Generation of 50-fs, 5-nJ pulses at 1.03 μm from a wave-breaking-free fiber laser

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We report the generation of 6-nJ chirped pulses from a mode-locked Yb fiber laser at 1.03 μm. A linear anomalous-dispersion segment suppresses wave-breaking effects of solitonlike pulse shaping at high energies. The dechirped pulse duration is 50 fs, and the energy is 5 nJ. This laser produces twice the pulse energy and average power, and approximately five times the peak power, of the previous best mode-locked fiber laser. It is to our knowledge the first fiber laser that directly offers performance similar to that of solid-state lasers such as Ti:sapphire. © 2003 Optical Society of America

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Short-pulse fiber lasers can have widespread applications as practical alternatives to bulk solid-state lasers, offering compact size, better stability, and freedom from misalignment. However, fiber lasers have generated pulses with energies significantly lower than those of solid-state lasers because of the inherent fiber nonlinearity.

The dynamics of femtosecond pulse formation is dominated by an interplay between anomalous group-velocity dispersion (GVD) and positive Kerr nonlinearity of the fiber.[1] Fiber lasers can be constructed entirely from anomalous-GVD fiber to operate in the soliton regime or with segments to provide normal GVD and anomalous GVD to operate in the stretched-pulse regime.[2] At 1 μm, standard fiber has normal dispersion only. Thus Nd- and Yb-doped fiber lasers at 1 μm have been constructed with prisms or diffraction gratings to provide the necessary anomalous GVD. Recently an Yb fiber laser that employs a photonic crystal fiber for dispersion control generated 100-fs and 1-nJ pulses.[3] Highly nonlinear photonic crystal fiber can be expected to present a formidable barrier to achieving higher energies. Stretched-pulse Er-doped fiber lasers have generated ~100-fs, 2.7-nJ pulses, which we believe are the highest pulse energy and peak power from a femtosecond fiber laser.[4] Significant energy resides in the wings of the pulse, which extend to ~1 ps. Generation of 50-fs and 1-nJ pulses from a Nd fiber laser has been reported[5]; these pulses have approximately the same peak power as the 2.7-nJ laser. An Yb fiber laser generated 50-fs and 0.7-nJ pulses.[6] The highest average power generated directly from a femtosecond fiber laser is ~100 mW.[4,6]

The stretched-pulse technique successfully reduces, but does not eliminate, the effects of nonlinearity through dispersion management. Direct management of nonlinearity has been proposed for substantial increases in pulse energy[7] but has not been demonstrated experimentally. Nonlinearity can limit pulse energy through either of two mechanisms: (i) Excess energy can result in wave breaking through the combined effects of dispersion and nonlinearity. (ii) The artificial saturable absorber (SA) can be overdriven at high peak powers, which will lead to multiple pulsing. The former limitation is the more fundamental of the two, which motivates us to explore it.

Here we recognize the importance of minimizing Kerr nonlinearity in the anomalous-GVD segment of a stretched-pulse laser designated for maximum pulse energy. We first consider the differences between the extreme cases of nonlinear and completely linear segments of anomalous GVD. The availability of highly doped Yb fiber permits partial decoupling of gain filtering from nonlinear pulse shaping. Extensive numerical simulations demonstrate that the limitation on pulse energy through wave breaking can be suppressed with a linear anomalous-GVD segment and a short gain fiber. We exploit this approach to demonstrate a fiber laser that maximizes the pulse energy and the peak power.

Although it is well known that solitonlike effects in anomalous-GVD fiber need to be minimized for best pulse quality,[8] these effects have not been fully explored experimentally, nor have their implications for pulse shaping been investigated. We focus on a cavity design similar to that of Ref. 6 to permit direct comparison with experiment. The oscillator is modeled to comprise three sections: a section of single-mode fiber (SMF), followed by a short gain section, and a final section with anomalous GVD. Diffraction gratings or a hypothetical fiber (with a mode area equal to that of the SMF) provides anomalous GVD for the linear and the nonlinear cases, respectively. For increased computational speed the SA is modeled with a transfer function of the form $u(z,t) \rightarrow u(z,t)\{(1-\xi) + \xi \sin^2[\pi|u(z,t)|^2/2I_{\rm sat}]\}^{1/2}$, where $u(z,t)$ is the field envelope, ξ is the modulation depth, and $I_{\rm sat}$ is the saturation intensity. Several transfer functions were tried, and the exact form was not found to be important for pulse energies that avoid overdriving the SA. Pulse propagation is described by an extended nonlinear Schrödinger equation that accounts for the effects of GVD, Kerr nonlinearity, and gain for Yb-doped fiber. Gain in the Yb-doped fiber is modeled as saturating with total energy and has a parabolic frequency dependence with a bandwidth of 40 nm.

