Recent development on CO_2-laser written long-period fiber gratings

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ABSTRACT

The paper reviews the recent progress on CO_2-laser writing of long-period fiber gratings (LPFGs) in different kinds of fibers, including conventional single-mode fiber (SMF), boron-doped SMF, polarization-maintaining fiber, photonic crystal fiber, and polarization-maintaining photonic crystal fiber. In particular, we report the writing dynamics for the understanding of the physical mechanisms involved in the writing process and show that the CO_2-laser pulses can not only relax the internal stress in the fiber core but also induce a frozen-in stress in the cladding of the fiber under tension. The applications of CO_2-laser written LPFGs, especially for the realization of broadband optical couplers, are also discussed.

Keywords: Long-period fiber grating (LPFG), CO_2 laser, residual stress relaxation, glass structure change, frozen-in viscoelasticity, boron-doped fiber, polarization-maintaining fiber, photonic crystal fiber, optical coupler.

1. INTRODUCTION

A long-period fiber grating (LPFG) formed in a single-mode fiber (SMF), which has a pitch of the order of 100 μm, enables strong light coupling from the guided core mode to selected cladding modes at specific wavelengths [1]. Being simple band-rejection filters, LPFGs have found wide applications in optical communications [2] and sensing [3]. The conventional ultra-violet (UV) writing method, which was developed originally for the fabrication of fiber Bragg gratings, can be employed to write LPFGs [1]. There are, however, many non-UV methods available for the fabrication of LPFGs, which include, for example, the CO_2-laser writing method [4]-[9], the femtosecond-pulse irradiation method [10], and the electric-discharge writing method [11]. Among these methods, the CO_2-laser writing method is particularly flexible, as it can be applied to practically any fibers and the writing process can be computer-controlled to fabricate sophisticated gratings without using amplitude masks [6],[9].

There have been many studies on the understanding of the physical mechanisms involved in the CO_2-laser writing process for different kinds of fibers [4]-[9],[12]-[17]. In this paper, we present a review of our recent studies on CO_2-laser writing of LPFGs in different kinds of fibers, including conventional SMF, boron-doped SMF, conventional polarization-maintaining fiber (PMF), and polarization-maintaining photonic crystal fiber (PM-PCF). In our studies, we used a focused pulsed CO_2 laser as the writing source, which could be computer-programmed to scan across a fiber and advance along a fixed length of fiber with a preset interval. The energy density of the laser pulses could be varied and the scanning cycle could be repeated many times over the same fiber section. Our studies focus on an analysis of the writing dynamics for the understanding of the physical mechanisms involved [9],[16],[17]. The applications of CO_2-laser written LPFGs are also highlighted in the paper.

2. LPFG WRITTEN IN CONVENTIONAL SMF

The CO_2-laser writing method for the fabrication of LPFGs in conventional SMFs was proposed about ten years ago [4],[18],[19],[14]. The grating was fabricated by direct exposure of the fiber to 10.6 μm CO_2 laser pulses. While

