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Self-similar erbium-doped fiber laser with large normal dispersion

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Abstract

We report a large normal dispersion erbium-doped fiber laser with self-similar pulse evolution in the gain fiber. The cavity is stabilized by the local nonlinear attractor in the gain fiber through the use of a narrow filter. Experimental results are accounted for by numerical simulations. This laser produces 3.5 nJ pulses, which can be dechirped to 70 fs with an external grating pair.

Self-similar evolution of parabolic pulses is of great interest in fiber optics. Such pulses avoid wave breaking in the presence of nonlinearity [1], so they are exploited in high-power amplifiers [2]. Excessive nonlinear phase accumulation commonly limits the pulse energy in fiber lasers, and attention has turned to exploiting self-similar pulses in oscillators. Ilday *et al.* [3] reported a fiber laser with self-similar evolution in passive normal-dispersion fiber. In this case the gain plays a minimal role, and the spectral bandwidth does not change much as the pulse traverses the cavity.

A remarkable feature of the self-similar solution (referred to as a “similariton”) in an amplifier is that it is a nonlinear attractor [2]. Recently Oktem *et al.* [4] developed an erbium-doped (Er-doped) fiber laser based on similariton formation in the gain segment. That segment is then a local nonlinear attractor within the laser cavity. Soliton formation in a segment of anomalous-dispersion fiber works along with a bandpass filter to prepare a proper seed pulse before the amplifier, which allows the pulse to reach the asymptotic parabolic solution in the gain fiber. Renninger *et al.* [5] used a narrow filter to prepare the initial pulse before the gain and generate parabolic pulses from an all-normal-dispersion ytterbiumdoped (Yb-doped) fiber oscillator. The filter provides freedom to manipulate the cavity design for other performance targets [6]. Aguergaray *et al.* [7] reported a similariton laser based on Raman gain in kilometers of fiber, which generated 6 ps pulses. The demonstration of oscillators based on self-similar evolution in such diverse contexts attests to the robust nature of the process.

Although the co-existence of two nonlinear attractors in the soliton-similariton laser [4] is scientifically interesting, soliton formation in the anomalous-dispersion segment is likely to limit the performance of such a laser. The net group-velocity dispersion (GVD) of that

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cavity is normal and small in magnitude (0.01 ps^2). It is of interest to develop similariton lasers based on Er fiber that employ normal dispersion components as much as possible.

Here we report similariton formation in Er-doped fiber lasers with large normal dispersion. The behavior of the laser agrees reasonably well with numerical simulations, and this kind of laser offers a combination of short, high-energy pulses that is among the best reported for Er fiber lasers [8,9]. Stable pulses are generated with energy as high as 3.5 nJ, and they can be dechirped to 70 fs duration.

Numerical simulations based on the split-step Fourier method were used to guide the experimental design and understand the intracavity pulse evolution. Figure 1 shows the schematic of the simulated cavity. When the cavity is in the steady state, the gain fiber works as an attractor to draw the pulse to the asymptotic parabolic solution. The self-similar evolution is cut back to its initial condition in both the spectral and temporal domains by the narrow filter before the gain segment. A saturable absorber with 100% modulation depth helps to start and stabilize mode locking. The absorber is assumed to saturate monotonically. A single polarization is assumed to propagate in the laser.

The proper choice of filter is needed to ensure that the input to the amplifier will be able to evolve to the desired solution within the limited gain length. To select an appropriate filter, we first consider self-similar evolution in an amplifier [2]. The optimal initial pulse duration, assuming the asymptotic solution is reached at the end of the gain fiber, is given by [2]:

$$T(0)=3\frac{\beta_2}{\gamma}\left(\frac{2}{3}\Omega_p^2\right)^{\frac{1}{3}}, \quad (1)$$

where $T(0)$ is the optimum initial pulse duration; Ω_p is the gain bandwidth, which is about 5 THz (about 40 nm) for erbium in silica; γ is the nonlinear coefficient of the fiber; and β_2 is the dispersion coefficient of the fiber. For the initial demonstration, we assumed that the gain fiber is 3 m long, with dispersion around 50 fs^2/mm and a mode field diameter of 4.2 µm. These values yield an initial pulse duration around 500 fs, which corresponds to a bandwidth of 7 nm for a transform-limited Gaussian pulse. For a chirped pulse, the bandwidth will be larger. Considering the impact of other components in the oscillator, we anticipate the need for a filter bandwidth between 1 and 10 nm.

