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High-Energy Q-Switched Fiber Laser Based on the Side-Pumped Active Fiber

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Abstract—A relatively simple fiber-laser system that is based on a dual fiber, is pumped by a single CW source with an output power of 12 W (976 nm), and provides an output pulse energy of up to 110 μJ at a wavelength of 1080 nm is demonstrated for the first time. The output-pulse repetition rate and duration can be varied in the ranges 45–140 kHz and 0.28–1.80 μs, respectively, with a variation in the pumping power. The maximum output power is 5 W. It is demonstrated that the generation instability observed at an output power of greater than 5 W gives rise to giant pulses that can induce the supercontinuum generation in the range 530–1750 nm in a relatively short microstructured fiber.

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INTRODUCTION

Lasers with a relatively high pulse energy (no less than hundreds of microjoules) are widely used in various applications. Multiple sources are based on solid-state lasers (Nd:YAG/YVO_4, Yb:YAG, Nd:YLF, etc.) [1, 2], and some of them employ hybrid solid-state–fiber technologies [3]. However, alternative sources are developed based on fiber lasers [4–9]. Relatively high pulse energies are normally reached in such systems using the master oscillator–power amplifier design. Note that different sources are used to pump the master oscillator and the amplifier in all-fiber systems. This is due to the fact that fiber beamsplitters cannot work at relatively high radiation powers and, hence, cannot deliver a relatively small part of the high-power pumping radiation to the master oscillator. Therefore, a conventional fiber master oscillator contains a low-power pumping source and the amplifier is pumped by one or several high-power sources [9].

In the systems with dual fibers (one of the fibers is active [8]), the active fiber can be easily and effectively side-pumped through a conventional passive quartz fiber. The pumping radiation is delivered to the cladding of the active fiber from the cladding of the passive fiber through the optical contact of these fibers along the entire fiber length. At a normal concentration of, for example, Yb ions in the active fiber and a fiber length of 20–25 m, about 90% of the double-sided pumping radiation from the passive fiber must be absorbed in the active fiber. When the length of the active fiber becomes smaller than the optimal length, corresponding to the 90% absorption of the pumping radiation, one can employ excess pumping in the amplifying stage (or several amplifying stages) of the system. In this regard, the master oscillator can be constructed using a short dual fiber and the pumping radiation that is not absorbed in the master oscillator can be delivered to a similar dual fiber of one or several amplifiers.

Such a system based on a passively Q-switched fiber laser is proposed for the first time and is experimentally tested in this work.

EXPERIMENT

Figure 1 demonstrates the scheme of the experimental setup. The master oscillator is based on a dual (Yb–quartz) fiber with a length of 3 or 5 m and an active core diameter of 7 μm. The radiation is delivered to and outcoupled from the active fiber using a microobjective. The laser is passively Q-switched due to the mirror with the saturable semiconductor absorber. The radiation is delivered to this mirror by a lens with a focal length of 100 mm. A polarizing beamsplitting cube serves as the output laser mirror and provides the linear polarization of the output radiation. The orthogonally polarized beam reflected by the beamsplitter is backreflected to the cavity by a highly reflective mirror. Using the polarization element as the output mirror, we obtain the linearly polarized output radiation.

Figure 2 shows a characteristic pulse generated by the system. It is seen that the main pulse is modulated by high-frequency satellites with relatively low amplitudes and that the time interval between the neighboring pulses of the high-frequency structure corresponds to the cavity roundtrip time (38 ns for the master oscillator with a cavity length of about 5 m). The satellite pulse duration is no greater than 10 ns, and the presence of these satellites indicates the initial stage of the mode locking. However, the mode locking was not fully implemented in the configuration under study.

The passively Q-switched operation of the laser is stable in the entire range (up to 200 mW) of the output

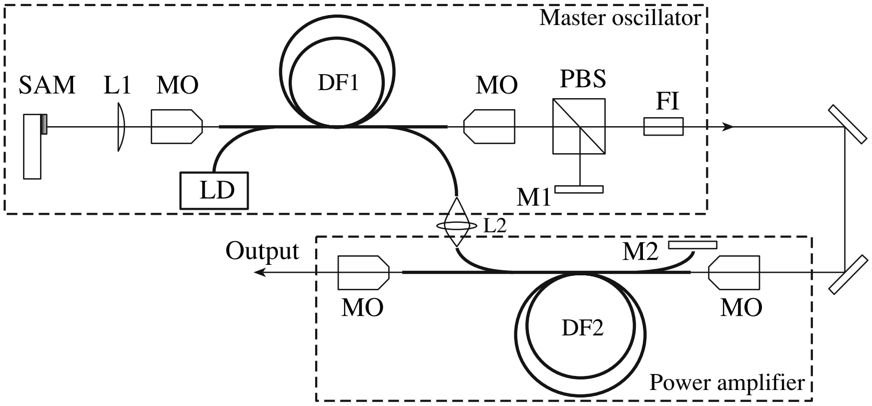

Fig. 1. Scheme of the dual-fiber laser: LD, pumping laser diode; DF1 and DF2, dual fibers; MO, microobjective; PBS, polarizing beamsplitter; M1, highly reflective mirror for the radiation of the master oscillator; M2, highly reflective mirror for the pumping radiation; FI, Faraday isolator; L1 and L2, focusing lenses; and SAM, saturable-absorber mirror.

