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Ultra-low timing jitter optical pulse trains from mode locked Er-fiber lasers

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Abstract. *For their outstanding characteristics, such as high gain, low noise, good thermal property, compactness, and ease in building and operation, femtosecond mode locked fiber lasers are finding more and more applications. Especially, ultralow noise characteristics of mode locked fiber lasers enable various time applications. According to the noise theory, ultralow timing jitter of mode-locked fiber lasers can be achieved at short pulse duration, high intra-cavity pulse energy and nearly zero net-cavity dispersion conditions. Stretched-pulse type mode locked Er-fiber lasers have femtosecond level short pulse duration and high intra-cavity pulse energy. Net-cavity dispersion of a stretched-pulse mode locked Er-fiber laser, consisting mostly of fibers, is controlled by changing the fiber length in cavity; timing jitter of laser is reduced by dispersion control. At the optimal dispersion conditions obtained by changing the length of SMF-28 fiber in the cavity, sub-100 attosecond timing jitter can be achieved from a mode locked fiber laser.*

Introduction

For their outstanding characteristics, such as high gain, low noise, good thermal property, compactness, and ease in building and operation, femtosecond mode locked fiber lasers are finding more and more applications. Especially, ultralow noise characteristics of mode locked fiber lasers enable various time applications. According to the noise theory, ultralow timing jitter of mode-locked fiber lasers can be achieved at short pulse duration, high intra-cavity pulse energy and nearly zero net-cavity dispersion conditions.

Femtosecond fiber lasers have attractive advantages. It is possible to make fiber lasers as compact size for flexibility of optical fiber. It need lower build cost than solid-state laser. It has similar performance to solid-state laser. As compact size and ultralow noise characteristics, mode locked fiber lasers are attractive as ultralow-jitter signal sources for high-precision scientific, engineering systems and various space missions.

Dispersion Control

In Haus-Namiki paper, timing jitter equation is

$$\langle|\Delta t(\Omega)|^2\rangle = \frac{16}{{T_R}^2}\left(\beta\frac{g}{{\Omega_g}^2}+D\right)^2\frac{D_{pp}}{\Omega^2\left(\Omega^2+\frac{1}{{\tau_p}^2}\right)} - \frac{8}{\tau_p T_R}\left(\beta\frac{g}{{\Omega_g}^2}+D\right)\frac{D_{pt}}{\Omega^2\left(\Omega^2+\frac{1}{{\tau_p}^2}\right)} + \frac{D_{tt}}{\Omega^2} \qquad (1)$$

and Chirp parameter is

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

According to the timing jitter equation, ultralow timing jitter of mode-locked fiber lasers can be achieved at nearly zero net-cavity dispersion conditions. To find the lowest jitter condition, dispersion control is performed by adding or cutting SMF-28 fiber inside fiber laser cavity, because cavity is made most of fiber section and short free space section that waveplates and PBS are aligned. Typical dispersion of SMF-28 is -220 fs^2/cm at 1550 nm. We can change net cavity dispersion by controlling length of SMF-28 in cavity. By changing length of SMF-28 in cavity, net cavity dispersion change from +0.002 ps^2 to -0.006 ps^2. After changing dispersion, measured timing jitters of each dispersion condition show maximum 10 dB change by 0.001 ps^2 dispersion change. In close-to-zero dispersion condition, timing noise is more sensitive to changing dispersion than other dispersion conditions. Timing jitter spectra continually lower when dispersion is reduced to -0.002 ps^2, and rise when dispersion is more reduced than -0.002 ps^2. In experiment, when dispersion changed from zero to low dispersion, we find laser mode locking condition is stable at near zero dispersion condition, but mode locking condition of laser is hard to find and unstable at far from zero dispersion condition.

