

LETTERS

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4.4-μm Raman laser based on hollow-core silica fibre

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Abstract. **A Raman laser with a wavelength exceeding 4 μm is designed for the first time. Using a revolver silica fibre with a hollow core filled with molecular hydrogen ($^1H_2$) as an active medium, we have obtained SRS lasing at a wavelength of 4.4 μm under pumping by a pulsed erbium fibre laser (λ = 1.56 μm, τ = 2 ns). The SRS conversion quantum efficiency reaches 15%, and the maximum output peak power at a wavelength of 4.4 μm is 0.6 kW.**

Keywords: *fibre lasers, hollow-core fibres, mid-IR region, simulated Raman scattering.*

Silica fibre lasers are widely used for solving scientific and applied problems because the structure of such lasers is mechanically stable and ensures compactness, long-term stability and high output beam quality. However, the spectral range of these fibre optic sources is principally limited by the silica glass transmission range (0.2–2.2 μm). Extension of the spectral range of fibre lasers to longer wavelengths is of great interest due to a variety of possible practical applications. In particular, lasers operating in the spectral range of 3–5 μm, which coincide with one of the atmospheric transparency windows, are required for biomedical applications, remote gas analysis, polymer detection and processing as well as defence technology [1, 2].

One of the approaches to the expansion of the wavelength range of silica fibre lasers to the mid-IR region is to use fibres made of mid-IR-transparent glasses instead of silica glasses. In particular, lasers based on erbium-doped fluoride glass fibres demonstrated cw radiation with powers up to 30 and 1.5 W at wavelengths of 2.94 and 3.44 μm, respectively [3–5]. In addition, the use of SRS in chalcogenide fibres made it possible to shift a laser wavelength from 3 to 3.77 μm and obtain an output power of ~0.1 W in a cw regime [6]. However, fluoride and chalcogenide fibres are considerably more difficult to manufacture than silica fibres; in addition, they have a lower optical strength, chemical resistance and thermal stability. All this strongly hinders the fabrication of mid-IR fibre lasers based on soft glasses, especially for applications that require high peak and/or average powers.

The development of hollow-core fibres (HCFs) with a negative curvature of the core–cladding interface opened new possibilities for developing mid-IR fibre lasers with the use of the well-developed technology of silica glass production. Among various types of these HCFs, the fibres with a cladding consisting of one layer of cylindrical silica capillaries have the simplest structure (the inset in Fig. 1). Such HCFs were proposed for the first time in [7] and later were called revolver fibres [8, 9]. Despite the simple design, revolver HCFs ensure extremely low overlap of the laser mode field with the cladding material. Because of this low overlap, optical losses become low even in the range of fundamental absorption of silica glass. In particular, paper [10] demonstrated a revolver silica fibre possessing waveguiding properties up to a wavelength of ~8 μm with measured optical losses at a wavelength of 3.39 μm being 50 dB km^{-1}, which is approximately 1000 times lower than material losses in silica glass [11].

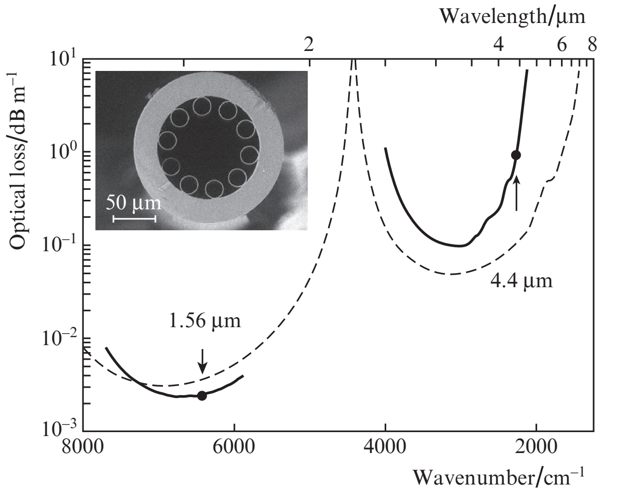

Figure 1. Calculated optical loss spectrum of the revolver HCF (solid curve). The dashed curves schematically show the fibre transmission bands. The points denote optical losses corresponding to the pump (1.56 μm) and SRS laser (4.4 μm) wavelengths. The inset presents an electron-microscope image of the fibre cross section.

