ISSN 1054-660X, Laser Physics, 2010, Vol. 20, No. 2, pp. 375–378.

All-Fiber High-Energy Supercontinuum Pulse Generator

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Received June 15, 2009

Abstract—An all-fiber supercontinuum generator with a record-high pulse energy of 40 μJ is presented. The generator is based on a nanosecond ultralong high-energy mode-locked Yb-doped fiber laser with an additional amplification stage. The supercontinuum spectrum belongs to the wavelength range 500–1750 nm, and a relatively uniform spectral distribution of the intensity is observed in the interval 1125–1550 nm. The mean power of the supercontinuum is greater than 1.5 W. The simulation of such a generator yields the integrity of the supercontinuum pulse on the nanosecond time scale and shows that the pulse can be characterized by a certain energy in contrast to the multipulse complicated trains of supercontinuum corresponding to the femtosecond and picosecond pumping.

DOI: 10.1134/S1054660X10040080

INTRODUCTION

Modern supercontinuum (SC) generators are employed in various applications: metrology of optical frequencies, telecommunication, spectroscopy, biomedicine, etc. [1]. One of the topical aspects in the study of the SC generation involves the extension of the range of parameters characterizing the broadband optical SC radiation needed for various applications. This problem is closely related to the problem of the creation of a generator with record-high parameters (maximum spectral width, maximum uniformity of the power spectral density, minimum noise level, maximum pulse-to-pulse coherence, maximum power spectral density, maximum power, etc.) [2]. The purpose of this work is the creation of the broadband pulse SC generator with a relatively high pulse energy.

One of the most evident approaches to the generation of the high-energy SC pulses is based on an increase in the peak power of the pumping pulses (e.g., owing to the application of several amplification stages). Note that the spectral broadening increases with an increase in the pumping power, since the SC generation results from the simultaneous action of several nonlinear optical effects. However, the corresponding energy loss due to the stimulated Raman scattering and the linear loss related to the propagation in optical fiber also increase. Thus, the output SC power is saturated at relatively high pumping powers, so that a further increase in the pumping power does not lead to an increase in the SC power [3]. Therefore, an alternative approach is needed for the further increase in the SC pulse energy. Such an approach must involve an increase in the pump pulse duration rather than an increase in the peak power. In this work, we implement this approach using an ultralong all-fiber all-positive-dispersion laser (the corresponding prototype can be found in [4]).

EXPERIMENT

Figure 1 demonstrates the scheme of the ultralong all-fiber ring laser. The Yb fiber that is free of the linear birefringence and that is cladding-pumped with the aid of a multimode coreless fiber serves as the active medium [5]. The length of the Yb-doped active fiber is 10 m, and the core diameter is 7 μm. The active fiber is pumped by a multimode diode laser with an output power of up to 1.5 W at a wavelength of 980 nm. The mode-locking results from nonlinear polarization evolution [6–8]. An increase in the cavity length using an SMF-28 fiber leads to a decrease in the pulse repetition rate and, hence, an increase in the pulse energy at the same mean power.

The laser makes it possible to generate pulses with a duration of 10 ns and an energy of 4 μJ at a repetition rate of 37 kHz. The mean output power (150 mW) is limited by the working range of the fiber polarization splitter that provides the outcoupling of radiation. The FWHM of the pulse spectrum is 0.5 nm, and the corresponding duration of the bandwidth-limited pulse is 2 ps. This circumstance indicates the gigantic chirp of the generated 10-ns pulses. Note that the single-pass dispersion broadening of the 2-ps bandwidth-limited pulse resulting in the 10-ns pulse is possible in the SMF-28 fiber with a length of about 500 km. In the laser, the significant pulse broadening is reached at a substantially smaller cavity length (8 km). The compression of the 10-ns pulses will make it possible to control the pulse duration and peak power and, hence, the efficiency of the SC generation and the SC spectral width. Using a variation in such an additional parameter, we will be able to independently vary the spectral width and the power (or power spectral density) of the SC pulses.

For a further increase in the pump-pulse energy, we employ an additional amplification stage based on the cladding-pumped Yb-doped fiber [5]. The energy of