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hydrogen loading of a fiber can enhance the writing efficiency, strong gratings can be written in untreated SMFs [4]. The spectral characteristics and the temperature stability of CO_2-laser written gratings [18],[19] and the CO_2-laser induced index distribution across the fiber have been studied extensively [14]. The residual stress relaxation in the fiber core by CO_2-laser irradiation is considered to be the dominant mechanism responsible for the formation of the grating [4]-[6],[12],[13]. While stress relaxation in the core leads to an axially uniform index change, one-side exposure to a large dose of CO_2-laser radiation can induce an additional, asymmetric index change across the cladding and thus give rise to coupling to non-axially symmetric cladding modes [8],[14]. The effects of such an asymmetric index change have been widely studied [4],[6],[8],[13]-[16]. For example, the asymmetric index distribution leads to a strong dependence of the light coupling efficiency on the orientation of the gratings in the realization of an optical coupler that consists of two parallel LPFGs [16]. It also leads to a large polarization dependent loss (PDL). The effect of the stress-induced birefringence on the PDL was investigated by the analysis of the two-dimensional axial stress profile [13]. To produce a symmetric index distribution, different methods have been proposed, which include the use of a specially designed reflector placed behind the fiber to divide the incident light into three beams separated in angle by 120° [8], multiple exposures by rotating the fiber [20],[21], the use of a hydrogen-loaded SMF [22], etc. Because the CO_2-laser power required for writing a grating in a hydrogen-loaded fiber is low [4],[22], the index change is induced mainly in the core, as in the case of a boron-doped fiber [16],[17]. By twisting the fiber during CO_2-laser exposure, a helicoidal LPFG can be formed, where the codirectional and contradirectional torsions of the fiber result in spectral shifts to shorter and longer wavelength, respectively. A flexible band-rejection filter with a tunable bandwidth can be achieved by connecting a pair of helicoidal gratings of opposite helicities in series [23]. By connecting two helicoidal gratings of the same helicity to the two ends of a hollow-core fiber, however, a tunable bandpass filter can be realized [24]. The CO_2-laser writing method allows the contrast of the grating to be controlled precisely. Gratings with very large contrasts (> 35 dB) [25] have been demonstrated, which can satisfy the more stringent filtering requirements in some applications. One can also use the CO_2 laser to carve a periodic groove on one side of a fiber to produce a LPFG [26], which is similar to a corrugated LPFG where the fiber cladding is chemically etched to produce a grating structure [3]. When a tensile load is applied to a CO_2-laser carved grating, the periodic variation in the fiber diameter results in a periodic strain variation along the fiber, and hence, a periodic refractive index variation. Such a grating shows enhanced strain sensitivity and can find many sensing applications [26]. A similar grating can also be produced in an optical polymer overlay on an optical fiber by laser ablation [27]. The laser-ablated grating has a high temperature tuning efficiency and a wide tunable wavelength range of ~105 nm. This kind of gratings, however, has a large PDL.

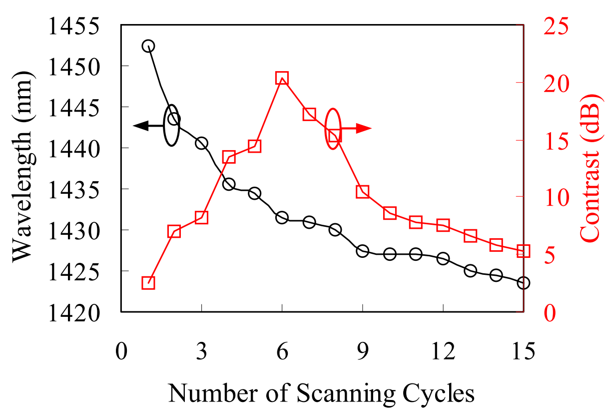

Fig. 1. Variations of the resonance wavelength and the grating contrast with the number of scanning cycles for a grating written in a conventional germanium-doped fiber with a CO_2-laser energy density of 6.0 J/mm^2. (Ref. [17])

CO_2-laser writing of LPFGs in conventional SMFs has been studied through an analysis of the writing dynamics [17]. Figure 1 shows the variations of the resonance wavelength and the grating contrast with the number of scanning cycles for a grating written in a conventional germanium-doped SMF, SMF-130V (POFC, Taiwan), at a typical energy density of 6.0 J/mm^2. As shown in Fig. 1, the resonance wavelength shifts towards a shorter wavelength by ~30 nm with 15 scanning cycles. The results can be explained by a decrease in the core index due to stress relaxation [12],[13]. The resonance wavelength of a LPFG, λ_0, is determined by the phase-matching condition [1]:

$$\lambda_0 = (N_{co} - N_{cl})\Lambda \tag{1}$$

where N_{co} and N_{cl} are the effective indexes of the guided core mode and the coupled cladding mode, respectively, and Λ is the grating pitch. According to Eq. (1), the general trend shown in Fig. 1 suggests that the core index decreases with the number of scanning cycles, which is consistent with the reported results [5]-[7],[12]-[14]. It is known that the manufacturing process of a conventional telecommunication SMF usually leaves a fairly large compressive stress in the core of the fiber and a small tensile stress in the cladding area close to the core [28]. When the fiber is irradiated with CO_2-laser pulses, the stress in the core is relaxed by the intense heating effect, which results in a decrease in the refractive index of the core at the point of irradiation [12],[13].

