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Spectrally breathing femtosecond pulses from an Er-doped fiber laser

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Abstract: We report order-of-magnitude spectral breathing in a dispersion-managed Er-fiber laser with an intracavity bandpass filter. This is to our knowledge the highest of any laser reported. Pulse energy is 1.7 nJ, width is 110 fs.
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Ultrafast fiber lasers attract much interest due to their potential to replace solid-state lasers in applications such as materials processing and optical frequency metrology owing to their excellent stability, simplicity of operation and low cost. Pulse formation is dominated by a rich interplay between group velocity dispersion (GVD) and nonlinear effects [1,2]. Developments leading to better performance are typically triggered by new pulse shaping concepts and better understanding of the underlying dynamics.

Here, we report an Er-fiber laser with a dispersion-managed cavity containing a narrow-band optical filter. The mode-locked operation is very robust and remarkably, the spectral width of the pulse changes by as much as 7 times within one roundtrip. This is the highest spectral variation reported to our knowledge for any laser cavity. Spectral broadening is inherently a nonlinear process. In this sense, this laser could be viewed as the most "nonlinear laser". The surprising feature here is that this is observed stably within a laser cavity, subject to periodic boundary conditions, i.e., all changes must be undone at the end of each roundtrip.

The experimental arrangement is illustrated in Fig. 1. The fiber section consists of 3 m of regular single-mode fiber (SMF) and 1 m of highly doped Er-doped fiber, followed by another 0.55 m of SMF. The Er-doped fiber has mode field diameter (MFD) of 3.57µm, numerical aperture (NA) of 0.322 and GVD of 76.8 fs^2/mm at 1.55 µm, while the SMF had MFD of 10.4 µm, NA of 0.14, and GVD of -22.83 fs^2/mm. The net GVD of the laser cavity was calculated to be about 0.011 ps^2. A maximum of 350 mW of pump light at 980 nm from a laser diode is delivered to the cavity via a 980/1550 nm wavelength division multiplexer. An optical isolator ensures unidirectional operation, which facilitates self-starting operation. Mode-locking is initiated and stabilized with nonlinear polarization evolution (NPE). Threshold pump power for modelocking is 300 mW. Self-starting modelocked operation is achieved readily and very stably by adjustment of the waveplates. The mode-locked laser produces a stable pulse train with 42.7 MHz of repetition rate. Although cw output power can be as high as 150 mW, in modelocked operation the average power is limited to 116 mW, which corresponds to an intracavity pulse energy of 2.7 nJ. The results of the characterization of the laser are shown in Fig. 2. We measured 12 nm, 64 nm, and 85 nm of full-width at half-maximum (FWHM) values for the optical spectra from 1% port, 5% port, and NPE port, respectively (Fig. 2 (a-b)). The corresponding spectral breathing ratio is 7.1. The laser generates ~700-fs-long chirped pulses, which are compressed to 110 fs with a 1.2-m-long SMF fiber outside of the laser cavity (Fig. 2 (c)), whereas zero-phase Fourier-transform calculation yields a theoretical lower limit of 75 fs.

We seek maximal understanding of the physics behind this mode of operation. An important factor is the effect of the net cavity GVD. A similar laser was constructed with close to zero dispersion (GVD_{net} -0.0007 ps^2), the FWHM values of the spectra were measured to be about 12 nm and 65 nm from the 1% port and the NPE port, respectively (Fig. 2 (d)). The laser mode-locks easily and stably. Wider spectra could also be obtained but those modes of operation were less stable. The spectral breathing ratio is lower, but it is still a remarkably high value of 5.5. Limiting behavior at large anomalous GVD (the soliton regime) should be straight-forward. Since the laser cavity forms pulses of significantly narrower bandwidth with increasing net anomalous GVD, the effect of the filter recedes to a gentle modification of the spectrum. Likewise, the limit of very large normal dispersion is known from recent results on fiber lasers operating in the all-normal GVD regime [2]. From a careful comtemplation of the experimental results and guided by simulations, a simple mental picture of how the pulse evolves can be constructed: upon filtering, the pulses enter the SMF, where they are too weak to regenerate the lost spectral width. The bulk of the broadening takes place within the normal-GVD Er-fiber, exhibiting an extreme case of similariton propagation [3] maintained without pulse break-up owing to beginning the evolution with a particularly narrow spectrum. Pulse shaping in the SMF after the gain fiber appears to be milder.

In conclusion, we report a novel mode of operation of an Er-doped fiber laser, with the spectrum of the pulse breathing by as much as 7 times. This corresponds to extremely strong nonlinear shaping of the pulse. In analogy to the stretched-pulse laser, where the pulse breaths in the time domain, this laser could be regarded as a "*stretched-spectrum*" laser. From a laser physics point of view, it is remarkable that under the influence of such strong nonlinear effects the laser is very robust, even more so than the regular stretched-pulse laser without the filter. Both of the lasers reported here have been running continuously in our laboratory for several weeks.

