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Effect of Temperature on Transmission in Lightguides

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Temperature effects on refractive index have been studied by monitoring pulse propagation delays in fiber-optic lightguides for temperatures between −40 and 67°C. Loss and dispersion properties did not change significantly from their room temperature values.

I. INTRODUCTION

Lightguides may be used for transmission in a variety of environments. The temperature of these environments may vary as a function of time. It is anticipated that optical waveguides will have an operating temperature range specification similar to that of cables currently being employed for telephony, which is −40 to +85°C. Variation within this temperature range causes changes in the optical properties of materials comprising the lightguide.

To maximize the signal-carrying capacity of lightguides, the refractive-index profile of multimode lightguides is carefully engineered to a specific shape. This is done to minimize mode dispersion. The refractive-index difference between core and cladding of a single-mode fiber must be controlled to provide a fiber which supports only the fundamental mode.

It is known that refractive-index dispersion is a function of temperature. In glasses such as those from which optical waveguides are currently being fabricated, two opposing factors regulate the direction and magnitude of the refractive-index variation with temperature, δn. As the material temperature increases, the positive coefficient of thermal expansion in glasses causes a decrease in density which decreases the refractive index. However, with an increase in the temperature, the other factor, electron polarizability, is increased and the ultraviolet absorption bands are shifted to a longer wavelength. This contributes to an increase in refractive index.[1–3]

In silicate glasses, electron polarizability dominates, and δn is positive below the glass transition temperature. But the magnitude can vary by a factor of ten or more as a function of glass composition.[4] The range of δn is approximately $1 - 20 \times 10^{-6}$ per °C in silicate glasses.

The refractive-index difference between core and cladding in a multimode optical waveguide with an NA of 0.2 is about 1.5×10^{-2}. Conceivably, the refractive-index difference could be changed by 10 percent within the operating temperature range previously mentioned if the difference in δn between the core and cladding glasses was 15×10^{-6} per °C, a possible figure. In single mode lightguides, Δn is roughly 1×10^{-3}. The change in Δn with temperature in this case could be 100 percent of the manufactured value. Obviously, this could be serious if the deviation were negative.

Since the glass compositions comprising the core and cladding of most lightguides are similar (80 mole percent silica), it was not expected that δn would be significantly different. For silica, δn is roughly 10×10^{-6} per °C and varies slightly with wavelength. But there are additional considerations that complicate any calculation of refractive-index variations. For example, as the temperature is changed, the stresses between the different compositions comprising the fiber core and cladding also change. This effect could influence the electron polarizability and density variations. Such possibilities suggested direct examination of the variation with temperature of pulse propagation in multimode and single-mode fibers to discern the significance of the temperature effect at the anticipated transmission wavelength.

II. EXPERIMENTAL

The fiber specimens examined were representative single-mode and multimode (GRIN, graded index) fibers with borosilicate (B_2O_3-SiO_2) cores and claddings and multimode (GRIN) fibers with germania borosilicate (GeO_2-B_2O_3-SiO_2) cores and silica (SiO_2) claddings. All were considered representative of fibers currently being used or strongly considered for use in optical communications systems. To eliminate externally induced mode-mixing effects, the specimens were coiled loosely with 30- to 40-cm diameters on individual aluminum trays.

The fibers that were analyzed individually were placed in a "Blue M" environmental control chamber modified to provide ambient temperatures in the chamber from −50 to +85°C.

The two ends of each fiber were run from the chamber through two 0.6-cm ports and aligned with the shuttle pulse analysis system.[5] The temperatures on and above the fiber holding tray were monitored by five systematically placed copper-constantan thermocouples. After the fiber and thermocouples were in place, the chamber was either heated to about +70°C or cooled to about −40°C. From this temperature extreme, the chamber was either monotonically cooled or heated respectively at about 1.5°C per min. The temperature of the chamber was held at −40°, 0°, +30°, and +70°C long enough for the temperature of the chamber to equilibrate and to allow a measurement of the pulse delay and shape to be made. The temperature gradient across the tray did not exceed 5°C at any temperature during measurement.

