FEMTOSECOND ELECTRO-OPTICAL SYNCHRONIZATION SYSTEM OVER DISTANCE UP TO 300 m*

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Abstract

This paper presents a novel solution for the timing distribution and the RF synchronization of multiple events at multiple remote locations in the accelerator facility with a femtosecond precision. In the framework of a collaboration between Sincrotrone Trieste (ST), Instrumentation Technologies and prof. M. Vidmar of the Faculty of Electrical Engineering of the University of Ljubljana (UL), a prototype has been developed to test the RF signal transmission over a stabilized fibre-optic link.

The proposed, patent pending, electro-optical synchronization system makes use of a commercial telecom single-mode optical fibre operating at 1550 nm. Such a fibre is subject to phase and group velocity changes correlated to temperature variations and acoustic perturbations. The synchronization system described makes use of a fibre-length stabilization, which transports a low-jitter microwave signal over a distance of 300 m. It consists of a transmitter, located at the place of the low-jitter master oscillator, and a receiver, located at the remote location. Both units are connected by a pair of optical single-mode fibres. Using a fibre pair instead of a single fibre allows compensation of fibre-length changes. The added timing jitter of 20 fs_{RMS} integrated from 100 Hz to 10 MHz has been measured on the first experimental synchronization system at University of Ljubljana and on a test stand installed at FERMI@Elettra [1]. Even lower jitter is expected by some planned improvements in the transfer system and its industrialization.

INTRODUCTION

State of the art timing and synchronization systems [2] are needed to operate fourth generation light sources based on linear accelerators driven Free Electron Lasers.

Known solutions (still under development) for the timing distribution and the RF synchronization use interferometric schemes [3,4,5] for the stabilization of fibre links that transport the clock signal or/and use mode-locked pulsed lasers [6]. The weaknesses of these solutions are in stabilizing the group velocity, the phase stability at the beginning of operation and the timing stability.

Previously proposed electro-optical scheme by Josef Frisch in 2001 [7] used single optical fibre and directly modulated Fabry-Perot laser. Since modulation frequency was lower than 1GHz, that solution did not gain better jitter results than coaxial distribution infrastructure.

Our proposed electro-optical synchronization system consists of the transmitter (Tx), located at the place of the low-jitter master oscillator and the receiver (Rx), located at the remote location, as shown in Fig. 1. Both units are connected with a singe-mode optical fibre pair, connected in a loop-back to achieve a phase-noise and phase-drift compensation.

SYNCHRONIZATION SYSTEM DESIGN

Operation Principle

The synchronization RF-reference signal at 2998.01 MHz from an external master oscillator modulates the optical carrier at 1550 nm with an electro-optical modulator (EOM). The modulated signal is then propagated to the receiving unit (solid line in Fig. 1) where a fraction of a signal is decoupled and demodulated on the PIN photodiode D3. Signal to noise ratio (SNR) at the output of the PIN photodiode is around 60 dB and such a signal is not suitable for further distribution. For this reason the output signal is cleaned in the phase-locked loop (PLL) using a temperature-controlled cavity filter as a flywheel.

To compensate clock-phase drifts in a link, most of the incoming optical signal is fed further to the return line (dashed line in Fig. 1), where the signal is demodulated on the PIN photodiode D1. The demodulated signal is then compared against the reference signal at the phase comparator 1. Phase-error signal is used for the laser-wavelength tuning (in range of approximately 5 nm). 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.

For an internal compensation of the EOM some portion of the modulated optical signal is also fed to the PIN photodiode D2 (dotted line in Fig. 1).

Tx/Rx Components

The detailed block diagram of the Tx and the Rx unit is shown in Fig. 2. The Tx unit is composed of two main compensation blocks and a laser source, while the Rx unit consists of a receiver block and a filtering electronics.

The source of an optical signal is a commercially-available DFB laser with integrated EOM and thermo-electric cooler/heater (TEC). The wavelength tuning used

