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175 fs-long pulses from a high-power single-mode Er-doped fiber laser at 1550 nm

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ABSTRACT

Development of Er-doped ultrafast lasers have lagged behind the corresponding developments in Yb- and Tm-doped lasers, in particular, fiber lasers. Various applications benefit from operation at a central wavelength of 1.5 μm and its second harmonic, including emerging applications such as 3D processing of silicon and 3D printing based on two-photon polymerization. We report a simple, robust fiber master oscillator power amplifier operating at 1.55 μm, implementing chirp pulse amplification using single-mode fibers for diffraction-limited beam quality. The laser generates 80 nJ pulses at a repetition rate of 43 MHz, corresponding to an average power of 3.5 W, which can be compressed down to 175 fs. The generation of short pulses was achieved using a design which is guided by numerical simulations of pulse propagation and amplification and manages to overturn gain narrowing with self-phase modulation, without invoking excessive Raman scattering processes. The seed source for the two-stage amplifier is a dispersion-managed passively mode-locked oscillator, which generates a ~40 nm-wide spectrum and 1.7-ps linearly chirped pulses.

1. Introduction

Due to their practicality, capability to operate stably outside research laboratory conditions, scalability to extremely high average powers and excellent beam quality, fiber lasers continue to attract a lot of attention, resulting in an intense worldwide development. Applications of fiber lasers have been extended to diverse areas such as spectroscopy [1,2], industrial material processing [3], and biomedical applications [4,5]. In particular, material processing with ultrafast pulses offers minimal collateral damage and high precision with the main downsides being slow processing speeds relative to alternative technologies and the complexities arising from using high-energy ultrafast laser systems [6]. To counter some of these disadvantages, ultrafast burst-mode fiber lasers that momentarily achieve high repetition rates have been developed, first with high energies [7–9] and later with high average powers [10,11]. Access to high repetition rates have allowed the demonstration of ablation-cooled laser material removal [12]. However, all of these developments, as well as record-breaking performances in terms of pulse energy and average power have been realized with ultrafast Yb-doped fiber lasers operating around 1 μm due to the low quantum defect and consequently high pumping efficiency [13,14]. On the other hand, several applications stand to benefit from the longer and telecom-compatible wavelength of Er-fiber lasers. These include relatively established and rapidly growing application of multi-photon polymerization [15], which typically uses second-harmonic of the Er-lasers, eye-safe remote sensing, which outperforms performance at 1 μm. In addition, there are exciting developments regarding 3D laser processing of silicon using pulsed Er-fiber lasers [16–19].

To date, power scaling of fiber lasers operating at 1.5 μm have encountered several complexity and technical issues mostly arising from high quantum defect, thermal effects and nonlinearity. Consequently, high-power and high-energy ultrafast fiber laser development at 1.5 μm has significantly lagged behind the much more rapid progress with Yb- and recently, Tm-fiber lasers, near 1 μm and 2 μm, respectively. Using large mode-area (LMA) fibers in order to overcome nonlinearity, Sobon, et al. demonstrated an Er–Yb co-doped chirped pulse amplification system with 50 MHz repetition rate, generating 835 fs-long compressed pulses at 8.65 W of average power [20], and Wang, et al. reported 850-fs pulses at 8 W of average power at a repetition rate of 35 MHz [21]. Using single-mode fibers, Pavlov, et al. reported achievement of 10-W average power at 165 MHz repetition rate with compressed pulse duration of 450 fs [22] and Dai, et al. demonstrated a 3.4-W output average power at 75-MHz repetition rate with compressed pulse duration of 765 fs [23]. In