Filling of hollow cores of fibres with molecular gases turns them into active media for fibre lasers. For example, lasing in the spectral range of 3.1–3.2 μm was achieved in a HCF filled with acetylene [12]. In this case, lasing occurred due to the formation of population inversion at vibrational–rotational levels of acetylene by optical pumping. The output peak power was 10 W. Another method of obtaining long-wavelength laser radiation in HCFs is SRS in gases filling the core of these HCFs. Especially attractive in this scheme is the use of

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molecular hydrogen, namely, of the most widespread light hydrogen isotope ^1H. The $^1H_2$ molecules are characterised by a very large frequency shift (4155 cm^{-1}) induced by vibrational Raman scattering. For comparison, the corresponding frequency shift in molecular deuterium is considerably smaller, 2991 cm^{-1}. Efficient SRS in hydrogen-filled HCFs was demonstrated in the near-IR range at λ = 1.8 [13] and 1.9 [8] μm. In these works, the fraction of pump photons with $\lambda \approx$ 1 μm transformed into the Stokes radiation was 80% and 60%, respectively. In recent work [14], SRS lasing in a revolver HCF filled with hydrogen isotopes was obtained in the mid-IR range at wavelengths of 2.9 and 3.5 μm with quantum efficiencies of 10% and 6%, respectively. The longest wavelength achieved to date by SRS in HCFs is 3.9 μm [15], but the quantum conversion efficiency in this case did not exceed 0.1%.

In the present work, we describe for the first time a fibre SRS laser with a wavelength exceeding 4 μm. By using a revolver silica HCF filled with molecular hydrogen ($^1H_2$), we obtained SRS lasing at a wavelength of 4.4 μm under pumping by a pulsed erbium fibre laser (λ = 1.56 μm, τ = 2 ns) with a high peak power. The quantum efficiency reached 15%, and the maximum output power at a wavelength of 4.4 μm was 0.6 kW.

A photograph of the cross section of the fibre used in this work is given in the inset in Fig. 1. The hollow core diameter was 77 μm, which corresponds to the fundamental mode field diameter d = 56 μm calculated at a pump wavelength of 1.56 μm. The fibre cladding was formed by ten noncontacting F300 silica capillaries. The capillary walls were 1.15 μm thick. The spectral positions of transmission bands of the fibre are schematically shown by the dashed curves in Fig. 1 (optical losses are estimated by the ARROW model [16] and decreased by a factor of 60). The results of detailed calculation performed with COMSOL for the most important spectral ranges of optical losses in the fibre are shown by solid curves in Fig. 1. One can see that the fibre has transmission bands with minimal losses near wavelengths of 1.5 and 3.3 μm. The calculated optical losses for fundamental modes at the Stokes wavelength of 4.4 μm (corresponds to the longest-wavelength transmission band, i.e. zero band) and at the pump wavelength of 1.56 μm (lies in the first band) are 0.92 and 0.0025 dB m^{-1}, respectively.

The fibre SRS laser was assembled according to the single-pass scheme (Fig. 2). A 15-m segment of the revolver HCF was filled with molecular hydrogen $^1H_2$ at a pressure of 30 atm. This pressure was chosen to achieve the maximum SRS gain [17]. The hollow fibre ends were hermetically glued into miniature gas cells with sapphire windows for light incoupling and outcoupling. To pump the SRS laser, we developed a pulsed erbium fibre laser emitting unpolarised light at a wavelength of 1.558 μm. As a master oscillator for the erbium laser, we used a semiconductor laser with a distributed feedback and a narrow (2 MHz) laser line, which emitted 2-ns pulses with a repetition rate of 25 Hz due to direct modulation by pumping current. The master oscillator radiation was amplified in a core-pumped two-cascade single-mode erbium fibre preamplifier and then directed through a narrow-band filter suppressing amplified spontaneous radiation. Then, the amplified radiation with λ = 1.558 μm was fed to a cladding-pumped power amplifier based on an erbium-doped fibre with a large mode field diameter. A more detailed description of a similar scheme can be found in [18]. The 1.558-μm radiation of the pump erbium laser was coupled into the hollow-core fibre using two plane-convex lenses L1 and L2 (Fig. 2); the average pump power coupled into the fibre reached 1.2 W, which corresponded to a peak power of 24 kW. The output radiation of the SRS laser was collimated by a ZnSe lens and, if necessary, transmitted through a germanium plate 2 mm thick, which served as an absorbing filter for near-IR radiation. After this, the SRS laser radiation was fed to an optical spectrum analyser (λ = 1–12 μm, Thorlabs OSA207) and a power meter.

