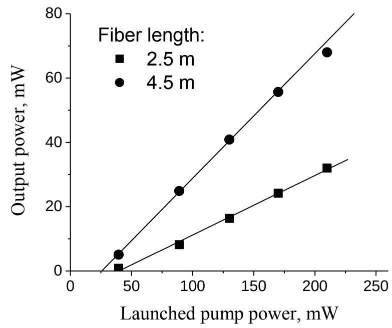

Fig. 4. The dependence of the output fiber laser power on the launched pump power for the two lasers of 2.5 and 4.5 m length of the active fiber.

The slope efficiency with respect to the launched pump power consisted of 26 and 37% for the short and long fiber lasers, respectively. The threshold was 40 and 25 mW for the short and long fiber lasers, respectively. Although the best slope efficiency of 37% is moderate, we suppose that the main reason for that are non-optimized laser parameters. Thus, the expected slope efficiency for this laser in the rough assumption of the complete absorbed pump conversion into the laser radiation is only ~60%. Optimization of laser parameters and components will allow further improvement of the efficiency.

The advantage of the 1.55 µm pumping is that usually no photodarkening with such pump wavelength is observed; in our experiments no change in the average output laser power during approximately one hour of operation has been observed.

The line-width of the laser emission was less than the experimental spectral resolution of 1 nm. The output spectra of both lasers also contain two spectral components at wavelengths of 1.84 and 1.884 µm (Fig. 5). Their intensities increased by a square law with the optical power of the central component at 1.862 µm. These symmetrical components were attributed to the four-wave mixing observed at relatively low powers due to operation in zero-dispersion region.

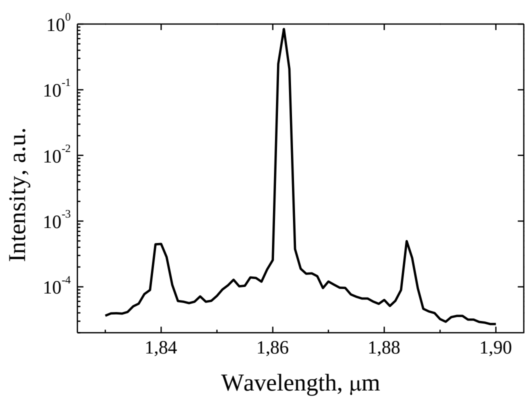

Fig. 5. The spectra of the output laser emission (70 mW of output power) of the fiber laser with the active fiber of 2.5 m length.

4. Theoretical analysis

The calculation of GVD has been based on the finite-element vectorial modelling of an effective refractive index of zero-order mode by the means of the COMSOL FEMLAB software package in combination with the Lumerical's MODE Solutions package. The

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wavelength dependence of the bulk material refractive index for different concentrations of germanium has been approximated by Sellmeier's formula in correspondence with Ref [6]. The obtained solutions have been compared with the analytical results for a step-shape profile of germanium-concentration. The corresponding Maple computer algebra introduction can be found in [11].

As the experimental inputs, the Ge-concentration profile presented in Fig. 1 (and also, for convenience, in the inset of Fig. 6) and the measured cut-off wavelength at 1.43 µm wavelength have been chosen. The geometry of Fig. 1 has been supposed to be axially symmetrical and to be fitted by 11 radial layers describing the experimental decrease of the Ge molar concentration from 55% to 0% (i.e. to a pure SiO_2). The external layer of a pure SiO_2 has been assumed to extend to 15 micrometers. This geometry has been covered by a rectangular mesh with 500x500 points (i.e. an external SiO_2 ring has been inscribed into a square with the rest of a square filled by air). The fiber size has been defined from calculation of the measured cut-off wavelength at 1.43 µm. Numerically, the following criterion has been used: the cut-off wavelength corresponds to loss of confinement of the higher-order modes when the fiber is bended. The bending radius has been chosen to be equal to 1000 micrometers.

