Post-Treatment Techniques for Enhancing Mode-Coupling in Long Period Fiber Gratings Induced by CO₂ Laser

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Abstract: Two promising post-treatment techniques, i.e. applying tensile strain and rising temperature, are demonstrated to enhance the mode-coupling efficiency of the CO₂-laser-induced long period fiber gratings (LPFGs) with periodic grooves. Such two post-treatment techniques can be used to enhance the resonant attenuation of the grating to achieve a LPFG-based filter with an extremely large attenuation and to tailor the transmission spectrum of the CO₂-laser-induced LPFG after grating fabrication.

Keywords: Long period fiber gratings, fiber Bragg gratings, optical fiber sensor, temperature, tensile strain, optical fiber device.

1. Introduction

Since Davis *et al*. reported the first CO₂-laser-induced long period fiber grating (LPFG) in a conventional glass fiber in 1998 [1], various CO₂ laser irradiation techniques have been demonstrated and improved to write high-quality LPFGs in different types of optical fibers such as conventional glass fibers [2, 3], solid-core photonic crystal fibers [4, 5], and air-core photonic bandgap fibers [6]. The enhancement of the grating-writing efficiency is critical to achieving a high-quality LPFG with desired mode-coupling efficiency. A few preprocessing techniques, e.g. hydrogen loading [7] and applying prestrain [2, 8–10], have been demonstrated to enhance the writing efficiency of

the CO₂-laser-induced LPFGs. As is well known, the use of hydrogen loading can enhance the photosensitivity of the Ge-doped fibers to ultra violet (UV) exposure [11]. Hydrogen loading is also found to enhance the writing efficiency of the CO₂-laser- induced LPFGs [1, 7]. Additionally, numerous experiments reveal that the writing efficiency of the CO₂-laser-induced LPFGs could be enhanced by means of applying a tensile strain to the fiber employed during CO₂ laser irradiation [2, 8, 9], which may be due to the frozen-in viscoelasticity in the fiber. For example, as shown in Fig. 1 in [2], one of the fiber ends was tensed by a small weight to provide an external tensile strain in the fiber in advance, thus enhancing the efficiency of the grating fabrication [2]. All of these techniques above are

used to enhance mode coupling during the writing process of grating, rather than after grating fabrication. In other words, they are so-called preprocessing techniques [12].
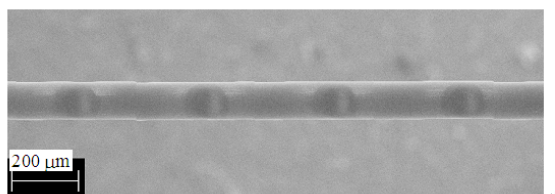

Fig. 1 SEM image of the asymmetric CO_2-laser-induced LPFG with periodic grooves (grating pitch: 400 m; number of periods: 20).

Authors recently 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 [13]. Mode coupling in such an asymmetrical CO_2-laser-induced LPFG with periodic grooves is very sensitive to the tensile strain applied and the change in external temperature. Based on these unique strain and temperature response of the CO_2-laser-induced LPFGs, we demonstrated two promising post-treatment techniques, i.e. applying tensile strain and rising temperature, for enhancing mode-coupling efficiency of the achieved LPFGs. Such post-techniques could be used to tailor the transmission spectrum of LPFGs after grating fabrication.

2. Applying tensile strain

An asymmetrical LPFG with 20 periods and a grating pitch of 400 m were written in a standard singe mode fiber (SMF) by the use of the CO_2-laser-carving technique reported in [13]. Periodic grooves were carved on the single-side surface of the fiber, as shown in Fig. 1. The resonant wavelength of this LPFG and the corresponding peak attenuation were 1512.51 nm and −28.34 dB, respectively. One end of the LPFG was fixed; whereas another end of the LPFG was tensed by a stretching force to investigate the response of mode coupling in the grating to the tensile strain applied.

