High-repetition-rate, 491 MHz, femtosecond fiber laser with low timing jitter

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We demonstrate a soliton fiber laser based on an anomalously dispersive erbium-doped fiber butt-coupled to a saturable absorber mirror for passive mode locking. The laser generates 180 fs pulses at a repetition rate of 491 MHz and exhibits a timing jitter as low as 20 fs over the frequency range 1 kHz–10 MHz. © 2008 Optical Society of America

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Compact, high-repetition-rate sources of femtosecond laser pulses are required for a variety of applications, such as frequency metrology [1] and ultrafast sampling [2]. Passive mode locking enables low jitter femtosecond pulses and alleviates the need for an optical modulator and a low noise electronic microwave driver. In the past, both polarization additive-pulse mode locking (P-APM) [3] and saturable Bragg reflector (SBR) mode locking [4–7] were used to mode lock lasers passively. The former has been successfully used in fiber lasers in both the soliton [8] and stretched-pulse [9] regimes, while the latter can lead to a more compact, high-repetition-rate cavity with fewer components required. Owing to the difficulty of appropriate polarization-control mechanisms at the integrated level, an SBR based approach seems to be the most promising toward realizing short-cavity, high-repetition-rate, passively mode-locked sources in integrated optics.

We demonstrate a simple, inexpensive, and low-jitter passively mode-locked femtosecond erbium-doped fiber (EDF) laser using a commercial SBR. Self-starting, it generates a pulse train at 491 MHz with a measured FWHM pulse duration of 180 fs and an average output power of 12 mW. The integrated timing jitter from 1 kHz to 10 MHz is measured to be 20 fs, and the measured optical spectrum FWHM of 15.4 nm is in good agreement with the Fourier prediction of 15.2 nm for 180 fs pulses.

The experimental setup is depicted in Fig. 1(a). The laser cavity consists of a 20.7 cm section of EDF (Liekki Er80-8/125) with group-velocity dispersion (GVD) of $-20\ \mathrm{fs}^2/\mathrm{mm}$, small-signal gain of 0.4 dB/cm at 1570 nm for a pump power of 260 mW, and doping concentration of $4.8\times10^{19}\ \mathrm{cm}^{-3}$. Using an anomalously dispersive gain fiber eliminates the need for an additional fiber section for dispersion compensation, which would reduce the repetition rate. One end of the cavity is butt-coupled to an SBR, and the other to a dielectric mirror, which acts as the output coupler. The SBR is a commercial unit (BATOP GmbH) with 6% modulation depth, a 2 ps recovery time, and a saturation fluence of $50\ \mu\mathrm{J/cm}^2$. Its dispersion and reflectance are depicted in Fig. 1(b). Pump light is provided by a 980 nm laser diode, free-space coupled through a dichroic beam splitter, and focused by an aspheric lens through the output coupler and into the EDF. The output coupler transmits 10% of intracavity power over the wavelength range from 1520 to 1640 nm with negligible dispersion. The output signal follows the same path in reverse and is separated from the pump by the dichroic beam splitter. The output pulses are split into three branches using a beam splitter and fiber couplers. The first branch is used to measure the autocorrelation, the second to monitor the microwave spectrum and phase noise with a 10 GHz photodiode, rf spectrum analyzer; and signal source analyzer (Agilent E5052), and the third to monitor the optical spectrum.

Figure 2 depicts the measured optical spectrum and interferometric nonlinear autocorrelation trace (IAC). The optical spectrum analyzer measurement shows a 15.4 nm FWHM optical bandwidth, implying 168 fs transform-limited FWHM pulse duration, while the autocorrelation measurement results in a 180 fs FWHM duration. The difference is attributed to the nonuniform gain profile of the EDF and the

