Generation of 36-femtosecond pulses from a ytterbium fiber laser

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Abstract: By optimizing the cavity dispersion map, 1.5-nJ pulses as short as 36 fs are obtained from a Yb-doped fiber laser. Residual higher-order dispersion currently limits the pulse duration, and it should be possible to generate pulses as short as 25-30 fs with Yb-doped fiber.

OCIS codes: (140.3510) Lasers, fiber; (320.7090) Ultrafast lasers

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Mode-locked fiber lasers have the potential to supplant solid-state lasers in some applications owing to their excellent stability, freedom from misalignment, and compact size. These attributes have motivated a substantial development effort over the past decade. The majority of progress has been made with Er- (1.55 μm) and Nd-doped (1 μm) fibers. Applications ranging from telecommunication to nonlinear microscopy have motivated exploration of correspondingly wide ranges of modelocking techniques and parameters. In the context of photophysical applications such as nonlinear microscopy, there is greatest interest in pulse repetition rates of tens to hundreds of megahertz, pulse durations of ~100 fs, and maximum

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pulse energy. Pulse energies as high as 2.7 nJ have been produced by stretched-pulse fiber lasers [1], and pulses less than 100 fs in duration were generated.

Recently, ytterbium has attracted much attention as a gain ion because it offers several advantageous properties. Spectroscopic properties include high quantum efficiency, absence of ground-state and excited-state absorptions, a long upper-state lifetime, and broad gain spectrum. A practical feature is that Yb can be pumped in convenient absorption bands at 915 and 980 nm. As a result of these properties, Yb-doped fiber seems likely to supercede Nd-doped fiber among materials that emit near 1 μm.

In the past year, several advances in the performance of Yb fiber lasers have been reported. The first mode-locked Yb fiber laser to generate pulse energies of ~1 nJ was described by Lim *et al*. [2]. This performance was comparable to that obtained with Er and Nd fibers, and pulses as short as 52 fs were measured. By suppressing the wave-breaking effects of soliton-like pulse shaping at high pulse energies, Ilday and co-workers were able to demonstrate a Yb fiber laser that generates 50-fs pulses with 5 nJ energy [3]. The 80-kW peak power of this laser is five times the previous maximum peak power from a femtosecond fiber laser [1,4]. These lasers employ only single-mode fibers. They are pumped in-core by diodes and as a result are stable and reliable instruments: they readily operate for weeks without adjustment. The use of diffraction gratings for control of group-velocity dispersion (GVD) in the lasers reported by Lim *et al*. [2] and Ilday *et al.* [3] counters some of the benefits of a waveguide device. As a step toward an integrated source, Lim *et al.* demonstrated a Yb fiber laser that employed photonic-crystal fiber for dispersion control [5]. This laser generated 1-nJ and 100-fs pulses but was not self-starting.

The highest-power standard mode-locked Ti:sapphire lasers produce 20-nJ pulses, but 5-10 nJ is more typical. Extended-cavity Ti:sapphire lasers generate ~150-nJ pulses, at repetition rates ~5 MHz and with increased complexity [6]. Theoretical calculations show that pulse energies of tens of nanojoules should be possible through the suppression of wave-breaking in Yb fiber lasers [7]. Thus, it appears that fiber lasers will be able to supply pulse energies comparable to those of solid-state lasers.

Given the recent advances in pulse energy, it seems appropriate to turn attention to the pulse duration, another parameter in which fiber lasers have historically lagged behind solid-state lasers. The shortest pulses produced by an Er fiber laser had duration 63 fs [8], while a Nd fiber laser generated pulses as short as 42 fs [4]. Here we report the results of an effort to minimize the pulse duration of a Yb fiber laser. By optimizing the group-velocity dispersion of the laser, pulses as short as 36 fs are generated. To date, these are the shortest pulses produced by a fiber laser. The pulse duration is limited by third-order dispersion (TOD), and ultimately it should be possible to generate pulses below 30 fs in duration.

Numerical simulations (details of which can be found in [2] and [3]) guided the design of the Yb fiber laser. The laser is modeled as 3.5 m of single-mode fiber (SMF), followed by 20 cm of Yb-doped gain fiber, 20 cm of SMF (which represents a collimator), a transfer function for nonlinear polarization evolution, and a linear dispersive delay (which is implemented experimentally with diffraction gratings). The TOD of the fiber and gratings are included in the simulations. In addition, the gain is modeled as a complex Lorentzian susceptibility [9], in place of the simple parabolic-gain model employed previously. The calculations show that the pulse duration is minimized in a cavity with segments of normal and anomalous dispersion, and net anomalous dispersion. Under these conditions strong soliton-like pulse-shaping occurs, along with substantial pulse-stretching. That is, the laser should be operated in the stretched-pulse regime, not the wave-breaking-free [3] or self-similar [7] regimes. The minimum pulse duration is obtained with net dispersion values between zero and $-0.01\ \mathrm{ps}^2$. A representative stable solution is shown in Fig. 1. The power spectrum exhibits significant structure. The FWHM pulse duration is ~40 fs, and the intensity profile includes secondary pulses or wings that typically encompass ~20% of the pulse energy.