The qualitative features of stretched-pulse operation are determined primarily by the total GVD (β_{net}) and to a lesser extent by the lengths of the normal- and anomalous-GVD sections. If the gain fiber is sufficiently short, most of the nonlinear shaping occurs in the SMF, decoupled from the bandwidth filtering in the gain fiber. Numerically simulated cavities with linear and nonlinear segments of anomalous GVD produce stable pulses with similar energies for $\beta_{\text{net}} \lesssim 0$. However, for increasing $\beta_{\text{net}} > 0$ (normal dispersion) the maximum pulse energy increases much faster when the anomalous-dispersion segment is linear. Qualitatively, if the anomalous-GVD section of the laser has negligible Kerr nonlinearity, the pulse evolves to a shape that maintains a monotonic chirp even in the presence of strong nonlinearity.[9] A higher pulse energy generates increased bandwidth, which in turn leads to larger pulse stretching. Increased stretching reduces the peak power, so nonlinear and dispersive effects balance. For instance, at $\beta_{\text{net}} = 0.012\ \text{ps}^2$, wave breaking can be avoided at a pulse energy that is ~25 times higher than that of a laser with a nonlinear anomalous-GVD section. We emphasize here that the predicted increases in energy may not be achieved experimentally because of competing effects such as overdriving the artificial SA. If an interferometric SA such as nonlinear polarization evolution[10] (NPE) is used, there is a trade-off between avoiding overdriving the NPE and ease of self-starting.

Following this approach, we built an Yb fiber laser (Fig. 1). A unidirectional ring geometry was chosen for self-starting operation.[11] The pump light is delivered by a wavelength-division multiplexing (WDM) coupler. The Yb fiber is only 23 cm long because of its high doping concentration (23,600 parts in 10^6). The 980-nm pump diode delivers 550 mW of power into a SMF. Mode-locked operation is initiated and stabilized by NPE, and the output is taken from the NPE rejection port.[12] Following the free-space section, there is a segment of SMF (cutoff wavelength, 920 nm). One can vary β_{net} of the cavity by adjusting the grating spacing. The laser produces positively chirped pulses, which are dechirped with a grating pair external to the cavity. We verified single-pulse operation by monitoring the pulse train with a fast detector (~0.5-ns resolution) and long-range (200 ps) autocorrelation.

The length of the SMF and β_{net} were varied systematically to optimize pulse energy and peak power. The SMF was initially chosen to be 3.5 m long (50-MHz repetition rate). The pulse energy could be increased while β_{net} was reduced from an initial value of $-0.020\ \text{ps}^2$. At $\beta_{\text{net}} = 0.001 \pm 0.002\ \text{ps}^2$ the pulse energy reached 4.5 nJ, limited by the pump power. The dechirped pulse duration was 70 fs.

To determine the maximum pulse energy we lowered the repetition rate to 40 MHz by increasing the length of the SMF by 1 m. For the same β_{net}, pulse energy could not exceed 4.1 nJ. Therefore β_{net} was increased. The maximum pulse energy of ~6 nJ (235-mW average power) was obtained at $\beta_{\text{net}} = 0.004 \pm 0.002\ \text{ps}^2$. The corresponding power spectra from the NPE port and a beam reflected from the first grating are shown in Fig. 2. The pulse energy exiting the Yb fiber was determined to be ~7.5 nJ, and the energy of the pulse coupled into the SMF was estimated as ~0.3 nJ. With this information, accurate numerical simulations could be achieved with experimentally determined parameters. The spectrum produced by the numerical simulations agrees with the experimental spectrum (Fig. 2, inset). The wings of the spectrum decay faster than those of a Gaussian pulse, which describes the pulse shape for a typical stretched-pulse laser with a nonlinear anomalous-GVD section.[13]

The interferometric autocorrelation of the dechirped pulses is presented in Fig. 3, along with the autocorrelation of the simulated pulses. The inferred pulse duration is 50 fs. Comparison of the intensity autocorrelations before and after dechirping reveals a compression factor of 30 (Fig. 3, inset). The dechirped pulse energy is 5 nJ, owing to loss at the grating compressor. Overall, the pulse energy and the average power obtained directly from the laser are improved by factors of 2.0 and 2.3, respectively, compared with those shown in Ref. 4. The peak power is ~80 kW, ~5 times greater than that of previous top-performance

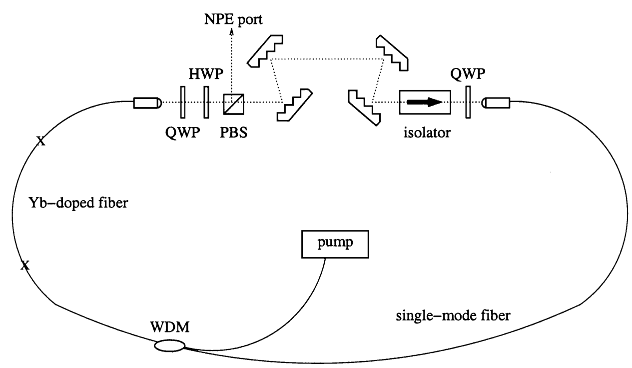

Fig. 1. Experimental setup: HWP, half-wave plate; QWPs, quarter-wave plates; PBS, polarizing beam splitter.

