FEMTOSECOND ELECTRO-OPTICAL SYNCHRONIZATION SYSTEM WITH LONG-TERM PHASE STABILITY RESULTS *

J. Tratnik, B. Batagelj, L. Pavlovic, M. Vidmar, University of Ljubljana, Ljubljana, Slovenia
P. Lemut#, V. Poucki, Instrumentation Technologies d.d., Solkan, Slovenia

Abstract

The new generation of accelerators requires timing distribution and RF synchronization with femtosecond precision in terms of jitter and long-term stability. The proposed electro-optical synchronization system makes use of commercial telecom single-mode optical fibre operating at 1550 nm. It operates on over 300 m distance. It consists of a transmitter, located near a low-jitter master oscillator, and receiver, located at the remote location. The field experiments have been done in the accelerator environment with the fibre pair laid in the tunnel. The prototype units were installed at the same location to make phase difference measurement simple. Temperature in various installation points, phase difference and both units internal operational parameters were continuously monitored and stored. Data was post-analysed and conclusions were used for hardware changes and mostly the long-term stability improvement. A dedicated phase detector was designed to monitor femtosecond-level changes. Results are showing 31.4 fs RMS stability over 65 hours. The prototype was redesigned for manufacturing with new features like improved long-term stability. It is now available as Libera Sync instrument.

INTRODUCTION

Precise synchronization systems [1,2] are needed to operate fourth generation light sources based on linear accelerators, commonly named Free Electron Lasers (FEL). Traditionally, coaxial cables have been used for RF and microwave clock distribution. Some evolving fiber-optic solutions for the timing distribution and the RF synchronization use interferometric schemes [3] for the stabilization of fibre links that transport the clock signal or/and use mode-locked pulsed lasers [4].

A previously-proposed electro-optical scheme in 2001 [5], similar to our solution was using a single optical fiber and a directly-modulated DFB laser. Our proposed electro-optical synchronization system includes a transmitter (Tx) located at the place of the low-jitter master oscillator and a receiver (Rx) located at the remote location. Both units are connected with a single mode optical-fiber pair in a loop-back to measure and correct fiber group-delay variations.

* Work supported by Instrumentation Technologies d.o.o., Slovenia, Synchrotrone Trieste S.C.p.A., Italy and Ministry of Higher Education, Science and Technology of the Republic of Slovenia under research program P2-0246.
# primoz.lemut@i-tech.si

SYNCHRONIZATION SYSTEM DESIGN

Principle of Operation

The simplified block diagram of the proposed synchronization system is shown in Fig. 1. The source of an optical signal is a commercially-available DFB laser with integrated electro-optical modulator (EOM) and thermo-electric cooler/heater (TEC). The external RF-reference signal at 2998.01 MHz modulates the optical carrier at 1550 nm with an EOM. The modulated signal is then propagated to the receiving unit where a fraction of a signal is decoupled, demodulated on the photodiode PD and filtered with the cavity band-pass filter.

To compensate clock-phase drifts in a link, most of the incoming optical signal is fed back to the return line. The returned signal is then compared with the reference signal at the wavelength controller. The control signal is then used for the laser-wavelength tuning by changing the temperature of the laser module. Exploiting the fibre's inherent chromatic dispersion link-length (RF-signal group delay) variations are compensated and therefore the RF-signal phase at the Rx is stabilized.

The principle of operation is described in more detail in Proceedings of FEL2009, paper FROA03 [6]. The implemented solution jointly developed between University of Ljubljana, Instrumentation Technologies and Sincrotrone Trieste is patent pending.

Temperature-compensation Range

Manageable temperature changes in the optical path are ±1.4 °C and can be calculated as:

$$\Delta T = \frac{c \cdot D \cdot \Delta\lambda}{k_n + n \cdot k_t}; \qquad (1)$$

where ΔT is the temperature change, c is the speed of light, D=17 ps/nm*km is the chromatic dispersion coefficient, Δλ is the wavelength-tuning range, n is the refractive index of the fiber, k_n= 8*10^-6/K is the temperature coefficient of the refractive index and k_t= 7.5*10^-7/K is the temperature expansion coefficient of the glass-fiber length. With a 5 nm laser-wavelength tuning range, 85 ps of a time delay at 2998.01 MHz can be achieved in a 1000 m fibre-loop length [7].

For both optical lines (transmission and return) it is assumed and measured [8] that the PMD is lower than 10 fs and can be neglected in the 300 m long fibre. To achieve such a low total PMD, optical fibre within the G.652 category with the lowest specific PMD needs to be used.

