An Integrated Optical Timing and RF Reference Distribution System for Large-Scale Linear Accelerators

A. Winter, Hamburg University, Hamburg, Germany,
J. Becker, F. Loehl, K. Rehlich, S. Simrock, P. Tege, DESY, Hamburg, Germany

Abstract

An optical synchronization system for linac-driven FELs providing 10 femtosecond precision over distances of several kilometers has been proposed in [1]. In addition, a picosecond-stable trigger and clock distribution system is required for operating the machine. In machines like the XFEL or ILC, the length to be covered ranges from few hundred meters to multiple kilometers. In the system approach described in this paper, the clock and timing distribution system is combined with the laser-based synchronization system. The two systems operate at wavelengths of 1550 nm (optical synchronization system) and 1310 nm (timing system) and utilize the same fiber for transmission and the same fiber length stabilization feedback. This does not only enable significant cost reduction, but also promises a stability level of the clock and trigger signals on the order of a few ps.

INTRODUCTION

One of the key challenges for large linac-driven accelerators or light sources is to implement an RF timing and synchronization system with sufficient accuracy to meet the luminosity requirements of a linear collider or the FEL-pulse stability of X-ray free electron laser. In case of the European XFEL, an X-ray pulse width of less than 50 fs is expected. Achieving an arrival time jitter of the FEL pulses below that number leads to extremely tight tolerances on the amplitude and phase stability of the RF in the accelerating cavities ($\sim 10^{-4}$ and $\sim 0.01\,(\mathrm{deg})$, respectively [2]. An ultra-stable reference frequency with a phase jitter in the 10 fs regime has to be distributed over a distance of several kilometers.

These demanding requirements cannot be met by conventional RF distribution systems based on microwave oscillators and semi-rigid coaxial cables. A promising alternative is an optical system, depicted schematically in Figure 1 [1]. A periodic train of sub-picosecond light pulses is generated in a mode-locked fiber laser and distributed along the linac through fibers with optical length stabilization. The synchronization information is contained in the precise repetition frequency of the pulse train. At the remote locations, low-level RF signals are generated by using a photo diode and a bandpass filter to pick the desired harmonic of the laser repetition rate, or by phase locking an RF source to a harmonic of the pulse train [3].

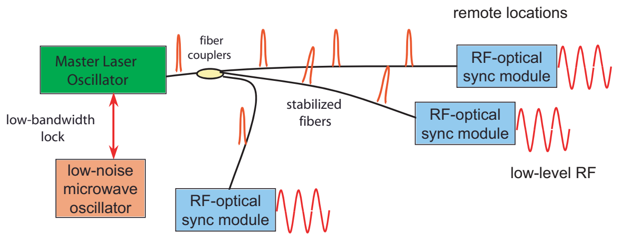

Figure 1: Schematic of the optical timing synchronization system.

A mode-locked laser serves as an ultra-stable laser master oscillator for the system. Fiber lasers are well suited for such purpose, because of the ease of coupling to the fiber distribution system, their excellent long-term stability, and the well-developed and mature components that are available at the optical communications wavelength of 1550 nm. A detailed description of the laser master oscillator can be found elsewhere [4].

In addition to the ultra-stable synchronization system, a general clock and trigger system with timing jitter on the order of $10\ \mathrm{ps}$ is needed for the XFEL. The purpose of this system is to trigger devices like kickers, klystrons, control and data acquisition modules, to provide synchronized clocks for ADC sampling and to distribute further reliable information. The timing of the trigger relative to the electron bunch is different for the various systems, so the delay needs to be adjusted individually. The transmission of the trigger signals will be done optically, using a single-frequency laser at a wavelength of 1310 nm as carrier onto which a frequency of 2.6 GHz, which is synchronized to the master oscillator of the machine, is modulated. The actual clock and trigger information is encoded in a phase modulation of the 2.6 GHz. From these coded events, variable gates and trigger signals with programmable delays are derived allowing the subsystems to adjust the timing events depending on their requirements. The optical links will be bidirectional to enable drift monitoring and, if needed, data transmission. As the synchronization system and clock/trigger system need to be distributed to the same locations in the machine, an integration of both systems is desirable. This would have a number of benefits. It saves design effort for the clock and trigger system and offers cost reduction potential in the final system. A synchronization system based on the distribution of optical pulses can

