LONG-TERM STABLE, LARGE-SCALE, OPTICAL TIMING DISTRIBUTION SYSTEMS WITH SUB-FEMTOSECOND TIMING STABILITY*

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Abstract

Sub-fs X-ray pulse generation in kilometre-scale FEL facilities will require sub-fs long-term timing stability between optical sources over kilometer distances. We present here key developments towards a completely fiber-coupled, pulsed optical timing distribution system capable of delivering such stability. First, we developed a novel 1.2-km dispersion-compensated, polarization-maintaining fiber link to eliminate drifts previously induced by polarization mode dispersion. Link stabilization for 16 days showed 0.6 fs RMS timing drift and during a 3-day interval only 0.13 fs drift. Second, we verified that ultralow-noise optical master oscillators for sub-fs timing distribution are available today; the measured jitter for two commercial femtosecond lasers is less than 70 as for frequencies above 1 kHz. Lastly, we fabricated a hybrid-integrated, balanced optical cross-correlator using PPKTP waveguides to eliminate alignment drifts and for future reduction of the link operation power by a factor of 10-100.

INTRODUCTION

Modern X-ray free-electron lasers (FELs) [1,2,3] require timing distribution systems with extremely high timing stability to synchronize RF and optical sources located up to several kilometers apart. Since conventional RF timing systems have already reached a practical limit of about 50-100 fs timing precision for such long distances, next-generation timing systems [4,5] are adopting fiber-optic technology to achieve superior performance with optical signal transport and timing distribution.

Over the past decade, we have been advancing technology for a pulsed optical timing distribution system [5]. Our system consists of a femtosecond mode-locked laser tightly locked to a microwave standard and stabilized fiber links for distributing the pulsed optical timing signal to remote locations. Link stabilization is performed using compact, single-crystal balanced optical cross-correlators (BOC), which are capable of attosecond-level timing resolution. Sub-10-fs system performance over days of operation has been achieved but is limited mainly by polarization mode dispersion (PMD) in standard single-mode fiber.

In the near future, it is necessary to improve timing distribution down to sub-fs precision since current facilities, such as LCLS at Stanford, can already produce X-ray pulses shorter than 10 fs [6] and concepts for sub-fs X-ray pulse generation are in place. Improving upon our previous work, we demonstrate here: 1) timing stabilization of a dispersion-slope-compensated 1.2-km polarization-maintaining (PM) fiber link with sub-fs residual timing drift over 16 days, 2) jitter measurements of two ultralow-noise, commercial femtosecond lasers for sub-100-as timing distribution, and 3) fiber-coupled, hybrid-integrated cross-correlators using periodically-poled $KTiOPO_4$ (PPKTP) waveguides for improved BOC timing sensitivities and overall system efficiency and robustness.

TIMING-STABILIZATION OF A 1.2-KM PM FIBER LINK

Link stabilization is critical for preserving the timing precision of the pulsed optical timing signal after long-distance propagation. Environmental disturbances to the fiber link (e.g. thermal fluctuations, acoustic noise, and vibrations) will cause pulse timing errors at the link output. To stabilize the link, we use a BOC to measure the round-trip link timing error with high timing resolution and correspondingly adjust a variable delay within the link path to compensate for the detected error.

Our previous results with a 300-m stabilized fiber link using standard single-mode fiber showed that PMD limited the link stability to about 10 fs over few days of operation and caused delay jumps as much as 100 fs when the fiber was significantly perturbed [6]. To eliminate PMD-induced drifts, we collaborated with OFS in designing and fabricating a 1.2-km PM link with 3rd-order dispersion-compensation. The PM link consists of 1088 m of standard PM fiber matched to 190 m of custom dispersion-compensating PM fiber (PM-DCF). The PM-DCF has a PANDA-like geometry containing Boron stress rods with 35-µm diameters, a core index profile similar to conventional DCF, and a 2nd and 3rd order dispersion of -104.1 ps/(nm·km) and -0.34 ps/(nm^2·km), respectively, at 1550 nm.

