AN INTEGRATED FEMTOSECOND TIMING DISTRIBUTION SYSTEM FOR XFELS

J. Kim#, J. Burnham, J. Chen, F. X. Kärtner, MIT, Cambridge, MA, USA
F. Ö. Ilday, Bilkent University, Ankara, Turkey
F. Ludwig, H. Schlarb, A. Winter, DESY, Hamburg, Germany
M. Ferianis, ELETTRA, Trieste, Italy
D. Cheever, MIT-Bates Linear Accelerator Center, Middleton, MA, USA

Abstract

Tightly synchronized lasers and RF-systems with timing jitter in the few femtoseconds range are necessary sub-systems for future X-ray free electron laser facilities. In this paper, we present an optical-microwave phase detector that is capable of extracting an RF-signal from an optical pulse stream without amplitude-to-phase conversion. Extraction of a microwave signal with 3 fs timing jitter (from 1 Hz to 10 MHz) from an optical pulse stream is demonstrated. Scaling of this component to sub-femtosecond resolution is discussed. Together with low noise mode-locked lasers, timing-stabilized optical fiber links and compact optical cross-correlators, a flexible femtosecond timing distribution system with potentially sub-10 fs precision over distances of a few kilometers can be constructed. Experimental results on both synchronized RF and laser sources will be presented.

INTRODUCTION

Seeding of free electron lasers operating in the EUV and soft X-ray regime with radiation generated via high harmonics from noble gases may result in a fully coherent X-ray laser. For seeding of such large-scale facilities spanning over several hundreds meters to a few kilometers, it is critical to synchronize low-level RF-systems, photo-injector lasers, seed radiation and potential probe lasers with low timing jitter in a long-term stable arrangement [1-4].

Figure 1 shows the schematic of a proposed timing distribution and synchronization system for such a facility. The pulse repetition rate of an optical master oscillator implemented as a mode-locked laser is stabilized to a frequency standard or a low noise microwave oscillator. The pulse train is distributed to all critical sub-systems by use of timing stabilized fiber links. Finally, a low-jitter, drift-free synchronization between the optical pulse trains and RF-signals will result in a fully synchronized timing system over the large-scale accelerator facility.

In this paper, we will address some of the key components and technologies developed for a scalable, integrated femtosecond-precision timing distribution system for a seeded XFEL. Currently, 30-fs jitter level synchronization is possible; it is further scalable to sub-10-fs level in the near future.

* Work supported by MIT, ONR, AFOSR, and DESY.
# jungwon@mit.edu

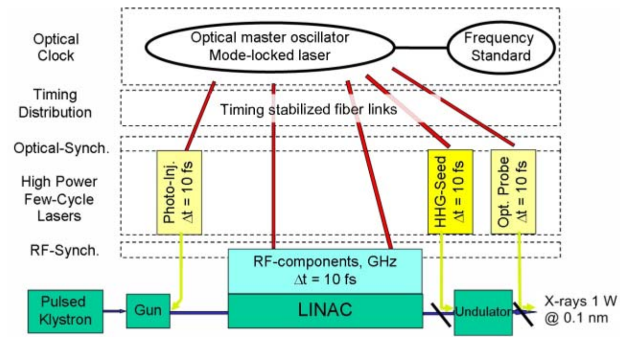

Figure 1: Schematic outline of timing distribution and synchronization for a seeded XFEL facility [1, 2].

OPTICAL MASTER OSCILLATOR – LOW-JITTER MODE-LOCKED LASER

It has been long recognized that mode-locked lasers have an enormous potential for generating ultra low-jitter RF-signals [5]. Currently the most promising candidates for ultra-low jitter optical master oscillators are Er/Yb-glass lasers [6], passively mode-locked Er-doped fiber lasers [7] and Yb-doped fiber lasers [8]. The crucial performance indicator for such a source is the phase noise or timing jitter integrated from c/2L, where c is the speed of light in the fiber and L is the fiber length, to the Nyquist frequency. Since this noise cannot be taken out by a timing-stabilized fiber link, the high-frequency jitter will set an inherent limitation to the precision in timing achievable with a given distribution system.

