Effect of CO$_2$ laser irradiation on the refractive-index change in optical fibers

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The effect of CO$_2$ laser irradiation on the refractive-index change in optical fibers is investigated by measuring the interference fringe shift formed by a long-period fiber grating pair. The refractive-index decrease on CO$_2$ laser irradiation was due to relaxation of the residual stress, which was formed in optical fibers during the drawing process, and the refractive-index decrease was found to increase linearly with the drawing force. The effect of the CO$_2$ laser output power on residual-stress relaxation, and fiber elongation was also studied. © 2002 Optical Society of America

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1. Introduction

Much attention has recently been on long period fiber gratings (LPGs) for application as fiber-optic devices such as band rejection filters and fiber-optic sensors. LPGs are usually fabricated by UV laser irradiation onto a bare optical fiber. An alternative method for LPG fabrication has been suggested that is based on CO$_2$ laser irradiation on a fiber. The LPGs can be formed by irradiating a CO$_2$ laser on periodic local areas of a fiber, which is under residual stress built up during the fiber-drawing process. The refractive-index change on the CO$_2$ laser irradiation is known to be due to residual-stress relaxation or densification. However, the grating formation mechanism by CO$_2$ laser irradiation has not yet been clearly explained.

During the cooling of an optical fiber in the drawing process, residual stress is developed across the cross section of the fiber by radial variations of the thermal expansion and viscoelastic properties. It is well known that residual stress in the fiber influences the refractive index of the fiber. The refractive index of the fiber core under residual stress $n_r$ in the radial direction is given by

$$n_r = n_0 + C_1\sigma_r + C_2(\sigma_\theta + \sigma_z),$$

(1)

where $n_0$ is the refractive index of the stress-free core and $C_1$ and $C_2$ are the stress-optic coefficients. The terms $\sigma_r$, $\sigma_\theta$, and $\sigma_z$ are the radial, circumferential, and axial components of the residual stress, respectively. The axial component of the residual stress is mainly a superposition of the thermal stress $\sigma_z^{th}$ and mechanical stress $\sigma_z^{me}$ in the axial direction. Recently we were able to measure directly the profile of the residual stress of the optical fiber and showed that only mechanical stress in the fiber was relaxed by the CO$_2$ laser irradiation, and the refractive-index change from the residual-stress relaxation was responsible for the formation of LPGs. Therefore the refractive-index change ($\Delta n_r^{sr} = \text{refractive index after irradiation} - \text{refractive index before irradiation}$) by residual-stress relaxation during CO$_2$ laser irradiation is caused by the mechanical stress change $\Delta \sigma_z^{me}$ and is given by

$$\Delta n_r^{sr} \approx C_2\Delta \sigma_z^{me},$$

(2)

where $C_2$ is known to be $-4.2 \times 10^{-12}$ Pa$^{-1}$ for pure silica glass.

In this paper, to obtain a better understanding of the refractive-index change mechanism by CO$_2$ laser irradiation, we examined the refractive-index change in an optical fiber on CO$_2$ laser irradiation by using an LPG pair. The effect of the drawing force during the fiber-drawing process, which influences the extent and distribution of the residual stress in the
fiber, on refractive-index change and subsequent refractive-index change on the CO$_2$ laser irradiation was investigated.

2. Interference Fringe Shift in a Long-Period-Fiber-Grating Pair

The refractive-index change in an optical fiber on CO$_2$ irradiation can be measured by interferometry. A Mach–Zehnder-type interferometer can be constructed in a fiber by inscribing two LPGs. Part of the incident beam after passing the first LPG is guided through the core of the fiber, whereas the rest of the beam is guided through the cladding. Two light beams guided in different optical paths are superposed after passing the second LPG, and the relative phase change in the beams between the two LPGs brings about formation of interference fringes in the spectral pattern. The interference fringes can be shifted if there is a change in optical path length between the LPGs. Since the relative optical path lengths are affected by the refractive-index change of the optical fiber on CO$_2$ laser irradiation, the refractive-index change due to CO$_2$ laser irradiation can be estimated by measuring the interference fringe shift.

