Properties of supercontinuum formed from different chaotic bunches

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ABSTRACT

We report on research into the properties of supercontinuum (SC) generated from low-coherence bursts of different duration in a 1-km long P_2O_5 fibre. It was found out that SC with a spectral width of ~135–150 nm is formed within the ~900–1200-nm range mostly due to cascaded Raman scattering of noise-like pulses with the variable envelope duration of 36–153 ps (sub-pulse duration was ~ 300 fs) and average power of 560 mW at 1080 nm. It was discovered that the spectral width of SC is predominantly affected by the duration of interaction between the pumping and Raman pulses.

Keywords: supercontinuum generation, noise-like pulse, Raman scattering,

1. INTRODUCTION

It is possible to generate supercontinuum (SC) - defined as radiation with much broader spectrum than the initial radiation - in many media using various mechanisms of spectral broadening[1–3]. Medium properties and the type of initial radiation are major factors governing the parameters of the generated SC. Supercontinuum formed from noise-like pulses has been already studied[4–6]. However, the predominant role in formation of SC was then played by phase self-modulation essentially brought about by fairly high peak radiation power of the initial ultra-short sub-pulses. Supercontinuum may be alternatively formed by multiple Raman scattering of the initial radiation with overlapping Stokes orders[7]. The condition of Stokes order overlap and generation of a continuous SC radiation spectrum is comparatively broad initial radiation spectrum, whose width has to exceed by order of value the Raman shift. In this case, a broad continuous SC spectrum may be formed by multiple Raman scattering.

This SC generation method is attractive because of relaxed requirements to the initial radiation wavelength. Conversely, this method is more stringent with respect to the spectral width of the initial radiation, which must exceed the spectral spacing between the adjacent Stokes components. Noise-like pulses with their relatively broad optical spectrum satisfy the conditions for SC generation by multiple Raman scattering. The present work reports on study of SC generated in this way. It should be noted that this method may be implemented in a standard optical fibre (with conventional dimensions) and does not require specialty fibre.

The question of uniformity of spectral distribution of the radiation energy in SC formed by multiple Raman scattering remains one of considerable nicety. However, initiation of Raman scattering with noise-like pulses characterised by comparatively broad radiation spectrum allows formation of wide uniform spectral distribution of radiation energy using this SC generation mechanism[4, 8]. This method's undoubted advantage is no need of miniature or micro-structured optical fibre, which is difficult to fabricate and use.

2. RESULTS

In this work, we investigated the single-pass Raman conversion of double-scale pulses with different envelope duration of pulsed clusters when passing through a 1 km long stretch of P_2O_5 fiber. To implement the SRS conversion, we created and used experimental setup shown in Fig. 1, which allows lasing in various pulsed regimes. A mode-locked fiber laser based on nonlinear polarization evolution was used as a source of double-scale pulses.

The ring cavity of the fiber laser contains a 5 m long segment of the active side-coupled Yb-doped fiber as gain medium, a polarization controllers for setup and control mode-locking regimes, an isolator for unidirectional generation mode, a polarisation beam-splitter as polarizator, and a polarization maintaining output coupler of the output radiation.

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The master oscillator is pumped by a multimode laser diode with a wavelength of 975 nm. The pumping radiation is delivered via the passive coreless fiber with a diameter of 125 µm of the side-coupled fiber. The mode-locking of the fiber laser results from the nonlinear rotation of the polarization.

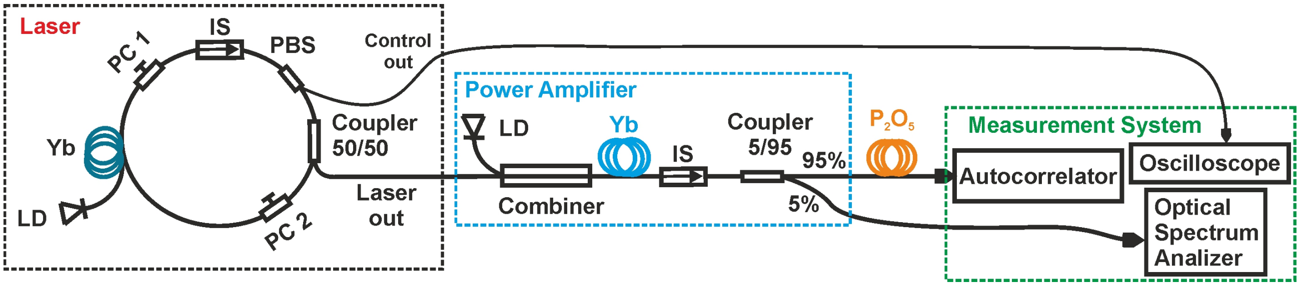

Fig. 1. Experimental setup: LD - pump laser diode, Yb - active fiber doped with ytterbium ions, PC1, PC2 - polarization controllers, IS - optical isolator, PBS - polarization splitter.

By adjusting the polarization controllers and varying the pump power, pulsed lasing modes were selected either with different heights of the central peak while maintaining the pulse duration ~ 25 ps (Fig. 2 (a)) or with different the envelope duration of pulses ta the ACF peak did not change and amounted to ~ 23% (Fig. 2 (b)). The envelope duration of double-scale pulses was varied from 36 ps to 153 ps (Fig. 2 (b)). The duration of sub-pulses in all pulse modes was ~ 300 fs.

