Controlling of symmetric and asymmetric mode coupling in long-period fiber gratings singe-side induced by long-pulse CO2 laser

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We report a simple fabricating approach to control the mode couplings in long-period fiber gratings (LPFGs) through side exposing fiber to long-pulse-10.6-μm laser from a cheap, internally modulated CO2 tube. By tuning focused-spot size on fibers, not only circularly symmetric mode coupling but also asymmetric mode couplings can be effectively achieved. Simulation of mode profiles in grating cross-section with Finite Element Method (FEM), and LPFG-cladding etching experiment with hydrofluoric acid (HF), support our explanation that asymmetric mode coupling in LPFGs depends on local refractive-index (RI) change within an azimuthally thin cladding layer, resulted from large-spot method induced deep melt flow on fiber surface during CO2 laser irradiation.

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1. Introduction

Long-period fiber gratings (LPFGs), consisting of periodic refractive-index (RI) perturbation with the order of hundreds of micrometers in fiber core, coupling core mode to co-propagating cladding modes, have been proposed to be widely used in optical communication and optical sensing systems [1–4]. Besides traditional method as ultraviolet (UV) beam irradiates photosensitive fiber through an amplitude mask, LPFGs can be fabricated by many other techniques [5–7], among which, kinds of point-to-point writing methods by exposing fiber to CO2 laser have been intensively researched in recent years [8–11], for their evident advantages such as high flexibility, high writing efficiency, no restriction on fiber type, high stability of grating spectrum, low insertion loss and a variety of unique characteristics. In terms of pulse duration or frequency of CO2 laser, so far most of these techniques mainly fall into two categories, one is long pulse (in the order of several hundreds of milliseconds) method [8,11] and the other is high-frequency (kHz) short pulse (in the order of microsecond) method [9]. There have been a lot of investigations on the physical mechanisms responsible for CO2 laser induced LPFGs. For conventional single mode fiber (SMF), a widely acceptable view point attributes RI perturbation in fiber core primarily to residual stress relaxation [12]. If higher CO2 dose is used to create geometric deformation on fiber, such as periodic grooves, corrugated, micro-bending or tapered structure, and if fiber is under high pulling tension during fabrication, optic-elastic effect, frozen in viscoelasticity, etc., also need consideration [10,13,14].

In the case of UV-induced LPFGs, RI perturbation is confined in fiber core, so core mode (LP01) coupling to the circularly symmetric modes (LP0m3) is absolutely predominant. However, for CO2 laser induced LPFGs, because all fused-silica materials perform high absorption at 10.6-μm wavelength, RI change in fiber cladding is inevitable. Moreover, side irradiation of CO2 laser leads to azimuthally asymmetric distribution of RI change, mainly in cladding, for the cladding area is much larger than core. As a result, coupling between LP01 and circularly asymmetric modes of LP1m3 are possibly involved, depending on the degree of RI asymmetry. On the one hand, enhanced asymmetric distribution of RI is of great benefit to LPFG-based sensors, sensitive to bending, twisting, loading and polarization, etc. [9,11,15]. On the other hand, high-order asymmetric cladding mode can be utilized in LPFG-based mode converters which couple fundamental mode to specific cladding modes, for dispersion compensation or delivering high-power femtosecond laser [16].

In this paper, we report a new alternative to write LPFGs, which basically belongs to the first category of CO2 laser writing techniques that fiber is exposed to line-focused and long-pulse CO2 laser from one side. Compared with previously reported techniques, our setup is as simplified, compact and more importantly, low cost as possible, because the irradiating source is a cheap CO2 tube. In our experiments, uniform LPFGs are made from SMF under small stretching force (10 g) without obvious deformation on fiber surface. With the irradiation of long-pulse (several hundreds of milliseconds), pure symmetric mode coupling and enhanced asymmetric mode coupling can be readily achieved by using small-spot method and large-spot (overlapping)
method respectively. Compared with tuning magnitude of coupling coefficient to realize asymmetric mode coupling in LPFGs [17], our method is easier to operate in practice. The circularly asymmetric mode coupling is attributed to local RI change within an azimuthally thin cladding layer [17], initiated by side irradiation of large spot induced deep melt flow, a conception generally concerned in the field of CO2 laser smoothing and damage repair on fused silica optics [18,19]. This explanation is verified by simulation of mode profiles in grating cross-section with Finite Element Method (FEM), and LPFG-cladding etching experiment with hydrofluoric acid (HF), in which the local RI change is removed so that asymmetric mode coupling disappears.