From the coupled-mode theory the relative phase term before the CO$_2$ laser irradiation can be expressed as

$$m \lambda_p = -(n_{\text{eff}}^c - n_{\text{eff}}^{cl}) L, \quad (3)$$

where $m$ is an integer and $n_{\text{eff}}^c$ and $n_{\text{eff}}^{cl}$ are the effective indices of the core and cladding of the fiber, respectively. In the case of CO$_2$ laser irradiation in the local region of a fiber between LPGs, the region can be physically elongated by the thermal effect of the CO$_2$ laser beam. Thus the relative phase term after the CO$_2$ laser irradiation can be modified with the addition of the fiber-elongation term:

$$m (\lambda_p + \Delta \lambda) = -(\Delta n_{\text{eff}}^c - \Delta n_{\text{eff}}^{cl}) W_{\text{eff}} - \Delta n_{\text{eff}} \Delta L$$

$$- \left( \frac{d \Delta n_{\text{eff}}}{d \lambda} \Delta \lambda \right) L, \quad (4)$$

where $\lambda_p$ and $\Delta \lambda$ are the peak wavelength of the interference fringe and the interference fringe shift, respectively. Symbols $\Delta n_{\text{eff}}^c$, $\Delta n_{\text{eff}}^{cl}$, and $\Delta n_{\text{eff}}$ are the effective index changes of core and cladding and the effective index difference between core and cladding, $n_{\text{eff}}^c - n_{\text{eff}}^{cl}$, respectively. $W_{\text{eff}}$ is the effective length of the region irradiated by the CO$_2$ laser and depends on the beam diameter and the output power of the laser. $L$ indicates the distance between two gratings. $\Delta L$ is the physically elongated length of the heated local region of the fiber during CO$_2$ laser irradiation. Equation (4) can be rearranged by using the effective group index, $\Delta M = n_{\text{eff}} - \lambda_p d \Delta n_{\text{eff}}/d \lambda$, and the fringe spacing, $S = \lambda_p^2/(\Delta M L)$, as follows:

$$\Delta n_{\text{eff}}^c W_{\text{eff}} + \Delta n_{\text{eff}} \Delta L = \frac{\Delta \lambda \lambda_p}{S}. \quad (5)$$

Equation (4) indicates that the interference fringe shift is induced by both the refractive-index change and the fiber elongation on CO$_2$ laser irradiation. The normalized interference fringe shift, $\Delta \lambda \lambda_p / S$, is known to be unaffected by the distance between two gratings $L$ and the position of the peak wavelength $\lambda_p$.

Consequently, the refractive-index change $\Delta n$ by CO$_2$ laser irradiation can be obtained by considering the fringe shift due to the fiber-elongation term $\Delta n_{\text{eff}} \Delta L$ and the field confinement factor in the core $\eta$ as follows:

$$\Delta n = \left( \frac{\Delta \lambda \lambda_p}{S} - \Delta n_{\text{eff}} \Delta L \right) (W_{\text{eff}} \eta). \quad (6)$$

3. Experiments

A. Sample Preparation

A Ge/B-codoped preform was fabricated by using the modified chemical deposition process. Germanium and boron were added in the core for a refractive-index increase of 0.0105, but no dopants were added for the inner cladding. Then fibers were drawn by using the preform at different drawing forces $F$ of 0.53, 1.38, 2.50, and 3.48 N to induce different amounts of residual stress in the fibers. The outer diameter of the fibers and the core diameter were 123 $\mu$m and 7.2 $\mu$m, respectively.

