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Raman fibre lasers emitting at a wavelength above 2 μm

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Abstract. Single-mode Raman fibre lasers emitting a few hundreds of milliwatts at wavelengths of 2.0 and 2.2 μm are built for the first time. Laser emission was amplified in a fibre with a germanium dioxide core and a silica cladding pumped by an Er/Yb-doped fibre laser.

Keywords: Raman fibre laser, Er/Yb-doped fibre laser, GeO_2 fibre.

By now a great progress has been achieved in the development of highly efficient cw Raman fibre lasers emitting in the near-IR region. By using double-clad ytterbium-doped fibre lasers for pumping and low-loss silica fibres doped with P_2O_5 and GeO_2 as Raman amplifying medium, it is possible to obtain lasing almost at any wavelength in the region from 1.1 to 1.7 μm [1]. The longest wavelength at which SRS was observed in fibres was so far $\sim 1.9 \mu\text{m}$: the $\sim 15\text{-mW}$ second Stokes component was generated with the efficiency up to 2% in the spectral range between 1.8 and 1.9 μm in a Raman fibre laser pumped at 1.55 μm [2]. It would be interesting to expand the emission range of Raman lasers beyond 2 μm in general and, in particular, outside the emission range of silica fibre lasers doped with Tm^{3+} and Ho^{3+} ions (approximately above 2.1 μm).

The long-wavelength boundary of highly efficient Raman silica fibre lasers (the literature on Raman lasers based on fibres of other types is not available at present) is determined by the reduction in the Raman gain in the fibre core and cladding with increasing the wavelength and mode field diameter, as well by the increase in optical losses in the fibre. As a result, the Raman gain cannot compensate for optical losses of radiation at reasonable pump powers.

The threshold pump power required for Raman lasers can be estimated by the order of magnitude by equating the gain to the distributed optical losses in the fibre (because it is

these losses that begin to play a key role near the long-wavelength boundary): $\alpha_S = g_0 P_{\text{th}}$, where α_S is optical losses in the fibre at the Raman lasing wavelength; g_0 is the Raman gain of the fibre; and P_{th} is threshold pump power (we neglect here a variation in P_{th} along the fibre length). The typical value of optical losses of standard germanosilicate fibres (with the silica core doped with GeO_2 at the molar concentration $\sim 3\%$) at $\lambda \approx 2.1 \mu\text{m}$ is $\alpha_S \approx 100 \text{ dB km}^{-1}$ for $g_0 < 3 \text{ dB km}^{-1} \text{ W}^{-1}$ [3]. Therefore, the lower bound of the threshold pump power for Raman lasers based on standard fibres in this spectral region gives a very high threshold power $P_{\text{th}} = \alpha_S / g_0 \sim 30 \text{ W}$.

The threshold pump power P_{th} can be reduced down to the acceptable value $\sim 1 \text{ W}$, in particular, by increasing the Raman gain by an order of magnitude or more.

The GeO_2 glass is a promising fibreoptic material for the spectral region above 2 μm because it has low optical losses ($\sim 0.22 \text{ dB km}^{-1}$ at a wavelength of 2 μm) and a high nonlinearity (see, for example, [4]). By using the MCVD (modified chemical vapour deposition) technology, we fabricated a single-mode silica fibre with the core containing 75% of GeO_2 and the reflecting SiO_2 cladding (hereafter, the GeO_2 fibre) [5].

The spectral dependence of optical losses in this fibre is shown in Fig. 1 where the distribution of optical losses in standard fibre with the SiO_2 core doped with GeO_2 (with molar content up to 3%) is also presented for comparison.

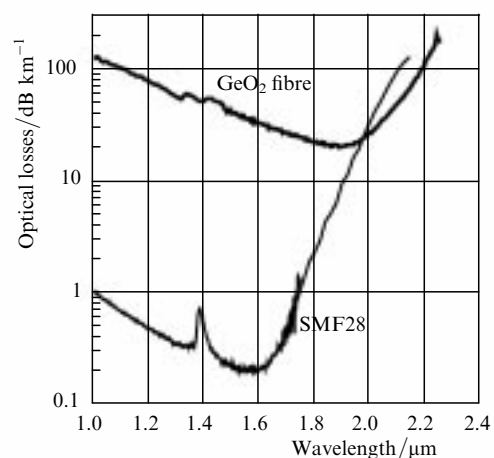


Figure 1. Spectral dependence of optical losses in the GeO_2 fibre with the 75% molar concentration of GeO_2 in the fibre core and the 1.4- μm cut-off wavelength and in a standard telecommunication SMF28 fibre with the $\sim 3\%$ molar concentration of GeO_2 .

