A Study on Refractive Index Changes Induced by Heating the Long-Period Fiber Gratings in Different Temperatures

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Abstract: A silica fiber and long-period gratings were heated to clarify the effect of the glass structure and the residual stress relaxations on the fiber index profile and resonance wavelengths. The profile changes were measured.

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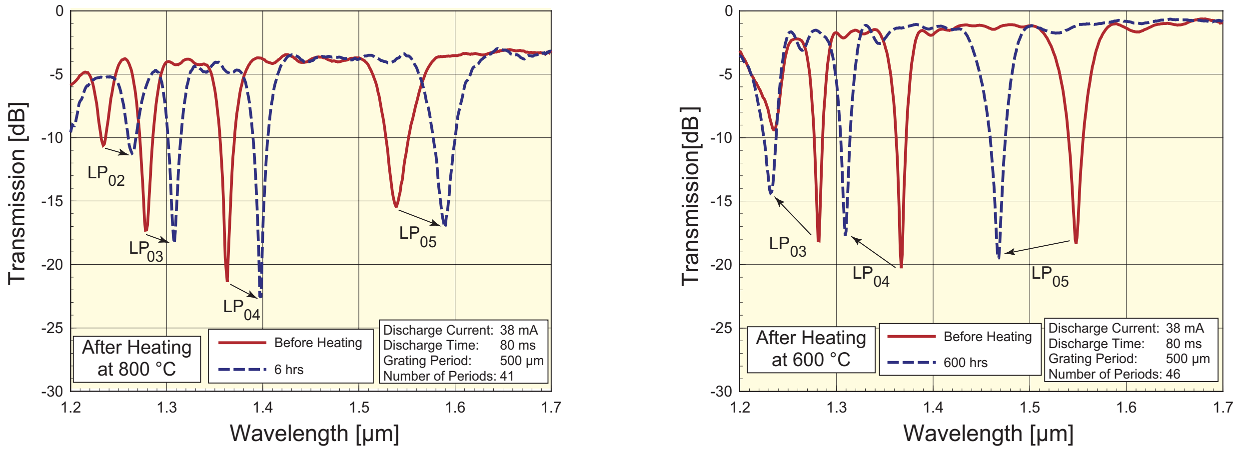
1. Introduction

Fiber gratings have been used in a wide variety of optical communication and sensing applications. Long-period gratings (LPGs) have become attractive for band-reject filters, erbium doped fiber amplifier gain flattening, and fiber based sensors. In all these devices, it is very important for practical use to adjust the transmission characteristics after grating fabrication. The resonance wavelengths of LPGs written by arc discharge were adjusted by heating [1], and the adjustable ranges of resonance wavelengths were broadened toward the blue wavelength side by decreasing heating temperature [2]. It was explained that the glass structure relaxed more slowly than the residual stress with decreasing heating temperature and the blue shift caused by the residual stress relaxation appeared more strongly at the early stage of heating. It is of high interest to clarify the effect of the glass structure and the residual stress relaxations on the fiber index profile and resonance wavelengths.

In this paper, we heated a standard silica fiber and LPGs written in it at different temperatures, and measured the change of the refractive index profile caused by heating for the first time as far as the authors know. The change of the core-cladding index difference was estimated by numerical analysis on the basis of experimental data.

