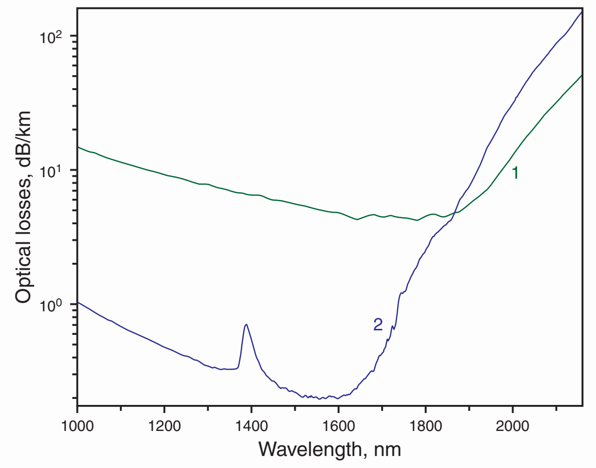
Abstract: We have realized supercontinuum source based on the silica-cladding fiber with the germanate-glass-core pumped by Q-switched Er-doped fiber laser. The long-wavelength edge of the spectrum obtained is located at 2.7 μm. To our best knowledge it is the longest wavelength for the silica based fiber. Average output power as high as 0.49 W was measured. Intensity variation in the range of 1.6 – 2.7 μm was much less than one decade. The fibers with different lengths were tested.



Optical losses spectrum in the heavily Ge-doped fiber (curve 1), in standard telecommunication fiber SMF-28 (curve 2)

Supercontinuum generation up to 2.7 μm in the germanate-glass-core and silica-glass-cladding fiber

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1. Introduction

Supercontinuum generation beyond 2 μm is of interest due to the potential application in spectroscopy, atmospheric analysis, medicine, etc. As a rule, to generate supercontinuum in this spectral range special fibers are applied. For example, in [1] sapphire fiber was used, in [2,3] – microstructured fiber based on oxide glass with complex composition. Using the fluoride fiber with femtosecond pump at wavelength of 1.45 μm allowed demonstrating optical generation above 3.8 μm [4]. Generation up to 4.8 μm was obtained in ZBLAN fiber [5]. Tapered tellurite microstructured fibers were used to get an emission up to 2.4 μm [6]. The main disadvantage of such sources consists in the bad compatibility with standard communication fiber technology.

Moreover, these sources are pumped by devices based on Ti:Sapphire femtosecond laser. Therefore using this approach it is difficult to build a compact all-fiber supercontinuum source for the practical applications. For the standard silica based fiber typical long-wavelength edge locates near 1.7 μm [7–10]. At the same time, in [11,12] all-fiber supercontinuum generation in standard telecommunication fibers was demonstrated due to the application of Q-switched Er-doped fiber laser. Supercontinuum spectrum was limited by the wavelength of approximately 2.4 μm.

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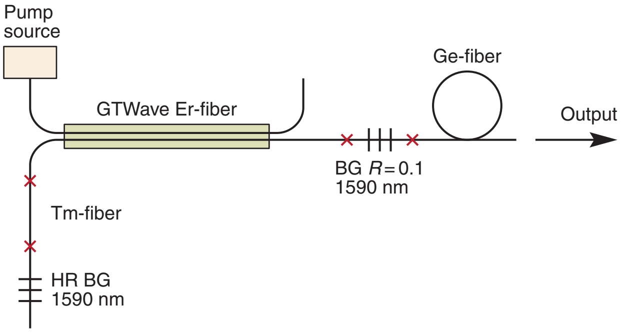

Figure 1 (online color at www.lphys.org) Scheme of the experimental setup. BG – fiber Bragg gratings and X – splicing points

Application of Ho-doped fiber amplifier as the non-linear medium allowed one to shift the long-wavelength limit up to 2.5 μm [13]. Oscillation at longer wavelengths is prevented by the absorption caused by the vibration band tail in silicate glasses. It is known that the vibration band of germanium dioxide is shifted to longer wavelength relatively silica. Then, germanate-glass-core fibers exhibit the smaller optical losses in 2 μm spectral range [14]. Therefore we can believe that an application of such fibers can allow one to obtain the supercontinuum at longer wavelength. As a rule, at 2-μm range optical fibers have anomalous chromatic dispersion – then supercontinuum is generated due to the Raman scattering mainly. Therefore it is important that Raman cross section in GeO_2 is nearly an order of magnitude greater than that of SiO_2 that allows one to use the shorter fiber [15]. Also these fibers exhibit the increased non-linear coefficient [16]. It should be noted that earlier such fibers were successfully used in Raman lasers [17,18] and in the fiber laser with intracavity spectrum transformation [19]. Fabrication and properties of the optical fibers with silica cladding and germanate glass core (when GeO_2 concentration being in the range of 50 – 100 mol.% prevails over other components) are reviewed in [20].