Figure 1 qualitatively illustrates refractive-index profiles corresponding to fiber specimens. Borosilicate fibers are fabricated with a uniform borosilicate (B_2O_3-SiO_2) cladding composition and a core in which the B_2O_3 dopant concentration decreases from its cladding concentration to a smaller percentage at the core center. The addition of B_2O_3 decreases the refractive-index of SiO_2 by $\Delta n \sim 0.008$ in the cladding. The maximum refractive index at the core center corresponds to pure silica as in Fig. 1a for multimode fibers (diameter ~50 μm) and Fig. 1b for small-core (diameter ~5 μm), single-mode fibers. In more common single mode fibers like Fig. 1c, the core diameter is approximately 10 μm and $\Delta n \sim 0.0015$. Germania borosilicate fibers are fabricated by

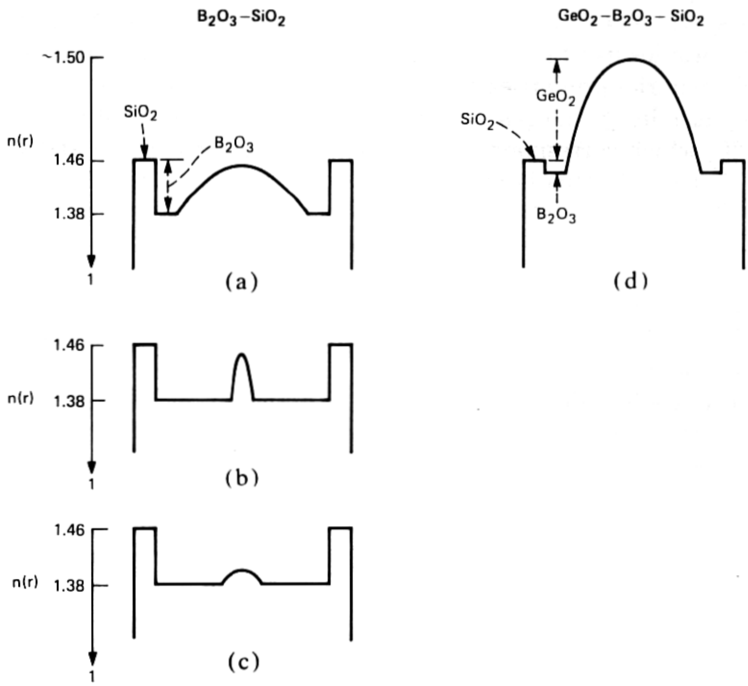

Fig. 1—Refractive-index profiles of fiber specimens. (a) B_2O_3-SiO_2 multimode GRIN (graded index) fiber with nearly pure silica core center, diameter ~50μm, $\Delta n \sim 0.008$. (b) B_2O_3-SiO_2 small core single mode fiber with nearly pure silica core center, diameter ~5μm, $\Delta n \sim 0.007$. (c) B_2O_3-SiO_2 large core single mode fiber with borosilicate core center, diameter, ~10μm, $\Delta n \sim 0.0015$. (d) GeO_2-B_2O_3-SiO_2 multimode GRIN fiber with germania borosilicate core center, diameter ~50 μm, $\Delta n \sim 0.014$.

depositing two borosilicate layers followed by a gradually increasing amount of GeO_2 towards the core center. Multimode fibers like Fig. 1a have 50-μm diameters and $\Delta n \sim 0.014$.