The rest of the cavity consists of a total of 90 cm of anomalous dispersion step-index fiber (SMF28) that represent fiber collimators and coupler pigtails (70 cm at the input end and 20 cm at the output end), and 54 cm of normal dispersion fiber (OFS 980) before and after the gain, from the pigtail of a WDM coupler. The cavity has net normal dispersion of magnitude 0.15 ps^2. The anomalous dispersion from the fiber pigtails is negligible compared with the net dispersion, so the laser is essentially an all-normal-disperson cavity. Simulations of lasers with varying filter bandwidths were performed.

Solutions converge to the self-similar evolution in the gain segment for a wide range of parameters. We find that for a given gain fiber, there is an optimum filter to get the highest energy and shortest pulse from the oscillator. The filter bandwidth is typically a factor of 2

smaller than that determined from the analytic expression above. Looking at filter bandwidths available experimentally, we first considered a 4 nm Gaussian filter.

A typical pulse evolution inside the cavity shows that the temporal and spectral profiles grow dramatically in the gain fiber [Fig. 2(a)] while the pulse is pulled to the parabolic shape [Fig. 2(b)]. The misfit parameter $M^2 = \int[|u| - |p|]^2 dt / \int |u|^4 dt$, with u the pulse being evaluated and p a parabolic pulse with the same energy and peak power. $M = 0.14$ for a Gaussian pulse, while $M \leq 0.06$ corresponds to a parabolic shape. The narrow filter is able to stabilize the evolution by satisfying both the boundary condition of the feedback system and the initial condition for the gain fiber.

For pump powers available from a single-mode diode, the simulations exhibit stable similariton pulses with energy up to 4.2 nJ and 53 nm bandwidth (Fig. 3). The spectral breathing ratio is about a factor of 10, and the transform-limited pulse duration is 82 fs.

A laser (indicated schematically in Fig. 4) was constructed following the simulated design closely. A 600 line/mm grating and a collimator with 0.5 mm diameter form a 4 nm Gaussian filter. Half- and quarter-wave plates before and after the fiber segments, along with the polarizing beam splitter (PBS), implement a saturable absorber based on nonlinear polarization evolution (NPE). The additional half-wave plate just before the grating adjusts the polarization for maximum diffraction efficiency.

Mode locking is easily achieved by adjusting the wave-plates. The mode-locked pulses are self-starting, with 45 MHz repetition rate. With one diode supplying a maximum of 500 mW power, 1.8-nJ pulses are generated (Fig. 5). Pulses are taken from the NPE output port, which creates structure on the spectrum. Thus, we cannot directly compare the simulated and measured spectra. The pulse is dechirped very close to the transform limit of 85 fs by a pair of gratings [Fig. 5(b)]. The dispersion required to dechirp the pulse is 51,000 fs^2, which is much less than the cavity dispersion. It is expected for self-similar evolution, and contrasts with the situation for dissipative solitons. Thus, the experimental results are consistent with theoretical expectations for self-similar evolution.

Simulations predict that with higher pump power, similaritons will be stable at substantially higher energy, and shorter dechirped pulses will be possible despite their spectral bandwidth slightly exceeding the gain bandwidth. In fact, the pulse spectrum [Fig. 5(a)] is already infringing on the gain spectrum, which typically limits the self-similar evolution. Wave-breaking is expected to occur in that situation, but that may not prevent stable pulse formation. We would expect that the pulse chirp would be adversely affected, so it may not be possible to dechirp the pulses to their transform limit.

