Synchronously pumped picosecond all-fibre Raman laser based on phosphorus-doped silica fibre

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Abstract: Reported for the first time is picosecond-range pulse generation in an all-fibre Raman laser based on P_2O_5-doped silica fibre. Employment of phosphor–silicate fibre made possible single-cascade spectral transformation of pumping pulses at 1084 nm into 270-ps long Raman laser pulses at 1270 nm. The highest observed fraction of the Stokes component radiation at 1270 nm in the total output of the Raman laser amounted to 30%. The identified optimal duration of the input pulses at which the amount of Stokes component radiation in a ~16-m long phosphorus-based Raman fibre converter reaches its maximum was 140–180 ps.

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References and links

1. E. M. Dianov and A. M. Prokhorov, "Medium-power CW Raman fiber lasers," IEEE J. Sel. Top. Quantum Electron. **6**(6), 1022–1028 (2000).
2. N. S. Kim, M. Prabhu, C. Li, J. Song, and K. Ueda, "1239/1484 nm cascaded phosphosilicate Raman fiber laser with CW output power of 1.36 W at 1484 nm pumped by CW Yb-doped double-clad fiber laser at 1064 nm and spectral continuum generation," Opt. Commun. **176**(1-3), 219–222 (2000).
3. Z. Xiong, N. Moore, Z. G. Li, and G. C. Lim, "10-W Raman fiber lasers at 1248 nm using phosphosilicate fibers," J. Lightwave Technol. **21**(10), 2377–2381 (2003).
4. E. M. Dianov, A. S. Kurkov, O. I. Medvedkov, V. M. Paramonov, O. N. Egorova, N. Kurukitkoson, and S. K. Turitsyn, "Raman fiber source for the 1.6–1.75 um spectral region," Laser Phys. **13**(3), 397–400 (2003).
5. S. K. Sim, H. C. Lim, L. W. Lee, L. C. Chia, R. F. Wu, I. Cristiani, M. Rini, and V. Degiorgio, "High power cascaded Raman fibre laser using phosphosilicate fiber," Electron. Lett. **40**(12), 738–739 (2004).
6. S. K. Smith, P. N. Kean, D. W. Crust, and W. Sibbett, "An experimental study of a synchronously pumped fibre Raman oscillator," J. Mod. Opt. **34**(9), 1227–1233 (1987).
7. M. Nakazawa, M. Kuznetsov, and E. P. Ippen, "Theory of the synchronously pumped fiber Raman laser," IEEE J. Quantum Electron. **22**(10), 1953–1966 (1986).
8. G. P. Agrawal, *Nonlinear Fiber Optics* (Academic Press, 2012).
9. D. Lin, S. U. Alam, P. S. Teh, K. K. Chen, and D. J. Richardson, "Tunable synchronously-pumped fiber Raman laser in the visible and near-infrared exploiting MOPA-generated rectangular pump pulses," Opt. Lett. **36**(11), 2050–2052 (2011).
10. A. S. Kurkov, V. V. Dvoyrin, V. M. Paramonov, O. I. Medvedkov, and E. M. Dianov, "All-fiber pulsed Raman source based on Yb:Bi fiber laser," Laser Phys. Lett. **4**(6), 449–451 (2007).
11. N. Akhmediev and A. Ankiewicz, *Dissipative Solitons: From Optics to Biology and Medicine, Lecture Notes in Physics* (Springer, 2008).
12. F. Anquez, I. E. Belkoura, P. Suret, S. Randoux, and E. Courtade, "Cell death induced by direct laser activation of singlet oxygen at 1270 nm," Laser Phys. **23**(2), 025601 (2013).
13. S. G. Sokolovski, S. A. Zolotovskaya, A. Goltsov, C. Pourreyron, A. P. South, and E. U. Rafailov, "Infrared laser pulse triggers increased singlet oxygen production in tumour cells," Sci. Rep. **3**, 3484 (2013).
14. V. J. Matsas, T. P. Newson, D. J. Richardson, and D. N. Payne, "Self-starting passively mode-locked fibre ring soliton laser exploiting nonlinear polarisation rotation," Electron. Lett. **28**(15), 1391–1393 (1992).
15. S. Kobtsev, S. Kukarin, S. Smirnov, and I. Ankudinov, "Cascaded SRS of single- and double-scale fiber laser pulses in long extra-cavity fiber," Opt. Express **22**(17), 20770–20775 (2014).
16. S. Smirnov, S. Kobtsev, S. Kukarin, and A. Ivanenko, "Three key regimes of single pulse generation per round trip of all-normal-dispersion fiber lasers mode-locked with nonlinear polarization rotation," Opt. Express **20**(24), 27447–27453 (2012).