3. LPFG WRITTEN IN BORON-DOPED SMF

Apart from conventional SMFs, there have been a number of studies on CO_2-laser writing of LPFGs in boron-doped fibers [5],[7],[12],[16],[17],[29]. For a boron-doped fiber, the writing mechanism is more complicated. The residual stress relaxation is still the dominant writing mechanism in a specially made boron-doped fiber that has a large residual stress [5],[12],[29]. The experimental results with a LPFG interferometer confirm that the refractive index change induced by residual stress relaxation accounts for the formation of the grating [29]. However, because the doping of boron can lower the fictive temperature of the core substantially, local heating of the fiber by CO_2-laser radiation or electric discharge can cause not only stress relaxation, but also glass structure changes in the core [7],[17],[30]-[33]. A study of the rewritability of a commercial boron-doped fiber shows that the refractive index change due to residual stress relaxation is not large enough to form a grating with a high contrast in such a fiber [7]. The maximum grating strength was only 1−2 dB for the grating induced by stress relaxation. The effects of glass densification and glass volume increase in the fiber core account for the formation of rewritable LPFGs [7]. The rewriting is based on glass densification in the core with unfocused CO_2-laser irradiation followed by glass volume increase in the core with focused CO_2-laser irradiation [7]. Therefore, the glass structure changes induced by the CO_2-laser radiation are the dominant effects in a commercial boron-doped fiber that contains only a small residual stress. Recently, the writing dynamics in a commercial boron-doped fiber that does not contain a large stress in the core has been studied, which reveals the dynamic interplay of various physical effects and provides a deeper insight into the formation of CO_2-laser written gratings in such a fiber [17].

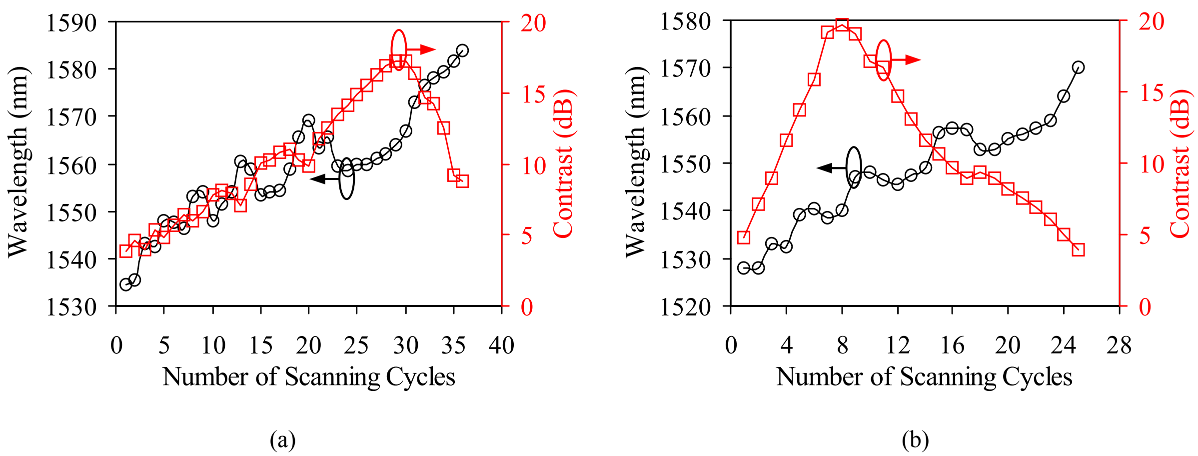

Fig. 2. Variations of the resonance wavelength and the grating contrast with the number of scanning cycles for a LPFG written in a boron-doped SMF with a CO_2-laser energy density of (a) 3.5 and (b) 4.5 J/mm^2. (Ref. [17])

Figure 2 shows the variations of the resonance wavelength and the grating contrast with the number of scanning cycles for a grating written in an unannealed boron-doped fiber for two energy densities: 3.5 and 4.5 J/mm^2. The general trend suggests that the core index increases with the number of scanning cycles and therefore glass densification should be the dominant mechanism under these writing conditions [17]. When a fiber is irradiated with CO_2-laser pulses, the fiber glass is heated at the point of irradiation because of infrared absorption. The glass volume varies with the glass temperature under different heating and cooling processes [17],[30]-[33]. Glass densification occurs when the glass is cooled rapidly from a heating temperature lower than the fictive temperature of the glass. The dynamics results in Fig. 2 show some fluctuations, which are more significant at a lower energy density. The fluctuations are of opposite trends for the resonance wavelength and the contrast, which can be attributed to the combined effect of glass densification and residual stress relaxation.

