31 nJ sub-200 fs pulse generation from an Erbium-doped fiber amplifier similariton oscillator

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Abstract: We demonstrated the highest femtosecond pulse energy from Erbium-doped fiber similariton or dissipative soliton oscillators (to our best knowledge). The output spectrum can be manipulated by waveplates and filter to support 86 fs transform-limited pulse.
OCIS codes: (320.7090) Ultrafast lasers; (320.7110) Ultrafast nonlinear optics;

1. Introduction

Sub-picosecond pulse up to 1 μJ has been produced by Ytterbium-doped fiber oscillators based on large-mode-area fiber and dissipative soliton [1]. Unfortunately, the pulse energy of the Erbium counterparts is much weaker due to (1) the erbium-doped fiber (EDF) core has to be small (subject to strong nonlinearity) to achieve normal dispersion at the lasing wavelength (~1.5 μm), (2) longer EDF is normally needed to provide high gain due to the lower doping concentration, (3) EDF has narrower gain bandwidth. Nevertheless, the longer lasing wavelength of EDF lasers is attractive in telecommunications, *in vivo* three-photon microscopy [2], and mid-infrared pulse generation [3]. The highest energy of sub-picosecond pulse from similariton or dissipative soliton EDF oscillators was 20 nJ (750 fs, 1.2 W pump) [4], where a short (59 cm) EDF and long (57 m) passive fibers were used to suppress the nonlinear chirp via strong normal dispersion. However, the grating-pair-compressed pulse still exhibited a highly oscillating tail with poor (56%) compression efficiency (defined as the energy in the temporal main lobe over the total energy) [5].

Previously we demonstrated a mode-locked fiber oscillator consisting of small-core EDF and an intracavity pulse shaper, producing 268 fs, 8.9 nJ pulse with 67% compression efficiency at 320 mW pump power [6]. The nonlinear chirp could be suppressed by adding spectral phase modulation via the pulse shaper without incurring extra dispersion. In this work, we report improvements on the pulse width (191 fs), pulse energy (31 nJ), and compression efficiency (90%) by a new cavity design and increased pump power (720 mW). The 31 nJ pulse energy is 1.6-fold of the previous record, while achieved at 60% of the pump power. The output spectrum could be manipulated by controlling the polarization and spectral filtering elements to support 86 fs (FWHM) transform-limited (TL) pulse at lower (21 nJ) energy.

2. Experiment

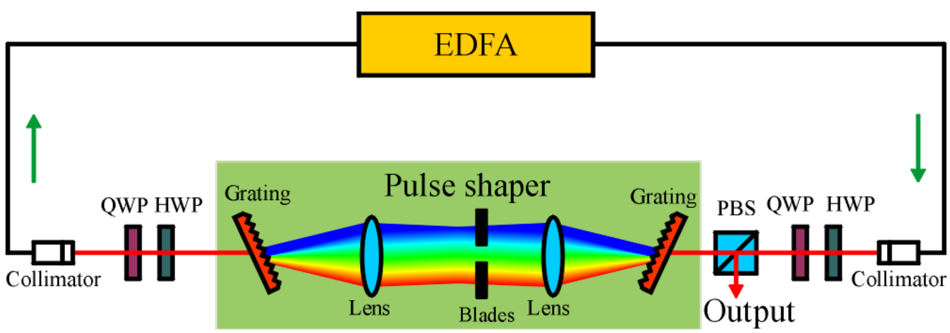

Fig. 1. Experiment setup. EDFA: Erbium-doped fiber amplifier; QWP: quarter waveplate; HWP: half waveplate; PBS: polarization beamsplitter.

Figure 1 shows the setup of our amplifier similariton EDF oscillator. A pulse shaper (shaded area) consisting of two gratings (1100 gr/mm), two lenses, and a pair of blades was placed inside the ring cavity as a tunable filter. The gain medium was a customized EDF amplifier (EDFA) made up of 30-m-long EDF (β_2=22.17 ps^2/km) and 4-m-long single-mode fiber (SMF, β_2=-21.94 ps^2/km) with a maximum pump power of ~720 mW. The total optical path length corresponded to 176 ns repetition period (5.68 MHz repetition rate). Mode-locking was initialized and stabilized by nonlinear polarization evolution and spectral filtering, respectively. By adjusting the four waveplates and the two blades (position and separation), different mode-locked spectra at the exit port could arise.