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Experimental Set-up

The timing stabilization set-up for the 1.2-km PM link (Fig. 1) begins with a free-running Er-doped fiber laser (Menlo) that outputs 160-fs pulses centered at 1560 nm with +20 dBm average power and 200 MHz repetition rate. The pulse width and repetition rate were selected to reduce higher-order dispersion and nonlinear fiber effects. The set-up is divided into the in-loop section, which performs link stabilization, and the out-of-loop section, which evaluates the in-loop performance.

In the in-loop section, the pulses are divided into a reference and signal path. The reference path serves as a timing reference for the in-loop BOC. The signal path consists of a voltage-controlled free-space delay, 45° Faraday rotator, 1.2-km PM fiber link, and output coupler. Pulse propagation is aligned to the slow axis of the PM fiber. The input power to the PM link was +11 dBm, which is near the onset of fiber nonlinearities. With a 90/10 output coupler, in-loop stabilization was achieved without the use of an optical amplifier. The in-loop BOC, which consists of a 4-mm PPKTP crystal operated in a double-pass configuration [7], measures the round-trip link timing error with a timing sensitivity of 21 mV/fs. The stabilization feedback loop consists of a PI controller (Menlo, PIC210), high voltage amplifier (Menlo, HVA150) and stacked combination of a 40-µm piezoelectric actuator (Thorlabs, PAS009) and 25-mm motorized delay stage (PI, M-112.12S) for short- and long-term stabilization, respectively. The feedback bandwidth was 20 Hz.

The out-of-loop BOC monitors the timing error between the link output pulses against the input pulse stream. The out-of-loop timing sensitivity was 2.3 mV/fs. For long-term drift measurements, the out-of-loop voltage is sampled at 1 Hz with an A/D converter. A low-pass filter with a 0.5-Hz bandwidth is used to improve signal-to-noise after detection. The time delay of the motor stage was also recorded simultaneously.

Temperature stabilization and vibration isolation are critical for sub-fs-level stability. Separate enclosures were built for the free-space optics and PM link. Each consisted of an external 2" layer of insulation foam and an internal Aluminum enclosure, which was temperature-controlled with a resistive heater pad and PID controller.

Long-Term Stabilization Results

Sub-fs link stabilization was achieved for 16 days. Link drift and motor delay measurements are shown in Fig. 2a. Although the data log for the motor delay faulted in day 13, the link stabilization remained unaffected. Overall, the motor delay corrected for over 65 ps of timing error while the link drift at the link output showed only a maximum deviation of 2.5 fs and a RMS value of 0.6 fs. This represents a suppression of timing fluctuations by a factor of more than 20,000 over 16 days, indicating that the PM fiber was effective in overcoming the previous 10-fs-level stability limit over few days of operation and eliminating large 100-fs delay jumps caused by PMD upon significant perturbation to the fiber.

Relative changes in the internal temperatures of the PM link and free-space enclosures and ambient temperature are plotted in Fig. 2b. The strong correlation between the link drift and ambient temperature confirms that the link drift is limited by environmental fluctuations penetrating into the free-space BOCs or causing drifts in the free-running laser repetition rate. This is reasonable because the free-space enclosure is large in volume, making it difficult to isolate the enclosed optics from the environment. Resolving these issues should yield 100-as-level stability or even better; this is evident during days 11-14 when ambient fluctuations were fortuitously minimal, resulting in a RMS timing drift of only 0.13 fs.