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17. S. Kobtsev, S. Smirnov, S. Kukarin, and S. Turitsyn, "Mode-locked fiber lasers with significant variability of generation regimes," Opt. Fiber Technol. **20**(6), 615–620 (2014).
18. D. V. Churkin, S. Sugavanam, N. Tarasov, S. Khorev, S. V. Smirnov, S. M. Kobtsev, and S. K. Turitsyn, "Stochasticity, periodicity and localized light structures in partially mode-locked fibre lasers," Nat. Commun. **6**, 7004 (2015).
19. S. Kobtsev, S. Kukarin, S. Smirnov, S. Turitsyn, and A. Latkin, "Generation of double-scale femto/pico-second optical lumps in mode-locked fiber lasers," Opt. Express **17**(23), 20707–20713 (2009).
20. D. Churin, J. Olson, R. A. Norwood, N. Peyghambarian, and K. Kieu, "High-power synchronously pumped femtosecond Raman fiber laser," Opt. Lett. **40**(11), 2529–2532 (2015).

1. Introduction

Phosphorus-doped silica fibres feature double-scale Stokes shift corresponding to SiO_2 (440 cm^{-1}) and P_2O_5 (1330 cm^{-1}) components of their structure. Application of a P_2O_5-doped silica fibre as the active medium in a spectral Raman converter makes it possible to effect considerable conversion of the pumping radiation wavelength, as it was amply demonstrated for CW radiation (see, for example [1–5]). For efficient Raman conversion, the Stokes radiation component is amplified in a multi-pass resonant cavity with a stretch of phosphosilicate fibre between fibre Bragg grating mirrors. In pulsed operation, efficient Raman conversion is achieved with synchronous pumping [6], in which pumping pulses are synchronised with Stokes pulses of the Raman laser circulating within its cavity. Such synchronisation is established through adjusting the Raman laser cavity length so that the Raman laser round-trip time is a multiple of the pumping pulse period. Compared to continuously pumped fibre Raman lasers, those using synchronous pulsed pumping are still much less explored [6–9], and there is exactly one published study of such a laser in an all-fibre configuration with a P_2O_5-doped silica fibre [10] where 3-μs pulses at 1254 nm were reported. When a fibre Raman laser is pumped with broad-spectrum pulses (i.e. in case of relatively short pulses or giant-chirp dissipative solitons [11]) the working spectral range of its cavity mirrors must at least match that of the pumping pulses spectrum, which may span up to ten nanometres and even broader ranges. In case of an all-fibre Raman laser configuration, this necessitates the use of wideband chirped fibre Bragg gratings, whose manufacture to this day remains a complicated special problem.

This research for the first time reports picosecond pulse generation in an all-fibre Raman laser based on P_2O_5-doped silica fibre. This laser was studied with the aim to obtain ultra-short light pulses at wavelengths around 1270 nm, which can be used in photodynamic therapy applications to produce singlet oxygen in photosensitiser-free biological tissues [12, 13].

2. Experiment

The experimental installation is schematically shown in Fig. 1. The Raman converter based on P_2O_5-doped silica fibre was pumped with a fibre MOPA system consisting of an all-normal-dispersion mode-locked Yb fibre master oscillator and a two-stage power amplifier using Yb-doped fibres. The master oscillator was passively mode-locked due to the effect of non-linear polarisation evolution [14], and its configuration was similar to that described in [15].

Selection of the needed mode-locked regime out of the possible great variety [16–18] was carried out by registering the auto-correlation function, spectrum, and sampling-scope trace of the master oscillator output (Fig. 2). The master oscillator spectrum was tuned to the central wavelength of 1084 nm needed to generate a P_2O_5-related stokes component at 1270 nm by adjustment of the active Yb-doped fibre length.

