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Review

Long Period Fiber Gratings Written in Photonic Crystal Fibers by Use of CO_2 Laser

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Abstract: Photonic crystal fibers are usually divided into two different types of fibers: solid-core photonic crystal fibers (PCFs) and air-core photonic bandgaps fibers (PBFs). We presented the fabrication methods and applications of long period fiber gratings (LPFGs) written in these two types of photonic crystal fibers by use of a CO_2 laser. A stain sensor with a high sensitivity was demonstrated by use of an LPFG written in solid-core PCFs. An in-fiber polarizer based on an LPFG was fabricated by use of a focused CO_2 laser beam to notch periodically on a PCF. A novel LPFG was written in an air-core PBF by use of a CO_2 laser to collapse periodically air holes in the fiber cladding.

Keywords: Long period fiber gratings, fiber Bragg gratings, photonic crystal fibers, photonic bandgap fibers, CO_2 lasers

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1. Introduction

Optical fiber gratings already play a vital role in the field of the optical communications and sensors. There are two types of in-fiber gratings: fiber Bragg gratings (FBGs) with periodicities of the order of the optical wavelength [1, 2] and long period fiber gratings (LPFGs) with periodicities of several hundred wavelengths [3–7]. Various fabrication methods, such as UV laser exposure [3], CO_2 laser irradiation [4, 8–11], electric arc discharge [12], femtosecond laser exposure [13], mechanical microbend [14], and etched corrugation [15], have been demonstrated to write LPFGs in different types of optical fibers. Compared with the ultraviolet (UV) laser exposure technique, the CO_2 laser irradiation technique is much more flexible and low cost because no photosensitivity and any other pretreated processes are required to write a grating in the glass fibers [4, 8–10]. Moreover, the CO_2 laser irradiation process can be controlled to generate complicated grating profiles via the well-known point-to-point technique without any expensive masks. This technique could be, hence, used to write LPFGs in almost all types of fibers including pure-silica photonic crystal fibers (PCFs). We reviewed the recent development of the CO_2-laser-induced LPFGs.

Over the past decade, photonic crystal fibers have attracted a great deal of interest due to their

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unique microstructures and optical properties [16]. Photonic crystal fibers are usually divided into two different types of fibers: solid-core photonic crystal fibers (PCFs) and air-core photonic bandgaps fibers (PBFs). This paper reviews the fabrication methods and applications of LPFGs written in both solid-core PCFs and air-core PBGs by use of a CO_2 laser.

2. CO_2 laser irradiation techniques for writing LPFGs

Since Davis *et al*. reported the first CO_2-laser-induced LPFG in a conventional glass fiber in 1998 [8, 17], various CO_2 laser irradiation techniques have been demonstrated and improved to write high-quality LPFGs in different types of optical fibers, such as conventional glass fibers, PCFs, and PBFs, and to achieve unique grating properties. This section reviews the development of the CO_2 laser irradiation techniques for writing LPFGs in conventional glass fibers, solid-core PCFs, and air-core PBFs.

Typically, in most of LPFG fabrication setups employing a CO_2 laser [8, 17–19], as shown in Fig. 1, the fiber is periodically moved along its axis direction via a computer-controlled translation stage, and the CO_2 laser beam irradiates periodically the fiber through a shutter controlled by a same computer. A light source and an optical spectrum analyzer are employed to monitor the evolution of the grating spectrum during the laser irradiation. This is a typical point-to-point technique for writing a grating in an optical fiber. Such an LPFG fabrication system usually requires an exactly controlling of both the shutter and the translation stage to achieve a good simultaneousness of the laser irradiation and the fiber movement. Additionally, the vibration of the employed fiber, resulting from the periodic movement of the fiber, could occur during the irradiation of the CO_2 laser beam, which is a disadvantage to the stability and repeatability of the grating fabrication.