Annealing provides a simple way to separate the effects of stress relaxation and glass structure changes [34]. The residual stress can be eliminated if the annealing temperature is sufficiently high. Because the cooling process is slow, annealing can also cause glass densification and hence an increase in the refractive index and a decrease in the fictive temperature [17],[30]-[33]. The grating writing efficiency can be increased with a fiber annealed at a sufficiently high temperature. Figure 3 shows the dependence of the grating contrast on the CO_2-laser energy density after one scanning cycle for different fiber samples. The annealing process can lower the fictive temperature of the fiber core. The fiber annealed at a temperature higher than 380 – 400 °C has a low enough fictive temperature, so that a low heating temperature (i.e., a low dose of CO_2-laser radiation) can cause significant glass structure changes. The heating temperature due to CO_2-laser irradiation can become higher than the fictive temperature of the annealed glass. In that case, the heating and cooling process due to CO_2-laser irradiation can cause a significant glass volume increase.

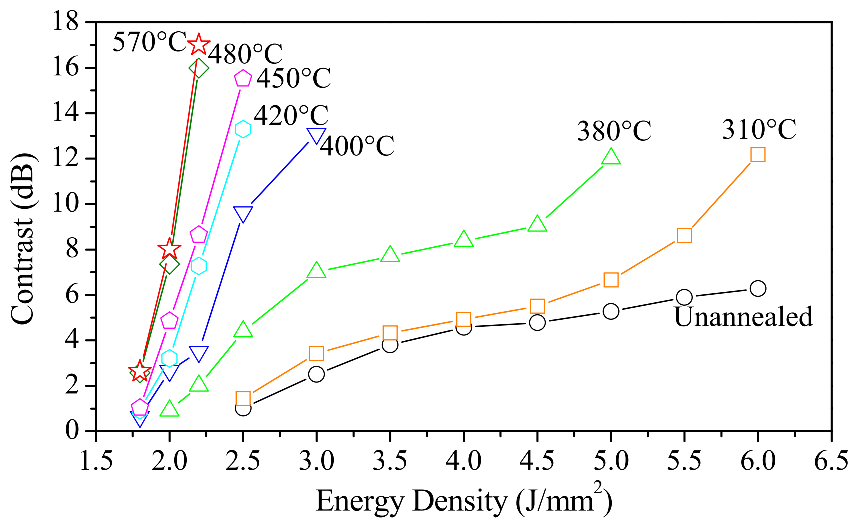

Fig. 3. Dependence of the grating contrast on the CO_2-laser energy density after one scanning cycle of CO_2-laser irradiation for gratings written in the unannealed fiber and the fibers annealed at different temperatures. (Ref. [17])

4. LPFG WRITTEN IN POLARIZATION-MAINTAINING SMF

LPFGs have been fabricated in hydrogen-loaded (i.e., photosensitive) polarization-maintaining (PM) fibers by the UV-writing method for applications as in-fiber polarizers and sensors [35]-[38]. LPFGs can be written in conventional PM fibers by CO_2-laser irradiation. Experimental results show that the writing efficiency is highest when the laser irradiation direction is along the slow axis of the fiber [9]. Figure 4 shows the change of the grating contrast with the number of scanning cycles, where the fiber cross-section is shown in the inset. When the fiber is irradiated along the slow axis, the grating reaches a maximum strength of ~15 dB with 5 scanning cycles. When the fiber is irradiated at 45° between the fast and slow axes, 9 scanning cycles are needed to reach the peak strength. When the fiber is irradiated along the fast axis, however, it takes as many as 36 scanning cycles to reach the peak strength. The amount of resonance wavelength shift per scanning cycle is largest when the irradiation direction is along the slow axis. The PM fiber has an asymmetric structure because of the presence of boron-doped stress-applying parts (SAPs) on both sides of the fiber core. When the irradiation direction is along the slow axis, one of the SAPs of the fiber is brought close to the irradiating CO_2-laser beam. The SAP is heated up by the direct absorption of the CO_2-laser beam and the heat transfer from the surface of the fiber cladding. Because a much lower CO_2-laser power is needed to write a LPFG in a boron-doped fiber than in a germanium-doped fiber due to the lower fictive temperature of the boron glass [7],[17], the heating effects result in a relaxation of the mechanical stress in the SAPs, which modifies the stress distribution and hence the refractive index in the fiber core. Therefore, the writing efficiency depends on the fiber orientation.