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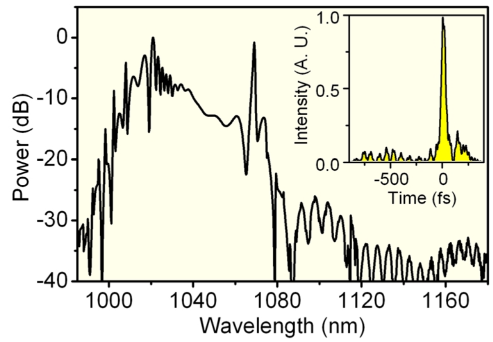

Fig. 1. Results of numerical simulations of the Yb fiber laser. Main figure: power spectrum plotted on logarithmic scale. Inset: temporal intensity profile of dechirped output pulse.

The experimental arrangement, which is similar to that described in [2], is illustrated in Fig. 2. The Yb fiber (NA = 0.12, core diameter 6 μm, 23,600 ppm doping, Institut National d'Optique, Canada) is 23 cm long to minimize nonlinear effects during amplification. Coupling in and out of the fiber section is facilitated with fiber-pigtailed collimators (OFR, Inc.). A maximum of 300 mW pump light at 980 nm from a laser diode is delivered to the cavity with a 980/1030-nm wavelength division multiplexer (Lightel Technologies, Inc.). The GVD and TOD of the fibers are estimated to be ~23 fs^2/mm and ~70 fs^3/mm, respectively. An optical isolator (OFR, Inc.) ensures unidirectional operation. The repetition rate of the laser was set to ~50 MHz, which corresponds to a fiber length sufficiently short to keep nonlinear effects manageable and to minimize difficulties with initiation of modelocking associated with residual birefringence. Shorter cavity lengths are possible, but the energy stored in the cavity would not be sufficient for nanojoule output energies. Once the fiber length was chosen, the net cavity dispersion was optimized for shortest pulse duration by adjusting the grating separation (~45° angle of incidence, 600 lines/mm groove density, GVD of -1400 fs^2/mm, and TOD of 2100 fs^3/mm, Optometrics LLC). As the dispersion was varied from large anomalous values toward zero, shorter pulses were observed, as expected. As is typical for fiber lasers, several distinct mode-locked states are accessible for a given choice of cavity dispersion, by adjustment of the wave-plates that control the nonlinear polarization evolution (NPE) [10]. The variation of the spectral shape, pulse energy and duration among different mode-locked states is most significant for small anomalous dispersion values. Because of this variation, a complete characterization of the minimum pulse duration for varying dispersion is not possible. Experimentally, the shortest pulses were obtained for dispersion values close to -0.01 ps^2. Increasing the dispersion further, so that the net dispersion was normal, produced longer pulses, and larger pulse energies could be supported. Highly-chirped pulses were switched out of the NPE rejection port and dechirped with a pair of diffraction gratings external to the cavity.

Measurements of the shortest pulses produced by the Yb fiber laser are shown in Fig. 3. The autocorrelation implies a FWHM pulse duration of 36 fs (assuming a gaussian pulse shape), which agrees with the pulse duration retrieved by fitting the measured interferometric autocorrelation and the power spectrum [11]. With 270 mW pump power, the output-pulse energies before and after dechirping are 1.8 and 1.5 nJ, respectively. We estimate that ~30% of the pulse energy resides in the secondary lobe that is visible in the autocorrelation. The resulting peak power is thus ~25 kW. Some care in setting the waveplates that control the NPE is required to obtain the shortest pulses. However, slightly longer pulses (40-45 fs) can be obtained quite routinely.

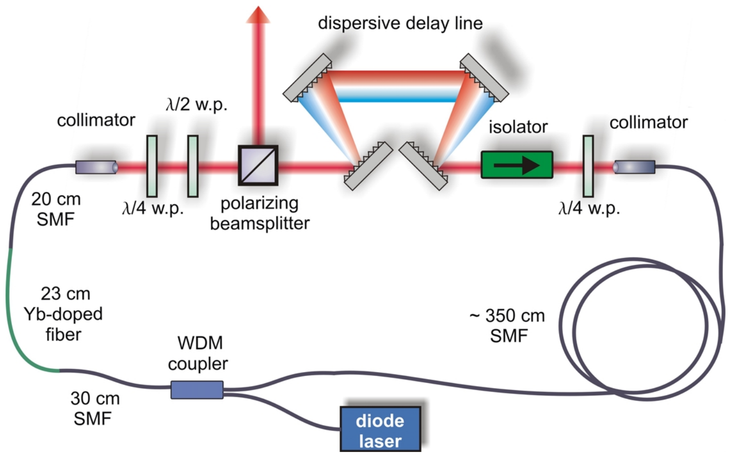

Fig. 2. Schematic of the Yb fiber laser. w.p.: waveplate.