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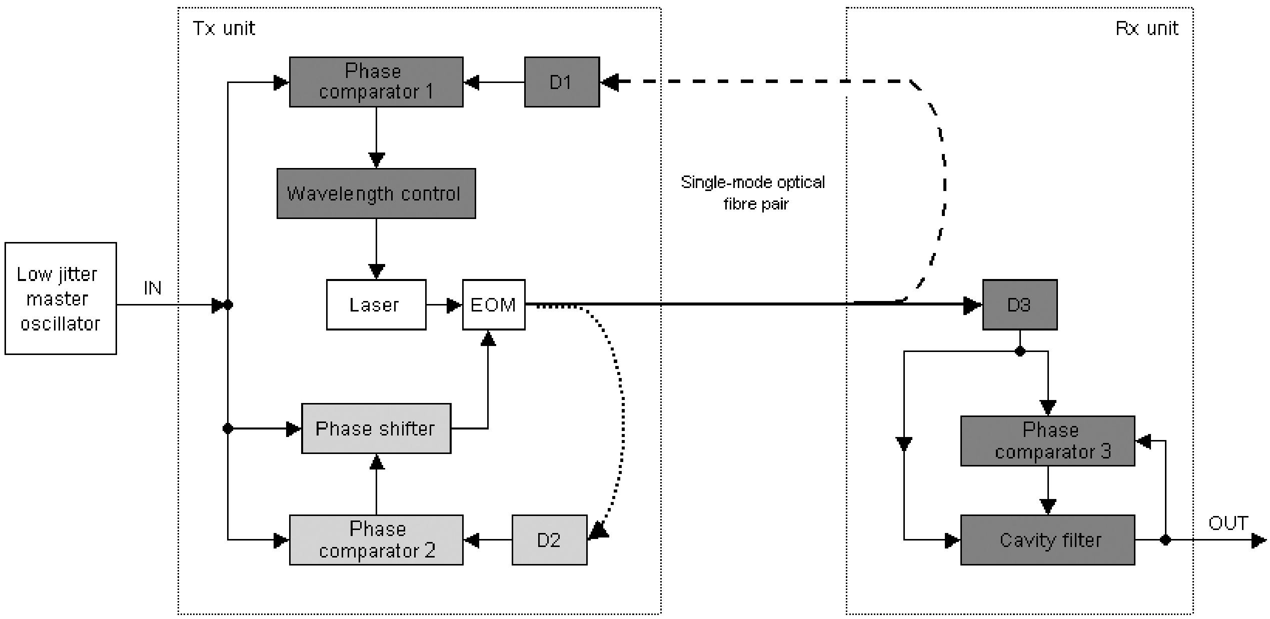

Figure 1: Block diagram of the Electro-optical synchronization system.

for the fibre phase-drift corrections is achieved by regulating the temperature of the laser chip with a PI regulator. Such type of a laser is also used because of a good price/performance ratio due to relatively high production quantities and tough requirements in the telecom environments.

All RF components except the laser source, which is independently heated or cooled, are kept in a precisely temperature-controlled blocks at the same temperature with a 0.01 degree C precision. Thus equal components (RF amplifiers, photodiodes, phase comparators) behave in the same way at different locations in both, the transmitting and the receiving unit. Temperature-stabilized chambers minimize thermal drifts that enable long-term stability. There are three identical blocks used in the system, two in the Tx unit and one in the Rx unit.