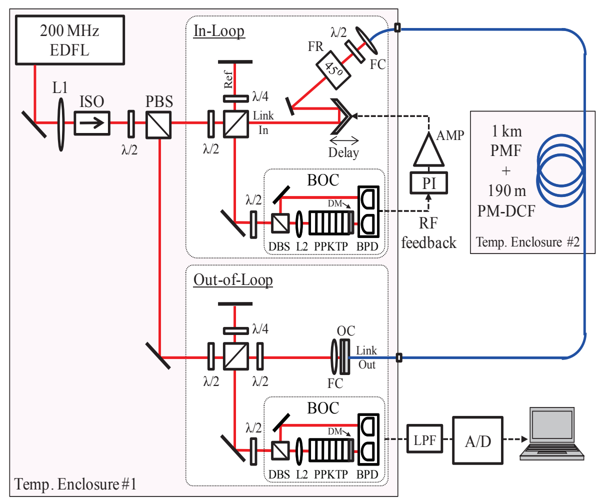

Figure 1: Schematic for the timing stabilization of the 1.2-km PM fiber link; EDFL, Erbium-doped fiber laser; L1, collimator; ISO, isolator; λ/2, half-wave plate; λ/4, quarter-wave plate; PBS, polarizing beam-splitter; FR, 45° Faraday rotator; FC, fiber collimator; PMF, standard PM fiber; PM-DCF, dispersion-compensating PM fiber; OC, output coupler; BOC, balanced optical cross-correlator; DBS, dichroic beam-splitter; L2, focusing lens; PPKTP, periodically-poled $KTiOPO_4$; DM, dichroic mirror; BPD, balanced photodetector; PI, proportional-integral controller; AMP, high voltage amplifier; LPF, low-pass filter; A/D, analog-to-digital converter.

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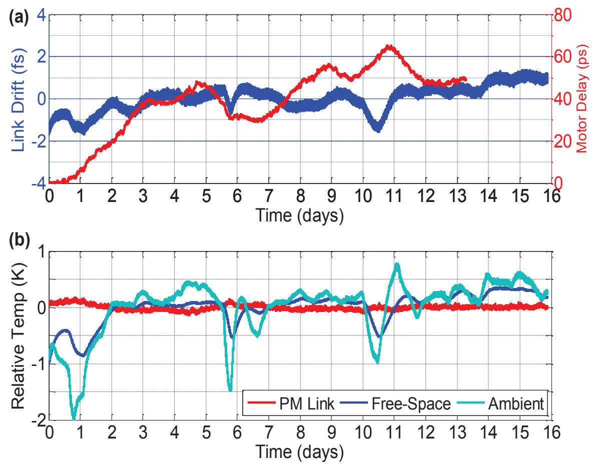

Figure 2: Long-termmeasurements for the timing-stabilized 1.2-km PM fiber link over 16 days; (a) link drift, as measured by the out-of-loop BOC, and time delay, as controlled by the in-loop motor stage; (b) relative changes in the internal temperatures for the PM link and free-space enclosures and ambient temperature.

TIMING JITTER MEASUREMENT OF ULTRA-LOW NOISE LASERS

We verified that ultralow-noise lasers for sub-fs timing systems are commercially available today. To measure their timing jitter, conventional methods via high-speed photodetectors and RF mixers cannot be used; excess phase noise during detection and limited resolution in the mixer prevent jitter characterization below 1 fs. An alternative approach is to use a BOC, which can precisely extract timing information with as-level resolution by avoiding intensity-conversion noise during detection [7].

Experimental Set-up

Based on the conventional two oscillator phase noise measurement, our timing jitter measurement set-up begins with two femtosecond lasers (Onefive, ORIGAMI), which produce 170 fs pulses centered at 1554 nm with 170 mW average power. The pulse trains are combined with orthogonal polarizationsin a polarization beam-splitter and sent to a BOC. The relative pulse timing is converted to a voltage signal with a timing sensitivity of 1.3 mV/fs. The error signal is fed back to the piezoelectric tuning port of the local laser to lock its repetition rate to that of the master laser. A "loose" lock is implemented so that the high-frequency laser timing jitter beyond the locking bandwidth can be directly measured using a signal source analyzer (Agilent, E5052B). The measured spectrum is divided by two since we assume that the two lasers have identical and uncorrelated jitter.

Results

The timing jitter spectral density and integrated timing jitter are given in Fig. 3. Within the locking bandwidth, the integrated jitter caused by acoustic noise below 200 Hz is suppressed to 100 as. Beyond the locking bandwidth, the integrated jitter from 1 kHz to 1 MHz is less than 70 as and from 10 kHz to 1 MHz is less than 15 as. This extremely low jitter indicates that these lasers are well-suited for sub-fs timing systems spanning kilometer distances.

