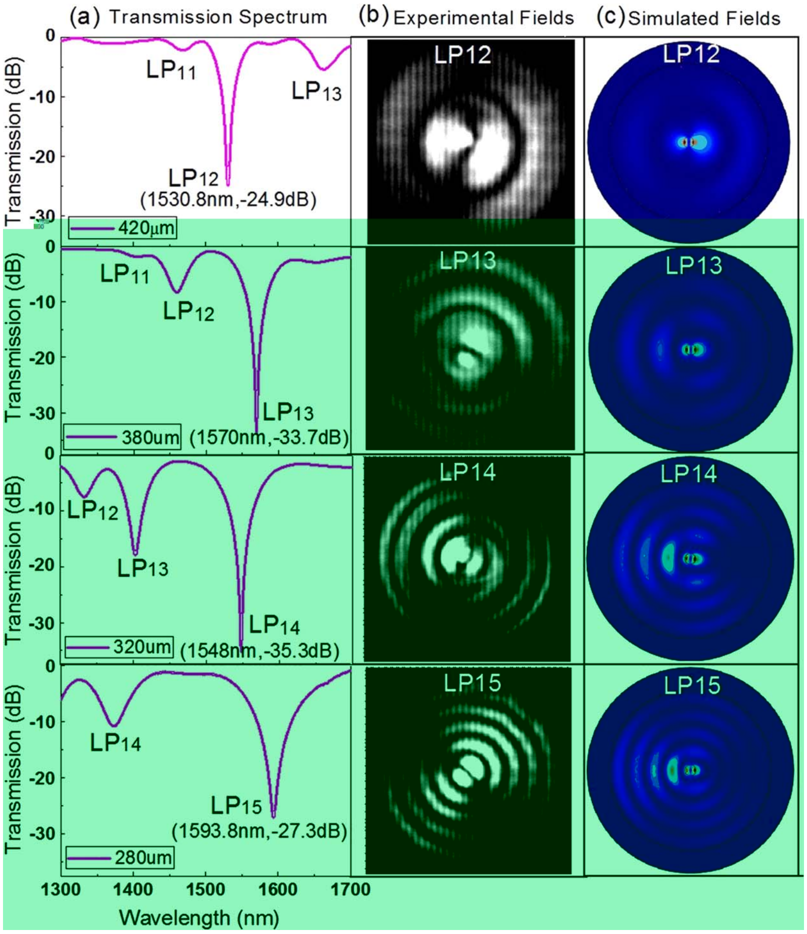


Fig. 5. (a) Transmission spectra, (b) experimental, and (c) simulated near field profiles of the CO$_2$-laser-inscribed LPFGs at the resonant wavelength, i.e., LPFG$_1$ at 1530.8 nm, LPFG$_2$ at 1570.0 nm, LPFG$_3$ at 1548.2 nm, and LPFG$_4$ at 1593.8 nm.

a tunable laser with a wavelength range from 1510 to 1612 nm (EXFO FLS-2600B) was input into one end of each LPFG. Another end of the LPFG was cleaved at the last grating period to observed its near fields by use of an infrared camera (Model 7290A, Electro Physics Corp.) and a microscope (Leica DM2500 M). As shown in Fig. 5(b), asymmetrical mode field profile was observed at the resonant wavelength of each LPFG. That is, the fundamental mode of LPFG$_1$ at the resonant wavelength of 1530.8 nm, LPFG$_2$ at the resonant wavelength of 1570.0 nm, LPFG$_3$ at the resonant wavelength of 1548.2 nm, and LPFG$_4$ at the resonant wavelength of 1593.8 nm, was coupled into the circularly asymmetric cladding mode of LP$_{12}$, LP$_{13}$, LP$_{14}$, and LP$_{15}$, respectively.

Moreover, it is easy seen from Fig. 5(b) that the cladding mode energy on one side is obviously larger than that on another side, that is, the cladding mode in the CO$_2$-laser-induced LPFG is asymmetrical within the cross section of the fiber cladding. This is due to the fact that, during the LPFG inscription, an circularly asymmetric refractive index modulation within the cross section of fiber is induced by the asymmetric residual stress relaxation resulting from the single side irradiation of CO$_2$ laser [26]–[28].