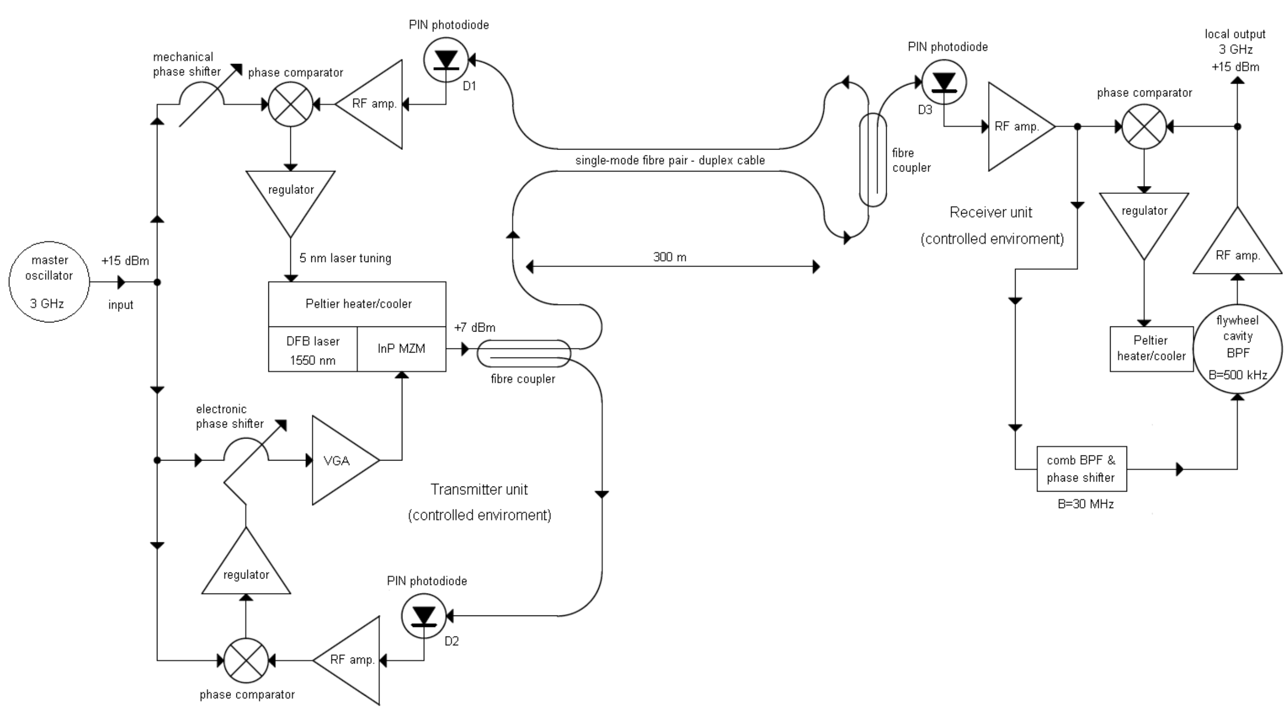

Figure 2: Detailed block diagram of the electro-optical synchronization system.

Each temperature-controlled block consists of a high-sensitivity PIN photodiode, a very-low-offset passive phase comparator and a low-noise pre-amplifier.

A mechanical phase shifter in the Tx unit is used for a rough phase setting at the beginning of the first operation so that the laser is put in the middle of its tuning range. At every subsequent start-up of the transmission system the phase of the RF signal does not have to be reset.

As mentioned before, a demodulated RF signal in the Rx unit has to be filtered for further distribution. The signal is firstly filtered with a comb band-pass filter (BPF), which is also used to set a correct phase slope of the phase comparator in a PLL loop. The second filter is a 500 kHz wide cavity BPF, temperature-locked to the RF phase using a Peltier element. This combination of filters effectively lowers the phase noise of the signal so that a slave oscillator as a flywheel is not even needed.

RF Phase Compensation Range and OpticalFibre Selection

With a 5 nm laser-wavelength tuning compensation of 48 ps time delay can be achieved (52° RF phase at 2998.01 MHz, 600 m fibre loop length, chromatic distortion coefficient D=16 ps/nm.km) [8]. Affordable temperature changes in the optical path can be calculated as:

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

where ΔT is a temperature change, c speed of light, D chromatic distortion coefficient, $\Delta\lambda$ tuning wavelength, n refractive index of the fibre, k_n temperature coefficient of the refractive index = 5*10^-6/K and k_t a temperature expansion coefficient of the fibre = 7.5*10^-7/K. The calculated value is around 4° C, which has also been proven during testing of the system.

For both optical lines (transmission and return) it is assumed and measured that the polarization mode dispersion (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. Standard G.652B or G.652D (without OH peak) types of fibre offer maximum PMD of 0.2 ps/√km. For this application a fibre with a PMD of 0.02 ps/√km was selected. The PMD value has been measured [9] on the actual fibres by the group of prof. A. Galtarossa from Padua University in the framework of a collaboration contract with ST.

MEASUREMENT RESULTS

First Measurements at UL Laboratory

Several different measurements were made on the proposed synchronization system with optical fibre lengths (transfer and return) of 1000 m, 360 m and 160m. One of them is the measurement of the RMS added jitter, shown in Fig. 3. A low-jitter master VCXO oscillator, developed at UL, is used as a reference signal and the output of the system is connected to an Agilent E5052A signal source analyser (SSA). RMS added jitter $jitt_{add}$ is than calculated as:

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

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

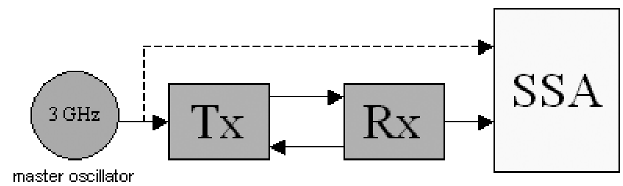

Figure 3: RMS jitter measurement diagram.

Field Measurements at FERMI@Elettra

The single mode optical fibres adopted for the distribution on the phase reference on FERMI@Elettra have been used during the field tests. The length of such optical links has been measured to be up to 360 m long. RMS added jitter of the synchronization system is 38 fs, integrated from 10 Hz to 10 MHz and 5 fs integrated from 100 Hz to 10 MHz, respectively. Measurement results are shown in Fig. 4 – 7.

