CHANGING RESONANCE WAVELENGTHS OF LONG-PERIOD FIBER GRATINGS BY THE GLASS STRUCTURE MODIFICATION

Katsumi Morishita[1] and Akihiro Kaino[2]
[1]Osaka Electro-Communication University, Neyagawa, Osaka 572-8530 Japan, e-mail: morisita@isc.osakac.ac.jp
[2]Osaka Electro-Communication University, Neyagawa, Osaka 572-8530 Japan, e-mail: m04105@isc.osakac.ac.jp

Abstract: Long-period fiber gratings written by arc discharge are heated at different temperatures, and the post-heating changes of transmission characteristics are investigated. The resonance wavelengths are shifted to longer wavelengths by heating at the lower temperature than the structural temperature of the fiber, and they move more quickly with increasing heating temperature. The resonance wavelength shifts more largely for the loss peak generated by the higher cladding mode. It becomes evident that the resonance wavelength can be changed and adjusted by heating temperature and heating time without significant degradation.

1. INTRODUCTION

Modifying refractive index locally is a very important technique for fabricating optical devices and changing their optical properties. Fiber gratings, which are commonly made by local index change, have been increasingly used in a wide variety of optical communication and sensing applications. It is very valuable for practical use to change and adjust their transmission characteristics. In this paper we have studied the possibility of changing resonance wavelengths of LPGs by the glass structure modification. The glass structure change is a simple and widely applicable method to modify refractive index. The index difference between the core and the cladding of dispersive fibers was controlled by the glass structure change generated by annealing [1, 2]. Mode-field transformers were made by the glass structure modification induced by heating locally [3]. Long-period gratings (LPGs) were written in a conventional silica fiber [4] and a pure silica holey fiber [5] by the rapid glass structure rearrangement induced by arc discharge.

The temperature sensitivity of LPGs written in silica fibers [6, 7] and a pure silica holey fiber [8] was investigated for temperatures up to about 1200 °C. The resonance wavelength shifted almost linearly with increasing temperature for up to about 800 °C for silica fibers and 900 °C for the holey fiber. For higher temperatures the resonance wavelength shift had a nonlinear dependence on temperatures. However the post-heating changes of the transmission characteristics of LPGs have not been examined yet.

In this paper, the LPGs are heated at different temperatures to change the glass structure, and the post-heating changes of resonance wavelengths and peak losses are examined against heating temperature and heating time. The mechanisms of the resonance wavelength shift and the peak loss change are investigated based on the glass structure change.

1. INDEX MODIFICATION BY THE GLASS STRUCTURE CHANGE

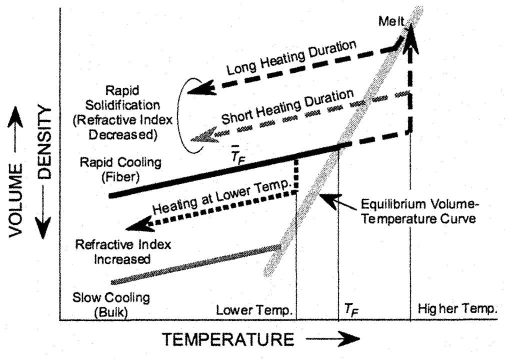

Figure 1. Schematic diagram of volume-temperature variation of a glass for heat treatments.

The index modification generated by the glass structure change results from the structural relaxation [9]. Figure 1 shows a schematic diagram of volume-temperature variation of a glass for heat treatments. When a glass is maintained at a constant temperature, the volume changes with time until it reaches a certain equilibrium glass structure. The temperature that corresponds to the equilibrium glass structure is called the structural temperature. The light gray line indicates an equilibrium volume-temperature curve. When temperature drops slowly, the glass structure changes with temperature, and the viscosity of the glass increases. Finally the glass cannot trace the equilibrium curve, and then the glass structure is frozen. The fiber glass is cooled faster than the bulk glass and the glass structure is frozen at the higher temperature T_F than that of the bulk glass. The density and the refractive index of the drawn fiber become lower than those of the bulk glass. Since the glass structure of the drawn fiber is the same as the equilibrium glass structure at T_F, the structural temperature of the fiber is expressed by $\overline{T_F}$.

