Quantum Electronics **48** (12) 1084–1088 (2018)

https://doi.org/10.1070/QEL16836

4.4-μm Raman generation with an average power above 1 W in silica revolver fibre

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Abstract. **We report the first gas-filled fibre Raman laser emitting at 4.42 μm with an average power of 1.4 W. Its gain medium is silica revolver fibre with a molecular hydrogen ($^1H_2$) filled hollow core. Owing to the use of linearly polarised 1.56-μm pump light and a polarisation-maintaining Raman laser configuration, we have achieved a quantum efficiency of 53% for single-stage 1.56 → 4.42 μm conversion. This fibre Raman laser can find application in medicine, gas analysis and other areas.**

Keywords: *fibre lasers, hollow-core fibre, mid-IR spectral region, stimulated Raman scattering.*

Mid-IR laser sources (with a wavelength $\lambda \geqslant 3$ μm) are important for many scientific and practical applications. Of particular interest are lasers emitting single-mode light in the mid-IR spectral region with an average power above 1 W [1]. Such light can be used to pump not only nonlinear crystals for obtaining wavelength-tunable parametric generation but also chalcogenide fibre for broadband supercontinuum generation with a high spectral power density (~1 mW nm^{-1}).

In recent years, significant advances have been made in broadband mid-IR generation in fluoride fibre [2]. The zero-dispersion wavelength of fluoride fibre is shorter than 2 μm, which allows for efficient pumping of such fibre using familiar thulium-doped fibre lasers ($\lambda \approx 2$ μm). This convenient pump scheme ensured supercontinuum generation in fluoride fibre in the spectral range 1.9–4.5 μm with an average power above 1 W [3]. The spectral range of supercontinuum sources can in principle be extended to ~7 μm by using sulphide (As_2S_3) fibre as a nonlinear medium [4]. However, practical implementation of this concept encounters serious difficulties, among which not least important is the absence of convenient pump sources emitting near the zero-dispersion wavelength of sulphide fibre ($\lambda \geqslant 4.5$ μm) [5]. Thus, the development of mid-IR pump lasers with a high average power and high beam quality is of great current interest for further harnessing the mid-IR spectral region.

Currently, there are several pump schemes for supercontinuum generation in sulphide fibre. In one of such schemes, use is made of parametric light sources capable of generating near the zero-dispersion wavelength of As_2S_3 fibre [6, 7]. However, parametric light sources have a complex design which requires alignments and often does not ensure single-mode operation. In another pump scheme, use is made of near-IR fibre lasers, which ensure high beam quality but operate at wavelengths under 2 μm. In this case, sulphide fibre is pumped in its normal dispersion region [8, 9].

If this pump scheme is used in the picosecond regime, supercontinuum generation can be initiated by self-phase modulation. This approach was demonstrated to be fruitful by Gattass et al. [8], who obtained supercontinuum generation in the spectral range 1.9–4.8 μm at an average power of 565 mW. If the pump scheme in question is employed in the nanosecond regime, supercontinuum generation can be initiated by stimulated Raman scattering (SRS). In this case, as a result of cascaded SRS the generation wavelength shifts to the anomalous dispersion region of the fibre, where modulation instability initiates temporal splitting of nanosecond pulses and leads to further broadening of their spectrum. To date, three to eight orders of cascaded SRS conversion have been observed in sulphide fibre pumped by nanosecond fibre laser pulses at wavelengths of ~1.55 and ~2 μm [5, 10, 11]. However, the longest wavelength thus reached is just 2.7 μm [11], which is associated with the small Stokes shift in sulphide fibre (340 cm^{-1}).

An alternative approach to making mid-IR laser sources is to use gas-filled fibre Raman lasers [12,13], whose operating principle is based on the use of large Stokes shifts of vibrational transitions in light molecular gases filling the hollow fibre core.

