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Invited paper

Intrinsic loss of optical fibers

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Abstract

Rayleigh scattering is a dominant factor in terms of optical fiber loss. We investigated the dopant concentration and fictive temperature dependence of Rayleigh scattering in silica-based optical fibers and their glass preforms fabricated by the vapor-phase axial deposition (VAD) technique. The lowest Rayleigh scattering coefficient, which was obtained for a P_2O_5-doped silica preform, was about 80% of the pure silica value. In contrast, the Rayleigh scattering coefficients of F-doped and GeO_2-doped and pure silica glass preforms increased by 5–10% when they were heated to 1800 °C because the density fluctuation is proportional to their fictive temperature. We also obtained very low Rayleigh scattering coefficients in fabricated fibers by controlling the preform composition or the fiber drawing conditions. We used these results to reevaluate the intrinsic losses of P_2O_5-doped, pure, and GeO_2-doped silica core fibers and found them to be 0.095–0.130 dB/km at 1.55 μm by using the Rayleigh scattering coefficients of their preforms.

Keywords: Optical fiber; Rayleigh scattering; Intrinsic loss; SMF

1. Introduction

Low loss optical fiber is essential for long distance and large capacity transmission systems. The development of wavelength-division-multiplexing (WDM) technologies has made it possible to enlarge the wavelength regions used for signal transmission through

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conventional single-mode fibers (SMFs). Under these conditions, a minimum loss of 0.1484 dB/km has been achieved in pure silica core SMF [1].

In contrast, photonic crystal fiber (PCF) with silica–air microstructures has received increasing attention because of its novel guiding properties, namely dispersion tailoring, a wide single-mode wavelength region, and a small bending loss [2–4]. We have developed a PCF whose optical loss is 0.28 dB/km at 1.55 μm [5]. To reduce the SMF and PCF losses even further, it is necessary to clarify their intrinsic losses.

In this paper, we describe the Rayleigh scattering properties of typical silica-based fibers and their preforms. In particular, we show the dependence of Rayleigh scattering on dopant concentration and fictive temperature, which enables us to reevaluate their intrinsic losses [6–11]. We define the intrinsic loss of each fiber as a practical target value for loss reduction, which is obtained from the Rayleigh scattering of preforms. We also discuss several approaches to reduce the actual loss so that it is as low as the intrinsic loss.

2. Rayleigh scattering of VAD preforms

We measured the Rayleigh scattering of preform samples with a dynamic light scattering spectrometer DLS700 (Otsuka Electronics). The scattering signal includes both Rayleigh scattering and Brillouin and Raman scattering. However, they all show $1/\text{wavelength}^4$ dependence and the Rayleigh scattering accounts for more than 85% of the scattering in silica glass [12]. Therefore, we assume that the observed scattering is Rayleigh scattering. We measured the Rayleigh ratio at two or three different points in each sample to ensure the validity of the experimental results. The deviations were less than ±5%, and we determined the Rayleigh scattering coefficient from the average value. Then we normalized the value with that for standard pure silica glass, and obtained R_n values. The infrared absorption spectrum was measured with a Fourier transform infrared spectrometer FT-IR (Nicolet). We also measured the viscosity of several samples by elongating them [13].

Pure, GeO_2-doped, and F-doped silica glass preforms were prepared to enable us to investigate the effect of thermal treatment on Rayleigh scattering. Figure 1 shows the thermal treatment diagram for two types of sample. Porous soot preforms were consolidated into glasses at around 1400 °C. They were then annealed from 1400 to 1250 °C at a cooling rate of 5 °C/min, and air-cooled to room temperature. We call these usual VAD preforms "annealed samples." Each "annealed sample" was cut into two pieces, one of which was reheated to 1800 °C and then air-cooled again to room temperature. These are the "reheated samples." In this study, as a measure of the dopant concentrations, we use the relative-refractive index differences between the samples and pure silica glass induced by each dopant. They are expressed as [GeO_2], [P_2O_5], and [F], respectively. Figure 2 shows the relationship between the dopant concentration and Rayleigh scattering coefficient for two types of sample with different thermal histories [8,9]. In Fig. 2, the deviations in the Rayleigh scattering coefficient of each sample are shown as solid bars (±2% at most). The Rayleigh scattering coefficients of the "reheated samples" were always 5–10% greater than those of the "annealed samples." The change in the R value (ΔR) in pure silica glass was 6%. These results indicate that the Rayleigh scattering coefficients of pure and doped silica