Rayleigh Scattering Reduction Method for Silica-Based Optical Fiber

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***Abstract*—The effect of the thermal treatment of silica-based glasses and glass fibers on their Rayleigh scattering is investigated experimentally. The Rayleigh scattering coefficients of bulk glasses are found to be increased 5–10% by heating them to 1800 °C because the density fluctuation is in proportion to their fictive temperature. Based on these results, we propose a method for reducing the Rayleigh scattering losses of silica-based optical fibers by drawing them slowly at low temperatures. We used this method to obtain a GeO_2 doped silica core single-mode fiber with a minimum loss of 0.16 dB/km at 1.55 μm. As a result, we confirmed that the reduction in the fictive temperature of silica-based glasses and glass fibers reduces their Rayleigh scattering.**

***Index Terms*—Drawing speed, drawing temperature, fictive temperature, loss reduction, optical fiber, Rayleigh scattering.**

I. Introduction

SILICA-BASED optical fibers are used throughout the world for large-capacity and long-distance transmission systems with erbium-doped fiber amplifiers (EDFAs). Fiber loss reduction will accelerate the construction of various transmission systems with longer repeater spacings.

With the development of the vapor-phase axial deposition technique (VAD) [1], it became possible to reduce optical losses induced by impurities in optical fibers such as OH absorption loss, and the lowest optical loss of 0.154 dB/km at a wavelength of 1.56 μm was achieved [2]. To reduce the additional imperfection loss, we proposed the viscosity-matching technique, which utilizes the dopants GeO_2 and fluorine (F) to match the core and cladding viscosities [3], [4]. We also investigated the Rayleigh scattering loss of silica-based glasses since it dominates the optical loss in the 1.55 μm wavelength region [5]–[8]. It was found that the Rayleigh scattering of glasses depends on the fictive temperature [7]. Moreover, it has been reported that Rayleigh scattering in optical fibers can be reduced by lowering their fictive temperatures [8], [9].

In this paper, we report in detail the effect of the thermal treatment of fluorine doped, GeO_2 doped and pure silica glasses on their Rayleigh scattering. Based on the results, we propose a method for reducing the Rayleigh scattering loss of optical fibers by lowering the drawing temperature. This method is applied to the fabrication of GeO_2 doped silica core fibers, which are widely used. We also confirmed the effect of our method on the fabrication of silica-based fibers experimentally.

Manuscript received March 16, 2000; revised July 24, 2000.

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Publisher Item Identifier S 0733-8724(00)09821-2.

II. Experimental Procedure

A. Preparation of Glass Samples

We fabricated pure, GeO_2 doped, and fluorine doped silica glass preforms by the VAD technique. Fig. 1 shows the thermal treatment diagram of two types of sample rods [7]. All the soot preforms were consolidated at around 1400 °C. They were then annealed from a temperature of 1400 to 1250 °C at a cooling rate of 5 °C/min, and air-cooled to room temperature. We call these samples "annealed samples." Each "annealed sample" was cut into two pieces, one of which was reheated to 1800 °C in a furnace and then air-cooled again to room temperature. These we call "reheated samples."

We measured the Rayleigh scattering of each rod sample (15-mm diameter and 50-mm length) with a dynamic light scattering spectrometer DLS700 (Otsuka Electronics). A 50-mw argon–ion laser operating at a wavelength of 488 nm was used as the light source. To minimize the effect of refraction and reflection, the samples were immersed in di–n–butyl–phthalate ($n_{d=589.3\,\mathrm{nm}} = 1.49$). We obtained the angular distribution of the Rayleigh ratio by measuring the scattering intensity every 5° from 30 to 150°. We measured the Rayleigh ratio in each sample twice, and estimated the Rayleigh scattering coefficient from their average value. After completing the Rayleigh scattering measurement, we cut each rod sample to a thickness of 1 mm and polished it to measure its infrared absorption. The infrared absorption spectrum was measured with a Fourier transform infrared spectrometer FT-IR (Nicolet).