2. Experiment configuration and operating principle

Fig. 1(a) shows the overall schematic diagram of our proposed LPFG-fabricating system, and Fig. 1(b) shows the local pictures including primary writing devices. The entire fabrication process is computer controlled with a custom Lab-View program. Compared with previously reported CO2 laser writing method, although our setup is simplified, the flexibility is not reduced, since the setup can be adjusted in many freedom degrees. In details, firstly, the irradiating resource is a very cheap glass-structure CO2 tube (TEM00 mode outputs, the price being much lower than high-frequency CO2 laser system) with full power of 20 W, widely used in commercial carving or marking. Secondly, a ZnSe cylindrical lens, set on a 2-D (X, Y as shown in Fig. 1(a)) holder, focus the initial laser beam into a line spot, perpendicular to fiber axis with tunable spot width through changing distance between lens and fiber. Since SMF diameter (125 μm) is far smaller than the line-spot length (5 mm), the incident beam can be treated as parallel light, thus the alignment difficulty is lowered significantly, compared with spherical lens in use. However, line-focused adoption requires high power output from CO2 tube, and if a shutter is used to produce pulse exposure [11], it is dangerous to operators’ eyes because of continuous strong laser scattering; and high temperature is really a challenge to the lifetime and precision of conventional mechanical shutter (arisen from heat-absorption on shutter surface when blocking lasing). Therefore thirdly, we propose another innovation that the electric power of the laser is driven by pulse signals from computer, so that laser pulses directly output from CO2 tube. The pulse duration is controlled by the signal width, and the pulse peak power depends on a precision rheostat connected to the electric power. It is worth mentioning that our configuration needs no any frequency-stabilization technology, as long as the pulse width is longer than 100 ms (maybe the reaction time of the CO2 tube). The fluctuation of pulse peak power can be limited to 0.1 W, examined by a laser power meter (UP series, Gentec-EO). Other operating principals are similar to else point-to-point writhing methods. SMF
is mounted on two alignment fixtures, one end clamped, the other end attached to a small weight to keep the fiber straight, and side incident laser irradiates the uncoated region of fiber to write grating. Then a computer-controlled translation stage drives the alignment fixtures step by step in Z direction, one step equaling to a grating pitch. A broadband source and an optical spectrum analyzer (OSA, EXFO) are used to monitor the evolution of transmission spectrum during LPFG fabrication. In addition, the writing process is not programmed automatic purposely, because sometimes repeated exposures at one period are required to induce sufficient RI perturbation.

3. Experimental results and discussion

In spite of that similar techniques have been reported before; nevertheless, to our knowledge, it’s rarely to present the correlation between focused-spot size and optical performance of LPFGs, fabricated by side-incident and long-pulse (hundreds of milliseconds) CO₂ laser. In our experiments, it’s found that the spot width affects RI distribution in cladding cross-section, and directly determine the degree of asymmetric mode couplings in LPFGs.

