Generation of sub-100-fs pulses at up to 200 MHz repetition rate from a passively mode-locked Yb-doped fiber laser

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Abstract: Generation of sub-100-fs pulses at repetition rates of 100-200 MHz from a passively mode-locked Yb-fiber laser via nonlinear polarization rotation is reported. The limitations to the repetition rate in terms of the pulse dynamics and the physical size of the cavity are discussed. We determine that physical size of the components dictate the maximum repetition rate and discuss the implications of a shorter cavity on the pulse shaping as a consequence of a weaker dispersion map.

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There is much recent interest in fiber lasers as sources of femtosecond pulses due to their excellent stability, compact size, and low cost. Rapid progress has been made with Yb-fiber lasers operating at 1 μm in the past two years. A new mode-locking regime exploiting self-similar pulse propagation has been demonstrated [1] and these lasers now routinely generate sub-100 fs pulses with over 5 nJ of energy at repetition rates of 30-50 MHz [2, 3]. These lasers were operated at relatively low repetition rates, typically at ∼30 MHz [2, 3, 5]. To our knowledge, only the lower limit to the repetition rate arising from residual birefringence has been studied [6]. Thus, it seems natural to explore the upper limitations to the repetition rate.

In addition, there is practical motivation; many applications demand repetition rates higher than ∼ 100 MHz. A leading example is optical frequency metrology, where several groups are exploring the use of fiber lasers[7, 8, 9, 10]. In this case, a high repetition rate ($\gtrsim$ 150 MHz) is desirable to attain sufficiently large comb line spacing. Higher repetition rates can be achieved with harmonically mode-locked lasers as well. However, active harmonic mode-locking leads to picosecond pulses and passive harmonic mode-locking is not stable enough for these applications. Furthermore, in combination with a Yb fiber amplifier [11], powerful, femtosecond pulses can be obtained, which would be particularly suited for applications such as micro-machining. To date, the repetition rates of fundamentally mode-locked fiber lasers with pulse durations of 100 fs or less have barely reached 100 MHz at 1 μm [5], and 130 MHz (with an Er/Yb-codoped glass waveguide amplifier) at 1.55 μm [12]. Repetition rates up to 300 MHz have been reported from Er-fiber lasers, however the pulse duration were limited to nearly 500 fs [13]. Here, we report systematically scaling the fundamental repetition rate of an Yb fiber laser up to 200 MHz, while preserving sub-100-fs pulse duration. We choose Yb fiber as the gain medium since it offers the highest gain per length among readily available fibers. Increasing the repetition rate of fiber lasers encounters two distinct challenges: (i) in practice, the cavity length is ultimately limited by the physical size of the components constituting the laser cavity, (ii) more fundamentally, there is a threshold power for initiating passive mode-locking.

The commonly used techniques for passive mode-locking of fiber lasers rely on intensity-dependent phase shifts accumulated by the pulse as it traverses through the fiber. Nonlinear polarization evolution (NPE) [14] is the most commonly used due to its large modulation depth (∼50%) and essentially instantaneous response. If a polarizing beamsplitter is used, the rejected light is extracted out of the cavity and acts as a useful output port. Other techniques include the nonlinear optical loop mirror [15] and its variants, which also have been demonstrated to generate high-energy, short pulses [16]. However, these techniques require longer fiber lengths, rendering them unsuitable for high repetition rate operation. Decreasing the cavity roundtrip time causes less energy to be stored in the cavity, limiting the peak power of the pulse, and for given power, a shorter fiber section results in smaller nonlinear phase shift to be accumulated.

Fig. 1. Experimental setup. Abbreviations: SMF single mode fiber, HWP half-wave retarder, QWP quarter-wave retarder, PSB, polarizing splitter beamcube, WDM wavelength demultiplexing coupler.

Therefore, with all other parameters unchanged, to first order, the pump power threshold for mode-locking increases quadratically with the repetition rate, unlike the linear dependence for a laser mode-locked by a saturable Bragg reflector.

The cavity setup (Fig. 1) is similar to the laser described in Ref. [5] with one important difference: the gain fiber is located at the beginning of the fiber section with respect to the direction of pulse propagation as in Ref. [17], in order to maximize the nonlinear effects. The lead fiber of the input collimator was kept as short (12 cm) as allowed for comfortable splicing to the Yb fiber. The highly-doped (23,000 ppm) Yb fiber (core diameter 6 μm, NA 0.16) is only 22 cm long. The calculated group-velocity dispersion (GVD) coefficient is 23 fs^2/mm. Pump light is delivered through a 980 nm/1030 nm wavelength demultiplexing (WDM) fiber coupler with Lucent-980 fiber (mode field diameter $\sim$5 μm, NA 0.16) with a GVD coefficient of 27 fs^2/mm [17]. The pump source is a fiber-coupled telecom-grade diode laser at 981 nm, which delivers a maximum power of 400 mW. The remaining fibers are that of the fiber collimators, standard single-mode fiber (SMF) for 1 μm wavelength with a calculated GVD of 24 fs^2/mm. A ring cavity was chosen for higher repetition rate. A bulk isolator (with an estimated dispersion of +3000 fs^2) imposes unidirectional operation. A pair of diffraction gratings (600 lines/mm, incidence angle of 45°) provides anomalous dispersion of adjustable magnitude. The gratings are of low quality with 50% total transmittance. Mode-locking is initiated and stabilized by NPE.