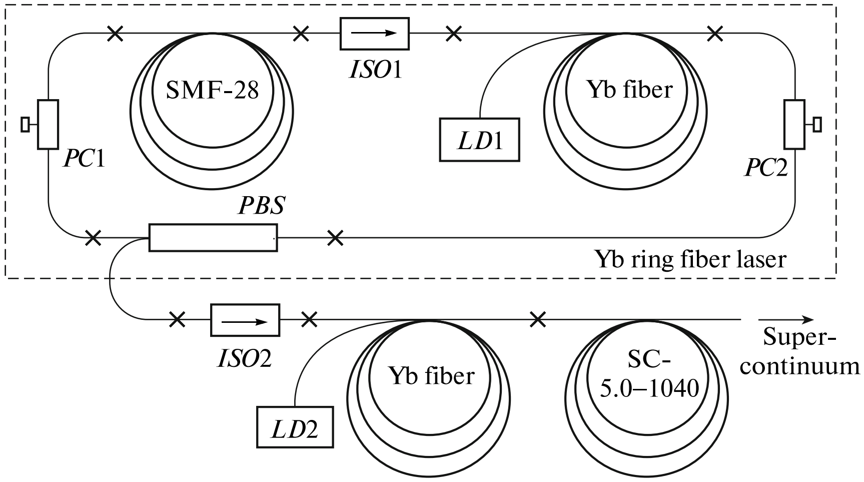

Fig. 1. Scheme of the all-fiber SC generator: *LD*1 and *LD*2 pumping laser diodes, *PC*1 and *PC*2 fiber polarization controllers, *ISO*1 and *ISO*2 polarization-insensitive optical isolators, and *PBS* fiber polarization beam splitter.

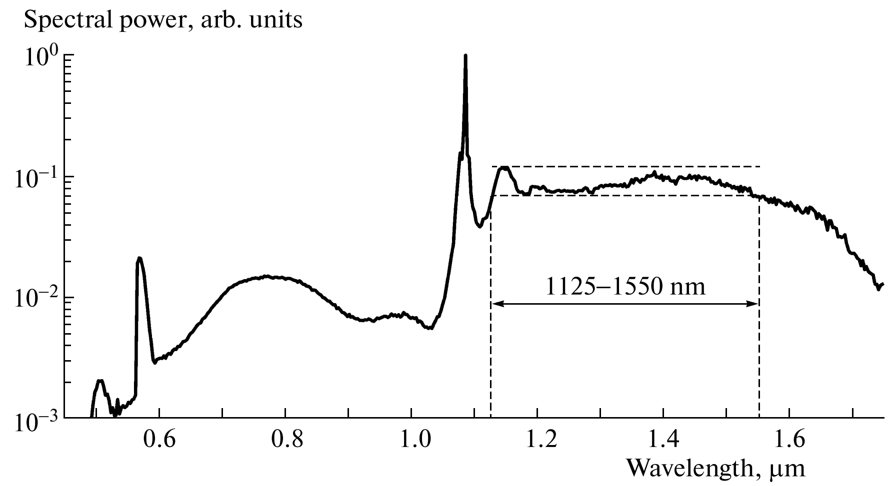

Fig. 2. Spectrum of the high-energy SC.

the amplified pulses is 80 μJ, and the mean power of the amplified radiation is 3 W (the pulse duration (10 ns) remains unchanged). The amplified pulses are fed to a segment of the SC-5.0-1040 microstructured fiber with a length of 30 m, where the SC radiation is generated in the spectral range 500–1750 nm. (Note that the measurements at the long-wavelength boundary are limited by the optical spectrum analyzer.) The spectrum of the SC radiation at the exit of the fiber exhibits a high-intensity peak in the vicinity of the pumping wavelength, which is also typical of the SC in the case of the cw pumping [9]. The presence of such a peak is related to an extremely high probability of the generation of low-energy solitons upon the decay of the continuous wave or the long pumping pulse owing to the modulation instability (note the *L*-shaped distribution of solitons with respect to energy [10]). The self-frequency shift is not observed for the low-energy solitons with a relatively low peak power. Therefore, a significant fraction of the input energy remains unconverted and the spectral peak emerges in the vicinity of the pumping wavelength. Another feature of the SC spectrum (Fig. 2) that is important for several practical applications is the presence of the wide plateau in the spectral interval 1125–1550 nm. In this interval, the SC power spectral density is varied by no greater than 1 dB.

In the above regime of the SC generation using nanosecond pumping pulses, the time structure of the output pulses is retained on the pulse time scale in contrast to the generation regime using femtosecond and picosecond pumping. Indeed, the SC generation under the femtosecond pumping in the range of the anomalous dispersion is initiated by the decay of input