The GVD corresponding to the geometry shown in Fig. 1 (and also in the inset in Fig. 6) is presented by the solid curve with the grey area defining the uncertainty limits. It has been found, that the wavelength of zero GVD shifts into a longer wavelength region with the decreasing core radius and that this wavelength is quite sensitive to the core size. Such behaviour corresponds to the domination of the waveguiding effects in the vicinity of the second zero point of the GVD. This domination results from the comparatively small core radius and the very high numerical aperture of the fiber, resembling the tapered and microstructured fibers. The calculated zero dispersion wavelength equals to 1.87 µm for the given Ge distribution.

The interesting property of GVD in such fibers is that the third-order dispersion is comparatively small in the vicinity of zero-dispersion wavelength [12]. Moreover, the analysis suggests that the GVD can be made almost flat in both anomalous and normal regions within a broad wavelength range by sharpening of the Ge-concentration profile. As an example, two GVD curves for a step-like behaviour of the Ge concentration are shown in Fig. 7 by a solid (core radius 1.5 µm) and dashed (core radius 1.2 µm) curves. Suppression of the higher-order dispersion is especially important for mode-locked oscillators (see e.g [13].). The dashed curve in Fig. 7 demonstrates that the all-normal-dispersion (ANDi) regime of mode-locking [14,15] is feasible for very small core radii. Such regime is of interest for generation of the energy-scalable femtosecond pulses [16]. It has been predicted that ANDi fiber oscillators can be perfectly energy-scalable by fiber length scaling [17]. One can expect that the core size can also be enlarged without transition to the anomalous dispersion regime by fiber microstructing [16]. The analysis of this possibility is under way now.

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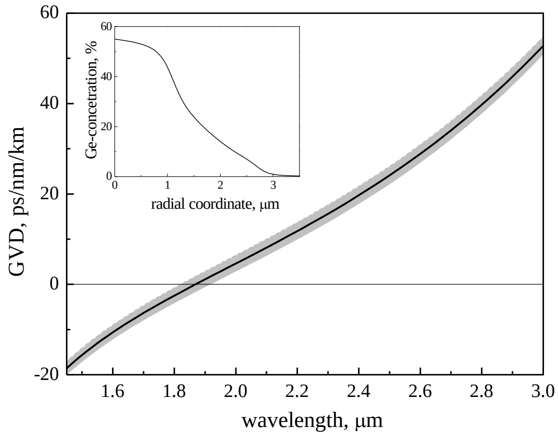

Fig. 6. Calculated dispersion of the fiber. The inset shows corresponding Ge distribution.

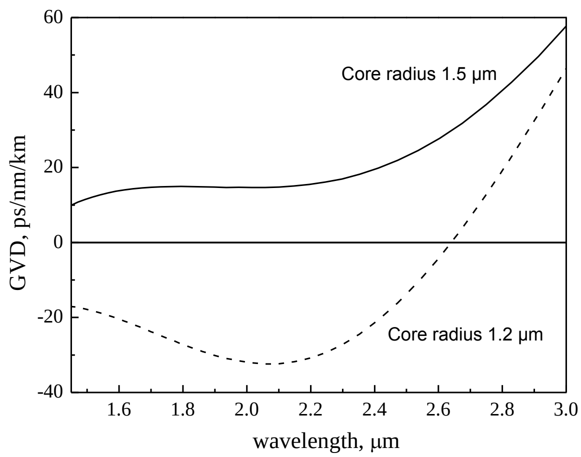

Fig. 7. Calculated dispersion of small-core step-index fibers with high GeO_2 doping.

5. Conclusion

We report the novel all-fiber laser based on the specially designed highly GeO_2-doped dispersion-shifted Tm-doped fiber, pumped at the 1.56 µm wavelength and lasing at the 1.862 µm wavelength with the slope efficiency up to 37%. The laser is based on the single-mode Tm-doped fiber with the $55GeO_2$-$45SiO_2$ core fabricated for the first time by MCVD technique. The laser produces spectral side bands, which are additional to the laser line and result from the four-wave mixing owing to the high nonlinearity and to the shifted to the laser wavelength zero-dispersion-wavelength in this fiber. We analyze this phenomenon both, theoretically and experimentally. The demonstrated in this work possibility to optimize the dispersion of the fiber opens up new perspectives on the way towards obtaining ultrashort pulses directly from the resonator of the all-fiber dispersion compensated laser.

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