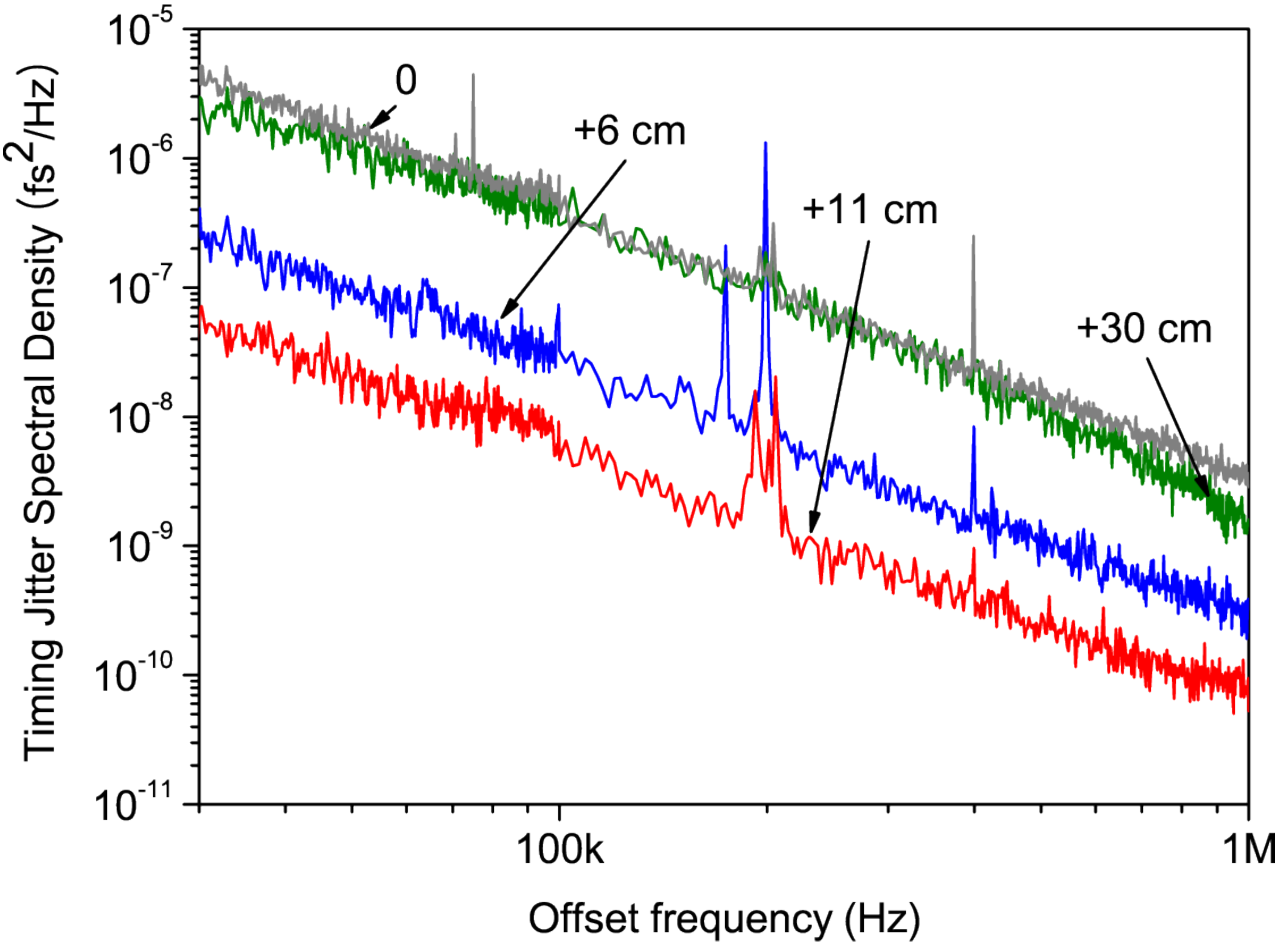

Figure 1. Typical timing jitter spectra measured at different dispersion conditions from a stretched pulse Er fiber laser.

Experimental Setup

We build almost identical 77.55 MHz repetition rate, stretched pulse Er fiber lasers for experiment. One of lasers is made ring cavity and another cavity is made sigma cavity with a PZT-mounted mirror for repetition rate locking by erbium-doped fiber (Liekki Er80-4/125) and standard single-mode fiber (SMF-28). Estimated net cavity dispersion of each cavity is close-to-zero. Mode locking of lasers is achieved by nonlinear polarization evolution using waveplates and polarizing beam splitter (PBS). Characteristics of laser parameters are written in Table 1. Inside cavity, we install fiber isolator that has 5% opposite direction output port from laser direction for measure parameters.