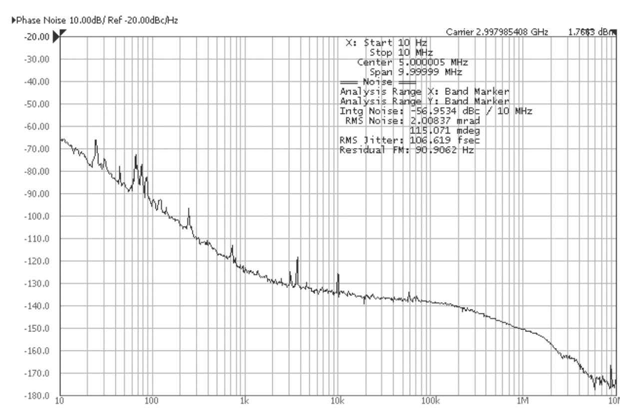

Figure 4: Measured RMS jitter of the reference signal is 106.6 fs, integrated from 10 Hz to 10 MHz.

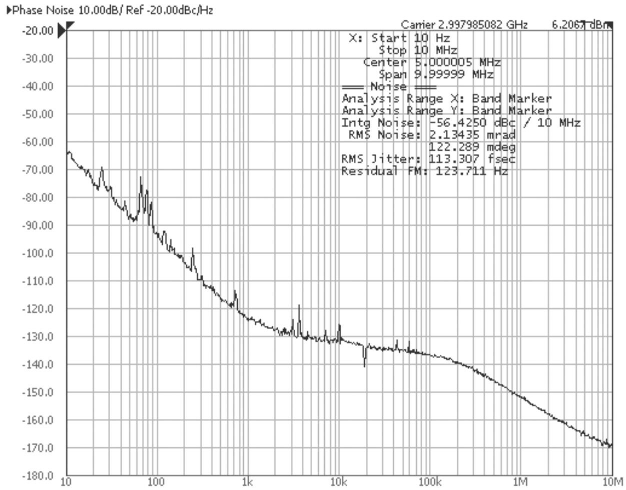

Figure 5: Measured RMS jitter of the Rx-output signal is 113.3 fs, integrated from 10 Hz to 10 MHz.

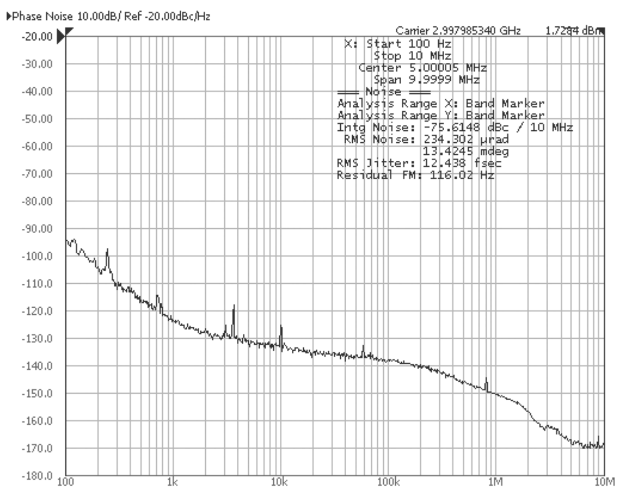

Figure 6: Measured RMS jitter of the reference signal is 12.4 fs, integrated from 100 Hz to 10 MHz.

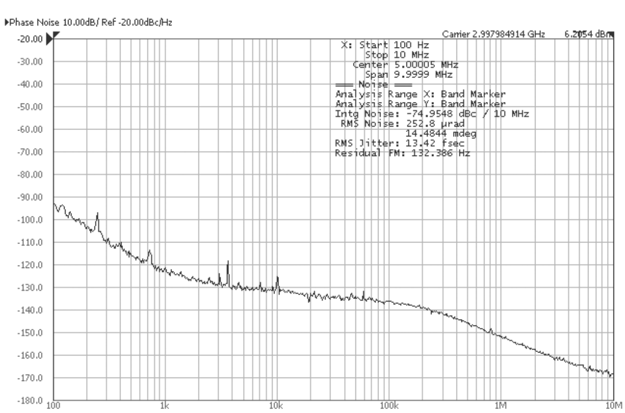

Figure 7: Measured RMS jitter of the Rx-output signal is 13.4 fs, integrated from 100 Hz to 10 MHz.

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 timing jitter, respectively. Group delay of the RF signal in the shown clock-distribution system is stabilized by the wavelength tuning and the chromatic dispersion of the optical fibres in the forward and the backward direction. Instead of a pair of optical fibres, a single optical fibre can be used with an additional Faraday mirror in the receiver unit. Encouraged by good results from the prototypes, Faculty of Electrical Engineering / University of Ljubljana and Instrumentation Technologies are now working on the redesign of the units to make them commercially available.

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