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COMMISSIONING AND LONG-TERM RESULTS OF A FULLY-AUTOMATED PULSE-BASED OPTICAL TIMING DISTRIBUTION SYSTEM AT DALIAN COHERENT LIGHT SOURCE

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Abstract

We report here a 15-link pulse-based optical timing distribution system (TDS) that was recently installed at Dalian Coherent Light Source, and initial long-term measurement results of the timing stability between remote clients. The timing stability of the remote microwave generation using a Balanced Optical Microwave Phase Detector (BOMPD) was 15 fs RMS over one hour, while that of the remote ultrafast laser synchronization using a Two-Color Balanced Optical Cross-correlator (TCBOC) was 13 fs RMS over four hours. Furthermore, the installed polarization-maintaining TDS has been operating continuously for 2.5 months, providing 24/7 fs-level timing distribution and remote synchronization.

INTRODUCTION

New generation light sources such as X-ray free-electron lasers [1] and attoscience centers [2] require high stability for timing synchronization, on the order of few femtoseconds or below, to generate ultrashort X-ray pulses that enable attosecond temporal and subatomic spatial resolution. The challenge in achieving such stability lies in part in a reliable, high-precision timing distribution system that can synchronize various optical and microwave sources across multi-km distances with good long-term stability. It was shown that the pulsed-optical timing distribution system, based on balanced optical cross-correlation (BOC) detection and balanced optical-microwave phase detectors (BOMPD), can deliver sub-fs long-term timing precision between remotely synchronized lasers and microwave sources in laboratory environment [3,4]. It was also reported that a large-scale turn-key timing distribution system (TDS) that is able to serve 15 remote optical and microwave sources via timing stabilized fiber links was developed and delivered less than 1-fs RMS timing jitter at the outputs of the fiber links over 2.5 days of operation [5].

Here, we present the latest results from the commissioning of China's first multi-link pulse-based optical timing distribution system (TDS) installed at Dalian Coherent Light Source. Long term operating results of the fully-automated polarization-maintaining TDS, as well as lessons learned and recommendations for future improvements, are presented, including performance of the microwave end-stations and ultrafast laser synchronization end-stations.

SYSTEM LAYOUT AND ARCHITECTURE

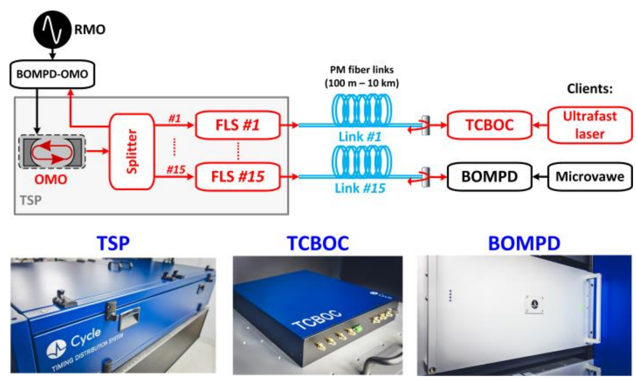

Figure 1: Layout of the timing distribution system (top sketch) and its individual modules (bottom pictures). RMO: RF master oscillator; OMO: optical master oscillator; TSP: temperature stabilized platform; FLS: fiber link stabilizer; TCBOC: two-color balanced optical cross-correlator; BOMPD: balanced optical-microwave phase detector.

Figure 1 shows a block diagram of the polarization-maintaining TDS that was installed at Dalian Coherent Light Source, which is capable of serving 15 remote end-station clients across the facility. The optical master oscillator (OMO) is a low-noise mode-locked laser that provides the optical clock signal that is distributed throughout the facility via timing stabilized optical fiber links. A BOMPD (i.e., BOMPD-OMO in Fig. 1) synchronizes precisely the repetition rate of the OMO to an external RF reference at 2856 MHz. The output of the OMO is then split into 15 separate polarization maintaining (PM) channels and distributed over PM fiber links, which are stabilized by fiber link stabilizers (FLS) to less than 1-fs RMS timing jitter. Time-of-flight fluctuations of the PM fiber links are detected by a BOC and compensated by a PM fiber stretcher and a motorized delay line in a feedback loop. Two-color BOCs (TCBOCs) and BOMPDs are used to synchronize ultrafast lasers and microwave sources to the link outputs at remote locations. Further details of the timing system can be found in [5].

In additional to the optical detectors, a fully-automated control system handles automatic starting, signal searching and centering, data-logging, and a user-friendly EPICS-based graphical user interface with remote VPN capability

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was also delivered, and helps to provide 24/7 fs-level timing and synchronization across the facility.

PERFORMANCE CHARACTERIZATION

Out-of-loop characterization of the TDS was carried out to ensure the system is performing as it was during factory acceptance tests (FAT) in Hamburg. Two measurements were taken to confirm the performance of the remote microwave generation by the BOMPDs and the remote ultrafast laser synchronization of the TCBOCs. Below two sections describe the results.

Remote Microwave Generation

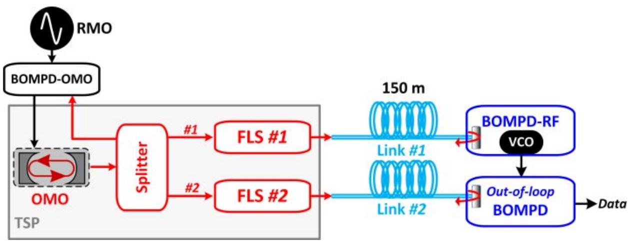

Figure 2: Measurement setup of the remote microwave generation using the BOMPDs. VCO: voltage-controlled oscillator.