Table 1. Measured and typically used laser parameters for Haus-Namiki Model

Measured Laser Parameters	
Reference pulse width, τ_0(fs)	36
Center wavelength (nm)	1582
Intra-cavity pulse energy (nJ)	1.6
Intra-cavity power (mW)	122
Output power (mW)	55
Saturated amplitude gain, g	0.39
Repetition rate (MHz)	77.55
Excess noise factor, Θ	14(±0.2)
Dispersion (ps^2)	-0.002(±0.001)
Typically Used Laser Parameters	
HWHM gain bandwidth (rad/s)	1.51×10^{13}
SAM-SPM ratio, α	0.1~0.3
Chirp parameter, β	-0.52 to -0.12

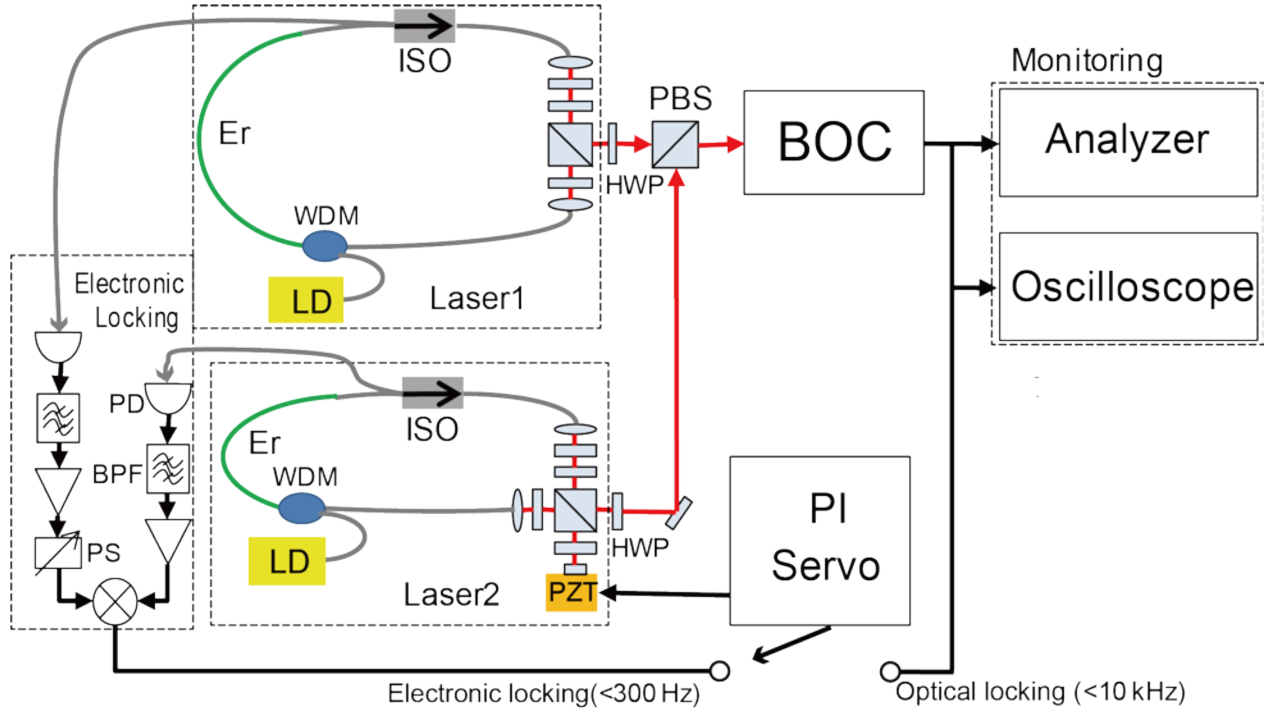

Figure 2. Experimental setup of stretched pulse Er fiber laser timing jitter measurement based on BOC. BOC, balanced optical cross correlator; BPF, bandpass filter; HWP, half-wave plate; ISO, fiber isolator with 5% output port; LD, 976 nm laser diode; PBS, polarization beamsplitter; PD, photodetector; PS, phase shifter; PZT, piezoelectric transducer.

Timing jitter is characterized by 24-as resolution BOC method. For confine output pulses from each laser in the linear detection range, repetition rate of two lasers is locked by low-bandwidth phase-locked loop using PZT mounted mirror inside cavity. In high frequency case, error signal from balanced photodetector is used for feedback signal of repetition rate locking. In low frequency case, photodetector and rf mixer are used for repetition rate locking. BOC is used to timing jitter characterization in whole frequency range. RF and FFT spectrum analyzer are used to measure cross-correlation signal from balanced photodetector. Because measured timing jitter power spectral density (PSD) is sum of timing jitter of two lasers, PSD is divided by 2 to get timing jitter of single laser since two lasers are almost identical and uncorrelated.