For the gain fiber described above, simulations produce stable pulses with energy as high as 18 nJ. Meanwhile, the analytic limit to the pulse energy in that gain fiber is 13 nJ. It will be interesting to explore the high-energy limit of similariton formation, but that will require the use of double-clad fiber to reach the requisite average powers.

As an initial exploration of the potential of similariton pulses to reach high energy, we added a second pump diode to the experimental setup. This allows pump powers up to 900 mW.

The spectral bandwidth increases with increasing pump power. Power as high as 140 mW could be obtained at 40 MHz, with single-pulse operation verified (Fig. 6). The dispersion required to dechirp the pulse is 44,000 fs^2, again small compared to the cavity dispersion. The 3.5-nJ pulses can be dechirped to 70 fs duration. However, the pulse does not dechirp to the transform limit, and the pulse has some energy in a pedestal.

For pulses shorter than 80 fs, the third-order dispersion of the cavity and grating pair together becomes significant and will cause some secondary structure on the dechirped autocorrelation. Even accounting for the energy in the pedestal, the peak power could be very high. With efficient gratings for dechirping, this kind of laser should reach 40 kW peak power, which would be the highest achieved by a femtosecond Er fiber laser to our knowledge [8,9].

The RF spectrum in Fig. 6(d) shows good amplitude stability, with structure at least 80 dB below the first harmonic, at frequencies in the range of gain relaxation oscillations. Finally, with the second pump diode we were able to mode-lock the laser with a 2 nm filter. For given pulse bandwidth, the pulse energy is higher than that obtained with the 4 nm filter. We are eager to continue this investigation, but the performance is limited by the pump power in the present setup.

In conclusion, we have shown that just a filter can stabilize self-similar evolution in an Er fiber laser. The operation of the laser agrees with numerical simulations. The simple design of the cavity offers flexibility for future modifications, such as the insertion of a dispersion map in the cavity. The initial performance results presented here already compare to the highest peak power achieved by femtosecond Er fiber lasers. Substantial improvements in the performance appear to be possible and we expect that this type of laser will be valuable in many different applications.

Acknowledgments

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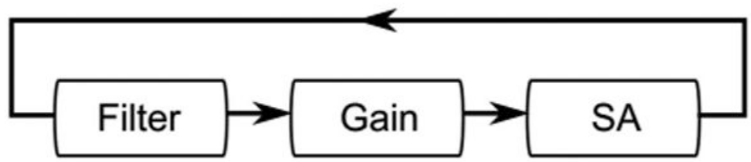

Fig. 1.
Schematic of similariton laser. SA, saturable absorber.

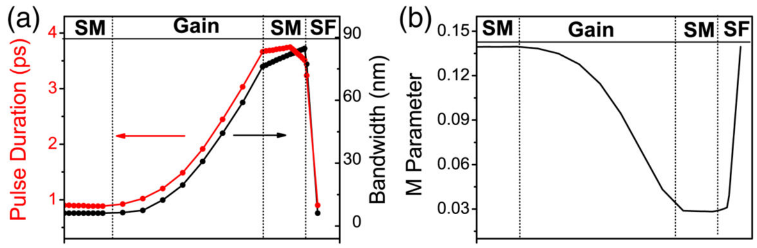

Fig. 2.

Pulse evolution inside the cavity. (a) Pulse duration (full width at half-maximum) and bandwidth (full width at one-fifth maximum) evolution. (b) Pulse shape evolution compared with a parabolic pulse.

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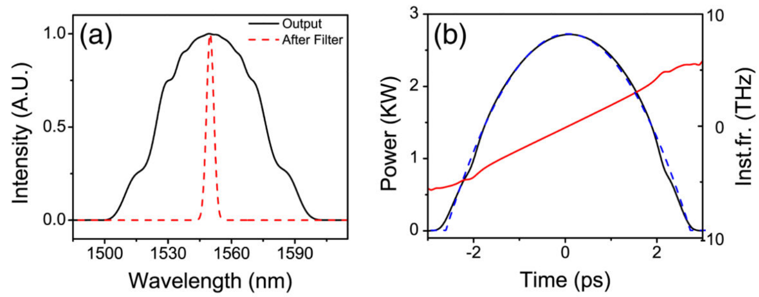

Fig. 3.