Rao *et al*. demonstrated, for the first time, a novel grating fabrication system based on 2-dimentional scanning of the CO_2 laser beam [9, 10], as shown in Fig. 2. One end of the employed fiber was fixed, and the other end was attached to a small weight to provide a constant prestrain in the fiber, thus enhancing the efficiency of the grating fabrication. The focused high-frequency CO_2 laser pulses scanned periodically across the employed fiber along the X direction and then shifted a grating pitch along the Y direction, i.e. the fiber axis, to create the next grating period by means of 2-dimensional optical scanners under the computer control. Compared with the typical point-to-point fabrication system shown in Fig. 1, no exactly simultaneous controlling was required in such a system because the employed fiber was not periodically moved along the fiber axis. Such a system could write high-quality LPFGs with a near-zero insertion loss.

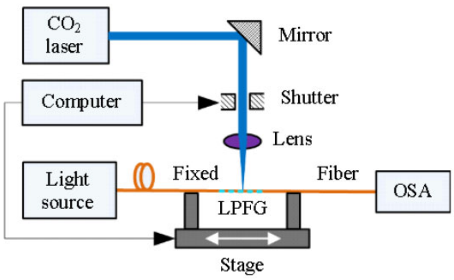


Fig. 1 Schematic diagram of a normal LPFG fabrication system based on the typical point-to-point technique employing a CO_2 laser.

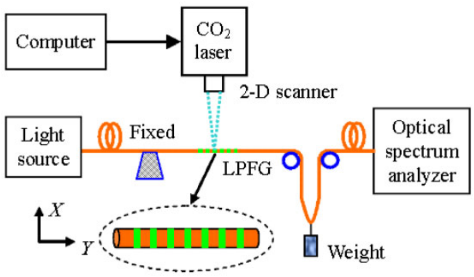
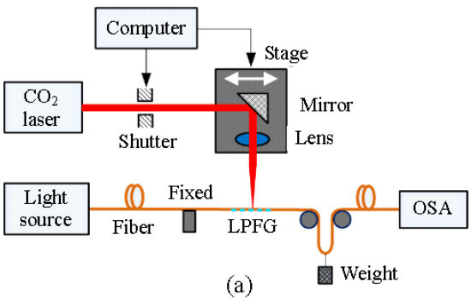
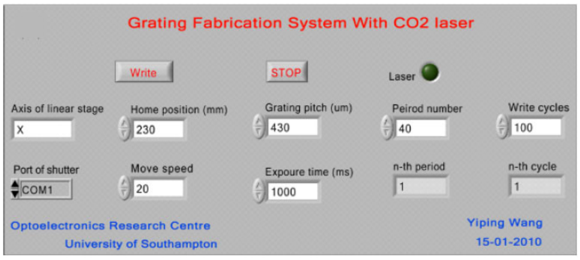


Fig. 2 Schematic diagram of an LPFG fabrication system based on 2-dimentional scanning of focused high-frequency CO_2 laser pulses [9].

The authors recently developed an improved LPFG fabrication system based on the point-to-point technique employing a CO_2 laser, as shown in Fig. 3, combining with the advantages of the two fabrication systems illustrated in Figs. 1 and 2. A CO_2 laser beam was, through a shutter and a mirror, focused on the fiber by a cylindrical lens with a focus length of 254 mm. Both the mirror and the lens were mounted on a linear air-bearing motor stage (ABL 1500 from Aerotech). A Labview program has been developed to control simultaneously the operation of both the linear motor stage and the shutter so that the fiber was exposed once as soon as the focused laser beam was shifted by a grating pitch via the mirror. In other words, the fiber was not periodically moved in this system, which overcame the disadvantage of the fiber vibration, resulting from the periodic movement of the fiber, in the normal point-to-point grating fabrication setup shown in Fig. 1. A desired LPFG can be achieved as soon as the required fabrication parameters, such as the grating pitch, number of grating periods, exposure time per period, and number of exposure cycles, are input via an operation interface illustrated in Fig. 3(b). Such an improved fabrication



(a)



(b)

Fig. 3 LPFG fabrication system with a CO_2 laser: (a) the schematic diagram of an improved LPFG fabrication system employing a CO_2 laser and (b) the operation interface of the fabrication system.

system could potentially be integrated with a fiber drawing tower to write continuously a large number of LPFGs during drawing a fiber.