Parameters of operation regime was controlled through the output of the polarization coupler (Control out). With the main output, the laser power was 10 mW, which was not enough to reach the SRS conversion threshold; therefore, an amplifier was used.

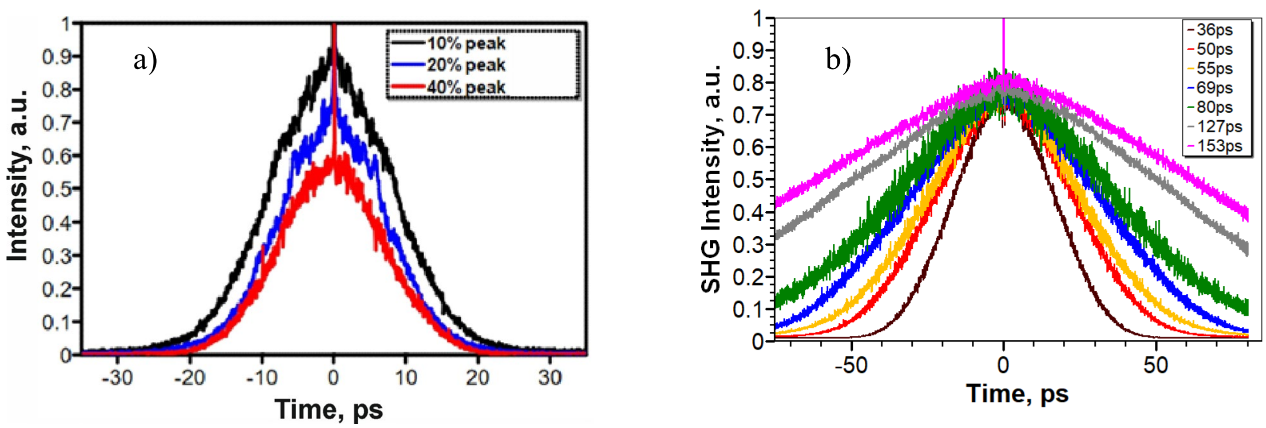

Fig. 2. (a) Autocorrelation functions of double-scale pulses with different peak heights in the central part of the ACF (with different levels of fluctuations) and (b) autocorrelation functions of double-scale pulses with different the envelope of double-scale pulses (from 36 to 153 ps) at different settings of polarization controllers and pump powers.

The master laser radiation was fed into an amplifier based on a 5m long segment of the active double-clade Yb-doped fiber, a combiner for combine pump and signal wave radiations, output isolator and polarization maintaining out 5/95 coupler, where it was amplified up to 600 mW.

During the experiment, for various modes, the power at the input to the fiber was maintained at the same level (~ 600 mW). The radiation from the amplifier entered the coil of a fiber doped with phosphorus oxide P_2O_5, 1 km long. The converted radiation spectra were recorded from the output of the P_2O_5 fiber.

The radiation intensity of Raman-converted pulses at 1270 nm was measured with an optical spectrum analyser Yokogawa AQ6370 with resolution 0.05 nm.

The APE pulseCheck autocorrelator with scanning range from 120 fs up to 150 ps was used for control envelope duration of pulses.

The Tektronix DPO 4034 oscilloscope with 350 MHz bandwith was used for control of pulse train.

Figure 3 (a) shows the optical conversion spectra of double-scale pulses depending on the change in the level of fluctuations (height of the central peak) of double-scale pulses while maintaining the envelope duration of about 25 ps. Figure 3 (b) shows the optical conversion spectra of double-scale pulses depending on the duration of the envelope of the double-scale pulses while maintaining the height of the central peak.

Figure 4 shows the dependence of the width of the optical spectrum of the generated radiation and the maximum generated wavelength at a level of 0.1 on the maximum on the duration of the envelope of the input pulses.