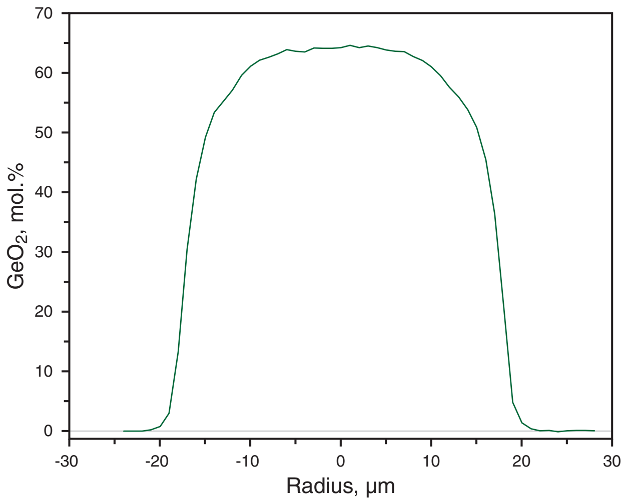

Figure 2 (online color at www.lphys.org) Radial distribution of GeO_2 in the fiber core

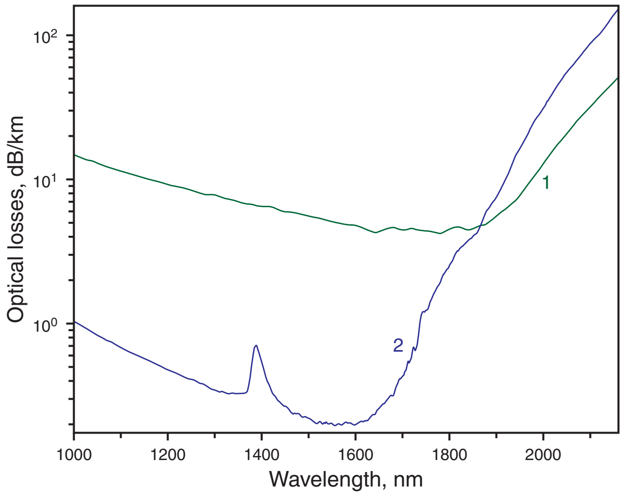

Figure 3 (online color at www.lphys.org) Optical losses spectrum in the heavily Ge-doped fiber (curve 1), in standard telecommunication fiber SMF-28 (curve 2)

2. Experimental setup

The scheme of the experimental setup is shown in Fig. 1. Cladding pumped Q-switched Er-doped fiber laser was used as the pump source [21]. Q-switching was realized by emplacement of a self-saturable absorber based on a Tm-doped fiber [22]. Lasing wavelength was of 1.59 μm, maximum output power was near 1 W with repetition rate of 4.4 kHz and pulse duration of 35 ns. Pulse energy of 0.21 mJ and peak power of 6 kW can be estimated.

As a nonlinear medium for generation of the supercontinuum we have used the silica based fiber having a germanium dioxide concentration in the core up to 64 mol.%. Fig. 2 illustrates the radial distribution of GeO_2, measured by X-ray microanalysis in a specially drawn fiber with large core diameter (about 40 μm). A fiber for optical experiments had a core diameter of approximately 5.5 μm. Cut-off wavelength of the fundamental mode can be estimated as approximately 3.5 μm. It means that the fiber supports the propagation of the several modes. Dispersion properties of the most of them are determined by the material dispersion which is zero at the wavelength of approximately 1.6 μm. Therefore, supercontinuum generation occurs in the field of the anomalous dispersion based on Raman mechanism mainly [23]. A value of the Raman gain can be estimated as 20 dB/W/km approximately. This es-

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timation is based on the results from [24]. Fig. 3 shows the optical losses spectrum of the germanate-glass-core fiber (curve 1) in comparison with corresponding spectrum of the standard telecommunication fiber SMF-28 (curve 2). In the range of 1.0 – 1.8 μm optical losses in SMF-28 are less than in the germanate-glass fiber. However the grows of the losses in the range of 1.8 – 2.2 μm for the last fiber is not so sharp. As a result, starting from 1.8 μm the germanate-glass-core fiber exhibits the smaller losses.

Output spectrum was measured by the optical spectrum analyzer up to 1.6 μm the spectrum. For longer wavelength we used the spectrometer with InGaAs and PbS photodetectors. Resolution of the spectrometer was of 2 nm.

3. Experimental results and discussions

We have tested 3 pieces of the germanate-glass-core fiber with a length of 11, 9, and 7 m. All samples were spliced with output fiber Bragg grating with the losses of approximately 3 dB. Using the different fiber length we tried to find an optimal length providing the spectrum with the longest boundary. It is clear that the increase of the length should lead to growth of the loss, but too short fiber cannot provide an efficient non-linear conversion.

Output spectrum in the case of 11 meters length sample is shown in Fig. 4a. One can see that the intensity falls after at the wavelengths higher than 2 μm. We believe that such behavior is caused by growing optical losses in this spectral region and by conversion to a shorter wavelength range. Also, we observed a weak green emission. Average output power was 0.42 W and 17% of this power is concentrated in the range 2.0 – 2.5 μm.

