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Germania-glass-core silica-glass-cladding modified chemical-vapor deposition optical fibers: optical losses, photorefractivity, and Raman amplification

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Germania-glass-core silica-glass-cladding single-mode fibers (Δn as great as 0.143) with a minimum loss of 20 dB/km at 1.85 μm were fabricated by modified chemical-vapor deposition. The fibers exhibit strong photorefractivity, with type IIa index modulation of 2×10^{-3}. A Raman gain of 300 dB/(km W) was determined at 1.12 μm. Only 3 m of such fibers is sufficient for constructing the 10-W Raman laser at 1.12 μm with a 13-W pump at 1.07 μm. © 2004 Optical Society of America

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Vitreous germanium dioxide (or germania glass) is a promising fiber optic material for 2-μm applications because of its potentially low optical loss[1,2] and high nonlinearity.[3,4] Earlier, multimode (MM) fibers based on germania glass had been prepared by vapor axial deposition (GeO_2-based core and cladding) and had minimum optical losses of 4 dB/km at 2 μm.[5] Modified chemical-vapor deposition (MCVD) multimode fibers with ~50-mol.% GeO_2 had optical losses of more than 100 dB/km.[6] Single-mode (SM) GeO_2-based-core fibers were fabricated by a rod-in-tube technique, with optical losses of 400 dB/km at 1.06 μm.[3]

We report on the development of SM MCVD fibers composed of a core with a GeO_2 concentration of as much as 97 mol.%, intermediate germanosilicate cladding, and P205- and F-doped silica cladding matched with a silica substrate tube. We also report on the photorefractive effect and on our preliminary study of Raman amplification and laser generation in such fibers. Note that GeO_2-based-core fibers with silica cladding seem to be especially suitable for telecommunication applications because of an evident possibility of low-loss fusion splicing of such fibers with common silica-based fibers.

Two fiber preforms with core compositions of $97GeO_2{-}3SiO_2$ (preform A) and $75GeO_2{-}25SiO_2$ (preform B) were fabricated. Radial distributions of glass composition measured by x-ray microanalysis in MM fibers drawn from these preforms are shown in Fig. 1. Neither fiber has the central dip in the GeO_2 concentration profile that is usually observed in MCVD germanosilicate fibers.

The available preform analyzer (York Technology P102) is not suitable for measuring correctly a core/cladding index difference of more than ~0.08. Therefore this value was calculated by use of a linear approximation of the dependence of index difference on GeO_2 concentration, $\Delta n = 1.47 \times 10^{-3} \times [GeO_2]\,[\text{mol.\%}]$, at $\lambda = 633$ nm. Thus we determined that $\Delta n(\text{A}) = 0.143$ and $\Delta n(\text{B}) = 0.11$. The core/cladding index difference obtained for MM fiber A by measurement of the fiber's numerical aperture ($\Delta n = 0.145 \pm 0.003$) confirmed the calculated value.

SM fibers were drawn from preforms A and B after additional jacketing with a drawing speed of ~50 m/min. Core diameters and cutoff wavelengths varied for the two samples in ranges of 1.4–2 and 1–1.4 μm, respectively. The shape of the core of preform B was appreciably different from a circle.

Figure 2 shows optical loss spectra in SM fibers. Losses of ~100 dB/km in SM fiber A with a cutoff of 1.3 μm were measured at $\lambda = 2.0$ μm. Note that minimum losses in MM fiber A with a core diameter of 8 μm were much lower, namely, 27 dB/km at 2.1 μm. The minimum losses of 20 dB/km at 1.85 μm were achieved in both SM fibers B ($\lambda_c \sim 1, \sim 1.4$ μm). The loss difference in the long-wavelength region (beyond 2 μm) in fibers B corresponds to the difference in their

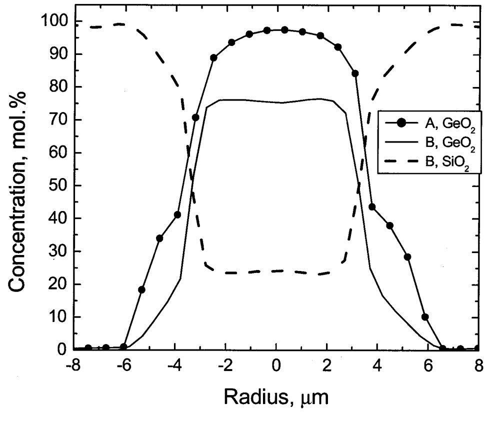

Fig. 1. GeO_2 and SiO_2 concentration profiles measured in multimode fibers A and B by x-ray microanalysis.