B. Fiber Fabrication

First we prepared a soot preform with a GeO_2 doped silica core and pure silica cladding by the VAD technique. To clarify the fictive temperature dependence of the optical loss, we prepared five single-mode fibers, each 2 km long, by drawing this preform at five different temperatures between 1800 and 2000 °C. When the drawing temperature is low, the drawing tension increases because the viscosity of the glass increases. This in turn increases the additional imperfection loss caused by the viscosity mismatch between the core and cladding [4]. Therefore, we reduced the drawing speed so as not to increase the drawing tension. The drawing speed and tension were typically about 1 m/s and 200 g, respectively. We measured the optical losses of the fibers at a wavelength of 1.0–1.7 μm by the conventional cut-back method.

III. Experimental Results

Fig. 2 shows the relationship between the relative-index difference and Rayleigh scattering coefficient for the two types of

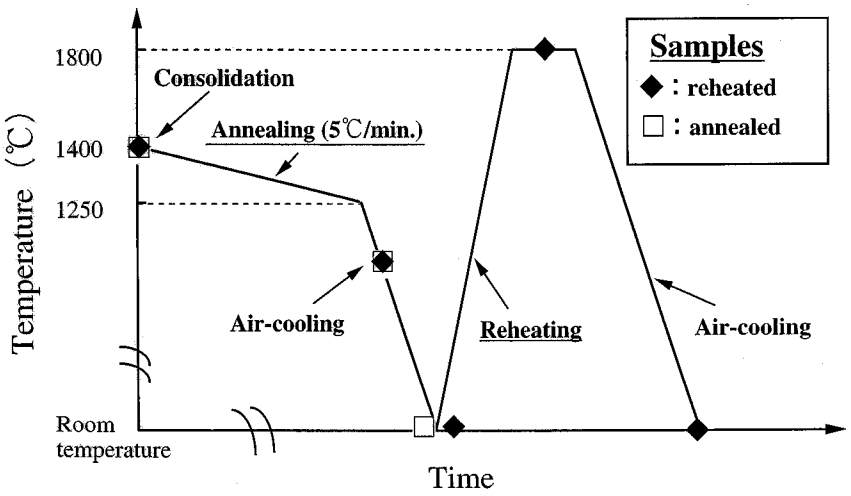

Fig. 1. Thermal treatment diagram of two types of sample.

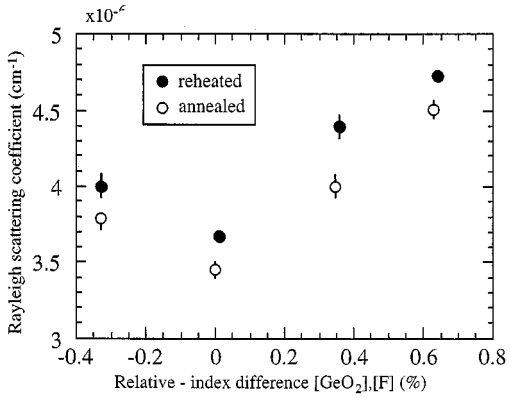

Fig. 2. Relationship between relative-index difference and Rayleigh scattering coefficient for all samples. The deviations of the Rayleigh scattering coefficient in each sample are shown as solid bars.

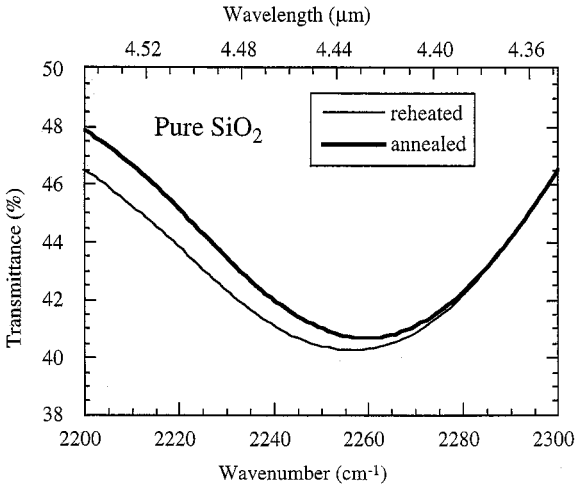

Fig. 3. Transmittance spectra of pure silica glasses at 2200–2300 cm^{-1}.

