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# Femtosecond passively mode-locked fiber lasers using saturable Bragg reflectors

Hyunil Byun, Jason Sickler, Jonathan Morse, Jeff Chen, Dominik Pudo, Erich P. Ippen, and Franz X. Kärtner

Department of Electrical Engineering and Computer Science, and Research Laboratory of
Electronics, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge,
Massachusetts 02139, USA
Email: hibyun@mit.edu

**Abstract.** We demonstrate a soliton fiber laser with 280-fs pulses at 408-MHz repetition rate, and a stretched-pulse regime fiber laser with 102-fs pulses at 234-MHz repetition rate. Both use saturable Bragg reflectors for mode-locking and/or self-starting.

## Introduction

Compact sources of femtosecond laser pulses are an attractive and versatile technology 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 external microwave oscillator. In the past, both polarization additive-pulse mode-locking (P-APM) and/or saturable Bragg reflector (SBR) mode-locking [3,4] were used. The former has been successfully used in high repetition rate fiber lasers in the soliton [5] and stretched-pulse [6] regimes. The latter can lead to a more compact cavity with fewer components required. Used in combination with P-APM, SBRs can enable self-starting and increase stability when fibers are too short for P-APM alone to self-start, allowing scaling up the repetition rate, while allowing for ultrashort pulse durations.

In this paper, we demonstrate two high repetition-rate, self-starting, passively mode-locked femtosecond erbium-doped fiber (EDF) lasers using commercial SBRs. The first is a simple, soliton-regime linear cavity modulated solely by an SBR, and the second is a compact, stretched-pulse-regime sigma cavity modulated by a combination of P-APM and an SBR. The linear cavity soliton source generates a pulse train at up to 408 MHz, with a corresponding full-width half maximum (FWHM) inferred pulse width of 280 fs, while the stretched-pulse sigma cavity results in a pulse train at 234 MHz repetition rate, consisting of 242 pJ, 102 fs pulses.

## Experimental Results

### Linear soliton laser

The experimental setup is depicted in Fig. 1. The laser cavity consists of a 25 cm section of EDF with a group-velocity dispersion (GVD) of -20 $fs^2$/mm. 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 with 14% modulation depth, a 2 ps recovery time, and a saturation fluence of 25 μJ/$cm^2$. Pump is provided by a 980 nm laser diode, free-space coupled through a dichroic beamsplitter, and focused by a collimating lens through the output coupler and into the EDF. The output signal follows the same path in reverse, and is separated from the pump by the dichroic beamsplitter. The output pulses are then amplified using an EDFA (980 nm pump, 200mA), detected using a 10 GHz photodiode, and measured with a 500 MHz sampling scope and a signal source analyzer (Agilent E5052).

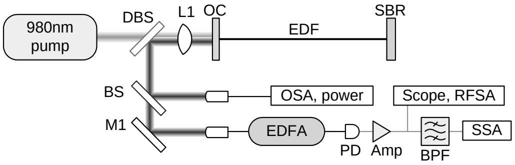


**Fig. 1.** Experimental setups of the linear soliton laser.

The 25 cm section of EDF yields a 408 MHz pulse repetition rate. Fig. 2 depicts a sampling scope trace, an optical spectrum, a 2 GHz bandwidth RF spectrum, and phase noise/timing jitter traces, respectively. Integrating the phase noise from 1 kHz to 10 MHz yields a root-mean-squared timing jitter of 196 fs.

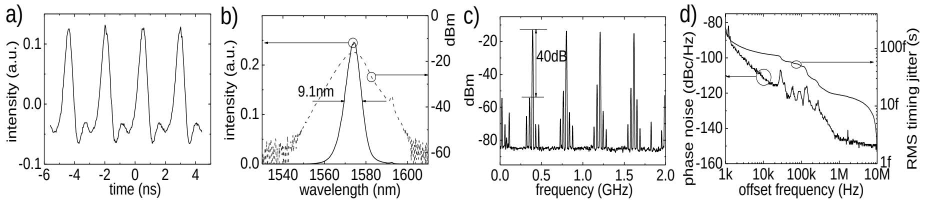


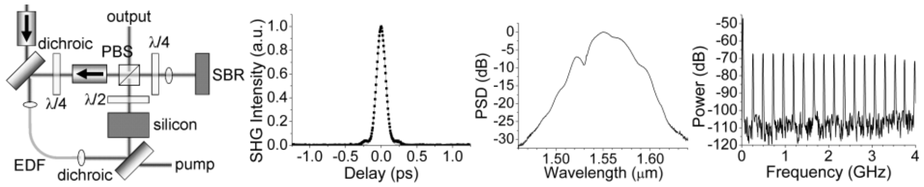
**Fig. 2.** Measurement traces at 400 MHz: a) sampling scope trace, b) optical spectrum, c) RF spectrum, and d) phase noise.