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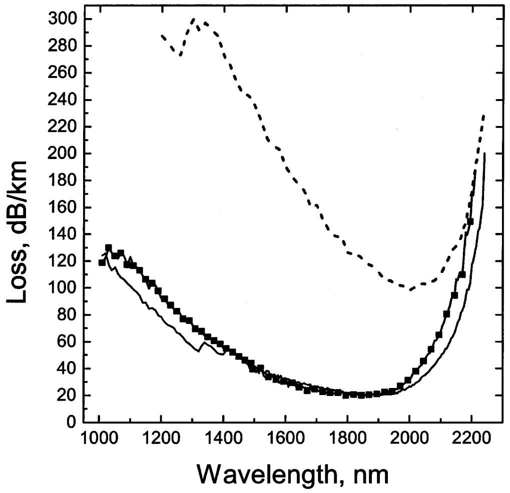

Fig. 2. Optical loss spectra in SM fiber A ($\lambda_c \cong 1.3$ μm, dashed curve) and in SM fibers B ($\lambda_c \cong 1.4$ μm, solid curve; $\lambda_c \cong 1$ μm, filled squares).

cutoff wavelengths and to a greater intrinsic absorption in the silica-based cladding compared with the germania-based core in this spectral range.

Scattering losses were measured at 0.647 and 1.064 μm in MM and SM fibers A by an integrating sphere technique. It turned out that the total attenuation was caused almost fully (within experimental error) by the scattering; the measured scattering loss exceeded Rayleigh scattering in bulk GeO_2 by 10–100 times.[2] The angular dependence of scattered light at 0.53 and 0.647 μm (see Fig. 3) has an intense forward-biased component, mainly in an angle range $\theta < 60°$ ($\theta = 0°$ is a forward direction), which is indicative of the presence of relatively large-scale optical inhomogeneities in the core region. To understand the nature of these inhomogeneities will require additional study. Earlier, large anomalous scattering at small angles was observed by Lines *et al.* in highly Ge-doped fibers.[7]

It is worth noting that the optical properties of germania-based-core fibers are stable enough; e.g., in fibers A the optical losses did not change during the course of 3 years.

As is generally known, the photosensitivity of germanosilicate fibers increases with increasing GeO_2 concentration. Therefore a study of the photosensitive properties of GeO_2 glass fibers could provide novel information about photosensitivity mechanisms. We performed a comparative study of the dynamics of Bragg grating formation in SM fibers A, B, and C (fiber C had a germanosilicate core doped with 24.5-mol.% GeO_2). The gratings were written in an interferometric scheme by cw 244-nm radiation ($I = 25$ W/cm^2, $\lambda_{\mathrm{Br}} \approx 1.55$ μm, $L = 4.5$ mm). The fibers were not hydrogen loaded. All the tested fibers exhibited type IIa dynamics of Bragg grating formation (Fig. 4). As is shown in Fig. 4(a), the larger the GeO_2 concentration is, the higher index modulation amplitude Δn_{mod} is and the lower the exposure required for saturating the grating is. The value of $\Delta n_{\mathrm{mod}} = 2 \times 10^{-3}$ was achieved in fiber A at an UV dose of 3 kJ/cm^2 and in fiber B at 10 kJ/cm^2, whereas in fiber C a nonsaturated type IIa grating with $\Delta n_{\mathrm{mod}} \approx 3 \times 10^{-4}$ was written with a dose of ~200 kJ/cm^2.

Figure 4 shows a strong dependence of index change dynamics in fibers A, B, and C on the GeO_2 concentration. In particular, the ratio of initial rates of type IIa Bragg grating formation for fibers A, B, and C is approximately 110:50:1, whereas the GeO_2 concentration ratio is 4:3:1 for these fibers. Note that the electrostriction model of the Bragg grating formation also predicts a strong power-law dependence of the phenomenon on GeO_2 content.[8]

An even stronger concentration effect was observed in the dynamics of mean-index change Δn_{mean} calculated from the Bragg wavelength shift [Fig. 4(b)]. In fiber C the value of Δn_{mean} is always positive and decreases only slightly at a high dose, whereas in fibers A and B Δn_{mean} quickly becomes negative and reaches a magnitude of -1.5×10^{-3}. To our knowledge this is the highest value of a negative mean-index change

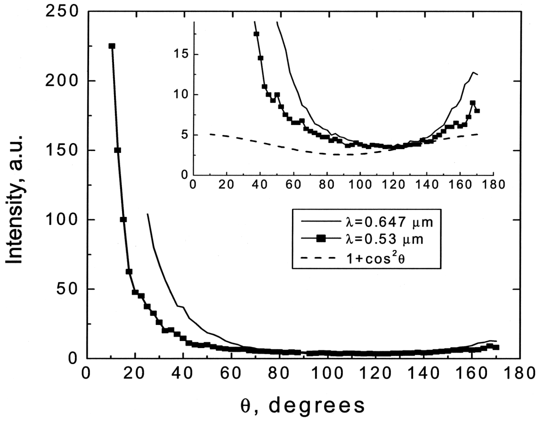

Fig. 3. Scattering indicatrix in multimode fiber A at wavelengths of 0.53 and 0.647 μm. The dashed curve in the inset is a Rayleigh scattering law, $I_{\mathrm{sc}} \sim (1 + \cos^2 \theta)$.