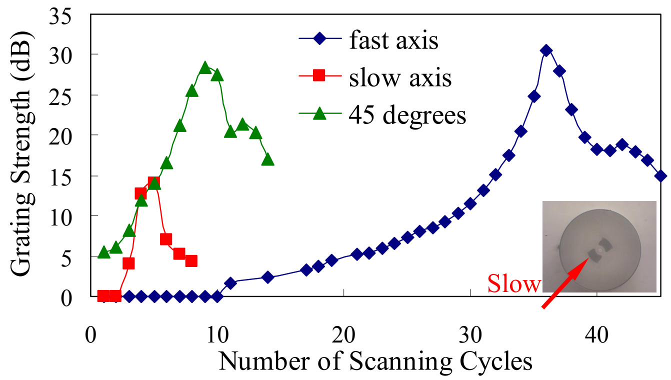

Fig. 4. Variation of the grating strength with the number of scanning cycles for three fiber orientations with respect to the irradiation direction of the writing beam for a conventional PM fiber at a CO_2-laser energy density of 7.2 J/mm^2, where the inset shows the fiber cross-section. (Ref. [9])

5. LPFG WRITTEN IN PHOTONIC CRYSTAL FIBER

Photonic crystal fiber (PCF) is a new kind of fiber, which has many promising applications in optical communications and sensing. LPFGs have been written in PCFs by tapering and deforming the fiber surface with a CO_2 laser [39]-[40]. Because of the collapse of the holes in the cladding, the effective cladding diameter decreases periodically along the fiber [39]. A phase-shifted LPFG formed in a PCF by the surface deformation technique has been demonstrated [40]. Glass structure changes can also be induced in PCFs by CO_2-laser irradiation, as in the case of the arc discharge method [31]. Therefore, LPFGs without geometry deformation can be written in PCFs using CO_2-laser pulses [41]. The strain and temperature characteristics of LPFGs written in endlessly single-mode solid silica core PCFs have been investigated experimentally and theoretically [42]. The effects of the waveguide dispersion characteristics of the cladding modes on the strain and temperature specifications have been studied experimentally. A temperature-insensitive strain sensor with a high sensitivity has been demonstrated with a CO_2-laser written LPFG [42]. LPFGs have also been formed in PCFs, including air-core PCFs, by the carving technique [43]-[45], where the periodic grooves are induced on one side of the fiber. When the fiber is stretched, the induced microbending along the fiber changes the index modulation of the grating. Therefore, the index modulation along the grating is the sum of the index changes induced by the residual stress relaxation, the perturbation of the periodic grooves, and the induced microbending [43]. Similar to a corrugated grating, such a carved grating has a high strain sensitivity. Owing to the large asymmetry of the structure, such a grating has a large PDL and can serve as a temperature-insensitive in-fiber polarizer [44]. A LPFG has been written successfully in a hollow-core PCF by the CO_2-laser carving technique [45]. The periodic perturbation of the fiber structure is considered to be the dominant factor for the formation of the grating. The collapse of the air holes in the cladding area changes the geometric structure and the mode field distribution, and hence the effective indices of the core, surface, and cladding modes [45]. One drawback of the carving technique is that the overall insertion loss of the grating can be too high, if the cladding of the fiber is excessively carved.

LPFGs have also been written in a polarization-maintaining photonic crystal fiber (PM-PCF). The dependence of the writing efficiency on the fiber orientation has been investigated [9]. Figure 5 shows the variation of the grating strength with the number of scanning cycles for two fiber orientations of a PM-PCF, where the fiber cross-section is shown in the inset. The writing efficiency obtained with the slow axis aligned with the irradiation direction is higher than that obtained with the fast axis aligned with irradiation direction, which is consistent with the finding for the conventional PM fiber. The orientation dependence of the writing efficiency is much less significant in the case of the PC PM fiber.

