

Raman-converted high-energy double-scale pulses at 1270 nm in P₂O₅-doped silica fiber

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Abstract: This work presents implementation of a new approach to single-cascade Raman conversion of laser pulses from the spectral range around 1.1 μm into the 1.3- μm wavelength region. The proposed conversion technique relies on double-scale pico-femtosecond pulses for synchronous pumping of an external cavity made of phosphosilicate fiber with high-precision adjustment of pulse repetition rate to the inter-mode frequency of the external cavity. This enabled generation of double-scale pulses centered at 1270 nm featuring a record energy of 63 nJ and the pulse envelope duration of 88–180 ps with the sub-pulse duration of 200 fs. The fraction of the radiation that was converted into the 1270 nm range amounted to 47 percent of the total Raman-converted radiation power. The generated results offer promising possibilities for new spectral ranges to be developed in the field of high-energy pulsed sources with unique double-scale temporal structure.

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1. Introduction

One of salient features of passively mode-locked fibre lasers is their ability to generate short wave packets (generally, in picosecond duration range) featuring unique spatio-temporal structure of electromagnetic field. Within the picosecond envelope of such a packet there are ultra-short femtosecond-scale field oscillations with relatively high intensity. These nonlinearly localised wave packets are most often called noise-like pulses [1–5], although several other terms are also used: double-scale pulses [6,7], clusters of femtosecond pulses [8], temporally localised multi-solitons [9]. Generation regimes of such pulses can be stable and well-reproducible, and they sparked significant interest due to their ability to carry record-high energy [10], provide uniquely high average radiation power [11], as well as because they feature comparatively high efficiency of non-linear conversion [12–14] and insensitivity to small perturbations [15]. For a fairly long period, double-scale pulses could only be observed in passively mode-locked fibre lasers, but recent publications report generation of such pulses also in solid-state lasers [16]. Double-scale pulses can be efficiently used in various applications, such as ablation of metals [17], supercontinuum generation [18,19], optical coherence tomography [20,21], and sensing [22].

Successful application of noise-like-pulse-pumped supercontinuum centred around 1.3 μm for ultrahigh-resolution optical coherence tomography [23] stimulates identification of optimal approaches to conversion of double-scale pulses into the 1.3- μm range in order to address bio-medical problems, including photosensitiser-free photodynamic therapy at the wavelength of 1270 nm [24].

One of the promising ways to generate double-scale pulses around 1.3 μm is spectral transformation of such pulses from 1.1- μm range through single-cascade Raman shift in phosphorus-doped silica fibre [25]. A few studies in this field have been carried out, however, the achieved pulse energy in the 1.3- μm range was rather low (15 nJ [26], 1.6 nJ [27]), and the fraction of radiation energy transformed into the 1.3- μm range did not exceed 30% of the total Raman-converted energy.

This work for the first time presents an experimental implementation of a new approach to single-cascade Raman conversion of laser pulses from the 1.1- μm into the 1.3- μm range. Conversion relied upon double-scale pico-femtosecond pulses for synchronous pumping of an external cavity made of phosphorus-doped silica fibre with the pulse repetition rate tuned onto the inter-mode frequency of the external cavity. This allowed generation of double-scale pulses centred at 1270 nm with record-setting energy of 63 nJ and 88–180-ps long pulse envelope filled with 200-fs sub-pulses. The fraction of the radiation converted into the 1270-nm domain reached 47% of the total Raman-converted radiation power.

2. Experimental setup

Single-cascade Raman conversion of laser pulses from the 1.1- μm range into the 1.3- μm one was done in an external multi-pass phosphorus-doped silica fibre ring cavity synchronously pumped with double-scale pico-femtosecond pulses. The ring cavity was 20-m long and for optimal synchronous pumping, the repetition rate of double-scale pulses was tuned close to the inter-mode frequency of the external ring cavity so as to maximise the power of the Stokes component at 1270 nm.