LPG pairs with a grating period of 200 $\mu$m as a sensor part were written by irradiating with UV light on the fiber drawn at 0.53 N. Then the fiber with the LPGs was cut into two pieces so that each fiber drawn at different drawing forces can be placed between the LPGs as shown in Fig. 1. To connect the fibers, the coating on the fibers was first stripped off and then the fibers were fusion-connected by use of the fusion splicer. Table 1 shows a detailed specification of the samples. The fibers are designated A, B1, B2, C, D, E, and F according to the drawing force and the connecting condition.

B. Measurement of Interference Fringe Shift on CO$_2$ Laser Irradiation

Figure 1 shows a schematic of the experimental setup for the CO$_2$ laser irradiation on the fiber. A pulsed CO$_2$ laser (Coherent, Diamond TM-62) of 10.6-$\mu$m wavelength with a beam diameter of 7.2 mm was irradiated on the fiber without focusing. The power of the CO$_2$ laser beam was of Gaussian distribution, and the pulse frequency was maintained at 450 Hz. CO$_2$ laser output power was varied by changing the duty cycle. The irradiated zone of the fiber was selected by using the translation stage. To apply a constant tension on the fiber during the CO$_2$ laser
Table 1. Specification of the Samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>( F ) (N)</th>
<th>( S^a ) (nm)</th>
<th>( \lambda_p ) (nm)</th>
<th>( L ) (cm)</th>
<th>C, L (^b) (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.53</td>
<td>1.93</td>
<td>1585</td>
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<td>7</td>
</tr>
<tr>
<td>B1</td>
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<td>2.56</td>
<td>1583</td>
<td>15</td>
<td>11</td>
</tr>
<tr>
<td>B2</td>
<td>3.43</td>
<td>2.65</td>
<td>1587</td>
<td>15</td>
<td>11</td>
</tr>
<tr>
<td>C</td>
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<td>2.89</td>
<td>1594</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>D</td>
<td>1.38</td>
<td>2.77</td>
<td>1580</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>E</td>
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<td>1.54</td>
<td>1596</td>
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<td>7</td>
</tr>
<tr>
<td>F</td>
<td>3.43</td>
<td>1.75</td>
<td>1582</td>
<td>15</td>
<td>7</td>
</tr>
</tbody>
</table>

\(^a\)S, fringe spacing.  
\(^b\)C, L, length of the connected fibers.

irradiation, a 3.1-g weight was attached to one side of the fiber as shown in Fig. 1.

To investigate the effect of CO\(_2\) laser output power on the refractive-index change and the elongation of the fibers, the CO\(_2\) laser was irradiated by varying the laser output powers (20.5–31.0 W) on the fibers drawn at various forces (\( F = 0.53–3.43 \) N). The broadband light source (Hewlett Packard 83437A) that has a maximum output power at a wavelength of 1550 nm was used as the light source injected into the core of the fibers. The shift of interference fringe on CO\(_2\) irradiation was measured by using the optical spectrum analyzer (Hewlett Packard 70951B).

C. Measurement of the Residual-Stress Profile
Residual stress in optical fibers mainly results from the superposition of thermal stress and mechanical stress (mechanically induced stress) developed during the fiber-drawing process.\(^6\) Thermal stress is induced by the difference in thermal expansion coefficients between the core and the cladding of the fiber. Positive stress, tension, is usually developed by the thermal stress in the core of optical fibers because the thermal expansion coefficient of the core increases by adding dopants, such as Ge or P, in the core. On the other hand, mechanical stress is induced by the variation in viscoelastic property of the fiber materials. Negative stress, compression, is usually developed by mechanical stress in the core of optical fibers because viscosity decreases from the addition of the dopants. The developed mechanical stress is known to linearly increase with an increase in drawing force.\(^6,8\)

Fig. 1. Schematic setup of the measurement of refractive-index change by using an LPG pair on CO\(_2\) laser irradiation: \( d \), axial position of the fiber that is the distance from the center of the CO\(_2\) laser-irradiated region; C.L., length of the connected fibers.

Fig. 2. Interference fringe shift of an LPG pair after CO\(_2\) laser irradiation with output power of 27.7 W for 35 min.