CO_2 laser irradiation may cause unexpected physical deformation, resulting from laser heating, of fiber structures during LPFG fabrication. Such a physical deformation is usually avoided to decrease the insertion loss of the written LPFGs during early grating fabrications with a CO_2 laser [8, 9, 17]. Wang *et al*. reported a novel technique for writing an asymmetric LPFG by means of carving periodic grooves on the surface of an optical fiber with a focused CO_2 laser beam [20], as shown in Fig. 4. Physical deformation, i.e. periodic grooves, in such an asymmetric LPFG, did not cause a large insertion loss because these grooves were totally confined within the outer cladding and had no influence on the light transmission in the fiber core. Moreover, such grooves enhanced the efficiency of the grating fabrication and introduced unique optical properties, e.g. extremely high strain sensitivity, into the gratings [20, 21]. Further investigations discovered that the insertion loss of LPFGs was mainly due to the nonperiodicity and the disorder of refractive index modulations in the gratings.

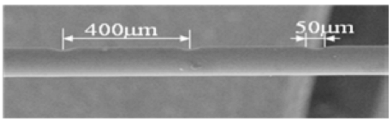


Fig. 4 Photograph of an asymmetric LPFG with periodic grooves [20].

3. To write LPFGs in solid-core PCFs

Over the past decade, PCFs have attracted a great deal of interest due to their unique microstructures and optical properties [16, 22]. Since Eggleton *et al*. reported the first grating in a photosensitive PCF with a Ge-doped core in 1999 [23], a large number of gratings have been written in different types of PCFs with or without photosensitivity by the use of various fabrication techniques such as UV laser exposure [24], CO_2 laser irradiation [18, 25–27], electric-arc discharge

[28], femtosecond laser exposure [29, 30], and two-photon absorption [31]. UV laser exposure is a common technique for writing an FBG/LPFG in a Ge-doped PCF with a photosensitivity [23, 32, 33]. In contrast, CO_2 laser irradiation can be used to write high-quality LPFGs with a near-zero insertion loss in different types of optical fibers without photosensitivity, including solid-core PCFs and air-core PBFs [18, 25–27].

As shown in Fig. 5, an asymmetrical LPFG with periodic grooves was written in a pure-silica large-mode-area PCF by the use of a focused CO_2 laser beam [26, 27]. The repeated scanning of the focused CO_2 laser beam created a local high temperature in the fiber, which led to the collapse of air holes and the gasification of SiO_2 on the fiber surface. Consequently, periodic grooves with a depth of about 15 μm and a width of about 50 μm were created on the fiber, as shown in Fig. 5(b). Such grooves, especially the collapse of air holes, induced periodic refractive index modulations along the fiber axis due to the well-known photoelastic effect, thus creating an LPFG in the PCF. This asymmetrical LPFG has unique optical properties, e.g. high strain sensitivity, low temperature sensitivity and high polarization dependence [26, 27].

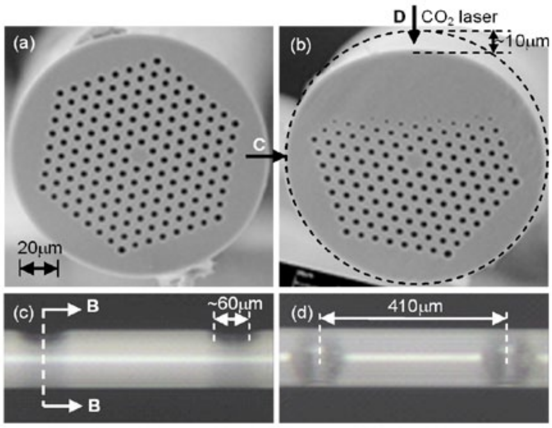


Fig. 5 Asymmetrical LPFG with periodic grooves in a pure-silica PCF [26].