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The minimal value of optical losses in the GeO₂ fibre equal to ~ 20 dB km⁻¹ is shifted to 1.85 μ m. Despite a comparatively high absolute level of losses in the region 2–2.2 μ m (~ 100 dB km⁻¹), coinciding by an order of magnitude with losses in a standard fibre, a great difference between the refractive index of the fibre core and its reflecting cladding ($\Delta n \sim 0.1$) and the high SRS cross section in GeO₂ compared to that in SiO₂ provide the high Raman gain in the GeO₂ fibre, which compensates for high optical losses at pump powers ~ 1 W.

The wavelength of the zero material dispersion of GeO₂ is 1.73 μ m [6]. The wavelength of the zero total dispersion of the GeO₂ fibre (~ 2.5 μ m) was estimated from the measured profile of the refractive index of the fibre and the fibre dispersion measured in the 1.3–1.6- μ m spectral range. Therefore, the zero-dispersion wavelength of the GeO₂ fibre is substantially shifted to the red compared to that for most other silica fibres, so that one can expect that the effect of the four-wave interaction on processes proceeding in the Raman GeO₂ fibre laser in the spectral range between 1.6 and 2.2 μ m will be insignificant because the phase-matching conditions are not fulfilled.

Our measurements of the Raman gain in the GeO₂ fibre performed by the Raman lasing threshold in the resonator with known losses gave the value $g_0(1.12/1.07) = 300$ dB km⁻¹ W⁻¹ for lasing at 1.12 μ m and pumping at 1.07 μ m. The Raman gains obtained by the same method for other wavelengths were $g_0(1.57/1.47) = 112$ dB km⁻¹ W⁻¹ and $g_0(1.725/1.608) = 59$ dB km⁻¹ W⁻¹. (For comparison, a fibre with the molar concentration of GeO₂ in the core equal to 20 %, has $g_0(1.500/1.407) = 18$ dB km⁻¹ W⁻¹, while a standard fibre with a shifted dispersion has $g_0(1.500/1.407) = 3$ dB km⁻¹ W⁻¹ [3].) Therefore, although the value of g_0 rapidly decreases with increasing wavelength, the GeO₂ fibre allows the fabrication of a 2- μ m Raman laser using the pump power of a few watts.

The study of the photosensitivity of the GeO₂ fibre showed that it is sufficient for Bragg gratings to be written in the fibre core using the second harmonic of an argon laser without any preliminary loading the fibre with hydrogen [5]. This circumstance allows the elimination of additional optical losses in embedded resonators of the Raman laser by writing Bragg gratings directly in the active fibre.

In this paper, we report the fabrication of three- and four-cascade lasers emitting at 2.06 and 2.2 μ m, respectively. The scheme of the four-cascade laser is shown in Fig. 2 (the scheme of the three-cascade laser is similar). Pumping was performed by a single-mode cw Er³⁺-doped fibre laser emitting at 1608 nm using a fibre with a two-element first cladding (like the GTWave fibre [7]) and the core codoped with Er³⁺ and Yb³⁺ ions. The erbium laser was pumped by the multimode 0.975- μ m radiation from a source based on laser diodes with the fibre output (New Optics, Great Britain). The maximum power at 1608 nm coupled to the GeO₂ fibre was 4.7 W.

The frequency shift corresponding to the maximum SRS gain in the GeO₂ fibre was 427 cm⁻¹, which is somewhat lower than the corresponding shift in fibres with a moderate content of GeO₂ (440 cm⁻¹).

