STABILIZED FIBER-OPTIC LINK-PROPAGATION DELAY FOR TIMING DISTRIBUTION IN PARTICLE ACCELERATOR FACILITY

B. Batagelj,[1,2] J. Tratnik[1] and M. Vidmar[1,2]
[1] University of Ljubljana, Faculty of Electrical Engineering,
Trzaska cesta 25, SI-1000 Ljubljana, Slovenia
[2] CO BIK, Velika pot 22, SI-5250 Solkan, Slovenia
Tel: +386 (0)1 4768 400
Fax: +386 (0)1 4768 424
E-mail: *bostjan.batagelj@fe.uni-lj.si*

Abstract

In a particle accelerator facility a precise timing-distribution system has a strong impact on performance of a several hundred meters long machine. In this scientific field, the synchronization/timing-distribution requirements for added jitter (short-term stability) and drift (long-term stability) are below a few tens of femtoseconds.

At the beginning this paper addresses main issues, which must be taken into consideration when designing a synchronization/timing system, such as transmission medium and timing frequency. The designed electro-optical synchronization system, which consists of an electro-optical transmitter, located near a low-jitter master RF oscillator, and an opto-electrical receiver, located at a remote location is described. Both units are connected with a single-mode optical fiber, connected in a loop-back to achieve stabilization of propagation delay. The optical transmission path has delay variations mainly due to temperature stretching of the fiber, very high thermal coefficient of the fiber refractive index and last but not least, microphonics and vibrations. Stabilization mechanisms of fiber-optic link-propagation delay are explained. Results of added jitter and drift over period of 24 hours are presented. The demonstrated synchronization system can be a very good candidate for a precise RF-clock distribution with low fluctuations in propagation delay.

INTRODUCTION

One of the challenging design requirements of modern particle accelerators, especially when talking about the fourth-generation light sources based on linear accelerator-driven Free Electron Lasers (FELs) **[1]**, is precise clock distribution and synchronization of the machine components and user experiments at different physical locations. The number of such locations is typically around 16 for 100 m-long linear accelerators and up to 50 in case of large linear-accelerator facilities (1 km+). Clock frequencies used for synchronization span from 200 MHz up to 12 GHz, depending on the application and/or timing performances. When designing a clock-distribution system, among many (secondary) technical issues such as transmission medium, maximum link length, total power consumption, user interface complexity, etc., the prime issue is (still) timing accuracy.

TIMING PARAMETERS

Timing accuracy includes at least two different specifications:
• Short-term inaccuracy described as phase noise or jitter.
• Long-term inaccuracy described as wander or drift.

Jitter is a time domain representation of random, short-term fluctuations of a signal (clock). When operating with radio/microwave frequencies, jitter is commonly calculated from the measured phase noise of a signal. The relationship between the RMS jitter J_{RMS} and the phase noise spectrum $L(f)$ can be written as

$$J_{RMS} = \frac{1}{2\pi f_c} \sqrt{2\int_{f_1}^{f_2} 10^{\frac{L(f)}{10}} df} \,, \tag{1}$$

where f_c is the carrier frequency and f_1 to f_2 are offset frequencies within the integration range **[2]**. The resulting jitter is inversely proportional to the frequency, therefore the performance of a timing system improves at higher frequencies provided that all other design parameters remain the same **[3]**. Because a clock-distribution system just transfers a clock signal, only the added jitter is important i.e. the amount of jitter the timing system adds to the transferred signal. The added RMS jitter J_{RMSadd} can be calculated as

$$J_{RMSadd} = \sqrt{J_{RMStotal}^2 - J_{RMSgen}^2} \,, \tag{2}$$

where $J_{RMStotal}$ is the measured jitter at the end of a clock-transfer chain and J_{RMSgen} is the jitter of a clock source. The measurement diagram is shown in Figure 1. Typical offset frequencies relevant for the operation of a 500 MHz and 3 GHz particle-accelerator timing system are from 100 Hz (in some cases from 10 Hz) to 10 MHz with values of the added jitter below 100 fs and 10 fs, respectively.

