Sub-100-as timing jitter optical pulse trains from mode-locked Er-fiber lasers

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We demonstrate sub-100-as timing jitter optical pulse trains generated from free-running, 77.6 MHz repetition-rate, mode-locked Er-fiber lasers. At $-0.002(\pm0.001)\,\mathrm{ps}^2$ net cavity dispersion, the rms timing jitter is 70 as (224 as) integrated from 10 kHz (1 kHz) to 38.8 MHz offset frequency, when measured by a 24 as resolution balanced optical cross correlator. To our knowledge, this result corresponds to the lowest rms timing jitter measured from any mode-locked fiber lasers so far. The measured result also agrees fairly well with the Namiki–Haus analytic model of quantum-limited timing jitter in stretched-pulse fiber lasers.   © 2011 Optical Society of America

OCIS codes: 060.3510, 140.4050, 270.2500, 320.7100.

Femtosecond mode-locked fiber lasers are finding more and more applications, ranging from materials processing to precision measurements, owing to their excellent characteristics, such as high gain, low noise, good thermal property, compactness, and ease in building and operation. In particular, the excellent noise properties of mode-locked fiber lasers enable various time-frequency applications. In the frequency domain, the extremely low optical phase noise of mode-locked fiber lasers has enabled submillihertz linewidth level frequency combs [1]. In the time domain, the fluctuation of pulse positions from perfectly periodic positions, i.e., timing jitter, has been expected to be extremely low, as well. The quantum-limited timing jitter of free-running mode-locked lasers has been expected to be well below a femtosecond [2–5]. Because of their inherently low level, only very recently has accurate measurement of timing jitter up to the Nyquist frequency been possible by using the balanced optical cross-correlation (BOC) method [6–8]. The use of the attosecond-resolution BOC method has enabled the demonstration of 20-as-level jitter from Ti:sapphire solid-state lasers at 800 nm [9] and 200-as-level jitter from Yb-fiber lasers at 1 μm [10].

The availability of mode-locked Er-fiber lasers at the telecomm wavelength (1.5–1.6 μm) with attosecond timing jitter enables a wide range of new applications in optical communications and photonic signal processing, such as analog-to-digital conversion and long-distance clock distribution via fiber optic links. So far, the best timing jitter performance demonstrated for free-running Er-fiber lasers is 2.6 fs (integrated from 10 kHz to 40 MHz) when the laser is operated at the stretched-pulse condition with positive net cavity dispersion [7]. The optimization of timing jitter in Er-fiber lasers toward the attosecond regime has not yet been shown.

In this Letter we demonstrate sub-100-as timing jitter optical pulse trains from 78 MHz free-running mode-locked Er-fiber lasers. The high-frequency timing jitter is scaled down by a factor of ~40 from the few-femtosecond level [7] to the sub-100-as level by a simple cavity dispersion control. At $-0.002(\pm0.001)\,\mathrm{ps}^2$ net

cavity dispersion at 1582 nm center wavelength, the rms timing jitter is measured to be 70 as (224 as) integrated from 10 kHz (1 kHz) to 38.8 MHz offset frequency. To our knowledge, this result corresponds to the lowest rms timing jitter measured up to the Nyquist frequency from any mode-locked fiber laser. By using directly measured laser parameters, we further find that the measured result agrees fairly well (within a few decibels difference) with the prediction of the Namiki–Haus analytic noise model [3] for quantum-limited timing jitter in stretched-pulse fiber lasers.

For timing jitter characterization and optimization, two almost identical, ~78 MHz repetition rate, nonlinear polarization evolution (NPE)-based Er-fiber lasers were built [Fig. 1(a)]. The net cavity dispersion is set to the close-to-zero range (-0.006 to $+0.002\,\mathrm{ps}^2$ in this work) by balancing the positive dispersion of Er-gain fiber (Liekki Er80-4/125) and the negative dispersion of standard single-mode fiber (SMF-28). For the jitter characterization, we put forth special effort to make two independent lasers running with almost identical laser parameters. The only difference between the two lasers is the geometry in the free-space section: a sigma cavity with a piezo-electric transducer (PZT)-mounted mirror is employed in one laser [Laser 2 in Fig. 1(a)] to enable repetition-rate locking between the two lasers. The output optical spectra and interferometric autocorrelation (IAC) traces of the two lasers at $-0.002(\pm0.001)\,\mathrm{ps}^2$ net cavity dispersion are shown in Fig. 1(b). Both lasers have a center wavelength of 1582 nm and FWHM output pulse width of ~60 fs.