Hollow-core fibre (HCF) can ensure low optical losses in the mid-IR spectral region even if the HCF cladding is made from silica glass. Recently, using a hollow-core silica revolver fibre filled with molecular hydrogen (Stokes shift of 4155 cm^{-1}), Gladyshev et al. [14] demonstrated the first single-stage 1.56 → 4.42 μm SRS conversion. The average power at a wavelength of 4.42 μm was 30 mW. Later, optimisation of the revolver fibre length and the hydrogen pressure in the hollow core made it possible to produce a Raman laser with a quantum efficiency of 36% and average output power of 250 mW at a wavelength of 4.42 μm. However, supercontinuum generation with a spectral power density of ~1 mW nm^{-1} requires pump sources with an average power above 1 W. The ability of gas-filled fibre Raman lasers to operate in the mid-IR spectral region at this average power requires experimental confirmation because 1.56 → 4.42 μm conversion has a large quantum defect, so that 65% of the pump energy is converted to heat.

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Received 9 October 2018; revision received 19 October 2018
Kvantovaya Elektronika **48** (12) 1084–1088 (2018)
Translated by O.M. Tsarev

In this paper, we report on the first single-mode gas-filled fibre Raman laser with an average power of 1.4 W at a wavelength of 4.42 μm. Optimising parameters of the erbium fibre laser used as a pump source (λ = 1.56 μm) allowed us to raise the quantum efficiency of the Raman laser (λ = 4.42 μm), reliably suppress the unwanted Stokes component at a wavelength of 1.72 μm and substantially increase the average output power at a wavelength of 4.42 μm.

The gas-filled fibre Raman laser had a single-pass configuration (Fig. 1). The pump source used was an erbium-doped fibre laser emitting at a wavelength of 1.56 μm. As a Raman-active medium, we used a molecular hydrogen-filled hollow-core revolver fibre similar to fibre used in previous studies [14, 15].

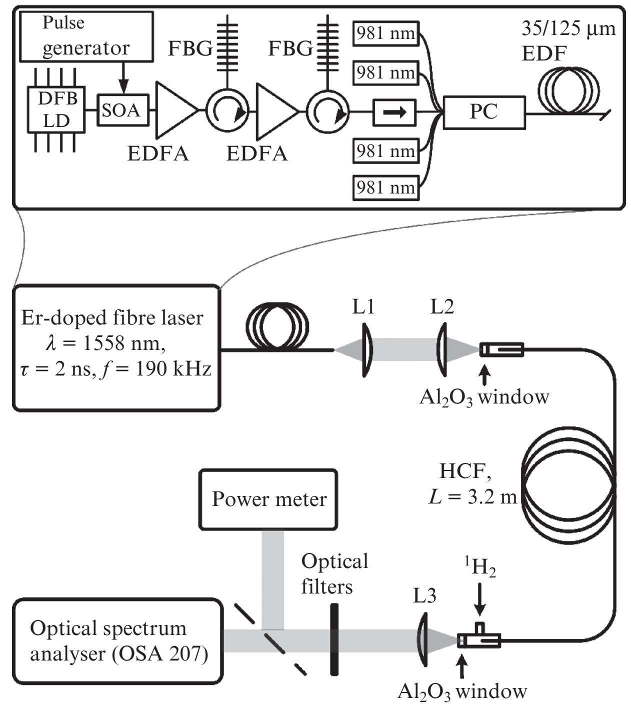

Figure 1. Schematic of the gas-filled fibre Raman laser: (DFB LD) distributed feedback semiconductor laser; (SOA) semiconductor optical amplifier; (EDFA) erbium-doped fibre amplifier; (FBG) fibre Bragg grating; (PC) pump combiner; (EDF) erbium-doped fibre; (L1, L2) fused quartz lenses; (HCF) hollow-core fibre; (L3) collimating ZnSe lens.

