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<td>Citation</td>
<td>Appl. Phys Lett., Vol. 50, No. 22, 1987</td>
</tr>
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<td>URL</td>
<td><a href="http://scitation.aip.org/content/aip/journal/apl">http://scitation.aip.org/content/aip/journal/apl</a></td>
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Residual stress effects on refractive indices in undoped silica-core single-mode fibers

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(Received 16 February 1987; accepted for publication 6 April 1987)

It is reported for the first time that refractive indices are reduced remarkably by residual stress in undoped silica-core/flurine-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.$^1$ 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.$^2$ 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.$^3$

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$^4$:

\[
F = 3\eta_1 A_1 \frac{\partial \nu}{\partial z} + 3\eta_2 A_2 \frac{\partial \nu}{\partial z} = 3\eta_1 A_1 \frac{\partial \nu}{\partial z} \left( 1 + \frac{\eta_2 A_2}{\eta_1 A_1} \right),
\]

where $\eta$ is the viscosity, $A$ is the sectional area, the subscripts 1 and 2 represent the core and cladding, respectively, $\nu$ is the local moving velocity of the neckdown region of the preform, and $z$ is the distance in the fiber axial direction. Since $\eta_1$ is much higher than $\eta_2$, 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 $\sigma_1$ applied to the core is given by

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

If the fiber strain is released after cooling, the residual stress in the SiO$_2$ core is obtained as follows$^5$:

\[
\sigma_1 = \frac{A_2 E_2}{A_1 E_1 + A_2 E_2} \frac{F}{A_1} \left( 1 + \frac{\eta_2 A_2}{\eta_1 A_1} \right)^{-1} + \sigma_R,
\]

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

The relationships between the refractive index and stress (photoelastic effects) are expressed as follows$^6$:

\[
\Delta n_x = C_a \sigma_x + C_b (\sigma_o + \sigma_r),
\]

\[
\Delta n_o = C_a \sigma_o + C_b (\sigma_x + \sigma_r),
\]

\[
\Delta n_t = C_a \sigma_t + C_b (\sigma_o + \sigma_o),
\]

where $C_a$ and $C_b$ are the photoelastic coefficients, $\Delta n_x$, $\Delta n_o$, and $\Delta n_t$ are the refractive index changes in the radial, circumferential, and axial directions, respectively, and $\sigma_x$, $\sigma_o$, and $\sigma_t$ 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,

\[
\sigma_t \approx \sigma_o + \sigma_x
\]

then

\[
\Delta n = C_b \sigma_t.
\]

Since the value of $C_b$ is $- 4.2 \times 10^{-12}$ Pa$^{-1}$, $\Delta n$ decreases with increasing $\sigma_t$.

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 $\Delta$ 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.](image-url)
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.

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 (Δ = 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.

The authors would like to thank T. Edahiro and M. Horiguchi for their encouragement and N. Kuwaki for his measurement of the refractive index profiles.