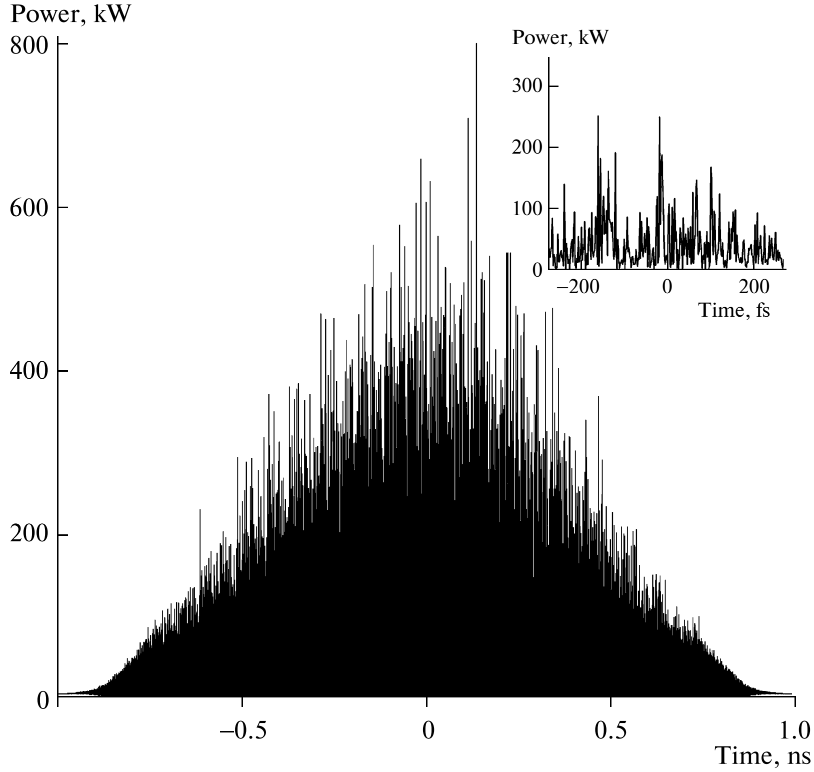

Fig. 3. Numerically simulated plot of the SC radiation intensity vs. time. The inset shows a fragment of the time distribution on a larger scale.

pulses to a series of solitons whose durations also belong to the femtosecond range [11]. In the course of the subsequent spectral broadening, the solitons are spread in time and give rise to a wave packet with a complicated time structure, such that the duration of the wave packet can be greater than the duration of the femtosecond pumping pulses by a factor of several tens. In the case of the picosecond pumping pulses, the initial stage of the SC generation is characterized by the development of the modulation instability, so that the picosecond pumping pulses decay into a stochastic series of subpulses (solitons) [11], whose duration (10–100 fs) depends on the pumping power and the dispersion of fiber. As in the case of the femtosecond pumping, the propagation of the soliton subpulses along the fiber is accompanied by the time spread owing to the group-velocity dispersion. The duration of the resulting wave packet of the SC radiation can be several times greater than the duration of the picosecond pumping pulses. Similar processes induced by the modulation instability and the decay of the excitation pulses to the soliton subpulses correspond to the SC generation in the presence of the nanosecond pumping. In contrast to the femtosecond and picosecond scenarios, the pulse duration at the entrance of the fiber is significantly greater than the characteristic spread of the SC soliton components, so that the duration of the SC wave packets at the exit of the fiber is almost the same as the duration of the pumping pulses. Figure 3 provides an illustration and presents the numerically simulated results based on the solution to the generalized nonlinear Schrödinger equation for the pumping pulse with a duration of 1 ns and an energy of 50 μJ in the SC-5.0-1040 microstructured fiber with a length of 30 cm. To reduce the computational time, we employ the pump-pulse duration and the fiber length that are less than the corresponding experimental parameters. It is seen that the SC radiation at the exit of the fiber represents a complicated wave packet that contains a large number of subpulses (optical solitons) (see inset to Fig. 3). The duration of such solitons is 10 fs, and the peak power is higher than the peak power of the pumping pulses by no less than an order of magnitude. In the course of propagation, the positions of solitons inside the wave packet are varied owing to the dispersion of fiber but the characteristic scale of such variations is tens of picoseconds and the duration of the nanosecond wave packet is retained in general. In the experimental measurements of the time distribution of the intensity, single solitons are not resolved and we measure the power averaged over a large number of solitons. Note that the averaging of the soliton spectra [9] yields a wide smooth SC spectrum in the experiments. The numerical simulation shows that the time-averaged power is weakly varied upon the spectral broadening, so that the shape of the nanosecond pulse remains almost unchanged upon the SC generation.

CONCLUSIONS

An all-fiber SC generator with the working range 500–1750 nm makes it possible to generate 10-ns SC pulses with an energy of 40 μJ at a repetition rate of 37 kHz and a mean power of 1.5 W. The simulation of such a generator shows that the integrity of the SC pulse is retained on the nanosecond time scale and that the SC pulse can be characterized by a certain energy in contrast to the multipulse complicated trains of the SC under the femtosecond and picosecond pumping. The compression of the highly chirped 10-ns pumping pulses will provide an additional variable parameter for the control of the SC characteristics [12].

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