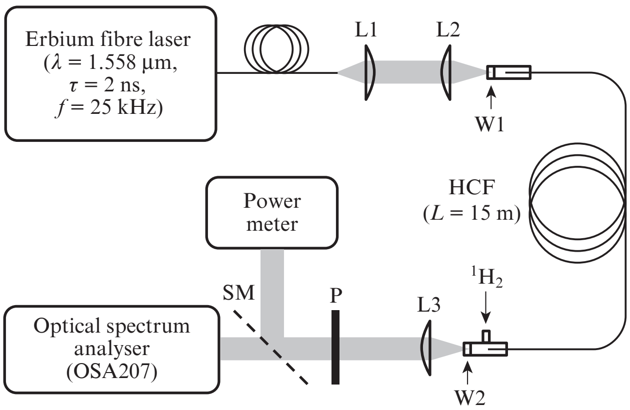

Figure 2. Optical scheme of the SRS laser:
(L1, L2) fused silica lenses; (W1, W2) sapphire windows of gas cells; (L3) ZnSe collimating lens at the exit of the fibre laser; (P) germanium plate 2 mm thick; (SM) semitransparent mirror; (L) HCF length.

The radiation spectra measured at the output of the hydrogen-filled HCF revealed two competing nonlinear processes (Fig. 3). It is seen that an increase in the pump power coupled into the hollow-core fibre leads to successive generation at wavelengths of 4.4 and 1.715 μm (Figs 3a, 3b). These spectral components result from SRS of pump radiation (λ = 1.558 μm) at the vibrational Q(1) (Ω_{vib} = 4155 cm^{-1}) and rotational $S_0(1)$ (Ω_{rot} = 587 cm^{-1}) transitions of molecular hydrogen. Further increase in the pump power led to generation at a wavelength of 1.906 μm, which corresponds to the second Stokes component of rotational SRS in hydrogen (Fig. 3c).

To measure the output power of the SRS laser in the mid-IR region, we filtered the intense pump radiation by a germanium plate. The total power of the Stokes components was measured behind the germanium filter and recalculated into the power at the fibre output taking into account losses in all the optical elements in the measuring channel [Fig. 4, curve (*1*)]. The power of each of the spectral components was reconstructed based on the relative amplitudes of the components in the measured spectra (Fig. 4). One can see that the vibrational Stokes component at a wavelength of 4.4 μm has the lowest threshold, which corresponds to the peak pump power of 4.7 kW. The highest quantum efficiency of conversion λ = 1.56 μm → λ = 4.4 μm was 15% (at a peak pump power of ~6.5 kW), while the maximum output peak power at a wavelength of 4.4 μm reached ~0.6 kW, which corresponds to an average power of ~30 mW (Fig. 4).

Based on the numerical solution of the system of coupled-wave equations for vibrational SRS in molecular hydrogen, we preliminarily theoretically considered SRS generation at a wavelength of 4.4 μm. In this consideration, we used calculated optical losses in HCFs of 0.0025 and 0.92 dB m^{-1} at wavelengths of 1.56 and 4.4 μm, respectively (Fig. 1), and the Raman gain coefficient g_R = 0.43 cm GW^{-1} calculated for the