In order to find the optimal repetition rate of the pumping double-scale pulses, we used an auxiliary pulsed seed laser (PiqoQuant laser diode) emitting at 1080 nm with the repetition rate of its output 50-ps pulses adjustable around 10 MHz. The radiation of this laser with the average power of 0.6 mW was boosted in a fibre-optical amplifier up to the average power level of 2.8 W and after that coupled into the external ring cavity through a broad-band fibre beam splitter. The repetition rate of the amplified picosecond pulses was adjusted for the highest power of the Stokes radiation component at 1270 nm (controlled with an optical spectrum analyser Yokogawa AQ6370). The optimal pulse repetition rate was found to be 10.25 MHz. The measured optimal pulse repetition rate was further used as the central frequency of an F8 fibre laser emitting double-scale pico-femtosecond pulses (see Fig. 1).

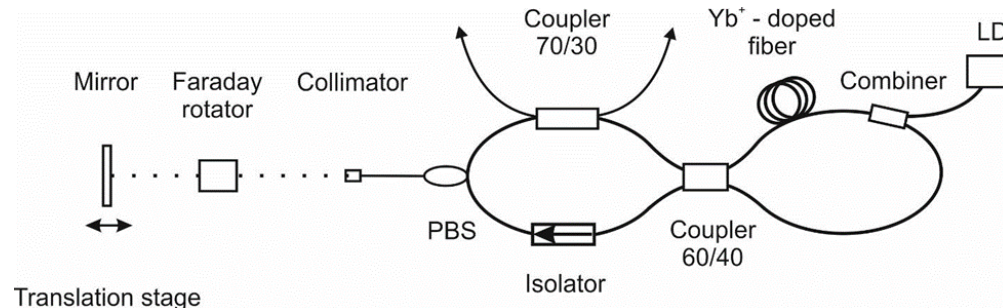


Fig. 1. Experimental setup of the F8 fibre laser pump source.

This laser was mode-locked via a nonlinear amplifying loop mirror. Yb-doped GTWave fibre [28] based on side-pumping fibre technology and pumped with a single 980-nm multi-mode laser diode was used as the active medium. In order to adjust the output pulse repetition rate, the passive loop of the F8 laser cavity had a linear branch whose length could be varied within ± 5 cm by translation of the end mirror. The intra-cavity radiation was branched off into the linear arm through a fibre-optical polarisation beam splitter. Polarisation rotation in the linear arm of the cavity was compensated with a Faraday rotator. This cavity layout enabled tuning of the output pulse repetition frequency within a ~ 25 -kHz range without collapse of the mode-locked operation. In a stable mode-locked regime, the laser generated 180-ps double-scale pulses [29] with the coherence peak contrast of 0.28 (Fig. 2(a)), central wavelength of 1080 nm, and the average output power of 150 mW.

The output radiation of the mode-locked F8 fibre laser was boosted in a fibre-optical amplifier up to the average power level exceeding 1 W and after that was coupled through a broad-band fibre-optical beam splitter into the 20-m long external ring cavity made of P₂O₅-

SiO₂ glass fibre (Fig. 2(b)). Autocorrelation function of the amplified pulses was identical to that of the pulses prior to amplification.

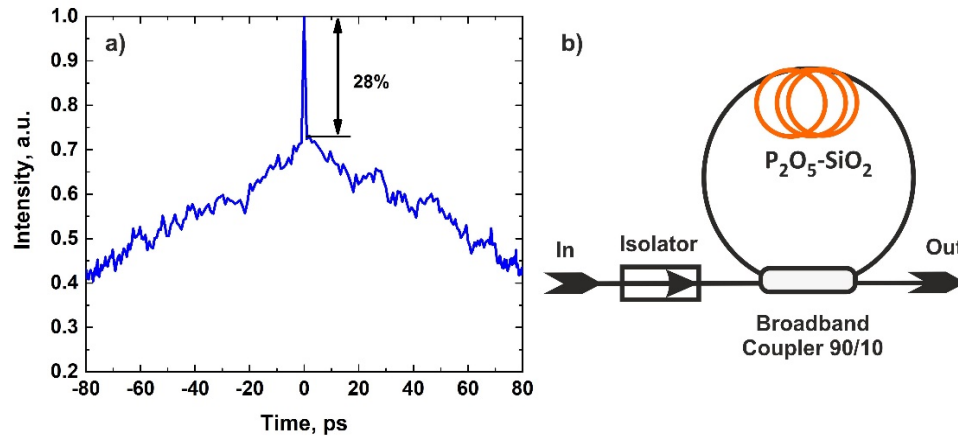


Fig. 2. (a) Autocorrelation function of the output pulses of the mode-locked F8 fibre laser measured with autocorrelator APE pulseCheck; (b) Layout of the Raman converter based on an external ring cavity made of P₂O₅-SiO₂ glass fibre.

