Highly doped silica-based fibers for nonlinear applications

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Abstract This paper reviews state-of-art of highly doped silica fibers manufactured by the MCVD technique and the applications of these fibers in a number of nonlinear devices.

Introduction

Much attention is currently being given to the applications of optical fibers to nonlinear optical devices for future high-capacity systems and photonic networks. Although optical nonlinearity of doped silica glass is relatively small, it can be compensated by a small spot-size of the guided waves and by almost an “infinite” interaction length, resulting from low transmission losses of doped silica fibers and their easy coupling to communication fibers. The purpose of this paper is to review the recent achievements in highly doped silica fibers manufactured by MCVD technique and to discuss some of their applications in nonlinear devices.

Highly GeO_2-doped silica fibers

It is well known that GeO_2 and F – most common silica dopants used to fabricate optical fibers for telecommunication – change the n_2-nonlinear refractive index of silica relatively moderately. For example, nonlinear index n_2 rises by 39% at 25 mol.% GeO_2 doping level [1]. Thus, the gain in nonlinearity in highly GeO_2-doped fibers is the result of mode-field diameter reduction, the latter being due to a large refractive index difference between the core and the cladding. At the same time, achieving sufficient efficiency of the nonlinear fiber devices requires that the optical losses in such fibers be reasonably low. The lowest level of optical losses was achieved in highly GeO_2-doped silica fibers fabricated by the VAD method only [2, 3]. At a doping level of 30 mol.% GeO_2 (Δ=2.9%, λ=1550nm) the optical losses were 1.4 dB/km in a fiber with a pure-silica cladding and 0.51 dB/km in a fiber doped with fluorine throughout the cladding [3].

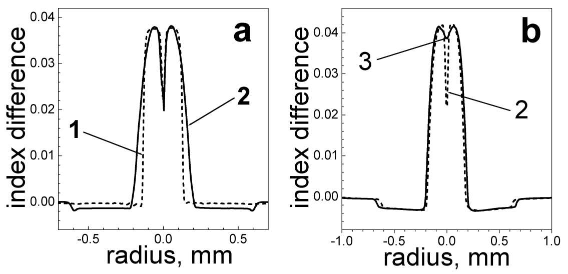

Fig.1. RIP of different types of GeO_2-doped fibers:1-step RIP fiber; 2 – graded RIP fiber; 3 – graded RIP fiber with eliminated central dip.

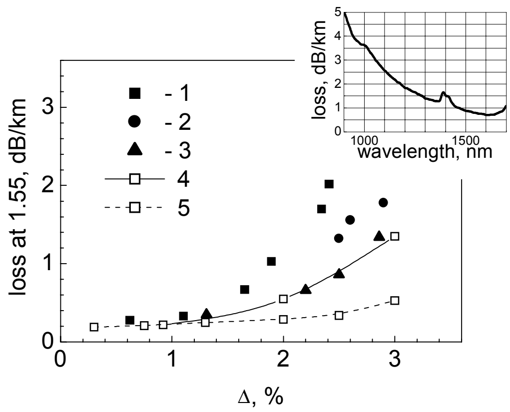

Fig.2. Fiber attenuation at 1550 nm for a series of GeO_2-SiO_2 core fibers. Closed symbols – [12]; open symbols – [3]. Insert: optical loss spectra in dip-free single-mode fiber doped with 26 mol.% GeO_2.

Until recently, fibers fabricated by the MCVD method have shown a high level of excess losses [4, 5]. Numerous investigations have been conducted to clarify the loss mechanisms in these fibers. The Rayleigh scattering losses were found to increase virtually monotonically with the GeO_2 doping level [6,7]. In fibers with $\Delta < 3\%$ the Rayleigh scattering was smaller than 0.35 dB/km at the wavelength of 1550 nm. The contribution of the UV absorption to the total loss does not exceed 0.1 dB/km in such fibers [8]. Thus, the combined contribution of the fundamental mechanisms into the total optical loss is lower than 0.45 dB/km at the wavelength of 1550 nm in fibers with $\Delta < 3\%$. Investigations of the angular distribution of scattered light have shown that large excess loss in highly GeO_2-doped single-mode fibers is mainly due to anomalous scattering [6, 7, 9, 10]. Intensity of this type of scattering is lower in graded-index fibers and fibers free of the central dip in the refractive index profile (RIP). The intensity of anomalous scattering strongly depended on the drawing temperature. This scattering arises at the core cladding interface [10, 11], and we bellieve that it is due to the viscosity mismatch between the core and the cladding.