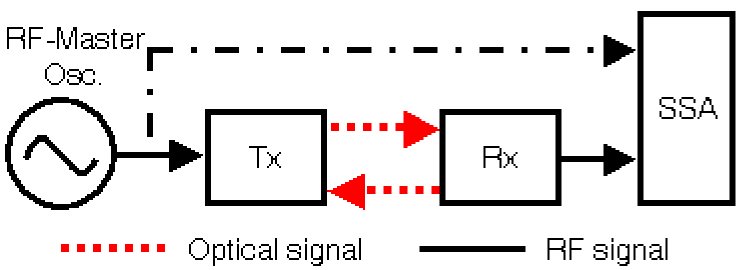

Figure 1. RMS added jitter measurement diagram. The first step (dash-dotted line): measurement of the oscillator + Signal Source Analyser (SSA). The second step (solid and dotted lines): measurement of the oscillator + Transmitter-Receiver + SSA.

Drift expresses the long-term stability of a timing system. It is mainly caused by temperature and other environmental variations, by power-supply variations, by component imperfections (AM-to-PM conversion), by component degradation and aging etc. Drift is more related to the technologies used and is not directly related to the theoretical design parameters of a timing system like its clock frequency. Drift requirements for the accelerator timing systems are different for each specific timing link or accelerator device being synchronized. For example, in general drift has to be below 1 ps or 100 fs in 24 hours for 500 MHz and 3 GHz-timing system, respectively.

TRANSMISSION MEDIUM

Conventionally, coaxial cables have been used for RF and microwave clock distribution. A coaxial clock-distribution infrastructure actually demonstrates quite good performances at shorter distances (a few tens of meters) and low frequencies. Because of high attenuation at high frequencies (where much lower added jitter can be expected) and demanding long-term stability control of the bulky cables, optical-cable infrastructure is a perfect solution for a clock-distribution at high frequencies with high (femtosecond) precision **[4]**. Some evolving fiber-optic solutions for the timing distribution and the RF synchronization use interferometric schemes for stabilization and correction of fiber links which transport the clock signal **[5]** or/and use mode-locked pulsed lasers **[6]**.

PROPOSED ELECTRO-OPTICAL CLOCK-DISTRIBUTION SYSTEM

The idea of the proposed electro-optical clock-distribution system is to use a well-known radio-over-fiber (RoF) technology for clock-signal distribution and to exploit fiber's chromatic dispersion (17 ps/nm.km @ 1550 nm) for link-length (microwave-signal group-delay) compensation. The clock-distribution system consists of a transmitter (Tx), located at the place of the low-jitter master RF oscillator and a receiver (Rx), located at the remote location. Both units are connected via a single-mode optical-fiber (SMF) pair in a loop-back in order to measure and correct slow (due to thermal changes) and fast (due to vibrations) fiber group-delay variations. In this paper the basic concept of optical-link stabilization is presented together with measurement results on 500 MHz **[7]** and 3 GHz-carrier systems.

CLOCK-DISTRIBUTION SYSTEM DESIGN

The block diagram of the transmitter and the receiver is shown in Figure 2. The transmitter includes two main compensation blocks and a laser source, while the receiver includes a third, identical compensation block and a clock-filtering circuit.