sample. In Fig. 2, as a measure of dopant concentration, the relative-refractive index differences between the samples and pure silica glass induced by GeO_2 and fluorine are expressed as $[GeO_2]$ and [F], respectively. The Rayleigh scattering coefficient of GeO_2 and flourine co-doped silica glass $A_{GeO2\text{-}F}$ is reported to be [6]

$$A_{GeO2\text{-}F} = A_{SiO2}\left(1 + 0.62\,[GeO_2] + 0.60\,[F]^2 + 0.44\,[GeO_2][F]^2\right) \quad (1)$$

where A_{SiO2} is the Rayleigh scattering coefficient of pure silica glass. In each type of sample, the measured values and those calculated by using (1) were in good agreement within a relative error of ±8%. Thus, it is confirmed that the Rayleigh scattering coefficient of GeO_2 and/or fluorine doped silica glasses that have the same thermal history can be described by (1). It is also seen that the Rayleigh scattering coefficients of "reheated samples" are always 5–10% greater than those of "annealed samples." For example, the difference between the Rayleigh scattering coefficients of two pure silica glasses (ΔA) was 6%. These results indicate that the Rayleigh scattering coefficients of pure, GeO_2 doped and flourine doped silica glasses are increased by reheating to 1800 °C [7].

Fig. 3 shows the transmittance spectra of pure silica glasses at 2200–2300 cm^{-1}. In Fig. 3, it is seen that reheating broadens the bandwidth of the spectrum and shifts the peak position to a lower wavenumber. That is, the 2260 cm^{-1} absorption band (first overtone of the SiO_4 stretching vibration) is affected by the thermal treatment. The relationship between the fictive temperature T_f and the peak frequency v_2 for some pure silica glasses is given as [10]

$$T_f = \frac{43\,809.21}{v_2 - 2228.64}. \quad (2)$$

Employing the v_2 values, we used (2) to estimate the T_f values of pure silica glasses and found them to be 1320 °C in the reheated glass and 1170 °C in the annealed glass. The difference between the T_f values (ΔT_f) was 150 °C.

Fig. 4 shows the optical loss spectra of test fibers drawn from the same preform [8]. The refractive index profile of the preform is also shown in the inset of Fig. 4. The drawing temperatures for fibers A and B were 1800 and 1900 °C, respectively. The optical losses of fiber A at wavelengths of 1.31 and 1.55 μm were 0.29 and 0.16 dB/km, respectively. These values were lower than those for fiber B.

TABLE I
LOSS COMPONENTS OF TEST FIBERS

		Fiber A	Fiber B	Fiber C
Core / Cladding dopant		GeO_2-SiO_2 / SiO_2	GeO_2-SiO_2 / SiO_2	SiO_2 / F-SiO_2
Mode field diameter at 1.55 μm	(μm)	10.0	10.0	10.0
Cutoff wavelength	(μm)	1.23	1.23	1.41
Relative-refractive index difference	(%)	0.33	0.33	0.30
Drawing temperature	(℃)	1800	1900	>2000
Loss at 1.31 μm	(dB/km)	0.29	0.33	0.31
Loss at 1.55 μm	(dB/km)	0.16	0.20	0.17
Rayleigh scattering coefficient	(dB/km/μm^4)	0.78	0.84	0.82
Imperfection loss at 1.55 μm	(dB/km)	0.01	0.05	0.02
IR absorption loss at 1.55 μm	(dB/km)	0.01	0.01	0.01
OH absorption loss at 1.55 μm	(dB/km)	<0.01	<0.01	<0.01

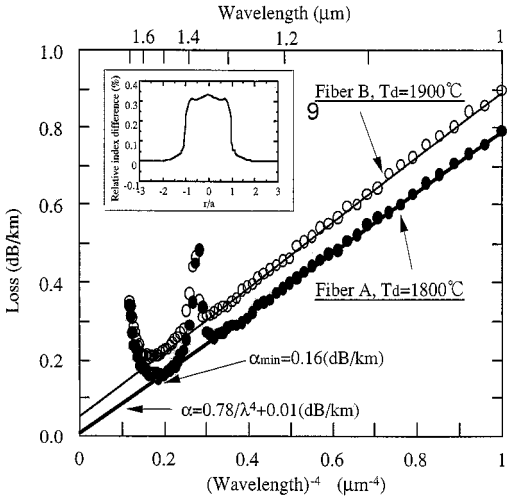

Fig. 4. Optical loss spectra of test fibers drawn from the same preform.

