Residual stress effects on refractive indices in undoped silica-core single-mode fibers

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It is reported for the first time that refractive indices are reduced remarkably by residual stress in undoped silica-core/fluorine-doped silica-clad single-mode fibers. The very high residual stress concentrated at the small diameter core is induced by drawing tension because of the difference in viscosity between the core and cladding. The decrease in refractive indices results from photoelastic effects due to residual stress in the core.

Recently undoped silica (SiO_2)-core single-mode optical fibers with fluorine-doped silica (F-SiO_2) claddings have been developed to improve the characteristics of optical loss and dispersion.[1-3] In order to attain very low optical loss, it is necessary to control fiber-manufacturing conditions precisely. It has been observed that the refractive indices of the SiO_2-core single-mode fibers decrease remarkably with increase in drawing tension.[4] The origin for the refractive index change is not yet clear although it is possible to make low-loss single-mode fibers by excluding the influence of drawing tensions.

In this paper, through theoretical consideration and distinct experimental data, the origin for the refractive index change is investigated. Residual stress of the fibers is considered as a strong origin because the drawing tension remains in optical fibers as residual stress.[5]

Consider the residual stress that is dependent on drawing tension in SiO_2 core/F-SiO_2-clad single-mode fibers. The drawing tension is due to shear stress of the molten neckdown region in the core and cladding, and is expressed as follows[6]:

$$F = 3\eta_1 A_1 \frac{\partial v}{\partial z} + 3\eta_2 A_2 \frac{\partial v}{\partial z} \tag{1}$$

$$= 3\eta_1 A_1 \frac{\partial v}{\partial z}\left(1 + \frac{\eta_2 A_2}{\eta_1 A_1}\right), \tag{2}$$

where η is the viscosity, A is the sectional area, the subscripts 1 and 2 represent the core and cladding, respectively, v is the local moving velocity of the neckdown region of the preform, and z is the distance in the fiber axial direction. Since η_1 is much higher than η_2, the drawing tension almost results from the SiO_2 core above the softening temperature T_1 of SiO_2. When the neckdown preform radius reaches the fiber radius at T_1, the stress σ_1 applied to the core is given by

$$\sigma_1 = \frac{F}{A_1}\left(1 + \frac{\eta_2 A_2}{\eta_1 A_1}\right)^{-1}. \tag{3}$$

If the fiber strain is released after cooling, the residual stress in the SiO_2 core is obtained as follows[5]:

$$\sigma_1 = \frac{A_2 E_2}{A_1 E_1 + A_2 E_2}\,\frac{F}{A_1}\left(1 + \frac{\eta_2 A_2}{\eta_1 A_1}\right)^{-1} + \sigma_T, \tag{4}$$

where E is the Young's modulus and σ_T is the stress due to the difference in thermal expansion coefficients between the core and cladding. In single-mode fibers, σ_T can be neglected because the core sectional area is very small.

The relationships between the refractive index and stress (photoelastic effects) are expressed as follows[7]:

$$\Delta n_r = C_a \sigma_r + C_b(\sigma_\theta + \sigma_z), \tag{5}$$

$$\Delta n_\theta = C_a \sigma_\theta + C_b(\sigma_z + \sigma_r), \tag{6}$$

$$\Delta n_z = C_a \sigma_z + C_b(\sigma_r + \sigma_\theta), \tag{7}$$

where C_a and C_b are the photoelastic coefficients, Δn_r, Δn_θ, and Δn_z are the refractive index changes in the radial, circumferential, and axial directions, respectively, and σ_r, σ_θ, and σ_z are the radial, circumferential, and axial components of the stress in the core. For light propagating in optical fibers, the refractive index in the radial direction is important. In the core of single-mode fibers,

$$\sigma_z \simeq \sigma_1 (\gg \sigma_r \text{ and } \sigma_\theta), \tag{8}$$

then

$$\Delta n_r \simeq C_b \sigma_1. \tag{9}$$

Since the value of C_b is $-4.2\times10^{-12}\ \mathrm{Pa}^{-1}$,[8] Δn_r decreases with increasing σ_1.

A preform was fabricated by the vapor phase axial deposition method. The preform had no SiO_2 layer outside of the F-SiO_2 cladding. The refractive index profile was a step type and the ratio Δ^- of the refractive index of the core to that of the cladding was 0.45% in the preform. The optical fibers

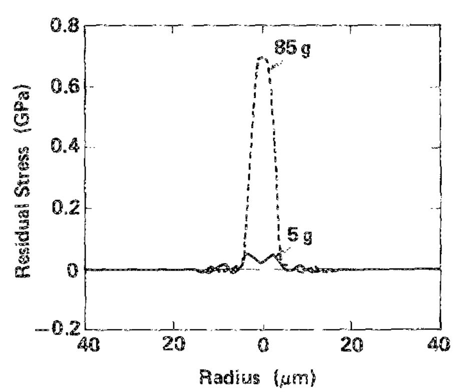

FIG. 1. Residual stress profiles in SiO_2-core single-mode fibers. The solid and dotted curves represent the profiles at drawing tensions of 85 and 5 g, respectively.

