Long-term stable remote laser synchronization over a 3.5-km fiber link with one-femtosecond residual timing jitter

Ming Xin[1], Kemal Şafak[1,2], Michael Y. Peng[3], Patrick T. Callahan[3], and Franz X. Kärtner[1,2,3,]*

[1]Center for Free-Electron Laser Science, Deutsches Elektronen-Synchrotron, Notkestrasse 85, Hamburg 22607, Germany, ming.xin@desy.de

[2]Physics Department, University of Hamburg and the Hamburg Center for Ultrafast Imaging, Luruper Chaussee 149, 22761 Hamburg, Germany, kemal.ahmed@desy.de

[3]Department of Electrical Engineering and Computer Science and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA, mypeng@mit.edu, pcallahn@mit.edu, [*]kaertner@mit.edu

Abstract

Long-term stable timing distribution over a 3.5-km polarization maintaining (PM) fiber link using balanced optical cross-correlators (BOC) for link stabilization and optical-to-optical synchronization is demonstrated. Link operation over 80 hours showed only 0.36 fs RMS timing jitter and drift integrated from 100 μHz to 1 MHz, and remote laser synchronization over 36 hours showed a residual timing jitter and drift of only 0.93 fs integrated from 100 μHz to 1MHz. This level of timing precision can closely meet the timing requirements of the next generation of free-electron lasers (FELs).

1. Introduction

Distributing stable timing signals is particularly important for modern large-scale scientific facilities, such as X-ray free-electron lasers (FELs) [1-3]. The European XFEL [1], the largest FEL under construction is 3.5 km long. New FEL designs for the Linac Coherent Light Source II are directed towards the production of sub-fs X-ray pulses. To reach the full potential of these facilities, long-term stable remote optical-to-optical laser synchronization with sub-fs precision over several kilometers of link length is desirable. Yet, there are no related reports at this level of timing precision from laser to laser on the kilometer distance scale.

Since a mode-locked laser can simultaneously provide ultralow-noise optical signals in the form of optical pulse trains, it has the inherent advantage to enable high-precision timing networks that can tightly synchronize multiple optical sources. We have been advancing such a pulsed approach to timing distribution systems for the past decade [4-6]. To realize optical-to-optical synchronization [4, 5], we made use of the balanced optical cross-correlation (BOC) locking method [4, 7], because it can easily achieve tight locking with high locking bandwidth. In our previous work, we implemented the first remote optical-to-optical synchronization using a 300-m standard single-mode fiber link over 3.5 hours, resulting in 2.3 fs rms-timing drift below 0.5 Hz [5]. Recently, we also achieved long-term stabilization of a 1.2-km polarization-maintaining (PM) fiber link within 0.6 fs rms-timing drift (<0.5 Hz) over 16 days of operation [6]. In this paper, we extend this work to remote laser synchronization over a 3.5 km polarization-maintaining fiber link. Synchronization of two 1.55-μm lasers at each end of the link within only 0.31 fs timing drift (<1 Hz) is achieved for 36 hours of continuous operation, and the integrated jitter from 100 μHz to 1 MHz is 0.93 fs. This level of precision closely meets the timing requirements of the next generation of FELs.

2. Experimental setup

The experimental setup for remote laser synchronization is shown in Fig. 1. The whole setup consists of four sections: link-stabilization, link-transmission, remote laser lock and out-of-loop measurement. The master laser operates with a 216.6665 MHz repetition rate, 150 fs pulse width, 1554.7 nm center wavelength and +22.4 dBm average output power, while the remote laser has a 216.6685 MHz repetition rate, 172 fs pulse width, 1553.4 nm center wavelength and +22.1 dBm average output power. These two lasers have ultra-low phase noise; our measurement results have shown that their integrated timing jitter above 10 kHz is below 100 as. The repetition rate of the master laser was locked to a microwave reference with a 10 Hz locking bandwidth, so as to reduce its timing drift below 10 Hz. The repetition rate

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of the remote laser can be coarsely tuned by a computer if it is too far away (out of the PZT tuning range) from that of the master laser.

