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Optical fibre with a germanate glass core for lasing near 2 μm

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Abstract. **An optical fibre with a core based on thulium-doped germanate glass ($45SiO_2-55GeO_2$) and a silica cladding is developed for the first time. Lasing on Tm^{3+} ions ($\lambda = 1.862$ μm) with an output power up to 70 mW at a slope efficiency of 37 % is obtained in a laser based on this fibre.**

Keywords: *optical fibres, fibre lasers.*

Modern fibre lasers operate in the spectral range of 1 – 2 μm (see, for example, [1]). Further advance to the mid-IR range is an undeniably important problem in view of wide application of fibre lasers in medicine, atmosphere probing, and other fields. The most widespread silica fibres provide high-power and efficient lasing in the range of 1.9 – 2 μm [2]. However, advance to longer wavelengths is hindered by the increase in optical loss, which is related to the fundamental multiphonon absorption edge of silica. In this context, it is of interest to study materials with a lower phonon energy. In addition, the optical nonlinearity of such materials, which potentially exceeds that of silica, should make it possible to use nonlinear effects to expand the spectral range of laser operation.

The aforementioned properties are characteristic of recently developed fibres with a core made of germanate glass (i.e., glass with a dominant content of germanium dioxide) and a silica cladding [3]. The fundamental optical loss minimum in glassy germanium dioxide is known to be near 2 μm and amount to ~ 0.2 dB km^{-1} [4], whereas in silica optical loss is minimum at a wavelength of 1.55 μm. The Raman cross section in glassy GeO_2 exceeds that in silica by a factor of about 10 [5]. In addition, due to the large difference in the core and cladding refractive indices ($\Delta n \sim 0.1$), such fibres have a small mode field diameter and, therefore, a high germanium dioxide concentration in the core is an additional factor that enhances their nonlinear properties.

The possibility of using such fibres as active media in fibre Raman lasers was demonstrated in [6] by an example of a laser with an output power of 10 W and fibre length of only 3 m and lasers with wavelengths up to 2.2 μm. These parameters were achieved using external pumping by ytterbium and erbium fibre lasers. To simplify the fibre laser design, it seems reasonable to use a combination of two media in the same fibre: rare earth-activated glass (to generate initial radiation) and a material for its efficient nonlinear conversion. Here, we solved the first part of this problem: developed a fibre with a core partially made of germanate glass doped with Tm^{3+} ions and designed a 1.86-μm laser based on this fibre, with its subsequent analysis.

The fibre preform with a germanate glass core was fabricated by the MCVD technique using a support silica tube (Heraeus). After depositing a buffer $SiO_2-P_2O_5-F$ glass cladding with a refractive index similar to that of silica, several germanosilicate layers were deposited, with a gradual increase in the GeO_2 concentration to about 20 mol %. At this stage thulium was introduced by chemical vapour deposition using volatile organometallic thulium complex $Tm(tmhd)_3$ as a starting material. Germanate glass of the core was deposited at the last stage. The chemical composition of this preform was determined by X-ray microanalysis. The maximum GeO_2 concentration was 55 mol %, while the thulium concentration was close to the detection level (about 0.2 wt %). A multimode fibre was pulled from the initial preform (an electron micrograph of the fibre face and GeO_2 distribution are shown in Fig. 1). After additional jacketing the initial preform, the single-mode fibre with a core diameter of about 2 μm and cutoff wavelength near 1.4 μm was pulled.

The optical-loss spectrum of the fibre, recorded with a PbS photodetector, is shown in Fig. 2. The broad absorption band peaking at 1.58 μm is due to the $^3H_6-{}^3F_4$ electronic transition of the Tm^{3+} ion, the narrow peak at 1.22 μm corresponds to the $^3H_6-{}^3H_5$ transition, and the peak at 1.43 μm is due to the cutoff of the higher order fibre modes and transition to the single-mode regime at longer wavelengths. The optical-loss minimum in the fibre is near 1990 nm; it amounts to 0.123 dB m^{-1}. This value is mainly determined by the Tm^{3+} absorption in the $^3H_6-{}^3F_4$ band and excess loss for small-angle scattering, which is related to the fibre technology at very high dopant concentrations [3]. The contribution of the Tm^{3+} band should decrease with an increase in the wavelength, while the excess loss can be significantly reduced by improving the technology. However, we should note that fibres of this type have a

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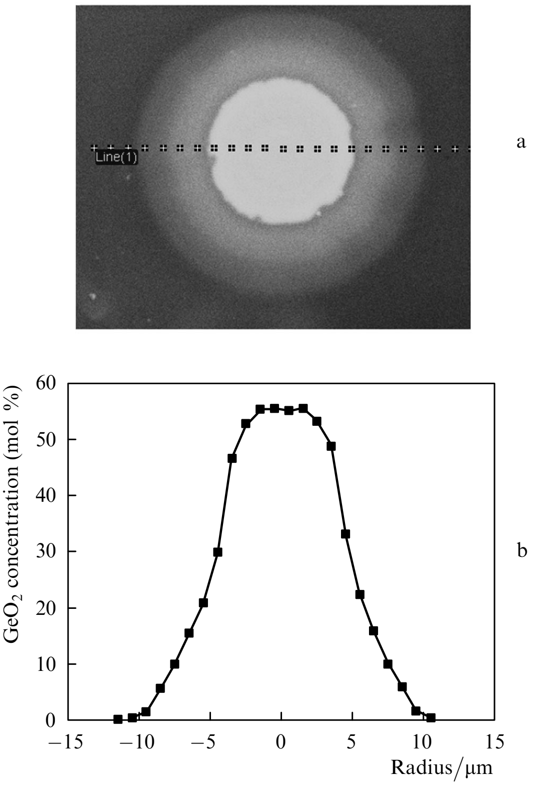

Figure 1. (a) Electron micrograph of a multimode fibre core and (b) the GeO_2 distribution, obtained by X-ray microanalysis. The distance between the measurement points is 1 μm.