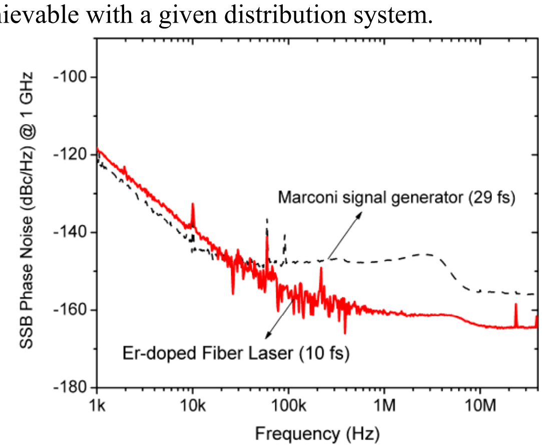

Figure 2: Phase noise spectra of Marconi 2041 signal generator and free-running Er-doped fiber laser [3].

The timing jitter is characterized by measuring the phase noise of one harmonic of the microwave signal obtained by direct photodetection of the pulse train. Figure 2 shows the single-sideband (SSB) phase noise of the stretched-pulse Er-fiber laser [7] measured at 1 GHz, in comparison with the performance of a commercial microwave signal generator. The integrated timing jitter from 1 kHz to 22 MHz (Nyquist bandwidth) is 10 fs, which is already better than a high-quality microwave signal generator. Note that the measurement was limited in precision by the direct photodetection and, in theory, it can reach down to sub-fs jitter level.

TIMING DISTRIBUTION

Precise transfer of RF-signals through fiber links for timing information dissemination has been demonstrated recently [9-11]. For timing distribution over a large-scale free electron laser facility, timing stabilized fiber links are used. If the fiber length is L, we assume that no length fluctuations are faster than 2L/c, where c is the speed of light in the fiber. Relative fiber expansion by temperature change is typically on the order of 10^{-7}/K, which can be compensated for by a fiber length control loop by referencing the back reflected pulse from the fiber end with a later pulse from the mode-locked laser.

Recently, we have demonstrated timing distribution over 500 meters in an accelerator environment (more detailed information on these experiments and results can be found in Refs. [3] and [4]). Figure 3 shows the in-loop phase noise measurement results for the fiber link stabilization using microwave mixers. When the loop is open, the jitter integrated from 0.1 Hz to 5 kHz is 66 fs; when the loop is closed, the jitter is suppressed down to 12 fs. Thus, a fiber link of 500 meters length can be readily stabilized to the 10-fs level over short time scales.

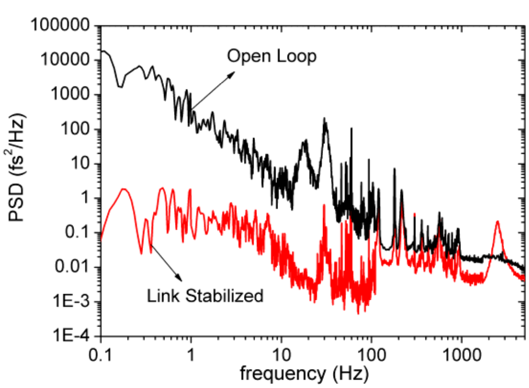

Figure 3: In-loop measurement result of the timing stabilized fiber link [3,4].

OPTICAL-TO-RF SYNCHRONIZATION

Once precise timing information encoded as an optical pulse train arrives at each remote location where we aim to synchronize, it is crucial to convert this optical signal into a low-jitter, drift-free RF-signal in a long-term stable way. Recently, it has been shown that the extraction of an RF-signal from an optical pulse train using direct photodetection is limited in precision by excess phase noise [12]. The major contribution to this excess noise was identified to be the amplitude-to-phase (AM-to-PM) conversion in the photodetector. The intensity noise of the laser can be converted into a significant amount of phase noise and drift by this process. Previously, we demonstrated a scheme to avoid this by transfer of timing information in the optical domain [13]. However, due to acoustic vibrations and poor phase noise properties of the voltage-controlled oscillator (VCO), the relative jitter was limited to 60 fs from 100 Hz to 10 MHz.

