Generation of pulses shorter than 200 fs from a passively mode-locked Er fiber laser

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The generation of stable bandwidth-limited pulses as short as 180 fs with pulse energies as high as 100 pJ is demonstrated with a passively mode-locked Er fiber laser. These are to our knowledge the shortest and most intense pulses directly produced from a mode-locked Er fiber laser to date. A wide stability regime is achieved by using a dispersion-compensated cavity and employing nonlinear polarization evolution for passive amplitude modulation.

Single-mode rare-earth-doped fibers[1] have recently been the subject of intensive investigations because of their applications as optical amplifiers and lasers. In particular, fiber laser oscillators[2] offer an opportunity for compact ultrashort-pulse sources.[3–5] Diode-pumped Nd fiber lasers have delivered pulses as short as 100 fs,[6] and with an ion-laser-pumped version pulse widths as short as 38 fs have been achieved,[7] which resulted in the mode locking of the full inhomogeneous bandwidth of Nd:silica glass. In contrast, passively cw mode-locked Er fiber lasers have delivered pulses of 290-fs widths,[8] well short of the potential limit of ≈60 fs set by the ≈40-nm bandwidth of Er silica glass.[9] One of the problems of passively mode-locked Er fiber lasers is their limited range of stable operation. For example, the figure-eight laser configuration[5,10] has recently been measured to allow pump-power fluctuations not larger than 1% for stable pulse generation. In other research stable pulse generation has not been observed at all[8] or has been limited to operation of the mode-locked laser close to threshold.[11,12] Pulses generated by mode-locked Er fiber lasers have typically occurred in chaotic bunches with no well-defined repetition rates. Here we describe a new Er fiber laser configuration that produced stable trains of pulses as short as 180 fs, with pulse energies of as much as 100 pJ. We achieve this by using a short Er fiber length mode locked through nonlinear polarization evolution and an extended cavity design with intracavity dispersion compensation.

The experimental setup is shown in Fig. 1. We used a 67-cm length of germanoaluminosilicate fiber with an Er doping level of $\approx 5 \times 10^{18}$ ions/cm^3. The numerical aperture was N.A. = 0.19, and the core diameter was 4.0 μm, which resulted in a cutoff wavelength of the first higher-order mode of 1.0 μm. We estimated the fiber group-velocity dispersion to be $\beta_2 \approx +4000 \pm 4000$ fs^2/m and calculated the third-order dispersion coefficient to be $\beta_3 \approx +90{,}000$ fs^3/m at the operation wavelength of 1.55 μm. The intracavity dispersion was adjusted with a single polarizing ZnS prism pair with a single-pass negative group-velocity dispersion of $\beta_2 = -10{,}500$ fs^2/m and a third-order dispersion coefficient of $\beta_3 = -22{,}000$ fs^3/m. Thus, in addition to second-order dispersion compensation, the cavity also allows for partial third-order dispersion compensation. The launch end of the fiber was butt coupled to a mirror totally reflecting at 1.55 μm. The free fiber end was cleaved at an angle of at least 15° to eliminate backreflections. The cavity was completed with a 12-mm antireflection-coated intracavity collimating lens and a 50% output coupler. The fiber was pumped with the 528-nm line from an argon laser with a maximum of 500-mW launched power. The maximum cw output power at 1.55 μm was 50 mW. Lasing threshold was obtained with 12-mW launched power. Mode locking was initiated with a weak modulation (<10% modulation depth) from an intracavity acousto-optic modulator with an estimated single-pass dispersion of 6500 fs^2. Femtosecond pulses were generated as a result of passive amplitude modulation's arising from nonlinear polarization evolution[4] in the Er-doped fiber. The polarization state in the fiber was adjusted for optimum pulse quality by means of polarization controllers. Once femtosecond pulses were obtained the modulator could be switched off and the pulses were self-sustaining.