Different RIPs of the highly GeO_2-doped fibers under investigation are shown in Fig.1. Figure 2 sums up the data on optical loss in different types of GeO_2-doped fibers. All fibers are drawn at a reduced temperature of 1860°C to minimize optical loss. One can see that the difference between the step and the graded RIP was very slight (Fig.1a); nevertheless, optical losses in graded-index fibers (Fig.2, symbols 2) are well below those in step-index fibers (Fig.2, symbols 1). Further loss lowering was achieved owing to the elimination of the central dip (RIPs are shown in Fig.1b). Losses in dip-free graded RIP fibers (Fig. 2, symbols 3) are very close to the lowest loss level of VAD fibers with a pure-silica cladding (symbols 4).

Further reduction of optical losses in highly GeO_2-doped VAD fibers was obtained by high fluorine doping (~1.5 at% F) throughout the cross-section of the cladding and by drawing fibers at a lower temperature. This resulted in a significant decrease of optical losses (Fig.2, symbols 5) [3]. We found that it was not possible to pull sufficiently long MCVD fibers at temperatures much below 1860°C, if silica substrate and jacketing tubes were used. Only by using highly F-doped (Δ^-=0.35%) high-purity substrate and jacketing tubes, further reduction of optical losses in MCVD fibers is possible. At present, such tubes are not commercially available.

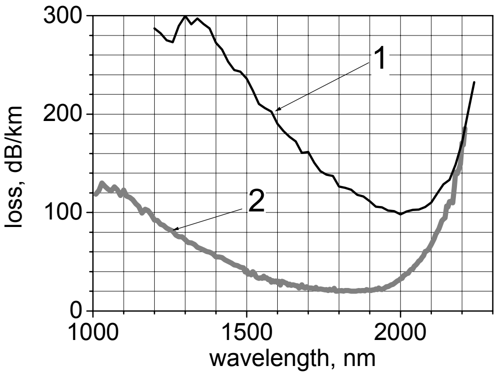

Fig.3. Optical loss spectra of single-mode germania-core fibers: 1 – 97 mol.% GeO_2, 2 – 75 mol.% GeO_2.

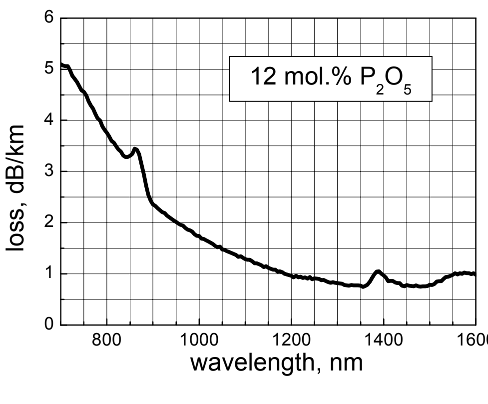

Fig.4. Optical loss spectrum in highly P_2O_5-doped single-mode fiber (cut off wavelength λ_c = 0.95 μm).

Fibers with germania core

The next step in the development of highly GeO_2-doped fiber technology was the manufacture of single-mode fibers with a germania core. Germania glass is a promising material for fiber optics, because of potentially low optical losses in the spectral range around 2 μm [13] and high nonlinearity [14].

The performs with a heavily GeO_2 doped core were manufactured by a technology based on the MCVD method with a GeO_2 content of 97 mol.% (Δn = 0.142) in perform A and of 75 mol.% in perform B (Δn = 0.110). After jacketing these perform with silica tubes, they were drawn into fibers [15]. Figure 3 shows optical loss spectra in these single-mode fibers.

Highly P_2O_5-doped fibers

In comparison with other silicate glasses used in fiber optics, the phosphosilicate glass is notable for its large Raman stokes shift of 1320 nm. For this reason, single-mode fibers with a P_2O_5-doped core can significantly simplify the Raman lasers design. To create a highly efficient Raman laser, heavily phosphorus-doped single-mode fibers with low optical losses are required. As compared to germania, phosphorus pentoxide is much more volatile and exhibits significant diffusion at elevated temperatures typical of the MCVD process, which prevents achieving a high phosphoria doping level in preforms. For this reason, the processes of deposition, sintering and preform collapsing were studied thoroughly [16]. A reduction of optical losses in P_2O_5-doped single-mode fibers to the value below 1 dB/km in the wavelength range 1.1-1.5 μm was achieved by means of decreasing the drawing temperature and by additional doping of the phosphosilicate fiber core with fluorine. A typical spectral attenuation in a single-mode P_2O_5-doped fiber (Δn = 0.010) is shown in Figure 4.