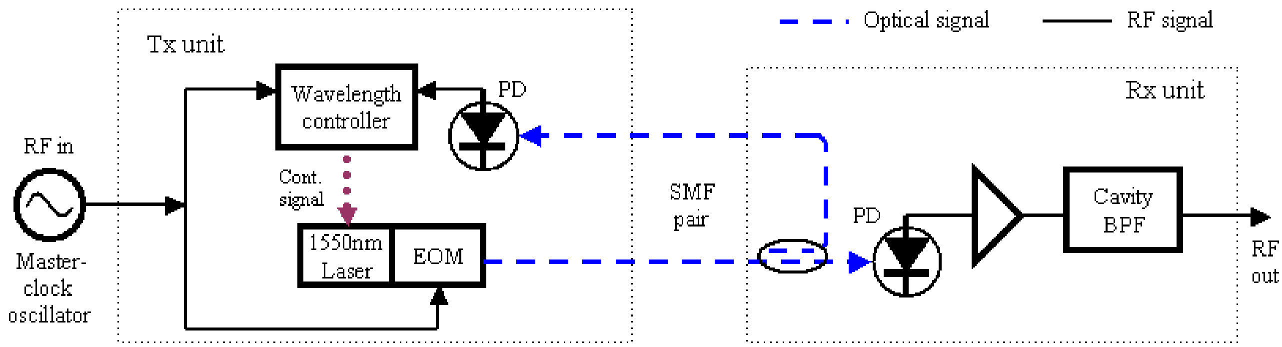

Figure 1: Simplified block diagram of the electro-optical synchronization system.

MEASUREMENT RESULTS

Several different measurements were made on the proposed synchronization system with different optical fibre lengths.

Measurement of the RMS Added Jitter

The setup for a measurement of the RMS added jitter is shown in Fig. 2. A low-jitter master VCXO oscillator, developed at University of Ljubljana, is used as a reference signal and the output of the system is connected to an Agilent E5052B signal source analyser (SSA). The RMS added jitter $jitt_{add}$ is than calculated as:

$$jitt_{add} = \sqrt{jitt_{meas}^2 - jitt_{gen}^2} \; ; \qquad (2)$$

where $jitt_{meas}$ is the measured RMS jitter of complete transfer chain and $jitt_{gen}$ is the master-oscillator jitter.

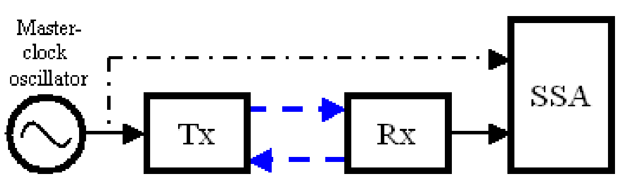

Figure 2: RMS added jitter measurement diagram.

Single-mode optical fibres of 360 m length used for the distribution of the phase reference on FERMI@Elettra, Italy, have been used for the field measurements of the RMS added jitter. The RMS added jitter of the synchronization system is 5 fs integrated from 100 Hz to 10 MHz and 38 fs integrated from 10 Hz to 10 MHz, respectively. Measurement results are shown in Fig. 3.

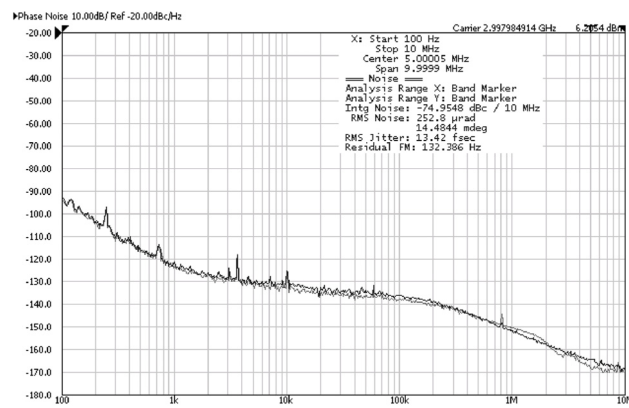

Figure 3: Measured RMS jitter of the Rx-output signal is 13.4 fs – dark curve and the RMS jitter of the reference signal is 12.4 fs – bright curve. The calculated RMS added jitter of the clock-distribution system is 5 fs. Integration range was 100 Hz to 10 MHz.