We obtained the shortest pulses with a prism separation of 1.22 m. The corresponding total intracav-

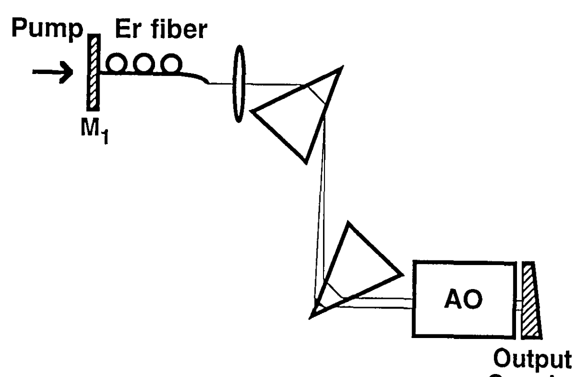

Fig. 1. Experimental setup of the passively mode-locked fiber laser. AO, acousto-optic modulator; M_1, mirror.

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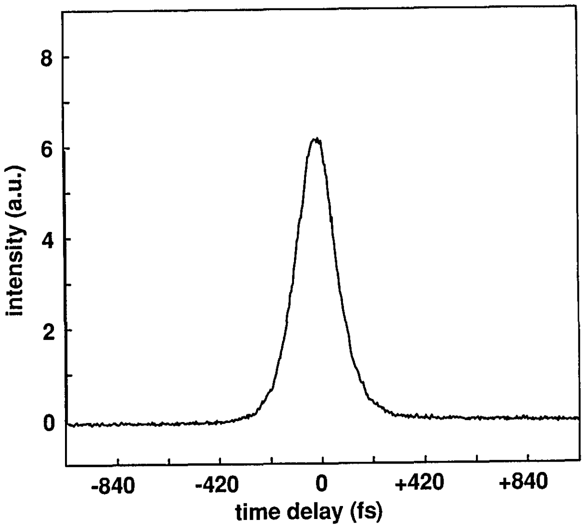

Fig. 2. Autocorrelation trace of generated pulses. The FWHM width is 180 fs assuming a $sech^2$ pulse shape.

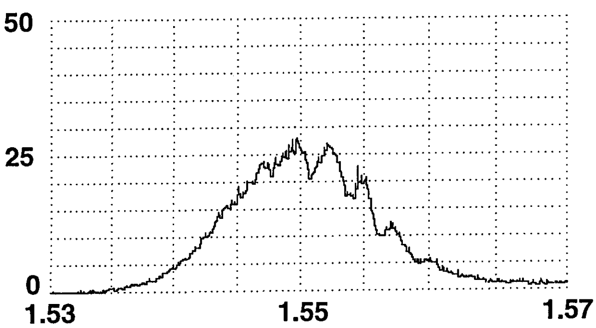

Fig. 3. Spectrum of generated pulses. The FWHM is 14 nm, the resolution is 0.1 nm, and the scales are 5 nm/division.

ity dispersion may then be calculated as approximately -7000 ± 5000 fs^2. An autocorrelation trace is shown in Fig. 2. Assuming a $sech^2$ pulse shape the pulse duration is 180 fs FWHM. The power spectrum is given in Fig. 3. The width of the spectrum is 14 nm, and the time–bandwidth product $\Delta\nu\Delta t$ is 0.31, indicating that the pulses are bandwidth limited. We believe that the structure on the pulse spectrum results from small residual reflections in the modulator, which was not antireflection coated at the operation wavelength. Spectral sidebands typical for mode-locked figure-eight lasers[12] were not observed. The relatively smooth spectrum is also indicative of the absence of any effects that are due to third-order dispersion, which typically leads to pulse breakup and a split spectrum.[13]

Unlike with most all-fiber Er lasers, the mode-locked pulse trains were stable and background free (the background was measured to be smaller than 3×10^{-6}). A photograph of a stable pulse train at the fundamental cavity frequency of 55 MHz is shown in Fig. 4. Stability was achieved with launched pump powers between 150 and 250 mW, which resulted in 3–6 mW of cw mode-locked power. Hence the maximum extractable pulse energy was $\approx$100 pJ. The nonlinear phase delays inside the stability regime may be calculated to be between 1.5π and 3.0π per round trip, where we assumed an average intracavity pulse width of 210 fs. Thus the fiber laser is more nonlinear compared with bulk solid-state lasers, where nonlinear phase delays larger than 2π are uncommon.