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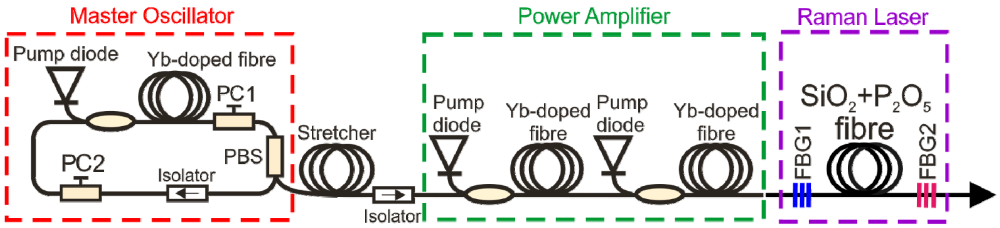

Fig. 1. Experimental set-up: PC1, PC2 – fibre-based polarisation controllers, PBS – fibre-based polarisation beam splitter.

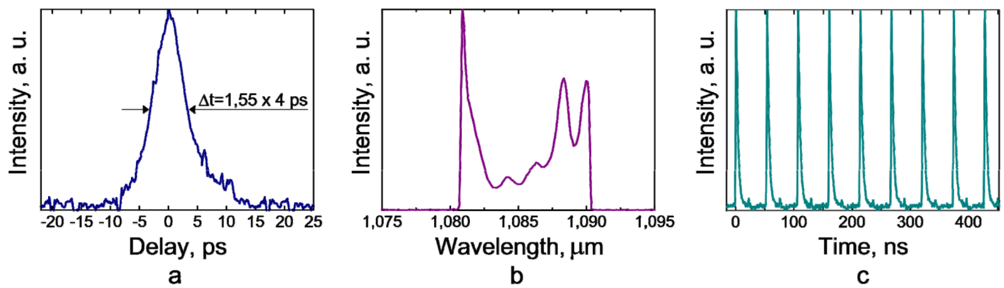

Fig. 2. Auto-correlation function (a), output spectrum (b) and output pulse train (c) of the master oscillator.

Master oscillator generated 4-ps long and 9-nm wide dissipative solitons at the repetition rate of ~19 MHz and the average output power of 40 mW. To raise the average power to above 1 W, an all-fibre power amplifier was then used that included two amplification stages. The first stage amplified the input pulses to the average power of 300 mW. In Fig. 3, the auto-correlation function and the spectrum of the pulses at the exit of the power amplifier are presented. The amplifier expanded the pulse duration at the output to 8 ps, while the pulse spectrum was broadened to 10 nm.

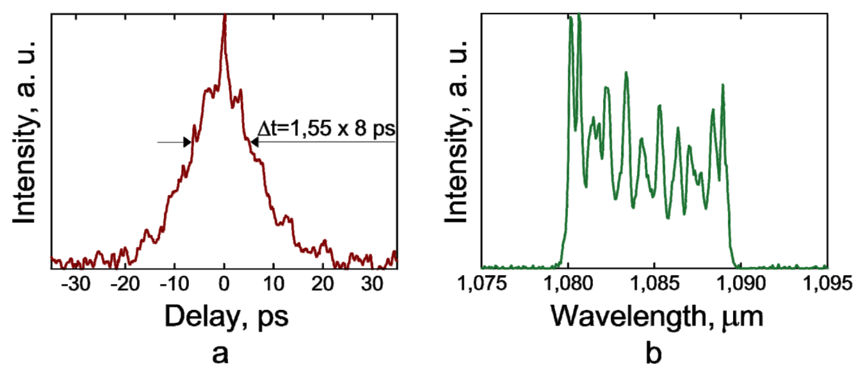

Fig. 3. Auto-correlation function (a) and spectrum (b) of pulses at the exit of the power amplifier.

For Raman conversion we used P_2O_5-doped silica fibre (made by FORC-Photonics) with P_2O_5 content of 9 mol%, core diameter 5 μm and Raman gain coefficient of 6 dB $(km·W)^{-1}$ (1084 μm / 1.27 μm). Since the power amplifier used Yb-doped fibre with core diameter 10 μm, we connected it to the Raman cavity through a tapered fibre fabricated in-house to provide a smooth transition between the cores of their fibres and thus reduce optical losses for radiation passing from the Yb-doped fibre to the phosphorus-doped silica fibre. Raman laser cavity was formed by a pair of wideband chirped Bragg gratings (fabricated by FORC-Photonics) with an 8-nm reflection spectral bandwidth, which practically did not distort the

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pumping radiation spectrum. Reflection spectra of these gratings are given in Fig. 4(a). The input grating reflected 99% around 1270 nm and the exit one had 30% reflectivity in the same spectral range. Because numerical aperture of fibre cores, in which Bragg gratings were recorded (NA = 0.11), was different from that of the phosphosilicate fibre (NA = 0.18), noticeable optical losses were observed at splicing points of these fibres. As a result, the total average power at the exit from the Raman laser cavity amounted to 1 W.