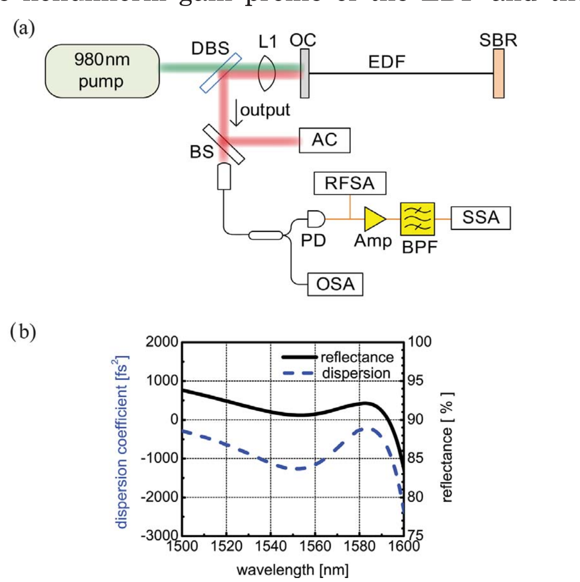

Fig. 1. (Color online) (a) Experimental setup for the linear soliton laser: DBS, dichroic beam splitter; OC, output coupler; PD, photodetector; BPF, bandpass filter. (b) Reflectance and dispersion of the SBR.

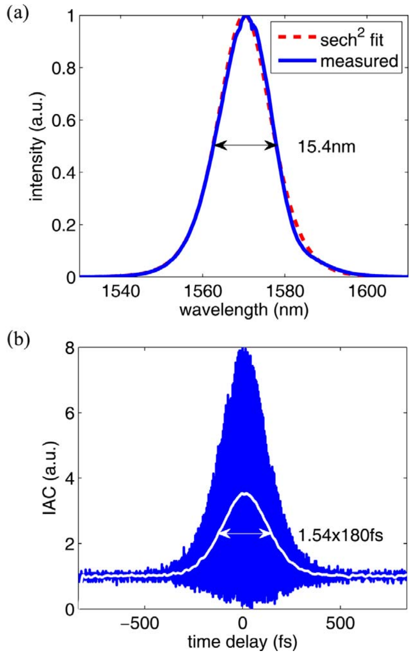

Fig. 2. (Color online) Experimental results at a repetition rate of 491 MHz: (a) Optical spectrum; (b) interferometric autocorrelation with inferred intensity autocorrelation (white).

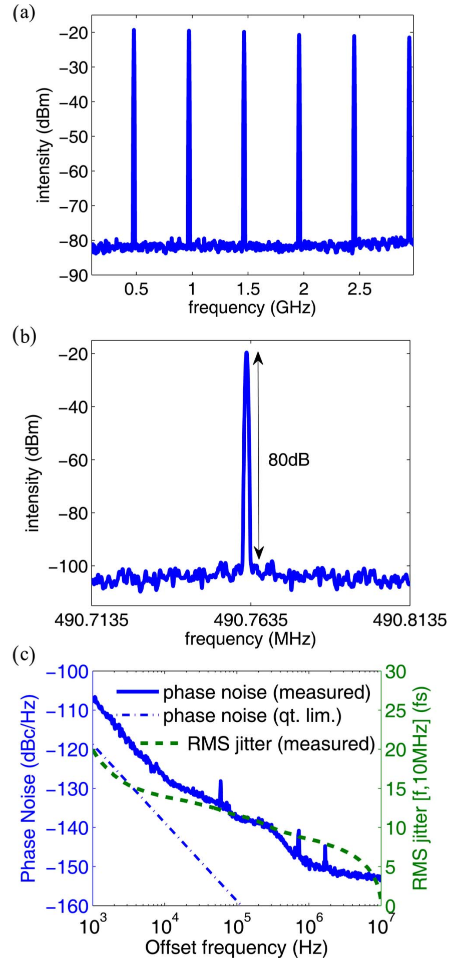

Fig. 3. (Color online) (a) Radio-frequency spectrum spanning from 0 to 3 GHz with resolution bandwidth of 10 MHz. (b) Radio frequency spectrum zoomed around the first harmonic with resolution bandwidth of 500 Hz. (c) SSB phase noise (solid) and integrated RMS jitter (dotted), compared with calculated quantum limit of phase noise (dash-dotted).

nonuniform dispersion profile of the SBR, causing a slight deviation of the measured optical spectrum from a sech^2 spectrum, as shown in Fig. 2(a). The dispersion of free-space optical components such as the output coupler substrate, focusing lens, and mode-matching optics in the IAC setup also contribute up to 6 fs of pulse broadening. The optical spectrum is centered around 1570 nm, which is determined by the wavelength-dependent reflectivity of SBR and the gain spectrum at the operating power level. The above values were obtained with 260 mW of cavity coupled pump power; the intracavity signal power was measured to be 121 mW, which corresponds to 251 pJ intracavity pulse energy. The laser was self-starting; as the pump power increased, the laser first operated in an unstable *Q*-switched mode-locking state and then changed to a cw soliton mode-locked state at a pump power of 95 mW. For pump powers greater than 300 mW, multiple pulsing occurred. As the pump power increases above 260 mW, the optical spectrum became broader, but the pulse duration did not decrease correspondingly, and the optical spectrum deviated still further from a sech^2 fit.

