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Author:
Wang, Yi-Ping; Wang, D. N.; Jin, Wei; Rao, Yun-Jiang; Peng, Gang-Ding

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Asymmetric long period fiber gratings fabricated by use of CO_2 laser to carve periodic grooves on the optical fiber

Yi-Ping Wang[a)]
Department of Electrical Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong, People's Republic of China and State Key Laboratory of Advanced Optical Communication Systems and Networks, Shanghai Jiao Tong University, Shanghai 200240, People's Republic of China

D. N. Wang[b)] and Wei Jin[c)]
Department of Electrical Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong, People's Republic of China

Yun-Jiang Rao
School of Communication and Information Engineering, University of Electronic Science and Technology of China, Chengdu 610054, People's Republic of China

Gang-Ding Peng
School of Electrical Engineering and Telecommunications, University of New South Wales, Sydney 2052, Australia

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An asymmetric long period fiber grating (LPFG) with a large attenuation of −47.39 dB and a low insertion loss of 0.34 dB is fabricated by use of focused CO_2 laser beam to carve periodic grooves on one side of the optical fiber. Such periodic grooves and the stretch-induced periodic microbends can effectively enhance the refractive index modulation and increase the average strain sensitivity of the resonant wavelength of the LPFG to −102.89 nm/mε. The resonant wavelength and the peak attenuation of the LPFG can be tuned by ~12 nm and ~20 dB, respectively, by the application of a stretching force. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2360253]

Long period fiber grating (LPFG) is one of the widely used passive optical fiber devices. Various LPFG fabrication techniques have been demonstrated, including ultraviolet laser irradiation,[1] CO_2 laser heat,[2,3] hydrofluoric acid etching corrugation,[4] and application of periodic microbend.[5] The strain sensitivity obtained for the CO_2-laser-induced LPFGs without physical deformation is usually very low, only −0.45 nm/mε.[2,3] In this letter, a technique of fabricating asymmetric LPFG by use of focused CO_2 laser beam to carve periodic grooves on one side of the optical fiber is presented. The LPFGs obtained exhibit a large peak transmission attenuation of −47.39 dB and a low insertion loss of 0.34 dB. Moreover, the average strain sensitivity of resonant wavelength of the LPFG is increased to −102.89 nm/mε.

Our experimental setup is shown in Fig. 1. A CO_2 laser (SYNRAD 48-1) with a maximum output power of 10 W, a light-emitting diode light source, and an optical spectrum analyzer (HP 70004A) were used. The optical fiber (Corning SMF-28) was situated in the focal plane of the CO_2 laser beam. One of the fiber ends was fixed and a small weight of ~5 g was used at the free end of the fiber to avoid the weight-induced macrobend and to provide a tensile strain in the fiber. The focused CO_2 laser beam scanned repeatedly for M times along the X direction at a location, corresponding to the first grating period, of the fiber via a two-dimensional optical scanner under the computer control. Then the laser beam was shifted by a grating period along the Y direction and scanned repeatedly for M times to generate the next grating period. This scanning and shifting process was carried out for N times (N is the number of grating periods) until the final grating period was created. The above mentioned process was repeated for K cycles until a high quality LPFG was produced. The repeated scanning of the focused CO_2 laser beam created a local high temperature in the fiber, which led to the gasification of SiO_2 on the surface of the fiber. As a result, periodic grooves were carved on the fiber as shown in Fig. 2. Such grooves induce periodic refractive index modulation along the fiber axis due to the photoelastic effect, thus creating a LPFG. The typical depth and width of the grooves obtained in our LPFGs were ~15 and ~50 μm, respectively. The depth of the grooves depends on a number of parameters, such as the diameter of the focused laser light spot, the scanning speed, the average laser output power determined by the repetition rate and the width of the laser pulses, and the values of M and K. In our experiments, the diameter of the focused CO_2 laser beam spot, the line speed of the scanning, the pulse repetition rate, the pulse width, and the average output power of the CO_2 laser were ~35 μm, 2.326 mm/s, 10 kHz, 4.1 μs, and ~0.5 W, respectively.