Here, a balanced optical-microwave phase detector for the extraction of low-jitter, high-power, and drift-free RF-signals from optical pulse trains is proposed and demonstrated. It is based on precise phase detection by use of a differentially-biased Sagnac fiber-loop and synchronous detection. We used the phase error signal from this balanced optical-microwave phase detector, which is robust against drifts and photodetector nonlinearities, to regenerate low-jitter RF-signals from optical pulse trains.

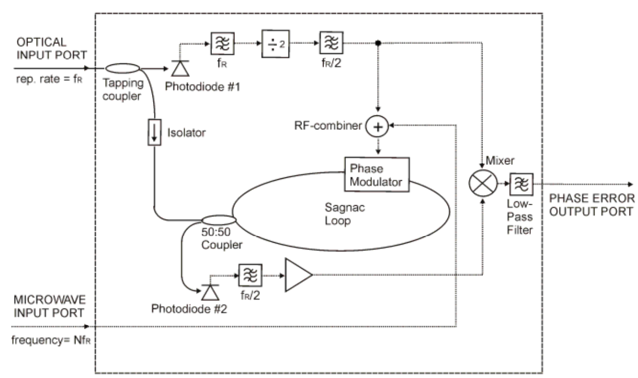

Figure 4: Schematic of the balanced optical-microwave phase detector.

Figure 4 shows the schematic of the balanced optical-microwave phase detector. Part of the input pulse train is tapped off by the Photodiode #1. This photodiode is used to generate a synchronous detection signal at half the repetition rate ($f_R/2$) of the optical pulse source. This signal is applied to both the phase modulator and the mixer. The rest of the input pulse train is sent to the Sagnac-loop. The phase modulation in the Sagnac loop is converted into an amplitude modulated signal at $f_R/2$ at the output of the Sagnac-loop. The amplitude of this signal is proportional to the phase error between the optical pulse train and the RF-signal (which is, the output from the VCO). The detected signal at the Photodiode #2 is band-pass filtered at $f_R/2$ and down-converted to the baseband by mixing with the reference signal. This error signal is filtered and controls the low-noise VCO to close the phase-locked loop.

For the demonstration experiment, a stretched-pulse Er-doped fiber laser [7] (repetition rate f_R = 44.26 MHz) is used as the optical pulse source. By closing the loop with a 10.225-GHz (231st harmonic of the fundamental repetition rate) VCO (PSI DRO-10.225), we can get a long-term stable locking between the laser and the VCO.

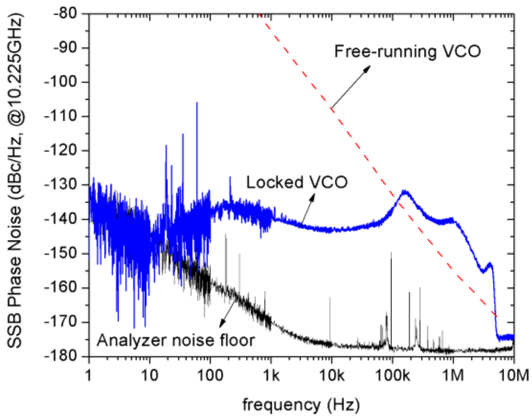

Figure 5: SSB in-loop phase noise spectra at 10.225 GHz. The integrated timing jitter from 1 Hz to 10 MHz is 3 fs when it is locked.

Figure 5 shows the measured in-loop phase noise spectra. The voltage signal from the phase detector was measured with a low-noise vector signal analyzer (VSA), and converted into single-sideband (SSB) phase noise at 10.225 GHz. This measurement shows that the integrated in-loop jitter is 3.0 fs ± 0.2 fs from 1 Hz to 10 MHz when it is locked. We are currently pursuing to further suppress the timing jitter to below 1 fs. The construction of a second loop is in progress to perform long-term out-of-loop measurements.

OPTICAL-TO-OPTICAL SYNCHRONIZATION

Synchronization is necessary not only between optical and RF-subsystems but also between different optical systems, for example, the photo-injector laser and the master oscillator as shown in Fig. 1.