The repetition rate of the cavity was increased in discrete steps, starting from 100 MHz, by shortening the undoped fibers. The grating spacing was adjusted accordingly to for desired cavity dispersion. The free-space section was 50 cm-long.

At a repetition rate of 162 MHz, the total fiber length is 90 cm. Mode-locking is easily obtained by adjusting the wave-retarders for the NPE. Once set, mode-locking is self-starting, and requires no further adjustment. The net cavity GVD was first set to net anomalous (negative) and systematically reduced to zero and changed to normal (positive) GVD. At each GVD setting, the laser was mode-locked similarly. This way, we observed the main features of the var-

ious pulse evolutions previously observed in fiber lasers: soliton-like pulses at negative GVD, dispersion-managed solitons around zero GVD [18] and some indications of self-similar pulses at positive GVD [1].
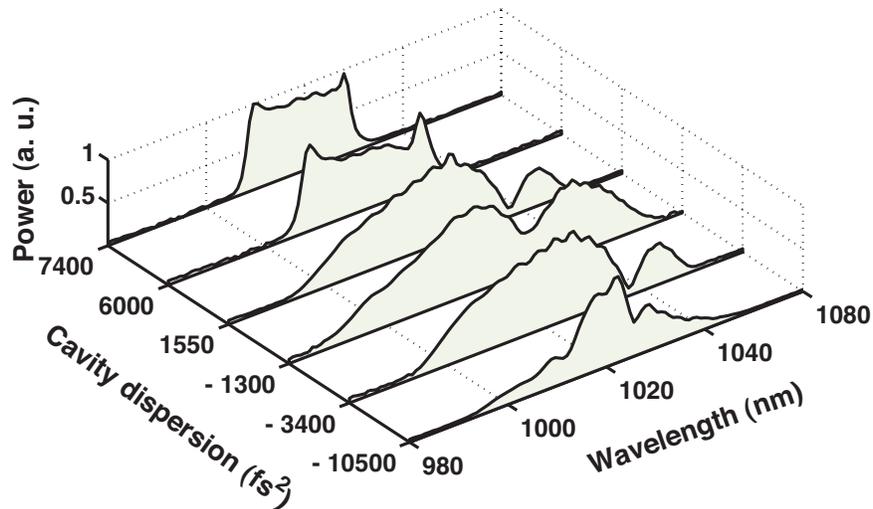

Fig. 2. Evolution of the pulse spectrum as the cavity dispersion is changed from -10500 fs^2 to $+7400$ fs^2.

The effect of increasing the repetition rate has consequences reaching beyond that of a higher mode-locking power threshold: the shorter fiber segment corresponds to a smaller swing in the dispersion map created by the positive GVD fibers and the negative GVD from the gratings. At sufficiently short lengths, the pulse would cease to stretch and compress and would simply experience the average GVD. At a repetition rate of 162 MHz, this effect is not severe yet and the typical transformation of the spectral shape reported in Ref. [5] is observed experimentally as the dispersion is adjusted from -10500 fs^2 to $+7400$ fs^2 (Fig. 2). Due to uncertainties in the GVD coefficients and the fiber lengths, we estimate that the absolute values of net GVD have an error of ± 1500 fs^2. However, relative changes to the net GVD are known precisely since the GVD of the gratings is well known. The pulse duration after external dechirping ranges from 70 fs to 135 fs. The corresponding characteristic dispersive length in the fiber segment ranges from 6.4 cm to 23.0 cm, which suggests an intracavity breathing ratio of $\sim$4, given the fiber length of 90 cm. This value is in contrast to the high-energy fiber lasers that were operated at 30-40 MHz repetition rate, commonly attaining intracavity breathing ratios of 10-30 [1, 2].

We describe the performance of the laser at 162 MHz with a view toward applications. In accordance with previous results [4], we attain the shortest pulses at small net negative GVD. At a net GVD of -1300 fs^2, the pulses rejected at the NPE port are dechirped to yield an intensity autocorrelation width of 96 fs, from which we infer a pulse width of 70 fs, assuming a Gaussian pulse shape (Fig. 3). The output pulse energy is 150 pJ, limited by the pump power. Measuring the power of a portion of the intracavity beam, which is reflected off the first grating, enables us to accurately determine the pulse energy in the fiber segment to be 0.65 nJ. Although multiple pulsing is not a serious concern at this energy level, long-range autocorrelation measurements and the rf spectra were checked to rule out this possibility. The rf spectrum shows that the pulse contrast is at least 60 dB (at the measurement bandwidth of 10 Hz) (Fig. 3).