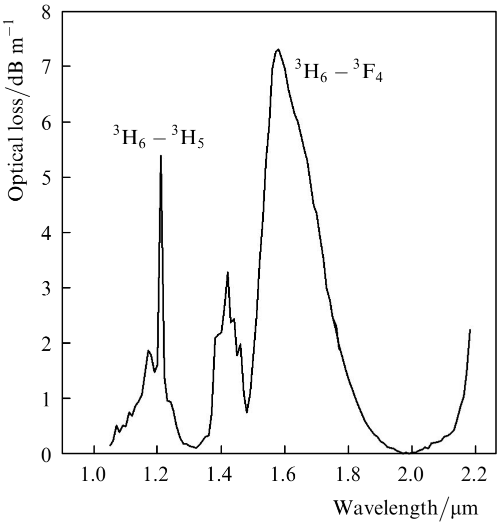

Figure 2. Optical-loss spectrum of the optical fibre under investigation. The peak near 1.43 μm is due to cutoff of the higher-order modes.

fundamental limitation, because of which their loss cannot be reduced to the level typical of pure GeO_2. It is the presence of SiO_2 both in the fibre core and cladding, which strongly absorbs light in the range of 2 – 3 μm. Even in the case of the pure germanate core, the power absorption for the mode propagating along the silica-glass cladding corresponds to the optical loss in a single-mode fibre at a level of 100 dB km^{-1} even at ~ 2500 nm.

Upon excitation at a wavelength of 1.064 μm in a 20-m fibre and detection of radiation emerging from the fibre output face, we revealed luminescence (typical of Tm^{3+} ions in silicate glasses) near 1.47 and 1.9 μm for the $^3H_4 - {}^3F_4$ and $^3F_4 - {}^3H_6$ transitions, respectively [7] (Fig. 3). The shift of the long-wavelength band peak to 1.9 μm, a value approximately corresponding to the optical-loss minimum, is apparently due to the reabsorption of radiation propagating along the fibre.

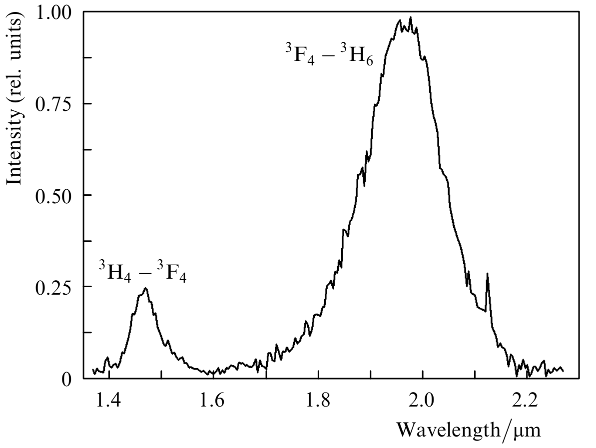

Figure 3. Luminescence spectrum upon excitation at a wavelength of 1.064 μm.

To implement lasing, we used fibres with lengths of 2.5 and 4.5 m. The cavity was formed by welding a fibre Bragg grating with a high (more than 20 dB) reflection coefficient at a wavelength of 1.862 μm to one of the active-fibre faces. The opposite face, with a reflectance of about 4 %, served as the output mirror. The optical-loss coefficient for a low signal in the fibre at this wavelength was 0.5 dB m^{-1} (Fig. 2).

Lasing was obtained upon pumping by an erbium fibre laser ($\lambda = 1.56$ μm) with a power up to 230 mW. For the short and long fibre segments, the differential lasing efficiencies were found to be 26 % and 37 %, and the lasing thresholds were 40 and 25 mW, respectively (Fig. 4).

Note that Raman scattering was not observed in the output lasing spectra (apparently, because of the low output power of the thulium laser: the maximum lasing power did

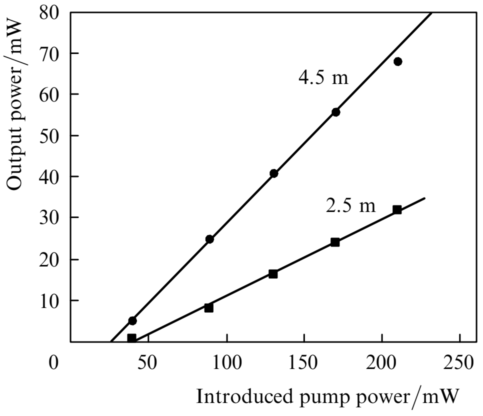

Figure 4. Dependences of the output power of thulium fibre laser ($\lambda_g = 1.862$ μm) on the introduced pump power ($\lambda_p = 1.56$ μm) for active-fibre lengths of 2.5 and 4.5 m.

not exceed 70 mW). This circumstance indicates that spectrally pure lasing can be obtained in the desired region for lasers based on this fibre, despite the high nonlinearity of the fibre material. However, the main tasks of further study are to implement nonlinear conversion of laser radiation (in order to advance to the long-wavelength spectral region) and to demonstrate other nonlinear effects in the fibres of this type.

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