Compact all-fiber high-energy fiber laser with sub-300-fs duration

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Abstract: We report a compact all-fiber high-energy fiber laser that consists of a laser oscillator and a compression section. The laser oscillator generates the pulses with high energy and large chirp. The compression section is made of a piece of standard single-mode fiber that dechirps the chirped pulses. The compact all-fiber fiber laser produces pulses with 8 nJ of the pulse energy and 290 fs of the pulse duration.

OCIS codes: (140.3500) Lasers, erbium; (060.5530) Pulse propagation and temporal solitons; (140.4050) Mode-locked lasers.

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1. Introduction

Fiber lasers have attracted extensive attention because of their simple design, low cost, high stability, and low alignment sensitivity [1–5]. Mode locking technique is the standard method of achieving short pulses from a fiber laser. The first all-fiber ring cavity to produce stable subpicosecond pulses was achieved by using the passive mode-locking technique of polarization additive pulse mode-locking (P-APM) [6,7]. Based on this kind of cavity design, fiber lasers emit chirp-free pulses with the secant-hyperbolic shape due to the balance between the fiber nonlinearity (i.e., self-phase modulation) and the fiber linear dispersion (i.e., GVD). This type of fiber lasers based on the balance of (positive) nonlinear and (negative) dispersive phase shifts typically generates relatively low-energy pulses (~10 pJ to 100 pJ) of picosecond duration (~0.5 ps to 1 ps). Usually, the pulse energy is limited to 0.1 nJ in standard single-mode fiber (SMF) by the soliton area theorem [7,8]. Although Yoshida *et al.* achieved a erbium-doped fiber (EDF) laser with pulse duration of 52 fs by using soliton narrowing and high order soliton compression, the pulse energy of their laser was very low (<0.01 nJ) [9].

To achieve higher energy pulses, EDF amplifier was employed to amplify the 250-fs seed pulses by using four 1480-nm pumps [10]. Although the pulse energy was increased to 8.7 nJ, it is obvious that the high-energy pulse was obtained by the combination of EDF laser and EDF amplifier (i.e., the system consists of a laser and a amplifier). Then this laser system becomes much expensive and less convenient for practical applications. Moreover, passively mode-locked fiber lasers based on large-mode-area fibers (e.g., photonic-crystal fiber (PCF) [11–13]), double-clad gain fibers [5,14], and other components [15,16] were proposed. Unfortunately, these kinds of lasers are not the all-fiber structure because some separate elements (e.g., dichroic mirrors and/or gratings) have to be added into the laser cavity. As a result, the cost of lasers is increased, and the stability is deteriorated because the laser cavity is susceptible to misalignment.

Recently, the parabolic-pulse laser [17], all-normal-dispersion laser [18,19], and dissipative laser [5] were proposed to generate high-energy pulses. Even, Pulses with energy of >20 nJ and duration of <200 fs had been achieved in an all-normal-dispersion fiber laser [20]. However, most of them were based on the Yb-doped fibers. These lasers emit large chirped pulses. The chirped pulses have to be dechirped with an additional external system [5,17,18,20], because the standard SMF does not compress these pulses with ~1 μm. In addition, although a laser oscillator delivering pulses with energies up to 10 nJ at 1.64 μm was achieved by using the pump source of Raman fiber laser, the pulse formation is subject to intrapulse Raman-scattering [21]. The pump efficiency is very low, and the laser cavity is not an all-fiber structure so that the stability is deteriorated.

The theoretical and experimental results show that the mode-locked fiber lasers are expected to generate high-energy pulses when they have longer cavity length [3,22] and larger net cavity GVD [18]. Taking into account the fact that the standard SMF has the capacity of compressing the pulses with ~1.55 μm, we have proposed a compact all-fiber mode-locking EDF laser with 25.5 m of cavity length and 0.8 ps^2 of net cavity GVD. The proposed laser generates the pulses with 8 nJ of the pulse energy and 290 fs of the pulse duration. We believe that the proposed laser with the simple design, high stability, ultrashort pulse, and high pulse-energy will have important applications.