A highly compact LPFG with only 8 periods and a short total length of 2.8 mm was written in a pure-silica large-mode-area PCF by the common point-by-point technique employing a CO_2 laser [18], in which clear physical deformation was also observed. In contrast, another LPFG without geometrical deformation and fiber elongation was written in an endless single-mode PCF by periodic stress relaxation resulting from CO_2 laser irradiation [34]. Moreover, an LPFG pair has been successfully created in a pure-silica PCF with a CO_2 laser to develop a stain sensor. A novel coupled local-mode theory could be used to model and analyze this type of PCF-based LPFGs with the periodic collapse of air holes [35]. Such a theory is based on calculating the variations of local-mode profiles and propagation constants over the perturbed regions and on solving the coupled local-mode equations to obtain a quantitative description of the intermodal energy exchange.

4. To write LPFGs in air-core PBFs

As discussed above, a large number of gratings have been demonstrated in different types of PCFs by the use of various fabrication techniques. All of these gratings, however, were written in index-guiding PCFs, instead of bandgap-guiding fibers. Recently, PBF-based gratings were also written in a new kind of bandgap-guiding fibers such as fluid-filled PBFs [36–40] and all-solid PBFs [41]. However, PBF-based gratings have not been reported in air-core PBFs until recent success in writing a high-quality LPFG in an air-core PBF [42].

Since almost 100% of the light propagates in the air holes of an air-core PBF and not in the glass, PBF-based gratings offer a number of unique features including: high dispersion, low nonlinearity, reduced environmental sensitivity, unusual mode coupling, and new possibilities for long-distance light-matter interactions (by incorporating additional materials into the air-holes). The bandgap-based grating in air-core PBFs, therefore, represents an important platform technology with manifest applications in areas such as communications, fiber lasers and sensing. Periodic index modulations are usually required to realize mode coupling in in-fiber gratings. Although this presents no difficulties in conventional glass fibers [8, 9], solid-core PCFs [23, 26], and solid-core PBFs [37], it is very difficult, even impossible, to directly induce index modulations in an air-core PBF due to the air core structure, thereby seriously obstructing the development of PBF-based gratings over the past decade.

As shown in Fig. 6, we reported what is believed to be the first example of gratings written in an air-core PBF by the use of a focused CO_2 laser beam to periodically deform/perturb air holes along the fiber axis in 2008 [42, 43]. This reveals that it is experimentally possible to write a grating in an air-core PBF. Both the excellent stability of the CO_2 laser power and the good repeatability of optical scanning are very critical to writing a high-quality grating in an air-core PBF. An experimental setup being similar to that in Fig. 2 was used to write an LPFG in an air-core PBF (Crystal-Fiber's HC-1500-02). Compared with the fabrication parameters for writing a grating in a solid-core PCF [26, 27], a lower average laser power of about 0.2 W and shorter total time of laser irradiation were used to write an LPFG in an air-core PBF [42]. The focused CO_2 beam scanned periodically the PBF with a line speed of scanning of 2.9 mm/s, causing the ablation of glass on the fiber surface and the partial or complete collapse of air holes in the cladding due to the CO_2-laser-induced local high temperature, as shown in Fig. 6. The outer rings of air holes in the cladding, facing to the CO_2 laser irradiation, were largely deformed; however, little or no deformation was observed in the innermost ring of air-holes and in the air core. As a result, periodic index modulations were achieved along the fiber axis due to the photoelastic effect, thus creating a novel LPFG in the air-core PBF. For the LPFG written in air-core PBF, periodic perturbations of the waveguide (geometric) structure could be the dominant factor that causes resonant mode coupling, although the stress-relaxation-induced index variation may also contribute a little.

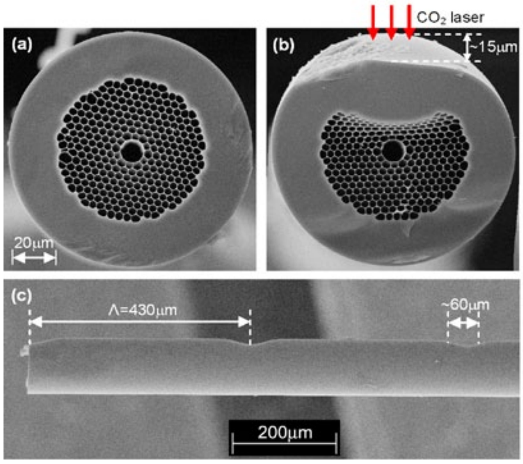


Fig. 6 Cross-section image of an air-core PBF (a) before and (b) after CO_2 laser irradiating, (c) side image of an LPFG written in the air-core PBF, where about two periods of the LPFG are illustrated [42].