The timing jitter is characterized by a 24 as resolution periodically poled potassium-titanyl-phosphate-based BOC in a way similar to that shown in [6,7]. To confine the jitter measurement in the linear detection range of BOC output [inset graph in Fig. 1(a)], the repetition rate of two lasers is locked by a low-bandwidth phase-locked loop (PLL) using the PZT-mounted mirror in Laser 2 [Fig. 1(a)]. The laser locking is achieved by optical locking using the BOC output or by electronic locking using the photodetected microwave signals (the 13th harmonic
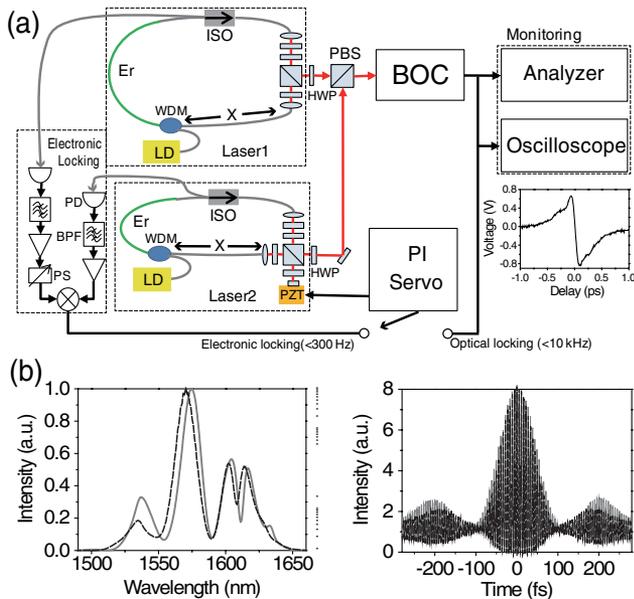
Fig. 1.   (Color online) (a) Experimental setup for timing jitter characterization and optimization of mode-locked Er-fiber lasers. BOC, balanced optical cross correlator; BPF, 1 GHz bandpass filter; Er, Er-gain fiber; ISO, isolator; PD, photodetector; PS, phase shifter; HWP, half-wave plate; LD, 980 nm laser diode; PI, proportional-integral; WDM, 980/1550 wavelength-division multiplexing coupler. The net cavity dispersion of each laser is controlled by changing the length of single-mode fiber (labeled with X). (b) Optical spectra and interferometric autocorrelation of lasers (dashed black curves, Laser 1; solid gray curves, Laser 2).

of repetition rate at ~1 GHz). Although the optical locking provides tighter long-term stable locking, it requires a sufficient locking bandwidth (at least a few kilohertz) to acquire and maintain the locking because of a large resonant peak near the locking bandwidth. This resonant peak was inevitable because we need to fully suppress strong acoustic noise peaks in the 100–300 Hz range, which are induced by instrument fan noise and other vibration noise sources. Combined with the limited locking range of the BOC (~80 fs peak to peak), stable optical locking was obtained only when the locking bandwidth was at least a few kilohertz, which results in a valid jitter measurement from a ~10 kHz offset frequency [7,8]. In order to measure timing jitter in the lower offset frequency range (below 10 kHz), we also use electronic locking with an ~100 Hz locking bandwidth and ~3 fs (rms) residual jitter, which enables the jitter measurement in the linear detection range of the BOC. Using these locking techniques, the measurement of timing jitter spectrum over five decades of offset frequency from 300 Hz to ~39 MHz (Nyquist frequency) is possible. An RF analyzer and a fast Fourier transform analyzer are used to measure the timing jitter spectral density of the BOC output in the 10 kHz–39 MHz and 300 Hz–10 kHz ranges, respectively. To get the timing jitter of a single laser, the measured jitter spectral density is divided by 2 because the two lasers are almost identical and uncorrelated [7].

