Sub-100 fs pulses from a low repetition rate Yb-doped fiber laser

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Abstract: We report on a passively mode-locked ytterbium-doped fiber laser with a repetition rate of 1.8 MHz. The laser was hybridly mode-locked via nonlinear polarization evolution and a semiconductor saturable absorber mirror. It generated chirped 3.8 ps long pulses with a pulse energy of 1.0 nJ which could be dechirped to a pulse duration of 93 fs.

OCIS codes: (320.7090) Ultrafast lasers; (140.7090) Ultrafast lasers; (140.3510) Lasers, fiber; (060.2320) Fiber optics amplifiers and oscillators.

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1. Introduction

Ytterbium-doped mode-locked fiber lasers are versatile sources of femtosecond optical pulses with pulse durations down to 28 fs and energies above 20 nJ [1,2]. These short-pulse fiber oscillators typically operate at fundamental repetition rates from 20 to 100 MHz [3]. Compared to solid state lasers the advantages of fiber lasers become significant as the resonator length increases due to the waveguide nature. In many applications like supercontinuum generation, micro-machining, cutting and imaging of biological tissue short-pulse oscillators with high pulse energy but low average power are required. This can be realized with a low repetition rate femtosecond laser which could serve as a seed source for a chirped pulse amplification (CPA) system to generate high-energy pulses. With this approach no complex and costly pulse picking unit is necessary.

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So far little effort has been made in developing mode-locked fiber oscillators with repetition rates in the low MHz range. Spectral filtering of highly-chirped pulses at a large normal cavity dispersion lead to highly chirped 150 ps long pulses at 3 MHz that could be amplified and compressed to 670 fs [4]. Further increase of the cavity length resulted in microjoule pulses with nanosecond duration [5]. Recently, researchers demonstrated a low repetition rate fiber laser at 2 MHz resulting in 0.23 nJ pulses with 400 fs duration at 1030 nm [6]. This laser was mode-locked via nonlinear polarization evolution (NPE) and operated in the soliton regime without intracavity third-order dispersion (TOD) compensation. Shorter pulse durations of 200 fs in the soliton regime were reached with hybrid mode-locking by NPE and a single-wall carbon nanotube saturable absorber in an erbium fiber laser [7].

In this work, we demonstrate a hybridly mode-locked ytterbium-doped fiber laser with a repetition rate of 1.8 MHz. The second-order dispersion (SOD) as well as the TOD of the fiber section was compensated for by a grating-prism (grism) arrangement inside the cavity. The oscillator generated 3.8 ps long pulses which could be compressed externally to 93 fs. The obtained pulse energy before compression was 1.0 nJ. To the best of our knowledge these are the shortest pulses from a passively mode-locked fiber laser with a repetition rate below 20 MHz.

2. Experimental setup

In Fig. 1 the schematic of the experimental setup is shown. The ring cavity consisted of a fiber section with a total length of about 115 m as well as a 2.8 m long free space section. All fibers had a mode field diameter of about 6 µm and thus supported single mode operation. Following the direction of pulse propagation the fiber section consisted of a 10 % fiber output coupler (FC), approximately 100 m of single-mode fiber (SMF), a second FC followed by a wavelength division multiplexer (WDM), 38 cm of ytterbium-doped gain fiber (YDF) and a third FC. Angle polished connectors together with collimators were used at both ends of the fiber section. The three incorporated output couplers provided the possibility to inter alia measure the optical spectrum at different positions of the fiber section and therefore to monitor the pulse evolution inside the oscillator. The port 4 served as the main output port. The single-mode pump diode emitted up to 600 mW output power at a wavelength of 976 nm.

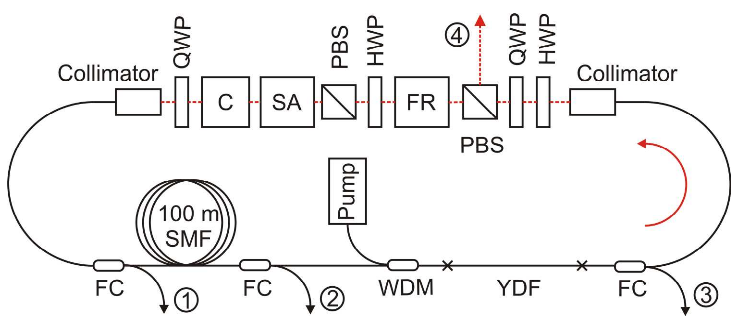

Fig. 1. Schematic of the experimental setup. HWP half-wave plate; QWP quarter-wave plate; C grism compressor; SA saturable absorber; PBS polarizing beam splitter; FR Faraday rotator; FC fiber output coupler; SMF single-mode fiber; WDM wavelength division multiplexer; YDF ytterbium-doped fiber. The different output ports are labeled by numbers. The arrow shows the direction of the propagating pulses in the oscillator.