Normal LPFGs written in the index-guiding fibers have a positive relationship between the resonant wavelength and grating pitch. In contrast, the LPFGs written in the bandgap-guiding air-core PBF have the distinct phase matching condition as a function of the wavelength. As shown in Fig. 7, the resonant wavelengths of the LPFGs written in an air-core PBF decrease with an increase in the grating

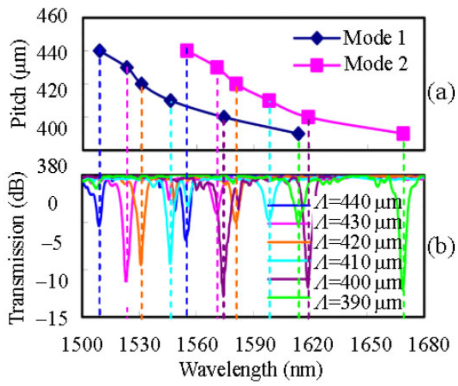


Fig. 7 Transmission spectra of LPFGs written in air-core PBFs: (a) the relationship between the pitch of each LPFG and the corresponding resonant wavelength, and (b) transmission spectra of six LPFGs with different grating pitches, where two attenuation dips for each LPFG are observed from 1500 nm to 1680 nm, indicating that the fundamental mode is coupled to two different higher order modes [42].

pitch, which is opposite to the LPFGs written in the index-guiding fibers [43]. Moreover, this PBF-based LPFG has unique optical properties such as very large polarization dependent loss (PDL), large strain sensitivity, and very small sensitivity or insensitivity to the temperature, bend and external refractive index, as shown in Fig. 4 in [42]. Further investigations are being done to well understand resonant mode coupling and unique optical properties in the gratings written in air-core PBFs.

Moreover, three years later, A. Iadicicco *et al*. reported on another fabrication method of LPFGs in hollow-core air-silica PBFs by using the pressure assisted electrode arc discharge (EAD) technique [44], as shown in Fig. 8. The EAD procedure combining with pressure actuation inside fiber holes enables the modification of the hole size and shape in both core and cladding regions avoiding the collapse of holes and thus acts as a useful tool to impress effective refractive index modulation leading to low loss gratings. Periodically repeated EAD treatments permit the fabrication of LPFG-based devices in hollow core optical fibers enabling new functionalities hitherto not possible. Here, the experimental demonstration of the LPFG prototype with different characteristics exhibiting attenuation bands with the depth up to 12 dB is reported.

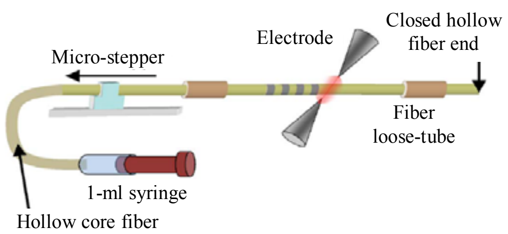


Fig. 8 Schematic diagram of LPFG fabrication employing a hollow-core PBF by using the pressure assisted EAD technique [44].

5. Applications of gratings writing in PCFs

5.1 Strain sensors

The CO_2-laser-induced LPFGs with physical deformation exhibit unique optical properties while a tensile strain is applied, thus being excellent strain sensing elements. As shown in Fig. 9, periodic microbends will be induced while a CO_2-laser-induced LPFG with asymmetric grooves is stretched [20, 21, 27]. Such stretch-induced microbends effectively enhance refractive index modulation in the gratings. As a result, such an LPFG had an extremely high strain sensitivity of −102.89 nm/με [20, 21], which was two orders of magnitude higher than that of other CO_2-laser- induced LPFGs without physics deformation in the same type of fibers [9].

