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Sub-100 fs pulses at watt-level powers from a dissipative-soliton fiber laser

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Abstract

We report a mode-locked fiber laser that exploits dissipative-soliton pulse shaping along with cladding pumping for high average power. The laser generates 31 nJ chirped pulses at 70 MHz repetition rate, for an average power of 2.2 W. After dechirping outside the laser, 80 fs pulses, with 200 kW peak power, are obtained.

Fiber lasers have been the subject of intense research and development recently. In a relatively short period of time the performance of lasers based on fiber technology has reached and even surpassed the levels that traditional solid-state lasers offer. Fiber format enables significant advantages such as passive cooling, maintenance-free operation, and lower cost. As a result, fiber lasers are quickly replacing solid-state lasers in various applications that require cw or *Q*-switched output. However, the performance of mode-locked fiber oscillators still lags behind that of solid-state counterparts such as Kerr-lens mode-locked Ti:sapphire lasers. Despite the drawbacks in cost, size, and required maintenance, Ti:sapphire remains the workhorse of ultrafast science. Lasers based on Yb-doped crystals have recently reached impressive performance levels, with thin-disk systems exceeding microjoule energies and megawatt peak powers in research laboratories [1]. Fiber sources with performance comparable to that of solid-state lasers should have tremendous potential for applications.

The accumulation of excessive nonlinear phase shift presents a fundamental challenge to the development of short-pulse fiber lasers. In the last decade, several new intracavity pulse evolutions that allow major increases in the pulse energy have been demonstrated. Tamura *et al.* demonstrated the stretched-pulse laser, which supports dispersion-managed solitons and allows the energy of single-mode fiber (SMF) lasers to reach the 1 nJ level [2]. Self-similar evolution allows the pulse energy to reach the 10 nJ level [3,4]. All-normal-dispersion lasers support dissipative solitons [5,6], and these reach the highest femtosecond-pulse energies (>20 nJ [7]) produced to date by lasers constructed of standard SMF. All of these pulse evolutions yield chirped pulses that can be dechirped to near their transform-limited duration outside the cavity. Scaling at constant nonlinear phase shift can be applied to any known pulse evolution and is accomplished by increasing the mode-field area. This approach has been employed with large-mode-area photonic-crystal rods and has produced very high (265 nJ) pulse energies but also relatively long (~0.4 ps) pulses [8]. Techniques for integration of the photonic-crystal rod may be developed in the future, but current implementations sacrifice the primary benefits of the fiber medium (only a small fraction of the laser is a waveguide) and require a mirror-defined cavity that is susceptible to misalignment.

The SMF lasers described above are all pumped in-core by single-mode diodes, which limits the pump power to ~1 W and the mode-locked output power to ~400 mW. The repetition rate (cavity length) must be reduced (increased) to demonstrate the high-energy pulses [7]. Thus, although the pulse-propagation physics allows pulse energies comparable to those of solid-state lasers, the average power is much lower. Typically, ~200 mW can be obtained after the required dechirping.

The use of double-clad (DC) gain fiber is common, and there are a few reports of mode-locked lasers that employ DC gain media with single-mode signal cores, which retain the practical features of ordinary SMF. Hideur *et al.* generated 24 nJ pulses with 670 fs duration from a V-groove pumped Yb fiber laser with a dispersive delay line in the cavity [9]. The pulse energy achieved in this work is impressive, but the pulse duration is rather long. Using the same pumping scheme, Ortac *et al.* demonstrated 90 fs pulse duration at 3 nJ pulse energy from a stretched-pulse laser [10]. Particularly relevant to this Letter is the report by An *et al.* of a normal-dispersion oscillator that produced 25 nJ pulses at 80 MHz [11]. The pulses were compressible to 150 fs FWHM, but with substantial energy in wings that extended out to 3 ps.

In this Letter, we describe the design and performance of an all-normal-dispersion laser with a DC gain segment. The laser generates chirped dissipative solitons with 31 nJ energy and 2.2 W average power. The pulses are compressed to 80 fs outside the cavity. To our knowledge this is the first fiber oscillator to deliver sub-100 fs pulses at >1 W power levels. The peak power is ~200 kW, so the performance competes directly with femtosecond solid-state lasers.

The gain fiber in core-pumped lasers constitutes <10% of the total fiber in the cavity, whereas in a DC laser, the gain fiber dominates (70%) the total fiber. Given that spectral filtering in the gain medium contributes significantly to the pulse shaping in normal-dispersion cavities, it is not clear that the pulse evolution will be the same in lasers made with DC and ordinary gain segments. Numerical simulations were performed to investigate the pulse evolution in the cavity. We used the standard split-step method in our simulations with the arrangement of the elements in the laser cavity shown in Fig. 1(a). The saturable absorber is assumed to have an instantaneous response, which is appropriate for nonlinear polarization rotation. The results show that stable pulse solutions do exist in the cavity for a range of parameters (spectral filter bandwidth, cavity dispersion, and pulse energy). Similar to the case of core-pumped lasers, pulse energies of tens of nanojoules are possible. The results of a numerical simulation performed with accurate fiber parameters (given below), 20 nm spectral filter, and 30 nJ pulse energy is shown in Fig. 1.

It is clear from the evolution of the pulse in the cavity that spectral filtering plays a dominant role in the pulse shaping. The pulse duration and bandwidth increase almost monotonically in the SMF segments and the gain fiber. The pulse is highly chirped at every point in the cavity. The saturable absorber helps to shorten the pulse. However, the filter has greater impact in shortening the pulse by cutting the edges of the spectrum while making it self-consistent over one cavity round trip. Thus, the numerical results indicate that the pulse evolution in the laser with a DC gain medium is similar to the evolution in the core-pumped counterpart. The spectrum exhibits the “cat ears” at its edges that are characteristic of dissipative solitons in normal-dispersion fiber lasers.