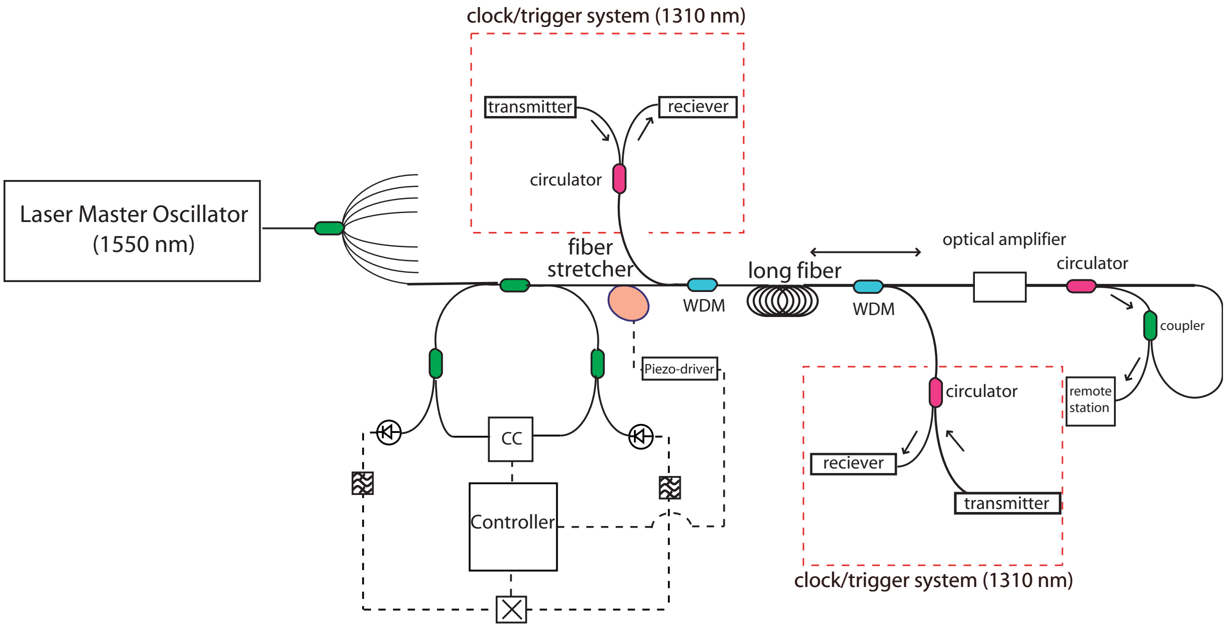

Figure 2: Schematic of the integrated synchronization and clock/trigger distribution system(CC - cross correlator, WDM - wavelength division multiplexer, transmitter - 1310 nm laser with amplitude modulator)

also enable new diagnostic possibilities, for instance beam arrival time monitors [8]. Furthermore the laser pulses can be directly used to seed for instance optical parametric amplifiers eliminating the need for a separate seed oscillator (e.g. for laser-wire stations to measure the emittance in the ILC).

TIMING STABILIZED FIBER LINKS

The distribution of the optical pulse train is done in a star-type topology in optical fibers. These exhibit a temperature dependent change of the refractive index of $5 \cdot 10^{-6} \frac{1}{^{\circ}\mathrm{C}}$ [5], which causes arrival time jitter of a pulse propagating through the fiber (10 ps for a link of 1 km length and a temperature stability of $1\ ^{\circ}\mathrm{C}$). This makes an optical path length stabilization system mandatory for both synchronization and trigger/clock distribution system.

The approach chosen for the synchronization system is as follows: Part of the light transmitted through the fiber is reflected at the end of the link and travels back through the same fiber. It is correlated with the periodic pulse train coming directly from the laser. This correlation is done in two different ways to enable a high-dynamic range and high-precision correlation. In the first scheme, the two pulse trains are detected using two high-bandwidth photo diodes. Out of the resulting RF spectrum a harmonic is selected and combined in quadrature in a mixer. The resulting phase error signal is fed back to the fiber stretcher which adjusts the optical fiber length my means of a piezo controller. The high-precision feedback utilizes an optical cross correlator. The RF-based feedback system has been demonstrated in a running accelerator environment [4] to stabilize the transmission to 12 fs over a timescale of a few seconds at a comparison frequency of 1 GHz. It should be emphasized that these results could be improved by choosing a higher harmonic for comparison. The residual timing jitter can be expected to be reduced to a few femtoseconds, if a comparison frequency in the 5-10 GHz range is used. This approach is very cost-effective, but potentially suffers from drift of mixers, amplifiers and bandpass filters. With a suitable temperature stabilization ($\sim 0.1\ ^{\circ}\mathrm{C}$), a long-term drift of around 100 fs can be expected over timescales of minutes to hours. If better drift stability is desired, using an optical cross correlator as phase detector has the potential to achieve sub-fs stability [6]. Both levels are much better than is needed for the clock and trigger distribution system. Current designs envision a stability on the order of 1 ps for the XFEL.

There are two major wavelengths used in the communications industry, one at 1310 nm and another one at 1550 nm with a mature component base available at either one. Different wavelengths can propagate interference-free in optical fibers and can be separated at arbitrary locations using wavelength-division-multiplexers (WDM). The multiple TBit/s data transfer rate obtained routinely today by multiplexing around 60 channels into a single fiber, is only possible through "dense WDM" with a channel spacing of 50 GHz.

