Femtosecond fiber lasers with pulse energies above 10 nJ

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A series of experiments aimed at determining the maximum pulse energy that can be produced by a femtosecond fiber laser is reported. Exploiting modes of pulse propagation that avoid wave breaking in a Yb fiber laser allows pulse energies up to 14 nJ to be achieved. The pulses can be dechirped to sub-100-fs duration to produce peak powers that reach 100 kW. The limitations to the maximum pulse energy are discussed.

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Femtosecond fiber lasers offer several advantages over bulk solid-state lasers, including greater stability, reduced alignment sensitivity, and compact design. Furthermore, fiber lasers are efficient. These qualities make short-pulse fiber lasers attractive for use in applications. However, mode-locked fiber lasers have lagged behind solid-state lasers with regard to pulse energy, which is limited by excessive nonlinear phase shifts accumulated on propagation through the fiber.

Femtosecond pulse formation in a fiber laser is dominated by the interplay between group-velocity dispersion (GVD) and the Kerr nonlinearity of the fiber. An effective saturable absorber is needed to start and stabilize the pulse train, and nonlinear polarization evolution (NPE)[1] is commonly employed for this purpose. Fiber lasers can be constructed entirely from anomalous-GVD fiber to operate in the soliton regime, where the pulse energy is limited by the soliton area theorem to ~0.1 nJ. At higher energy, wave breaking occurs and is manifested as multiple pulsing. Stretched-pulse lasers are constructed with fiber segments with normal and anomalous GVD[2] and have produced 100-fs pulses with energy as high as 2.7 nJ.[3] A laser based on double-clad Yb fiber produced 11.8 nJ chirped pulses (110 mW average power), which were dechirped to 200 fs outside the laser.[4] This laser contained two pairs of diffraction gratings in the cavity along with an acousto-optic modulator to initiate mode locking. Much of the laser cavity is actually not fiber; the unguided propagation and low efficiency of this laser naturally counter some of the main benefits of fiber sources.

Theoretically, wave breaking is suppressed if a pulse develops a monotonic frequency chirp as it propagates. Such a pulse evolves self-similarly; i.e., the pulse is always a scaled version of itself. These pulses tend toward a parabolic shape and accumulate a linear chirp. Ilday *et al.* recently showed that self-similar propagation can occur in a laser oscillator.[5] This represents a new regime of operation of mode-locked lasers. The evolution of the pulse as it traverses the laser is fundamentally distinct from the evolution in soliton and stretched-pulse lasers. The pulse is always positively chirped inside the laser, with the temporal duration varying from ~3 to ~50 times the transform limit. However, it can be dechirped outside the laser to the transform limit. According to numerical simulations, lasers based on self-similar evolution can generate stable pulses with energies 2 orders of magnitude larger than are possible by other means. In the initial experimental demonstration, the pulse energy was intentionally limited to 2 nJ to isolate the pulse evolution and avoid the limitations of other processes in the laser.[5] A preliminary result of 10 nJ pulse energy was mentioned. Ilday *et al.* also reported a Yb fiber laser that generated 5 nJ pulses as short as 50 fs by avoiding wave breaking, but the intracavity pulse evolution was not self-similar.[6] To our knowledge, this performance represents the highest peak power (85 kW) and average power (200 mW) produced by a femtosecond fiber laser to date.

Here we report an investigation of the maximum pulse energies and peak powers that can be obtained from a femtosecond fiber oscillator. Pulse energies as high as 14 nJ can be generated, and the pulses can be dechirped to ~100 fs duration. The results suggest that the pulse energy is limited by the use of NPE as the effective saturable absorber.

We built a Yb fiber laser similar to those described in Refs. 5 and 6 (Fig. 1). Highly doped (23,900 parts in 10^6) Yb gain fiber allows the use of a short (~60 cm) gain segment, which follows an ~4.65 m segment of single-mode fiber (SMF). Following the gain fiber, the pulse passes through 1.33 m of SMF.

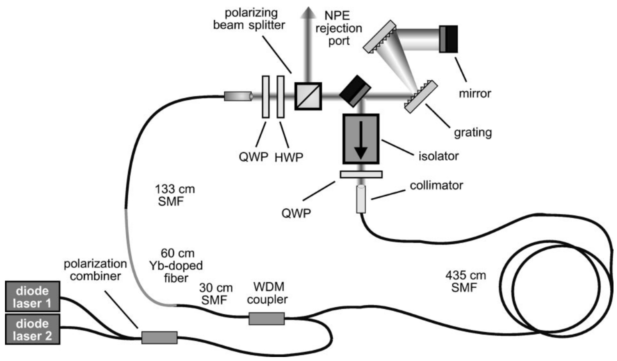

Fig. 1. Schematic of a fiber laser: HWP, half-wave plate; QWP, quarter-wave plate; WDM, wavelength division multiplexer.