To examine the effect of residual-stress relaxation on refractive-index change by the CO\(_2\) laser irradiation, the residual-stress profiles of the fibers (sample C, \( F = 0.53 \) N; sample F, 3.43 N) were measured at different axial positions \( d \) by using the technique described in Ref. 15. In the technique the axially symmetric cross-section profile of the fibers was assumed. Even though the residual stress was relaxed by the unidirectional CO\(_2\) laser irradiation onto the fiber, no significant nonsymmetry of the stress profiles was found because of a rather long irradiation time of 15 min. Since residual stress causes birefringence in optical fibers through the stress-optic effect,\(^7,9\) the profile of the residual stress was measured by determining the phase shift induced by the birefringence.\(^15,16\)

4. Results
A. Interference Fringe Shift on CO\(_2\) Laser Irradiation
To investigate the effect of CO\(_2\) laser output power on the refractive-index change and the elongation of the fibers, the CO\(_2\) laser was irradiated on the fibers (Sample A, \( F = 0.53 \) N; Samples B1, B2, \( F = 3.43 \) N) with different laser output powers. The laser output power was varied from 20.5 to 31.0 W. The CO\(_2\) laser was irradiated for 5 min at each irradiation.

Fig. 3. Normalized interference fringe shift by CO\(_2\) laser irradiation with different output power.
Total cumulative irradiation time was as long as 35 min, and the irradiation position was not moved during all the irradiations. The characteristic interference fringe of the fiber drawn at 3.43 N (Sample B2) before and after the CO₂ laser irradiation is shown in Fig. 2. After CO₂ laser irradiation with output power of 27.7 W for 35 min, the fringe was shifted −0.8 nm toward the shorter-wavelength side.

Figure 3 shows the normalized interference fringe shift of the fibers. For fibers with a high drawing force (Samples B1, B2, F = 3.43 N) the fringes shifted to the shorter wavelength (blue shift), indicating that the compressive residual was relaxed by CO₂ laser irradiation. The blue shift was approximately −0.23 μm by irradiation at an output power of 22.5 W for 15 min. The extent of the blue shift was found to be larger at a higher output power, and the blue shift at the output power of 27.7 W (Sample B2) was saturated at approximately 0.5 μm after irradiation for 15 min.

On the other hand, the fringe shifted to a longer wavelength (red shift) for the fiber drawn at a low drawing force (Sample A, F = 0.53 N). This result indicates that other than the residual-stress relaxation, fiber elongation during the CO₂ laser irradiation plays a role in the fringe shift. The fringe shift was approximately 0.08 μm at output power of 22.5 W for 15 min. The red shift also increased with an increase in laser output power, and this implies that fiber elongation was greater at higher power because of greater heat generation due to CO₂ laser.

Figure 4 shows a normalized interference fringe shift of the fibers drawn at different drawing forces (Samples C, D, E, and F, F = 0.53–3.43 N) with sequential CO₂ laser irradiation. After irradiation onto the fiber the next irradiations were subsequently made at positions 2 mm from the center of the previous irradiation position on the same fiber by using the translation stage. The CO₂ laser output power and the irradiation time were maintained at 22.5 W and 15 min, respectively, for all the irradiations. The fringe linearly shifted toward the longer-wavelength side for the fibers drawn at the low drawing forces (Sample C, F = 0.53 N, Sample D, 1.38 N).

However, it shifted linearly toward the shorter-wavelength side for the fibers drawn at the high drawing forces (Sample E, F = 2.50 N; Sample F, 3.43 N). The observed blue shift in the fibers drawn at the higher drawing forces is attributed to the fact that the contribution of the relaxation of the large compressive residual stress is larger than that of the fiber elongation.