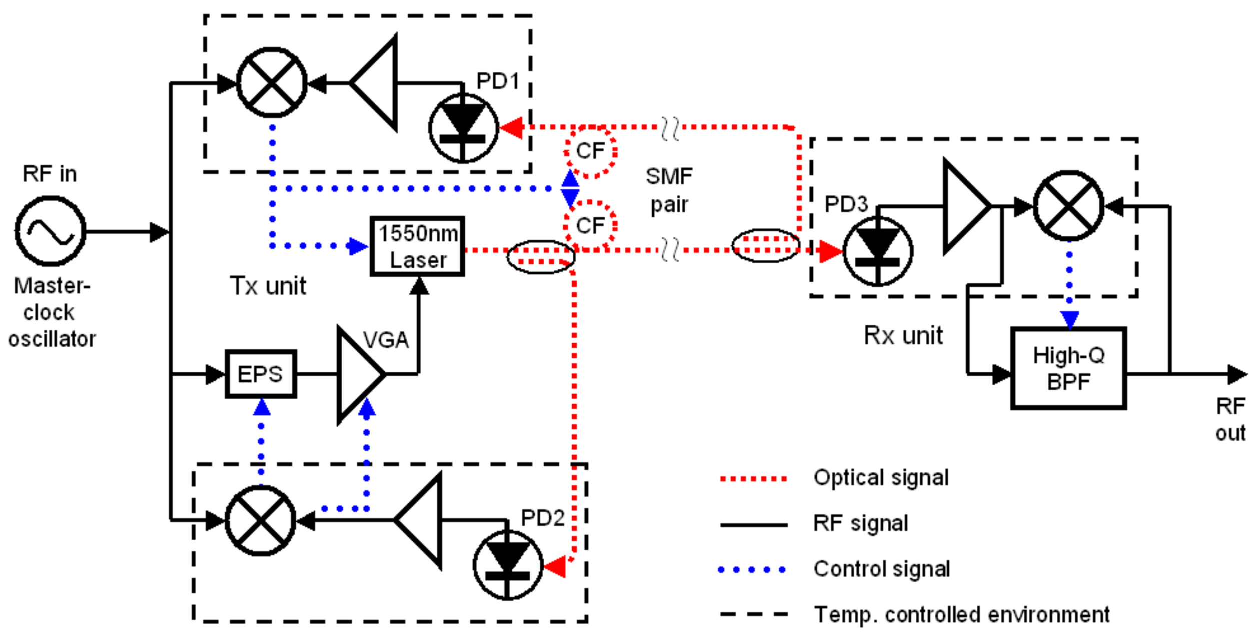

Figure 2. Simplified block diagram of the electro-optical clock-distribution system.

The source of the optical signal is a commercially-available DFB laser at 1550 nm, with an integrated thermo-electric cooler/heater (TEC). The modulation of CW optical carrier can be realised with an electro-optical modulator (used in the 3 GHz timing system) or with direct modulation of the laser (used in the 500 MHz timing system). In any case, the source of the RF signal is an external master-clock oscillator. The modulated signal is then propagated to the Rx unit, where part of the signal is decoupled and demodulated on the photodiode PD3. At the output of the photodiode ceramic or cavity, high-quality band-pass filters (BPFs) are used to filter the microwave-clock signal. Since any frequency drifts of the filter (ageing, thermal) are converted to unwanted phase shifts, the filter is electrically (in case of ceramic design) or thermoelectrically (in case of cavity design) fine-tuned by a phase-locked loop (PLL).

To compensate fiber group-delay variations, most of the incoming optical signal is fed back to the Tx unit using a second, identical optical fiber, where the signal is demodulated on the photodiode PD1 and compared with the reference signal. Gilbert cells or double balanced diode mixers are used as phase detectors. The phase-error signal directly controls the integrated TEC and in this way tunes the laser wavelength. Exploiting the fiber's inherent chromatic dispersion, link-length (RF-signal group-delay) variations are compensated, stabilizing the RF-signal phase throughout the forward and backward optical links.

Part of the modulated optical signal is also fed to the photodiode PD2 and compared with the reference signal to correct any phase changes in the laser, EOM, if used, and corresponding RF driver with an electrical phase shifter (EPS). A variable gain amplifier (VGA) is used to maintain a constant modulation depth.

All RF components except the laser module, which is independently heated or cooled, are kept in precisely temperature-controlled chambers to an accuracy of +/-0.01 °C to minimize thermal drifts of electronics. Most important, three identical control blocks with three identical photodiodes PD1, PD2, PD3, identical amplifiers and identical phase comparators are used so that any temperature, long-term ageing, RF signal amplitude, modulator harmonics, power-supply and other variations effectively cancel out in the final output-signal phase. The principle of operation is described in more detail in **[8]**.

OPTICAL-LINK STABILIZATION

To effectively compensate any link-length variations, there are two different compensation approaches implemented in the proposed clock-distribution system. Temperature-induced variations are compensated with laser-TEC control and the temperature-compensation range of the system is extended with two heated/cooled compensation-fiber spools (CFs) in the Tx. The total control bandwidth of the system is a few Hz, which is fast enough to compensate any perturbations on the transport fiber placed e.g. in the accelerator tunnel. However, if needed, the compensation bandwidth can be extended up to 2 kHz with fast laser-bias-current control.

With a 50 °C of laser-temperature tuning range (using TEC), a 5 nm laser-wavelength change can be obtained (51 ps of time delay) as shown in Figure 3. Time delay Δt can be calculated as

$$\Delta t = L \cdot D \cdot \Delta\lambda \,, \tag{3}$$

where L=0.6 km is the optic-fiber length, D=17 ps/nm·km is the chromatic dispersion coefficient and $\Delta\lambda$ is the wavelength-tuning range **[9]**.