As shown in Fig. 2, the resonant wavelength of the CO_2-laser-induced LPFG with periodic grooves shifted toward the shorter wavelength with an increase in the tensile strain. And the peak attenuation at the resonant wavelength was enhanced from −28.34 dB to −54.82 dB while the tensile strain applied was increased to 305 με and then reduced to −48.45 dB while the tensile stain further was increased to 620 με. Moreover, the polarization dependence in the CO_2-laser-induced LPFG also was enhanced and then reduced with an increase in the tensile strain applied, as shown in Fig. 3. Maximum polarization dependent loss (PDL) in the grating was enhanced to 27.3 dB while the tensile strain applied was increased to 305 με.
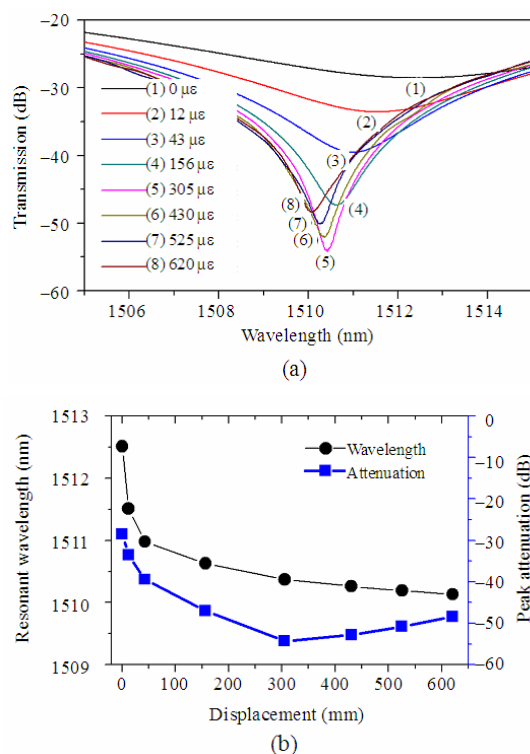

(a)

(b)

Fig. 2 Strain response of the CO_2-laser-induced LPFG: (a) transmission spectrum evolution of the CO_2-laser-induced LPFG with an increase of the tensile stain applied, and (b) resonant wavelength and peak attenuation of the LPFG as a function of the tensile strain.

Such evolutions of the transmission spectrum and polarization dependence in the CO_2-laser-induced LPFG are attributed to the enhanced coupling from the fundamental mode to the cladding mode, resulting from the stretch-induced periodic
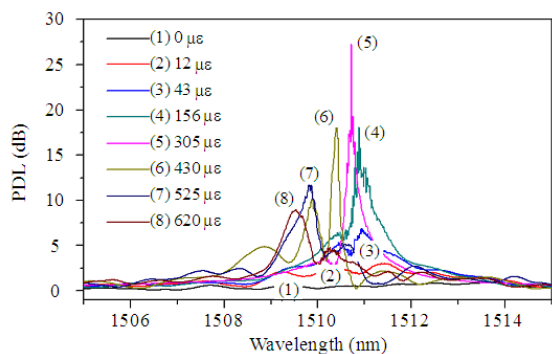
Xizhen XU *et al.*: Post-Treatment Techniques for Enhancing Mode-Coupling in Long Period Fiber Gratings Induced
by CO_2 Laser

341

Fig. 3 Polarization dependence evolution of the
CO_2-laser-induced LPFG with an increase in the tensile stain
applied.

microbends of the fiber. As shown in Fig. 4, small
lateral bends, i.e. periodic microbends, will be
induced, resulting from the asymmetric structure, at
each grooved section while the CO_2-laser-induced
LPFG with asymmetric grooves is stretched
longitudinally [14, 15]. As a result, additional
refractive index perturbation is induced by the
stretch-induced microbend in the grating due to the
photoelastic effect, thus enhancing refractive index
modulation in the CO_2-laser- induced LPFG, which
is similar to the case of the microbend-induced
LPFG [16–18]. Consequently, the coupling from the
fundamental mode to the cladding modes in the
grating is enhanced with an increase in the tensile
strain applied, which could be considered as the
continuance of the grating writing process. When the
tensile strain is increased to a critical value of about
305 $\mu\varepsilon$, the deepest attenuation dip of –54.82 dB is
observed at the resonant wavelength of 1510.40 nm,
indicating that the light at the resonant wavelength is
almost fully coupled into the cladding mode. In
other words, the optimum coupling occurs in the
grating because the exact coupling condition of
$kL=\pi/2$ is achieved, where k is the coupling
coefficient and L is the grating length. Then the
so-call over-coupling occurs with a further increase
in the tensile strain. In other word, the light that has
been coupled into the cladding mode starts to couple
back into the core mode. Thus the peak attenuation

is gradually reduced while a stronger tensile strain
of more than 305 $\mu\varepsilon$ is applied. Since the
microbend-induced refractive index perturbation in
the grating is asymmetric within the cross-section of
the fiber, the polarization dependence also is
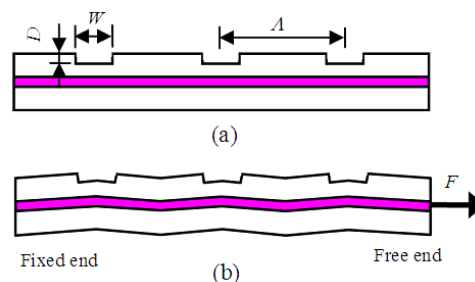enhanced with an increase in the tensile strain
applied, as shown in Fig. 3.