In the link-stabilization section, the pulse train from the master laser was divided up by PBS 3 into pulse trains in the reference path and in the link path. The reference path is only 4 cm to minimize environmental instability. The link stabilization loop begins with the in-loop BOC 1, which consists of a single 4 mm periodically-poled $KTiOPO_4$ (PPKTP) crystal operated in a double-pass configuration with appropriate dichroic elements [8]. The balanced photo-detector (BPD) has a 3-dB bandwidth of 1 MHz. The output voltage of a proportional-integral (PI) controller was divided into two paths. The first path was amplified to control a PM fiber stretcher, which was responsible for compensating fast link length fluctuations. The second path was sampled by a data acquisition (DAQ) card, and used to control a motorized stage through a Labview program. Both the second and third order dispersion of the 3.5 km long link were carefully compensated, and we achieved a pulse width of 400 fs at the EDFA's output.

In the remote laser lock section, the link output was combined with the remote laser output using PBS 4. Then the two pulse trains were launched into a BOC to generate the timing error signal for feedback control. The BOC output voltage was first filtered by a PI controller. After that, the voltage was separated into two paths; the first path was sent directly to a home-built voltage adder without amplification, to guarantee enough phase margin for stable locking; and the second path was sampled by a DAQ card and analyzed by a Labview program, which outputs a DC offset voltage. After amplification, this signal was responsible for large range compensation. Finally the voltage adder output was used to drive the PZT in the remote laser, which has a sensitivity of 17.4 Hz/V.

Temperature stabilization and vibration isolation of the free-space optics are important to measure the true residual timing errors accurately. A super invar face sheet was placed on the top of a water-cooled breadboard, which was controlled by a chiller to stabilize the temperature of the invar face sheet with ±0.1°C variation. All the free-space components were fixed on this invar sheet to reduce the measurement errors induced by temperature changes. Lead foam was placed beneath the water-cooled breadboard to dampen vibrations from the table. A two-layer enclosure with acoustic heavy foil for the inner layer and high-density polyethylene (HDPE) for the outer layer was also built to isolate the setup from acoustic noise.

