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Study on harmonic generation regimes of Raman dissipative solitons in an external fibre cavity in a spectral region of 1.3 μm

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Abstract. **We have studied the harmonic generation regimes in a pulsed SRS laser with synchronous pumping. The use of phosphosilicate polarisation-maintaining fibre made it possible to obtain stable generation of Raman dissipative solitons (RDS's) with a wavelength of 1.3 μm, and a fold increase in the length of the external cavity relative to that of the pump laser cavity by a dispersion-shifted fibre allowed us to raise the threshold for the transition to noise-like pulses and to increase the RDS energy up to 2.5 nJ with an estimated duration of a transform-limited pulse of about 200 fs.**

Keywords: *fibre lasers, femtosecond lasers, synchronous pumping, stimulated Raman scattering.*

1. Introduction

The wavelength of an ultrashort pulse source is often as important as its energy and duration. Thus, for biomedical applications (primarily for various types of nonlinear microscopy), relatively inexpensive and reliable sources of subpicosecond pulses with a high peak power and a generation wavelength near 1.3 and 1.7 μm are in demand [1]. The choice of these wavelengths is due to the fact that within these ranges the absorption of OH groups is minimal, which means that the transparency of biological tissues attains its maximum. At the same time, the region near 1.3 μm has an additional advantage since it allows one to work with conventional fluorophores [2, 3]. However, until recently [4, 5] there have been no active medium for this region. Traditionally, optical parametric oscillators pumped by solid-state Ti:sapphire lasers are used as radiation sources for biomedical applications. The cost and complexity of such systems are extremely high, making it difficult to implement them widely in practice. However, a high peak power can also be provided by all-fibre lasers in the generation of highly chirped dissipative solitons (HCDS's) [6]. At the same time, lasing at new wavelengths is possible using stimulated Raman scattering (SRS). Recently, a successful combination of both approaches has been demonstrated, i.e. SRS generation of HCDS's at new wavelengths both inside the cavity of a pulsed fibre laser [7] and in an external ring cavity with synchronous pumping [8]. Such pulses are called Raman dissipative solitons (RDS's) by the method of their generation [7, 9].

To increase the SRS wavelength shift which was ~ 13 THz in works [7 – 9], other types of fibres can be used, for example, phosphosilicate fibres (doped with P_2O_5), which have an additional gain peak that is shifted by about 39 THz [10]. When pumped in the region of 1.1 μm, such a fibre allows lasing at a wavelength of 1.3 μm. This possibility has been actively studied by various groups in recent years [11 – 16], but only a few were able to demonstrate the generation of pulses compressible to less than 1 ps [14, 16].

In this paper, we continue to study the features of RDS generation in the region of 1.3 μm in an external cavity using phosphosilicate fibre. To improve the long-term stability, as well as to provide the shift of the generation wavelength and the fast tuning of the pulse repetition rate, the pump laser was modified. The increased external cavity length was a multiple of the length of the pump laser cavity, which made it possible to obtain and investigate the regimes of so-called harmonic generation. The length of the phosphosilicate fibre was reduced to 10 m, while the standard single-mode fibre and the dispersion-shifted fibre were used to increase the total cavity length.

2. Experimental setup

The experimental scheme is shown in Fig. 1. As a first step, the pump laser was significantly modified to improve the long-term operation stability and to shift the resulting carrier wavelength closer to the 1.3 μm value. In contrast to [6, 14], in addition to the standard fibre with a mode diameter of 6.6 μm, a bandpass filter (BF) with a centre wavelength of 1093 nm and a width of 9 nm (at a level of 3 dB) was used in the pump laser cavity. This made it possible not only to shift the lasing wavelength (Fig. 2), but also to get rid of the temperature dependence of transmission spectrum, which is a feature of the Lyot fibre filter. The fibre variable delay line (VDL), which is an air gap between two collimators with fibre outputs mounted on a motorised translation stage, was transferred from the external cavity to the pump cavity, which provided frequency tuning of the generated pulses at 70 kHz. In other respects, the pump laser scheme repeats that from work [6]: the cavity consists of two types of fibres – with polarisation maintenance (PM) and without it, the propagation direction is set by a polarisation-sensitive isolator (ISO), and a polarisation controller (PC) serves to attain the mode-locking regime. For pumping, a single continuous wave multimode laser diode (LD) is used, the radiation of which is introduced through a pump combiner into the cavity and then into the active double-clad single-mode fibre (SM Yb^{3+}). The radia-