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2. Experimental setup and operation principle

The proposed all-fiber laser system is shown schematically in Fig. 1. It consists of a laser oscillator and a compression section. The laser oscillator is made of a polarization-sensitive isolator, two sets of polarization controllers, a wavelength-division-multiplexed coupler, a 18-m-long EDF with absorption 6 dB/m at 980 nm, and a fused coupler with 70% output. The polarization-sensitive isolator, which provides unidirectional operation and polarization selectivity in a ring-cavity configuration, together with two polarization controllers form a P-APM system. The EDF has a dispersion parameter of about 54×10^{-3} ps^2/m at 1550 nm. A 977-nm laser diode provides the pump power for laser system. The polarization state of waves in the laser cavity can be controlled by adjusting two polarization controllers. The compression section is the standard SMF with the anomalous dispersion of about -22×10^{-3} ps^2/m and a length of about 80 m.

Because the total length of laser oscillator is 25.5 m with the net cavity GVD of about 0.8 ps^2, pulses that can exist at large positive net-cavity-dispersion rely on the dissipative processes. Then the proposed laser oscillator would presumably have to exploit dissipative processes in the mode-locked pulse shaping, and it emits pulses that can be considered as dissipative solitons [8]. Since the laser oscillator has the strong normal GVD, it generates the pulses with high energy and large chirp. Pulses are output via a fused coupler, and launched into a compression section that is made of a piece of standard SMF. Then the chirped pulses are dechirped to chirp-free pulses with sub-300-fs duration.

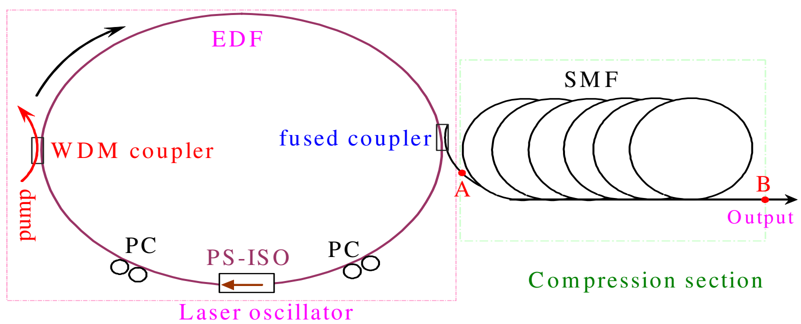

Fig. 1. Schematic diagram of the experimental setup for compact all-fiber high-energy fiber laser. PC: polarization controller; PS-ISO: polarization-sensitive isolator; WDM: wavelength-division-multiplexed; SMF: single-mode fiber; EDF: erbium-doped fiber.

3. Experimental results and discussions

The P-APM mode-locking technique is used to generate stable, self-starting, high-energy, sub-300-fs pulses at the fundamental repetition rate from a unidirectional fiber ring laser. By appropriately adjusting two polarization controllers of the laser oscillator, self-started mode locking of the laser can be achieved when the pump power is beyond a threshold value ~70 mW. After mode locking, the laser generates stable pulses with the fundamental cavity repetition rate ~8.2 MHz. The oscilloscope trace and the radio-frequency (RF) spectrum are shown in Figs. 2(a) and 2(b), respectively.

When the pump power is a range of ~70 mw to ~150 mW, the proposed laser operates on the single-pulse state. Figures 3 and 4 show the optical spectrum and the autocorrelation trace of pulse emitted from the laser oscillator (i.e., before the compression) at pump power of ~125 mW, respectively. We can observe from Fig. 3 that the optical spectrum of pulses has steep spectral edges with about 18 nm of the edge-to-edge width. Figure 4 shows that the autocorrelation trace has a full width at half maximum (FWHM) of about 32.6 ps. If a Gaussian pulse profile is assumed, the pulse width is about 23.1 ps. Therefore the pulse is strongly chirped.