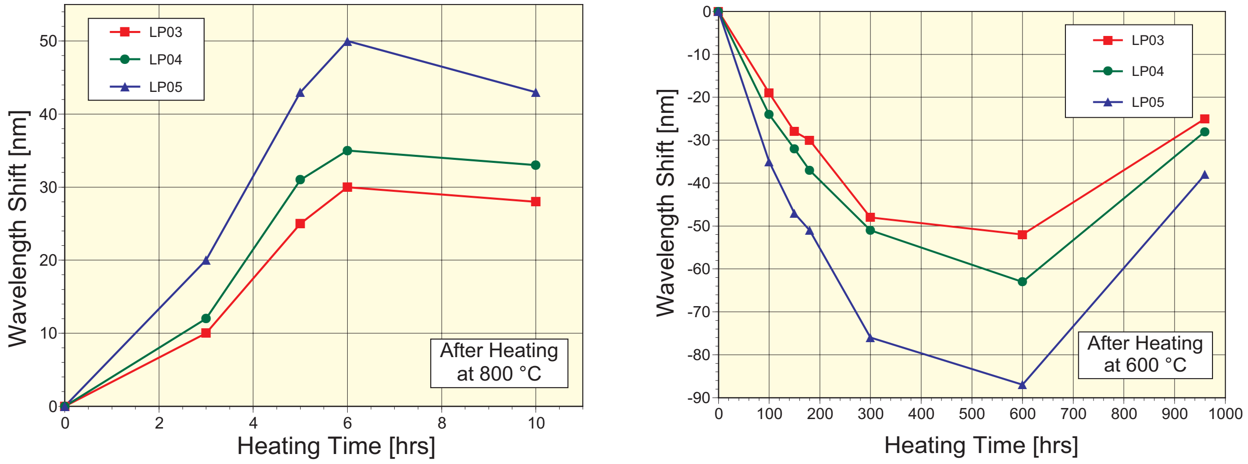
2. Experimental results

LPGs were written in a conventional silica fiber (Corning SMF-28e) by a point-by-point arc technique. We removed all coating of the fibers that the LPGs were written in, and put these samples as well as the bared fibers without LPGs inside a muffle furnace. The samples of LPGs and the bared fibers were heated at different temperatures for various time durations to investigate the core and the cladding refractive index changes. After heating, we let the fibers and the LPGs cool down gradually inside the furnace to the room temperature. Fig. 1(a) and (b) shows the transmission spectra of the LPGs before and after heating at 800 °C for 6 hours and 600 °C for 600 hours, respectively. The loss peaks are generated by coupling from the LP_{01} core mode to the LP_{0m} (m=2, 3, 4, and 5) cladding modes.



(a) (b)

Fig. 1 Changes of transmission spectra of the LPGs before and after heating at (a) 800 °C and (b) 600 °C



(a) (b)

Fig. 2 Resonance wavelength shifts of LP_{0m} (m=3, 4, 5) as heating time at (a) 800 °C and (b) 600 °C

Fig. 2 shows the resonance wavelength shifts of the LP_{03}, LP_{04}, and LP_{05} modes against heating time at heating temperature of 800 °C and 600 °C. For Fig. 2(a), the maximum red wavelength shift occurs around 6 hours and this shift is more for the higher order cladding mode. Fig. 2(b) shows that the resonance wavelengths shift to the blue side at the beginning of heating and they become minimum at about 600 hours, and then they begin to shift to the red wavelength side.

To investigate the change of the core and cladding refractive indexes induced by heating, we measured the index profile of the fiber at 0.675-µm wavelength using the refracted near-field (RNF) technique. The refractive index of the matching oil used in this measurement was 1.48127 at 20 °C for 0.675 µm and the temperature coefficient was –0.000377/°C. Fig. 3 shows the index profile of the fiber unheated (solid), heated for 300 hours (broken) and 960 hours (dotted) at 600 °C. We can see that the cladding refractive index increases with increasing heating time. However we cannot recognize the change of the core-cladding index difference as shown in the inset because of the limitation of the index profile resolution.

3. Discussion

The resonance wavelength shifts caused by heating was illustrated by the competition between the glass structure and the residual stress relaxations [2]. The refractive index of a glass can be modified by the glass structure relaxation. The temperature that corresponds to the equilibrium glass structure is called the fictive temperature. In case a glass is heated at a higher temperature and a lower temperature than its fictive temperature and is cooled rapidly, the glass structure is modified and the refractive index is decreased and increased, respectively. In the LPG fabrication a fiber is heated locally by arc discharge at a higher temperature than the fictive temperature of the drawn fiber T_F and cooled rapidly.

When the fiber glass is rapidly taken to the temperature T_H, the change of the fictive temperature of the fiber glass $\overline{T}(t)$ can be expressed by Tool's equation as follows [3]:

$$\frac{d\overline{T}(t)}{dt} = A\left(T_H - \overline{T}(t)\right) \qquad (1)$$

where A is approximately reciprocal of the viscosity. The fictive temperature of drawn silica fibers is known to be around 1600 °C. The LPGs written in the silica fiber were heated at a lower temperature T_H than T_F and the refractive indexes of the core and the cladding in the non-discharged region increase owing to the decrease of the fictive temperature and the increase of the density. The core index is thought to be increased slightly more than the cladding index by heating, because the viscosity of the core glass, Ge-doped silica, is a little lower than that of the cladding glass, pure silica. Therefore the effective index of the LP_{01} core mode n_{01} increases more than that of the LP_{0m} cladding mode n_{0m}, and ($n_{01}- n_{0m}$) is increased. The resonance wavelengths are shifted to the red side, because the resonance wavelength λ_{res} is obtained by the phase-matching condition:

$$\lambda_{res} = (n_{01} - n_{0m})\Lambda \qquad (2)$$

where Λ is the grating period. The resonance wavelengths shift until the glass structure in the non-discharged region reaches the equilibrium state [1, 2]. After reaching the equilibrium state, the resonance wavelengths become steady.

