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Scaling of dissipative soliton fiber lasers to megawatt peak powers by use of large-area photonic crystal fiber

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Abstract

We report an all-normal dispersion femtosecond laser based on large-mode-area Yb-doped photonic crystal fiber. Self-starting mode-locked pulses are obtained with an average power of 12 W at 84 MHz repetition rate, corresponding to 140 nJ of chirped pulse energy. These are dechirped to a near transform-limited duration of 115 fs. Experimental results are consistent with numerical simulations of dissipative soliton intracavity pulse evolution, and demonstrate scaling of 100 fs pulses to megawatt peak powers.

Ultrashort pulse lasers have opened up new scientific and technical frontiers in time-resolved material and chemical studies, nonlinear microscopy, precision machining, and metrology. Mode-locked Ti:sapphire oscillators [1] have long been the workhorses of ultrafast science because of their broadband gain, large tunability, and advantageous laser material qualities. However, they are limited by the power available from high-beam-quality solid-state pump lasers. Diode-pumped solid-state lasers, both in crystal [2] and thin-disk format [3], offer competitive performance but still present thermal and mechanical limitations. As an alternative, rare-earth doped fiber lasers offer very high gain per pass, excellent thermo-optical properties, and waveguiding of the pump and signal for high mechanical stability. They offer the potential for integrated and passively cooled ultrashort pulse sources.

The pulse energy attainable in fiber lasers is fundamentally limited by self-phase-modulation-induced wavebreaking [4]. Understanding the role of nonlinearity in ultrashort pulse evolution is thus critical. In the anomalous dispersion regime, the stretched-pulse laser [5] uses temporal breathing of the pulse to reduce nonlinear phase accumulation. In the normal dispersion regime, the self-similar [6] and all-normal dispersion (ANDi) lasers [7] display evolutions that preserve pulse quality at high nonlinear phase shift. In particular, the ANDi laser uses spectral filtering of a chirped pulse to achieve self-consistent evolution, delivering high-pulse energies and broad bandwidth through a simple design. These pulses are well modeled by dissipative soliton solutions [8].

In parallel to fundamental understanding of pulse evolution, technological advances have enabled reductions of effective fiber nonlinearities and the delivery of higher pump power. Cladding-pumped fiber lasers with performance matching those of solid-state oscillators have been demonstrated [9]. In parallel, fibers with increasing mode-field areas have reduced nonlinearity at given pulse energies. A fiber laser based on multimode fiber has

been demonstrated [10], but suppressing higher-order modes to obtain stable mode-locking remains a challenge. Microstructured fibers can combine large mode area with a clean fundamental mode. Using a fiber with rings of different refractive indices, the scaling to large mode area of intracavity soliton evolution was first demonstrated [11]. Recently, photonic crystal fibers (PCF) have enabled the production of very large single-mode cores. Using a polarizing and bendable PCF in an all-normal dispersion cavity, pulse energies up to 63 nJ with 150 fs dechirped pulses have been reached [12]. Microstructured rigid rods offer the largest areas and have enabled microjoule energies directly from a single oscillator [13], but pulse duration was limited to hundreds of femtoseconds.

In this Letter, we report a dissipative soliton laser based on large-mode-area Yb-doped photonic crystal fiber. Numerical simulations show that such a cavity can support dissipative solitons with energies up to 300 nJ with dechirped pulse duration less than 100 fs. The measured performances matches theoretical predictions and reaches 12 W of average power at 84 MHz repetition rate, corresponding to 142 nJ pulses, which dechirp to a transform-limited duration of 115 fs. Performance is currently limited by the available pump power.

The high pump absorption and the difficulty of efficiently splicing or coupling from PCF into other fibers dictate that the cavity be made of only a short length of active fiber. This reduces the total cavity dispersion, implying weaker pulse shaping by chirped-pulse spectral filtering. To determine if such a cavity can support dissipative soliton pulses, numerical simulations were performed with the cavity elements of Fig. 1, and the experimental parameters given below. A stable solution obtained with a 12 nm spectral filter is shown, with the output taken after the saturable absorber having 140 nJ energy and a dechirped duration of 105 fs. The simulated pulse evolution is qualitatively similar to that in [14]. This demonstrates that spectrally filtered dissipative solitons are possible in such a cavity despite low nonlinearity and dispersion. This is in contrast to [12,13], where spectral breathing is weak and pulse-shaping is dominated by self-amplitude modulation in a semiconductor saturable absorber mirror (SESAM) along with gain filtering. Here, despite the low nonlinearity in the PCF, the introduction of a narrow enough spectral filter combined with high pump power provides sufficient pulse shaping to produce self-consistent dissipative solitons. Stable solutions were found for energies up to 160 nJ with a 12 nm spectral filter, and above 300 nJ for a 20 nm filter, both with sub-100 fs dechirped durations.