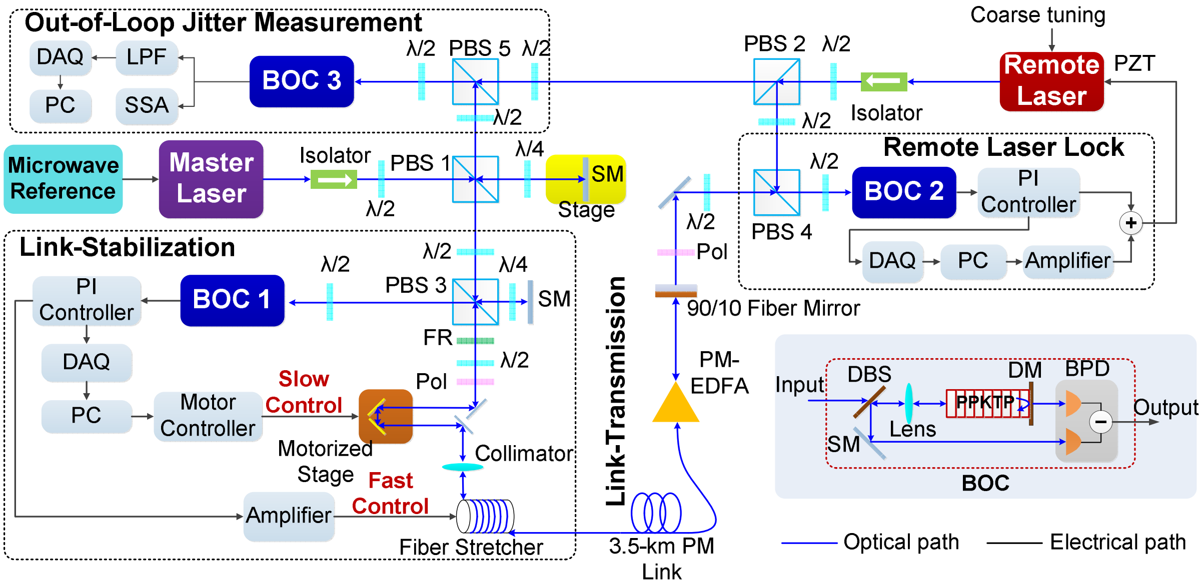

Fig. 1. Experimental setup for remote laser synchronization. PBS: polarization beam splitter cube; SM: silver mirror; λ/2: half wave plate; λ/4: quarter wave plate; FR: 45° Faraday rotator; Pol: polarizer; DBS: dichroic beam splitter; DM: dichroic mirror; PPKTP: periodically-poled KTiOPO4; BPD: balanced photo detector; BOC: balanced optical cross-correlator; PM-EDFA: polarization-maintaining erbium-doped optical fiber amplifier; PI controller: proportional-integral controller; DAQ: data acquisition card; LPF: 1-Hz low pass filter; SSA: signal source analyzer.

For measuring the residual timing jitter of the link only, we can use a reduced setup. The link-stabilization section was still used to perform link stabilization; the out-of-loop section can be used to evaluate the link stability by comparing the timing difference between the link output pulse and the original pulse of the master laser.

3. Measurement results

A link stabilization measurement was first taken using the reduced setup. The in-loop BOC curve was measured using the high gain setting (2×106 V/A) of the BPD. The sensitivity at the zero crossing point was about 14 mV/fs, which is enough to realize tight locking for link stabilization. While for the out-of-loop BOC, a sensitivity of 260 mV/fs with the high gain setting was achieved due to the higher input power for both arms. In order to measure the low-frequency jitter, the out-of-loop BOC voltage was first filtered by a 1-Hz low pass filter (LPF) to avoid aliasing, and then recorded by a DAQ card with 2-Hz sampling rate. Link stabilization for 80 hours was achieved without interruption. In Fig. 2(a), the link drift below 1Hz has a maximum deviation of about 1.4 fs and an rms-value of 0.176 fs. The output of the out-of-loop BOC was also sent to a signal source analyzer (SSA), to measure the power spectral density of the residual timing jitter above 1 Hz. By taking the Fourier transform of the link drift data in Fig. 2(a) and then combining it with the SSA measurement results, we can obtain the complete jitter spectral density from 4 μHz to 1 MHz, as shown in Fig. 2(b). The calculated integrated jitter from 100 μHz to 1 MHz is only 0.36 fs.

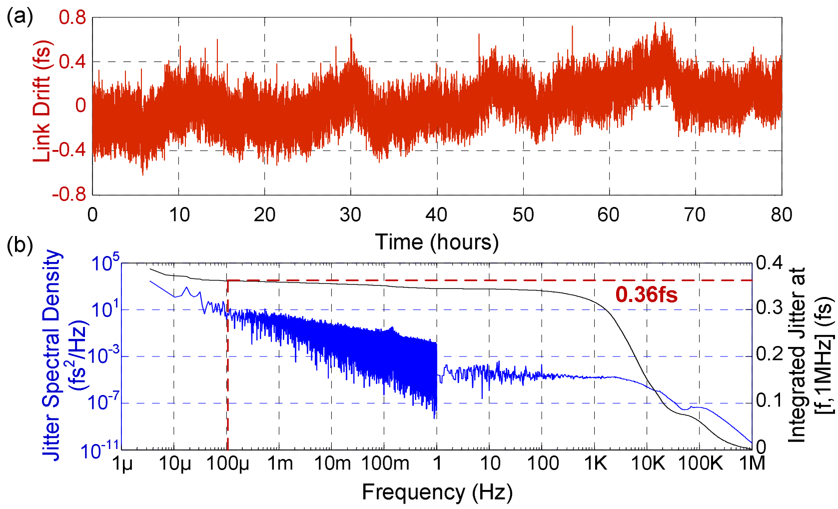

Fig. 2. Link stabilization measurement results. (a) link drift over 80 hours; (b) complete jitter spectral density from 4 μHz to 1 MHz and its corresponding integrated timing jitter.