B. Residual-Stress Profiles after CO₂ Laser Irradiation

Figure 5 shows the residual-stress (axial-stress) profiles of the fibers drawn with two different drawing forces (Sample C, F = 0.53 N; Sample F, F = 3.43 N) at different axial positions after the CO₂ laser irradiation with output power of 22.5 W for 15 min. The radial position r of the fiber in Fig. 5, 0–3.6, 3.6–9.8, 9.8–42.0, and 42.0–61.5 μm, represents the core, inner cladding, outer cladding (substrate tube), and jacketing tube, respectively.

While the core of the fiber drawn at a low drawing force (F = 0.53 N) at d = 5 mm was found to be under a tension of 28 MPa, the cladding was under a slight tension of 1 MPa [Fig. 5(a)]. The stress profiles at the other axial positions after CO₂ laser irradiation were similar to that at d = 5 mm. This means that the effect of CO₂ laser irradiation on the residual-stress relaxation in the fiber is negligible with the irradiation condition.

However, in the case of the fiber drawn at a high drawing force (F = 3.43 N) the effect of CO₂ laser irradiation on the relaxation was significant as shown in Fig. 5(b). At d = 4.80 mm the core was under the compression of 126 MPa, and the outer cladding was under the tension of 19 MPa. The stress profile at d = 2.80 mm was almost the same as that at d = 4.80 mm. However, the stress profile at
$d = 0 \text{–} 1.30 \text{ mm}$ became different. At $d = 0 \text{ mm}$ the core was under a compression of 50 MPa and the cladding was under a tension of 16 MPa.

Figure 6 shows the distribution of the net core stress $\sigma_{\text{core}}$ in the fibers drawn at 0.53 N (Sample C) and 3.43 N (Sample F) after the CO$_2$ laser irradiation with an output power of 22.5 W for 15 min. The net core stress was defined as $\sigma_{\text{core}} = \text{(average stress of the core) - (average stress of the inner cladding, the outer cladding, and the jacketing tube)}$. In the fiber drawn at a high drawing force ($F = 3.43$ N) the net core stress was significantly affected by the irradiation. The stress was almost constant at the side region of the irradiated center, $d \geq 3 \text{ mm}$, and the value was between $-150$ and $-156 \text{ MPa}$. At $d = 0 \text{ mm}$ (irradiation center) the stress was changed to approximately $-95 \text{ MPa}$, by the irradiation. Thus the relaxed core stress at the center of the irradiated region is $-61 \text{ MPa}$, and the relaxed stress can induce the refractive index decrease by $2.6 \times 10^{-4}$ in the core. The net core stress curve versus axial position was well fitted by the Gaussian curve, and this means that the residual-stress relaxation was dependent on the power distribution of the CO$_2$ laser beam, which is Gaussian too. However, the net core stress was almost unchanged by the CO$_2$ laser irradiation for the fibers drawn at a low drawing force ($F = 0.53$ N). Regardless of the axial position the net core stress was $-16 \text{ MPa}$.