powers of the master oscillator. Note that a variation in the output power is accompanied by variations in the pulse repetition rate and duration. Figure 3 demonstrates the dependences of these parameters on the output power of the master oscillator. The pulse duration is varied from 1.8 μs to 280 ns at the maximum output power, and the pulse repetition rate ranges from 45 to 140 kHz. The master oscillator (and the system as a whole) is pumped by a diode laser with a radiation wavelength of 980 nm and a power of 12 W. A small part of the pumping radiation (~2–3 W) is absorbed in the master oscillator owing to its shortened length, whereas the remaining part of the pumping radiation is delivered to the passive part of the dual fiber that serves as the amplifier. The output radiation of the master oscillator is delivered to the active fiber of the amplifier using the microobjective. The mean output power of the amplifier amounts to 5 W, so that the output pulse energies are 36 and 110 μJ at the maximum (140 kHz) and minimum (45 kHz) repetition rates, respectively.

When the mean output power exceeds 5 W, we observe an instability of the laser system caused by the incomplete optical isolation of the master oscillator and the amplifier. The input/output end faces of the fibers are cut at an angle of 90°, which gives rise to the feedback from the amplifier at a relatively high radiation power and in the presence of a single-stage Faraday isolator. In this case, irregular high-power (giant) pulses are observed in the pulse train. The time distribution of the radiation intensity typical of the unstable generation is presented in Fig. 4. The time distribution of the intensity of the high-power irregular pulses differs from the distribution of the pulse intensity corresponding to the stationary regime by an increased amplitude of the satellite high-frequency spikes at the top of the pulse.

The giant pulses generated in the unstable regime are characterized by a significantly higher peak power and a decrease in the pulse duration. The experimental results show that the giant pulses can induce the supercontinuum generation in the microstructured fiber with a length of only 3 m. Figure 5 shows the spectrum of the generated supercontinuum. The spectral width is greater than 1200 nm (530–1750 nm). Note that the long-wavelength wing of the supercontinuum spectrum is extended to wavelengths of greater than 1750 nm. We fail to measure the corresponding spectral components due to the limited spectral range of the optical spectrum analyzer.

When the mean power of the output radiation is less than 5 W, we observe the stable pulse generation in the entire range of the radiation powers. The radiation having passed through the amplifier preserves its polarization state although the amplifier is based on a nonpolarization-maintaining active fiber. Nevertheless, the output radiation of the amplifier is linearly polarized,

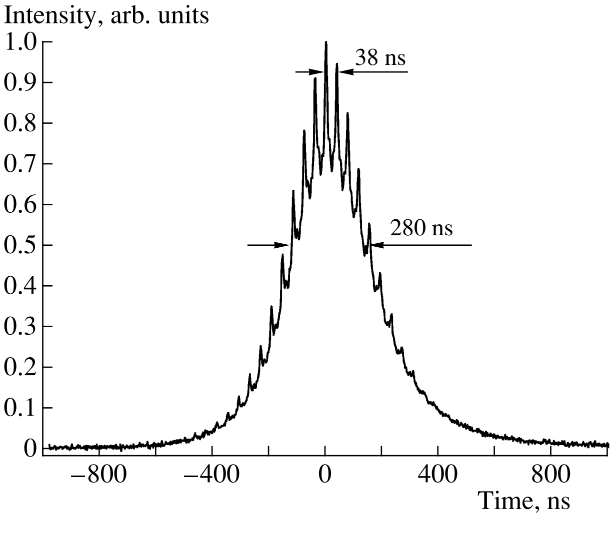

Fig. 2 Output pulse of the laser system with a satellite-pulse period of 38 ns.

