Femtosecond Erbium-doped Fiber Oscillator with Pulse Energy up to 58 nJ

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Abstract:

Mode-locked Erbium fiber oscillator with pulse energy up to 58 nJ is experimentally demonstrated, the highest value to our best knowledge. The broadest spectrum corresponds to a transform-limited pulse of 93 fs duration.

I. INTRODUCTION

Dissipative soliton lasers have enhanced the pulse energy of mode-locked fiber oscillators by more than one order of magnitude [1]. However, the pulse energy of the Erbium-doped fiber (EDF) oscillator remains much weaker than the Yitterbium counterpart for a couple of reasons. (1) The 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 is attractive for in vivo three-photon microscopy [2], telecommunications and mid-infrared pulse generation [3]. Some of the highest pulse energies reported to date were 34 nJ (369 fs after compression) [4], 20 nJ (750 fs, after compression) [5], and 19 nJ (83 fs, transform-limit) [6], respectively.

We have previously demonstrated a mode-locked fiber oscillator consisting of small-core EDF and an intracavity pulse shaper, producing 191 fs, 31 nJ pulse with 90% compression efficiency at 750 mW pump power [7]. The nonlinear chirp (and wave breaking) could be suppressed by adding spectral phase modulation via the pulse shaper without incurring extra nonlinearity. In this contribution, we enhanced the pulse energy to 58 nJ by increasing the pump power (1.5 W) and intracavity spectral phase modulation. The mode-locked spectrum could be manipulated by controlling the wave plates and spectral filtering elements. The broadest mode-locked spectrum supports a transform-limited (TL) pulse of 93 fs duration (FWHM) at 39 nJ energy.

II. THEORY AND EXPERIMENTAL RESULTS

Figure 1 shows the setup of our EDF oscillator. An intra-cavity pulse shaper consists of two gratings (1100 gr/mm), two lenses (f=20 cm), a liquid crystal modulator (LCM) and a slit (placed inside the ring cavity as a tunable filter to control the central wavelength). The gain medium was a customized EDF amplifier (EDFA) made up of 40-m-long EDF (β_2 =14 ps²/km) and 2-m-long single-mode fiber (SMF, β_2 = -21.94 ps²/km) with a total group delay dispersion (GDD) of 0.516 ps² and maximum

pump power of ~1.5 W. The total optical path length corresponded to a repetition rate of 4.5 MHz. Mode-locking was initialized and stabilized by nonlinear polarization evolution and spectral filtering, respectively. By adjusting the orientations of the four wave plates and the slit width, different mode-locked spectra at the exit port could be obtained.



Fig. 1. Experimental setup. EDFA, Erbium-doped fiber amplifier; HWP#, half-wave plate; QWP#, quarter-wave plate; PBS, polarization beam splitter; G#, grating; L#, lens; LCM: liquid crystal modulator.

Figure 2(a) shows the characterization results of the oscillator at 58 nJ pulse energy (260 mW average power). The high pulse energy was achieved by introducing a very strong normal GDD ((8.02 ps^2)) and an extra cubic spectral phase coefficient of 5.98 ps^3 via the LCM. The power spectrum (blue curve) extended from 1550 nm to 1566 nm (at -30 dB level), corresponding to a TL pulse width of 306 fs. The inset figure (red curve) shows the intensity autocorrelation trace of the output pulse in the absence of dechirping, where the correlation width (10.4 ps) is significantly longer than the TL pulse width due to large residual chirp. Figure 2(b) shows the electric oscilloscope trace of the pulse train, showing a repetition period of 222 ns.



Fig. 2. Measurement of 58 nJ pulse train. (a) The power spectrum. The inset figure is the intensity autocorrelation trace. (b) The oscilloscope trace.

By adjusting the wave plates and intracavity spectral phase modulation, different mode-locked spectra could be obtained. Figure 3 shows the characterization results of the EDF oscillator at a "broad bandwidth mode". The power spectrum (blue curve) spans over 1539-1604 nm (at -30 dB level), corresponding to 93 fs TL pulse width. The pulse energy is reduced to 39 nJ (average power is 175 mW). The corresponding intensity autocorrelation trace (inset figure) has a correlation width of 1.16 ps.



Fig. 3. The power spectrum and the intensity autocorrelation trace (inset) of the 39 nJ pulse train.

III. CONCLUSIONS

We have experimentally demonstrated a tunable modelocked EDF oscillator with pulse energy up to 58 nJ (the highest among femtosecond EDF oscillators to the best of our knowledge) and TL pulse width down to 93 fs (FWHM). This work was support by the Ministry of Science and Technology of Taiwan under grants MOST 103-2221-E-007-056, 103-2218-E-007-010. The authors acknowledge Dr. Chiang-Chung Fu for this generous financial support.

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