The 40 dB RF side-mode suppression ratio indicates an energy stability to better than 1%. The 9.1 nm FWHM optical bandwidth implies 280 fs duration transform-limited pulses. An autocorrelation measurement is in progress. All measurements were done with 130 mW of cavity-coupled pump power; the intracavity signal power was measured to be 136 mW, resulting in 330 pJ intracavity pulse energies. The laser was self-starting; as the pump power increased, the laser first operated in an unstable Q-switching state, changing to a continuous-wave soliton mode-locked state at pump powers of 115 mW. For pump powers greater than 160 mW, multiple pulsing occurred.

We subsequently increased the EDF length to 50 cm, resulting in a 197.8 MHz repetition rate. With 58 mW of cavity-coupled pump power, the intracavity signal power was measured to be 22.4 mW, yielding 113 pJ intracavity pulse energies. The optical signal exhibited a 6 nm FWHM bandwidth, corresponding to a 420 fs transform-limited pulse duration. Here, the continuous-wave soliton mode-locking, and multiple-pulsing threshold pump powers were 50 mW and 60 mW, respectively. The smaller threshold powers (as compared to the 408 MHz setup) come from the fact that a lower repetition rate at the same intracavity power correspondingly increases the pulse energy, and along with it, the nonlinear phase shift. Phase noise measurements yielded a timing jitter of 502 fs from 1 kHz to 10 MHz.

## Stretched-pulse laser

The stretched-pulse laser is shown in Fig. 3a. The cavity is in a sigma configuration to provide a point of reflection for the SBR, and includes an isolator for unidirectional operation, a polarizing beam splitter as the P-APM analyzer and output coupler, and various waveplates to control the polarization evolution. A silicon slab is included in the cavity to prevent residual pump power from reaching the SBR, and to provide normal GVD that, together with the anomalous GVD of the 60 cm of gain fiber, leads to stretched-pulse operation.



a) b) c) d)

**Fig. 3**. The stretched pulse schematic is shown in a). Laser performance is demonstrated with b) the autocorrelation trace ($\tau_{gaussian}$ = 102 fs), c) optical spectrum ($\Delta\omega_{FWHM}$=35.8 nm), and d) RF spectrum of the detected pulse train.

Fig. 3b-d shows the laser performance. The laser is free-space pumped with 980 nm light, resulting in an average laser output power of 56.7 mW. At the repetition rate of 234 MHz, this corresponds to 242 pJ pulses. The output pulses are normally chirped, and compress to 102 fs using 71.7 cm of single-mode fiber. The optical spectrum FWHM is 35.8 nm, which corresponds to 73 fs transform-limited pulses, indicating the presence of some residual chirp. The clean RF-spectrum indicates single pulse operation as was the case for the linear cavity laser.

## Discussion and conclusion

We demonstrated two stable, passively mode-locked lasers using SBRs. The first is a soliton laser generating 280 fs pulses at 408 MHz, using 25 cm of EDF as the cavity. Such a design provides a simple, fiber-compatible low-jitter femtosecond source without the need for driving electronics for active modulation. The laser provides good stability in a simple and potentially scalable design. No polarization control or active stabilization is required, and the laser self-starts. Still higher repetition rates can be achieved by further reducing the cavity length while optimizing the pumping scheme.

The second is a stretched-pulse laser that produces 242 pJ pulses compressible to at least 102 fs at 234 MHz repetition rate. The SBR enables self-starting, and P-APM provides a strong saturable absorber mechanism, leading to very stable, and most importantly, shorter pulses. The laser offers a higher pulse energy alternative to the linear cavity, and with improved cavity and pump optimization, such a system should also be scalable to higher repetition rates.

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