Refractive-index variations, δn, with environmental temperature, T, can be sensitively determined by monitoring the change in pulse propagation delay,

$$\frac{\delta \tau}{\delta T} = \frac{1}{c}\left[\frac{\delta n}{\delta T} L + n \frac{\delta L}{\delta T}\right],$$

through a fiber. The propagation delay change, $\delta \tau$, occurs because both refractive index, δn, and fiber length, δL, change with temperature. The fiber length change with temperature can be expressed as $\delta L / \delta T = \alpha L$, where $\alpha \approx 8 \times 10^{-7}$ per °C is the thermal expansion coefficient for the combined fiber core and cladding. Malitson's results[6] for bulk-fused silica specimens indicate that $\delta n / \delta T \approx 1 \times 10^{-5} \gg \alpha$. Therefore, propagation delay changes in doped fused silica fibers should be primarily due to the refractive-index variation with temperature expressed by $\delta \tau \approx \delta n L / c$. Figure 2 summarizes results for several fiber specimens by plotting $\delta \tau$ versus T. Borosilicate-clad fibers 1 and 2 had profiles like Figs. 1a and 1b with nearly pure silica core centers. Their material properties should correspond to pure silica. Transmission pulse delay changes were monitored to be $\delta \tau(S) \sim 36$ ps per Km per °C, which corresponds to a refractive-index change $\delta n(S)/\delta T \sim 1 \times 10^{-5}$ per °C. This is in good agreement with a value obtained on bulk-fused silica specimens by Malitson.[6] Borosilicate fiber 3 had a profile like Fig. 1c with a large, 14 mole percent B_2O_3 dopant concentration at the core center. Its material properties appear to be significantly different from those of pure silica curves and fiber 2 since $\delta \tau(BS) \sim 65$ ps per Km per °C corresponds to a refractive-index change $\delta n(S) \sim 1.8 \times 10^{-5}$ per °C. Germania borosilicate fibers 4, 5 had profiles like Fig. 1d with a 14 mole percent GeO_2 dopant concentration at the core center. Their thermal material properties are similar to those of pure silica since $\delta \tau(\text{GBS}) \sim 33$ ps per Km per °C, which correspond to $\delta n(\text{GBS}) \sim 0.91 \times 10^{-5}$ per °C.

Thermal effects on lightguide transmission properties can be estimated from refractive-index versus temperature properties deduced from Fig. 2. Pulse dispersion properties are related to the change of $\Delta n = [n(\text{core}) - n(\text{clad})]$ with temperature. Graded-index multimode borosilicate fibers have a nearly pure silica core center and a borosilicate cladding. Therefore, $\delta(\Delta n) = 0.8 \times 10^{-5}$ per °C can be estimated from delay differences between curves 3 and 1, 2. The maximum core-to-cladding refractive-index difference should be $\Delta n \sim 0.008 \pm 0.00032$ for a ±50°C variation about room temperature. This ±4-percent maximum variation means that refractive-index changes between succes-