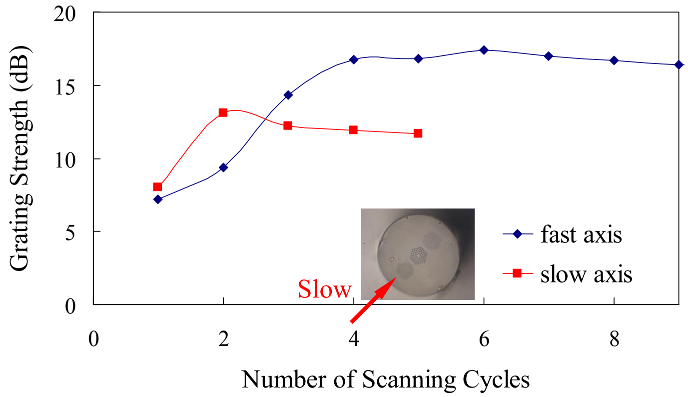

Fig. 5. Variation of the grating strength with the number of scanning cycles for two fiber orientations with respect to the irradiation direction of the writing beam for a PM-PCF at a CO_2-laser energy density of 9.0 J/mm^2, where the inset shows the fiber cross-section. (Ref. [9])

6. LPFG WRITTEN IN CONVENTIONAL SMF UNDER TENSION

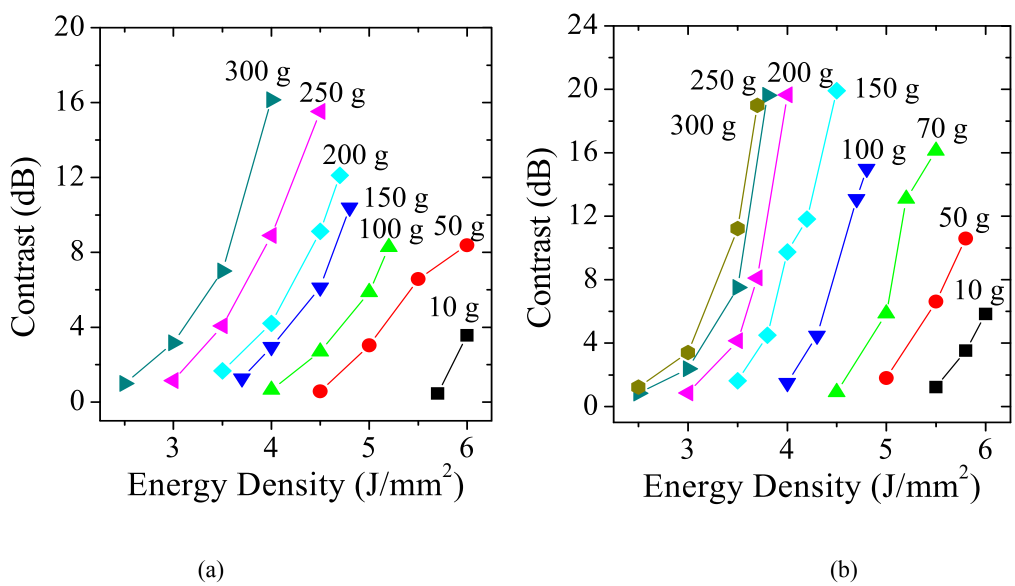

Fig. 6. Dependence of the grating contrast on the CO_2-laser energy density for LPFGs written in (a) SMF-130V and (b) SMF-28e fibers subject to different applied weights using one scanning cycle of CO_2-laser irradiation. (Ref. [50])

Recent studies [46],[47] show that, in addition to the elastic stresses, freezing of tensile inelastic stresses into the glass network structure ("frozen-in viscoelasticity") can take place during the fiber draw, which can lower the refractive index of the fiber cladding significantly [46]-[49]. Refractive-index changes due to frozen-in viscoelasticity should also be possible by heat treatment of a post-draw fiber under tension [46]-[49]. Although residual elastic stress relaxation is considered to be the dominant physical mechanism in the CO_2-laser writing process for a conventional SMF, the CO_2-laser writing efficiency can be enhanced with a fiber under tension due to frozen-in viscoelasticity [50]. The writing efficiency increases with the amount of tension applied to the fiber [50].