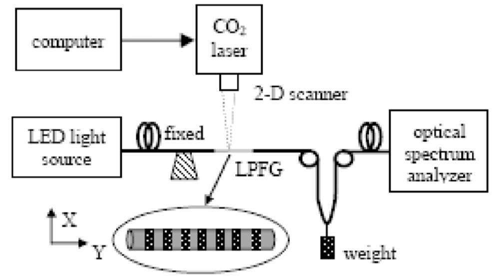

FIG. 1. Experimental setup for LPFG fabrication.

a)Electronic mail: ypwang@china.com
b)Electronic mail: eednwang@polyu.edu.hk
c)Electronic mail: eewjin@polyu.edu.hk

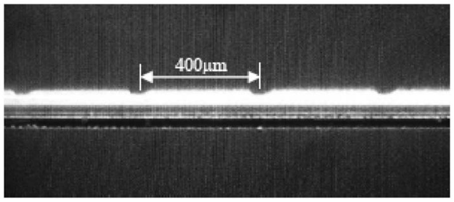

FIG. 2. Photograph, obtained from a charge-coupled device camera, of the CO_2-laser-carved LPFG with a grating pitch of 400 μm.

Figure 3 illustrates the transmission spectra of the LPFGs with grating periods (grooves) of 20, 40, 60, 70, and 80, respectively. It can be seen from this figure that, with the increase of the number of grating periods, the resonant wavelength of the LPFG shifts toward the shorter wavelength, the transmission attenuation is increased, and the 3 dB bandwidth of the attenuation is decreased. The transmission spectrum evolution of a LPFG with the increased number of scanning cycles is illustrated in Fig. 4. One high quality LPFG with a large peak attenuation of −47.39 dB at the resonant wavelength of 1520.10 nm and a low insertion loss of 0.34 dB can be obtained after nine scanning cycles.

In order to observe the strain characteristic of the LPFG produced, an external stretching force was applied to a CO_2-laser-carved LPFG with a resonant wavelength of 1569.53 nm and a peak transmission attenuation of −21.062 dB. As shown in Fig. 5, with the tensile strain increasing, the resonant wavelength of the LPFG shifts to 1557.39 nm and the peak attenuation first increases rapidly to −41.193 dB and then decreases. However, the insertion loss of the LPFG hardly changes during this process.

When an optical fiber with asymmetric structure, e.g., periodic grooves on one side of the fiber, is stretched longitudinally, small lateral bends, i.e., periodic microbends, will be induced in the grooved section of the fiber.[6] So periodic microbends will be observed when a CO_2-laser-carved LPFG with asymmetric grooves is stretched, as shown in Fig. 6. Thus, refractive index modulation in the stretched CO_2-laser-carved LPFG can be expressed as

$$\Delta n = \Delta n_{\mathrm{residual}} + \Delta n_{\mathrm{groove}} + \Delta n_{\mathrm{stretch}}, \tag{1}$$

where $\Delta n_{\mathrm{residual}}$ is the initial refractive index perturbation induced by the residual stress relaxation resulting from the high local temperature, which is similar to the case of the CO_2-laser-induced LPFGs without periodic grooves;[2,3]

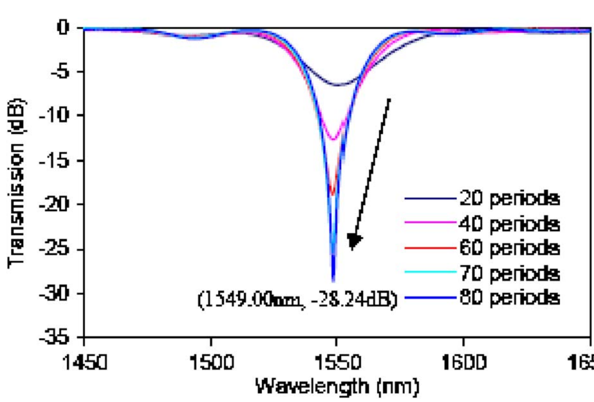

FIG. 3. (Color online) Transmission spectrum evolution of the LPFG with a grating pitch of 400 μm while N varies from 20 to 80, where M=20 and K=1.

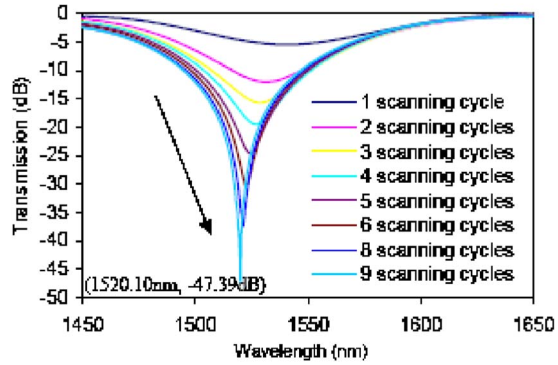

FIG. 4. (Color online) Transmission spectrum evolution of the LPFG with a grating pitch of 400 μm while K varies from 1 to 9, where N=20 and M=8.