3. Results and discussion

Figure 3 presents optical spectra at the exit of the Raman converter as a function of input pulse repetition rate. Spectra of the Raman converter output radiation at the input pulse repetition rate close to the inter-mode frequency of the ring Raman cavity exhibited prominent silica-related and phosphorus-related first-order Stokes components around 1040 and 1270 nm, as well as a relatively weak spectral component at 1340 nm, which corresponds to the phosphorus-related first-order Stokes wave for the pump radiation at 1040 nm. The highest fraction of the radiation energy converted into the 1270-nm range was observed at the input pulse repetition rate of 10.2521 MHz. The output spectrum of the Raman converter at the input pulse repetition rate of 10.2521 MHz is given in Fig. 4. The total average output radiation power exiting the Raman converter amounted to 1.38 W, the power of radiation around 1270 nm reaching 650 mW, which corresponds to 47% of the total output radiation power.

Shown in Fig. 5(a) is the dependence of the relative radiation power around 1270 nm upon the total power of the output radiation as a function of the input pulse repetition rate. It is quite sharp and the relative radiation power in the vicinity of 1270 nm changes substantially when the input pulse repetition rate deviates from the optimum by just a few kHz. The measured dependence visually illustrates the importance of precise matching of the input pulse repetition frequency to the inter-mode frequency of the Raman converter when using synchronous pumping: the tuning precision should be no worse than 0.01%. Continuous adjustment of the input pulse repetition rate available during the present work ensured the necessary tuning precision and allowed boosting the relative radiation power around 1270 nm up to a record 47% as a result of single-cascade Raman shift in phosphorus-doped silica fibre. High efficiency of non-linear conversion of double-scale pulses used for synchronous pumping of the Raman converter was an additional factor improving the overall high efficiency of the process.

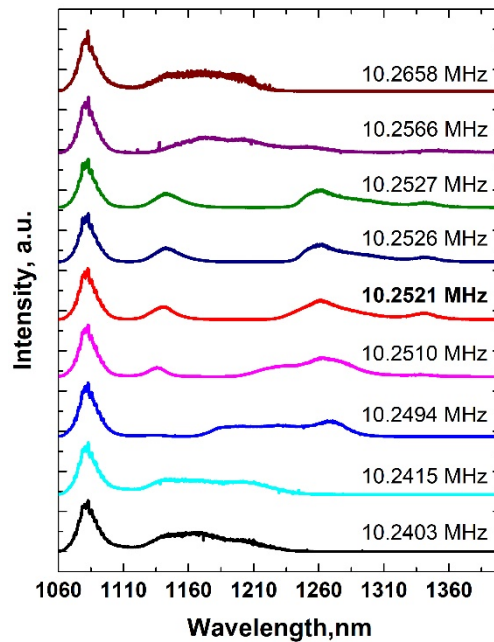


Fig. 3. Spectra of the output radiation of the Raman converter at different repetition rates of the input pulses.

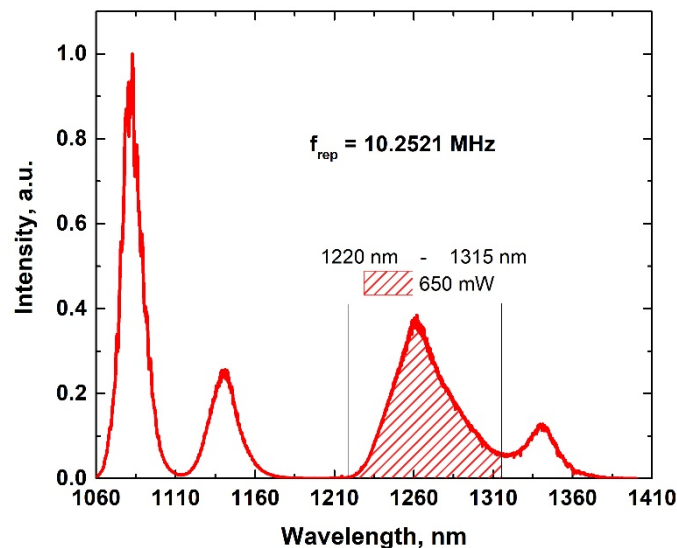


Fig. 4. The output spectrum of the Raman converter corresponding to the input pulse repetition rate of 10.2521 MHz.