C. Refractive-Index Change from CO$_2$ Laser Irradiation

Figure 7 shows the normalized interference fringe shift from CO$_2$ laser irradiation in the fibers (Samples C, D, E, and F) drawn at different drawing forces from 0.53 to 3.43 N, and the corresponding refractive-index change results from residual-stress relaxation by the irradiation. All the samples were subsequently irradiated 5 times with 2-mm intervals in an axial position with output power of 22.5 W for 15 min at each irradiation. The refractive-index change by CO$_2$ laser irradiation was calculated from the measured fringe shift by using Eq. (6). We assumed that the fiberelongation term ($\Delta n_{\text{eff}} \Delta L$) is constant regardless of the drawing forces of the fibers because the CO$_2$ laser-irradiation condition and fiber diameter are the same in all the fibers. Therefore the fringe shift, 0.78 $\mu$m, extrapolated for the zero drawing force was used as the fiber-elongation term in all the fibers. Since the effective index difference between core and cladding $\Delta n_{\text{eff}}$ is 0.0078, the elongated length of the fiber was estimated to be $\sim 100 \text{ m}$. Possible shrinkage of the fiber due to the structural relaxation by the thermal effect during the CO$_2$ laser irradiation can also be considered, but it is neglected because the extent is far less than the elongation. The effective length $W_{\text{eff}}$ of the CO$_2$ laser-irradiated region was estimated to be $\sim 2 \text{ mm}$ from the net core stress distribution of the fiber (Sample F) shown in Fig. 6. Thus the total effective length of the irradiated region was $\sim 10 \text{ mm}$ after sequentially irradiating a CO$_2$ laser 5 times. The field confinement factor $\eta$ of 0.83 and the stress-optic coefficient $C_2$ of the pure silica glass, $-4.2 \times 10^{-12}$ Pa$^{-1}$, were used for the calculation.$^{10}$ The contribution of dopants, Ge and B, to the stress-optic coefficient of the core glass composition was neglected.$^{17}$ The calculated refractive-index changes were $-3.6 \times 10^{-8}, -8.0 \times 10^{-5}, -1.7 \times 10^{-4}, -2.1 \times 10^{-4}$ for the fibers drawn at 0.53, 1.38, 2.50, and 3.43 N, respectively. Both the fringe shift and the refractive change were found to increase with the increase in the drawing force linearly. The linear dependence of the refractive-index change by the CO$_2$ laser irradiation can be explained by the fact that the mechanical stress developed in the fibers linearly increases with the increase in the drawing force by the viscoelastic property difference between the core and cladding.$^{6,8}$

5. Discussion

A. Fiber Elongation by CO$_2$ Laser Irradiation

The observed fringe shift toward the longer-wavelength side, especially for the fibers (Samples A, C, and D) drawn at a low drawing force as shown in
It is evident that the larger the magnitude of the weight the greater the fiber elongation.

B. Estimation of Refractive-Index Change from the Relaxed Residual Stress

The relaxed net core stress distribution with the axial position was obtained from the distribution of the net core stress shown by the bottom curve in Fig. 6, and the result is shown as a vertically hatched area in Fig. 9. To estimate the effectively relaxed net core stress that corresponds to the effective irradiation length of 2 mm, we modified the relaxed net core stress distribution into a rectangular distribution of the same area (horizontally hatched area) with \( d = 1 \) mm. Thus the height of the horizontally hatched area corresponds to the effectively relaxed net core stress. The relaxed net core stress for the effective irradiation length of 2 mm was \(-66\) MPa. The refractive-index change due to the residual-stress relaxation by using Eq. (2) was also estimated to be \(-2.8 \times 10^{-4}\), which is in good agreement with the value obtained by using an LPG pair \((-2.1 \times 10^{-4}\).

The result demonstrates that the residual-stress relaxation is the main mechanism for the refractive-index change in the optical fibers by the CO\(_2\) laser irradiation.

6. Conclusion

The refractive-index changes in the optical fibers on CO\(_2\) laser irradiation were estimated by measuring the interference fringe shift of the fibers with an LPG pair. The refractive-index changes by the CO\(_2\) laser irradiation were approximately \(-8.0 \times 10^{-5}\) and \(-2.1 \times 10^{-4}\) for the fibers drawn at 1.38 and 3.43 N, respectively. The refractive-index change was found to change linearly with the drawing force. The refractive-index change was also estimated by the relaxed net core stress and found to be in good agreement with the measured index change by using an LPG pair. The residual-stress relaxation by CO\(_2\) laser irradiation was found to be the main mechanism for the refractive-index change in the optical fibers drawn at high drawing forces. It was experimentally demonstrated that the interference fringe shifted toward the longer-wavelength side in the fibers drawn at low drawing forces (0.53 and 1.38 N) was caused by the large contribution of the fiber elongation. On the other hand, the fringe shifted toward the shorter-wavelength side in the fiber drawn at a high drawing force (2.50 and 3.43 N) was induced by a large contribution of residual-stress relaxation. The rate of fiber elongation and residual-stress relaxation was also found to increase with an increase in CO\(_2\) laser output power.

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