# SUB-100-ATTOSECOND TIMING JITTER ULTRAFAST FIBER LASERS FOR FEL OPTICAL MASTER OSCILLATORS

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## *Abstract*

Future FELs require femtosecond and even sub-femtosecond timing precision over the entire facility. To meet this timing demand, optical techniques based on modulated cw lasers or ultrafast pulsed lasers have been investigated intensively. It has recently been shown that the timing system based on ultrafast fiber lasers and timing-stabilized fiber links enables long-term stable, sub-10-femtosecond level synchronization [1]. In order to achieve sub-femtosecond level synchronization, the optimization of timing jitter in ultrafast fiber lasers is required. In this work, by operating the fiber lasers at close-to-zero intra-cavity dispersion, we optimize the timing jitter of ultrafast fiber lasers toward sub-femtoescond level. The measured timing jitter of 80-MHz Er-fiber and Yb-fiber lasers is 70-attosecond and 175-attosecond when integrated from 10 kHz to 40 MHz offset frequency. To our knowledge, this is the lowest high-frequency timing jitter from ultrafast fiber lasers so far. The sub-100-attosecond timing jitter from optical master oscillators is the first step toward attosecond-precision FEL timing systems.

## INTRODUCTION

In order to generate and manipulate femtosecond X-ray pulses in X-ray Free Electron Lasers (XFELs), tight synchronization of electron beam-driving RF sources and various optical lasers is required. To meet this stringent timing requirement for femtosecond and eventually sub-femtosecond precision, the use of optical techniques (both cw laser-based and pulsed laser-based) has been actively investigated in the last few years [1,2,3]. Recently, modulated cw laser-based timing systems have been successfully installed in real FEL facilities [2,3], which shows the promise and potentials of optical timing and synchronization systems.

The use of optical pulse trains from femtosecond mode-locked lasers has many advantages for timing distribution and synchronization in FELs. Figure 1 summarizes the schematic and principle of the timing system based on ultrafast lasers. Because the high-frequency timing jitter of mode-locked lasers can be extremely low (can be below a femtosecond range) [4], mode-locked lasers can serve as an ultra-low-jitter optical master oscillator (OMO). By locking the mode-locked laser to a stable RF master oscillator (RMO), one can simultaneously exploit excellent phase stability of RMO in the low offset frequency and ultralow timing jitter of OMO in the high offset frequency. In addition, by employing optical cross-correlation techniques, one can stabilize hundreds-meter fiber-optic timing links with sub-6-femtosecond stability maintained over more than 10 days [5] and further synchronize mode-locked lasers with sub-femtosecond stability for many hours [1]. Because ultralow-phase noise RF signals are encoded in the repetition rate of optical pulse trains, one can also extract ultralow-phase noise RF signals with femtosecond relative stability maintained for many hours [1,6], which can be used for driving the accelerators. Finally, the optical pulse trains can be directly used for optical amplifier seeding, E/O sampling and electron beam arrival time monitoring [7], and high-resolution down conversion of RF signals [8]. Note that each component for sub-10-fs precision pulsed timing system (e.g., stable, low-jitter femtosecond lasers, timing-stabilized fiber links, balanced optical cross-correlators, and stable microwave-optical synchronizers) is also commercially available nowadays.

Over the last decade, there have been great advancements in the performance and stability of ultrafast fiber and solid-state lasers, which now makes them as an attractive option for FEL OMOs. In particular, it turned out that standard passively mode-locked fiber or solid-state lasers can already achieve sub-10-fs short-term (e.g., >1 kHz offset frequency) timing jitter, when measured by direct photo-detection, selecting one RF harmonic component, and measuring the phase noise of the RF component by signal source analyzers [9,10,11]. In order to achieve sub-femtosecond precision timing and synchronization, it is necessary to further optimize the timing jitter of ultrafast lasers into the attosecond regime. Previously, the optimization of timing jitter in ultrafast lasers has been limited by the measurement resolution of photodetection and signal source analyzers, a few fs level over the Nyquist frequency at best.

In this paper, we employed a sub-20-attosecond resolution balanced optical cross-correlation (BOC) method to measure and optimize the timing jitter of ultrafast fiber lasers. By operating the fiber lasers at close-to-zero intra-cavity dispersion condition, we find that the high-frequency timing jitter can be reduced down to sub-100-attosecond levels. The measured timing jitter of 80-MHz repetition rate Er-fiber and Yb-fiber lasers is 70-attosecond and 175-attosecond, respectively, when integrated from 10 kHz to 40 MHz offset frequency. To our knowledge, these performances are the lowest high-frequency timing jitter from ultrafast fiber lasers so far.