To extend the temperature-compensation range of the system, two spools of 60 m G.652D optical fibers are implemented in each optical path (forward and return). With 40 °C of temperature range of CFs, the achieved time delay Δt is four-times larger than the laser wavelength-tuning range and can be calculated as

$$\Delta t = \frac{L \cdot \Delta T \cdot (k_n + n \cdot k_t)}{c}, \tag{4}$$

where ΔT is the temperature change, n is the refractive index of the fiber, k_n=8×10^{-6}/K is the temperature coefficient of the refractive index, k_t=7.5×10^{-7}/K is the temperature expansion coefficient of the glass-fiber length, and c is the speed of light. The temperature-compensation range is however dependent on a transport-fiber cable installed in the facility (tight/loose-buffered isolation) and can vary by a factor of 2 to 4 **[10]**.

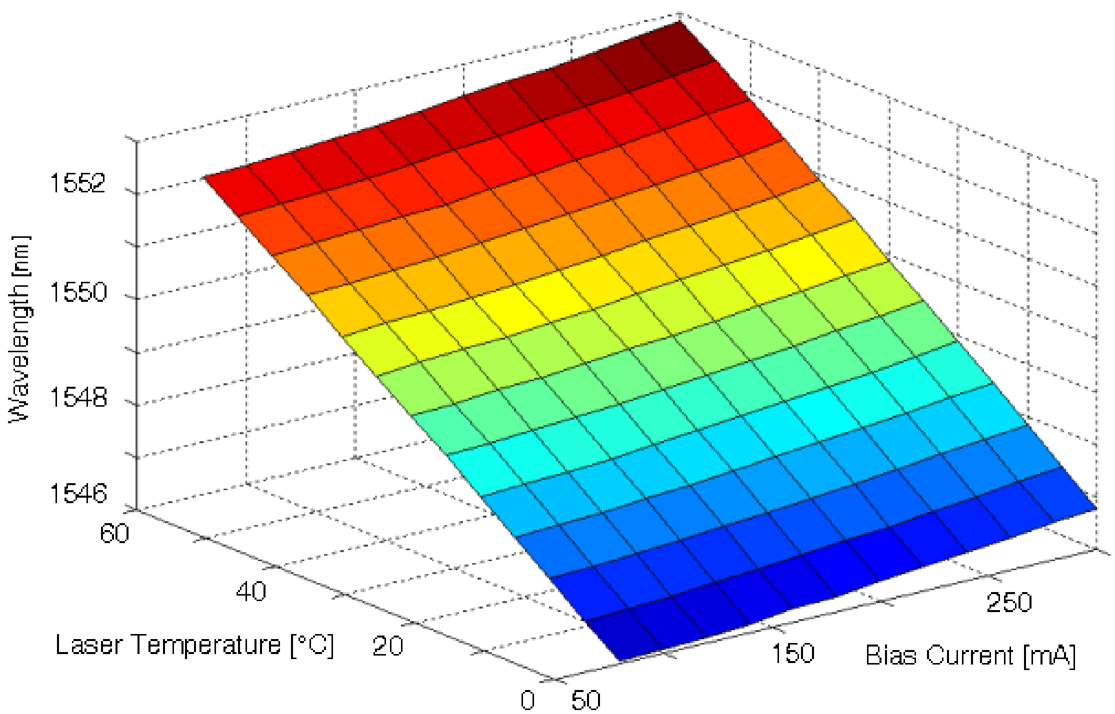

Figure 3. Measured relationship between the laser-bias current, laser temperature and laser wavelength.

The proposed electro-optical system is however not compensating the polarization-mode dispersion (PMD) effects. For both optical lines (forward and return) it was assumed (and confirmed by measurements) that the PMD is lower than 10 fs and can be neglected in the 300 m long fiber. To achieve such a low total PMD, G.652 category optical fibers with a specified PMD of less than 0.02 ps/(km)$^{1/2}$ were selected. To cancel out the undesirable PMD effects at longer distances, implementation of a single-fiber solution using a combination of optical circulator and a Faraday-rotator mirror (F) is possible as shown in Figure 4. Electronics of the timing system however remain the same.