For the optical-to-optical synchronization, we can use a balanced optical cross-correlator [14]. The technique uses nonlinear optical processes as an extremely sensitive detector for timing differences between optical pulses (a detailed description of operation can be found in Ref. [14]). Figure 6 shows the long-term timing jitter measurement between Ti:sapphire and Cr:forsterite lasers. The pulses from two lasers are locked with 380 as jitter over 12 hours without thermal drift.

In the long run, we aim to use the optical-microwave phase detector described in the previous section to synchronize optical pulses in an alignment-insensitive way. We first generate an RF signal from a VCO locked to the pulse train of the first laser. This locked RF-signal drives the phase modulator of another RF-synchronization module. However, instead of driving the VCO, the error signal drives the PZT to control the repetition rate of the second laser. In this way, an effective synchronization of multiple lasers is also possible by locking lasers to the same RF signal synchronized to one laser.

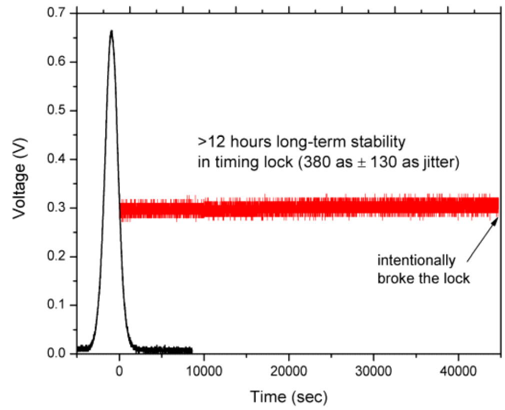

Figure 6: Long-term out-of-loop cross-correlation trace. A 380-as timing jitter (bandwidth=2.3 MHz) between two mode-locked lasers is measured, and maintained over 12 hours.

CONCLUSION AND OUTLOOK

In summary, we introduced a scalable, integrated timing distribution and synchronization system for future accelerator and seeded XFEL facilities. The key components and technologies, i.e., low-jitter optical master oscillator, timing distribution by stabilized fiber links, and long-term stable optical-to-RF and optical-to-optical synchronization modules, are demonstrated. Today, 30-fs jitter level synchronization over several hundreds of meters is possible. These results are scalable to sub-10-fs jitter in a long-term stable arrangement using optical techniques.

REFERENCES

[1] J. Kim et al., "Large-scale timing distribution and RF-synchronization for FEL facilities", FEL 2004.
[2] F. X. Kärtner et al, "Progress in Large-Scale Femtosecond Timing Distribution and RF-Synchronization", PAC 2005.
[3] A. Winter et al., "High-Precision Optical Synchronization Systems for X-Ray Free Electron Lasers", FEL 2005.
[4] F. Ö. Ilday et al., "Long-Distance Optical Synchronization System for X-ray Free Electron Lasers" CLEO 2006.
[5] S. Namiki and H. A. Haus, IEEE J. Quantum Electron. **33**, 660 (1997).
[6] J. B. Schlager, B. E. Callicoatt, R. P. Mirin, N. A. Sanford, and D. J. Jones, J. Ye, Opt. Lett. **28**, 2411 (2003).
[7] G. Lenz, K. Tamura, H. A. Haus, and E. P. Ippen, Opt. Lett. **20**, 1289 (1995).
[8] F. Ö. Ilday, J. R. Buckley, H. Lim, F. W. Wise, and W. G. Clark, Opt. Lett. **28**, 1365 (2003).
[9] J. Ye et al., J. Opt. Soc. Am. B **20**, 1459 (2003).
[10] K. W. Holman, D. J. Jones, D. D. Hudson, and J. Ye, Opt. Lett. **29**, 1554 (2004).
[11] D. D. Hudson, S. M. Foreman, S. T. Cundiff, and J. Ye, Opt. Lett. **31**, 1951 (2006).
[12] E. N. Ivanov, S. A. Diddams and L. Hollberg, IEEE J. Sel. Top. Quant. Elec. **9**, 1059 (2003).
[13] J. Kim, F. X. Kärtner, and M. H. Perrott, Opt. Lett. **29**, 2076 (2004).
[14] T. R. Schibli et al., Opt. Lett. **28**, 947 (2003).