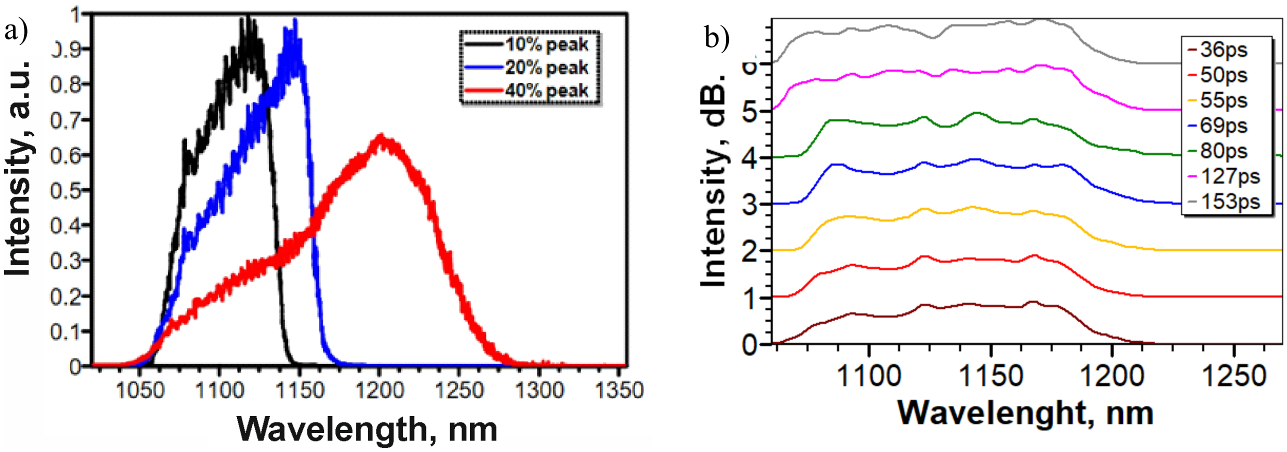

Fig. 3. (a) Optical spectra at the P_2O_5 fiber output versus the different peak heights in the central part of the ACF and (b) optical spectra at the P_2O_5 fiber output versus the envelope duration of the input double-scale pulses.

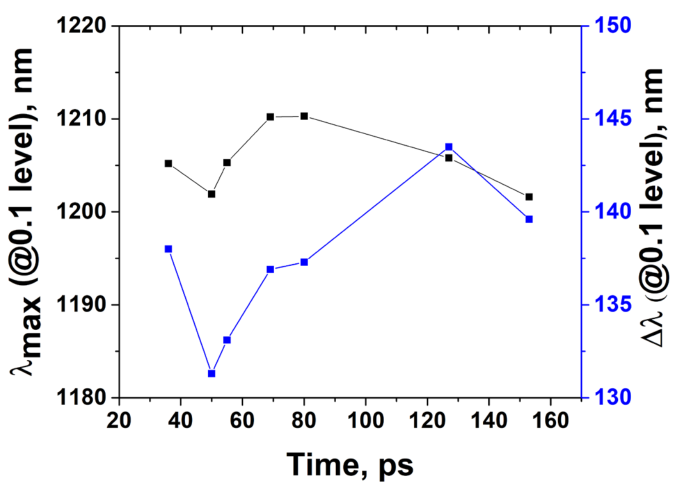

Fig. 4. Dependence of the maximum generated wavelength measured at a level of 0.1 from the maximum on the duration of the envelope of the pump pulses (black line) and dependence of the width of the generated spectrum (blue line) measured at a level of 0.1 from the maximum on the duration of the envelope of the pump pulses.

3. DISCUSSION

The height of the central peak of the ACF is proportional to the level of fluctuations in the pulse train[5]. The higher peak height then the higher the level of fluctuations within a pulsed cluster and the lower the degree of coherence of such pulses. It can be seen from the results obtained that the degree of coherence of double-scale pulses significantly affects not only the wavelength and intensity of the Stokes wave, but also the width and shape of its radiation spectrum. The pulses with the lowest degree of coherence are distinguished by more intense intra-pulse fluctuations of the field, which causes a more significant nonlinear transformation of these pulses. When the height of the central peak changes from

10% to 40%, the width of the emission spectrum of the Stokes wave can change more than twice. In this case, in the case of single-pass SRS lasing, due to the dispersive runaway of the pump and SRS pulses, a long pump pulse duration provides a longer interaction with SRS pulses and provides a greater pumping rate despite a decrease in the peak pump power. Double-scale pulses with duration of 36 ps and 153 ps have a spectral distribution similar in width with a long-wavelength cutoff in the region of ~ 1205 nm. Obviously, at a fixed average power level and at the same degree of coherence and duration of sub-pulses, the peak power of double-scale pulses will be inversely proportional to their envelope duration. However, in the case of a single-pass SRS generation scheme in the presence of dispersion, an important role is also played by the interaction length of the pump pulse and the generated SRS pulse. In this regard, the long duration of the pump pulses leads to a longer interaction length and to an increase in the conversion efficiency, which compensates for the effect of a decrease in the peak power of the pump pulses.

4. CONCLUSION

In this paper, it is shown for the first time that the degree of coherence of double-scale pulses generated in mode-locked fiber lasers significantly affects the key properties of their SRS conversion.

It is necessary to note that the degree of coherence of these pulses is not zero (even though their internal structure is noise-like). The degree of coherence of noise-like pulses may be non-zero and variable within certain limits, affecting the efficiency of certain nonlinear processes.

The use of double-scale pulses with the highest level of fluctuations (the height of the central peak of the ACF is 40%) makes it possible to increase the width of the optical spectrum of the converted radiation by more than 2 times.

It was demonstrated that, despite an increase in the envelope duration of pulsed clusters, the efficiency of nonlinear conversion of such pulses does not decrease. Thus, the double-scale pulses generated in fiber lasers do not need to be compressed for such spectral transformations.

The results obtained open up new prospects for the use of double-scale pulses for nonlinear spectral transformations of pulsed radiation into the long-wavelength region and generation of a supercontinuum.

These findings also contribute to the important field of new methods for nonlinear transformation of light field in all-fiber and fiber-integrated devices[9-11].

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