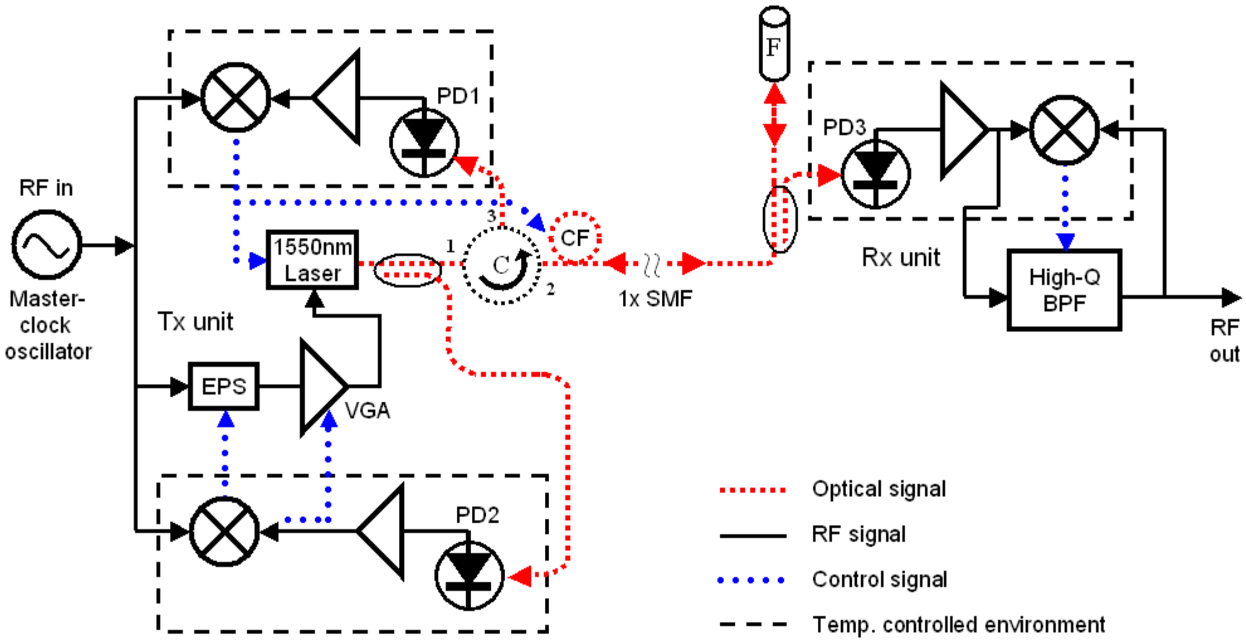

Figure 4. Simplified block diagram of the single-fiber electro-optical clock-distribution system.

MEASUREMENT RESULTS

Several measurements of the RMS added jitter and long-term stability were made on the proposed two-fiber clock-distribution systems at 499.654 MHz and 2998.01 MHz-carrier frequencies at fiber distances of 180 m and 300 m, respectively.

MEASUREMENTS OF RMS ADDED JITTER

For the RMS added-jitter measurements, the output of the timing system was connected to a signal source analyser (SSA) Agilent E5052A, as shown in Figure 1. In this case, fiber length between Tx and Rx was 300 m, regardless of the carrier frequency the timing system was set for.

When measuring jitter of the 3 GHz timing system, an ultra-low jitter generator, developed at University of Ljubljana, was used as a master-clock oscillator. Measured jitter of the 3 GHz oscillator (integrated phase noise from 100 Hz to 10 MHz) is J_{RMSgen}=13.1 fs (generator + SSA) and the total jitter of the system including oscillator is $J_{RMStotal}$ =15.3 fs. The calculated RMS added jitter (Equation 2) of the 3 GHz clock-distribution system itself is J_{RMSadd}=7.9 fs. The latter is calculated from phase-noise plots shown in Figure 5. When measuring jitter of the 500 MHz timing system, a Rohde & Schwarz SMA 100A was used as a master-clock oscillator with measured jitter J_{RMSgen}=30.0 fs (integrated phase noise from 100 Hz to 10 MHz). Measured total jitter is $J_{RMStotal}$=72.1 fs and the RMS added jitter of the clock-distribution system is then J_{RMSadd}=65.0 fs. Phase-noise plots at 500 MHz are shown in Figure 6.