The pulse then travels through quarter- and half-wave plates for the NPE and a pair of diffraction gratings that provide anomalous GVD before returning to the SMF. The laser is pumped in core by two fiber-coupled 500 mW diodes or by the polarization-combined outputs of two master oscillator power amplifiers. Approximately 800 mW of pump power at 980 nm can be coupled into the gain fiber, which produces a continuous-wave output power of ~500 mW. The output is taken from the NPE rejection port. The pulse repetition rate is 28 MHz in the experiments reported here. The laser produces positively chirped pulses, which are dechirped with a grating pair external to the cavity.

A systematic search for the maximum pulse energy and peak power was undertaken. Theoretically, self-similar pulses with increasing energy can be tolerated with increasing normal cavity GVD.[5] Starting with the cavity GVD near zero, the wave plates (i.e., the NPE) are adjusted to produce a stable pulse train with maximum power. Once the maximum energy is obtained at a given value of the net GVD, the GVD is then increased slightly and the wave plates are readjusted to produce a stable pulse train. In each case, single-pulse operation is verified by monitoring the pulse train with a fast detector (~0.5 ns resolution) and long-range (200 ps) autocorrelation. In addition, we monitor the spectrum with a high-resolution (0.07 nm) optical spectrum analyzer against the presence of secondary pulses.

Information about the intracavity pulse evolution is inferred from the magnitude of the anomalous GVD required to dechirp the pulse. A stretched-pulse laser has minima of the pulse duration near the middle of each segment of the dispersion map. For average output powers above ~50 mW (which corresponds to nominal single-pulse energies of ~2 nJ), stretched-pulse operation produces multipulsing. In contrast, the modes of operation that allow stable pulses with higher energies have minima of the pulse duration near either end of the SMF segment.

A convenient experimental signature of the self-similar regime is the characteristic spectral shape [Fig. 2(a)] with its approximately parabolic top and steep sides. In practice, the wave plates are adjusted to produce this spectrum. With a net GVD of $0.008 \pm 0.002\ \mathrm{ps}^2$, ~5ps pulses of 14 nJ energy were generated in self-similar operation. The corresponding average power was 400 mW. These pulses could be dechirped to 170 fs [Fig. 2(b)], which exceeds the Fourier-transform limit by ~15%. The anomalous dispersion required to dechirp the output pulses is approximately $0.25\ \mathrm{ps}^2$, whereas the intracavity grating pair provides $0.15\ \mathrm{ps}^2$. Therefore, we conclude that the pulse duration is minimum (but not transform limited) near the beginning of the SMF. These observations are consistent with the evolution observed in numerical simulations.[5] The resemblance of the spectra transmitted and rejected by the NPE port [Fig. 2(a)] suggests that NPE does not play a strong role in pulse shaping in this regime, as expected theoretically.[5] We found that a minimum of ~1 m of SMF is needed between the Yb gain fiber and the output collimator to obtain self-similar operation at 28 MHz. We suspect that the nonlinear phase shift in that segment enhances the NPE, which is otherwise rather weak owing to the large output coupling.

High-energy pulses are also produced by a mode of operation distinct from the self-similar propagation described above. Adjustment of the wave plates can produce the broader and more-structured spectrum of Fig. 3(a). In this case, the dispersion required to dechirp the output pulses is approximately $0.065\ \mathrm{ps}^2$, whereas the intracavity dispersion remains at $0.15\ \mathrm{ps}^2$. This implies that the pulse enters the SMF with a significant negative chirp, which would decrease in magnitude as the pulse approaches the gain fiber. We estimate that the pulse reaches minimum duration near the end of the SMF. Ilday *et al.* obtained pulses with 85 kW peak power in a similar mode of operation.[6] This evolution is not exhibited by numerical simulations that model the NPE as a lumped element after the gain medium, so we do not understand it thoroughly. The difference between the spectra transmitted and rejected by the NPE port [Fig. 3(a)] implies that the NPE plays a stronger role in the pulse shaping in this mode than in the self-similar mode. Pulse energies up to 13 nJ could be obtained. With a net cavity GVD of $0.004 \pm 0.002\ \mathrm{ps}^2$, the chirped pulse duration was ~3 ps, and the dechirped pulse duration was 85 fs [Fig. 3(b)], which is close to the transform-limited value obtained from the zero-phase Fourier transform of the power spec-