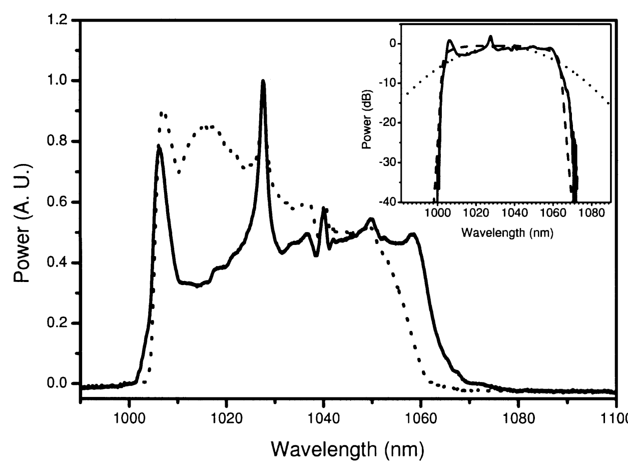

Fig. 2. Spectra of the pulse from the NPE rejection port (solid curve) and of the pulses from a reflection off a diffraction grating (dashed curve). Inset, experimental (solid curve) and calculated (dashed curve) spectra and a Gaussian fit (dotted curve) plotted on a logarithmic scale.

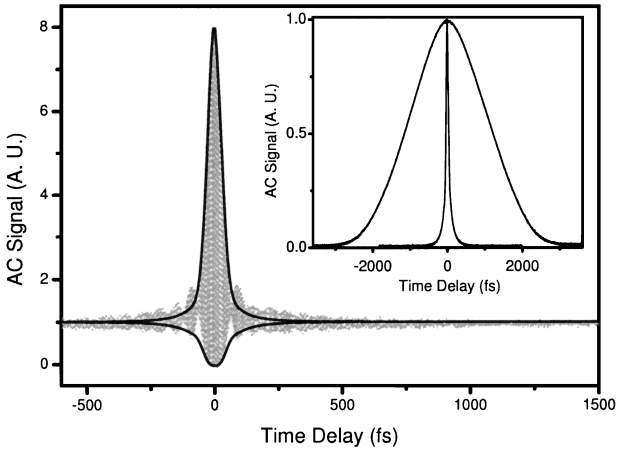

Fig. 3. Experimental autocorrelation of the deciphered pulses (gray symbols) along with the envelopes of the autocorrelation produced by numerical simulation (solid curves). Inset, intensity autocorrelations of pulses directly from the laser and the dechirped pulses.[2]

fiber lasers.[4,5] In addition, this laser is more practical than previous top-performance lasers because it is diode pumped with a wavelength-division multiplexing coupler.

The pulse energy was limited not by pump power but by the onset of double pulsing. According to our calculations, at least order-of-magnitude higher pulse energies should be possible by increasing β_{net}. Experimentally, mode locking becomes difficult for $\beta_{\mathrm{net}} > 0.004\ \mathrm{ps}^2$. Increasing the SMF's length by 2 m did not permit operation at larger β_{net}. We conclude that the pulse energy is currently limited to 6 nJ, and we attribute the difficulty in mode locking at larger β_{net} to failure of NPE action.

In conclusion, we have demonstrated an Yb fiber laser that generates what we believe are the highest pulse energy, peak power, and average power of any mode-locked fiber laser. Its efficiency is 43%, which to our knowledge is the highest of any short-pulse laser. The improvements in pulse energy and peak power are possible through the prevention of soliton-like effects in the anomalous-GVD segment and by partial decoupling of gain filtering from nonlinear pulse shaping. Preliminary observations and calculations indicate that this device is a first step toward a laser that supports self-similar pulses.[14–16] We are conducting research on this exciting possibility. The stability of the laser is similar to that of the all-fiber stretched-pulse Er lasers in our laboratory. We attribute the high stability to diode pumping with a wavelength-division multiplexer and to the existence of fewer mode-locking regimes because of the linearity of the anomalous-GVD section. Fiber lasers with bulk components can thus be viewed as a class of devices that offers performance comparable with that of bulk solid-state lasers with nearly all the advantages of stability and compactness of all-fiber lasers.

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