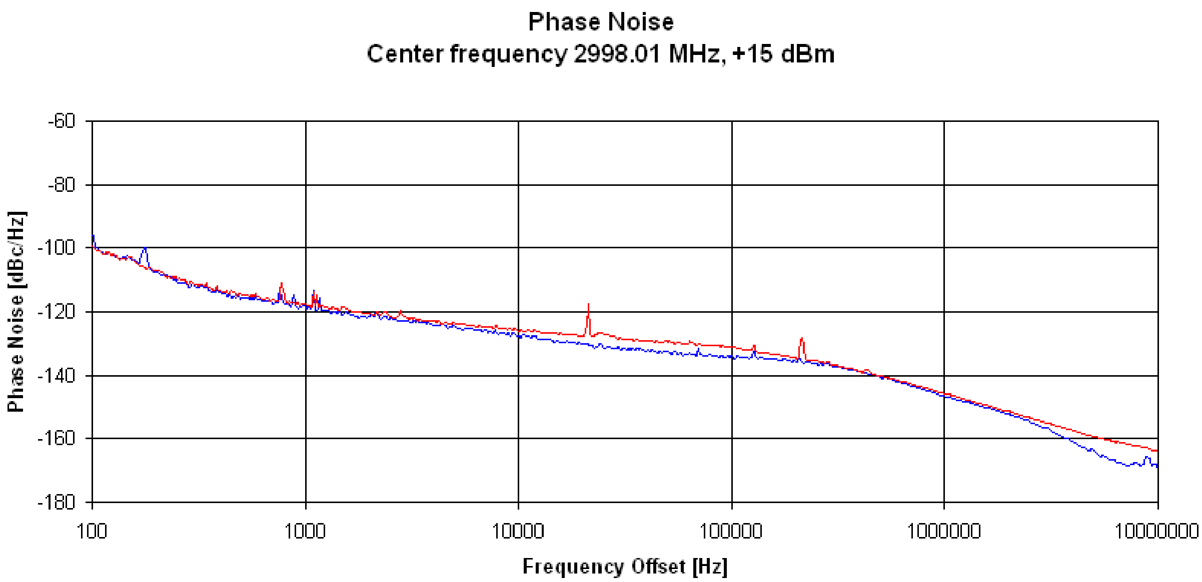

Figure 5. Measured phase noise at 3 GHz. J_{RMSgen} is 13.1 fs (blue curve), $J_{RMStotal}$ is 15.3 fs (red curve) and J_{RMSadd} is 7.9 fs.

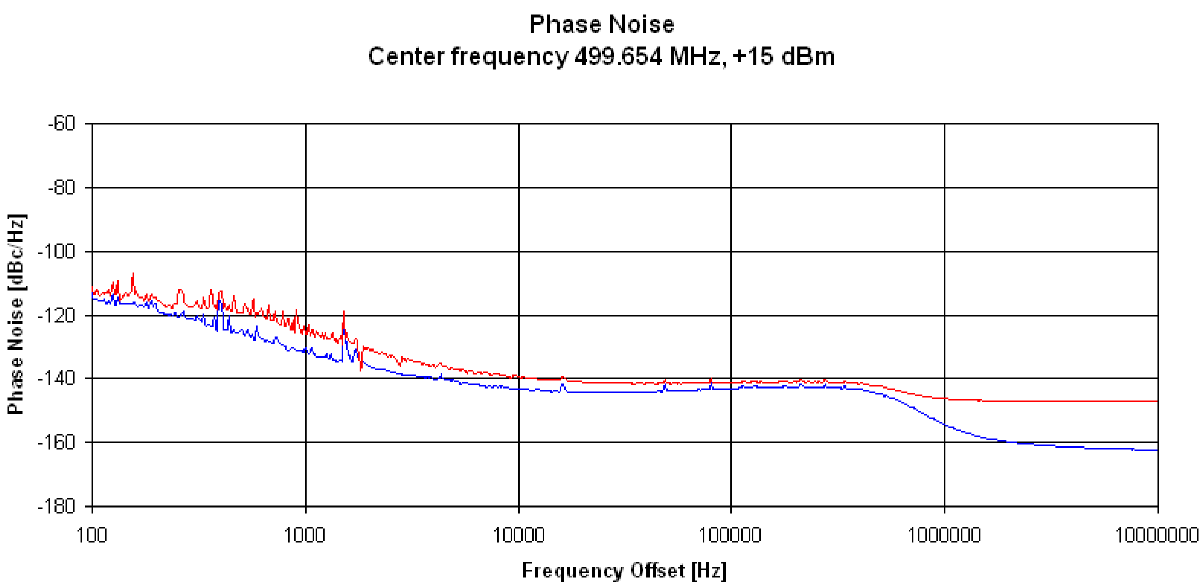

Figure 6. Measured phase noise at 500 MHz. J_{RMSgen} is 30.0 fs (blue curve), $J_{RMStotal}$ is 72.1 fs (red curve) and J_{RMSadd} is 65.0 fs.