In the LPG fabrication, a drawn fiber is heated locally to above the melting temperature, and then is cooled rapidly. The refractive index is decreased by rapid solidification as indicated by the broken lines. The index reduction can be adjusted by heating temperature and heating time. In case of heating at the lower temperature than T_F, the fiber glass approaches the equilibrium state, and the refractive index is increased as shown by the dotted line. In this paper, LPGs are written in a standard silica fiber (Corning SMF-28) by arc discharge with moving the discharge point periodically [4], and the LPGs are heated at the lower temperature than T_F to change the transmission characteristics.

1. SPECTRAL TRANSMISSION CHANGES INDUCED BY HEATING LONG-PERIOD FIBER GRATINGS

It was shown that the observed structural temperatures of the drawn fibers were in the range of 1150 – 1660 °C for single-mode silica fibers [10]. The fabricated LPGs, therefore, are heated at different temperatures below 1150 °C to increase the refractive index of the fiber, and the post-heating variations of the transmission characteristics are investigated.

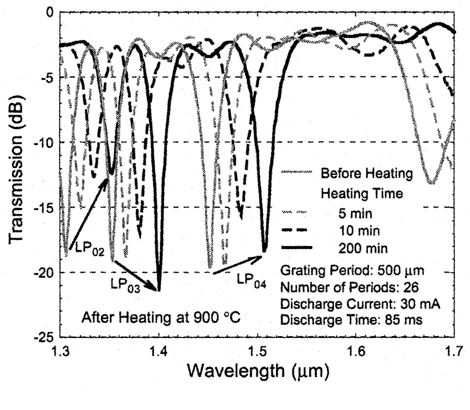

Figure 2. The transmission spectra of the LPG written with the discharge current and time of 30 mA and 85 ms before and after heating at 900 °C for 5, 10, and 200 minutes.

Figure 2 indicates the transmission spectra of the LPG with the grating period of 500 μm before and after heating at 900 °C for 5, 10, and 200 minutes. The LPG is written with the discharge current and time of 30 mA and 85 ms. The number of periods is 26. The LPG is heated by a ceramic heater. The spectral transmissions of the LPG are recorded after cooling to room temperature. The loss peaks are generated by coupling from the LP_{01} core mode to the LP_{02}, LP_{03}, and LP_{04} cladding modes, and are indicated by LP_{02}, LP_{03}, and LP_{04}, respectively. The resonance wavelengths are shifted to the longer wavelength region with heating time. The peak loss of the LP_{02} mode decreases with heating time, and those of the LP_{03} and LP_{04} modes decrease at the beginning, and begin to increase after that.

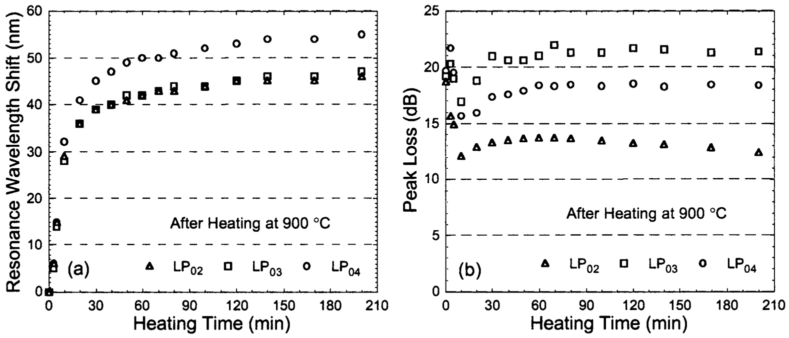

Figure 3. The changes of (a) the resonance wavelengths and (b) the peak losses of the LPG with the grating period of 500 μm against heating time at 900 °C. The discharge current and time are 30 mA and 85 ms, and the number of periods is 26.