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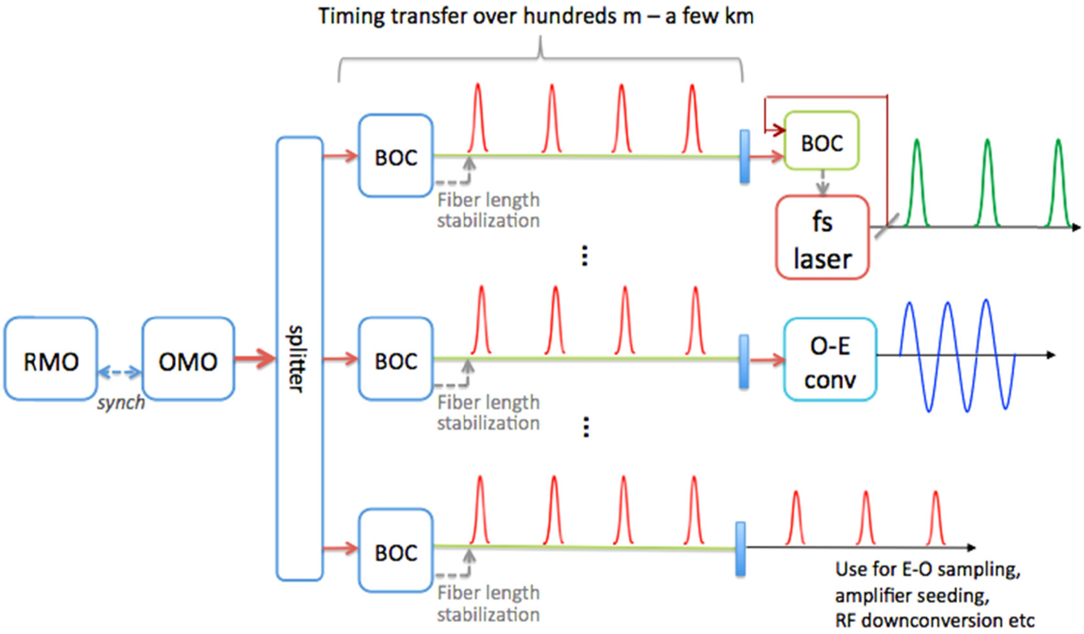

Figure 1: Schematic overview of the pulsed laser timing and synchronization system. RMO, RF master oscillator; OMO, optical master oscillator (femtosecond mode-locked laser); BOC, balanced optical cross-correlator.

## TIMING JITTER MEASUREMENT BY THE BOC METHOD

The timing jitter of free-running ultrafast fiber lasers is characterized by the balanced optical cross-correlation (BOC) method [10]. Figure 2 shows the schematic and principle of the BOC method. The BOC measures timing jitter in the optical domain by nonlinear optic techniques (e.g., sum-frequency generation). As a result, the BOC timing resolution can easily reach sub-fs level with minimal influence of amplitude noise and thermal effects. For the optimization of Er-fiber lasers at 1550 nm, we used a type-II phase-matched PPKTP crystal [10] for both generating sum-frequency signals and providing group delay between two output pulse trains from the two lasers. For the optimization of Yb-fiber lasers at 1 μm, a 400 μm thick type-II phase-matched BBO optimized for 1040 nm is used [12]. The shot-noise-limited timing resolution of the constructed BOCs is 24-as and 20-as (integrated over the Nyquist frequency, 40 MHz) for Er-fiber and Yb-fiber lasers, respectively. In order to confine the timing measurement in the linear detection range of the BOC, the two lasers are synchronized by a low-bandwidth phase-locked loop. An rf spectrum analyzer is used to measure the cross-correlation signal outside the locking bandwidth, which follows the sum of timing jitter power spectral density of two lasers. The measured spectral density is divided by two to get the spectral density of a single laser since the two lasers are nearly identical and uncorrelated. More detailed information on the use of BOC for measuring timing jitter is provided in refs. [10] and [12].

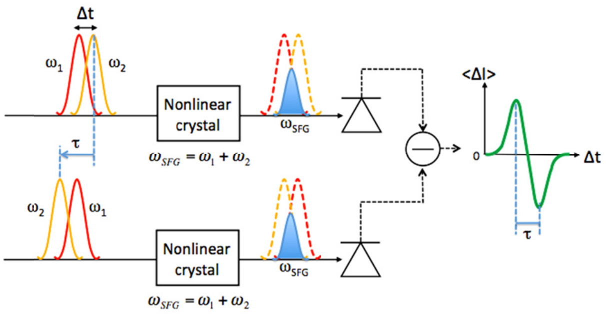

Figure 2: Principle of the BOC for timing detection.