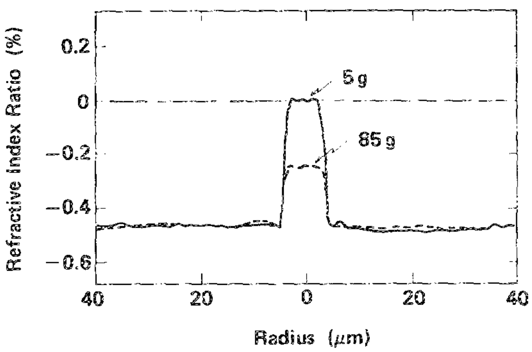

FIG. 2. Refractive index profiles in SiO_2-core single-mode fibers. The solid and dotted curves represent the profiles at drawing tensions of 85 and 5 g, respectively.

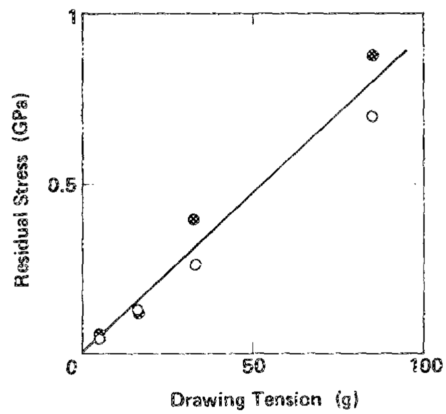

FIG. 3. Relationship between residual stress and drawing tension. The open and closed circles represent the residual stresses measured by the photoelastic CT methods and calculated from Eq. (9) in the text, respectively.

were drawn from the preform at various temperatures, i.e., various tensions at a constant velocity (0.5 m/s). The drawing temperature varied from 2120 to 2310 K. The fiber diameter was 125 μm. The residual stress of the fibers was measured by the photoelastic computer tomography (CT) method[9] and the refractive index profile was measured by the refracted, near field pattern (RNFP) method.[10]

The residual stress profiles of the SiO_2-core/F-SiO_2-clad single-mode fibers drawn at tensions of 5 and 85 g are shown in Fig. 1. Residual stress is concentrated at the core where the viscosity is much higher than that of the F-SiO_2 cladding. The residual stress at tension of 85 g is about 0.7 GPa, and is much larger than that at 5 g. As predicted in the theoretical part of this paper, these results indicate that the residual stress in the core is due to drawing tension.

The refractive index profiles of the fibers at drawing tensions of 5 and 85 g are shown in Fig. 2. It is noticeable that Δ^- in the core decreases by more than 50% at 85 g, whereas the core diameter and the step-type shape remain unchanged. The decrease in the refractive index of the core was confirmed by comparison with the refractive index of the matching oil. The unchanged profile shape indicates that the diffusion length of fluorine from the cladding to the core is negligibly small.

The relationship between residual stress and drawing tension is summarized in Fig. 3. The open and closed circles represent the residual stresses measured by the photoelastic CT method and calculated from Eq. (9), respectively. The calculated stress coincides well with the measured values. Moreover, it is clear that both are proportional to the drawing tension. These results support the relationship expressed by Eq. (9), i.e., the refractive index in the core is reduced proportionally by the residual stress. Assuming that the Young's modulus is almost equal in SiO_2 and F-SiO_2, the slope of the line in Fig. 3 is related to the ratio β of the viscosity of the cladding to that of the core, as described by Eq. (3). The value of β was estimated at 0.11, which is to be expected.

Furthermore, the SiO_2-core single-mode fibers drawn at a tension of 85 g were annealed at 1000 °C for 10 min. This annealing released the residual stress due to drawing tension and then the core was made almost unstressed. When the residual stress in the core was released, the reduced index difference reverted to the initial state ($\Delta^- = 0.45\%$). From these results it is confirmed that the refractive index is reduced by residual stress in SiO_2-core single-mode fibers.

Drawing-induced changes in refractive indices were examined in SiO_2-core/F-SiO_2-clad fibers. The refractive index of the core decreased with increase in drawing tension. The drawing tension resulted in very large residual stress in the SiO_2 core. The decrease in refractive index can be explained by photoelastic effects due to the residual stress in the SiO_2 core.

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[1] R. Csensits, P. J. Lemaire, W. A. Reed, D. S. Shenk, and K. L. Walker, *Conference on Optical Fiber Communication, Technical Digest TUI3* (OSA/IEEE, New Orleans, 1984).
[2] H. Etzkorn and W. E. Heinlein, Electron. Lett. **20**, 423 (1984).
[3] F. Hanawa, Y. Ohmori, and M. Nakahara, Trans. IECE Jpn. Sec. C **J68-C** 597 (1985) (in Japanese).
[4] F. Hanawa, Y. Hibino, M. Shimizu, Y. Suda, and M. Horiguchi (unpublished).
[5] U. C. Paek and C. R. Kurkjian, J. Am. Ceram. Soc. **58**, 330 (1975).
[6] U. C. Paek and R. B. Runk, J. Appl. Phys. **49**, 4417 (1978).
[7] M. Born and E. Wolf, *Principles of Optics* (Macmillan, New York, 1964), p. 704.
[8] W. Primak and D. Post, J. Appl. Phys. **30**, 779 (1959).
[9] T. Abe, Y. Mistunaga, and H. Koga, J. Opt. Soc. Am. A **3**, 133 (1986).
[10] K. I. White, Opt. Quantum Electron. **11**, 185 (1979).