Figure 3(a) shows the resonance wavelength shifts of the loss peaks generated by the LP_{02}, LP_{03}, and LP_{04} cladding modes against heating time at 900 °C. We measure the resonance wavelength shift after taking the LPG from the heater and then take it back in the heater for the longer heating time. Heating time is the accumulated total time. The resonance wavelength shift is larger for the higher cladding mode. The resonance wavelength increases with heating time. The increase rate is large at the beginning of heating and then becomes smaller with heating time.

The resonance wavelength λ_{res} is obtained by the phase-matching condition

$$\lambda_{res} = (n_{01} - n_{0m})\Lambda, \qquad (1)$$

where Λ is the grating period, and n_{01} and n_{0m} are the effective indexes of the LP_{01} core mode and the LP_{0m} cladding mode. The refractive indexes of the core and the cladding are raised by heating the LPG at the lower temperature than T_F. The effective index is increased more greatly for the lower mode because of its larger power fraction within the fiber. Therefore the effective index difference, ($n_{01} - n_{0m}$), is increased more largely for the higher cladding mode, and the resonance wavelength shift becomes larger for the higher cladding mode as shown in Figure 3(a).

When the fiber glass with the structural temperature of $\bar{T}_F$ is rapidly taken to the temperature T_H, the structural temperature $\bar{T}(t)$ changes as follows [9]:

$$\frac{d\bar{T}(t)}{dt} = A\left(\bar{T}_H - \bar{T}(t)\right), \qquad (2)$$

where A is the reciprocal of the viscosity, and $\bar{T}_H$ is the structural temperature corresponding to the equilibrium glass structure at the heating temperature T_H. The structural temperature $\bar{T}(t)$ is obtained by solving (2), and is shown by

$$\bar{T}(t) = \bar{T}_H + (\bar{T}_F - \bar{T}_H)\exp(-At). \quad (3)$$

The change of the structure temperature decreases exponentially with time, and the structural temperature $\bar{T}(t)$ approaches $\bar{T}_H$. The change becomes faster for the higher heating temperature T_H because of the lower viscosity. In case the heating temperature T_H is lower than the structural temperature of the drawn fiber $\bar{T}_F$, the refractive indexes of the core and the cladding increase and their increase rates decrease exponentially with heating time. Therefore the resonance wavelength grows quickly at the beginning of heating and then increases more slowly with heating time as shown in Figure 3(a).

Figure 3(b) shows peak losses generated by the LP_{02}, LP_{03}, and LP_{04} cladding modes against heating time at 900 °C. The peak losses decrease rapidly within about 10 minutes, and then gradually increase, and come to change just a little. The change of the peak loss is caused by the variation of the coupling coefficient between the core and the cladding modes, which is determined by the form of the index reduction generated by arc discharge along the fiber. The residual stress is released at the middle of the discharged area, but is not released completely around the discharged region. When the LPG is heated, the residual stress around the discharged part is released quickly, and the stress relaxation changes the coupling coefficients and the peak losses.

The residual stress relaxation in the undischarged part modifies the effective indexes and moves the resonance wavelengths. The resonance wavelength of a LPG written in SMF-28 shifted by 1.2 nm to short wavelengths owing to the stress relaxation induced by heating at 800 °C for 1 hour [7]. The residual stress of pure-silica-core/fluorine-doped-silica cladding fibers was almost removed by heating at 900 °C within 10 minutes [11]. Therefore we consider that the residual stress of a Ge-doped-silica core/pure-silica cladding fiber, SMF-28, is almost released by heating at 900 °C within 10 minutes and the peak losses change rapidly within 10 minutes. After the residual stress relaxation within 10 minutes, the glass structure change becomes a main factor of the peak loss variations. The glass structure changes more slowly with heating time, and the form of the index modification changes moderately, and the peak losses vary slowly as shown in Figure 3(b).