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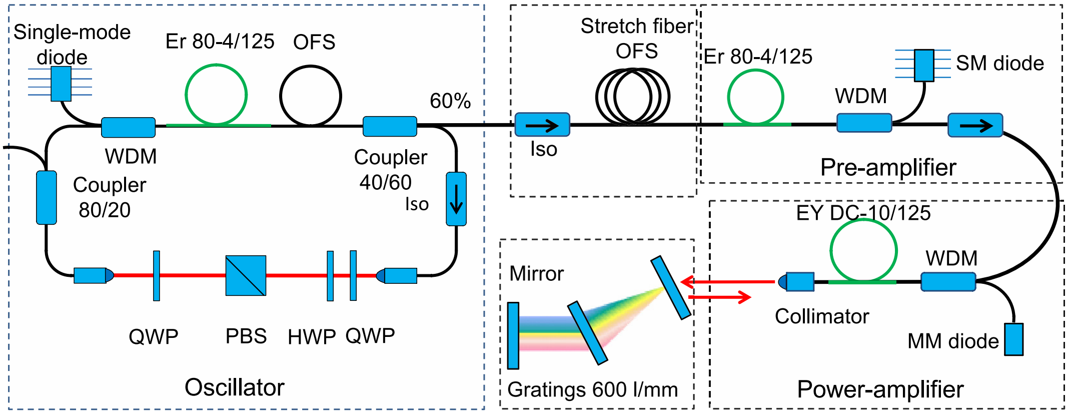

Fig. 1. (a) Schematic diagram of the experimental setup. WDM: wavelength division multiplexer, PBS: polarizing beam splitter, HWP: half-wave plate, QWP: quarter-wave plate, SM: single-mode, MM: multi-mode.

addition to these high-power, MHz-repetition rate lasers, higher-energy lasers operating at kHz repetition rates were developed using large-mode-area Er–Yb co-doped fibers. Morin, et al. achieved 1.5 μJ pulse energy with 605-fs compressed pulse duration at 300 kHz [24] and Sobon, et al. demonstrated sub-picosecond pulses with energies above 2 μJ [25]. However, the highest energy levels, by far, have been achieved by X. Peng and colleagues, generating 0.9-mJ pulses with compressed pulse duration of ~500 fs, using a special fiber boasting a mode area of 2290 μm^2 and length of only 28 cm, which they referred to as high efficiency gain media [26]. However, all of these sources produced pulse duration in the range of approximately 0.5 to 1 ps. There is a lack of high-power sources generating shorter pulses, ideally in the range of 100–200 fs, particularly for the emerging applications discussed above.

Here, we report an all-fiber high-power ultrafast chirped pulse amplifier-laser built of single-mode fiber operating at a central wavelength of 1560 nm. The amplifier has a master-oscillator power-amplifier all-fiber architecture first demonstration for femtosecond pulses in [27] and generates 3.5 W of average power at 43 MHz. The amplified pulses are dechirped with a grating compressor to 175 fs. To our knowledge, these are the shortest pulse durations from a high-power single-mode Er laser-amplifier system comprising only off-the-shelf commercial components, which ensures that it can easily be duplicated by other researchers. Furthermore, the simulation-guided design, that not only balances gain narrowing with Kerr nonlinearity, but even extends it in the last stage of amplification, suggests routes for scaling up to higher pulse energies.

2. Experiments and results

2.1. The dispersion-managed mode-locked oscillator

Fig. 1 shows the schematic of the experimental setup, which consists of an oscillator followed by two amplifier stages. The oscillator is a 43-MHz home-built passively mode-locked dispersion-managed laser cavity designed with the aid of pulse propagation simulation based on the models described in [28,29]. The simulation results in Fig. 2(a) indicate more than 2-fold spectral breathing (width from 18 to 39 nm) and 20-fold variation in pulse width (90 fs to 1.9 ps). The passive fiber sections of the cavity consist of a total of 255 cm-long SMF-28 with anomalous dispersion (Corning Inc., $\beta_2 = -22.8$ fs^2/mm at 1550 nm), 70 cm-long normal dispersion (OFS Inc., $\beta_2 = +56.7$ fs^2/mm at 1550 nm), and 100 cm-long gain fiber with normal dispersion (Er-80-4/125, Thorlabs, Inc., $\beta_2 = 33$ fs^2/mm at 1550 nm and 55 dB/m of absorption at 976). This combination of fibers yields a slightly positive net cavity group dispersion delay (GDD) of 0.01 ps^2, similar to [30]. The core and cladding diameters of the gain fiber are 4 μm and 125 μm, respectively. The pump source is a single-mode diode laser centered at 976 nm, and the pump light is coupled to the cavity through a wavelength division multiplexer.