Fig. 6 shows the variations of the grating contrasts with the writing energy densities for the gratings written in two kinds of single-mode fibers, SMF-130V and SMF-28e (Corning). It can be seen that the threshold energy density of the CO_2-

laser radiation required for the writing of a grating decreases dramatically with an increase in the applied tension. The significant enhancement in the writing efficiency with an applied tension is attributed to the mechanism of frozen-in viscoelasticity in the fiber at the spots of the CO_2-laser irradiation [50]. To write a grating in an unstressed fiber, a sufficiently high temperature in the core is needed to relax the residual stress in the core, which demands a high dose of CO_2-laser irradiation, because the temperature inside the irradiated fiber decreases rapidly from the surface towards the core [14],[51]. To write a grating in a strongly stressed fiber, however, only a sufficiently high temperature on the fiber surface is needed to induce viscoelastic strains in the exposed cladding, which can be achieved with a relatively low CO_2-laser energy density [50]. The exposed side of the fiber is much hotter than the other side during the CO_2-laser irradiation [51] and hence has a much stronger induced frozen-in inelastic strain. The index distribution generated by frozen-in viscoelasticity is non-axially symmetric across the fiber. The experimental results confirm that the frozen-in stress can be relaxed again [50], which could be explored as a means for the fabrication of rewritable gratings. As the writing efficiency is sensitive to the applied tension, controlling the stress distribution along a fiber during the CO_2-laser writing process could be used as a means of realizing special grating characteristics.

7. APPLICATIONS OF CO_2-LASER WRITTEN LPFGS

7.1 Optical fiber sensors

LPFGs have been widely used as optical fiber sensors [3]. Thanks to their special asymmetric characteristics, CO_2-laser written LPFGs have been used as bending and torsion sensors [6],[52]. The dependences of the bending and torsion characteristics on the fiber orientation have been investigated experimentally. The fiber orientation dependence of the LPFG is determined by its asymmetric index distribution across the fiber section [6],[14],[52]. Because a CO_2-laser written LPFG has a high temperature stability [19], it can be used as a sensor for the measurement of ultra-high temperature for industry applications. The temperature sensing properties of CO_2-laser written LPFGs have been studied by different research groups [6],[27],[42],[53]. LPFGs written by the CO_2-laser carving technique are promising strain sensors [26]. Thanks to their low temperature sensitivity, LPFGs written in PCFs have been demonstrated as temperature-insensitive strain sensors [43].

7.2 Optical filters

LPFGs are intrinsically band-rejection filters [1]. Thanks to their special asymmetric index distributions, CO_2-laser written LPFGs can be used as variable optical attenuators and tunable filters [54]. By designing the bending structure, the filter characteristics can be controlled mechanically [14],[54]. Helicoidal LPFGs can be configured to function as tunable band-rejection filters [23] or bandpass filters [24]. An EDFA gain equalizer based on a LPFG written in a bend-insensitive fiber has been demonstrated [55], where the contrast of the LPFG is controlled by bending the grating at a specific circular orientation. A gain equalizer using a LPFG written directly in an erbium-doped fiber has also been demonstrated [56], where the resonance wavelength and the grating contrast are actively controlled by the changing the pump power of the erbium-doped fiber. The tuning property of a LPFG written in a PCF by the carving technique has been employed to realize a temperature-insensitive in-fiber polarizer [44]. By changing the strain applied to the carved grating, the filter characteristics of the grating can be changed. CO_2-laser carved LPFGs written in hollow-core PCFs can find many applications as special optical filters by exploring their special characteristics, such as large PDL, temperature insensitivity, large strain sensitivity, etc [45].