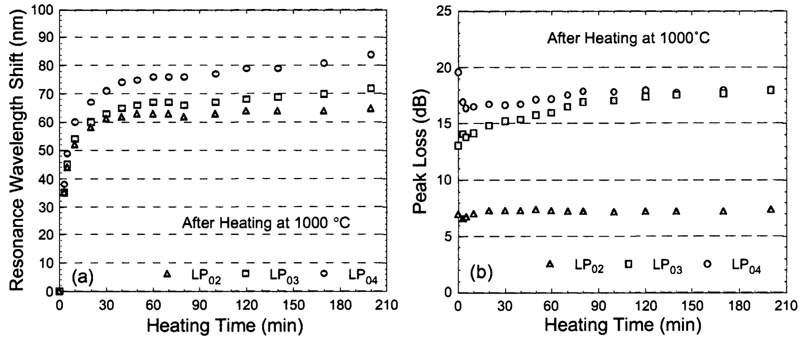

Figure 4. The changes of (a) the resonance wavelengths and (b) the peak losses of the LPG with the grating period of 500 μm against heating time at 1000 °C. The discharge current and time are 33 mA and 100 ms, and the number of periods is 30.

Figure 4(a) shows the resonance wavelength shifts of the LPG against heating time at 1000 °C. The resonance wavelength increases with heating time. The increase rate at 1000 °C is very great at the start of heating and larger than that at 900 °C, and then becomes smaller. Since the viscosity becomes lower at the higher temperature, the glass structure changes faster and reaches the equilibrium state in the shorter time as shown by (3). Therefore the resonance wavelength moves more quickly at 1000 °C than 900 °C and reaches a constant value earlier. The resonance wavelengths become almost constant at about 80 minutes, and after 80 minutes the resonance wavelengths begin to increase again. The increase after 80 minutes would be caused by elongation of the fiber.

Figure 4(b) shows peak losses generated by the LP_{02}, LP_{03}, and LP_{04} cladding modes against heating time at 1000 °C. The peak losses change rapidly within 5 minutes, and then gradually increase. We consider that the rapid changes of peak losses within 5 minutes result from the residual stress relaxation, because the residual stress is relaxed faster at 1000 °C than 900 °C. The peak losses are almost constant after 80 minutes, and it becomes evident that heating at 1000 °C does not degrade the LPG until 200 minutes.

Figure 5(a) shows the resonance wavelength shifts of the LPG against heating time at 1100 °C. The resonance wavelengths move rapidly to longer wavelengths within 3 minutes, and then shift slowly to longer and shorter wavelengths. The glass structure changes faster and reaches the equilibrium state in the shorter time at 1100 °C than 1000 °C. The glass structure in the undischarged area is thought almost to reach the equilibrium state in about 5 minutes. Therefore the effective indexes of the core and the cladding modes, n_{01} and n_{0m}, hardly increase after 5 minutes, and the resonance wavelengths change little. The resonance wavelength shifts after heating time of 20 minutes result from broadening of loss peaks, elongation of the fiber, and degradation of the LPG.

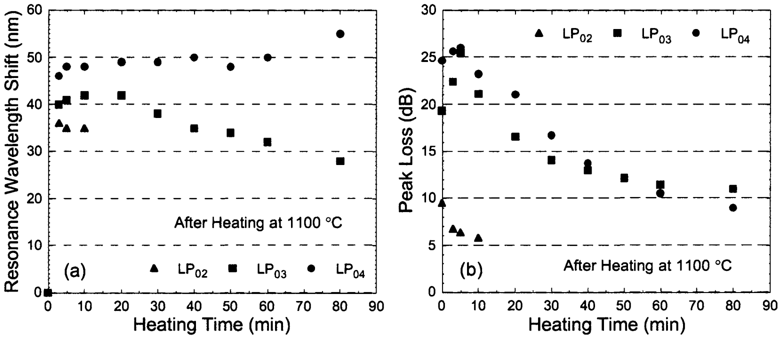

Figure 5. The changes of (a) the resonance wavelengths and (b) the peak losses of the LPG with the grating period of 500 μm against heating time at 1100 °C. The discharge current and time are 33 mA and 95 ms, and the number of periods is 32.

Figure 5(b) shows the peak losses generated by the LP_{02}, LP_{03}, and LP_{04} cladding modes against heating time at 1100 °C. All peak losses reduce for the longer heating time than 5 minutes. The glass structure in the undischarged part almost reaches the equilibrium state in about 5 minutes, but that in the discharged part does not become equilibrium yet owing to the higher structural temperature. Therefore the glass structure in the discharged part continue to approaches the equilibrium state after 5 minutes, and the index difference between the discharged and the undischarged parts decreases with heating time. That reduces the amplitude of the index modification along the LPG, and the loss peaks become shallower and broader with heating time. Since heating at 1100 °C makes the residual stress release very fast and the glass structure change very rapidly, it is difficult to observe the peak loss variations caused by the residual stress relaxation.