We simulated the cladding mode field in a LPFG written in a standard SMF by use of a mode solver (COMSOL version 3.5) based on the Finite Element Method (FEM). It has been found that, in case the CO$_2$ laser irradiation induces a low refractive index modulation in the LPFG, a linear, quadratic or exponential refractive-index profile assumed in the numerical simulations results in a small quantitative difference, rather than a qualitative change, in the simulation results [26]. Thus we assumed a linear refractive index profile within the cross-section of the grating to simply the simulation of near field profiles of the CO_2-laser-inscribed LPFGs. Assuming refractive index within the cross-section of the grating is linearly modulated with a relationship of $n = n_0 + (1 - X/2R) \times \Delta n$ (n_0 is the cladding refractive index before CO_2 laser irradiation; Δn is the amplitude of refractive index modulation after CO_2 laser irradiation; X is the distance of CO_2 laser irradiation and R is the fiber radius). For $\Delta n = 0.5 \times 10^{-6}$, the simulated near mode filed profile of the four LPFGs are illustrated in Fig. 5(c), which is similar to the experimental results shown in Fig. 5(b). Hence, the circularly asymmetric mode field profiles shown in Fig. 5 experimentally and theoretically verify that asymmetry refractive index modulation are induced within the cross section of the CO_2-laser-induced LPFGs. However, nonuniform absorption of laser energy results in an asymmetrical refractive index profile within the cross-section of the grating, which is more complicated than a simple linear profile. As a result, the simulated near filed profiles are somehow different from the observed ones.

4. Conclusion

A promising CO_2 laser irradiation system based on an improved 2-D scanning technique was demonstrated to inscribe high-quality LPFGs. Compared with other CO_2 laser inscribing systems, in our system the laser beam was fixed and the employed fiber was periodically moved along X-direction and shifted along Y-direction so that the focused laser beam periodically scans/irradiates the fiber. About 5 minutes were required to inscribe a high-quality LPFG with a large attenuation dip of -35.7 dB, a bandwidth of 87.8 nm, and 30 grating periods in a standard single mode fiber by use of our current experimental system with an improved power stability of less than ±2% and the 2-D scanning technique. In contrast, more time, e.g., about 30 minutes, have to be required to inscribe a LPFG with a small attenuation dip of about -25.1 dB, and a bandwidth of 12.0 nm and 55 grating periods in the same type of optical fiber by use of our previous experimental system with a poor power stability of less than ±10% [22], [23]. Circularly asymmetric mode field profiles indicates asymmetry mode coupling in the CO_2-laser-induced LPFGs. Moreover, a control program with a easy-to-use operation interface was developed; therefore, our system has the widespread commercial value and the prospects for development.

References

[1] A. M. Vengsarkar *et al.*, “Long-period fiber gratings as band-rejection filters,” *J. Lightw. Technol.*, vol. 14, no. 1, pp. 58–65, Jan. 1996.
[2] Y. Wang, “Review of long period fiber gratings written by CO_2 laser,” *J. Appl. Phys.*, vol. 108, no. 8, pp. 081101-1–081101-18, Oct. 2010.
[3] Y. P. Wang, Y. J. Rao, Z. L. Ran, T. Zhu, and X. K. Zeng, “Bend-insensitive long-period fiber grating sensors,” *Opt. Lasers Eng.*, vol. 41, no. 1, pp. 233–239, Jan. 2004.
[4] Y.-P. Wang, J.-P. Chen, and Y.-J. Rao, “Torsion characteristics of long-period fiber gratings induced by high-frequency CO_2 laser pulses,” *J. Opt. Soc. Amer. B, Opt. Phys.*, vol. 22, no. 6, pp. 1167–1172, Jun. 2005.
[5] Y. P. Wang, Y. J. Rao, Z. L. Ran, and T. Zhu, “Unique characteristics of long-period fibre gratings fabricated by high-frequency CO_2 laser pulses,” *Acta Phys. Sin.*, vol. 52, no. 6, pp. 1432–1437, Jun. 2003.
[6] S. G. Kosinski and A. M. Vengsarkar, “Splicer-based long-period fiber gratings,” in *OFC Conf. Exhib. Tech. Dig.*, 1998, pp. 278–279.
[7] Y. Kondo *et al.*, “Fabrication of long-period fiber gratings by focused irradiation of infrared femtosecond laser pulses,” *Opt. Lett.*, vol. 24, no. 10, pp. 646–648, May 1999.
[8] Y. J. Rao *et al.*, “Temperature-strain discrimination sensor using a WDM chirped in-fibre Bragg grating and an extrinsic Fabry–Perot,” *Chin. Phys. Lett.*, vol. 18, no. 5, pp. 643–645, May 2001.
[9] I. K. Hwang, S. H. Yun, and B. Y. Kim, “Long-period fiber gratings based on periodic microbends,” *Opt. Lett.*, vol. 24, no. 18, pp. 1263–1265, Sep. 1999.
[10] C. Y. Lin and L. A. Wang, “Loss-tunable long period fibre grating made from etched corrugation structure,” *Electron. Lett.*, vol. 35, no. 21, pp. 1872–1873, Oct. 14, 1999.
[11] J. Qu, L. Liu, Y. Shao, H. Niu, and B. Z. Gao, “Recent progress in multifocal multiphoton microscopy,” *J. Innov. Opt. Health Sci.*, vol. 5, no. 3, pp. 626–627, Jul. 2012.
[12] M. Fujimaki, Y. Nishihara, Y. Ohki, J. L. Brebner, and S. Roorda, “Ion-implantation-induced densification in silica-based glass for fabrication of optical fiber gratings,” *J. Appl. Phys.*, vol. 88, no. 10, pp. 5534–5537, Nov. 2000.