$\Delta n_{\mathrm{groove}}$ is the initial refractive index perturbation induced by the periodic grooves on the fiber, which is similar to $\Delta n_{\mathrm{corrugated}}$ in the corrugated LPFGs fabricated by hydrofluoric acid etching;[4] $\Delta n_{\mathrm{stretch}}$ is the refractive index perturbation induced by the stretching force and can be expressed as

$$\Delta n_{\mathrm{stretch}} = \Delta n_{\mathrm{strain}} + \Delta n_{\mathrm{microbend}}, \tag{2}$$

where $\Delta n_{\mathrm{strain}}$ is the refractive index perturbation induced by the difference between the stretch-induced tensile strains in the grooved and the ungrooved regions due to the photoelastic effect;[4,6] $\Delta n_{\mathrm{microbend}}$ is the refractive index perturbation induced by the stretch-induced microbends.[5,6] Such stretch-induced microbends effectively enhance refractive index modulation in the CO_2-laser-carved LPFGs, which is similar to the case of the microbend-induced LPFG.[5] Therefore, the refractive index modulation efficiency in the CO_2-laser-carved LPFG is higher than that of the CO_2-laser-induced LPFG without periodic grooves. As a result, a large peak attenuation of −47.39 dB and a low insertion loss of 0.34 dB can be obtained in the CO_2-laser-carved LPFG, as shown in Fig. 4. By contrast, the peak attenuation of the LPFGs without periodic grooves is typically ∼ −25 dB.[1–3]

Both the difference between the stretch-induced tensile strains in the grooved and the ungrooved regions and the amplitude of the stretch-induced microbends increase with the increase of the stretching force, which leads to the increase of $\Delta n_{\mathrm{strain}}$ and $\Delta n_{\mathrm{microbend}}$. As shown in Fig. 5, the resonant wavelength shifts toward the shorter wavelength by ∼−12 nm and the peak attenuation increases by ∼20 dB when a stretching force is applied. It can also be seen from Fig. 5 that the transmission attenuation changes to the opposite direction when the tensile strain is increased beyond a critical value of ∼100 $\mu\varepsilon$. This is due to the overcoupling between the fundamental core mode and the cladding mode

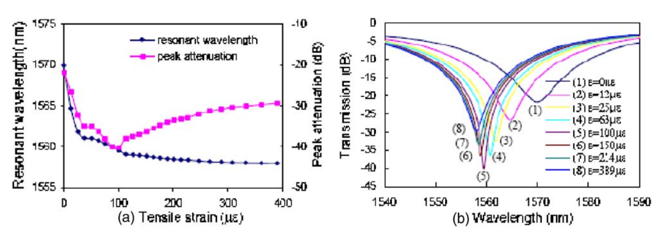

FIG. 5. (Color online) (a) Variations of the resonant wavelength and the peak attenuation, (b) transmission spectrum evolution of the CO_2-laser-carved LPFG with the tensile strain.

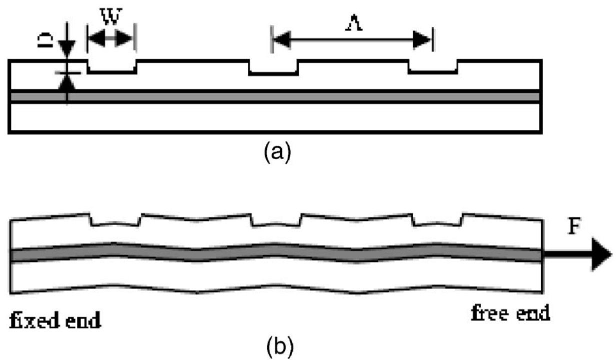

FIG. 6. Schematic diagram of the CO_2-laser-carved LPFG (a) before and (b) after a stretching force F is applied, where Λ, D, and W are grating pitch, the depth, and the width of the grooves, respectively.