In the schematic depicted in Figure 2, two WDM couplers for 1310/1550 nm are introduced into a timing stabilized fiber link. The clock and trigger distribution system operates at a wavelength of 1310 nm and uses of the stabilized fiber link constructed for the synchronization system. As the WDM couplers offer wavelength separation with extinction ratios of up to 60 dB, the two different carrier wavelengths can be separated virtually without residue

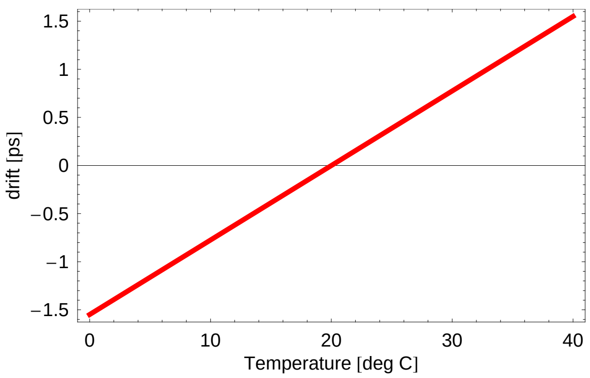

Figure 3: Arrival time difference between 1310 nm and 1550 nm for a 1 km long fiber link vs. temperature. The length of the optical fiber is stabilized at 1550 nm using the feedback described in the text.

in the other channel. If a circulator is used after the coupler, the link becomes effectively bidirectional and can be used to transmit data back to the start point of the links.

As the stabilization feedback is done at a wavelength of 1550 nm, there is a certain degradation in performance to be expected due to the wavelength difference. Using the temperature dependent Sellmeier coefficients for pure SiO_2 fibers [7], one can calculate the temperature dependent difference in index of refraction for the two wavelengths of interest. Figure 3 shows the temperature-induced drift between 1310 nm and 1550 nm in a 1 km long fiber link, where the difference at 20^o has been subtracted. It should be noted, that the relation is linear. The longest fiber link in the XFEL will be 3 km (6 km roundtrip), so the drift due to a large temperature fluctuation of $\pm 10^o$ will be $\pm 2.3\ \mathrm{ps}$. This is still significantly better than the current design stability level of the clock and trigger distribution system. Further compensation of this drift can be achieved electronically. As the amount of fiber elongation introduced by the feedback at $1550\ \mathrm{nm}$ is known, it is possible to compute an average corresponding temperature change in the link and thus correct for the difference at $1310\ \mathrm{nm}$ with an electronic delay chip in the clock and trigger emitter board.

CONCLUSION AND OUTLOOK

In this paper we have presented an approach to combine the distribution of the synchronization and clock and trigger signals into one system. The synchronization system is operated at a wavelength of $1550\ \mathrm{nm}$ which is also the wavelength at which the fiber length stabilization feedback is done. The clock and timing signals utilize the other telecommunications wavelength band around $1310\ \mathrm{nm}$. Both signals propagate through the same fiber and thus make use of a single stabilization system. Simulations show that the residual drift for the clock and trigger distribution caused by a temperature shift of 10^0 for a 3 km long fiber link (which is the longest link in the XFEL) is on the order of $2.3\ \mathrm{ps}$, which is significantly better than required for the clock/trigger distribution. The integrated approach offers significant effort and cost reduction for the clock and trigger distribution system.

REFERENCES

[1] J. W. Kim et. al., “Large scale timing distribution and RF-synchronization for FEL facilities,” FEL Conference 2004, Trieste, Italy, 2004.

[2] H. Schlarb et. al., “Next Generation Synchronization System For The VUV-FEL at DESY” FEL Conference 2004, Trieste, Italy, 2004.

[3] J. Kim, F. X. Kärtner, and M. H. Perrott, “Femtosecond synchronization of radio frequency signals with optical pulse trains,” Opt. Lett. **29**, 2076-2078 (2004).

[4] A. Winter et. al., “Towards high-performance optical master oscillators for energy recovery linacs,” Nucl. Inst. Meth. A **557**, 299-304 (2006).

[5] C. E. Lee, H. F. Taylor, A. M. Markus, and E. Udd, “Optical-fiber Fabry-Perot embedded sensor,” Opt. Lett. **14**, 1225-1227 (1989).

[6] T. R. Schibli, J. Kim, O. Kuzucu, J. T. Gopinath, S. N. Tandon, G. S. Petrich, L. A. Kolodziejski, J. G. Fujimoto, E. P. Ippen, and F. X. Kärtner, “Attosecond active synchronization of passively mode-locked lasers by balanced cross correlation,” Opt. Lett. **28**, 947 (2003).

[7] G. Ghosh, M. Endo, and T. Iwasalu,“Temperature-Dependent Sellmeier Coefficients and Chromatic Dispersions for Some Optical Fiber Glasses,” J. Lightwave Techn. **12**, 1338-1342 (1994)

[8] F. Loehl et. al., “A sub-100 fs Electron Bunch Arrival-time Monitor for the VUVFEL,” EPAC 2006, Edinburgh, UK, 2006.