MEASUREMENTS OF LONG-TERM STABILITY

The long-term phase stability of the proposed system was measured with a measurement setup shown in Figure 7. The master-RF-oscillator signal was compared to the signal transferred over the compensated optical link with an independent phase detector (Analog Devices AD8302). The phase detector was installed in its own, independent, thermally-stabilized enclosure. The detected phase difference on the phase detector was measured with a 24-bit analog-to-digital converter (ADC) using an integration time of 5 seconds and sampled every 10 seconds. The stability of the phase detector together with connecting Sucoflex 404 RF cables is 2 fs_{RMS} in 72 hours. With such a system we obtained a time drift of 9.5 fs_{RMS} in 24 h and 52.2 fs_{RMS} in 16 h with 3 GHz and 500 MHz timing system, respectively. Long-term stability measurement results are shown in Figure 8 and Figure 9.

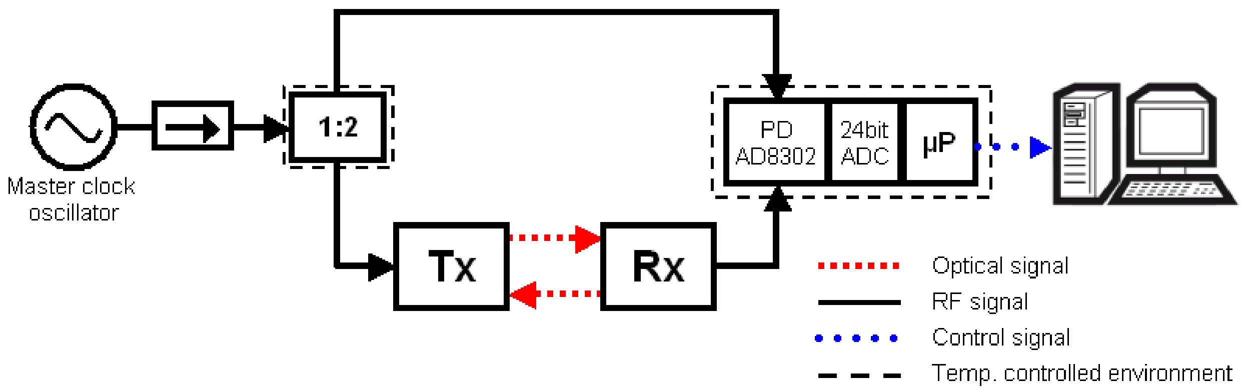

Figure 7. Long-term stability measurement setup.

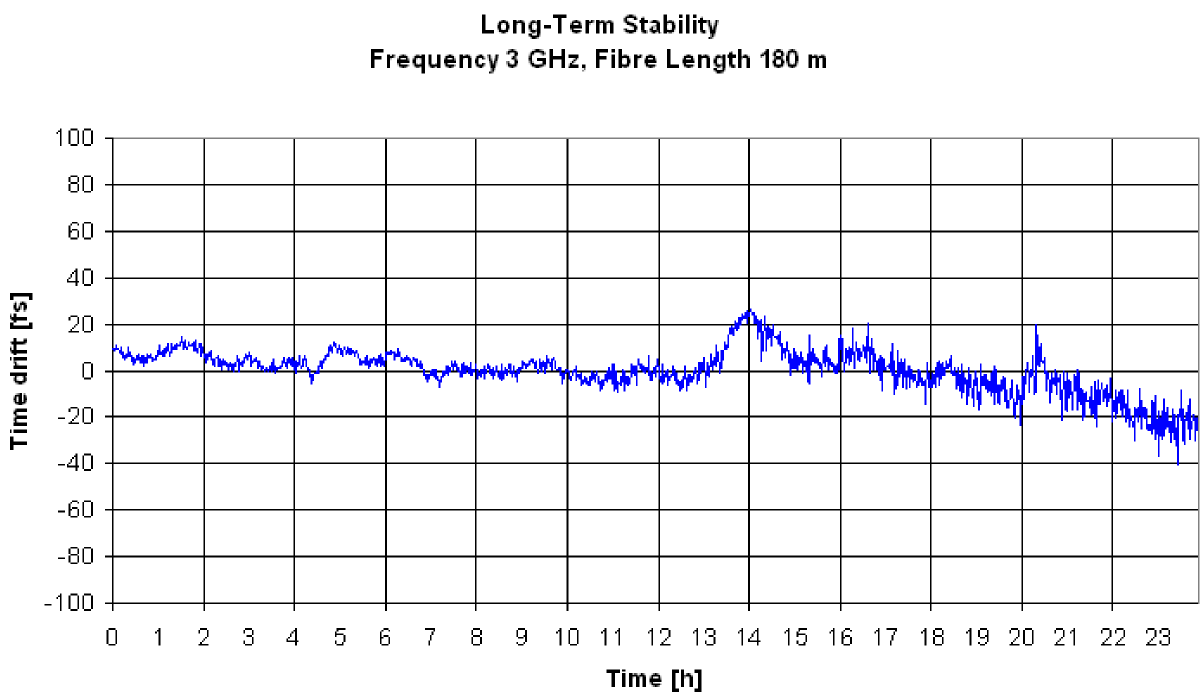

Figure 8. Long-term stability of the 3 GHz timing system is 9.5 fs in 24 hours.