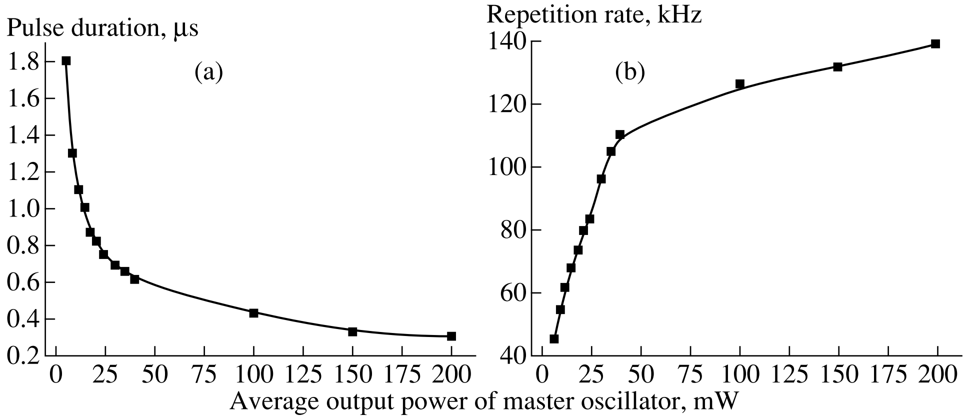

Fig. 3. Plots of the output-pulse (a) duration and (b) repetition rate vs. the output power of the master oscillator.

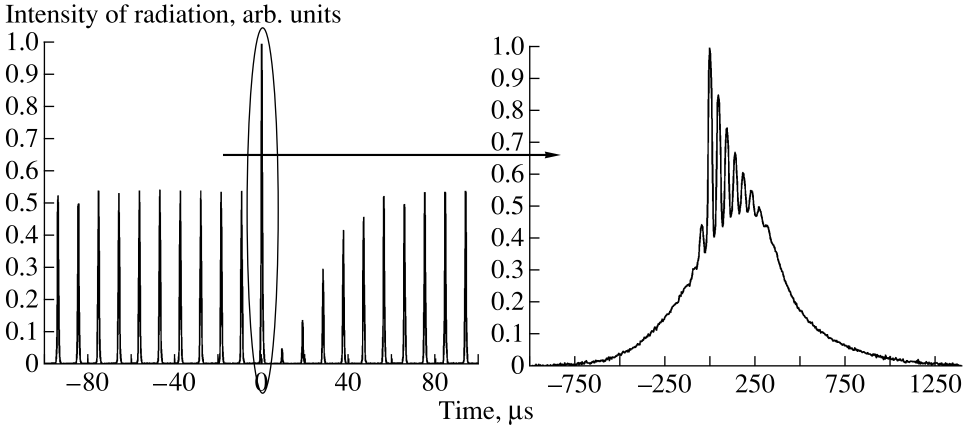

Fig. 4. Time distribution of the radiation intensity for the unstable lasing that emerges due to the feedback existing between the master oscillator and the amplifier at a relatively high pumping power.

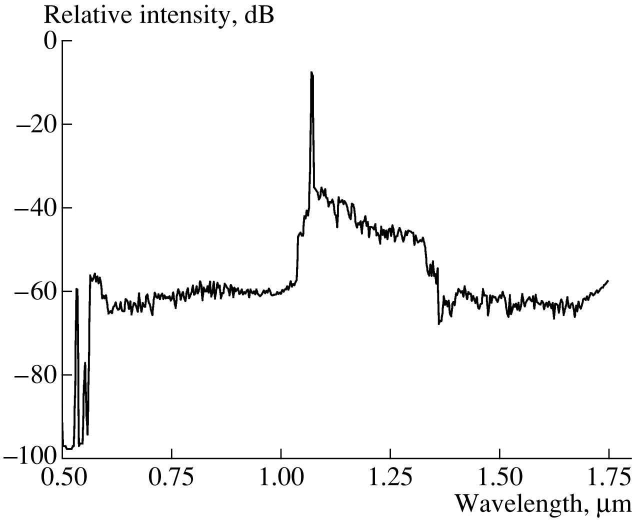

Fig. 5. The spectrum of supercontinuum that is generated in a 3-m-long SC-5.0-1040 microstructured fiber pumped by the giant pulses generated in the unstable regime.

which opens the prospects for the further nonlinear spectral conversion of the laser radiation.

CONCLUSIONS

For the first time, we experimentally demonstrate the possibility of a relatively simple Q-switched fiber laser system (with an output pulse energy of up to 110 μJ at a wavelength of 1080 nm) that is pumped by a single CW source with a power of 12 W and a wavelength of 980 nm. The duration and repetition rate of the generated pulses depend on the pumping power and can range from 280 ns to 1.8 μs and from 45 to 140 kHz, respectively. The maximum mean output power is 5 W. Note that the mean output power (and the pulse energy) of the laser system can easily be increased in the presence of a Faraday isolator that isolates the master oscillator from the amplifier and provides for a better suppression of the backward radiation.

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