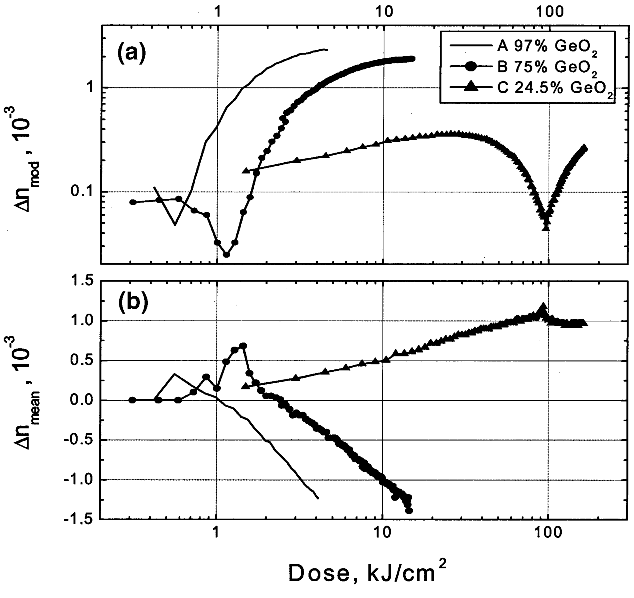

Fig. 4. (a) Index modulation Δn_{mod} and (b) mean-index change Δn_{mean} in the Bragg gratings written in fibers A, B, and C versus doses of 244-nm radiation.

observed in Bragg gratings (see, e.g., Ref. 9). Possibly this effect is due to rupture of valence bonds in the core glass, which are under a great tension (of the order of 200 MPa in fiber A). As a result, the lowering of a mean density of the core glass can decrease the mean refractive index.

Our fibers have demonstrated a rather high loss level. But the high values of Δn and of nonlinearity should result in a high fiber Raman gain coefficient (g_0) that can compensate for a high loss level under sufficiently low pump power. As an active Raman fiber we used SM fiber B with a cutoff wavelength of ~1.4 μm. As a pump source, a laser-diode-pumped SM cw Yb fiber laser with output wavelength $\lambda_p = 1.07$ μm was used. The Raman gain of the fiber was measured at $\lambda_s = 1.12$ μm, with a cleaved end face of the fiber as the output coupler. The length of the fiber in this case was 20 m. We determined that $g_0 \approx 300$ dB/(km W), using the condition of equality of gain and losses in a cavity at the lasing threshold. This value is at least 1 order of magnitude higher than the Raman gain coefficients for Ge-doped silica core fibers published so far.[10]

For a lasing experiment an almost optimum scheme that included a single-stage Raman fiber laser with a resonator formed by a pair of Bragg gratings (highly reflective and with $R \approx 50\%$ at $\lambda_s = 1.12$ μm) was developed. The length of the fiber turned out to be only 3 m. All the Bragg gratings were written directly in fiber B. The highest output power of the Raman fiber laser was ~10 W (at 13 W of pump power) and was restricted only by the threshold of second-Stokes lasing in the cavity, formed by end faces of the GeO_2-based fiber and of the Yb-doped fiber. The optical-to-optical efficiency of the Raman fiber laser was as high as 70%.

During these measurements a fusion splicing of fiber B (75-mol.% GeO_2 in the core) with the standard germanosilicate fiber (~6-mol.% GeO_2 in the core) was made. Typical splicing losses were in the range 0.3–0.8 dB. Thus our fibers with a germania-based core are quite compatible with low-germania-core silica-based fibers.

These results demonstrate the potential of the GeO_2-based fibers as an active medium of Raman fiber lasers. The optical loss spectra in these fibers point to the possibility of particularly efficient Raman laser operation in the 2-μm spectral band. Besides, the short lengths, high Δn, and low bending loss have permitted miniature Raman fiber lasers to be developed.

Germania-glass-core silica-glass-cladding single-mode fibers (Δn of as much as 0.143) were fabricated by MCVD. Minimum optical losses of 20 dB/km at 1.85 μm were achieved in the fibers with 75-mol.% GeO_2 in the core (Δn of ~0.11). Forward-biased scattering was the main source of the loss. Novel fibers were found to be quite compatible with silica-based fibers.

The GeO_2-core-based fibers possess a high photorefractivity under UV exposure. Growth of the GeO_2 content strongly increases both the rate of writing and the index modulation in the type IIa region. A strong mean-index decrease ($\Delta n_{\mathrm{mean}} = -1.5 \times 10^{-3}$) was found, for the first time to our knowledge. Raman gain as high as 300 dB/(km W) was measured for the fiber with 75-mol.% GeO_2 in the core at a wavelength of 1.12 μm (first Stokes at 1.07-μm pump), and the output power of the 3-m-long single-stage Raman fiber laser was 10 W, with optical efficiency as high as 70%.

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