The length of a GeO₂ fibre in the three-cascade Raman laser was 13 m. This length was determined by the numerical simulation of the Raman laser as optimal for obtaining the maximum output power in our experiments. The

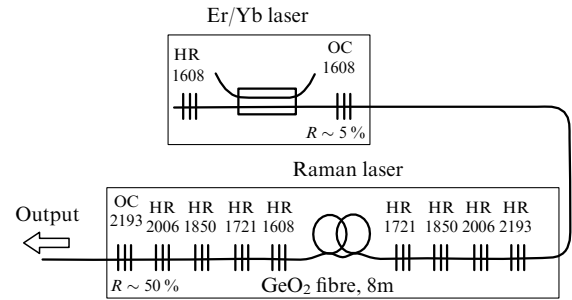


Figure 2. Scheme of the four-cascade fibre laser emitting at 2.2 μ m; (HR) the Bragg grating with the reflectivity R close to 100%; (OC) output Bragg gratings of lasers with the corresponding resonance wavelengths (in nm).

optimal length of the four-cascade laser proved to be 8 m. The frequency shifts between the cascades were taken approximately corresponding to the maximum Raman gain.

We managed to obtain lasing at 2 μ m in the three-cascade Raman laser. Figure 3a shows the emission spectrum recorded with an MDR-4 monochromator equipped with a PbSe photodetector. The peaks in the spectrum correspond to the pump radiation (1608 nm) and radiation in the first (1732 nm), second (1864 nm), and third (2027 nm) cascades of the Raman laser. The threshold pump power for the third cascade was 1.6 W, while the maximum output power of the laser at 2 μ m was 900 mW, corresponding to the total lasing efficiency of 19%, the slope efficiency amounting to 39%. Thus, we have demonstrated the principal possibility of the development of efficient Raman lasers emitting at 2 μ m.

Generation at a wavelength of 2.2 μ m in the four-cascade Raman GeO₂ fibre laser is hampered by a drastic increase of the optical losses in the fibre in the spectral range from 2 to 2.2 μ m. While optical losses in the three-cascade laser at any of the emission wavelengths did not exceed 40 dB km⁻¹, the optical losses at 2.2 μ m achieved ~ 150 dB km⁻¹, resulting in the reduction of the optimal length of the fibre (8 m) and a substantial decrease in the efficiency of the four-cascade laser. Nevertheless, we man-

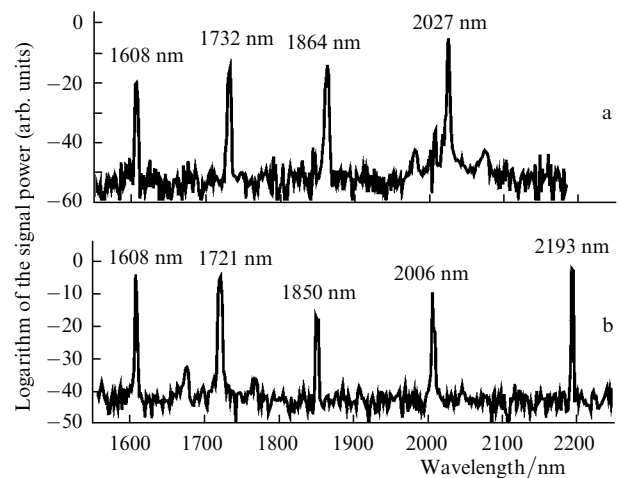


Figure 3. Output emission spectra of the three-cascade 2.0- μ m (a) and four-cascade 2.2- μ m (b) Raman GeO₂ fibre lasers.

aged to obtain lasing at 2.2 μm . The wavelengths of all the cascades of the laser are indicated in the emission spectrum in Fig. 3b. The threshold pump power for lasing in the fourth cascade was 1.1 W, and the maximum output power at 2.2 μm was 215 mW upon pumping by 4.2 W at 1608 nm. The total lasing efficiency was $\sim 5\%$.

Therefore, we have demonstrated for the first time emission of a Raman fibre laser at wavelengths up to 2.2 μm . By using fibres with the GeO_2 core, we can obtain lasing at any wavelength in the range from 1.7 to 2.2 μm by selecting appropriately the pump wavelength and employing a Raman laser with the required number of cascades and the required frequency shift in each cascade.

A further reduction of optical losses in GeO_2 fibres will provide the extension of the emission region of Raman lasers up to $\sim 3 \mu\text{m}$.

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