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LARGE-SCALE TURNKEY TIMING DISTRIBUTION SYSTEM FOR NEW GENERATION PHOTON SCIENCE FACILITIES

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Abstract

We report a large-scale turnkey timing distribution system able to satisfy the most stringent synchronization requirements demanded by new generation light sources such as X-ray free-electron lasers and attoscience centers. Based on the pulsed-optical timing synchronization scheme, the system can serve 15 remote optical and microwave sources in parallel via timing stabilized fiber links. Relative timing jitter between two link outputs is less than 1 fs RMS integrated over an extended measurement time from 1 µs to 2.5 days. The current system is also able to generate stabilized microwaves at the link outputs with 25-fs RMS precision over 10 h, which can be easily improved to few-femtosecond regime with higher quality VCOs.

INTRODUCTION

Low-noise transfer of time and frequency standards over large distances provides high temporal resolution for ambitious scientific explorations such as sensitive imaging of astronomical objects using multi-telescope arrays [1], comparison of distant optical clocks [2] or gravitational-wave detection using large laser interferometers [3]. In particular, rapidly-emerging new generation light sources such as X-ray free-electron lasers (FELs) [4] and attoscience centers [5] have the most challenging synchronization requirements on the order of few femtoseconds or below to generate ultrashort X-ray pulses for the benefit of creating super-microscopes with sub-atomic spatiotemporal resolution. The critical task in these facilities is to synchronize various pulsed lasers and microwave sources across multi-kilometer distances as required for seeded FELs and attosecond pump-probe experiments.

Recently, it has been shown that the pulsed-optical timing synchronization scheme based on balanced optical cross-correlators (BOCs) and balanced optical-microwave phase detectors (BOMPDs) can deliver sub-femtosecond precision between remotely synchronized lasers and microwave sources in laboratory environment [6,7]. Here, we transform this experimental system into a large-scale turnkey timing distribution system (TDS) that is able to serve 15 remote optical and microwave sources via timing stabilized fiber links. The system exhibits less than 1-fs RMS timing jitter at the outputs of the fiber links over 2.5 days of operation. The current system is able to serve remote microwave devices with 25-fs RMS precision over 10 h which can be easily improved to few femtoseconds with higher quality VCOs.

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In this paper, we describe the layout of the TDS together with its dedicated control system. We also discuss the characterization measurements of the timing stabilized fiber links and the remote microwave synchronization.

SYSTEM LAYOUT AND ARCHITECTURE

Figure 1 shows the layout of the TDS capable of serving 15 remote clients. The optical master oscillator (OMO) is a low-noise mode-locked laser operating at 1550-nm center wavelength with a free-running timing jitter of 0.4 fs RMS integrated between 1 kHz and 1 MHz [8]. A BOMPD (i.e., BOMPD-OMO in Fig. 1) is employed to lock the OMO to an external RF master oscillator in order to ensure the TDS operates synchronously with the facility's RF reference (e.g., low-level RF system). Then the output of the OMO is split into 15 separate polarization maintaining (PM) fiber links. In order to preserve the low noise properties of the OMO during the delivery to remote locations, fiber link stabilizers (FLS) are developed. Each FLS contains a BOC to detect the time-of-flight fluctuations of the optical pulses during fiber-link transmission with attosecond precision. Then, the integral control elements of the FLS (i.e., a fiber stretcher and a motorized delay line) are activated to stabilize the arrival time of the delivered optical pulses at the fiber link output. Once the fiber links are stabilized, two-color BOCs (TCBOCs) and BOMPDs are activated to synchronize ultrafast lasers and microwave sources to the link outputs at remote locations. The TCBOC detects the timing error between the two optical pulse trains, emanating from the fiber link output and the remote slave laser. The voltage response of the TCBOC is then used as a feedback signal to control the frequency of the remote slave laser via its

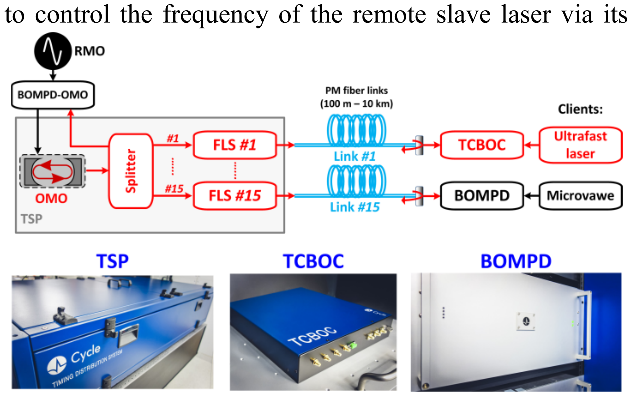

Figure 1: Layout of the timing distribution system (top sketch) and its individual modules as built in the lab (bottom pictures). RMO: RF master oscillator; OMO: optical master oscillator; TSP: temperature-stabilized platform; FLS: fiber link stabilizer; TCBOC: two-color balanced optical cross-correlator;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

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intracavity Piezo actuators. The BOMPD, on the other hand, relies on an optoelectronic-phase-detection scheme between the optical and microwave inputs where the timing error is converted into an intensity modulation of the optical pulse train. The intensity modulation is detected by a balanced detector which generates a voltage signal that is proportional to the phase error between the microwave signal and the optical pulse repetition rate. The voltage signal (or the error signal) is fed back to the microwave source, e.g., to a voltage controlled oscillator (VCO) to correct for its phase error with respect to the optical pulse train.