It is known that nonlinear properties of fibers correlate with the dopant concentration. Therefore, the development of highly doped fibers was motivated by the necessity to obtain high nonlinearity, including a high fiber Raman gain coefficient (FRGC). At the same time, the investigations of P_2O_5-doped fibers showed that optical losses increase dramatically for P_2O_5 concentrations above 13 mol.%. As follows from the theoretical analysis of the efficiency of Raman fiber laser (RFL) performed in [17], applicability of a fiber to RFL can be characterized by P_F-parameter. This parameter is determined by the loss values at the pumping wavelength and the corresponding Stokes wavelengths and by the FRGC values at these wavelengths. To increase the RFL efficiency, the P_F-parameter should be lowered. The dependence of the P_F-parameter calculated for a one-cascade RFL [17] on the refractive index difference between the core and the cladding is given in Figure 5. Note that Δn is proportional to the P_2O_5 concentration. As is seen in Figure 5, the P_F-parameter increases and the RFL efficiency decreases starting from Δn=0.011 (~ 12.5 mol.% P_2O_5) in fibers with a central dip. However, dip-free fibers demonstrate an increase of the RFL efficiency at Δn>0.011, which can be explained by a faster rise of the FRGC as compared to the rise of optical losses.

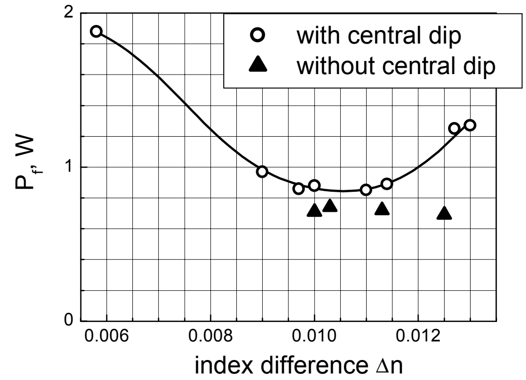

Fig.5. P_F dependence on P_2O_5 content in single-mode fibers with and without central dip.

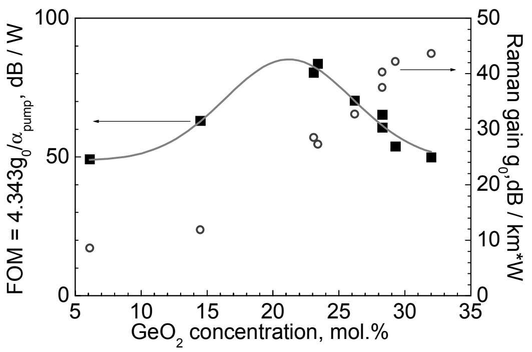

Fig.6. FOM and Raman gain dependence on GeO_2 concentration.

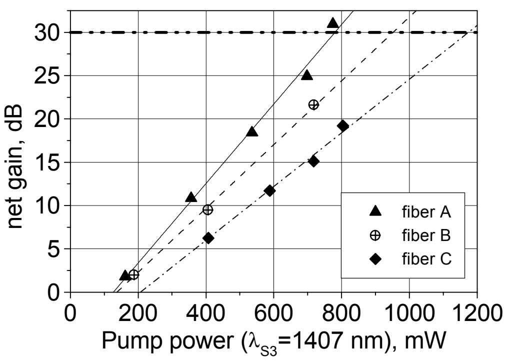

Fig.7. Variation of small signal net gain at 1500nm with input pump power: fiber A – HGDF; fiber B – NZ DSF; fiber C – LEAF.

The quantum efficiency of Raman lasers strongly depends on the lumped losses, which can be noticeably decreased by writing gratings directly in the P_2O_5-doped fiber. Our investigations showed that using 193nm emission of an eximer laser allows writing strong Bragg gratings in H_2-loaded phosphosilicate fibers [18].