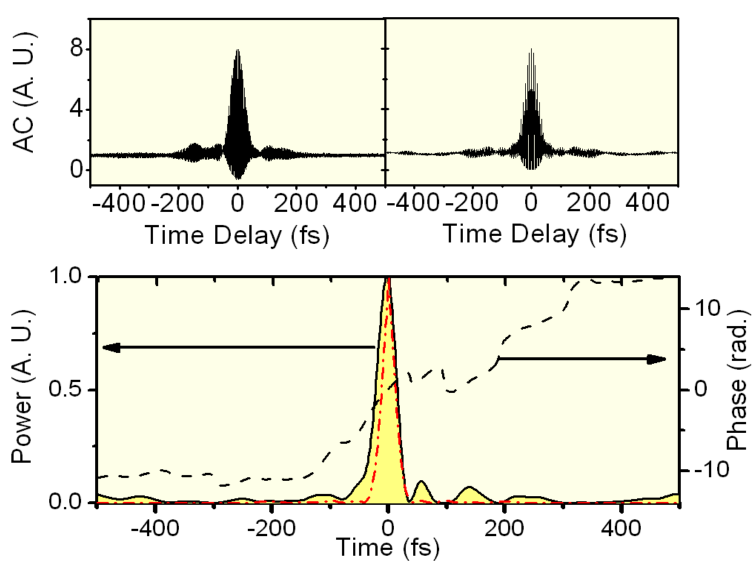

Fig. 3. Output of the Yb fiber laser. Measured interferometric autocorrelation (top left panel) along with the interferometric autocorrelation of the pulse retrieved by PICASO (top right panel). Bottom panel: retrieved intensity and phase profiles compared to the transform-limited pulse (dash-dotted line).

The minimum pulse duration is ~30% larger than the transform-limited value (~27 fs), which is obtained from the zero-phase Fourier transform of the power spectrum (Fig. 4). The deviation from the transform limit is somewhat larger than that observed in previous short-pulse fiber lasers [12]. The third-order dispersion of the laser is ~0.001 ps^3, which presents a significant impediment to the formation of sub-50-fs pulses.

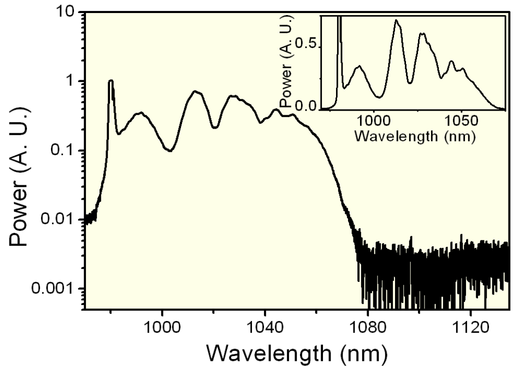

Fig. 4. Measured power spectrum plotted on semi-logarithmic scales. The component at 980 nm is unabsorbed pump light. The inset shows the spectrum on linear scales.

We believe that the bandwidths of components such as the collimators and wavelength-division multiplexing coupler used for pumping slightly limit the achievable pulse spectrum. With improvements in these components, and by reduction of third-order dispersion of the cavity, reduction of the pulse duration to ~30 fs may be possible. The power spectrum of the 36-fs pulses is already broader than the ~40-nm gain bandwidth of Yb-doped fiber. There is currently great interest in the development of ultra-broadband sources, and it is naturally desirable to extend the present performance to even broader spectra/shorter pulses. Larger spectral widths may be possible with stronger self-phase modulation, but the initiation and stability of mode-locked operation will be increasingly difficult. The structured spectrum of Fig. 4 is qualitatively similar to the spectra produced by mode-locked solid-state lasers operated close to the limitations of the gain bandwidth. Among solid-state lasers that emit near 1050 nm, we are not aware of pulse durations less than 60 fs, which are achieved by Nd:glass [13] and Yb:glass [14] lasers.

In conclusion, we have demonstrated a Yb fiber laser that produces 36-fs pulses. The laser is a stable instrument, so we expect that the short pulses demonstrated here will find applications in ultrafast science. Pulses as short as 25-30 fs should be obtained in the future.

Acknowledgments

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