During our experiments, we observed an effect of significant shortening of Raman pulses at small frequency detuning from the optimum. For example, when the input repetition rate was reduced by 1.1 kHz compared to the optimum, the duration of the output Raman pulses at 1270 nm was shortened down to 88 ps, while the output power in the vicinity of 1270 nm also dropped, but not significantly, only to 510 mW. The observed more dramatic change in the pulse duration as compared to the average output power as a function of the deviation of the input pulse repetition rate from the optimal value comes from the fact that at the average input power within the range of 600–650 mW, Raman conversion of radiation into 1270 nm is

saturated. This is indicated by emergence of longer-wavelength Stokes components in the output. Because of this saturation, detuning the Raman conversion parameters from the optimum only affects weakly the average output radiation, whereas the pulse duration experiences a much more pronounced change. The output pulse shortening is a stronger effect because when the input pulse repetition rate does not precisely match the inter-mode frequency of the ring Raman cavity, the pump pulses only partially overlap the Raman pulses in time, and stronger the mismatch leads to even less overlap. This effect can be, in principle, harnessed to produce shorter Raman pulses, provided that the output Raman power can be kept at an acceptable level.

In Fig. 5(b) we show the pulse auto-correlation functions at the optimal repetition frequency and at the frequency corresponding to the shortest output Raman pulses.

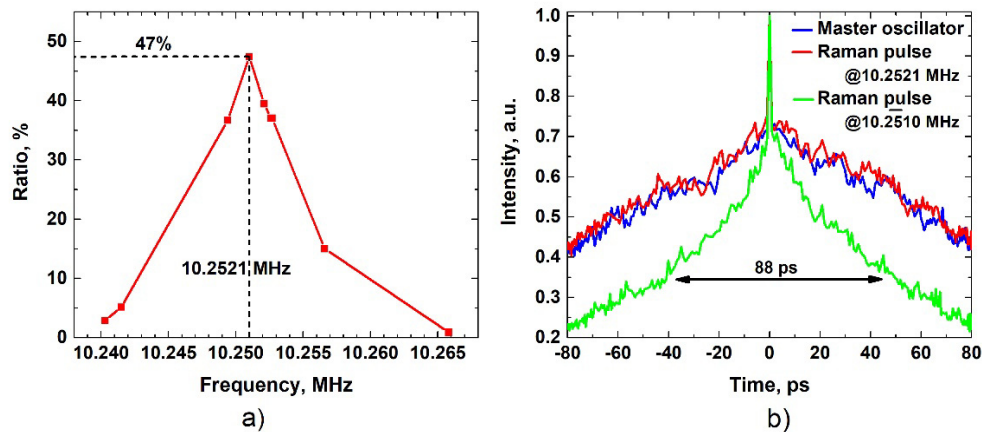


Fig. 5. (a) Ratio of the output radiation power around 1270 nm to the total output power as a function of the pulse repetition rate; (b) Autocorrelation functions of output pulses at the optimal repetition rate and that corresponding to the shortest output Raman pulses.

4. Conclusion

In this work, it was for the first time experimentally shown that double-scale pulses around 1080 nm can be Raman-converted into the 1270-nm range as a result of single-cascade shift in phosphorus-doped silica fibre with record-setting parameters: the ratio of the output power around 1270 nm to the total output power as high as 47% and the energy of Raman double-scale pulses at 1270 nm as high as 63 nJ. The highest observed average output power at 1270 nm was equal to 650 mW with a 180-ps long pulse envelope filled with 200-fs long sub-pulses. The pulse envelope duration at this wavelength could be shortened to 88 ps at the expense of the average output power drop to 510 mW. It was found that during synchronous pumping, the input pulse repetition rate must coincide with the inter-mode frequency of the Raman converter to the precision better than 0.01%. The proposed in this work approach for generation of high-energy Raman double-scale pulses at 1270 nm opens up broad prospects of development of next-generation sources of laser pulses for bio-medical and other applications.

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