Non-linear applications of heavily doped fibers

The highly GeO_2 and P_2O_5 doped fibers described above were developed for use in Raman fiber lasers (RFL) and amplifiers (RFA). At present, the most promising pumping source for RFL is a diode pumped Yb-doped fiber laser operating around 1000 nm. This region should be converted to the region of 1400-1480 nm which is demanded for pumping Er-doped and Raman optical amplifiers operating in the 1550nm spectral region. A P_2O_5-doped fiber exhibits a relatively high FRGC with a large Stokes shift of 1330 cm^{-1}, which allows one to decrease the number of cascades and to simplify the RFL design.

A two-cascaded (1.06-1.24-1.48 μm) RFL was developed on the basis of a P_2O_5-doped fiber [19]. Bragg gratings forming the laser cavity were written directly in the P_2O_5-doped fiber, which reduced the lumped losses and allowed the fiber length to be shortened to 100 meters. The power efficiency of this RFL achieved 45% (quantum efficiency of 62%), the power and quantum slope efficiency being 60% and 83%, respectively.

P_2O_5 doped fibers have one more unique feature. Their Raman gain spectrum consists of two strong bands at 440 cm^{-1} and 1330 cm^{-1} corresponding to Si-O and P=O bands. Combining these bands and using a tunable Yb-doped fiber laser as a pump source, it is possible to develop an efficient RFL operating at practically any wavelength in the spectral region of 1.1-1.6 μm. In particular, a RFL for 1407 nm was demonstrated, which is a promising pumping source for the 1.5 μm RFA.

To attain the necessary wavelength of 1407 nm, one P=O and two Si-O related Stokes shifts were used. A Nd fiber laser emitting at λ_p = 1062 nm with an output power of 3.8 W was used as the pump source. The laser slope efficiency of 35% was achieved at the output power of 1W [20]. At present, the twin gain peak of P_2O_5-doped silica fibers has found widespread use for various applications [21, 22].

Highly GeO_2-doped fibers are an attractive medium for the discrete RFA. These fibers allow minimization of the pump power and the fiber length. On the other hand, the communication fibers are very suitable for distributed Raman amplifiers. For this reason, three different fibers were compared as a medium of a Raman amplifier pumped by a 1407 nm RFL. A highly

GeO_2-doped silica fiber (HGDF), an NZ dispersion shifted (NZ DSF) fiber, and a large effective mode area fiber (LEAF) were tested [23]. The fiber performance in the RFA was evaluated in terms of FOM which is proportional to the ratio of FRGC to the fiber losses at the pumping wavelength. Figure 6 shows that an HGDF fabricated by the MCVD method has the maximum FOM at a GeO_2 content of 23 mol.%. The Figure 7 summarize the main results of the measurements. The HGDF ensured the highest gain of 31 dB for a pump power of 770mW.

Fibers with a near-pure-GeO_2 core demonstrated a much higher optical loss level of 20-90 dB/km as compared to fibers with a 20-30 mol.% GeO_2 content. Nevertheless, a very high value of $\Delta n \geq 0.11$ between the core and the cladding of these fibers resulted in a high FRGC which compensated the high losses. When using an Yb-doped fiber laser as a pump source, the FRGC was measured to be g_0=300 dB/km·W at a 70 mol.% GeO_2 content. This FRGC value is at least one order of magnitude higher than that of fibers with a doping level of 20 mol.% GeO_2. For this reason, a 3 meter length of such a fiber was sufficient to obtain a 10 W output power of a one-cascade Raman laser at the wavelength of 1120 nm. This output power value was limited only by the threshold of the second Stokes lasing in the cavity formed by the GeO_2 fiber endfaces. The optical to optical efficiency of this Raman laser turned out to be 70% [24].

Nonlinear properties of highly GeO_2-doped fibers are mainly determined by the positive component of the refractive index difference between the core and the cladding (Δ^+). Therefore, although optical losses in highly GeO_2-doped fibers fabricated by the MCVD technique are somewhat greater than those in the VAD fibers, the MCVD fibers can find wide use in a variety of optoelectronic devices, such as dispersion compensators, supercontinuum generators, optical parametric amplifiers, and so on.

Conclusions

State-of-art of the properties of highly GeO_2- and P_2O_5-doped silica fibers as well as near-pure-GeO_2-core fibers produced by the MCVD-technique has been reviewed. Such fibers are shown to be promising active media for various Raman fiber lasers and amplifiers and other optoelectronic devices.

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