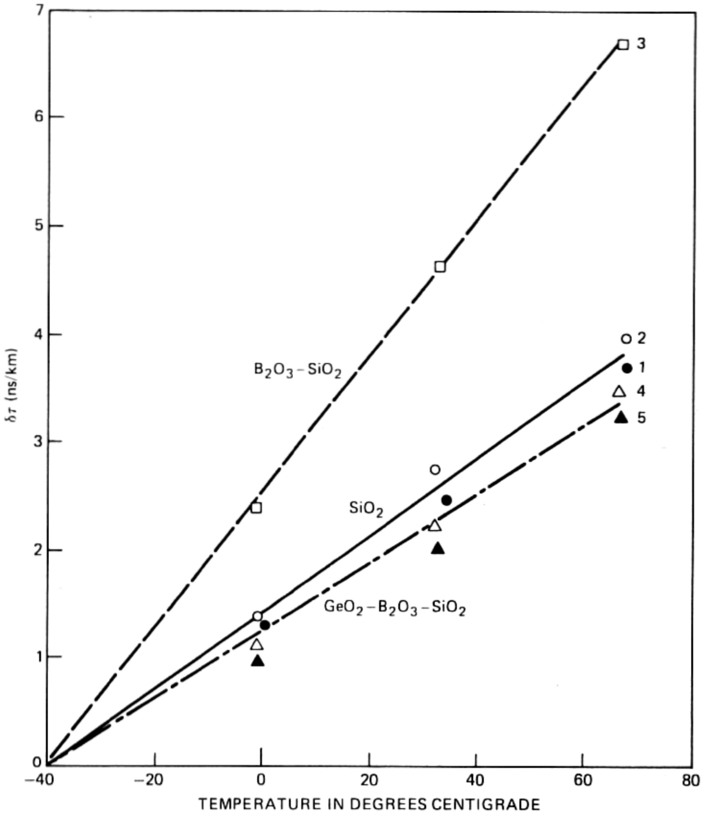

Fig. 2—Pulse propagation delay change, $\delta\tau$ vs environmental temperature, T. Fibers 1, 2, 3, and 4–5 have profiles corresponding to Figs. 1b, 1a, 1c, and 1d, respectively.

sively deposited core layers should not significantly affect the shape of the fiber's graded-index profile. The temperature dependence of Δn in a multimode germania borosilicate fiber, deduced from delay differences between curves 3 and 4, 5 in Fig. 2 are even less than for borosilicate clad fibers. Therefore, dispersion properties of multimode borosilicate and germania borosilicate fibers should not be significantly affected by environmental temperature changes.

Thermal effects on transmission properties of borosilicate single mode fibers can also be estimated from Fig. 2. Single mode fibers 2, 3 are characterized by a parameter $V = (\pi/\lambda)\ \sqrt{2n\Delta n} \sim 2.3$ at $\lambda = 0.908$ μm. Only one mode propagates as long as $V < 2.41$. Fiber 2 has a nearly pure silica core and a borosilicate cladding. Its V number variation with temperature is less than ±2 percent for a ±50°C variation about room temperature. This change is very small and should not significantly affect attenuation or waveguide dispersion. The only cause for concern might be if the V number at the signal wavelength were within ±2 percent of the cut-off V number of the LP_{11} mode. In that case, the fiber could change from single-mode to two-mode operation. Single-mode fiber 3 has a $\Delta n \sim 0.0015$ index difference between its borosilicate core and cladding. Temperature-dependent material differences are insignificant between its core and cladding.

Deductions based on Fig. 2 were confirmed by measurements of pulse dispersion and attenuation as a function of temperature. The optical shuttle pulse technique was used to improve measurement precision by extending fiber specimen lengths by an order of magnitude.[5] Intermodal pulse dispersion changed by less than 0.04 ns per km for a temperature variation between −40°C and 67°C. This change is small both in an absolute sense and when compared to the total 0.2 ns per km dispersion observed in the borosilicate graded-index fibers and 0.38 ns per km dispersion observed in the germania borosilicate fibers. Attenuation in the single-mode fibers changed by less than 0.2 dB per km.

III. CONCLUSIONS

The temperature dependence of refractive-index in fiber optic lightguides has been studied within a −40°C to 67°C range. Pulse delay measurements indicate that the core center refractive-index changes by $\delta n(S) \sim 1 \times 10^{-5}$ per °C in fibers with nearly pure fused silica core centers, by $\delta n(BS) \sim 1.8 \times 10^{-5}$ per °C in fibers with borosilicate (B_2O_3-SiO_2) core centers, and by $\delta n(\text{GBS}) \sim 0.9 \times 10^{-5}$ per °C in fibers with germania borosilicate (GeO_2-B_2O_3-SiO_2) core centers. Core-to-cladding refractive-index differences change by a very small amount, $\delta(\Delta n) < \pm 0.00032$ for a ±50°C variation about room temperature. No significant changes in loss or pulse dispersion characteristics were observed after propagation through multikilometer fiber lengths. This implies that fiberguide system properties will not be significantly affected by environmental temperature effects on refractive index.

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