Following these numerical results, the laser in Fig. 2 was built. The gain medium is 1.25 m of nominally single-mode Yb-doped large mode-area PCF (Crystal-Fibre DC-170-40-Yb), with a mode-field diameter of 33 μm and effective NA ≈ 0.03 . An air cladding with a diameter of 170 μm and an NA of ≈ 0.62 at 950 nm guides the pump. The fiber length is chosen to optimize pump absorption. The dispersion of the fiber was estimated to be 0.019 ps²/m around 1 μm [15]. The output of a fiber-coupled laser diode that provides up to 35 W with a 0.5 nm bandwidth around 976 nm is injected in the cavity using a short-pass dichroic mirror. A polarization sensitive isolator ensures unidirectional ring operation. Spectral filtering is provided by placing a quartz plate in front of the input polarizer of the isolator to create a birefringent filter with 12 nm bandwidth. Nonlinear polarization evolution (NPE) in the fiber is converted to amplitude modulation by the waveplates and a polarizing beam splitter. The output is taken from the NPE port. A grating pair compressor compensates the chirp of the output pulse.

The laser produces stable, self-starting pulse trains at 84 MHz repetition rate, which were monitored using a sampling oscilloscope with 30 ps resolution. Single pulsing was checked with an autocorrelator with up to 50 ps delay. The spectra in Fig. 3 correspond to stable experimental mode-locked states with neighboring NPE waveplate settings. As output coupling from the NPE port is reduced and intracavity energy increased (lower output

energy), self-phase modulation generates broader bandwidth and deeper modulation at the center of the spectrum. This is the same trend as in [14], consistent with a spectrally filtered dissipative soliton pulse evolution in the cavity. We note small spectral fringes with a period of 2–3 nm, which we suspect are due to spectral interference with a weakly guided second mode. From the modulation depth, we estimate this mode carries less than 1% of the total energy.

Figure 4 shows a high-energy state with a short, clean pulse. With about 24 W of pump light coupled into the cladding, the average output power is 12 W, corresponding to a chirped pulse energy of 142 nJ. After dechirping with a grating pair providing -0.035 ps^2 of dispersion, the interferometric autocorrelation shows a clean pulse nearly identical to the calculated transform limit of the spectrum. From this, we infer a pulse FWHM duration of 115 fs. Assuming a 25% loss from a well-designed grating compressor, this corresponds to a peak power of about 1 MW. The RF spectrum shows good amplitude stability with only small sidebands more than 70 dB down from the first harmonic, at frequencies in the range of gain relaxation oscillations. The dynamic range is limited by the detector/spectrum analyzer combination. Despite minor environmental drifts, mode locking was sustained over many hours.

Pulse energy is expected to scale with mode area at constant nonlinear phase shift. By scaling from [9], 100 fs pulses with energy up to 300 nJ should be possible, in agreement with the numerical simulations. The current laser achieves pulse duration similar to [9] and nearly 5 times higher pulse energy. The energy is currently limited by available pump power. Peak power is comparable to that obtained from the photonic crystal rod laser in [13]; the shorter pulses free from residual phase provided by the present laser compensate for the lower pulse energy. The average and peak powers exceed those of Ti:sapphire lasers [1] and approach that of state-of-the-art chirped pulse oscillators [16]. At first, fiber endface damage was sometimes observed, presumably due to self- Q -switching in non-mode-locked waveplate settings. This can be prevented by careful surface preparation, where the microstructure is collapsed at the fiber ends before cleaving. Existing endcap technology [17] can also be used should damage occur again at higher powers.

One of the advantages of fiber gain media is the possibility of integration into compact, robust sources. The laser presented here uses free-space pumping and signal coupling, as well as a PCF gain medium with high bending loss below a radius of 0.5 m. However, recent technological advances have produced similar fibers with bending radii down to 30 cm. Fiber-coupled pump combiners using ring mirrors around the air-clad PCF have been demonstrated [18], as well as interfacing PCF to single-mode fiber [19]. Integration of the laser design presented here is thus within the reach of current technology.

In conclusion, we have presented an all-normal dispersion Yb fiber laser based on large-mode-area PCF. The laser delivers 12 W at an 84 MHz repetition rate. The 140 nJ pulses can be dechirped extracavity to 115 fs. The megawatt peak power that can be reached with this laser matches that of fiber lasers and approaches that of the highest-performance solid-state lasers. Numerical simulations confirm dissipative soliton evolution and indicate that pulse energies around 300 nJ are possible given sufficient pump power and endface damage protection, which demonstrates scalability of the ANDi laser concept to the frontier of ultrafast laser performance.

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Fig. 1. (a) Simulated pulse evolution: SA, saturable absorber; SF, spectral filter. Output pulse (b) spectrum, (c) chirped, and (d) transform-limited time profiles.

Fig. 2.
Experimental PCF ring laser design: DM, dichroic mirror; HWP and QWP, half- and quarter-waveplates; PBS, polarizing beam splitter; BRP, birefringent plate; DDL, dispersive delay line.

Fig. 3.
Mode-locked spectra with output energies (a) 154 nJ, (b) 124 nJ, (c) 52 nJ.

Fig. 4. Mode-locked output: (a) spectrum, (b) dechirped interferometric autocorrelation (gray) and spectrum transform limited envelope (dotted black), (c) RF noise spectrum, 2 MHz span, 1 kHz resolution, and (d) pulse train, 50 ns/div, 400 kHz bandwidth.