1. CONCLUSIONS

Long-period fiber gratings written by arc discharge are heated at different temperatures, and the post-heating changes of resonance wavelengths and peak losses are investigated. It is shown that the resonance wavelengths can be changed and adjusted by heating temperature and heating time without significant degradation. The resonance wavelengths are shifted to longer wavelengths by heating LPGs at the lower temperature than the structural temperature of the fiber. The resonance wavelength shifts more greatly for the loss peak generated by the higher cladding mode because of its lower power fraction within the fiber. Heating at the higher temperature moves the resonance wavelengths more quickly and makes them reach constant values earlier. The resonance wavelengths come almost to constant values at 1100 °C for 5 minutes. However all peak losses are reduced after 5 minutes at 1100 °C without the large resonance wavelength shift, and the LPG is degraded. The residual stress relaxation influences the peak loss though the residual stress is small.

REFERENCES

[1] J. Nishimura and K. Morishita, "Control of spectral characteristics of dispersive optical fibers by annealing", *J. Lightwave Technol.*, vol. 15, no. 2, pp. 294-298, Feb. 1997.

[2] J. Nishimura and K. Morishita, "Changing multimode dispersive fibers into single-mode fibers by annealing and guided mode analysis of annealed fibers", *J. Lightwave Technol.*, vol. 16, no. 6, pp. 990-997, June 1998.

[3] J. Nishimura and K. Morishita, "Mode-field expansion and reduction in dispersive fibers by local heat treatments", *IEEE J. Select. Topics Quantum Electron.*, vol. 5, no. 5, pp. 1260-1265, Sept./Oct. 1999.

[4] K. Morishita, S. F. Yuan, Y. Miyake and T. Fujihara, "Refractive index variations and long-period fiber gratings made by the glass structure change", *IEICE Trans. Electron.*, vol. E86-C, no. 8, pp. 1749-1758, Aug. 2003.

[5] K. Morishita and Y. Miyake, "Fabrication and resonance wavelengths of long-period gratings written in a pure silica photonic crystal fiber by the glass structure change," *J. Lightwave Technol.*, vol. 22, no. 2, pp. 625-630, Feb. 2004.

[6] G. Rego, O. Okhotnikov, E. Dianov, and V. Sulimov, "High-temperature stability of long-period fiber gratings produced using an electric arc," *J. Lightwave Technol.*, vol. 19, no. 10, pp. 1574-1579, Oct. 2001.

[7] G. Humbert and A. Malki, "Electric-arc-induced gratings in non-hydrogenated fibres: fabrication and high-temperature characterizations," *J. Opt. A*, vol.4, no. 2, pp. 194-198, Feb. 2002.

[8] G. Humbert, A. Malki, S. Février, P. Roy, and D. Pagnoux, "Characterizations at high temperatures of long-period gratings written in germanium-free air-silica microstructure fiber," *Opt. Lett.*, vol. 29, no. 1, pp. 38- 40, Jan. 2004.

[9] T. S. Izumitani Optical Glass, American Institute of Physics, New York, 1986, ch. 1

[10] D. –L. Kim, M. Tomozawa, S. Dubois, and G. Orcel, "Fictive temperature measurement of single-mode optical-fiber core and cladding," *J. Lightwave Technol.*, vol. 19, no. 8, pp. 1155-1158, Aug. 2001.

[11] S. Ishikawa, H. Kanamori, T. Kohgo, M. Nishimura, and H. Yokota, "New mode-field conversion technique in optical fiber using thermal relaxation of residual stress," in *Tech. Dig. Conf. Optic. Fiber Commun./Int. Conf. Integrated Optics Optic. Fiber Commun. (OFC-IOOC)*, 1993, San Jose, USA, paper TuB4.