[13] X. Zhang *et al.*, “Long-wavelength, photostable, two-photon excitable BODIPY Fluorophores readily modifiable for molecular probes,” *J. Organic Chem.*, vol. 78, no. 18, pp. 9153–9160, Sep. 2013.

[14] T. Zhu, Y.-J. Rao, and Q.-J. Mo, “Simultaneous measurement of refractive index and temperature using a single ultralong-period fiber grating,” *IEEE Photon. Technol. Lett.*, vol. 17, no. 12, pp. 2700–2702, Dec. 2005.

[15] T. Zhu *et al.*, “Characterization of long-period fiber gratings written by CO_2 laser in twisted single-mode fibers,” *IEEE J. Lightw. Technol.*, vol. 27, no. 21, pp. 4863–4869, Nov. 2009.

[16] D. D. Davis *et al.*, “Long-period fibre grating fabrication with focused CO_2 laser pulses,” *Electron. Lett.*, vol. 34, no. 3, pp. 302–303, Feb. 1998.

[17] Y. J. Rao, Y. P. Wang, Z. L. Ran, T. Zhu, and B. M. Yu, “Characteristics of novel long-period fiber gratings written by focused high-frequency CO_2 laser pulses,” in *Proc. SPIE*, 2001, pp. 327–333.

[18] H. M. Chan, F. Alhassen, I. V. Tomov, and H. P. Lee, “Fabrication and mode identification of compact long-period gratings written by CO_2 laser,” *IEEE Photon. Technol. Lett.*, vol. 20, no. 8, pp. 611–613, Apr. 2008.

[19] Y. P. Wang, L. M. Xiao, D. N. Wang, and W. Jin, “Highly sensitive long-period fiber-grating strain sensor with low temperature sensitivity,” *Opt. Lett.*, vol. 31, no. 23, pp. 3414–3416, Dec. 1, 2006.

[20] Y. J. Rao, D. W. Duan, Y. E. Fan, T. Kai, and M. Xin, “High-temperature annealing behaviors of CO_2 laser pulse-induced long-period fiber grating in a photonic crystal fiber,” *J. Lightw. Technol.*, vol. 28, no. 10, pp. 1530–1535, May 2010.

[21] Y. P. Wang *et al.*, “Long period gratings in air-core photonic bandgap fibers,” *Opt. Exp.*, vol. 16, no. 4, pp. 2784–2790, Feb. 2008.

[22] Y. J. Rao, Y. P. Wang, Z. L. Ran, and T. Zhu, “Novel fiber-optic sensors based on long-period fiber gratings written by high-frequency CO_2 laser pulses,” *J. Lightw. Technol.*, vol. 21, no. 5, pp. 1320–1327, May 2003.

[23] Y. P. Wang, D. N. Wang, W. Jin, Y. J. Rao, and G. D. Peng, “Asymmetric long period fiber gratings fabricated by use of CO_2 laser to carve periodic grooves on the optical fiber,” *Appl. Phys. Lett.*, vol. 89, no. 15, pp. 151105-1–151105-3, Oct. 2006.

[24] Y. Liu and K. S. Chiang, “CO_2 laser writing of long-period fiber gratings in optical fibers under tension,” *Opt. Lett.*, vol. 33, no. 17, pp. 1933–1935, Sep. 2008.

[25] H. W. Lee and K. S. Chiang, “CO_2 laser writing of long-period fiber grating in photonic crystal fiber under tension,” *Opt. Exp.*, vol. 17, no. 16, pp. 4533–4539, Mar. 2009.

[26] R. Slavík, “Coupling to circularly asymmetric modes via long-period gratings made in a standard straight fiber,” *Opt. Commun.*, vol. 275, no. 1, pp. 90–93, Jul. 2007.

[27] Y. P. Wang, D. N. Wang, W. Jin, H. L. Ho, and H. Ju, “Mode field profile and polarization dependence of long period fiber gratings written by CO_2 laser,” *Opt. Commun.*, vol. 281, no. 9, pp. 2522–2525, May 2008.

[28] G. D. VanWiggeren *et al.*, “Axial rotation dependence of resonances in curved CO_2-laser-induced long-period fibre gratings,” *Electron. Lett.*, vol. 36, no. 16, pp. 1354–1355, Aug. 2000.