Next we analyzed the loss components of the test fibers. The spectral loss α of an optical fiber is expanded as

$$\alpha = A/\lambda^4 + \alpha_{\rm IM} + \alpha_{\rm IR} + \alpha_{\rm OH} \tag{3}$$

where A is the Rayleigh scattering coefficient, $\alpha_{\rm IM}$ the imperfection loss, $\alpha_{\rm IR}$ the infrared absorption loss, and $\alpha_{\rm OH}$ the OH absorption loss. Table I shows the loss components. We estimate these values by fitting measured data to (3) using the nonlinear regression method. For comparison, we show the values of a conventional pure silica core fiber (fiber C), which is one of the lowest loss optical fibers currently available.

From Table I, the losses of fiber A were even lower than those of fiber C. The Rayleigh scattering coefficient of fiber A was smaller than that of fiber C, despite the fact that the core of fiber A was GeO_2 doped. The other loss factors were the same as or less than those of fiber C. We estimated the intrinsic loss of fiber A, which is a summation of the Rayleigh scattering and the infrared absorption, to be 0.15 dB/km at 1.55 μm.

IV. DISCUSSION

Here, we discuss the relationship between the Rayleigh scattering and the fictive temperature T_f. In general, the Rayleigh scattering coefficient A can be expressed by (4), where A_d and A_c are the Rayleigh scattering coefficients due to density and concentration fluctuations, respectively. A_d is expressed as (5), where n is the refractive index, p the photoelastic coefficient, k the Boltzmann constant, and β_T the isothermal compressibility at T_f [11], [12]

$$A = A_d + A_c \tag{4}$$

$$A_d = \tfrac{8}{3}\pi^3 n^8 p^2 k \beta_T T_f \tag{5}$$

(5) indicates that A_d is in proportion to T_f, and this has been confirmed by the fact that the Rayleigh scattering exhibits a linear relation with T_f in pure silica glasses and pure silica core fibers, which have only density fluctuation [9], [13], [14].

T_f is defined as a temperature at which no further structural relaxation occurs in glasses. Therefore, T_f changes depending on the glass viscosity and the cooling rate [15]. As expected, the T_f of the annealed pure silica was 1170 °C, which is almost the same as the annealing temperature 1250 °C (Fig. 1). In contrast, the T_f of reheated pure silica was 1320 °C, which is much lower than the reheating temperature of 1800 °C. We probably obtained this result because there was structural relaxation and the T_f decreased during the air-cooling from 1800 °C since the relaxation time of pure silica glass is very short over 1300 °C [14], [15]. As mentioned in Section III, ΔA was 6% for a ΔT_f of 150 °C in pure silica glasses, which is almost the same as the reported value [14], that is about 8% for a ΔT_f of 150 °C. Therefore, we concluded that reheating increases the A_d value of pure silica glass in proportion to its fictive temperature.

In both types of sample, the T_f of GeO_2 or fluorine doped glasses should be slightly lower than that of pure silica glass because their viscosities are lower. However, the ΔT_f values of doped glasses are assumed to be almost the same as that of pure silica glass (150 °C), because the temperature dependence of the viscosities of doped and pure silica glasses are almost the same [16], [17]. This is why the ΔA values are almost constant in Fig. 2 (5–10%). In other words, the concentration fluctuation A_c is independent of T_f, although it is dominated by the dopant concentrations [GeO_2] or [F]. However, the density fluctuation A_d changes depending on T_f in doped glasses as well as pure silica glass. Therefore, the total Rayleigh scattering coefficient A of silica-based glasses can be controlled by changing their T_f

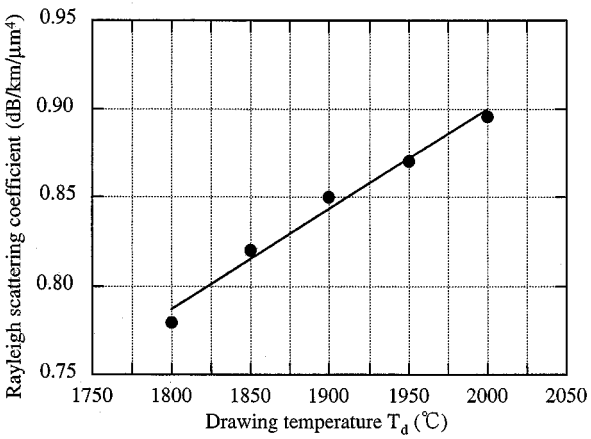

Fig. 5. Relationship between the Rayleigh scattering coefficient of test fibers and their drawing temperature T_d

values by means of appropriate thermal treatment [see (4) and (5)].