Long-term Phase Stability

The long-term phase stability of the proposed system, relative time difference between the master RF oscillator and the 180 m long compensated fiber link was measured with the measurement setup shown in Fig. 4. The master-RF-oscillator signal was compared to the signal transfered over the compensated optical link with an independent phase detector. The phase detector was installed in its own, thermally-stabilized enclosure. The detected phase

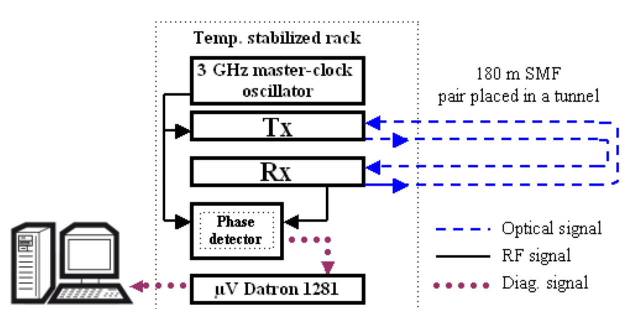

Figure 4: Long-term stability measurement setup.

difference on the phase detector was measured with a Datron 1281 multimeter and sampled with a computer acquisitioning system. We obtained a 31.4 fs RMS time drift in a 65-hour period as shown in Fig. 5. The sampling integration time was 5 seconds.

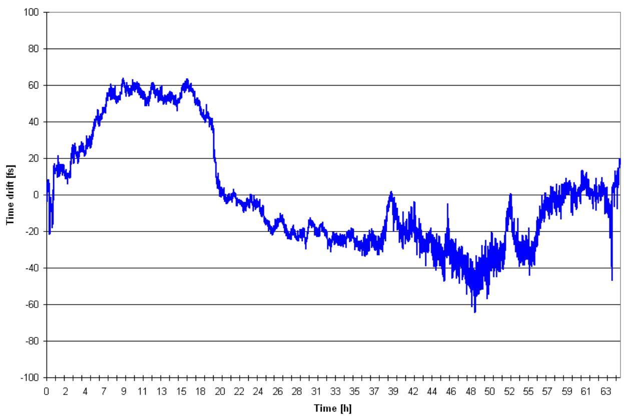

Figure 5: Relative time difference between the master-RF oscillator and the 180 m fiber link is 31.4 fs RMS (128 fs peak-peak) in a 65 h period.

CONCLUSION

We have shown that a CW-clock transfer is possible over several-hundred-meter long link using affordable and commercially-available optical and RF components with an extremely-low added phase-noise and high long-term stability. Group delay variations of the RF signal in the proposed clock-distribution system are stabilized by the laser-wavelength tuning and the exploitation of chromatic dispersion of the optical fibres. Encouraged by good results from the prototype instruments, Faculty of Electrical Engineering / University of Ljubljana and Instrumentation Technologies d.d. [9] have redesigned the optical synchronization system which is available as Libera Sync instrument for deployment in FELs.

REFERENCES

[1] E. Allaria et al. "FERMI@Elettra: a seeded FEL facility for EUV and soft x-rays" FEL 2006, Berlin.

[2] M. Ferianis "State of the Art in High-Stability Timing, Phase Reference Distribution and Synchronization Systems", PAC09, Vancouver, BC CA, 2009, WE3GRI02.

[3] J. M. Byrd, L. Doolittle, A. Ratti, R. Wilcox, “Timing distribution in accelerators via stabilized optical fiber links”, LINAC 2006, Knoxville, Tennessee USA, 2006, THP007, p. 577-579.

[4] A. Winter, J. Becker, F. Loehl, K. Rehlich, S. Simrock, P. Tege, “An integrated optical timing and RF reference distribution system for large-scale linear accelerators” LINAC 2006, Knoxville, Tennessee USA, 2006, THP003, p. 565-567.

[5] J. Frisch, D. Bernstein, D. Brown, E. Cisneros, “A high stability, low noise RF distribution system” Particle Accelerator Conference 2001, Chicago, 2001, p. 816-818.

[6] J. Tratnik, B. Batagelj, L. Naglic, L. Pavlovic, M. Vidmar, P. Lemut et al, “Femtosecond electro-optical synchronization system over distance up to 300 m”, FEL2009, Liverpool, UK, 2009, FROA03, p. 772-775.

[7] E. Udd et al, “Fiber optic sensors”, John Wiley & Sons, Inc., Canada, 2006, p.134.

[8] A. Galtarossa, "Relazione Tecnica alle misure di dispersione di Polarizzazione", Technical Note, Photonics Group at Univ. Padua, http://peg.dei.unipd.it

[9] Instrumentation Technologies, “Libera Sync”, http://www.i-tech.si/products.php?meni1=16.