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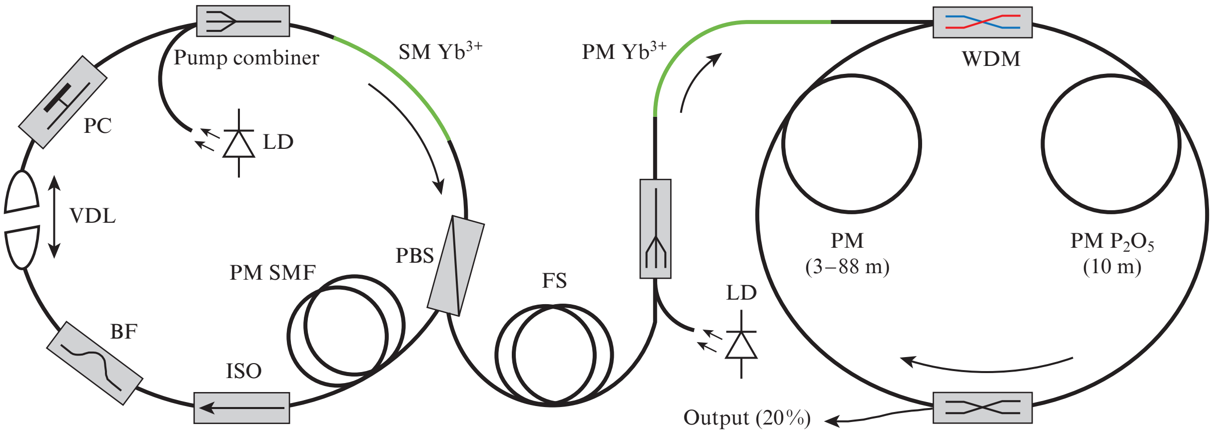

Figure 1. Schematic of the experiment: (left) pump laser cavity and (right) external cavity for RDS generation in phosphosilicate fibre.

tion is coupled out through a polarisation beam splitter (PBS). The regime of mode-locking is attained due to the effect of nonlinear polarisation evolution in the cavity section made of non-polarisation-maintaining fibre, with the PC properly tuned. The laser generates chirped pulses with a repetition rate of 15.45 MHz and a duration of 8 ps (see the inset in Fig. 2).

Further, the pulses pass through a fibre stretcher (FS) and are amplified in the segment of an active double-clad polarisation-maintaining fibre (SM Yb^{3+}) to a level of 220 mW (average power), which corresponds to a pulse energy of 15 nJ. The duration of stretched pulses was ~ 50 ps.

The external cavity for RDS generation (see Fig. 1) is simplified significantly and consists of only four elements: a wavelength division multiplexer (WDM) for pump radiation input, a segment of PM P_2O_5 (FORC RAS) phosphosilicate polarisation-maintaining fibre, a 20/80 coupler for radiation output, and a segment of PM fibre for cavity length adjustment. In this case, the entire scheme is an all-fibre one, and only polarisation-maintaining fibres are used for RDS generation. The repetition rate of RDS's is set by the pump laser, and their generation starts only when the optical lengths of both cavities are in strict compliance (divergence of less than 1 mm). We should separately mention the possibility of extremely simple implementation of the so-called harmonic generation in the external cavity, when its length is a multiple of the length of the pump laser cavity. To this end, the PM fibre length in the last section beyond the output coupler was properly selected (see Fig. 1). In contrast to work [14], where the external cavity was four times longer and consisted mainly of phosphosilicate fibre, we used a fibre shortened to 10 m, which made it possible to align the lengths of both cavities. In addition, cavities with a ratio of lengths of 2 : 1 and 8 : 1 were investigated. To increase the external cavity length, a Fujikura DS15-PS dispersion-shifted fibre (DSF) with a mode diameter of 8 μm and a Fujikura SM98 PS (SM) standard polarisation-maintaining fibre with a mode diameter of 6.6 μm were used.

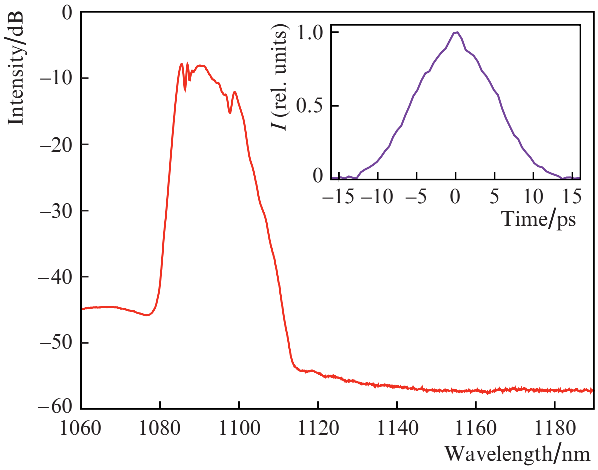

Figure 2. Optical spectrum and autocorrelation function (inset) of a pump laser pulse for the RDS generator.