To find the lowest jitter condition, dispersion control is performed by adding or cutting SMF-28 fiber inside the laser cavity [Fig. 1(a), X section]. The net cavity dispersion is tuned in the near-zero and slightly negative dispersion regime ranging from –0.006 to +0.002 ps^2 with

~0.001 ps^2 intervals at a 1582 nm center wavelength by adding or cutting the SMF-28 fiber at ~5 cm intervals. The net cavity dispersion is measured by an *in situ* dispersion measurement method, as used in [10,11]. Within a rather narrow range of dispersion from –0.006 to +0.002 ps^2, the measured timing jitter spectral density level changed by more than 20 dB, similar to the recent result for Yb-fiber lasers [10]. Such a dramatic change in jitter is mainly due to the change in pulse width and pulse chirp for different cavity dispersion conditions. The contribution of a slight change in repetition rate by adding or cutting fiber segments to the laser jitter is negligible. For the Er-fiber lasers used in this experiment, the lowest timing jitter is achieved when the intracavity dispersion is set to –0.002(±0.001) ps^2 at a 1582 nm center wavelength.

The measured lowest timing jitter spectral density is shown in Fig. 2 [curve (a)]. The jitter spectral density shows a $1/f^2$ slope from 300 Hz to 2 MHz offset frequency, which is a characteristic of the random walk nature of the timing jitter in a free-running laser. In the high offset frequency above 8 MHz, the jitter measurement is limited by the BOC photodetector noise [at ~3 × 10^{-12} fs^2/Hz level, curve (b) in Fig. 2]. If a higher-resolution measurement is possible, the high-frequency jitter spectrum will be limited by the relative intensity noise (RIN)-coupled timing jitter from the Kramers–Kronig relationship [4,10]. From the RIN measurement of the laser used, we find that the projected RIN-coupled jitter contribution [curve (c) in Fig. 2] is slightly lower than the detector noise [curve (b) in Fig. 2]. The integrated rms timing jitter from 10 kHz (1 kHz) to 38.8 MHz offset frequency is 70 as (224 as). To our knowledge, this is the lowest timing jitter ever achieved for free-running mode-locked fiber lasers. For comparison, we also plot the equivalent timing jitter of commercial microwave signal generators with the lowest phase noise [sapphire loaded cavity oscillator (SLCO) [12], curve (d) in Fig. 2] and the
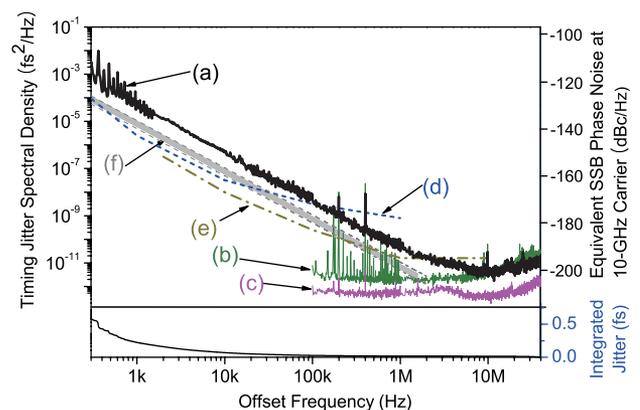

Fig. 2.   (Color online) (a) Best timing jitter spectral density result of mode-locked Er-fiber lasers. The integrated timing jitter is 70 as (224 as) when integrated from 10 kHz (1 kHz) to 38.8 MHz offset frequency. (b) BOC photodetector noise floor. (c) Projected RIN-coupled timing jitter. (d) Equivalent timing jitter spectral density of SLCO [12] for comparison. (e) Best timing jitter spectral density of mode-locked Ti:sapphire lasers [9] for comparison. (f) Predicted timing jitter range from the Namiki–Haus analytic model based on measured laser parameters.