The Raman converter cavity was 16.44-m long and the Stokes pulse round-trip time in this cavity was 3 times longer than the period between adjacent pumping pulses (pumping pulse repetition rate was 18.8 MHz). The Raman converter cavity length was chosen as a working compromise between the spectral transformation efficiency (higher in a longer resonator) and relative temporal shift of the pumping and the Stokes pulses due to group velocity difference (lower in a shorter resonator). In the first approximation, the interaction length of the pumping pulse and the Stokes wave depends linearly on the duration of the pumping pulse and at the pumping pulse duration of, say, 8 ps in a quartz waveguide it is equal to 6 m at the pump and Stokes wavelengths of 1084 and 1270 nm correspondingly.

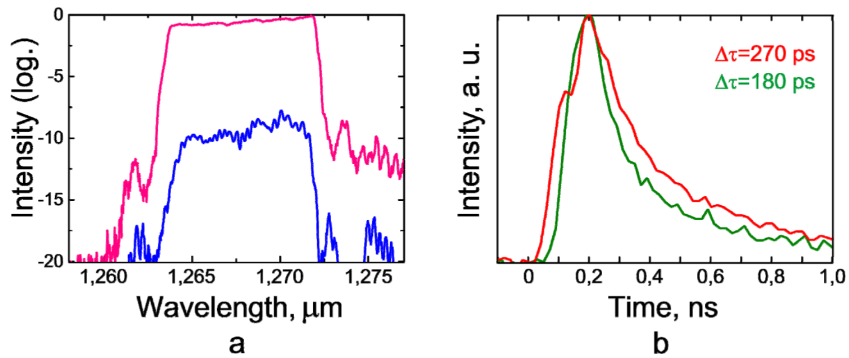

Fig. 4. (a) – Bragg grating reflection spectra (pink curve – input grating FBG1, blue curve – output grating FBG2); (b) – temporal dependencies of radiation intensity (green curve – after the stretching fibre, red line – at the output of the Raman laser at 1270 nm).

Relatively short duration of pulses from the power amplifier used to pump the Raman converter leads to the following specific difficulties:

1. Given 8-ps long input pulses, synchronous pumping requires selection of the Raman converter fibre cavity length to the precision of better than 1 cm or, conversely, the ability to adjust the length of the master oscillator resonator within 1 cm in order to match the pumping pulse repetition rate to the inter-mode frequency spacing of the Raman converter cavity. This is a challenge in an all-fibre system, since the fibre of one or another cavity must be lengthened or shortened by just a few millimetres;
2. Relatively high peak power of such pulses gives rise to generation of one or several Stokes components at (unwanted) quartz-specific wavelengths and to the initial stage of super-continuum generation, both effects reducing the intended conversion of 1084-nm radiation into that at 1270 nm.

The first problem was solved and the second minimised by temporal stretching of the pumping radiation pulses. This stretching was performed in a 150 to 400-m length of SMF-28 fibre spliced between the master oscillator and power amplifier. Adjustment of the stretching fibre length led to the pumping pulse duration at the input of the Raman converter varying between 8 and 300 ps. Figure 4(b) contains typical temporal dependences of radiation intensity after the stretching fibre and at the output of the Raman laser at 1270 nm. The process of Raman conversion further stretched the pumping pulses by ~50%, while preserving their shape.

Figure 5 demonstrates the dependence of the ratio of the converter average output power at 1270 nm to the total radiation average power at the converter output up-on pulse duration at

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the input of the Raman converter. The radiation power around 1270 nm was measured by isolating it from the output radiation of the Raman laser with a prism.