3. Results and discussion

Since the optimal parameters of the pump pulse duration and the cavity output coupling ratio were obtained earlier in work [14], in this work the efforts were focused on shifting the lasing spectrum closer to 1.3 μm and studying various regimes of RDS harmonic generation in the external cavity. The use of a bandpass filter allowed us to obtain stable generation of dissipative solitons with a centre wavelength of 1090 nm, which resulted in a shift in the wavelength of the generated RDS's from 1245 to 1270 nm (Fig. 3). Such a result was impossible with the Lyot filter because of its periodic nature – with a shift of transmission maximum to the long-wavelength side, the generation began at the maximum of the neighbouring period. It is seen from Fig. 3 that the generation regime has not changed – the optical spectrum has sharp edges that are typical of highly chirped dissipative solitons, while a noise peak near 1340 nm indicates that the lasing threshold for the next SRS germanosilicate component has been reached. It was these parameters that were controlled in all subsequent experiments, i.e. the qualitative view of the spectrum and the appearance of the SRS noise peak, leading ultimately to the transition to the generation regime of noise-like pulses [17].

Figure 4 shows the RDS optical spectrum evolution with increasing pump power for a configuration with a 2 : 1 cavity length ratio. The DSF was used as PM fibre. The spectral width increased monotonically from 14 nm (dashed curve) to 23 nm (solid curve). The estimated duration of the transform-limited pulse in the latter case was 200 fs. A further increase in

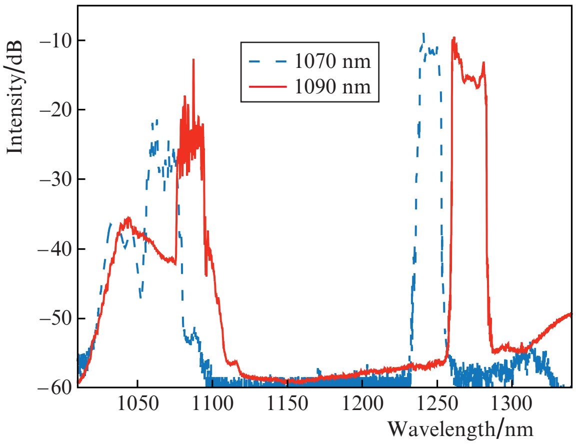

Figure 3. Change in the carrier wavelength of RDS generation.

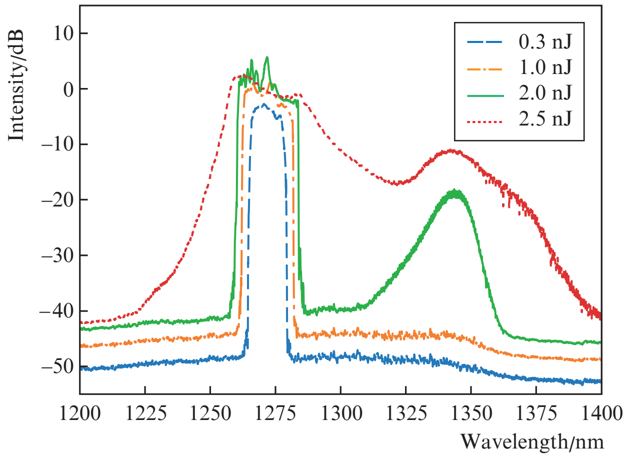

Figure 4. Optical spectrum evolution with increasing energy of generated RDS's (cavity length ratio 2:1, DSF).

the pump power led to a significant increase in the parasitic SRS generation at the germanosilicate peak (1340 nm) and the destruction of the dissipative soliton regime – the main spectrum at 1270 nm qualitatively changed its shape and merged with the peak at 1340 nm (dotted curve).