Figure 2 shows the measurements setup used to characterize the BOMPD performance after installation at the facility. One in-loop BOMPD, with an integrated voltage-controlled oscillator (VCO), was used in a feedback loop to generate a microwave signal at 2856 MHz, where the zero crossings of the RF signal are tightly synchronized to the pulse arrival times at the output of the timing-stabilized fiber links, while a second out-of-loop BOMPD was used to measure the residual timing drift. The baseband error signal from the out-of-loop BOMPD was recorded using a standard laboratory data acquisition device at 2 Hz sampling rate, and a lowpass filter with a 1-Hz corner frequency was used to prevent aliasing. Figure 3 shows the measured timing drift of the BOMPD over one hour. The out-of-loop drift was 15 fs RMS, which confirms performance of the BOMPD on-site is similar to that during FAT.

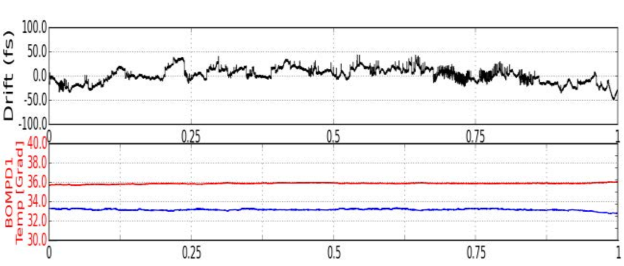

Figure 3: Out-of-loop measurement on the timing drift of the remotely generated microwave signal using the BOMPDs installed at Dalian Coherent Light Source (top). Temperature inside the BOMPD enclosure during the measurement time (bottom).

Remote Ultrafast Laser Synchronization

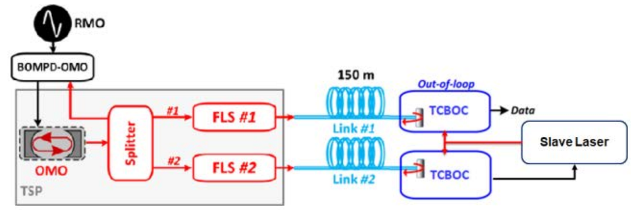

Figure 4: Performance characterization setup of the remote-station ultrafast laser synchronization using the TCBOC.

Figure 4 shows the measurement setup for charactering the out-of-loop timing drift of the installed TCBOC. One in-loop TCBOC was used to tightly synchronize the repetition rate of the seed laser (Coherent Vitara) to the output of the timing-stabilized fiber link, while a second out-of-loop TCBOC was used to measure the residual timing drift. The baseband error signal from the out-of-loop TCBOC was recorded using a standard laboratory data acquisition device at 2 Hz sampling rate, and a lowpass filter with a 1-Hz corner frequency was used to prevent aliasing. Figure 5 shows the measured timing drift of the TCBOC over four hours. The out-of-loop drift was 13 fs RMS, which confirms performance of the TCBOC on-site is similar to that during FAT.

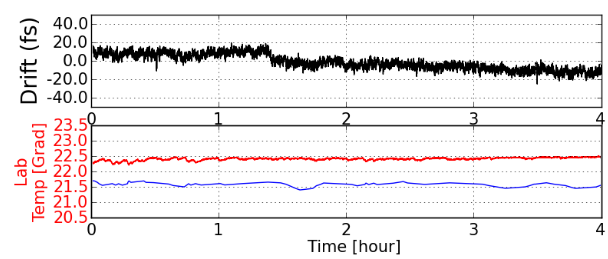

Figure 5: Out-of-loop measurement on the timing drift of the synchronized seed laser using the TCBOCs installed at Dalian Coherent Light Source (top). Temperature in the seed laser room during the measurement time. (bottom)

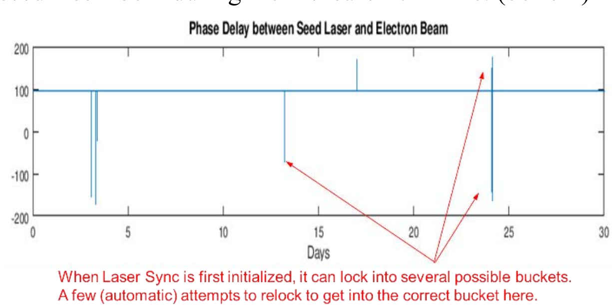

Figure 6: Coarse phase monitor of the remote seed laser compared to the electron bunch.

Since the seed laser operates at 79.33 MHz, whereas the OMO produces a pulse train at 238.00 MHz, it is possible to lock the remote seed laser into three time-buckets. Therefore, a coarse phase detector was built to monitor the phase delay between the seed laser pulses with respect to

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the electron bunches, to ensure that the laser is locked into the appropriate bucket whenever the TCBOC lock is initiated. Figure 6 shows the phase monitor measurement, where it is shown that the TCBOC was locked continuously at approx. 100-degrees phase offset over a period of 30 days. One could also see from such monitoring, the long-term reliability and stability of the reported TDS, where 24/7 continuous operation of the TDS is indicated, except for several instances where the system was turned off or restarted by the operator.

CONCLUSION & OUTLOOK

It has been shown that the reported large-scale turnkey TDS has performed reliably, while providing 24/7 timing distribution at the fs-level. Long term timing drift measurement of the remote microwave generation was shown to be 15 fs RMS over one hour, while measurement on the remote ultrafast laser synchronization of the seed laser shows a stability of 13 fs RMS over a measurement time of four hours. Measurements from a facility monitor on the phase-offset between the seed laser and the electron bunches show continuous 24/7 operation of the TDS over a 30-day period, while, at the time of paper submission, the TDS has been running continuously for over 2.5 months, providing 24/7 precise timing distribution and synchronization to support experiments at Dalian Coherent Light Source.

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