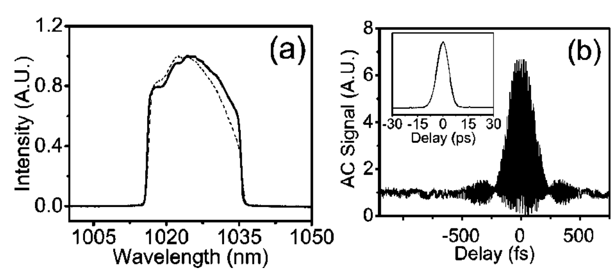

Fig. 2. (a) Spectra of 14 nJ pulses transmitted (dotted curve) and rejected (solid curve) from the NPE port in self-similar operation. (b) Dechirped autocorrelation of pulses rejected from the NPE port. Inset, intensity autocorrelation of the chirped output pulse.

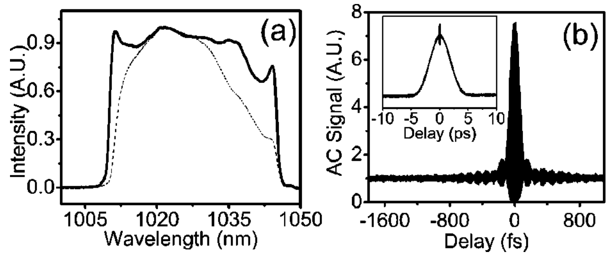

Fig. 3. (a) Spectra of 13 nJ pulses transmitted (dotted curve) and rejected (solid curve) from the NPE port. (b) Dechirped autocorrelation of pulses rejected from the NPE port. Inset, intensity autocorrelation of the chirped output pulse.

trum. With new, high-efficiency gratings the dechirped pulse energy is 10 nJ and the peak power is 100 kW.

At lower repetition rates, higher pulse energies are energetically possible for a given average power, but we were unable to exceed the pulse energies above. For example, at 20 MHz, 10 nJ pulses were generated in self-similar operation, but only ~1 nJ could be obtained in the mode with a pulse duration minimum near the gain fiber. At 15 MHz, only self-similar operation produced single pulsing, and the pulse energy was ~4 nJ.

It is important to consider likely limitations to the pulse energy. The 13 and 14 nJ pulses were generated with all the available pump power. However, the proximity of multipulsing states and the relative difficulty of observing stable single-pulse trains convince us that the pulse energy has essentially reached the limits determined by nonlinearity. On the basis of the experiments reported here, we cannot decisively conclude whether the pulse energy is limited by wave breaking or by overdriving of the NPE (i.e., by the accumulation of such a large phase shift that the transmission of the NPE decreases with intensity and thus works against pulse formation). However, numerical simulations that model the NPE as a lumped element, with transmittance increasing monotonically with pulse energy, predict that stable pulses should exist at energies exceeding 100 nJ.[5] This suggests that NPE is the current limitation. The experimental results support this suggestion to some extent. First, the highest pulse energies were obtained with the sacrifice of self-starting operation. The largest energies may be accommodated by biasing the NPE such that the transmittance does not increase adequately at low energy. Second, the maximum single-pulse energy that can be achieved declines when the cavity length becomes comparable to the beat length of the fiber (5–10 m), which suggests that uncontrolled birefringence may be playing a role. Finally, the observation of a small amount of excess bandwidth in the highest-energy self-similar pulses suggests that small deviations from a linear chirp can be tolerated in propagation. Further work is clearly needed to understand the limitations to pulse energy. Simulations that model the NPE as distributed along the fiber should help identify the limitation to pulse energy and understand the mode of pulse propagation that has minimum pulse duration near the gain fiber.

Owing to the proximity of multipulsing states, careful alignment of the wave plates is required to obtain the maximum pulse energies, and mode locking can be extinguished by environmental perturbations. On the other hand, with pulse energies in the range of 5–7 nJ, operation is stable indefinitely. The ~400 mW average powers are the highest obtained from a short-pulse fiber laser. This laser achieves greater than 50% optical efficiency when mode locked. Advances in pump diodes and the use of photonic bandgap fiber for dispersion control[7] should allow the development of stable, integrated versions of the present laser.

In conclusion, we have experimentally demonstrated that a fiber laser can generate ~100 fs pulses with pulse energy greater than 10 nJ. Numerical simulations and preliminary observations suggest that NPE limits the pulse energy, and work is in progress to understand and circumvent this limitation.

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