Simulation results. (a) Spectra before (red, dashed) and after (black, solid) the gain. (b) Chirped pulse (solid blue), parabolic fit (dashed blue), and instantaneous frequency (dotted red).

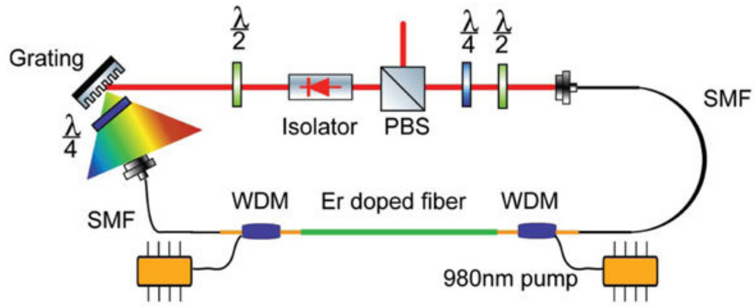

Fig. 4.
Experimental setup.

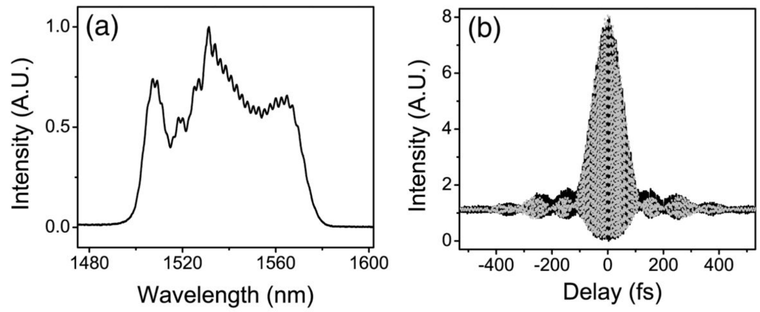

Fig. 5.

Experimental results. (a) Spectrum from the NPE output port. (b) Dechirped autocorrelation (black line) and calculated transform limited autocorrelation (gray line).

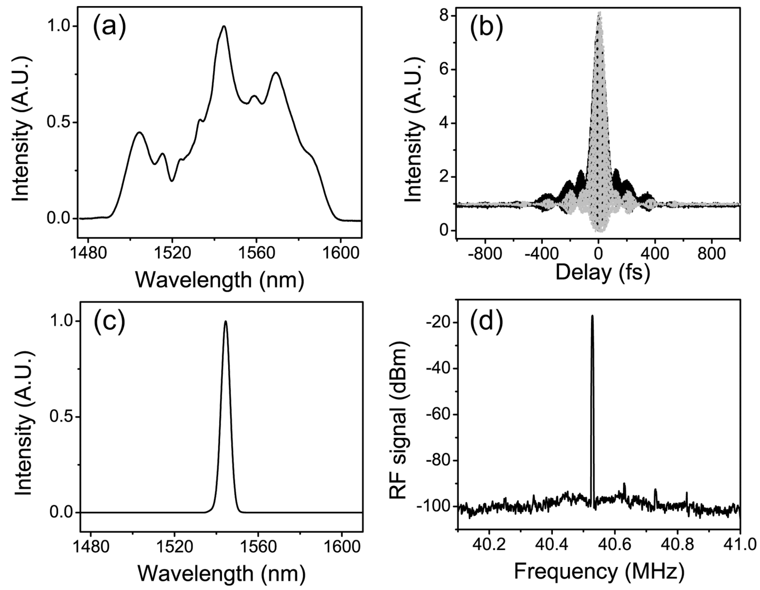

Fig. 6.

Experimental results: (a) Spectrum from the NPE output port. (b) Dechirped autocorrelation (black line) and calculated transform-limited autocorrelation (gray line). (c) Spectrum before the gain. (d) Radio frequency spectrum.