7.3 Optical couplers and add/drop multiplexers

To enhance the functionality of LPFGs, the structure of two parallel LPFGs has been proposed as a broadband optical coupler or optical add/drop multiplexer (OADM) for application in coarse wavelength-division-multiplexing (CWDM) systems [57]-[61], where light launched into one fiber is coupled into the other fiber through evanescent-field coupling between the cladding modes of the two parallel gratings. Recently, an optical coupler with an exceptionally large bandwidth (> 100 nm) has been realized by using two parallel specially designed gratings [62]. The coupling efficiencies that have been achieved are 50 – 65% [57]-[62]. Using the structure of three parallel gratings, a six-port balanced coupler with a coupling efficiency of 85% [63] and a symmetric 3×3 power distributor with a total power throughput of 72% [64] have been demonstrated. All these demonstrated couplers [57]-[64] employ gratings fabricated by the UV-writing method. Recently, a peak coupling efficiency of ~86% has been achieved with two parallel CO_2-laser written LPFGs in boron-doped fibers by using a suitable surrounding refractive index and offset distance between the two gratings [16].

For the LPFG written in the boron-doped SMF, the index change is induced only in the core due to the weak CO_2-laser radiation and the resultant index distribution is axially symmetric. As a result, the LPFG can give a clean transmission spectrum, just like a UV-written LPFG [16]. In the experiments, the two gratings were kept straight and placed in close contact with each other by applying a suitable tension along the fibers. The experimental results show that the coupling efficiency was practically independent of the fiber orientation. Figure 7(a) shows the variation of the peak coupling efficiency with the offset distance *s* with the surrounding index fixed at 1.0 (air) and 1.420, respectively. The peak coupling efficiency increases with the offset distance. The maximum peak coupling efficiency, measured at *s* = 60 mm with the surrounding index 1.420, is –0.66 dB, which corresponds to a power conversion efficiency of 85.9%. Figure 7(b) shows the normalized output spectra from the coupled fiber measured with the surrounding index 1.420 at different offset distances.

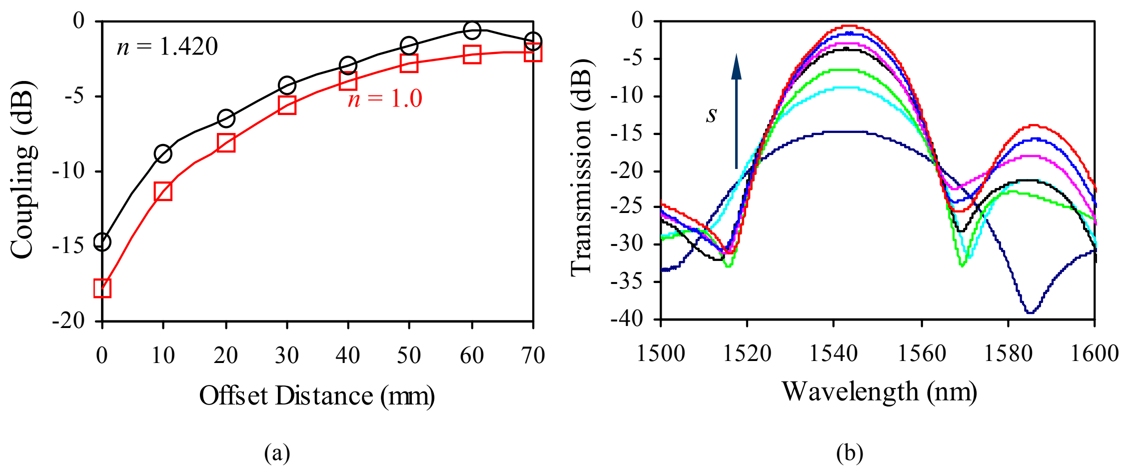

Fig. 7. (a) Dependence of the peak coupling efficiency on the offset distance with the surrounding index *n* fixed at 1.0 (air) and 1.420. (b) Normalized output spectra from the tapping fiber measured with the surrounding index 1.420 at the offset distances: *s* = 0, 10, 20, 30, 40, 50, and 60 mm. (Ref. [16])

8. CONCLUSION

We present a brief review of the recent progress on CO_2-laser writing of LPFGs in different kinds of fibers, including conventional SMF, boron-doped SMF, PMF, and PM-PCF. We show that the physical mechanisms in the writing processes can be studied fruitfully by analyzing the writing dynamics and the writing efficiency can be enhanced by applying a suitable tension along the fiber. CO_2-laser written LPFGs are finding more and more applications in both optical communications and sensing. Given the flexibility of the writing method and the increasing understanding of the writing mechanisms, we expect to see more sophisticated grating-based devices using CO_2-laser written LPFGs in the future.

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