The inset in Fig. 2 shows a cross-sectional micrograph of the fibre. The diameter of the hollow core is 75 μm, which corresponds to the mode field diameter d = 55 μm calculated for the fundamental mode of the fibre. The fibre cladding was formed by ten noncontacting F300 quartz glass capillary tubes having 1.15-μm-thick walls. The position of the transmission bands of the fibre (numerical simulation with COMSOL software) is shown in Fig. 2 by a dashed line. The calculated optical losses for the fundamental mode at the Stokes wavelength (4.42 μm) and at the pump wavelength (1.56 μm) are 0.92 and 0.0025 dB m^{-1}, respectively. The optical loss spectrum below 2 μm was measured using a supercontinuum source (Fianium). To determine the optical loss at a wavelength of 4.4 μm, a previously designed Raman fibre laser was used as a light source [14]. The measured optical loss was 1.1 dB m^{-1} at a wavelength of 4.42 μm and 0.03 dB m^{-1} at 1.56 μm, in good agreement with the above theoretical calculation results (Fig. 2). A 3.2-m-long revolver fibre segment was filled with molecular hydrogen ($^1H_2$) at a pressure of 50 atm. These optimal fibre length and hydrogen pressure were found experimentally in our previous studies and allowed us to raise the average output power at a wavelength of 4.42 μm from 30 to 250 mW [14, 15].

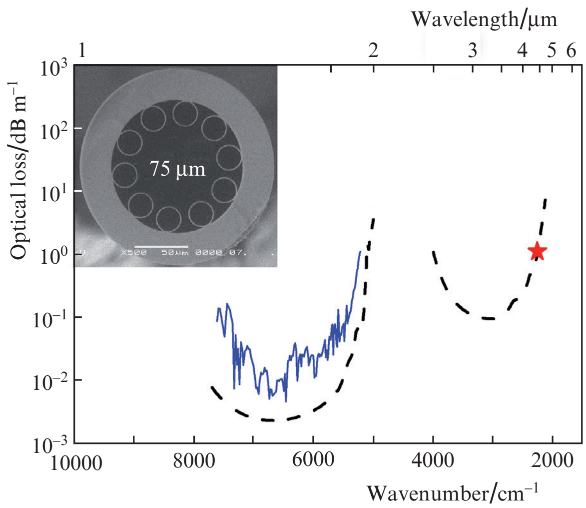

Figure 2. Calculated optical loss spectrum of a hollow-core revolver fibre (dashed line), near-IR loss spectrum measured using a supercontinuum source (solid line) and optical loss measured at λ = 4.4 μm using a narrow-band laser (asterisk). Inset: cross-sectional electron-microscopic image of the fibre.

To further optimise characteristics of the gas-filled fibre Raman laser, we modified the 1.56-μm pump fibre laser design (Fig. 1). The most important changes include the use of polarisation-maintaining fibre, which helps to raise the quantum efficiency of Raman conversion; replacement of pump diodes with a wavelength of 976 nm in the output amplification stage of the erbium-doped fibre laser by diodes operating at 981 nm (BWT Beijing Ltd), a wavelength which is better suited to the position of the absorption peak of Er^{3+} ions in silica glass; and an increase in pump diode power from 54 to 108 W. It is worth noting that the efficiency of the erbium fibre laser was just ~10%, which limited the average output power at a wavelength of 1.56 μm to a level of ~11 W. Raising the efficiency of the erbium fibre laser was beyond the scope of this work, which focused on optimising 1.56 → 4.42 μm Raman conversion.

The erbium fibre laser, which served to pump the Raman laser, had a master oscillator/power amplifier (MOPA) configuration (Fig. 1). As a master oscillator, we used a distributed feedback semiconductor laser diode (DFB LD) having a narrow (~2 MHz) emission line at a wavelength of 1558 nm. Continuous radiation from the fibre output of the master oscillator was passed through a semiconductor optical amplifier (SOA), which generated optical pulses as a result of amplitude modulation of the light. The optical pulse duration and repetition rate were set by an electrical pulse generator (Fig. 1). Next, the optical pulses were amplified in two core-pumped single-mode erbium-doped fibre amplifier (EDFA) stages. To suppress amplified spontaneous emission, narrow-band filters consisting of a circulator and a fibre Bragg grating (FBG) were placed after each amplifier stage. The output amplifier stage (power amplifier) was based on a large mode area erbium-doped fibre similar to fibre used in a previous study [16]. Pumping was performed to the cladding of the active fibre. To suppress back reflection of light to the active fibre core, the output facet of the erbium fibre laser was cleaved at ~10°.