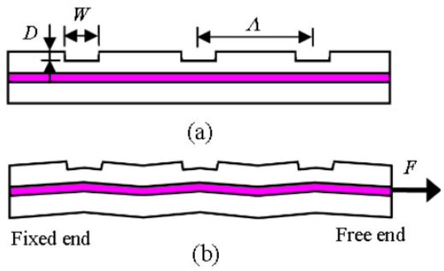


Fig. 9 Schematic diagram of the CO_2-laser-carved LPFG with asymmetric grooves (a) before and (b) after a stretching force is applied to the grating [20].

An LPFG strain sensor with a high strain sensitivity of –7.6 pm/με and a very low temperature sensitivity of 3.91 pm/℃ has been developed by the use of the focused CO_2 laser beam to carve periodic grooves on the large mode area PCF [27]. Such a strain sensor could effectively reduce the cross-sensitivity between the strain and temperature, and the temperature-induced strain error obtained was only 0.5 με/℃ without temperature compensation. Another strain sensor based on a CO_2-laser-induced LPFG pair in a PCF exhibited a high stain sensitivity of about –3 pm/με and a low temperature sensitivity of about 4.6 pm/℃ [45]. Theoretical analysis reveals that a simple, low-cost LPG sensor with approximately zero temperature sensitivity but large strain sensitivity could be realized by selecting an appropriate grating period [46].

5.2 Polarizers

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 the optical fiber. The CO_2-laser-induced LPFGs have clear polarization dependence due to their asymmetric refractive index profile, resulting from single-side laser irradiation, within the cross-section of the gratings [20, 21], thus being a potential in-fiber polarizing device. Moreover, the polarization dependence of the CO_2-laser-induced LPFG with periodic grooves can be greatly enhanced by applying a tensile strain [21] or increasing temperature[47]. So a promising in-fiber polarizer based on an LPFG was developed by the use of a focused CO_2 laser beam to collapse or perturb periodically air holes in a pure-silica PCF, as shown in Fig. 10 [26]. In practical operation, a stretch strain was applied to the LPFG-based polarizer to enhance the polarization dependence of the grating. As a result, the maximum PDL and the maximum polarization extinction ratio of the LPFG were increased to 27.27 dB and 22.83 dB, respectively, as shown in Fig. 8. Such an LPFG-based polarizer thus exhibited a high polarization extinction ratio of more than 20 dB over a wide wavelength range of about 11 nm near the communication wavelength of 1550 nm [26]. Moreover, this polarizer had a very low temperature sensitivity of 3.9 pm/℃, which overcame the disadvantages of the temperature sensitivity in other in-fiber polarizers created in conventional glass fibers.

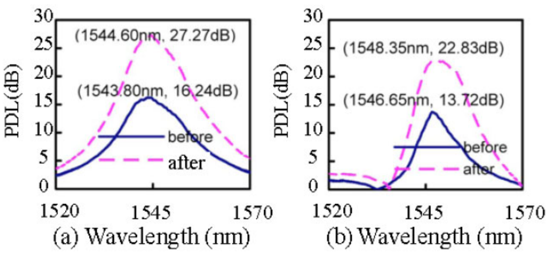


Fig. 10 Polarization dependence, (a) PDL and (b) polarization extinction ratio (PER), of the LPFG-based polarizer before (dashed curve) and after (solid curve) a stretch strain of 500 με is applied [26].

6. Conclusions

LPFGs could be written in different photonic crystal fibers, including solid-core PCFs and air-core PBGs by use of a focused laser beam. Compared with the UV laser exposure technique, the CO_2 laser irradiation technique is much more flexible and low cost because no photosensitivity and any other pretreated processes are required to induce a grating in the glass fibers. Moreover, the CO_2 laser irradiation process can be controlled to generate complicated grating profiles via the well-known point-to-point technique without any expensive masks. In-fiber gratings written in PCFs have found promising sensing and communication applications.

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