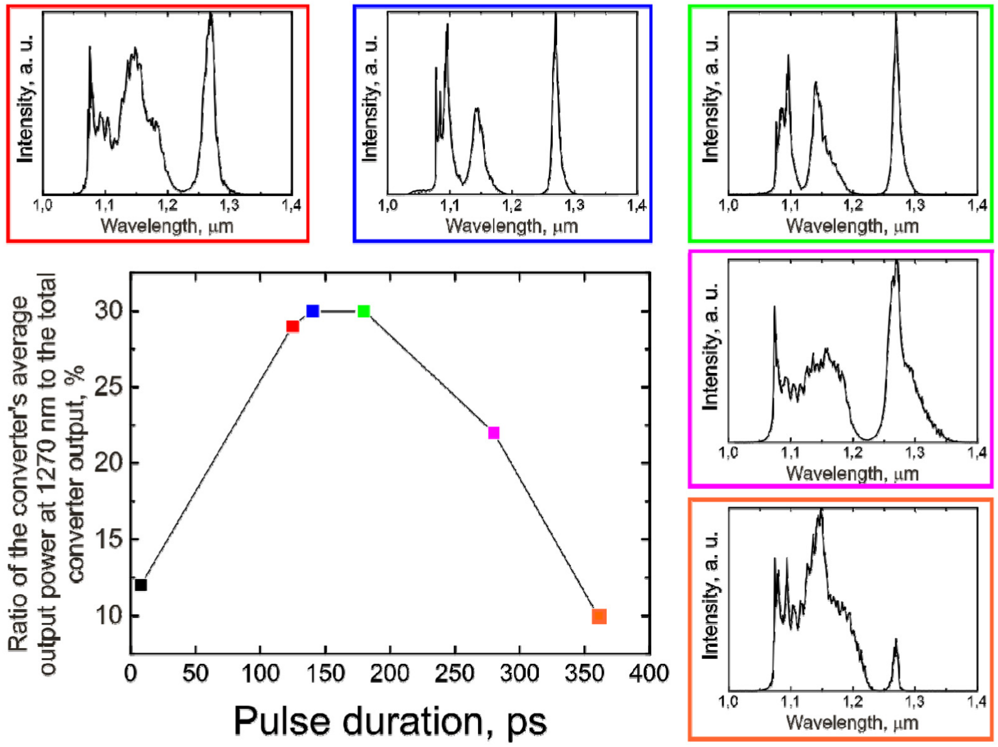

Fig. 5. Ratio of the converter's average output power at 1270 nm to the total converter output power *vs.* input pulse duration. Coloured frames show the converter output spectra at the correspondingly coloured points of the main dependence.

It can be seen from Fig. 5 that the highest proportion of the Stokes component at 1270 nm in the output radiation of the Raman laser, amounting to 30%, is reached at pumping pulse duration (measured at the input of the Raman converter) in the range of 140–180 ps. On passing through the Raman converter, these pulses are additionally stretched to 270 ps without substantial deformation of their relatively broad spectrum. It is therefore quite likely that these output pulses are amenable to significant temporal compression.

The Raman laser's output spectrum contains an isolated peak at 1270 nm and other shorter-wavelength peaks corresponding to the residual pump radiation and Raman radiation of the quartz Stokes component. Pumping pulse duration in the range of 140–180 ps corresponded to the smallest intensity of the short-wavelength peaks. The solitary peak at 1270 nm can be easily separated from the rest of the output by conventional spectral selection, including fibre-based techniques, such as WDM output couplers or band-pass filters based on a combination of optical fibre circulator and fibre Bragg grating.

3. Conclusion

In summary, to the best of our knowledge, we have for the first time demonstrated a picosecond all-fibre Raman laser based on phosphorus-doped silica fibre synchronously pumped with 10-nm wide dissipative solitons. Single-cascaded spectral conversion of pumping pulses at 1084 nm generated 270-ps pulses at 1270 nm, the average output power reaching 300 mW. Unlike double-scale pulses [19], these coherent output pulses exhibit only one temporal scale and are amenable to subsequent efficient temporal compression. The experimentally identified optimal duration of the pumping pulses at the Raman laser cavity length of ~16 m is between 140 and 180 ps, where the amount of the Stokes component power at 1270 nm in the output radiation of the Raman laser reaches 30%. The main factors limiting the proportion of the P_2O_5-generated Stokes component are generation of SiO_2-related Stokes radiation and incomplete transformation of the launched radiation caused by a comparatively short Raman laser cavity. Efficiency of transformation of the pumping radiation into a P_2O_5-related component was limited in the present work by significant optical losses at splicing points between the P_2O_5 fibre and another fibre with a different numerical aperture, in which Bragg gratings were recorded. Fibres with matching numerical aperture or a ring Raman laser cavity [20] can be used to eliminate these losses.

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