It should be noted that the erbium fibre laser configuration used allowed us to maintain linear polarisation of the laser output. The first two amplifier stages used polarisation-maintaining fibre and, in the initially isotropic fibre of the third stage, birefringence was produced by coiling the fibre at a 15 cm radius in the horizontal plane. At the fusion splice between the second and third amplifier stages, a linear vertical polarisation of the light was set. As a result, the erbium fibre laser reliably ensured a linear (vertical) polarisation of the output light at a wavelength of 1.56 μm without additional adjustments.

The pump pulse duration was 2 ns and the pulse repetition rate was 190 kHz. The average output power of the erbium fibre laser reached 10.7 W, which corresponded to a peak power of 28 kW. The pump laser linewidth was smaller than the resolving power (0.02 nm) of the AQ6317B optical spectrum analyser.

The erbium fibre laser beam was launched into the HCF using L1 and L2 plano-convex lenses. With allowance for all optical components at the fibre input, the pump coupling efficiency was 70%. The HCF ends were secured in hermetically sealed miniature gas cells, which had sapphire windows for light incoupling and outcoupling. At the hollow-core fibre output, the beam was collimated by a ZnSe lens, passed through optical filters and directed to a Thorlabs OSA207 optical spectrum analyser or Ophir 3A-P-SH-V1 power meter.

A characteristic output emission spectrum of the gas-filled fibre Raman laser is presented in Fig. 3. There are only two spectral components, corresponding to the residual pump light (1.56 μm) and the Stokes wave (4.42 μm) due to vibrational SRS in molecular hydrogen. It is seen that the rotational Stokes components observed previously at wavelengths of 1.72 and 1.91 μm [14] are completely suppressed. The 4.42-μm generation linewidth did not exceed 0.25 cm^{-1}, which corresponded to the resolving power of the optical spectrum analyser (OSA207).

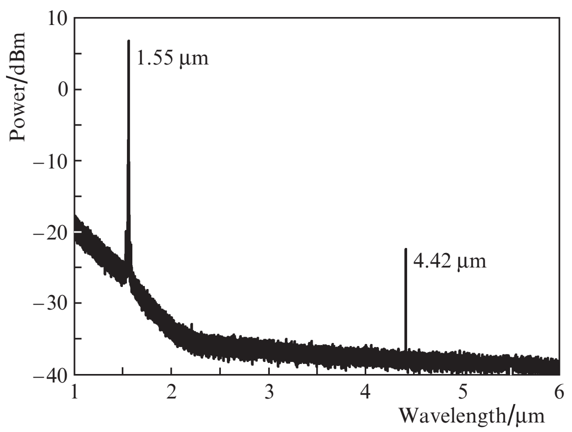

Figure 3. Characteristic output emission spectrum of the gas-filled fibre Raman laser.

Figure 4 shows the average output power of the gas-filled fibre Raman laser as a function of the average launched pump power. It is seen that, at a launched pump power of 10.7 W, the maximum average power at a wavelength of 4.42 μm is 1.4 W, which is a factor of 5.6 higher than that reported previously [15]. Even though a substantial fraction of the pump power (2.6 W) is converted to heat just because of the large quantum defect of the 1.56 → 4.42 μm conversion, the Raman laser showed reliable operation for several hours, with no signs of overheating or output power degradation.

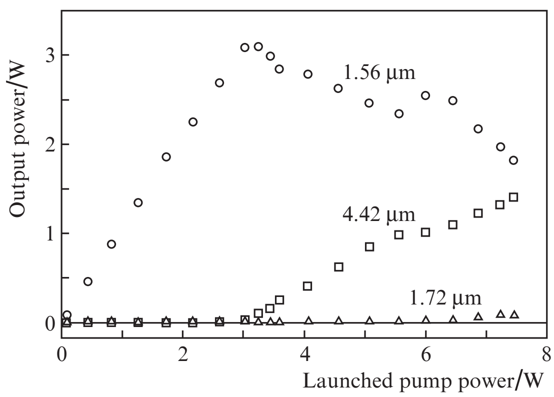

Figure 4. Average output power of the fibre Raman laser as a function of the average pump power launched into the revolver fibre at the pump wavelength (1.56 μm) and the Stokes wavelengths of vibrational (4.42 μm) and rotational (1.72 μm) SRS.

