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Spectral Broadening of Femtosecond Pulses in an Nonlinear Optical Fiber Amplifier

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Abstract—A promising method for the generation of a supercontinuum with a high spectral power density based on the spectral broadening of ultrashort pulses in a fiber amplifier is considered. The advantage of the method, as compared to the conventional way of the supercontinuum generation in a microstructure fiber, is a lower pulse spectral broadening rate, which allows one to achieve higher SC spectral power densities. The initial stage of the supercontinuum generation in an ytterbium fiber amplifier (a fiber core diameter of 7 μm) with side pumping from an array of laser diodes with a total power of 8 W at a wavelength of 976 nm is experimentally studied. Yb:KYW laser pulses with a duration of 250 fs, a central wavelength of 1046 nm, and an average power of 150 mW have been supplied to the input of the amplifier. In this case spectrally broadened radiation with an average spectral power density of higher than 65 mW/nm and a spectrum width of 50 nm has been obtained.

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INTRODUCTION

The propagation of ultrashort light pulses in nonlinear optical fibers may result in a considerable broadening of their spectrum and the generation of a continuum (or a supercontinuum) in the spectral region that exceeds one to three spectral octaves [1–5]. At the initial stage of the spectrum broadening, the spectral power density of the radiation at the output of the nonlinear fiber depends almost linearly on the peak radiation power of pump pulses; however, as the peak radiation power of pump pulses further increases, the growth of the spectral power density of the radiation at the output of the nonlinear fiber noticeably slows down due to radiation losses in the ultraviolet and infrared spectral regions, which is caused by increasing radiation absorption in the fiber and due to stimulated Raman scattering. In this relation, methods of relatively slow broadening of the radiation spectrum of ultrashort pump pulses with increasing their peak radiation power are of interest for achieving an increased spectral power density of the broadband radiation. It is shown in this paper that one of these promising methods is the spectral broadening of femtosecond pulses in a nonlinear optical fiber amplifier. A similar nonlinear regime of the amplification of radiation pulses with a duration of 20–40 ns was observed in [6].

EXPERIMENT

The schematic diagram of the experimental setup is shown in Fig. 1. A Femto-Star Yb:KYW femtosecond laser (from Technoscan) was used as a source of pumping radiation. The average power of the laser output radiation was 400 mW at a wavelength of 1046 nm, the pulse duration did not exceed 250 fs for a radiation spectrum width of 8.5 nm (Fig. 2) and a repetition rate of ~100 MHz.

The fiber amplifier based on double-clad fiber (GTWave technology [7]) was used for the laser radiation amplification. This amplifier consists of two fibers in optical contact along the whole length. One of the fibers is active (in this case, it was an ytterbium-doped fiber) and the second fiber is passive (common quartz fiber, for example, SMF-28). The diameter of the light guiding core of the active fiber makes 7 μm, the shell diameter was 125 μm. The length of the fiber amplifier was 12 m.

Laser radiation was input into the fiber amplifier via a Faraday insulator, a micro-objective, and an auxiliary SMF-28 light guide with a length of 0.5 m, which was welded with the active fiber of the amplifier. The average radiation power at the input of the SMF-28 light guide was 150 mW. The amplifier was pumped via the passive light guide using a diode laser with a radiation power of 8 W at a wavelength of 976 nm. The pumping was performed using the counter scheme; i.e., the direction of propagation of the pumping radiation in the fiber was opposite to that of the amplified radiation. The nonabsorbed pumping