Table 1.   Measured and Typically Used Laser Parameters for Namiki–Haus Model

Measured Laser Parameters	
Reference pulse width, τ_0 (fs)	36
Center wavelength (nm)	1582
Intracavity pulse energy, w (nJ)	1.6
Saturated amplitude gain, g	0.39
Excess noise factor, Θ	$14(\pm 0.2)$
Net intracavity dispersion, D (ps^2)	$-0.002(\pm 0.001)$
Typically Used Laser Parameters	
HWHM gain bandwidth, Ω_g (rad/s)	1.51×10^{13} [7]
SAM–SPM ratio, α	0.1–0.3 [3]
Chirp parameter, β	-0.52 to -0.12 [3]

lowest timing jitter result of 80 MHz Ti:sapphire lasers [9] [curve (e) in Fig. 2].

We further compare the measured jitter spectrum with the Namiki–Haus analytic model of quantum-limited timing jitter in stretched-pulse fiber lasers [3]. To compute the theoretical jitter accurately, we measured most of the laser parameters used in the model. The measured and typically used laser parameters are summarized in Table 1. A Gaussian-shaped pulse with the reference pulse width τ_0 of 36 fs ($60\,\mathrm{fs}/2\sqrt{\ln 2}$) is determined by the PICASO algorithm [13] using the measured optical spectrum and IAC trace. Intracavity pulse energy w (1.6 nJ) is obtained by measuring the repetition rate and the average power from a 5% output port located right after the Er-gain fiber. The saturated amplitude gain g (0.39) is evaluated by compensating the total cavity loss (55%) per round trip in the steady state. To determine the excess noise factor of gain medium Θ, we built an Er-doped fiber amplifier (EDFA) with Er-fiber length and pump power level identical to those in the fiber laser. The excess noise factor Θ is determined by measuring the amplified spontaneous emission spectral density at a particular gain level in the EDFA, similar to the method shown in [14], which results in $14(\pm 0.2)$. The proportionality factor α, which is the ratio of self-amplitude modulation (SAM) to self-phase modulation (SPM), typically ranges from 0.1 to 0.3 in NPE-based fiber lasers [3], and we use this range of α in the model. The chirp parameter β is accordingly calculated from [3]

$$\beta = \tan\left\{\frac{1}{2}\left[\arg(\alpha - j) - \arg\left(\frac{g}{\Omega_g} + jD\right)\right]\right\},$$

which results in β ranging from -0.52 to -0.12. Using these parameters, the predicted jitter spectra of the Namiki–Haus model are shown by gray region (f) in Fig. 2. The upper and lower bound corresponds to the parameter combinations of $(D,\alpha,\beta,\Theta) = (-0.003\,\mathrm{ps}^2, 0.1, -0.22, 14.2)$ and $(-0.001\,\mathrm{ps}^2, 0.3, -0.40, 13.8)$, respectively. The measured jitter spectrum [curve (a) in Fig. 2] agrees fairly well with the prediction of analytic model within a 5–8 dB difference. The discrepancy of a few decibels between the measurement and the model might

be due to higher-order effects, such as third-order dispersion and nonlinear chirp present in the fiber laser.

In summary, we have scaled down the timing jitter of mode-locked Er-fiber lasers toward the sub-100-as regime by intracavity dispersion control. At $-0.002(\pm 0.001)\,\mathrm{ps}^2$ dispersion condition, the integrated rms timing jitter from 10 kHz (1 kHz) to 38.8 MHz is measured to be 70 as (224 as), which is a factor of ~ 40 improvement from the previously reported result [7]. As shown in Fig. 2, the measured timing jitter spectrum of Er-fiber lasers is comparable to those of the best microwave sources [12] and Ti:sapphire lasers [9]. Although Ti:sapphire lasers can provide lower jitter (~ 20 as) due to their much shorter pulse width (<10 fs) and less chirp, the performance of Er-fiber lasers with ~ 70 as jitter demonstrated in this work are expected to be attractive photonic signal sources due to their lower cost, simpler design and implementation, and compatibility with 1550 nm telecomm devices and fibers. We further show that the Namiki–Haus analytic model based on measured laser parameters can predict the jitter spectrum fairly well within a few decibels difference, which suggests that one can effectively use an existing analytic model for optimizing the fiber laser design for the targeted jitter performances.

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