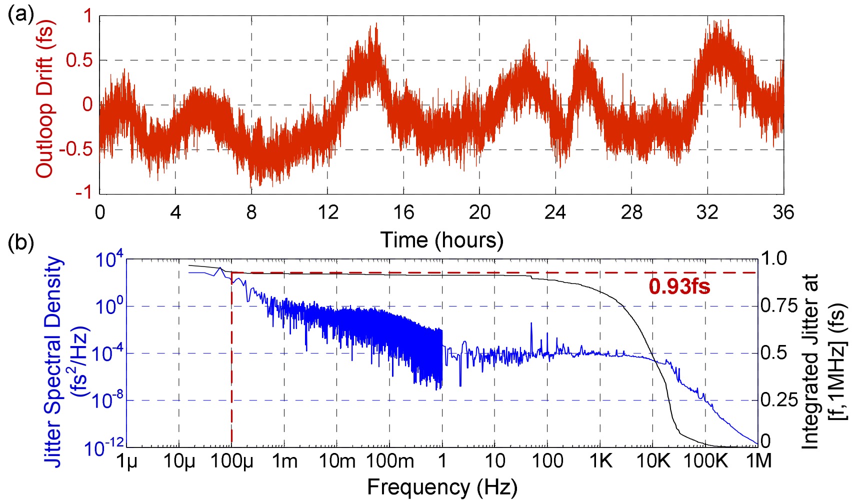

Fig. 3. Remote optical-to-optical synchronization measurement results. (a) out-of-loop drift over 36 hours; (b) complete jitter spectral density from 8 μHz to 1 MHz and its corresponding integrated timing jitter.

After stabilizing the link, we evaluated the performance of remote optical-to-optical synchronization using the setup in Fig. 1. The sensitivity of BOC 1 and 2 with the high gain setting are 14 mV/fs and 390 mV/fs, respectively, which indicate that both of the two BOCs were capable of tight locking. For the out-of-loop BOC, a sensitivity of 160 mV/fs at medium gain or 3.2 V/fs at high gain was reached. In order to measure the low frequency jitter, the out-of-loop BOC voltage was again filtered by a 1-Hz LPF and then recorded by a DAQ card with 2-Hz sampling rate. 36 hours of uninterrupted operation was achieved. The residual timing drift between both lasers had an rms-value of 0.31 fs and +/-1 fs peak-to-peak, as shown in Fig. 3(a). By taking the Fourier transform of the link drift data in Fig. 3(a) and then connecting it with the high frequency jitter measurement results from SSA, we obtained the complete jitter spectral density from 8 μHz to 1 MHz, as shown in Fig. 3(b). The calculated integrated jitter at [100 μHz, 1 MHz] is only 0.93 fs. Therefore, long-term stable remote laser synchronization at the 1-fs timing level has been successfully realized.

4. Conclusion

We have successfully demonstrated long-term stable, sub-femtosecond timing distribution over a 3.5-km PM fiber link for 80 hours with only 0.36 fs of RMS timing jitter integrated from 100 μHz to 1 MHz. This is comparable to the jitter performance we have achieved for a 1.2-km link, but with a three times longer link, to match the length required for the European XFEL. Remote optical-to-optical synchronization of lasers via this link has also been demonstrated for 36 hours with 0.31 fs timing drift below 1Hz. The RMS timing jitter integrated from 100 μHz to 1 MHz is only 0.93 fs. This is the lowest jitter result that has ever been achieved for remote laser synchronization with the longest link length and longest uninterrupted locking time. Continuing towards sub-100-as precision for link stabilization and sub-fs for remote laser synchronization, ongoing work is focused on suppressing the power fluctuations in the link power, optimizing the feedback loops for both link and remote laser locking, and developing an all-integrated BOC [9] to greatly reduce the temperature-dependent drift while simultaneously increasing BOC timing sensitivities for tighter locking of feedback loops.

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