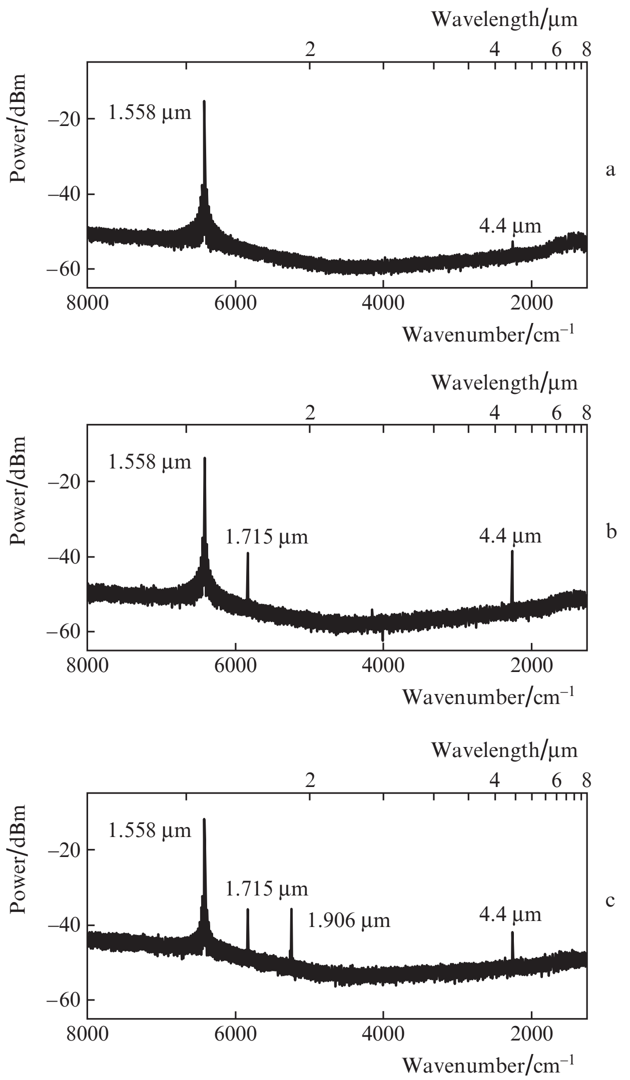

Figure 3. Emission spectra at the output of the HCF filled with $^1H_2$ at a pressure of 30 atm measured at peak pump powers of (a) 4.7, (b) 5.4 and (c) 18 kW.

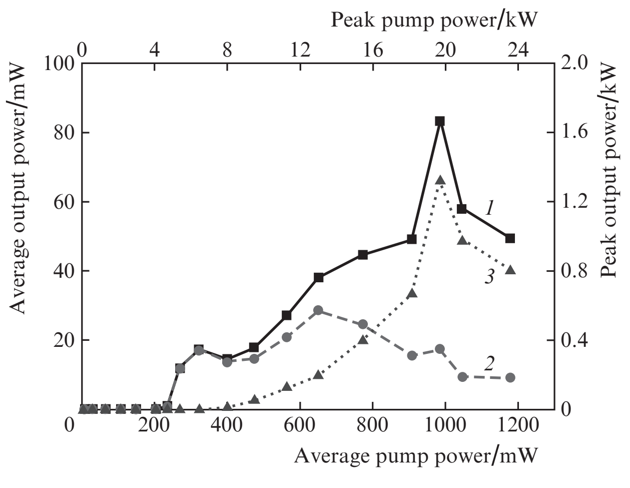

Figure 4. Dependences of the average (peak) power at the output of the fibre SRS laser on the average (peak) pump power launched into the fibre for the total radiation passed through the germanium filter (*1*), as well as for the spectral components at wavelengths of (*2*) 4.4 and (*3*) 1.906 μm.

conversion λ = 1.56 μm → λ = 4.4 μm from known linewidths and scattering cross section for the vibrational Q(1) transition of H_2 molecules [19, 20]. The threshold peak power was theoretically estimated to be 3.3 kW. The slight difference between the theoretical and experimental (4.7 kW) lasing thresholds can be explained by the fact that the real optical losses at a wavelength of 4.4 μm somewhat exceed the calculated value. The optimal SRS laser length theoretically estimated for a peak pump power of 24 kW was ~3.5 m, which is considerably lower than the length of the hollow-core fibre used in our experiment (15 m). Therefore, optimisation of the hollow-core fibre length in subsequent experiments may considerably increase the output power and efficiency of SRS lasers at a wavelength of 4.4 μm.

Thus, in the present work we described for the first time a silica fibre laser emitting in the mid-IR range at a wavelength longer than 4 μm. As an active medium, we used a revolver HCF filled with molecular hydrogen $^1H_2$. SRS lasing at a wavelength of 4.4 μm was obtained by pumping the revolver HCF by a pulsed erbium fibre laser (λ = 1.56 μm, τ = 2 ns) with a high peak power. The SRS quantum efficiency reached 15%, and the maximum output peak power at a wavelength of 4.4 μm was 0.6 kW. These values can be considerably increased by optimising the length and the geometrical cross section parameters of the revolver fibre, as well as by creating an all-fibre system including SRS and pump lasers.

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