We have also developed a cost-effective and reliable control system based on the Xilinx hardware platform, with FPGA for fast signal processing, and an ARM core for interfacing and high-level processing. The hardware platform is distributed, with individual control processor dedicated to each element in the TDS (e.g., BOC, TCBOC, etc.). Operation signals are digitized with low-noise, high-bandwidth ADCs, and sampled by the FPGA. These signals can then be processed and output directly to high bandwidth DACs, or passed onto the ARM core, which runs the Linux and EPICS interfaces. Since the hardware description and software development are carried out in the Xilinx-Vivado architecture, the existing control system can be transferred easily to other hardware platforms such as ATCA and MicroTCA.

Figure 2 shows the overview panel of the graphical user interface (GUI) developed for the easy supervision of the TDS where all subsystems can be automatically started and observed. Advance settings of the individual synchronization modules can also be accessed via the TDS-GUI; for instance, to optimize the feedback parameters of the FLS, TCBOC and BOMPD.

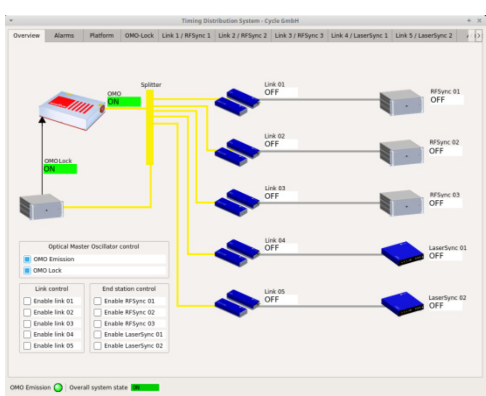

Figure 2: Interactive overview panel of the TDS-GUI.

Another significant development in the control system is the Digital Synchronization Unit (DSU), which is specifically designed to aid the slave oscillator synchronization of the TDS. The DSU carries out a low-noise digital microwave locking that pre-locks the slave optical and microwave oscillators so that the BOC- or the BOMPD-locks can be initiated automatically. The DSU has also an FPGA interface for programmability and offers three important features. First, it can divide the input frequency, so that a frequency can be locked to its (sub-) harmonic. Second, it provides a clock synthesis option. It can generate various low-voltage locking signals with low latency and jitter, which can be a (sub-) harmonic of the reference input. Third, it has the ability to delay one of the input signals allowing a digitally controlled delay scan between the two sources.

PERFORMANCE CHARACTERIZATION

Timing-stabilized fiber link

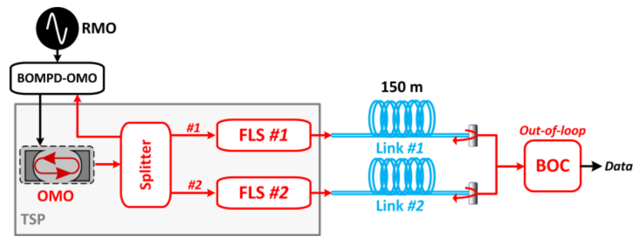

Figure 4: Performance characterization setup of the timing-stabilized fiber links.

The first set of measurements is performed to characterize the relative timing jitter of the fiber links with the setup shown in Fig. 3. Two 150-m long PM fiber links are stabilized with two FLS units where roundtrip delay fluctuations are detected by the BOCs and fed back to the motorized delay lines and the fiber stretchers. Once the control system is activated, it performs an automatic search and locks the fiber links to the zero-voltage crossing of the BOC error signal. Then, the outputs of these two fiber links are combined into a free-running BOC serving as the out-of-loop timing detector.

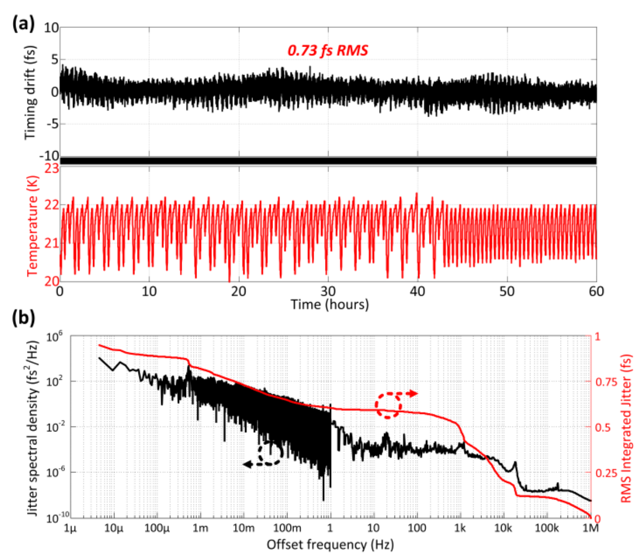

Figure 5: Performance measurements of the timing-stabilized fiber links. (a) Long-term timing drift and environmental temperature. (b) Timing jitter spectral density and integrated timing jitter between 4.6 μHz and 1 MHz.