Fig. 4 Schematic diagram of the CO_2-laser-induced LPFG
with asymmetric grooves (a) before and (b) after a stretching
force is applied to the grating.

3. Rising temperature

To demonstrate another post-treatment
technique for enhancing the mode coupling in the
grating, we wrote another asymmetrical LPFG with
20 periods and grating pitch of 405 μm in a standard
SMF by the use of the same technique. The resonant
wavelength of this CO_2-laser-induced LPFG with
periodic grooves and the corresponding peak
attenuation were 1516.90 nm and –39.34 dB,
respectively. Then we measured the response of the
CO_2-laser-induced LPFG to the change in external
temperature. As shown in Fig. 5, the resonant
wavelength of the CO_2-laser-induced LPFG with
periodic grooves shifted from 1516.90 nm toward
the longer wavelength of 1522.89 nm while the
temperature rose from 20℃ to 100℃. And the peak
attenuation at the resonant wavelength was
enhanced from –39.34 dB to –48.53 dB with the
temperature rising. Moreover, the polarization
dependence was also enhanced with the rise of the
temperature, as shown in Fig. 6. The maximum PDL
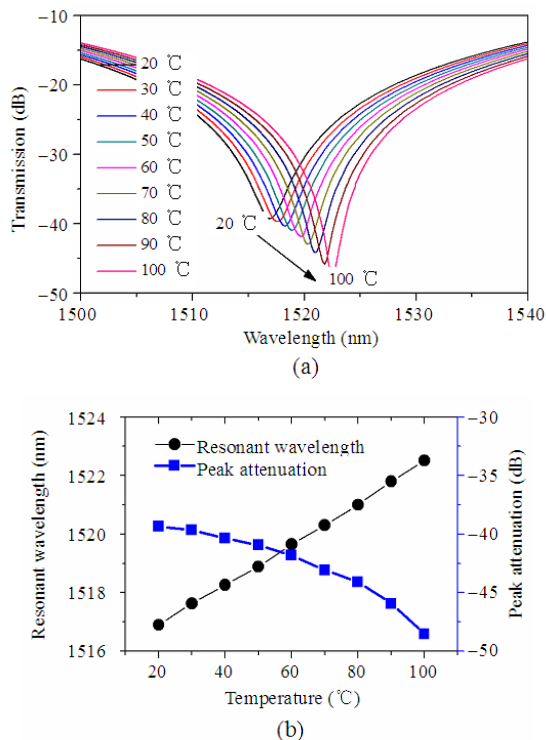in the grating was enhanced to 6.83 dB when the
temperature rose to 100℃.

(a)

(b)

Fig. 5 Temperature response of the CO_2-laser-induced LPFG: (a) transmission spectrum evolution of the CO_2-laser-induced LPFG with the rise of temperature and (b) resonant wavelength and peak attenuation of the LPFG as a function of temperature.
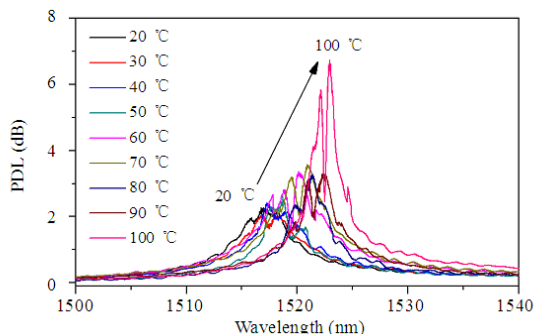

Fig. 6 Polarization dependence evolution of the CO_2-laser-induced LPFG with the rise of temperature.