Stable and self starting mode-lock state of the oscillator yields to multi-pulsing when pump power exceeds 320 mW. Hence, the oscillator was operated at 250 mW pump, for which case the output power from the 60% port of the 60/40 coupler was 18 mW. The optical spectrum and autocorrelation of the output signals from the oscillator was measured after traversing 1.1 m of SMF-28 fiber, as shown in Fig. 3(a) and (b), respectively. The spectrum is centered at around 1560 nm with a full-width half-maximum width of 40 nm. The intensity autocorrelation measurement indicates a pulse width of 740 fs, assuming a Gaussian pulse shape. These values match the simulation results closely, which predict a pulse width of 1.74 ps and a spectral width of 39 nm at the oscillator output (shown with the vertical dashed line in Fig. 2(a)), and point to the compression of the apparently positively-chirped pulse following the output, considering the anomalous dispersion of the 1.1 m-long SMF-28 ($D = 18$ ps/(nm km)). The oscillator's single-pulsed operation and high short term stability are confirmed, respectively, by radio frequency (RF) spectral measurements for 10-GHz scan range at 100-kHz resolution bandwidth (Fig. 3(c)), and its close-up version with 800-Hz span and 10-Hz resolution bandwidth (Fig. 3(d)), which shows a 75-dB signal-to-noise ratio at the fundamental repetition rate.

2.2. Chirped-pulse amplification

The amplifier is seeded with 18-mW output signal from the oscillator, which is transmitted through an in-line isolator to protect mode-locking against any back-reflections and then a fiber-based pulse stretcher made of 10 m-long normal-dispersion OFS fiber, where pulses are stretched to 18 ps. After the isolator and stretch fiber, the average power drops to 8 mW, due to 20% loss in the isolator and 40% SMF-28-to-OFS splice loss as a result of the mismatch between the mode field diameters of the two fiber types (10.4 μm for SMF-28, 6.6 μm for OFS). The pulse train is then amplified to 200 mW with a single-mode pre-amplifier built from 120-cm Er-fiber (Er-80-4/125, Thorlabs, Inc.) pumped by 540 mW, indicating a pump conversion efficiency of 37%. Fig. 4(a) shows the measured optical spectrum at the preamplifier output where the spectral width is narrowed down to 18.5 nm as a result of gain filtering, while the nonlinearity is too low to fully counteract this effect. The measured autocorrelation signal is presented in Fig. 4(b), which indicates a 7.5 ps-long, largely linearly chirped pulse duration (assuming a gaussian pulse deconvolution factor). The power amplifier comprises of a 140-cm long double-clad Er–Yb co-doped fiber (DCF-EY, CorActive, Inc.) with a 10-μm core diameter and a 128-μm cladding diameter. The cladding absorption of the gain fiber is 2.4 dB/m at 915 nm. A multimode pump-signal combiner was used to deliver pump light from a wavelength-stabilized diode laser (BWT, Inc.) to the cladding