3.1. Single-dip resonance and multi-dip resonance

Two writing styles, denoted as small-spot method and large-spot method respectively, are used to write LPFGs on Corning SMF-28, with identical grating period of 625 μm. In the first style, fiber core is placed close to the focus point of the cylindrical lens, the spot width being as narrow as 120 μm (measured at 1/e² of Gauss shape), as illustrated in the left of Fig. 2, and the duration, the peak power of laser pulses are 120 ms and 2.7 W, respectively. A representative transmission spectrum of the resulting LPFGs is shown in Fig. 3(a), single-dip resonance at 1532 nm with maximum rejection of 38 dB, when 30 periods were written. It corresponds to a typical mode coupling between circularly symmetric modes (LP₀₁ and LP₀₃), as the cases resulted from spot-focused writing methods. However, we attempt to fabricate LPFGs in an unusual way, in which distance between fiber and cylindrical lens is increased by 2 mm, as illustrated in the right of Fig. 2, so the spot width is enlarged to 1 mm (even larger than one grating pitch), with pulse duration and peak power added to 500 ms and 4.0 W, either. Then it’s found as the increase of period number, arising and subsiding multi-dip resonance evolution appears in transmission spectra, as shown in Fig. 3(b). Three resonant dips at the wavelengths of 1512, 1521 and 1552 nm, reached the maximum rejection at 104 periods, 94 periods and 127 periods respectively. It should be pointed out that these resonance dips present themselves within a narrow wavelength range (1510 nm – 1570 nm), not in several hundreds of nanometers, so we believed LP₀₁ mode coupling to asymmetric cladding modes (LP₁ₙ₅₅) necessarily happen. We repeated the fabrication process with the pulse peak power varied from 3.4 W to 4.9 W under same spot size, and found multi-dip resonance always appeared, although accompanied with slightly different resonance wavelengths or coupling strengths. If the pulse power is decreased further, no grating effect was produced at all, for energy density is too low with so large spot. But when using small-spot method at high pulse power, single-dip resonance returns. Thus, the presence of multi-dip resonance is confirmed not power but spot width dependent. According to the conclusion in [17], asymmetric RI change in cladding should be induced, with the large-spot method. The detailed origin explanation is as followed.

3.2. Asymmetric mode coupling induced by large-spot writing method

The resonance wavelength of LPFGs λₘ is determined by phase-matching equation:

$$\lambda_{res} = \left( n_{eff}^{core} - n_{eff}^{clad} \right) \Lambda$$

where, $n_{eff}^{core}$, $n_{eff}^{clad}$ are effective indices (EI) of core mode and cladding mode respectively, and $\Lambda$ is grating period. Based on the coupled-mode theory, the transmission of core mode is characterized by cos
diffusion from the silica surface in polar coordinates [18], which is also the viscosity is larger by a factor of 10 relative to the value on surface. The melt-flow because the mode process irradiation makes RI change asymmetrically distributed, predominately, or low asymmetric mode coupling in other words. In contrast, irradiation of as large as overlapping spot, accompanied with longer pulse duration generates much deeper melt flow on fiber surface, as the shadow part in Fig. 2, and the glass structure is rearranged quickly with viscosity change under long pulse; then the molten glass is cooled rapidly after each pulse irradiation. So the local RI decreases dramatically [22], resulting in asymmetric distribution of RI change in cladding and enhanced asymmetric mode coupling at last. Actually, still considerable laser energy yields RI perturbation in fiber core. Thus the result shown in Fig. 3 (b) reveals hybrid mode couplings. However, according to Eq. (1), pure asymmetric mode coupling can be achieved in a narrow wavelength range of several tens of nanometers, like in C-band, by adopting proper grating period.

### 3.3. Simulation by FEM

To validate the above explanation and identify the mode orders shown in spectra of our LPFGs, we use the FEM to simulate the mode profiles, under different RI distributions in the cross-section of LPFGs, with the software of COMSOL Multiphysics 4.0 (RF module). After irradiation of CO2 laser, based on our model, the azimuthal RI distribution in cross-section of a LPFG is:

$$n = \begin{cases} 
  n_1 - \Delta n & \text{(core, } r < r_0) \\
  n_2 - r\Delta n & \text{(cladding, } 20 \mu m < r < R, \phi = \phi_0) \\
  n_2 & \text{(otherwise cladding)} \\
  1 & \text{(air, } r > R)
\end{cases}$$

where, $n_1$ and $n_2$ are refractive-indices of unperturbed core and cladding before irradiation, $dn$ is the uniform RI change in core, without considering the birefringence in core [17]; the key parameter $\Delta n$ is the coefficient of RI change in cladding, characterizing the magnitude of laser induced RI variation, for a region with depth of 20 μm and azimuth range of $\phi_0$; $r_0$ and $R$ are the core and fiber radii, and $r$ is the distance from the fiber center. All parameter values used in simulation are listed in Table 1. Taking account that energy density in large-spot method is lower than that in small-spot method, the value of $dn$ is different correspondingly. As a supplement, the form of linear variation of RI in cladding and the value of $\phi_0$ are supposed, and precise RI distribution, unknown in our experiments, may be obtained using technology of micro-interferometric optical phase tomography [23]. Nevertheless, it doesn't seem to matter much for qualitative demonstration, for a series of other forms or values have been tested and results are similar.

