High-power sub-picosecond all-fiber laser source at 1.56 μm

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We demonstrate an all-fiber, high-power, and high stability ultrafast laser source operating at 1563 nm. A highly stable, self-starting carbon nanotube (CNT) mode-locked femtosecond fiber laser is used as the seed source. The amplifier stage uses a fiber chirped pulse amplification configuration. The main power amplifier is based on a cladding-pumped Er–Yb co-doped fiber with 10 μm active single-mode core diameter. The laser source provides 3.4 W average output power at 75 MHz repetition rate. The pulses are compressed to 765 fs by a low-loss transmission grating pair. The robust, compact, and high-power 1560 nm fiber laser source can be used for eye surgery and solar cell micromachining.

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High-power, high-repetition-rate ultrafast laser sources operating at 1.56 μm have extensive applications such as micromachining of solar cell[1], corneal surgery[2], and seeding the mid-infrared supercontinuum generation for opto-electrical countermeasure[3], in industry, medicine, and military fields. A fiber laser configuration is advantageous for the realization of such practical applications mainly because fiber lasers are inherently environmentally stable, robust, compact, and can be directly pumped by low-cost high brightness laser diodes for high-efficiency laser operation[4–8].

Several high-power fiber laser systems operating close to 1.56 μm have been demonstrated in recent years[9–12]. In 2009, Morin *et al.*[10] reported a 1.5 μJ, 605 fs femtosecond laser output based on a chirped pulse amplification configuration. The repetition rate was 300 kHz and the output pulse energy was 460 mW. In 2012, Pavlov *et al.*[11] achieved 10 W output power at a repetition rate of 156 MHz using a passively mode-locked Er-fiber laser-seeded double-cladding (DC) Er–Yb co-doped fiber amplifier. The pulses were compressed to 450 fs by grating pair after power amplification. In 2014, Sobon *et al.*[12] demonstrated 835 fs laser pulses output with 8.65 W average power at 50 MHz repetition rate. A graphene mode-locked fiber laser was used as seeding in order to obtain self-starting operation. A multi-mode large-mode area Er–Yb co-doped fiber was used in power amplification stage.

We demonstrated a high average power, high-repetition-rate all-fiber laser system operating at 1.56 μm. A highly stable self-started carbon nanotube (CNT) mode-locked fiber laser was used as a seed. After stretching in a segment of dispersion compensation fiber (DCF) and pre-amplification, the seed pulse was power amplified in a DC Er–Yb co-doped fiber with single-mode active fiber core. The amplifier provided 3.4 W average power at 75 MHz repetition rate. The output pulses were compressed to 765 fs by a low loss transmission grating pair.

The experimental setup is shown in Fig. 1. The seed source is based on an all-fiber oscillator mode locked by CNT, which operates in the soliton regime at 75 MHz repetition rate. The oscillator consists of 50 cm long Er-doped fiber (Liekki Er80-4/125), which is pumped by a 980 nm single-mode laser diode. The output laser is obtained from a 30% fiber coupler. An in-line polarization controller (PC) is used to control the laser polarization. The self-starting mode-locking is obtained by CNT, which is deposited on a fiber ferrule[13] for all-fiber integration. The CNT sample is prepared by Yamashita group at the University of Tokyo. The self-starting mode-locking is achieved with a pump power of 40 mW. The seed generates a near transform-limited pulse with 0.887 ps full-width at half-maximum (FWHM) pulse duration, assuming sech^2 pulse shape. The average power is 1.5 mW. The optical spectrum is centered at 1564 nm. The mode-locking is stable and can operate for hours without disturbance.

The amplifier stage is based on a fiber chirped pulse amplification (FCPA) configuration. The pulses from the oscillator are temporally stretched in a segment of DCF. The dispersion of the stretching fiber is -87 ps/km/nm. The stretched pulse duration is estimated to be 15 ps. The laser power after the stretching fiber is less than 1 mW. After stretching, the seed

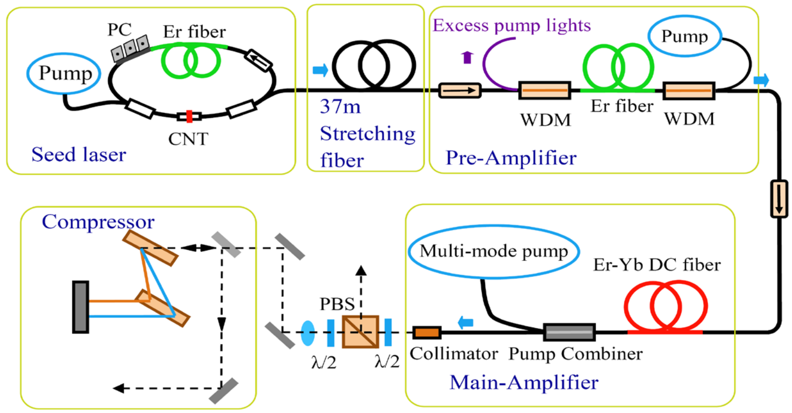

Fig. 1. Schematic of the high-power fiber chirped pulse amplifier. PBS, polarization beam splitter.

pulse is pre-amplified in a 2 m long Er-fiber (Corning Er-1600-L3), which is backward pumped by a single-mode pump diode operating at 976 nm. Two stages of isolation and a wavelength division multiplexer (WDM) are used to deplete excess pump light in order to avoid its interruption of oscillator mode-locking. The pre-amplified laser power is 48 mW. The power amplifier is based on a 4.5 m long DC Er–Yb co-doped fiber (CorActive DCF-EY-7/128), which is backward pumped in the cladding by a 10 W fiber-coupled multimode laser diode at 976 nm through a pump combiner. The amplified laser pulses are collimated by an aspheric lens with 35 mm focal length. The optical spectrum at the output of seed oscillator, stretcher, pre-amplifier, and power amplifier is shown in sequence in Fig. 2. The maximum average output power is 3.4 W at 10 W pump power. The single-pulse energy is 45.3 nJ. The estimated B-integral of the main amplifier is 2.1π. The output power and the corresponding optical spectrum at different pump power are shown in Figs. 3(a) and (b), respectively. The slope efficiency of the amplifier is 32.5%. Slight self-phase modulation-induced spectral broadening is observed with the increase in pump power.