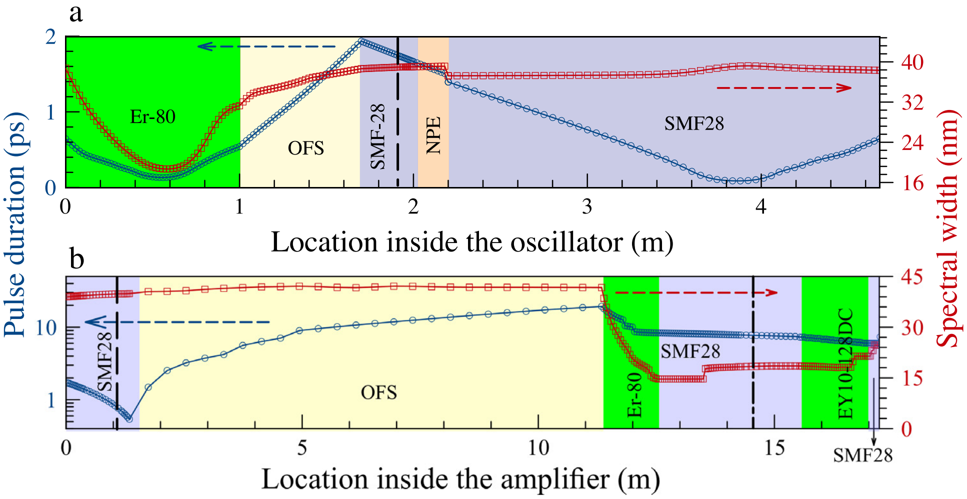

Fig. 2. Simulation results for evolution of the pulse duration and spectral width (a) along the oscillator cavity (vertical dashed-line indicates the output point for the oscillator where simulated pulse width is 1.74 ps and spectral width is 39 nm), (b) along the amplifier system, starting with the oscillator output (vertical dashed line indicates measurement point at output of the oscillator and the vertical dash-dotted line on the right indicates measurement point at the power amplifier input).

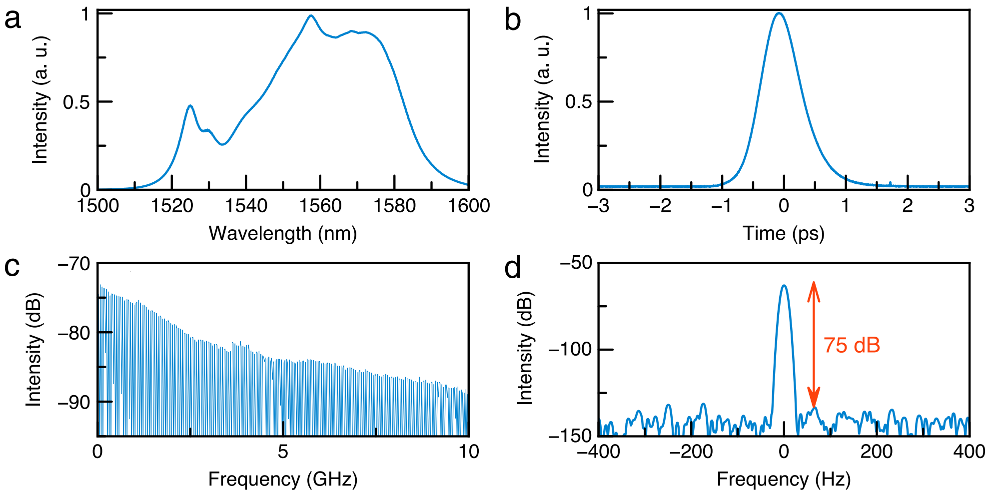

Fig. 3. Oscillator characterization: (a) Optical spectrum measured from the 60% output coupler. (b) Corresponding intensity autocorrelation. (c) Measured radio frequency (RF) spectrum with 10-GHz span and 100-kHz bandwidth resolution, showing single-pulsed operation. (d) RF spectrum with 800-Hz span and 10-Hz bandwidth resolution, indicating good short-term stability. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