A free-space isolator consisting of two polarizing beam splitters, one Faraday rotator and a half-wave plate assured unidirectional beam propagation. For passive mode-locking a commercially available semiconductor saturable absorber mirror (SESAM) (Batop GmbH) together with the nonlinear polarization evolution in the fiber section were used. The beam was focused on the SESAM in a reflective setup. To properly adjust the polarization state for the NPE three additional wave plates were placed inside the resonator.

To compensate for the normal group delay dispersion introduced by the fiber section we implemented a grism compressor [8,9] into the resonator. The device comprises a highly

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efficient transmission grating with a groove density of 700/mm and a fused silica prism providing anomalous SOD as well as anomalous TOD. The advantage of such a grism compressor is the potential of simultaneous compensation of SOD and TOD of the fiber section, which is not possible with a standard two grating arrangement. We estimated the SOD and TOD of the fiber section to be (2.66 ± 0.1) ps^2 and (3.31 ± 0.14) × 10^{-3} ps^3, respectively. By varying the angles of incidence the ratio of TOD and SOD of the grism compressor has been adjusted to match the one of the fiber section which we assumed to be 1.2 fs.

3. Experimental results

Once the wave plates were adjusted accurately the mode-locking was self-starting at pump powers above 189 mW. At this pump level we usually observed multiple pulsing. Stable single-pulse operation with 1.8 MHz repetition frequency was achieved by decreasing the pump power to 160 mW. We found the shortest pulses at a net cavity SOD of about (-3.8 ± 20) × 10^{-2} ps^2. Figure 2(a) shows the stable single pulse train measured with a fast photodiode having a rise time of 100 ps. A long-range autocorrelator with a 150 ps delay as well as a 70 GHz sampling oscilloscope together with a photodiode with a 100 ps rise time were used to confirm single pulse operation. The laser output power was 1.8 mW corresponding to a pulse energy of 1.0 nJ. In Fig. 2(b) the output spectrum of the emitted pulses is shown. The spectrum had a central wavelength of 1035 nm and a root mean square (RMS) width of 22 nm.

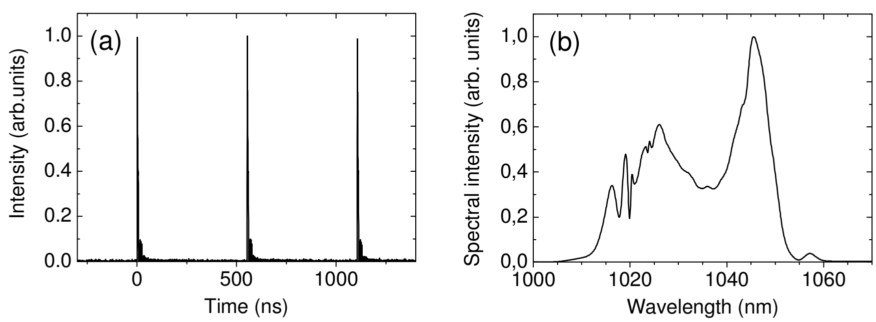

Fig. 2. (a) Pulse train monitored with a fast photodiode. The temporal separation of the pulses was 554 ns according to a repetition rate of 1.8 MHz. (b) Spectrum of the 1.0 nJ pulses with a central wavelength of 1035 nm and a RMS width of 22 nm. Both measurements were taken at port 4.

Figure 3 shows the intensity autocorrelation traces of the laser pulses before and after compression with a common two grating arrangement with a grating line density of 600/mm. The background of the autocorrelation function at large absolute values of the delay was identical to the case when the beam was blocked. The full widths at half maximum (FWHM) of the autocorrelation functions were 5.3 ps and 128 fs, respectively. This corresponds to a pulse duration of 3.8 ps before and 93 fs after compression assuming a deconvolution factor of 1.38 which was calculated by using the ratio of the FWHM of the bandwidth-limited autocorrelation and the FWHM of the Fourier transform of the power spectrum assuming a zero phase. For comparison the Fourier limited autocorrelation assuming zero phase with a FWHM of 67 fs is also shown in Fig. 3 (b). The compressed pulse duration was 37 % above the Fourier transform limit. As indicated by the side lobes in the autocorrelation shown in Fig. 3(b) we assume that due to the strong self-phase modulation (SPM) induced spectral broadening in the fiber section the pulses were nonlinearly chirped. This nonlinear chirp could not be compensated for by the compressor and lead to a 2.1 times longer RMS width of the measured autocorrelation compared to the RMS width of 156 fs of the transform limited autocorrelation. The dispersion provided by the grating pair for maximum compression was (-2.74 ± 0.14) × 10^{-2} ps^2 for SOD and (3.82 ± 0.19) × 10^{-5} ps^3 for TOD. While measuring the

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autocorrelation two artefacts at delays of ±9.6 ps were always observed as can be seen in Fig. 3(a). These were present independently of the pulse duration and of the operation state of the laser and were caused by the approximately 1 mm thick beam splitter of the commercially available autocorrelator.