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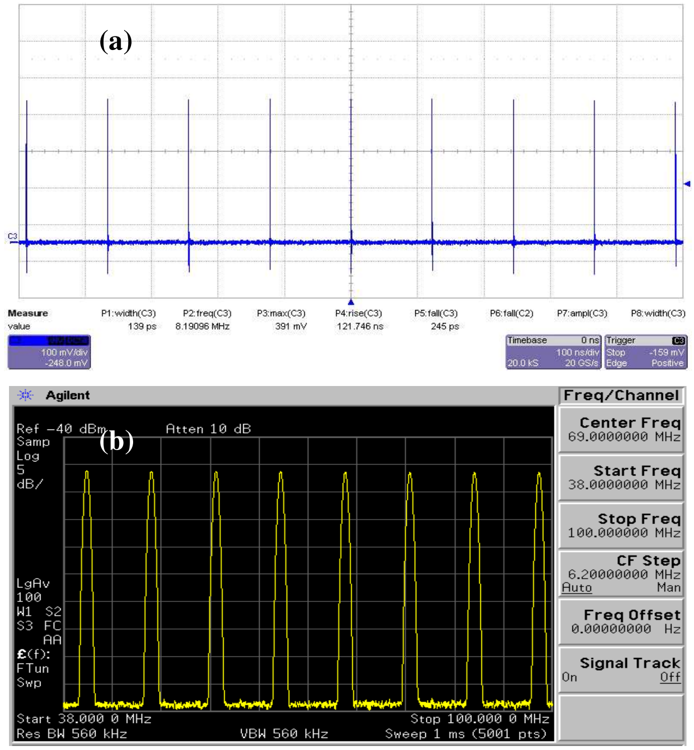

Fig. 2. (a) Oscilloscope trace and (b) RF spectrum at the fundamental cavity repetition rate.

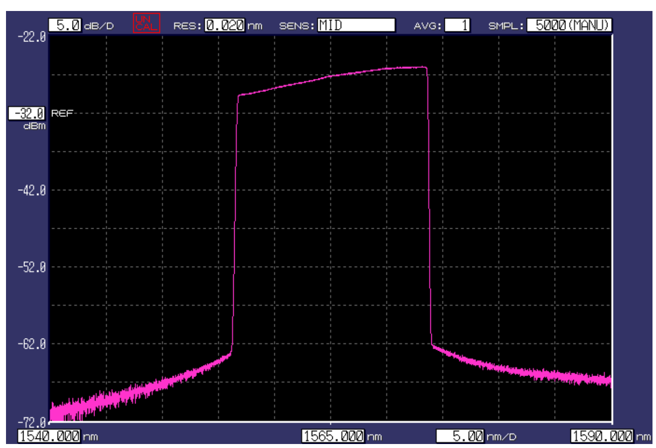

Fig. 3. Optical spectra of pulses.

After the compression section (Fig. 1), the chirped pulses are dechirped to the chirp-free pulses. In experiments, the length of SMF in compression section is gradually shortened from 300 m to 20 m in order to achieve the best compression for pulses. Experiment results show that the best length of SMF in our laser is about 80 m in this state. The autocorrelation trace of pulses after the best compression is shown in Fig. 5. One can see from Fig. 5 that the autocorrelation trace has a FWHM of about 0.4 ps. On the assumption of a Gaussian pulse profile, the chirp-free pulses have about 290 fs of the pulse duration. We can observe from Fig. 5 that the small satellites exist on the dechirped pulse and they contain about 7% of pulse energy. The satellites result from the nonlinear chirp of the pulse edges. Note that both the

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chirp and the spectral width of pulse determine the length of SMF in compression section, and the larger net cavity dispersion and the narrower spectral width, the longer SMF for the best compression.

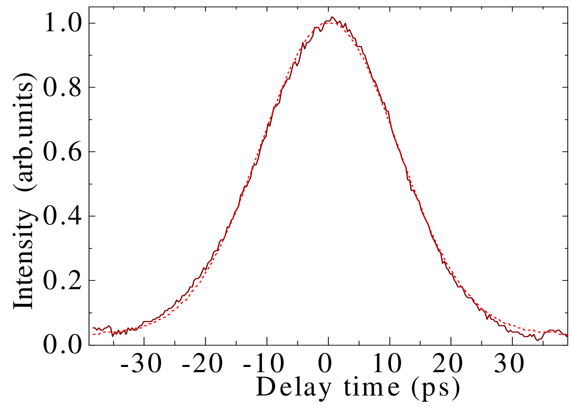

Fig. 4. Autocorrelation trace of pulses before the compression. The experimental results are measured at port A in Fig. 1. The solid and dashed curves denote the experimental results and the Gauss-fit curve, respectively.