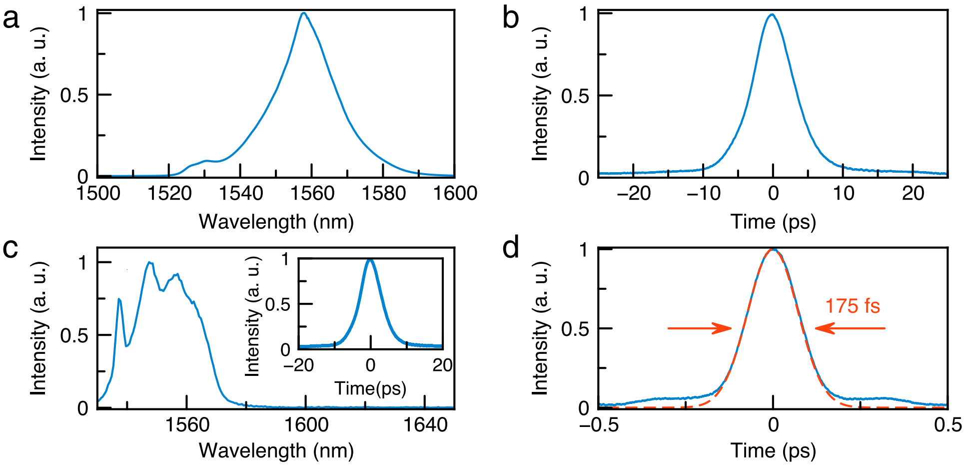

Fig. 4. Amplifier characterization: (a) Measured optical spectrum after the pre-amplifier. (b) Corresponding intensity autocorrelation measurement. (c) Measured output optical spectrum at 3.5 W of average power. Inset: Corresponding measured intensity autocorrelation. (d) Measured output intensity autocorrelation at 3.5 W after dechirping with a diffraction grating compressor (blue solid line) along with Gaussian fit (red dashed line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

region of the gain fiber. The maximum output power of the pump diode is 18 W.

We achieved 3.5 W of output power with 13.5 W of pump power, yielding a pump-to-signal conversion of 26%, where the main limitation on power level is imposed by the onset of the Raman effect. The output beam is strictly single-mode, which is taken from a collimator using SMF-28 as its pigtail fiber, as characterized and reported in [22]. Measured optical spectrum at 3.5 W of output power is shown in Fig. 4(c). The measured spectral width is about 26 nm and the center shifts to 1550 nm. The inset of Fig. 4(c) shows the corresponding intensity autocorrelation with 7-ps long temporal width. The pulse propagation simulation results for the amplifier (Fig. 2(b)) predict a spectral width of 40 nm and a chirped-pulse pulse duration of 1.74 ps at a point of 1.1 m into the amplifier system, 18.4 nm and 7.7 ps, respectively, at the power amplifier input and 25 nm and 6.2 ps, respectively, at the output of the amplifier, all of which agree closely with the measurement results given above. The simulation results also predict the compression in time at the input of the amplifier due to the positive chirp of the seed pulse and anomalous dispersion of the SMF-28. Furthermore, the narrowing effects of the preamplifier on both the spectrum and pulse width are clearly visible. Finally, the pulses are experimentally compressed to 175 fs using a 300-l/mm transmission grating pair with an overall efficiency of 56%. Considering the 26-nm spectral width, the compressed duration is about 1.3 times the transform-limited pulse width. We believe this small deviation to arise mainly from the uncompensated third-order dispersion of the grating pair.

3. Conclusion

We have demonstrated an ultrafast Er fiber laser-amplifier system able to generate 3.5 W of average power at the output corresponding to 80-nJ pulses at the 43-MHz repetition rate. The amplifier has an integrated fiber architecture. Compressed pulses with 175 fs width and very clean form have been obtained. The experimental development of the system was guided and verified at each step by numerical simulations of pulse generation in the oscillator and pulse propagation in the amplifier. Importantly, we have demonstrated deliberate use of self-phase modulation to balance gain narrowing in the power amplifier system, which leads to 40% spectral rebroadening in the last half meter of the system. While the present results are limited by the onset of Raman scattering for the present chirped pulse duration, the use of longer pulses is open, as long as a form of third-order dispersion control is implemented for the grating compressor. In that case, our simulation results suggest the possibility of substantially scaling up the pulse energy, up to at least 1 μJ, without causing the final pulse duration to increase. To the contrary, the amplified bandwidth demonstrated here is capable of supporting 135 fs, following higher-order chirp control.

This system generates the shortest pulses at the multi-watt power range for Er-doped lasers, to the best of our knowledge. By virtue of operating at 1.55 μm, it may find applications in 3D silicon processing or 3D printing based on two-photon polymerization following a second-harmonic generation stage.

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