The design of the laser (Fig. 2) is conceptually similar to prior normal-dispersion lasers [5] but with the DC fiber replacing almost all of the SMF. The gain fiber has a 10 μm core, 125 μm first cladding diameter, and 6.8 dB/m cladding absorption (Liekki DC1200-10/125). The 2 m length of the gain fiber was chosen to absorb most of the pump light while keeping the

group-velocity dispersion (GVD) moderate; the bandwidth of the output spectrum tends to be larger at smaller cavity GVD, and the dechirped pulse duration is shorter [12]. The total dispersion of the cavity is $\sim 0.05 \text{ ps}^2$. The pump power is delivered through a multimode fiber with $105 \text{ }\mu\text{m}$ core diameter. The maximum power that the pump laser can provide is 18 W. A fused fiber pump–signal combiner fabricated in our laboratory is used to launch the 976 nm pump light into the cladding of the gain fiber. The pump coupling efficiency is $\sim 85\%$, and the loss to the signal is negligible ($<5\%$). Fiber collimators with lengths of 15 and 35 cm are spliced to the ends of the gain fiber. The fibers attached to the collimators are standard SMF with $6 \text{ }\mu\text{m}$ core diameter. The calculated splice loss between the DC gain fiber (with $10 \text{ }\mu\text{m}$ core diameter) and the standard passive fiber is about 1 dB. To reduce this loss the gain fiber was spliced to the passive SMF through a few millimeters of a fiber with about $8.5 \text{ }\mu\text{m}$ core diameter. With this intermediate fiber, the estimated loss of the fiber portion of the laser is reduced to about 0.5 dB. The pump–signal combiner was fused at the junction of the gain and passive fibers, so there is no unpumped gain fiber in the cavity. Wave plates are used in combination with a polarizing beam splitter to implement nonlinear polarization evolution. The spectral filter is created with a birefringent quartz plate. A high-power free-space isolator ensures unidirectional operation.

The introduction of the filter into the cavity is crucial to mode-locked operation. Experiments were performed using filters with a range of spectral bandwidths. Mode locking was easiest to achieve with a 15 nm bandwidth filter, but the output spectrum was narrow and the maximal achievable pulse energy was only about 20 nJ. The laser also tended to multiple pulse with this filter. On the other hand, stable mode locking was not achieved with a filter with 25 nm bandwidth even with 9 W pump power. At higher pump power the collimator was damaged during adjustment of the wave plates. The best performance was obtained with a filter with 20 nm bandwidth.

At appropriate pump power, self-starting mode locking occurs through the adjustment of the wave plates. The laser produces a stable pulse train with 70 MHz repetition rate. Single-pulse operation is monitored using an autocorrelator with 100 ps delay range in combination with a fast detector with 25 ps time resolution. Stable single pulsing is achieved with up to $\sim 8 \text{ W}$ of pump power and 2.2 W output power. This corresponds to a pulse energy of 31 nJ. The spectrum at maximal output power [Fig. 3(a)] is similar to the simulated result. The laser generates 4.5 ps chirped pulses, which are dechirped to 80 fs [Fig. 3(b)] outside the laser by a pair of diffraction gratings. With 15 nJ in 80 fs after dechirping, the peak power is approximately 200 kW. Lower loss in the dechirping stage can be obtained by the use of transmission gratings, which can provide $>80\%$ efficiency [13]. This would increase the peak power to 300 kW. The stability of the output pulse train was investigated using an rf spectrum analyzer. The resolution and dynamic range of the spectra are instrument limited, but still confirm the stable mode locking and absence of sidebands and harmonic frequencies to 70 dB below the fundamental frequency [Figs. 3(c) and 3(d)].

If the pump power is increased beyond 8 W, the laser sporadically switches to cw operation every few seconds. Attempts to stabilize mode locking by readjusting the wave plates fail. The time scale may suggest a thermal or thermo-optical origin of the instability, but more work needs to be done on this point.

The pulse energy achieved in our laser is comparable to that reported by An *et al.* [11], but the FWHM pulse duration is a factor of 2 less, and the pulse is much cleaner. Comparison of the respective autocorrelations indicates that the peak power is approximately five times that achieved by the laser of [11]. The peak power of our laser is comparable to that of a standard Ti:sapphire laser. As a secondary point, the laser described here is actually an efficient and

practical instrument that has been employed in experiments, while that of An *et al.* [11] employs free-space pumping and is quite inefficient.

In conclusion, we have demonstrated and characterized a dissipative-soliton laser based on double-clad fiber. The laser generates 80 fs pulses with ~200 kW peak power and well over 1 W average power. The pulse parameters are comparable to those of solid-state femtosecond lasers, but the laser benefits from fiber construction. A future goal will be complete fiber integration of this class of laser, without major sacrifice of performance. The performance reported here should already be attractive for many applications.

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Fig. 1.

(Color online) Numerical simulation results. (a) schematic of the laser. A ring cavity is simulated; the pulse enters the first SMF after the spectral filter (SF). Results of pulse duration and spectral evolution are shown at the bottom. Power spectrum (b) and intensity profile (c) of the laser output (after the SA).

Fig. 2.
(Color online) Schematic of the DC-pump all-normal dispersion fiber laser.

Fig. 3. (Color online) (a) Output spectrum. (b) Measured intensity autocorrelation. Inset: measured interferometric autocorrelation. (c) RF spectrum, 1 MHz span. (d) RF spectrum, 1 GHz span.