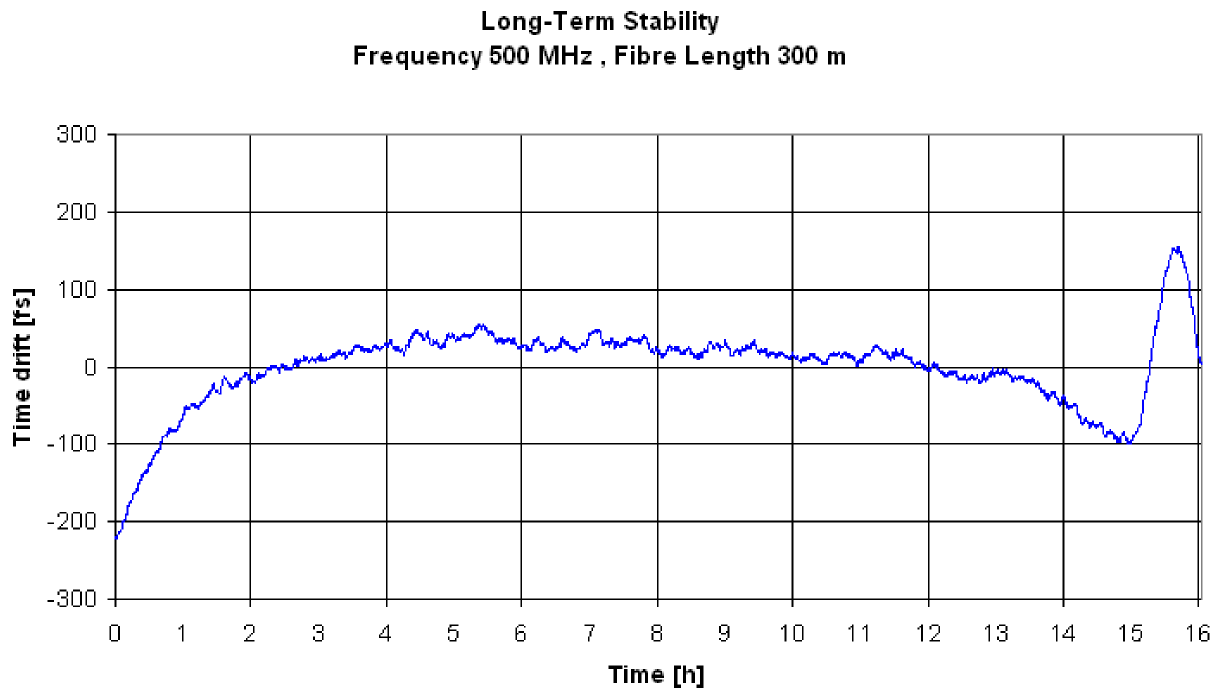

Figure 9. Long-term stability of the 500 MHz timing system is 52.2 fs in 16 hours.

CONCLUSION

We have shown that a CW-clock transfer with a femtosecond precision is possible over several-hundred-meter long links using affordable and commercially-available telecom-grade optical and RF components. Group-delay variations of the RF signal in the presented clock-distribution system are compensated by the laser-wavelength tuning and the exploitation of the chromatic dispersion of the optical fibers in the forward and backward direction. A quite narrow control bandwidth of the system is however fast enough to compensate the most of perturbations induced on the transport fiber. Although PMD effects were not compensated in our system, we experimentally confirmed that all fiber tolerances including PMD are tight enough to allow almost perfect tracking in an inexpensive fiber pair both on 3 GHz and 500 MHz timing system.

ACKNOWLEDGEMENTS

This work was supported by Instrumentation Technologies d.d., Slovenia and COBIK - Centre of excellence for Biosensors, Instrumentation and Process Control, Slovenia. The authors are grateful to Primoz Lemut and Miha Leskovec for help with phase noise and long-term stability measurements.

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