Figure 2 shows the characterization results of the oscillator at the highest energy (31 nJ) mode. The power spectrum [Fig. 2(a)] extended from 1523 to 1597 nm, corresponding to a TL pulse width of 151 fs. Figure 2(b) is the oscilloscope trace (limited by the 100 MHz photodetector), confirming the CW mode-locking operation. Figure 2(c) and its inset illustrate are the RF spectra (detuned from the 5.68 MHz repetition rate) over 1 kHz and 250 MHz spectral ranges, respectively. The 80 dB noise suppression along with the uniformly spaced peaks (5.68 MHz separation) imply the single-pulse operation. By using the standard RF spectral analysis [7], we got 0.22% amplitude noise and 4.2 ps timing jitter, respectively. Figures 2(d), 2(e), 2(f) show the frequency-resolved optical gating (FROG) measurement of the pulse after compressed by a grating pair. The low FROG error (0.0038) and the good agreement between the measured and retrieved power spectra [Fig. 2(e), shaded and solid] prove the data integrity. The temporal width (FWHM), peak power (after considering the 70% loss of the grating compressor), and pulse compression efficiency of the grating-pair-compressed pulse [Fig. 3(f)] were 191 fs, 40 kW, and 90%, substantially better than those (750 fs, 5 kW, 56%) reported in [4].

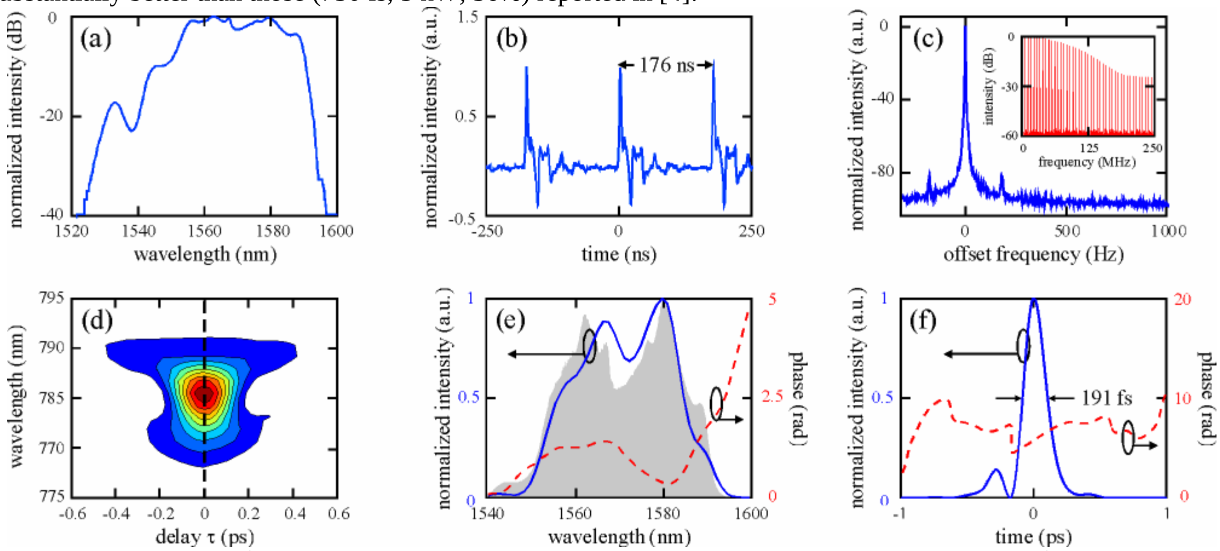

Fig. 2. Measurement results of the 31 nJ pulse train. (a) Power spectrum. (b) Oscilloscope trace. (c) RF spectrum detuned from 5.68 MHz with 1 Hz resolution. Inset: RF spectrum from 1 kHz to 250 MHz with 10 kHz resolution. (d-f) FROG measurement of the pulse compressed by a grating pair. (d) Measured (left) and retrieved (right) FROG traces. (e) Power spectra measured by optical spectrum analyzer (shaded) and retrieved by FROG (solid). Spectral phase (dashed) retrieved by FROG. (f) Temporal intensity (solid) and phase (dashed) retrieved by FROG.

We also adjusted the four wave-plates and the separation between the blades to get the broadest spectrum at the cost of reduced pulse energy (21 nJ). The power spectrum (not shown here) became structured (but still CW mode-locked and of single-pulse operation), corresponding to a TL pulse width of 86 fs.

3. Conclusion

We have experimentally demonstrated a stably mode-locked sub-picosecond EDF oscillator with 31 nJ pulse energy, 1.6-fold of the previous record. The grating-pair-compressed pulse had 191 fs width, 40 kW peak power, and 90% pulse compression efficiency, respectively. Furthermore, the broadest spectrum achieved by our EDF oscillator corresponded to 86 fs TL pulse width (FWHM). This work was supported by the National Science Council in Taiwan under grant NSC 100-2221-E-007-093-MY3, and by the National Tsing Hua University under grant 101N2081E1.

4. References

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