Experiment Result and Conclusion

At -0.002 (±0.001) ps^2 dispersion conditions, sub-100 attosecond timing jitter can be achieved from a mode-locked fiber laser. The integrated rms timing jitter of stretched pulse Er-fiber lasers from 10 kHz (1 kHz) to 38.8 MHz is measured to be 70 as (224 as). As shown in graph, the measured timing jitter spectrum of Er-fiber lasers is comparable to those of the best microwave sources and Ti:sapphire lasers. 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.

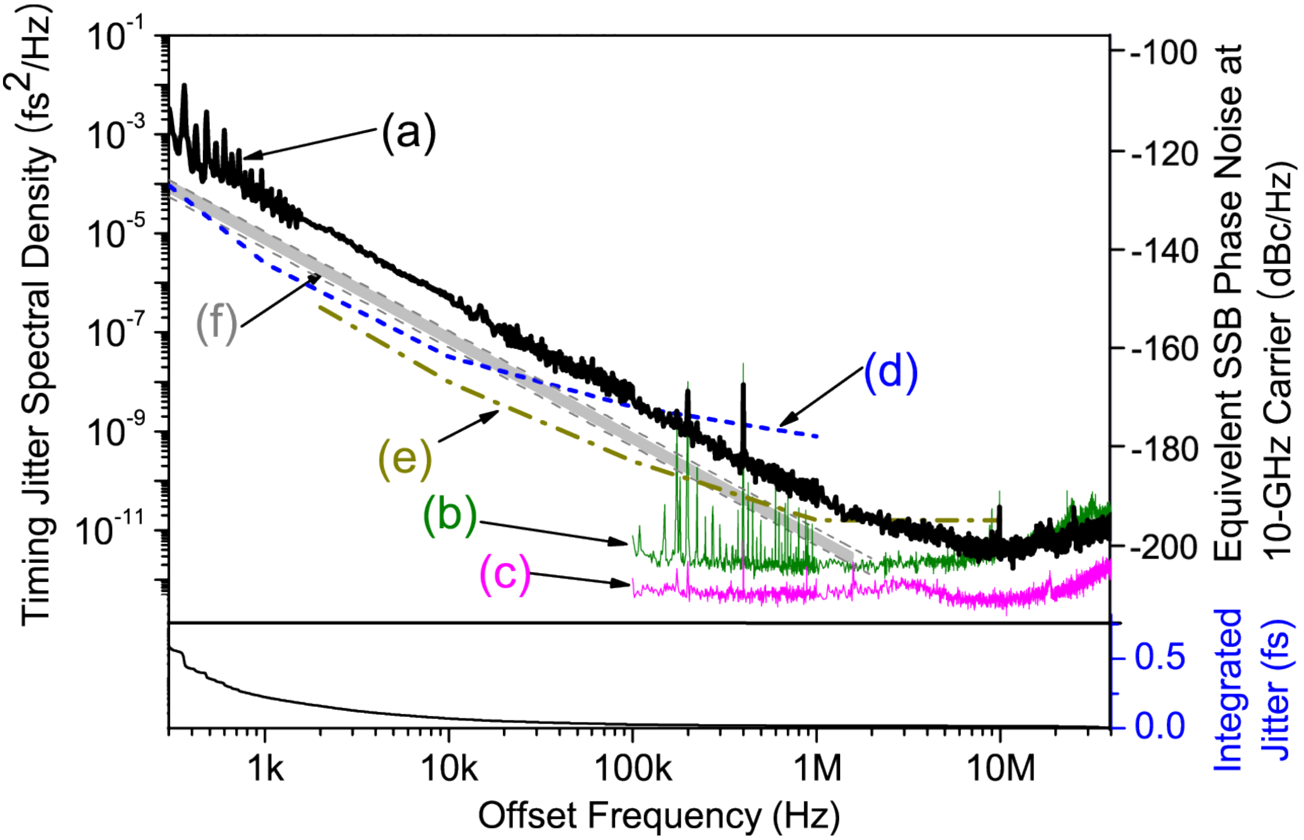

Figure 3. (a) Best timing jitter spectral density result of mode-locked Er-fiber lasers. The integrated timing jitter is 70 as (224 as) when integrated from 10 kHz (1 kHz) to 38.8 MHz offset frequency. (b) BOC photodetector noise floor. (c) Projected RIN-coupled timing jitter. (d) Equivalent timing jitter spectral density of SLCO for comparison. (e) Best timing jitter spectral density of mode-locked Ti:sapphire lasers for comparison. (f) Predicted timing jitter range from the Namiki–Haus analytic model based on measured laser parameters.

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