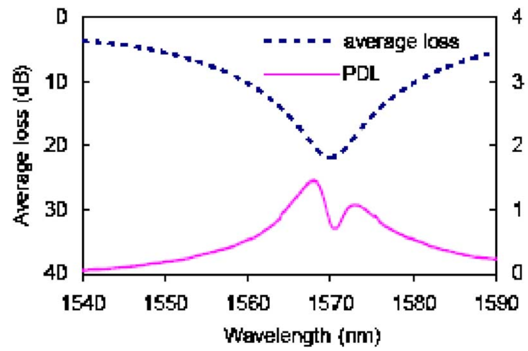

FIG. 7. (Color online) Average loss and PDL of the CO_2-laser-carved LPFG in the free state.

when a large refractive index modulation in the grating leads to the occurrence of the maximum coupling efficiency. With the increase of the tensile strain before the overcoupling, the resonant wavelength of the CO_2-laser-carved LPFG shifts from 1569.93 to 1559.58 nm with an extremely high average sensitivity of -102.89 nm/mε, compared with the value obtained with the CO_2-laser-induced LPFGs without periodic grooves, which is only -0.45 nm/mε.[3] It becomes clear that the strain sensitivity of the resonant wavelength of the LPFGs written by the CO_2 laser in the same type of optical fiber (Corning SMF-28) can be increased by 229 times by carving periodic grooves on one side of the fiber. As reported by Lin *et al.*,[4] the resonant wavelengths of the corrugated LPFG with symmetric grooves are insensitive to the tensile strain. Thus, during the LPFG fabrication, asymmetric periodic grooves, instead of symmetric periodic grooves, should be created to increase the strain sensitivity of resonant wavelength. The CO_2-laser-carved LPFG can be used both as a tunable filter with a large wavelength tuning range and as a highly sensitive strain sensor based on wavelength shift and/or intensity modulation. Compared with the strain sensors based on piezoelectric effect[7] or magnetostriction effect,[8] our LPFG sensor exhibits the advantages of electromagnetic immunity, easy fabrication, simple configuration, and no backreflection.

Single side incidence of CO_2 laser beam induces an asymmetric index profile within the cross section of the CO_2-laser-carved LPFG, which is similar to the case of the CO_2-laser-induced LPFG without physical deformation.[3,9–11] Consequently, a clear polarization dependence exists in the CO_2-laser-carved LPFG as shown in Fig. 7, where the average loss and the polarization dependent loss (PDL) are measured by an Agilent 81910A photonic all-parameter analyzer. The maximum PDL of 1.35 dB in the CO_2-laser-carved LPFG is close to the value, i.e., 1.2 dB, of that in the CO_2-laser-induced LPFGs without periodic grooves.[9,10] This indicates that the periodic grooves will not enhance the polarization dependence in the LPFG. The reason is that, although periodic grooves increase the refractive index modulation, they are confined within the outer cladding region and do not strongly influence the asymmetry of index profile within the cross section of the core and inner cladding of the LPFG.

During our LPFG fabrication process, the focused CO_2 laser beam with a high energy density, resulting from a small focused light spot with a diameter of only ~35 μm, scans repeatedly and heats continuously at each grating groove location. As a result, periodic grooves are carved on the surface of the fiber. By contrast, there is no physical deformation in the LPFGs fabricated by Davis *et al.*[2] and Rao *et al.*[3] using the CO_2 laser. Such periodic grooves in our LPFGs have essentially no contribution to the insertion loss, similar to the case of the corrugated LPFG fabricated by hydrofluoric acid etching.[4] This is due to the fact that these grooves are totally confined within the outer cladding and have no influence on the light transmission in the fiber core. Experimental results show that, as long as the grooves do not touch the central region near the fiber core, no obvious insertion loss is observed. The insertion loss of the LPFG is mainly due to the nonperiodicity and the disorder of the refractive index change.

In conclusion, asymmetric LPFGs with large peak attenuation of -47.39 dB and low insertion loss of 0.34 dB have been fabricated by use of focused CO_2 laser beam to carve periodic grooves on one side of the optical fiber. Such LPFGs combine the features of the CO_2-laser-induced LPFG without physical deformation, the corrugated LPFG created by hydrofluoric acid etching, and the microbend-induced LPFG. The resonant wavelength of the LPFG obtained can be tuned by ~12 nm with an extremely high sensitivity of -102.89 nm/mε and the peak attenuation can be changed by ~20 dB.

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