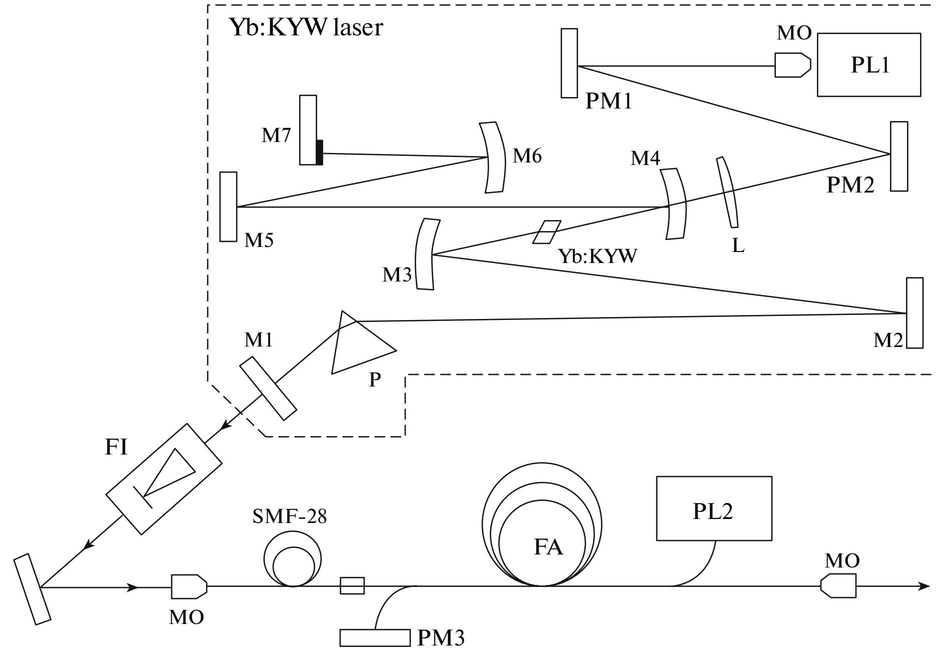

Fig. 1. Schematic diagram of experimental setup: PL1, PL2 are the pumping diode lasers; PM1–PM3 are the mirrors reflecting pumping radiation; M1–M7 are the Yb:KYW laser mirrors; L is the focusing lens; P is the prism; MO is the micro-objective; FI is the Faraday isolator; FA is the fiber amplifier; and SMF-28 is the quartz fiber.

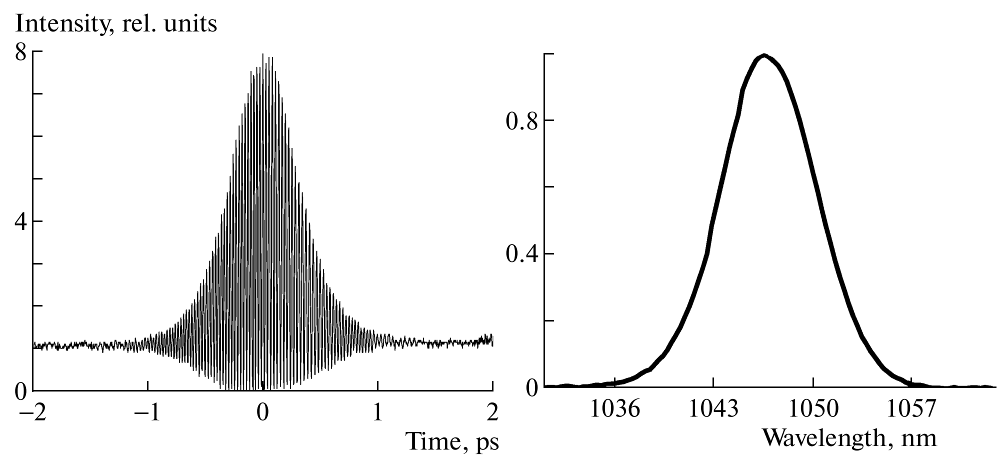

Fig. 2. (left) Interference autocorrelation function of laser radiation pulses; (right) laser radiation spectrum.

radiation (~1.5 W) leaving the passive fiber was returned back into the fiber with the help of a reflecting mirror (PM3 in Fig. 1). The reflecting mirror was placed close to the edge of the passive light guide with a gap of 0.1–0.05 mm. The maximal average power of the amplified radiation reached 3.4 W. It should be noted that, in our experiment, the amplifier operated in the short-wavelength wing of the spectral amplification band, since the maximum of amplification was achieved at wavelengths near 1075–1080 nm [8]. This explains the moderate (42.5%) efficiency of the applied fiber amplifier.