As shown in Fig. 1, periodic grooves are carved on the single-side surface of the fiber. The grooved region of the LPFG is a stress concentration area due to the sharp material deformation. When the temperature rises from the room temperature at which the LPFGs are created, the thermal expansion of the fiber structure will also produce a geometric change in the dimension of the asymmetrical LPFG with periodic grooves. Furthermore, a new stress field is induced in each grooved region due to

different thermal strains (or thermal expansion) in the notched and ungrooved sections of the LPFG. As a result, this temperature-induced stress field produces an additional refractive index perturbation in the LPFG due to the photoelastic effect, which increases the refractive index modulation in the LPFG. Moreover, the refractive index of the glass itself varies slightly with temperature (also known as dn/dT), resulting from the well-known thermo-optic effect [19, 20]. Consequently, the coupling from the fundamental core mode to the cladding mode is enhanced with the rise of temperature, hence significantly enhancing the transmission attenuation of the LPFG, as shown in Fig. 5. In our experiments, we failed to observe the over-coupling between the fundamental mode and the cladding mode in the CO_2-laser-induced LPFG due to the limit of temperature adjustment range in the heating oven employed. It is expected that the over-coupling phenomenon occurs if the grating is heated to a higher temperature. In addition, the temperature-induced strain field is asymmetric within the cross-section of the grooved regions, resulting in asymmetric grooves on the single-side surface of the fiber. As a result, the polarization dependence is also enhanced with the rise of temperature, as shown in Fig. 6.

4. Discussion

As discussed above, the mode coupling in the CO_2-laser-induced LPFG is very sensitive to the tensile stain applied and the change in external temperature. Hence, after a CO_2-laser-induced LPFG is achieved, the coupling efficiency in the grating could be greatly enhanced by means of the two post-treatment techniques: applying a suitable tensile strain to the grating and raising the temperature of the grating. Such post-treatment techniques provide an easy way for achieving a LPFG-based filter with an extremely deep attenuation dip. As is well known, the most important application of LPFGs is to be used as promising band-rejection filters owing to attenuation

Xizhen XU *et al.*: Post-Treatment Techniques for Enhancing Mode-Coupling in Long Period Fiber Gratings Induced by CO_2 Laser

343

property of LPFGs at desired wavelength. The LPFG-based filters with an extremely deep attenuation dip recently find interesting applications, e.g. subpicosecond pulse-shaping [21]. However, the experimentally attainable level of control, especially for the coupling coefficient, usually does not allow a LPFG to reach the resonant attenuation values over 35 dB [22]. Fortunately, as shown in Fig. 2, the peak attenuation of the CO_2-laser-induced LPFGs can be enhanced to an extremely large value of -54.82 dB by applying a suitable tensile strain to obtain the optimum coupling, $kL=\pi/2$, at the resonant wavelength. In our experiments, an optical spectrum analyzer with a resolution of 0.02 nm was used to measure the transmission spectrum of the grating. Providing an excellent OSA with a higher wavelength resolution is employed, it is expected to observe a larger peak attenuation of more than 70 dB at the resonant wavelength while the tensile strain applied is increased by a smaller step.

Moreover, our post-treatment techniques also provide a promising method for tailoring the transmission spectrum of the LPFG to obtain desired attenuation at the expected wavelength after grating fabrication, which is required in another typical application, i.e. gain equalization of erbium-doped fiber amplifiers (EDFAs), of LPFGs. It is usually very difficult, even is impossible, to achieve an LPFG, during grating fabrication, with a desired transmission spectrum that can exactly equalize the gain of an EDFA. As shown in Fig. 2, while a tensile strain is applied to the CO_2-laser-induced LPFG, the resonant wavelength shifts toward the longer wavelength and the attenuation is enhanced. Whereas, as shown in Fig. 5, while the temperature of the CO_2-laser-induced LPFG rises, the resonant wavelength shifts toward the shorter wavelength, and the attenuation is also enhance. Hence, after an LPFG is written by the CO_2-laser-carving technique, its transmission spectrum could be tailored to exactly equalize the gain of an EDFA by the use of the proposed two post-treatment techniques above:

applying a suitable tensile strain to the grating and combining with adjusting the temperature of the grating.

5. Conclusions

The resonant wavelength of the CO_2-laser-induced LPFG with periodic grooves shifts toward the longer wavelength and the attenuation is enhanced with an increase in the tensile strain applied. Moreover, the resonant wavelength of such an LPFG shifts toward the shorter wavelength, and the attenuation is also enhanced with the rise of the external temperature. Based on these unique optical properties of the CO_2-laser-induced LPFG, two promising post-treatment techniques, applying tensile strain and raising temperature, are demonstrated to enhance mode-coupling efficiency in the grating. Such two post-treatment techniques can be used to enhance the peak attenuation to achieve an LPFG-based filter with an extremely large attenuation and to tailor the transmission spectrum of the grating to exactly equalize the gain of EDFAs.

Acknowledgement

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