## FEMTOSECOND MODE-LOCKED FIBER LASER SYSTEMS

With the attosecond-resolution BOC method, we investigated the pulse-dynamics-related timing jitter of ultrafast fiber lasers. For the lasers, we used the most standard types of ultrafast fiber lasers – Er-fiber lasers at 1550 nm and Yb-fiber lasers at 1 μm, both mode-locked by the nonlinear polarization evolution (NPE).

The theory on noise in mode-locked lasers has been well developed since the 1990s [4,13,14]. In order to generate lower jitter optical pulse trains, shorter pulse duration, higher intra-cavity energy, and nearly zero intra-cavity dispersion are required [13,14]. Stretched-pulse fiber lasers operating at close-to-zero dispersion condition can satisfy most of these requirements.

### *Stretched-Pulse Er-Fiber Lasers*

Er-fiber or Er/Yb-waveguide lasers are a natural choice for the FEL OMO because of the availability of well-developed, reliable and low-price components at 1550 nm (optical communication band) and the easiness of distribution of optical pulse trains via telecomm-level single-mode optical fiber links. To optimize the timing jitter of Er-fiber lasers, we built two almost identical, 78 MHz repetition rate, stretched-pulse Er-fiber lasers based on the standard NPE mode-locking mechanism. The Er-fiber lasers are made of ~1.2 m Er-doped gain fiber (Liekki Er80-4/125) and ~1 m standard single-mode fiber (SMF-28). One laser is made by a ring cavity structure and the other laser is made by a σ-cavity with a PZT-mounted mirror for repetition-rate locking. We changed the intra-cavity dispersion by adding or subtracting ~5 cm piece of SMF-28 fiber (~ -0.001 $ps^2$) to find the best jitter condition. We controlled the dispersion from -0.005 to +0.001 $ps^2$ range, and found the lowest jitter spectrum at -0.002(±0.001) $ps^2$. At this condition, the output pulse width is 60 fs (FWHM) and the output power is 55 mW. The optical spectrum shows 80nm 3-dB bandwidth at 1582 nm center wavelength. Figure 3 shows the schematic of the Er-fiber lasers and experimental set-up.

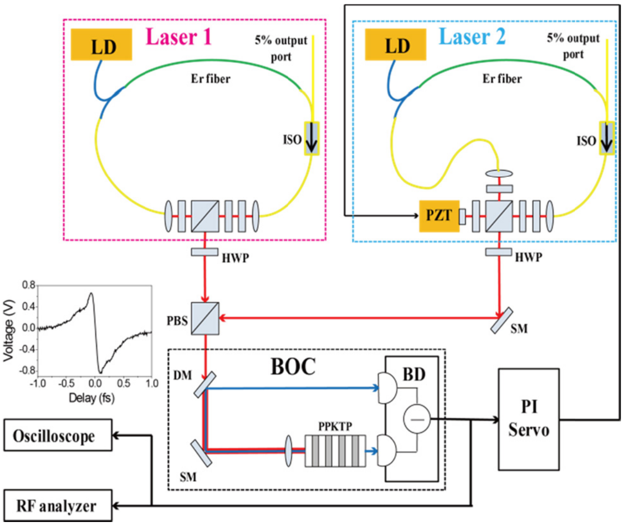

Figure 3: Experimental set-up for the timing jitter measurement of Er-fiber lasers.

### Stretched-Pulse Yb-Fiber Lasers

Yb-fiber lasers are useful to generate high-energy femtosecond optical pulses at 1 µm, which can be a useful laser source in FELs. Thus, we also built 80 MHz repetition rate, stretched-pulse Yb-fiber lasers to study and optimize the timing jitter. To compensate for fiber dispersion, a 600 line/mm grating pair is installed in each laser cavity. The use of grating pair enables fine tuning of intra-cavity dispersion by adjusting the separation of grating pair. The intra-cavity dispersion is changed from +0.002 $ps^2$ to -0.004 $ps^2$ range.