The simulation results are shown in Fig. 4, including four neighboring cladding modes, LP02, LP11e, LP03 and LP12e, within the wavelength range from 1400 nm to 1600 nm. In small-spot method, RI change is basically limited in core, leaving symmetric RI

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**Table 1**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$n_1$</th>
<th>$n_2$</th>
<th>$dn$</th>
<th>$\Delta n$</th>
<th>$R$</th>
<th>$\phi_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Writing method</td>
<td>Small-spot method</td>
<td>1.44948</td>
<td>1.444024</td>
<td>$3 \times 10^{-4}$</td>
<td>(\)</td>
<td>62.5 μm</td>
</tr>
<tr>
<td></td>
<td>Large-spot method</td>
<td>(\)</td>
<td>(\)</td>
<td>$2 \times 10^{-4}$</td>
<td>$2 \times 10^{-6}$</td>
<td>62.5 μm</td>
</tr>
<tr>
<td></td>
<td>After etching cladding</td>
<td>(\)</td>
<td>(\)</td>
<td>(\)</td>
<td>$40 \mu m$</td>
<td>(\)</td>
</tr>
</tbody>
</table>
distribution in cladding unchanged, so the mode profiles are circularly symmetric, as shown in Fig. 4(a), and mode coupling merely occurs between LP01 and LP02, LP03. When large-spot method is used, RI distribution in cladding turns to be asymmetric; mode profiles in cladding are distorted significantly. More importantly, circularly asymmetric modes of LP11e and LP12e have field components in fiber core, as shown in Fig. 4(b), so according to Eq. (2), resonances between them and LP01 become possible.

3.4. Etching part of cladding of LPFG

To experimentally verify our viewpoints, another LPFG sample written by large-spot method was immersed into 40% HF solution, for removing part of cladding containing the local RI change. During the process, the transmission spectrum was monitored in real time. As the cladding radius was reduced, at first, all resonant dips moved to longer wavelengths, because the differences of RI between core mode and cladding modes increased [24]. Later, asymmetric mode coupling between LP01 and LP11e became weaker and weaker until disappeared, when about 22.5 μm cladding was removed, leaving only symmetric mode coupling on LP02 and LP03, as shown in Fig. 5(a)–(d). Corresponding FEM simulation is also presented in Fig. 4(c), in which, the RI perturbation in core is kept the same as before etching, while the remaining cladding returns to the case with symmetric RI distribution, and the mode profiles of LP11e, LP12e no more overlap with fiber core. So our explanation is experimentally supported.

4. Conclusion

We report a simplified and low-cost setup for point-to-point writing LPFGs, by side exposing fiber to line-focused, internally modulated long-pulse CO2 laser. This setup can fabricate not only common LPFGs with single-dip resonance in small-spot writing method, but also LPFGs with multi-dip resonance in large-spot writing method, by which core mode coupling to circularly asymmetric cladding modes can be effectively enhanced. Theoretically, side irradiation of large-spot and long-pulse CO2 laser creates much deeper melt flow under fused silica surface than small spot. This leads to local RI change within an azimuthally thin cladding layer, and make the entire RI distribution in fiber cross-section asymmetric, resulting in circularly asymmetric mode coupling at last. The explanation has been verified by FEM simulation on mode profiles in fiber cross-section and cladding–etching experiment of removing the local RI change. So our setup is able to fabricate both commonly used LPFGs with low asymmetric mode coupling and special LPFGs with enhanced asymmetric mode coupling, meaningful for LPFG-based mode converters or sensing systems.

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