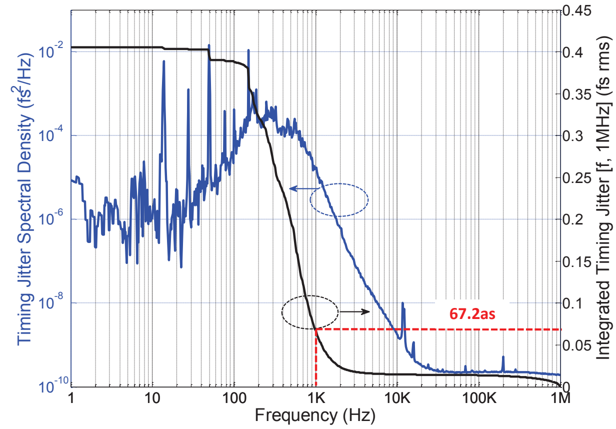

Figure 3: Measured timing jitter spectral density for an individual laser and its integrated timing jitter for the frequency range [f, 1 MHz].

INTEGRATED BALANCED OPTICAL CROSS-CORRELATOR

To further improve the precision of our timing system, fiber-coupled integrated BOCs are an absolute necessity. One major benefit is that an all-fiber implementation will eliminate drifts caused by beam misalignments. Also, the second-harmonic generation (SHG) conversion efficiency of the integrated BOC will be 1-2 orders of magnitude better than that of bulk-crystal BOCs[8]. In collaboration with AdvR, the PPKTP waveguides were fabricated with improved mode sizes and poling quality and mounted into robust fiber-coupled packages.

SHG Conversion Efficiency in Waveguides

The waveguides were fabricated by Rb+ ion exchange on a KTP substrate and were diced and polished to a length of 1 cm. An anti-reflective coating at 1550±50 nm and 775±25 nm was deposited on the front facet, and a dichroic coating highly-reflective at 1550±50 nm and anti-reflective at 775±25 nm was deposited on the rear facet. Pulses at the fundamental (FH) wavelength of 1560 nm are therefore reflected at the rear facet back into the waveguide, thus generating another second-harmonic (SH) pulse on the return path for balanced operation of a cross-correlator. A peak normalized SH conversion efficiency of 1.76 %/[W-cm^2] was extracted at 1560 nm. The integrated BOC is expected to improve timing sensitivity by a factor of 50 over that of bulk-optic BOCs.

Fiber-Coupled Device Operation

The coated PPKTP waveguides were mounted in a robust fiber-coupled package. The PM fiber at the module input couples FH pulses into the waveguide and couples the reverse-generated SH out. The multi-mode fiber at the

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other end collects the forward-generated SH. The module was tested in a fiber-coupled, cross-correlator configuration. Due to excess coupling loss between the PM fiber and the waveguide for the reverse-generated SH, the SH power collected on the forward path was approximately 10 dB higher than that of the reverse path. Therefore, a 10-dB attenuator was inserted to symmetrize the cross-correlation curve. Preliminary device operation yields a timing sensitivity of 4 mV/fs (Fig. 4), which is comparable to that of a single-crystal BOC operated with the same input pulses. With improved SH output coupling, the waveguide BOC can potentially operate at least 3 times lower input power while maintaining the same output signal. A thorough characterization of the device performance and packaging optimization is in process.

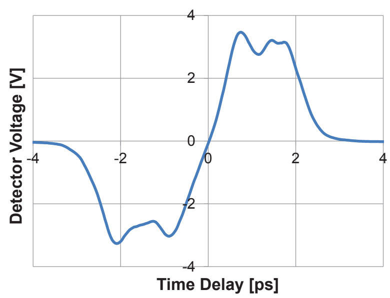

Figure 4: BOC voltage response as a function of pulse time delay.

SUMMARY

In summary, we have presented key technologies towards an all-optical, fiber-based timing distribution system capable of sub-femtosecond precision. Timing distribution over a timing-stabilized 1.2-km PM link using BOCs was demonstrated for 16 days with 0.6 fs RMS timing drift and during a 3-day interval only 0.13 fs drift. Jitter characterization of two identical commercial femtosecond lasers using the BOC method verified sub-100-as timing jitter for frequencies greater than 1 kHz. Lastly, preliminary operation of a fiber-coupled, hybrid-integrated BOC using PPKTP waveguides indicates great potential for improved timing sensitivity and overall system efficiency and robustness.

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