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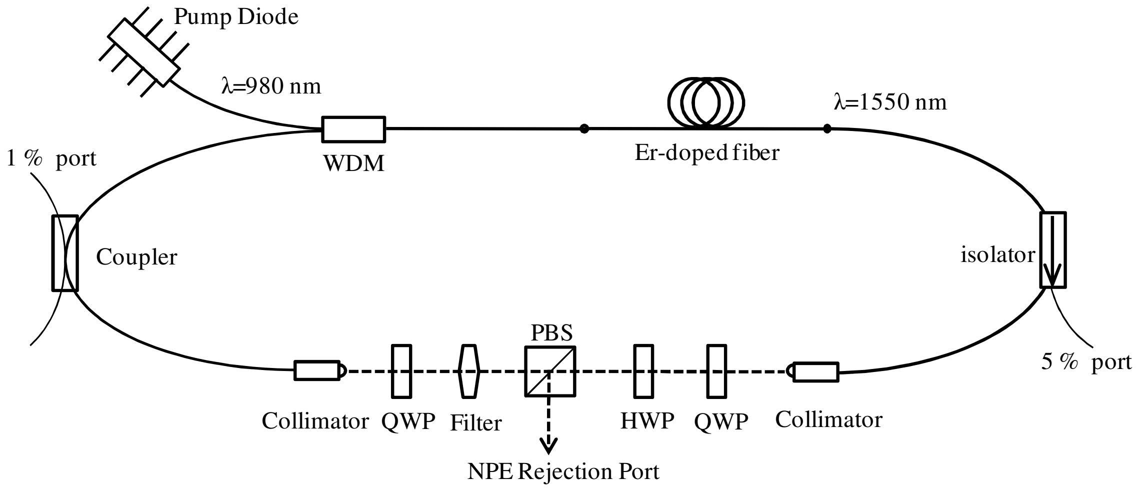

Fig. 1. Schematic of the Er-doped fiber laser, QWP: quarter waveplate; HWP: half-waveplate; PBS: polarizing beam splitter; WDM: wavelength-division multiplexer.

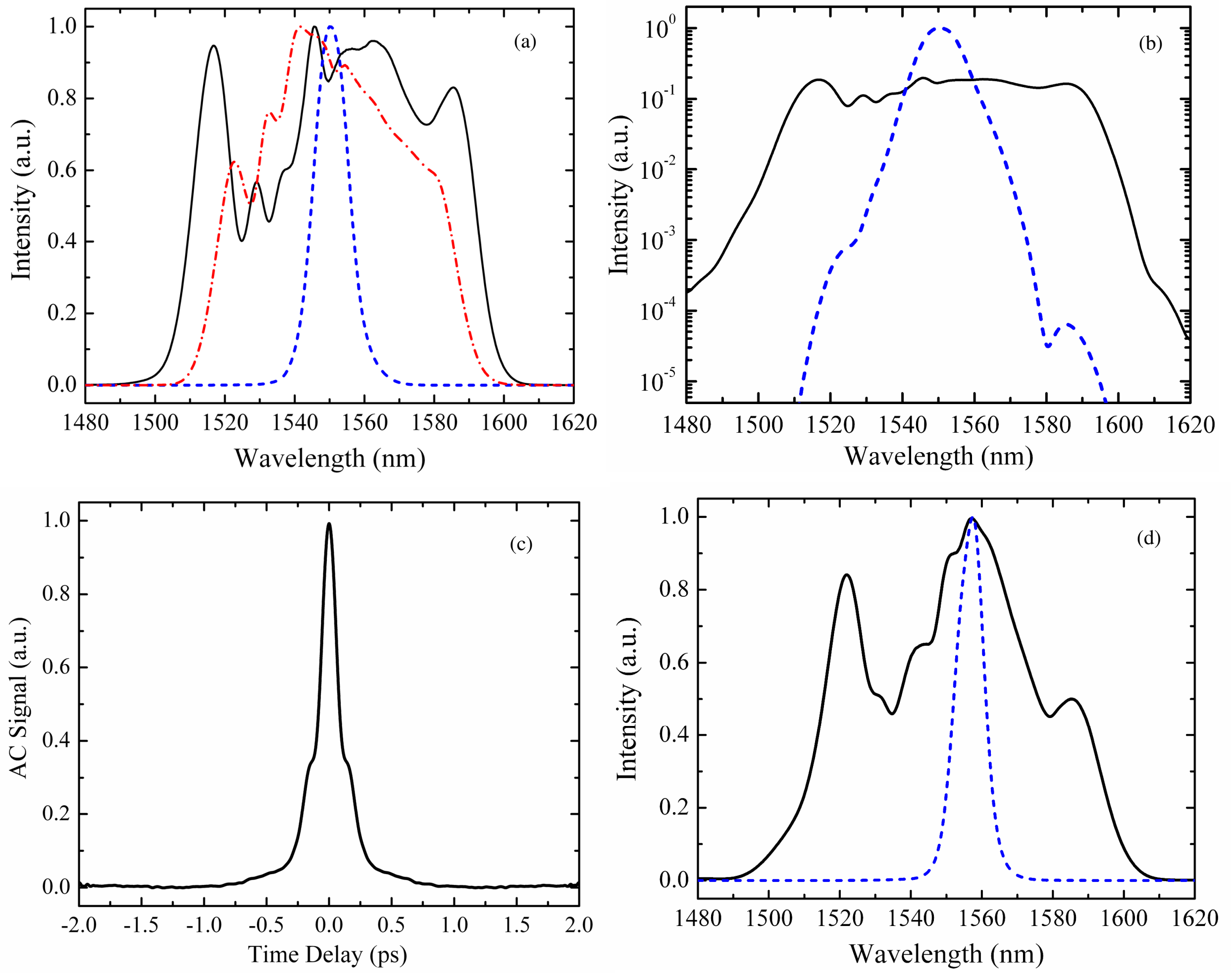

Fig. 2. Output of the Er -doped fiber laser at 0.011 ps^2 of net dispersion with filter: (a) Measured spectra of the pulse from NPE rejection port (black, solid line), 5% port (red, dash-dotted line) and 1% port (blue, dashed line), (b) measured spectra of the pulse from NPE rejection port (black solid line), 1% port (dashed curve) plotted on a logarithmic scale, (c) measured intensity autocorrelation of the pulse. (d) Output of the Er-doped fiber laser at -0.0007 ps^2 of net dispersion with filter: spectra from the NPE port (black, solid line) and 1% port (blue dashed line).

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