## TIMING JITTER MEASUREMENT RESULTS

### Measurement Result of Er-Fiber Lasers

We measured the timing jitter spectral density of Er-fiber lasers by the PPKTP-BOC at -0.002 (±0.001) $ps^2$ intra-cavity dispersion conditions. Figure 4 shows the timing jitter measurement result of Er-fiber lasers along with those of Yb-fiber lasers and other commercial RF signal generators. Measurement result shows a $1/f^2$-slope from 1 kHz to 2 MHz offset frequency range, which indicates the spontaneous emission noise-induced random walk. As the shot noise level corresponds to ~$10^{-12}$ $fs^2$/Hz, the measurement result is not limited by the BOC resolution. It turns out that the relative intensity noise (RIN)-coupled timing jitter [14] causes the flat jitter spectrum above 7 MHz offset frequency. The integrated rms timing jitter from 10 kHz (1 kHz) to 40 MHz offset frequency is 70 attoseconds (220 attoseconds) [15].

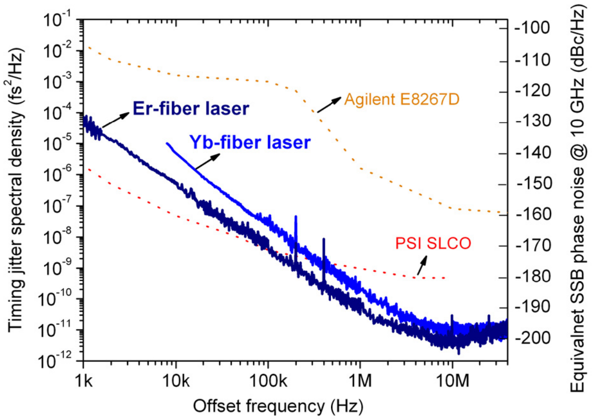

Figure 4: Timing jitter measurement results of Er-fiber and Yb-fiber lasers.

### Measurement Result of Yb-Fiber Lasers

We also measured the timing jitter spectral density of Yb-fiber lasers by the BBO-BOC. For Yb-fiber laser case, the minimum jitter is obtained at 0.000 (±0.001) $ps^2$ intra-cavity dispersion condition. Interestingly, sub-200-attosecond jitter could be obtained in a rather broad range of dispersion, from -0.004 to 0 $ps^2$, if the right mode-locking condition is found. More detailed study on the pulse dynamics and dispersion related jitter behavior of Yb-fiber lasers is presented in refs. [12] and [16]. The measurement result is shown in Fig. 4, and the behavior is very similar to that of Er-fiber lasers, such as $1/f^2$-slope (induced by amplified spontaneous emission noise) in the low offset frequency range and the flat spectrum (induced by the RIN) in the high offset frequency range. The rms timing jitter integrated from 10 kHz to 40 MHz (Nyquist frequency) offset frequency is 175 attoseconds. The

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reason why the Yb-fiber lasers have higher jitter than Er-fiber lasers is mainly due to higher cavity loss introduced by grating pairs (lower cavity Q-factor). We believe that the jitter performance can be significantly improved by replacing the grating pair to lower loss devices, such as photonic crystal fibers or chirped mirrors, which provide negative dispersion at 1 μm.

## SUMMARY AND DISCUSSION

In this work, by operating the stretched-pulse fiber lasers at close-to-zero intra-cavity dispersion and carefully measuring the jitter by the BOC method, we optimize the timing jitter of ultrafast fiber lasers toward the sub-femtoescond level. The measured rms timing jitter of 80-MHz Er-fiber and Yb-fiber lasers is 70-attosecond and 175-attosecond, respectively, when integrated from 10 kHz to 40 MHz offset frequency. To our knowledge, this is the lowest high-frequency timing jitter from ultrafast fiber lasers so far. The demonstration of such low jitter lasers is, we believe, the first step toward the attosecond-precision FEL timing systems.

In order to be employed in real FEL facilities, however, two major issues should be further addressed. First, the ultrafast lasers (as the OMO) should operate in a very reliable way without mode-locking state drop-outs or operation interruptions. Fortunately, there has been remarkable progress toward this direction recently – for example, some commercial lasers based on semiconductor saturable absorbers and polarization-maintaining fiber show excellent long-term stability. It will be interesting to test the stability of such lasers over several months to evaluate its suitability as the FEL OMO. Second, the excess noise and shot-noise limit in the optical-to-RF conversion process should be minimized. It has been shown that the use of electro-optic sampling and feedback control enables long-term stable RF signal extraction from optical pulse trains with less than 10 fs drift over many hours [1, 5, 6]. As the next step, the demonstration of the same performance in a real FEL environment is necessary for future deployment of such techniques. In the high offset frequency, the shot-noise limited noise floor, typically ranging from -140 dBc/Hz to -160 dBc/Hz, should be also suppressed below -160 dBc/Hz to regenerate RF signals with sub-femtosecond jitter relative to the delivered optical pulse trains.

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