Even though mode-locked operation is possible at large positive GVD (Fig. 2), there are differences from previous results reported for similar Yb fiber lasers at lower repetition rates
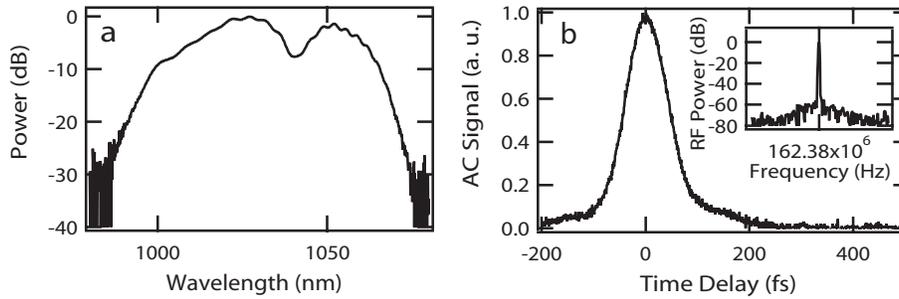
Fig. 3. (a) Optical spectrum at cavity dispersion of -1300 fs^2 at 162 MHz repetition rate. (b) Intensity autocorrelation of the pulses after external dechirping. Inset: rf spectrum of the pulses.

due to the weaker dispersion map. It was not possible to operate this laser exhibiting self-similar pulse (similariton) evolution with all of its characteristic features [1]. Operation at $+6000$ fs^2 and $+7400$ fs^2 has little intra-cavity breathing and the spectral shape is different from that of similariton lasers. For the latter case, the amount of dispersion necessary to dechirp the pulses is twice that provided by the grating pair inside the cavity. From the measured autocorrelation and the known magnitudes of dispersion from the gratings, we determine that the pulse always maintains a large positive chirp within cavity, varying from ~ 3.5 times the transform-limit at the beginning of the fiber section to ~ 7 times at the end of the fiber section. Even though these pulses exhibit the monotonic stretching of positively chirped pulses in the fiber segment as in self-similar propagation, the pulse breathing is much weaker and the pulse shape does not appear to be parabolic. This deviation is not surprising, considering that the self-similar mode of operation necessitates significant reshaping of the pulse during each roundtrip [19]. We expect that it would be possible to attain true self-similar operation at higher repetition rates with the use of specialty fibers with a higher dispersion coefficient to ensure sufficient pulse breathing and a tighter mode confinement (alternatively, higher pump power) for stronger nonlinear effects.
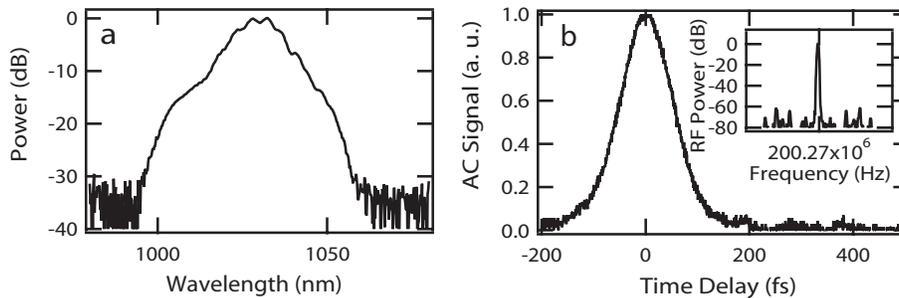

Fig. 4. (a) Optical spectrum at cavity dispersion of -8400 fs^2 at 200 MHz repetition rate. (b) Intensity autocorrelation of the pulses after external dechirping. Inset: rf spectrum of the pulses.

It was possible to increase the repetition rate up to 200 MHz by reducing the total fiber length to 66 cm, which is finally limited by the physical size of the cavity elements. At this repetition rate, mode-locking could be obtained only when the net GVD of the cavity is anomalous. Attempts at mode-locking for GVD smaller than -3000 fs^2 have failed. Mode-locking at large

negative GVD is not more difficult than at 162 MHz, so we attribute failure of mode-locking at zero and positive GVD partially to insufficient strength of the dispersion map [20], or simply to the self-starting mechanism being too weak. At net GVD of -8400 fs^2, where mode-locking is obtained easily, the pulse energy is 145 pJ (average power of 29 mW). The optical spectrum, autocorrelation, and rf spectrum are shown in Fig. 4. The inferred pulse duration is 85 fs (assuming a Gaussian pulse shape). The mode-locked train and the rf spectrum indicate clean mode-locking. Since the physical size of the cavity restricts us to ~ 200 MHz, we conclude that insufficient nonlinearity is not the immediate limitation to repetition rate in femtosecond fiber lasers mode-locked by NPE. We estimate that the repetition rate can be increased to 250-300 MHz by shrinking the free-space region and minimizing the undoped fiber length with a careful engineering effort.

In conclusion, we have demonstrated sub-100 fs pulse generation from a fiber laser with repetition rates up to 200 MHz. This laser is a reliable and inexpensive tool constructed entirely from commercially available components. Along with previous results for low repetition rates [6], it is now established that passively mode-locked Yb fiber lasers producing ~ 100-fs pulses can be operated with repetition rates anywhere between 20 and 200 MHz. With external amplification, this laser can serve as an ideal seed source for super-continuum generation for applications that benefit from higher repetition rates, such as frequency metrology, micromachining, and bio-medical imaging.

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