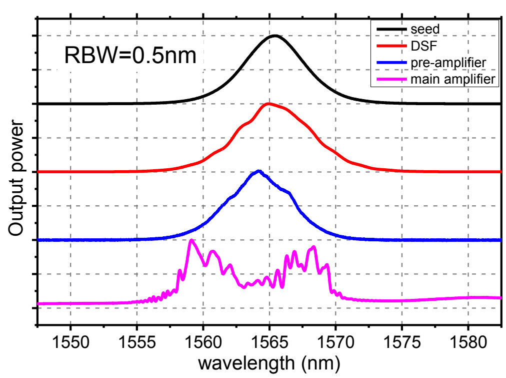

Fig. 2. Measured optical spectrum of the seed, dispersion shifted fiber, pre-amplifier. and main amplifier output.

In order to check the signal-to-noise ratio (SNR) and satellite pulse of the pulse train, some percentage of the output power from the main amplifier is tapped out and coupled into a 10 GHz photodetector with < 37 ps rise time, which results in an electrical pulse train. The SNR of the first harmonic of the pulse train is above 65 dB at a resolution bandwidth (RBW) of 30 kHz, as shown in Fig. 4(a). The pulse train measured by a 20 GHz sampling oscilloscope (HP 83485A) confirms there is no satellite pulse formation in the amplification stage, as shown in Fig. 4(b).

A bulk transmission grating pair with groove density of 966 lines/mm and 93% diffraction efficiency is used to dechirp the amplified laser pulses. The dechirped laser pulse duration is characterized by a commercial autocorrelator. The FWHM pulse duration of the pulse we obtained is 765 fs, assuming a hyperbolic secant pulse shape. Figure 5 shows the measured autocorrelation trace with sech^2 fitting in both 15 and 50 ps scan range. The output average power after dispersion compensation is 1.8 W. The output average power stability is characterized using a power meter after 20 min of system warm-up. The output power fluctuation is $< 1\%$ during 1 h test, as shown in Fig. 6. The experiment shows that this Er-fiber amplifier system is reliable in a lab level working environment.

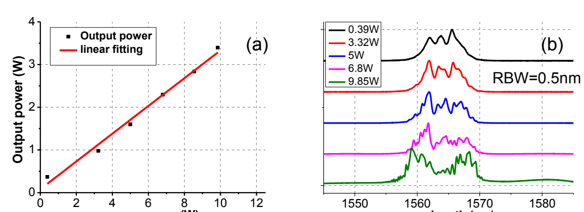

Fig. 3(a) Average output power of the system versus pump power. (b) Optical spectrum measured with different pumping power.

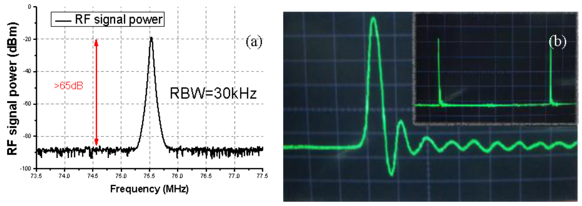

Fig. 4(a) RF spectrum of the output pulse. (b) Pulse train observed by a digital sampling oscilloscope.

In conclusion, we demonstrate a high-power, high-repetition-rate, all-fiber laser system delivering 3.4 W of average power at 1564 nm. The laser system is seeded with a highly stable CNT mode-locked Er-fiber laser oscillator operating at the soliton regime. The amplifier is designed as FCPA configuration. The output pulse can be dechirped to 765 fs pulses using a low-loss transmission grating pair. The experiment is carried out at in a lab level working environment with stable temperature. In order to work at various working environments, a robust all-polarization configuration is required. Such a robust, compact, high-power 1560 nm fiber laser source can be potentially used for eye surgery and solar cell micromachining in the future.

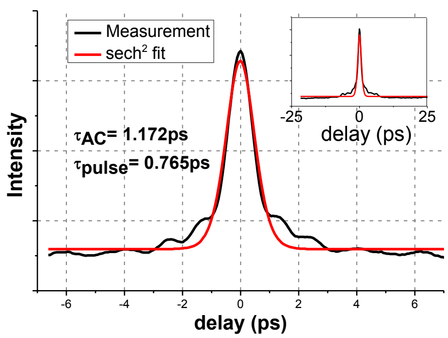

Fig. 5. Intensity autocorrelation trace of the dechirped pulses at 15 ps scan range together with the sech^2 fit. Inset: autocorrelation trace measured in 50 ps scan range.

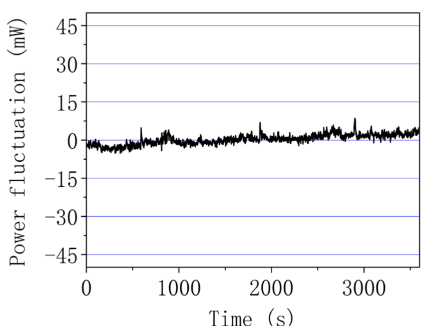

Fig. 6. Power fluctuation of the main amplification stage output over 1 h. The data are obtained after the grating pair, and the average power is 1.8 W.

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