Stabilization of the two fiber links is operated for 60 h without any interruption. The black curve in Fig. 4(a) shows the residual timing drift between the two link outputs measured with 2-Hz sampling, whereas the red curve underneath shows the environmental temperature outside the TSP where the fiber links are placed. Even though the environmental temperature is modulated by 2˚C peak-to-

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peak with a period of 30 mins, the TDS is able to keep the system synchronized continuously without showing any locking volatility. The out-of-loop timing drift is only 0.73 fs RMS measured over 60 h between the two link outputs. Figure 5(b) shows the timing jitter spectral density between 4.6 μHz and 1 MHz. The links exhibit a total integrated timing jitter of less than 1 fs RMS where high frequency noise above 1 Hz amounts to 0.6 fs RMS proving both long-term and short-term sub-femtosecond operation precision of the TDS.

Microwave generation at link ends

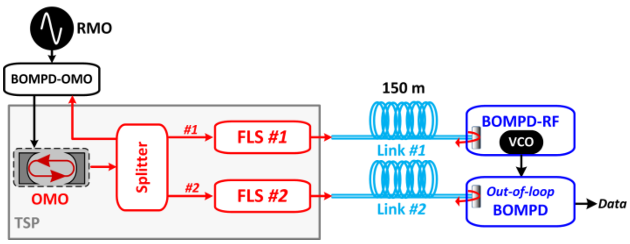

Figure 6: Performance characterization setup of the microwave generation at link ends.

Next, we perform remote microwave synchronization experiments with the setup illustrated in Fig. 5. At the remote of ends of two fiber links, two BOMPDs are constructed which use the timing-stabilized pulse trains of the fiber links as their optical input signals. The first BOMPD (i.e., BOMPD-RF in Fig. 5) contains an integral VCO whose frequency (i.e., 2.856 GHz) is locked to the Link #1 output. The second BOMPD, on the other hand, is used as a free-running detector to measure the out-of-loop timing jitter between the remotely synchronized VCO and the link #2 output.

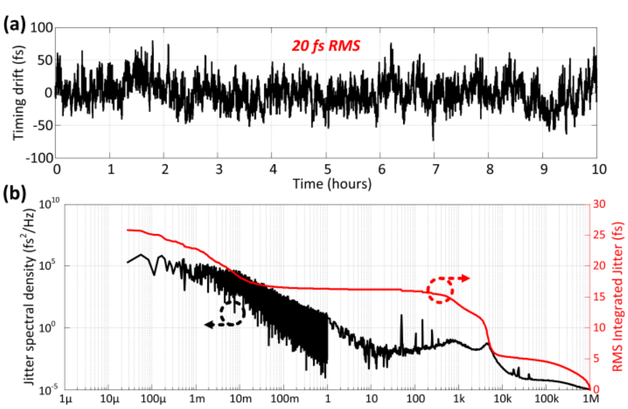

Figure 7: Performance measurements of the microwave generation at link ends. (a) Long-term timing drift sampled at 2 Hz. (b) Timing jitter spectral density and integrated timing jitter between 28 μHz and 1 MHz.

Figure 7 shows the long- and short-term stability measurements of the generated microwave with respect to the second fiber link. Out-of-loop timing drift is ~20 fs RMS over 10 h (see Fig. 6(a)), whereas total timing jitter integrated from 28 μHz to 1 MHz is ~25 fs RMS (see Fig. 6(b)). As can be inferred from the red curve in Figure 7(b), there are two frequency regions where the remote microwave acquires excess noise. First, high frequency noise above 1 kHz amounts to ~15 fs RMS which is mainly limited by the inherent noise of the VCO. High frequency performance could be easily improved to few-femtosecond regime by employing higher quality VCOs. Second, low frequency noise below 0.03 Hz (i.e., 33 s) cause the main timing drift contribution with ~20 fs RMS. Uncompensated fiber paths used for the intensity modulation of the optical pulse train is quite susceptible to the environmental fluctuations. Long-term performance of the remote microwave synchronization could be also improved by isolating or minimizing such fiber paths.

CONCLUSION & OUTLOOK

The TDS discussed here could enable sub-femtosecond precision synchronization of optical lasers and microwave sources in X-ray photon-science facilities. The current system can serve 15 separate clients via timing stabilized fiber links which exhibit less than 1-fs RMS timing jitter integrated over an extended measurement time from 1 μs to 2.5 days. Microwave synchronization experiments at the link outputs show ~25-fs RMS jitter for the frequency range of 28 μHz - 1 MHz. Higher quality VCOs and better environmental isolation of the BOMPD would improve the microwave precision to few femtoseconds. We are currently working also on the remote synchronization of pulsed-laser systems using TCBOCs, which is essential for highly time-resolved pump-probe experiments in new generation light sources.

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