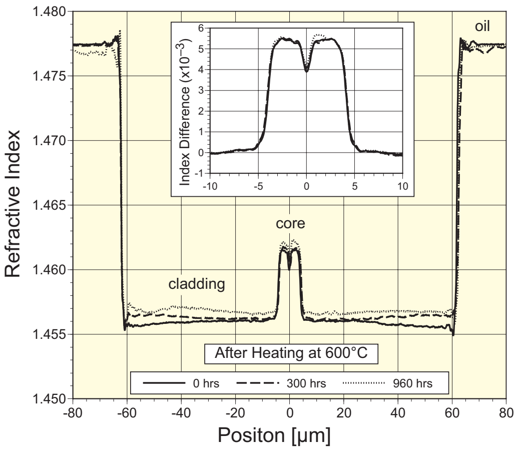


Fig. 3 Measured refractive index profiles of the fibers heated at 600 °C for different heating times.

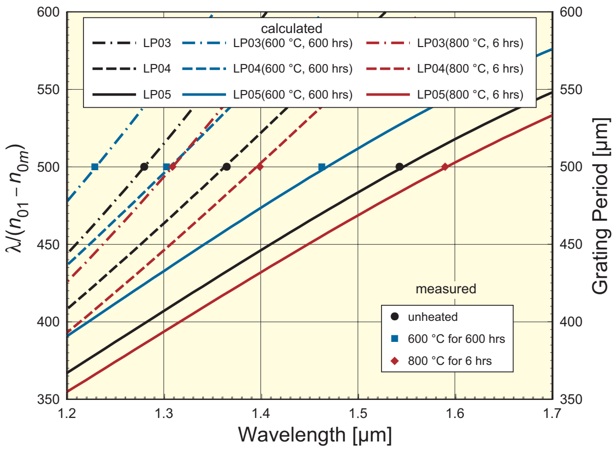


Fig. 4 Calculated relationship between resonance wavelengths and grating periods, and the measured resonance wavelengths.

Since the SMF-28e is Ge-doped silica core/pure-silica cladding fiber, the residual stress produced by fiber drawing is compressive in the core and tensile in the cladding [4]. The refractive indexes of the core and the cladding are reduced and increased by the residual stress relaxation induced by heating, respectively, and the core-cladding index difference and ($n_{01}-n_{0m}$) decrease, then the resonance wavelengths are shifted to the blue side. The resonance wavelengths move to the blue side until about 600 hours at 600 °C as shown in Fig. 2(b), and then begin to grow. The residual stress is thought to be almost released by heating for about 600 hours at 600 °C. Since the core and the cladding indexes increase with heating time as shown in Fig. 3, it becomes clear that the red shifts are due to the glass structure relaxation induced by heating. The increase of the cladding index shown in Fig. 3 becomes larger near the fiber surface. The index increase near the surface might contribute to the blue shift. It is necessary to measure the change of the residual stress of the heated fibers in order to clarify the cause of the blue shift.

As it is difficult to measure the small change of the core-cladding index difference, we are going to estimate the amount of the change by numerical analysis using the equivalent staircase index profile. We applied the scalar approximation to calculate the effective indexes of the LP_{01} core mode (n_{01}) and the LP_{0m} cladding mode (n_{0m}) in a fiber with three layers of core, cladding, and air. Fig. 4 shows the calculated relationship between resonance wavelengths and grating periods. The solid, broken, and dot-dash lines are $\lambda_{res}/(n_{01}-n_{0m})$ calculated for the LP_{05}, LP_{04} and LP_{03} cladding modes, respectively. The black circles are the measured resonance wavelengths of the LPG with grating period of 500 µm without heating and agree well with the calculated ones. The blue squares in this figure are the resonance wavelengths blue-shifted most after heating at 600 °C for 600 hours. The reduction of the core-cladding index difference was estimated at -2.3×10^{-4}. The red diamonds are the observed resonance wavelengths of the LPG after heating at 800 °C for 6 hours. The increase of the index difference was evaluated at $+1.4\times10^{-4}$, and the calculated resonance wavelength shifts correspond almost with the measured shifts.

3. Conclusions

We studied the refractive index change of a silica fiber caused by heating to clarify the effect of the glass structure and the residual stress relaxations on resonance wavelengths shifts. The change of the refractive index profile caused by heating was measured for the first time. It becomes clear that the wavelength shifts to the red side induced by heating are due to the increase of the core and the cladding indexes caused by the glass structure relaxation.

Acknowledgments

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