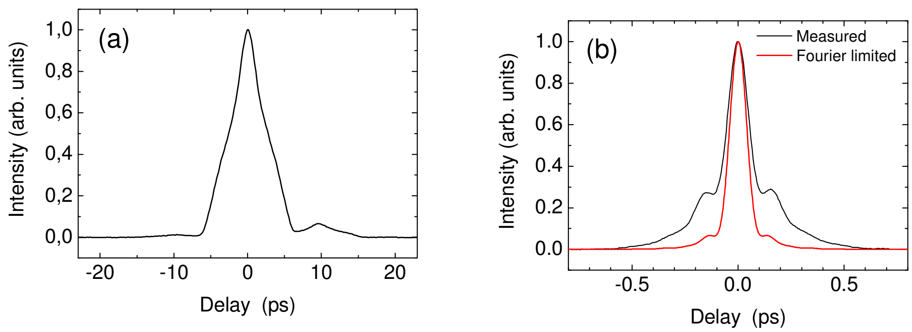

Fig. 3. (a) Intensity autocorrelation measured at output port 4 with a FWHM of 5.3 ps. (b) Measured intensity autocorrelation of the compressed pulses (black) and calculated Fourier limited autocorrelation assuming zero phase (red). The measured autocorrelation has a FWHM of 128 fs. corresponding to a pulse duration of 93 fs assuming a deconvolution factor of 1.38.

In order to achieve information about the intracavity spectral evolution the spectra at the four different output ports of the fiber laser were measured as can be seen in Fig. 4. The central wavelength of the spectra at ports 1 and 2 was 1027 nm. The RMS width at port 2 was 9 nm after propagation through the stretching part of the fiber section and the second 10 % coupler compared to 11 nm measured at port 1. The spectrum at port 3 is strongly broadened to a RMS width of 20 nm and the central wavelength changed to 1030 nm. The spectral narrowing between ports 1 and 2 could be explained by a strong anomalous chirp after propagating through the grism compressor and SPM in the 100 m long fiber section. The spectral broadening between ports 2 and 3 should have its origin in strong SPM. We further suppose that the filtering effect of the NPE and the SESAM resulted in the spectral narrowing observed between ports 3 and 1 as both mode-locking mechanisms filtered the chirped pulse nonlinearly in the time domain resulting in a spectral narrowing. The fact that the output pulses could be dechirped externally with much less than the internal grism induced SOD and the net cavity dispersion close to zero implicated laser operation in the stretched-pulse regime.

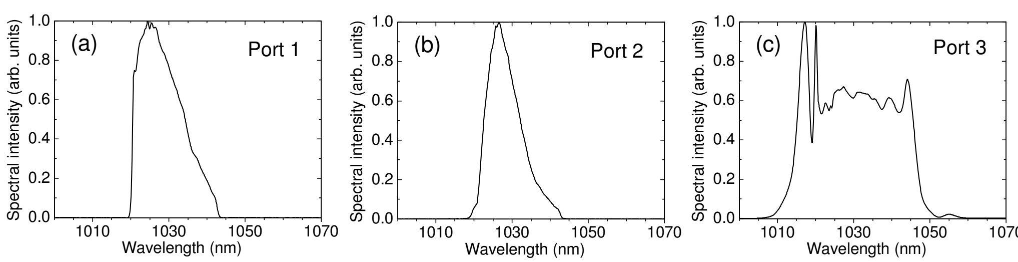

Fig. 4. The figure indicates the spectral evolution inside the laser. The spectra are measured at the different output ports of the oscillator as denoted in Fig. 1. (a) Port 1, (b) port 2 , and (c) port 3.

4. Conclusion

In conclusion we present a passively mode-locked ytterbium-doped fiber oscillator with a low repetition rate of 1.8 MHz. An intracavity grism compressor was used for dispersion compensation. The laser emitted chirped pulses with an energy of 1.0 nJ which could be dechirped externally to a pulse duration of 93 fs using a conventional grating pair. To the best of our knowledge these are the shortest pulses from a fiber oscillator with a repetition rate

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below 20 MHz. We believe that the intracavity TOD compensation was the root of achieving sub-100 fs pulses from a low repetition rate fiber oscillator incorporating more than 100 m of fiber.

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