Although the shortest pulses were obtained with the conditions discussed above, stable pulse trains with durations in the several hundred femtosecond range could be produced over a fairly large parameter range. Note that the pulse and spectral widths inside the stability regime varied only by 10–30% as a function of pump power, where the longest pulses were observed with the lowest pump power. Further, the prism separation could be changed by ± 3 cm without affecting the pulse width. The pulse widths were not critically dependent on fiber length. An increase in fiber length by as much as 20 cm was found to have no measurable effect. However, for fiber lengths shorter than 65 cm it became increasingly difficult to obtain emission at 1.55 μm, since the three-level nature of the Er lasing transition favors lasing on the 1.53-μm band for large laser inversions. The resulting pulse widths were then approximately 1 ps, since the 1.53-μm band has a smaller bandwidth compared with the 1.55-μm band.

A degradation of the pulse train could be observed when the pump power was increased above the stability range. Most common was the development of a cw background (observable as spikes on the mode-locked spectrum), which removes excess energy from the mode-locked pulses. Less frequently, higher harmonic mode locking or the development of large satellite pulses was observed. Keeping the modulator on while the pump power was increased hindered the development of a cw background, which generally allowed higher stable pulse energies but at the same time led to more severe instabilities such as unstable repetition rates. Note that energy limitations for mode-locked fiber lasers were first measured in a figure-eight laser,[10] where the maximum pulse energies were typically an order of magnitude smaller.

There are several differences between our laser design and previously reported femtosecond Er fiber

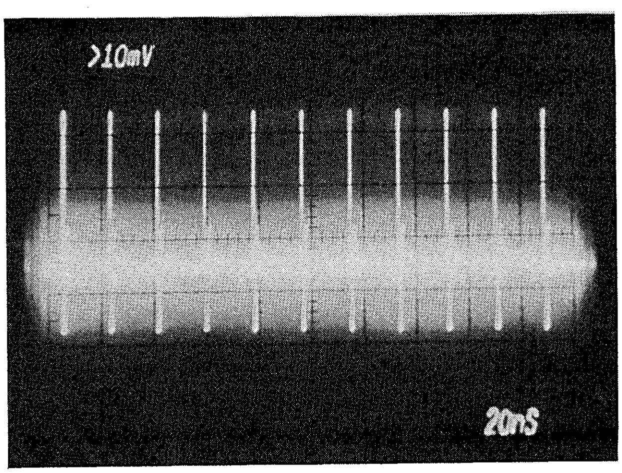

Fig. 4. Photograph of stable pulse train in the Er fiber laser.

lasers. Some of the factors that may be important for explaining the improved stability achieved in our experiments are as follows: (1) Our research has been performed in a dispersion-compensated cavity, which allows for chirp linearization through the interaction of dispersion and self-phase modulation in the fiber. Previous research has utilized fixed, negatively dispersive fibers, which may lead to instabilities, e.g., through the soliton self-frequency shift.[12,14] (2) Our short fiber length (< 1 m) reduces the amount of pulse reshaping per pass. (3) Mode locking is achieved through nonlinear polarization evolution. In contrast to the nonlinear loop mirror used in the figure-eight laser, the power dependence of the nonlinear loss can be tuned by adjusting the polarization controller, and the ratio of the nonlinear loss to the nonlinear phase shift is smaller. Note that the large amount of passive amplitude modulation possible with a figure-eight laser is advantageous for self-starting[15] but also increases the susceptibility to a self-Q-switching instability.[16] Owing to the long spontaneous lifetime ($\sim$10 ms) of the Er lasing transition, stability against Q switching is an important consideration.

In conclusion, we have demonstrated stable pulse generation in passively mode-locked Er fiber lasers over a large range of cavity parameters. Laser instabilities were reduced by minimizing intracavity reflections and reducing passive amplitude modulation with respect to passive frequency modulation. Pulse energies were maximized by using short fiber lengths. These optimizations have resulted in what are to our knowledge the shortest and most intense pulses obtained from a passively mode-locked Er fiber laser to date.

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