If the linear optical fiber amplifier is used, the spectrum of the amplified radiation repeats the spectrum of the generating radiation. In our experiment, due to the relatively small transverse size of the amplifying fiber core (a diameter of 7 μm), the fiber amplifier operated in the nonlinear regime, since it not only amplified the generating radiation, but also broadened its spectrum. The spectra of the output radiation in relation to the average power are shown in Fig. 3. If the average power of output radiation increases from 50 mW to a maximal value of 3.4 W, the radiation spectrum width at the output of the amplifier increased from 8.5 nm (the radiation spectrum width

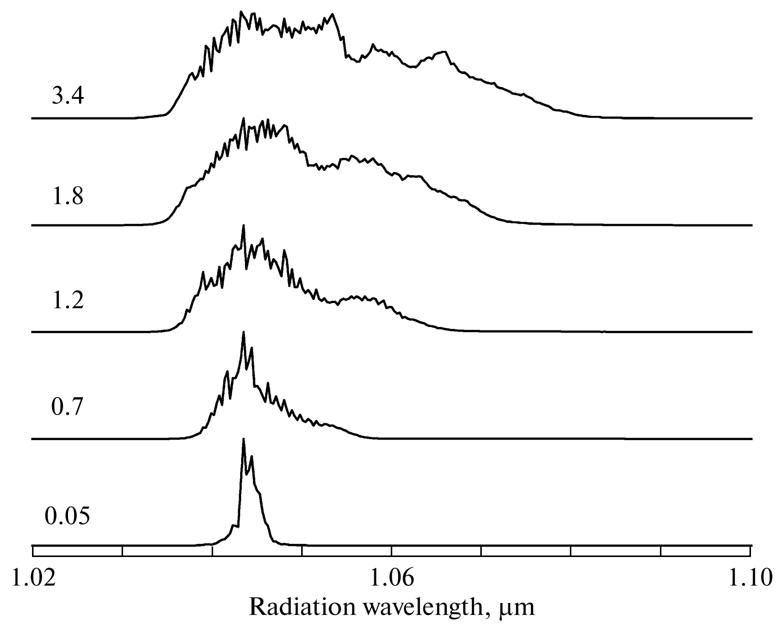

Fig. 3. Radiation spectra at the output of the nonlinear optical fiber amplifier for an average output radiation power of 0.05, 0.7, 1.2, 1.8, and 3.4 W.

of the master oscillator) up to 50 nm. The rate of the broadening of the spectrum of the amplified radiation was 12.4 nm/W. The spectrum broadening rate for the radiation of femtosecond pulses in the nonlinear optical fiber amplifier obtained in this experiment is considerably lower (by 1–2 orders of magnitude) than the spectrum broadening rate for ultrashort light pulses in microstructure or oblong fibers. The relatively low spectral broadening rate of radiation in the nonlinear amplifier allows one to achieve high radiation spectral density which considerably exceeds the spectral density of the supercontinuum at the output of microstructure or tapered fibers [9, 10].

CONCLUSIONS

In this work, the spectral broadening of femtosecond pulses of a Yb:KYW laser with a central wavelength of 1046 nm in the ytterbium amplifier operating in the nonlinear regime was studied. For the average power of amplified radiation, the rate of the broadening of the radiation spectrum of pump pulses was 12.4 nm/W. For a maximal average power of the amplified radiation, 3.4 W, the spectrum width of the amplified radiation exceeded 50 nm, and the average radiation spectral power density was higher than 65 mW/nm. It should be noted that the average radiation spectral power density at the output of the nonlinear optical fiber amplifier considerably exceeds the similar parameter of the supercontinuum in microstructure or tapered fibers, which usually does not exceed 4–5 mW/nm. Thus, nonlinear optical fiber amplifiers are quite promising for obtaining spectrally broadened radiation with a considerably higher spectral power density.

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