Next, we investigated the fictive temperatures of the test fibers. In general, fiber preforms are heated to the drawing temperature (∼2000 °C) and then quenched in the atmosphere. Therefore, the T_f value of optical fibers is assumed to be higher than that of their preforms, just as "reheated samples" have higher T_f values than "annealed samples." In fact, it has been reported that the T_f value of pure silica core fibers drawn at a temperature higher than 2000 °C is around 1600 °C [9]. Their Rayleigh scattering coefficients are also reported to be 0.6 and 0.8 dB/km/μm^4 at T_f values of 1200 and 1600 °C, respectively (i.e., the $\Delta A/\Delta T_f$ value of pure silica core fibers was 5×10^{-4} dB/km/μm^4/°C). These values were measured for a short segment of fiber [9]. Fig. 5 shows the relationship between the Rayleigh scattering coefficient of test fibers and their drawing temperature. Here, we define the drawing temperature T_d as the maximum temperature in a drawing furnace. The Rayleigh scattering coefficient A decreased linearly as T_d decreased [8]. The slope of the line obtained by the least squares method in Fig. 5 ($\Delta A/\Delta T_d$) was 5.6×10^{-4}, which almost coincides with the $\Delta A/\Delta T_f$ value of pure silica core fiber, 5×10^{-4}. The Rayleigh scattering coefficient of the test fiber was reduced to 0.78 dB/km/μm^4 by drawing it at 1800 °C. This value is even lower than that of pure silica core fiber whose T_d and T_f are assumed to be about 2000 and 1600 °C, respectively (see Table I). These results strongly suggest that the T_f value of the test fibers decreases linearly with decreasing T_d, and that T_f is always a few hundred degrees lower than T_d. As temperature has a vertical distribution in the furnace, the temperature around its bottom ($T_{\min}$) is a few hundred degrees lower than T_d. Reference [15] has pointed out that the structural relaxation time of pure silica core fiber is a few seconds at above 1400 °C. Therefore, if $T_{\min}$ is about 1400 °C and the drawing speed is kept slow enough (∼1 m/s in our experiment), it is possible that the structural relaxation occurs in the core glass and its T_f is reduced to near $T_{\min}$ during the drawing process. This possibility is supported by the fact that the T_f value in the interior of the cladding is much lower than that of the surface in a conventional GeO_2 doped silica core fiber [18]. Our findings indicate that the Rayleigh scattering of silica-based optical fibers can be reduced by a simple method; drawing the fiber slowly at low temperatures.

Finally, we discuss the possibility of further loss reduction. The viscosities of the core and cladding of the present fibers were mismatched. If we apply the viscosity-matching techniques to the present fibers, a reduction in the imperfection loss can be expected [3], [4]. In addition, the Rayleigh scattering due to concentration fluctuation will be suppressed because we can reduce the amount of GeO_2 in the core without changing the relative-refractive index difference. Moreover, it will be possible to draw the fiber slowly at even lower temperatures to reduce the Rayleigh scattering due to density fluctuation, because the viscosity of the whole fiber decreases when the cladding is doped by fluorine.

V. Conclusion

We investigated the effect of the thermal treatment of silica-based glasses on their Rayleigh scattering in detail experimentally. The Rayleigh scattering coefficients of the glasses increased 5–10% by heating them to 1800 °C. This is because the density fluctuation of the glasses increases in proportion to their fictive temperature. Based on these results, we proposed a method for reducing the Rayleigh scattering of silica-based optical fibers by drawing them slowly at low temperatures. We used this method to obtain a GeO_2 doped silica core single-mode fiber with a minimum loss of 0.16 dB/km at 1.55 μm and a Rayleigh scattering coefficient of 0.78 dB/km/μm^4. This is because the fictive temperature of the fiber decreased as the drawing temperature decreased. We believe that this method is applicable to the fabrication of various types of silica-based optical fiber and will be effective in reducing their Rayleigh scattering.

Acknowledgment

The authors thank K. Shiraki, M. Tateda and T. Horiguchi for fruitful discussions.

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