Figure 3 shows the rf spectrum and single sideband (SSB) phase noise. The 80 dB rf signal-to-background ratio, shown in Fig. 3(b), indicates excellent energy stability. Figure 3(c) shows the SSB phase noise of the fourth harmonic (1.963 GHz) of the laser. The timing jitter integrated from 10 MHz progressively down to 1 kHz is also shown. Over that full interval the net jitter is 20 fs. The phase noise below 1 kHz that follows a slope of −20 dBc/dec (decibel change by a factor of ten) can be suppressed by controlling the fiber length with a piezo-based stretcher and locking the repetition rate to an electronic oscillator with better long-term stability. The bandwidth limitations of this approach will likely limit such suppression of phase noise to frequencies below ~10 kHz. The measured phase noise was also compared to the quantum limit set by amplified spontaneous emission in the laser. The dashed-dotted curve in Fig. 3(c) shows the calculated quantum limit of the above laser. [10] The quantum-limited timing jitter in the frequency range [1 kHz, 10 MHz] is estimated to be 4 fs. The discrepancy by a factor of 5 may be easily explainable by the uncertainty in the exact excess noise factor of the erbium-doped fiber amplifier (EDFA) under saturated conditions, which we estimated to be 10 and additional noise due to the intensity noise of the pump diode, which will need further investigation.

The experimentally observed pulse characteristics can be compared with theoretical predictions based on the area theorem, using our erbium-doped fiber and SBR parameters. Table 1 summarizes the values used, while Table 2 compares the predicted and experimental laser characteristics.

Good agreement between the experimental and predicted values is obtained. Some discrepancy may

Table 1. Laser Parameters

n	1.475
n_2 (m^2/W)	3×10^{-20}
A_{eff} (μm^2)	70.9
$\beta_{2,EDF}$ (fs^2/mm)	–20
$\beta_{2,EDF}$ (fs^2)	–735

be attributed to the nonuniform dispersion profile of the SBR, as its dispersion can change as much as 1000 fs^2 within the optical bandwidth of the laser output (inset of Fig. 1).

The pulse duration of a soliton decreases with increased pulse energy or a smaller ratio of dispersion to self-phase modulation (SPM). For example, using an SBR with normal dispersion can decrease the total cavity dispersion without affecting the SPM coefficient and yield shorter pulses. The lower limit for the soliton pulse duration is set by available pump power, recovery time of SBR, gain bandwidth, or uniformity of gain spectrum over the signal wavelength.

The above results also testify to the scaling potential of such designs, provided that pumping is sufficient to ensure operation above the mode-locked *Q*-switching regime. The scalability of this laser is further enhanced by using an anomalously dispersive gain medium, which eliminates the needs for a passive, dispersion-compensating fiber section and allows maximizing the amount of gain with respect to the cavity length. For lower repetition rates, we previously demonstrated a 200 MHz laser based on the same configuration in [11]. At higher repetition rates, the dispersion of the SBR may eventually dominate over the dispersion of the gain fiber. In order to ensure soliton operation, one will have to either tailor the response of the SBR or force the lasing wavelength to coincide with the anomalously dispersive regime of the SBR.

Table 2. Experimental and Simulated Results

Repetition rate (MHz)	491	
Intracavity energy (pJ)	251	
Cavity losses (%)	20	
Pulsewidth (fs)	Measured 180	Simulated 175
Optical spectrum FWHM (nm)	Measured 15.4	Simulated 15.2

In conclusion, we demonstrated a passively mode-locked soliton EDF laser generating 180 fs pulses at 491 MHz. Mode locking is ensured by a commercially available SBR with a 6% modulation depth and 2 ps response time, and experimental measurements are in good agreement with theoretical predictions. The laser is self-starting, does not incorporate any form of active stabilization or polarization control, and offers a significant potential for further increase in repetition rate. Finally, its low timing jitter makes the laser a competitive candidate for ultralow jitter applications, such as high-speed optical sampling.

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