In addition to the length ratio of 2:1, ratios of 1:1 and 8:1 were studied using DSF, and the ratio of 2:1 was studied with the use of standard PM fivre (SM) for which the zero-dispersion point was located near 1.27 µm [18]. The maximum achievable energy and the optical spectrum width which directly determines the minimum possible duration of the compressed pulse were measured. The measurement results for all configurations are shown in Fig. 5, in which crosses mark the points of transition to the regime of noise-like pulses. Thus, in the case of the 1:1 ratio, the transition is observed already at an energy of 0.8 nJ. Doubling the cavity length due to the standard fibre led to an increase in the width of the optical spectrum and an increase in energy to 1.7 nJ. This broadening can be explained by the fact that the nonlinear phase shift increased with a full cavity round-trip, while the net dispersion did not change much.

When replacing the standard SM fibre with the DSF, an even greater increase in the destruction threshold of the soliton generation regime and a slight decrease in the optical spectrum width are observed. Here the increased mode field diameter is of importance rather than the added dispersion increment. This is confirmed by the results of measuring the RDS duration at the output (Fig. 6). At the same time, the width of the autocorrelation function (ACF) for both regimes was almost the same, i.e. 30 ps. With a further increase in the DSF length to the to the cavity length ratio of 8:1, both nonlinear and dispersion phase shifts increase simultaneously, which in terms of HCDS generation should lead to a proportional increase in the pulse energy due to an increase in the pulse duration [19]. In practice, it was possible to increase the energy to 2.5 nJ without switching to the noise-like pulse generation regime (squares in Fig.5) at the optical spectrum width of 17 nm. In this case, the ACF width increased to 60 ps (see Fig.6).

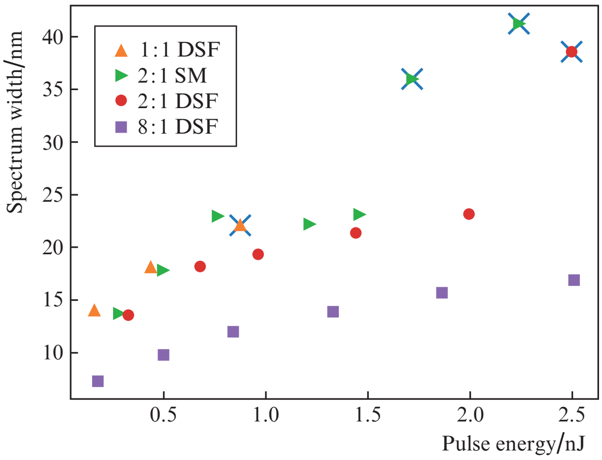

Figure 5. Optical spectrum width (at a level −10 dB) of the generated pulse vs. pulse energy.

It should be noted that the maximum width of the RDS spectrum in all configurations did not exceed 25 nm. This limit can be determined both by the length of the phosphosilicate fibre used (10 m) and by the duration and width of the spectrum of pump pulses. The width of the gain spectrum for the phosphosilicate peak may also play a significant role. Numerical calculations, the starting point of

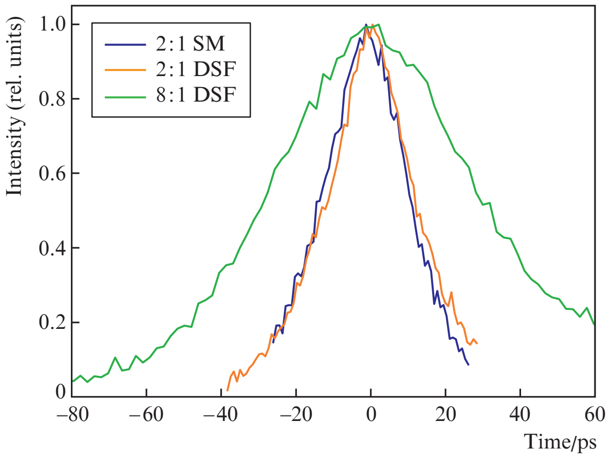

Figure 6. (Colour online) Autocorrelation function of the generated pulse at different cavity configurations.

which can be the results of this work, should help answer these questions.

4. Conclusions

In this work, the harmonic generation of Raman dissipative solitons in an external cavity using a phosphosilicate fibre has been studied. The centre wavelength was 1270 nm, with a maximum energy up to 2.5 nJ, a repetition rate of 15.45 MHz, and a spectrum width up to 23 nm. In this case, the spectrum has sharp edges that are typical of a dissipative soliton, as in [14]. The estimated duration of a transform-limited pulse was ~ 200 fs. It was found that the RDS destruction threshold can be increased by varying the total dispersion and external cavity length. Amplified radiation from this source may be of interest for biological applications, especially for multiphoton microscopy.

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