The intensity distribution across the laser beam at a wavelength of 4.42 μm (Fig. 5) was measured with an Ophir Pyrocam IV IR camera having an uncoated entrance window. The obtained distribution indicates that the Raman laser emits essentially single-mode 4.42-μm radiation corresponding to the fundamental transverse mode of the revolver fibre (the mode intensity distribution is superimposed by the interference pattern resulting from reflections at the entrance window of the IR camera). Output angular divergence measurements at $\lambda = 4.42$ μm allowed us to evaluate the beam quality factor: $M^2 = 1.4$.

The quantum efficiency of the 1.56 → 4.42 μm conversion was 53% (Fig. 6). The quantum efficiency exceeding the previously reported 36% [15] was achieved by using linearly polarised pump light (1.56 μm) and a polarisation-maintaining Raman laser configuration.

It is known that the polarisation state of pump light can have a significant effect on Raman gain efficiency [17]. A maximum gain is possible when the Stokes and pump waves have identical relationships between and orientations of their major polarisation axes. However, in the case of birefringent fibre, the ellipticity and orientation of the axes of the polarisation ellipse for the pump and Stokes waves vary differently along the length of the fibre, because these spectral components differ significantly in wavelength. Thus, at an arbitrary pump polarisation orientation the effective Raman gain in birefringent fibre can be reduced. To avoid this, it is necessary to use linearly polarised pump light whose plane of polarisation coincides with the fast or slow axis of the active fibre [17].