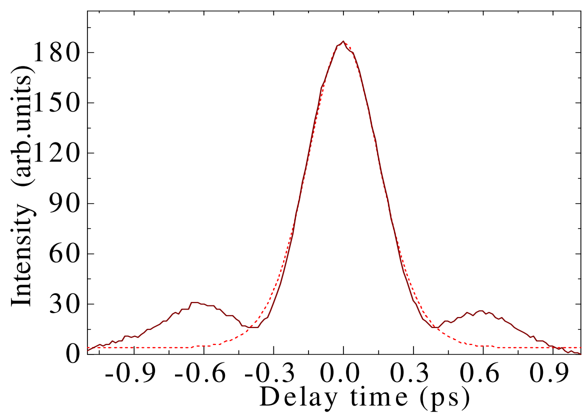

Fig. 5. Autocorrelation trace of pulses after the compression. The experimental results are measured at port B in Fig. 1. The solid and dashed curves denote the experimental results and the Gauss-fit curve, respectively.

Figure 6 shows the pulse energy as a function of the pump power. The experimental results show that the average power of pulse for our fiber laser can be up to ~65 mW, corresponding to about 8 nJ of the pulse energy, under the pump power of ~125 mW. The proposed laser will operate on the multi-pulse state when the pump power is more than ~150 mW. Usually, the spectral filtering and/or the overdrive of nonlinear polarization (NP) effect may play essential roles in the multiple pulse formation in the large-normal-dispersion fiber lasers [2,8]. The spectral and temporal widths of pulses become narrower once an additional pulse is generated, and then they are increased with the increase of pump power. The experimental observations show that, with the appropriate setting of two polarization controllers, the soliton breakup effect can be sufficiently eliminated. As it happens, however, the pulses are difficult to be compressed to be less than 1 ps.

Apparently, the pulse energy of our laser is over 80 times higher than that of the conventional fiber soliton lasers, which is limited to 0.1 nJ [8]. As a result, our fiber laser has the capacity of generating ulstrashort high-energy pulses without the chirped pulse amplification (CPA) technique that is extensively used in conventional high-energy laser system [22,23]. Because the proposed fiber laser has the compact all-fiber configuration, both

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long-term stability and short-term stability are excellent and hence the 8-nJ, sub-300-fs pulsed laser can find important applications on commercially available components. Experimental results show that our laser can stably operate with little fluctuations for several days, and it can effectively withstand the environmental effects such as mechanical perturbation and moderate temperature variations.

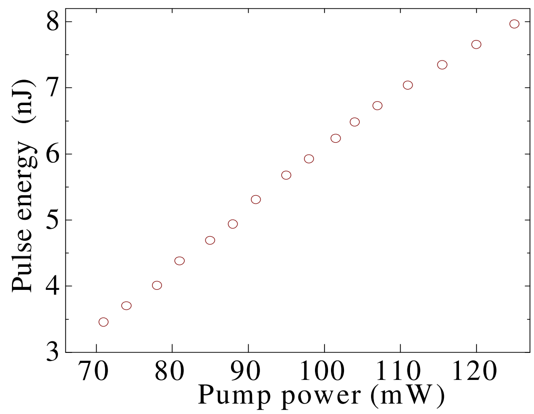

Fig. 6. Relationship of the pulse energy versus the pump power.

4. Conclusion

In this paper, we have proposed a compact all-fiber mode-locking fiber laser that consists of a laser oscillator and a compression section. The laser oscillator generates the highly chirped pulses that are dechirped to chirp-free pulses by a compression section. Our compact all-fiber fiber laser generates pulses with more than 8 nJ of the pulse energy and about 290 fs of the pulse duration. Comparing with the conventional fiber soliton lasers, the pulse energy of our laser is increased more than 80 times [7,8]. The compact all-fiber fiber laser with the high energy and ultrashort pulses has the simple design and excellent stability so that it can find important applications on commercially available components, ultrafast process analysis, multiphoton microscopy, control of the fast response of optoelectronic devices, etc.

Acknowledgments

This work was supported by the “Hundreds of Talents Programs” of the Chinese Academy of Sciences and by the National Natural Science Foundation of China under Grants 10874239 and 10604066. The author would especially like to thank Leiran Wang for help with the experiments.

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