Application of a sample with the length of 9 meter allowed one to obtain a wider and flatter spectrum presented in Fig. 4b. Long-wavelength limit of supercontinuum is shifted to 2.6 μm. This fact confirms the influence of optical losses in fiber. In short wavelength range at the same time, we observed the significant decreasing of intensity in comparison with previous case, because interaction length was not enough for parametrical processes. Output average output power was measured as 0.49 W and the part of power in the range 2.0 – 2.6 μm was of 55%.

A further decrease in fiber length to 7 meters led to a broadening of the spectrum to 2.7 μm, the shape of the spectrum remains flat. Average output power was of 0.5 W and the part of power in the range 2.0 – 2.7 μm was of 58%. A sharp long-wavelength boundary of the spectrum can be caused by OH-group absorption centered near 2.8 μm [25].

As noted above, stimulated Raman scattering (SRS) is the main effect that leads to broadening of spectrum to the long wavelength range. So fiber with large SRS factor can provide more effective supercontinuum generation in the range 2.0 – 2.7 μm. In standard silica fibers with the low Ge-concentration in the core, both this factor is extremely low in this range and losses are high. As a result, we cannot provide an efficient generation at the wavelength above 2.4 μm. In the heavily germanium doped fiber SRS factor is higher, and losses in this spectral range are less. As a result, long wavelength limit is shifted up to 2.7 μm. Also a nonlinear factor is higher in the germanate-glass-core fiber

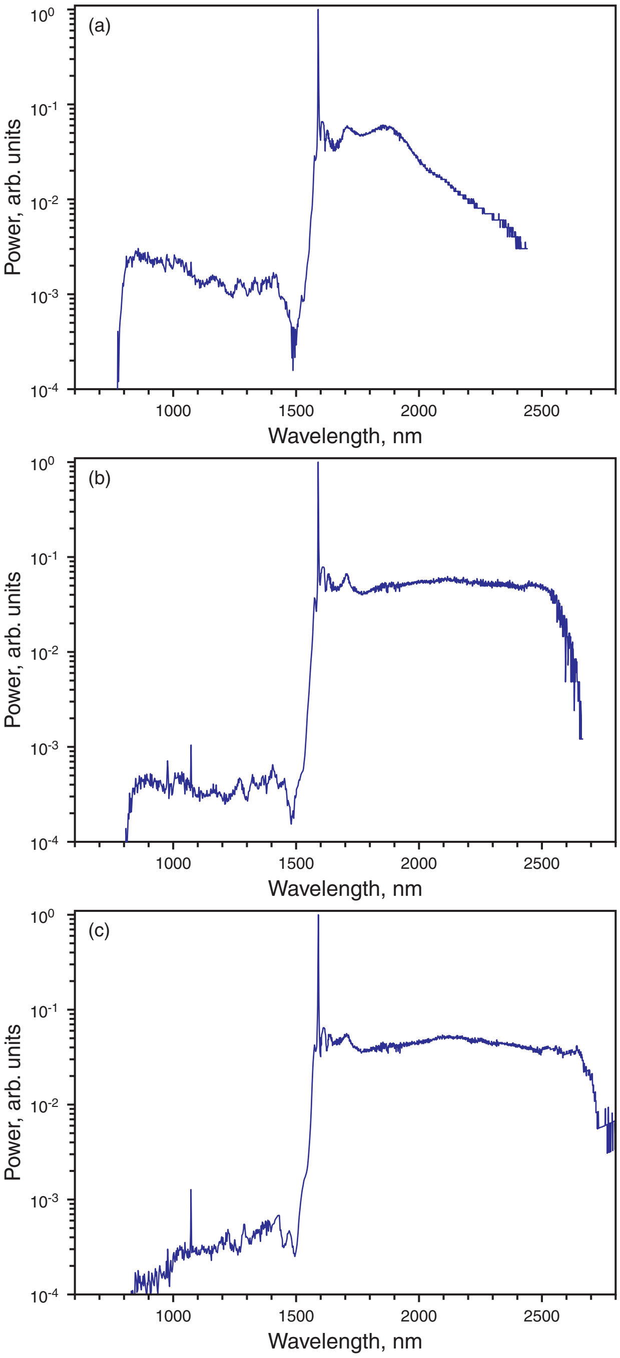

Figure 4 (online color at www.lphys.org) Output supercontinuum spectrum. (a) – fiber length 11 meters,(b) – 9 meters, and (c) – 7 meters

that confirms by the short wavelength generation. At the same time these fibers are compatible with telecommunication fibers from the viewpoint of fusion splicing because their cladding consists of silica glass. So they can be applied in all-fiber devices as the special nonlinear medium.

4. Conclusion

All-fiber source of supercontinuum with long-wavelength limit near 2.7 μm was demonstrated. Dependence of efficiency of the spectral conversion on the fiber length was studied. Achieved maximum average power was measured as 0.5 W. Spectral intensity of the supercontinuum in the range of 1.6 – 2.6 μm was practically constant, in the range of 1.6 – 2.7 μm its variation was much less than one decade.

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