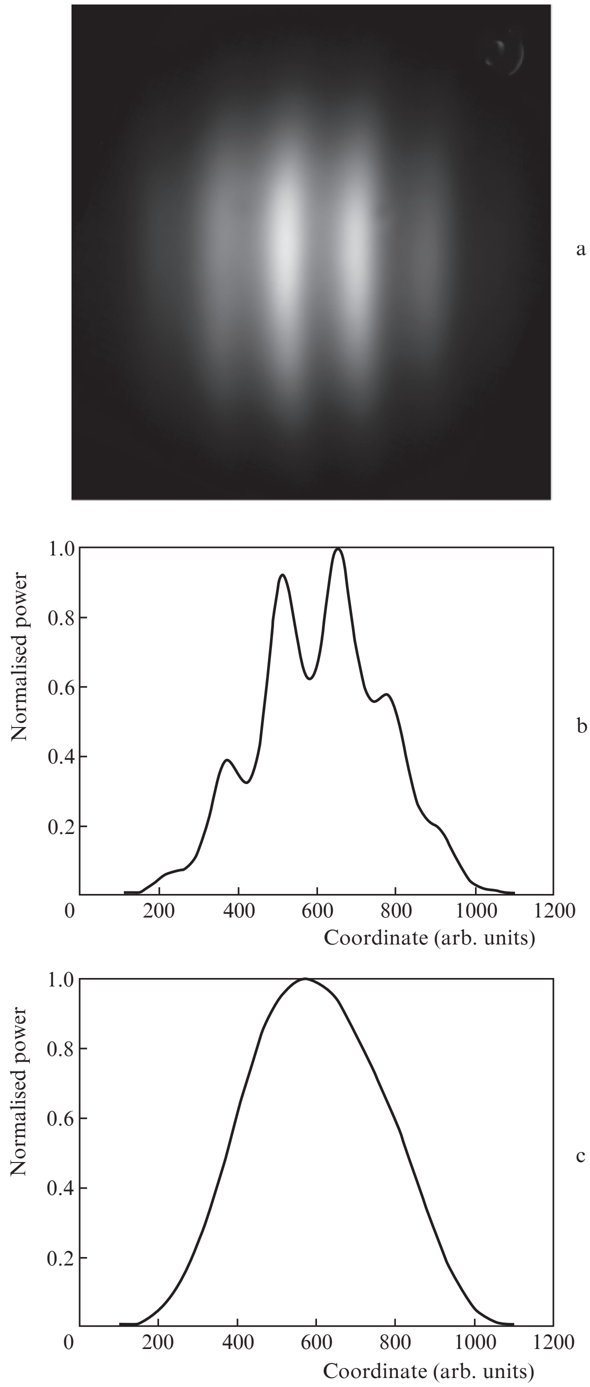

Figure 5. Intensity distribution across the gas-filled fibre Raman laser beam at a wavelength of 4.4 μm (a) (the intensity oscillations are due to interference on the uncoated entrance window of the IR camera); output beam intensity profiles across the interference fringes (b) and along the strongest interference fringe (c).

In the case of HCF, birefringence can be induced by bending the fibre. As shown earlier [18], a hollow-core revolver fibre coiled without tension at a radius of 15 cm has birefringence of $\sim 10^{-7}$. Nevertheless, such birefringence is sufficient for sensibly changing the polarisation state of light in ~2-m-long hollow-core fibres [18].

In this study, we used a hollow-core revolver fibre coiled at a radius of 15 cm. The coils were placed horizontally so that the major axes of the HCF were oriented vertically and

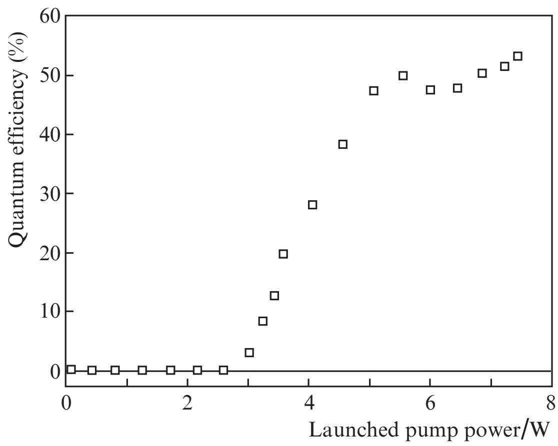

Figure 6. Quantum efficiency of the 1.56 → 4.42 μm Raman conversion as a function of average launched pump power.

horizontally. To maximise the effective Raman gain, the pump beam (λ = 1.56 μm) at the hollow-core fibre input had vertically oriented linear polarisation, which thus coincided with one of the major axes of the hollow-core fibre.

An additional advantage of linearly polarised pump light for vibrational SRS in gases is the suppression of rotational SRS, a competing process [19, 20]. In the case of molecular hydrogen, vibrational SRS ensures 1.56 → 4.42 μm conversion (Stokes shift of 4155 cm^{-1}), whereas rotational SRS leads to the generation of an unwanted spectral component at a wavelength of 1.72 μm (Stokes shift of 587 cm^{-1}) [12, 14]. To maximise the quantum efficiency of vibrational SRS, it is necessary that linear polarisation of pump light persist throughout the length of the active fibre. In this study, owing to the linear polarisation of the pump beam and the polarisation-maintaining Raman laser configuration, the 1.72-μm spectral component was reliably suppressed (Figs 3, 4).

Thus, we have demonstrated the first gas-filled fibre Raman laser emitting single-mode radiation at a wavelength of 4.42 μm with an average power above 1 W. Owing to the use of a linear polarisation-maintaining Raman laser configuration, we have obtained Raman generation with an average power of 1.4 W and quantum efficiency of 53%, surpassing previous results by a factor of 5.6 and 1.5, respectively. This type of laser source can be used for pumping a variety of nonlinear crystals and optical fibres with the aim of obtaining tunable or broadband mid-IR light sources, which are much in demand for diverse applications in biomedicine, gas analysis and other areas.

Acknowledgements. This work was supported by the Russian Science Foundation (Grant No. 16-19-10513).

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