STABILIZATION OF THE PROPAGATION DELAY IN FIBER OPTICS IN A FREQUENCY DISTRIBUTION LINK USING ELECTRONIC DELAY LINES: FIRST MEASUREMENT RESULTS

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Abstract

In this paper, we present measurement results of the Digital Locked Loop system, developed by AGH University of Science and Technology, for microwave frequency distribution (here, 5 or 10 MHz) over optical fiber with precise stabilization of propagation delay in a relatively wide range of temperature variations. The main principle of the operation of the electronic delay lines is explained and the first measurement results obtained with the experimental setup using 20 km of optic fiber link are discussed. The stability of frequency transfer at the level of $2{\cdot}10^{-17}$ (the Allan deviation) for about a 24-hour averaging time was achieved, with the stability of propagation delay at a level below 15 ps (peak-to-peak). Such systems are a very good prospect for the evolution of atomic clock comparison and precise time and frequency transfer.

INTRODUCTION

Nowadays, primary frequency standards feature 1-day Allan deviations at the level of 10^{-14} for commercial cesium clocks **[1]** or 10^{-15} for active hydrogen masers **[2]**. Highly advanced cesium-fountain clocks offer stability on the order of 10^{-16} **[0]** and, with the advent of optical clocks **[0]**, further increases of stability become possible. Operation and maintenance of such atomic standards are a complex task, however; thus, usually only specialized laboratories have direct access to the highest precision reference signals.

In order to allow external users to access the atomic standard, its signal may be transmitted to some remote location. Such a transfer, however, is inevitably affected by variations of the propagation delay of the transmission medium. Usually, the frequency transfer is performed using satellite links, which allows bridging even laboratories separated by large distances. Satellite techniques, however, have moderate accuracy **[5]** and are often not adequate for performing scientific experiments or comparing modern atomic sources.

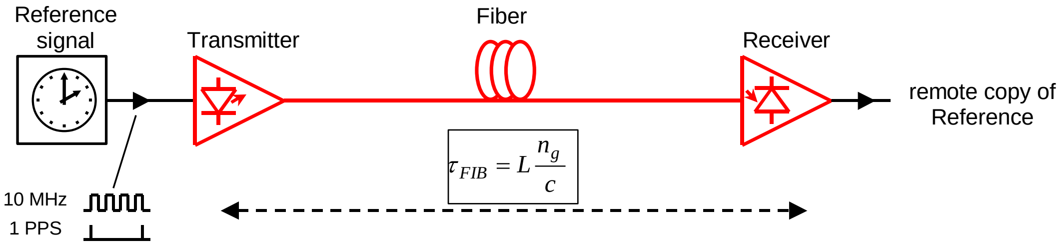


Figure 1. Scheme for unidirectional frequency distribution.

For such more demanding applications, link-based optical fibers may be used for frequency transfer. It is known, however, that the temperature affects the propagation delay of the optical fiber link. In unidirectional frequency distribution (Fig. 1), resulting fluctuations may be approximated using eq. 1:

$$\Delta\tau_{FIB} = \frac{L}{c}\frac{\partial n_g}{\partial T}\Delta T_{FIB} + \frac{Ln_g}{c}\frac{\partial L}{L\partial T}\Delta T_{FIB} + \frac{L}{c}\frac{\partial n_g}{\partial \lambda}\Delta\lambda_{LAS}, \tag{1}$$

where ΔT_{FIB} is the temperature change of the fiber, $\Delta\lambda_{LAS}$ is the shift of the laser wavelength, n_g is the group refractive index, L is the length of the fiber span, and c is the speed of light in vacuum. In practice, the dominating effect is caused by the thermal changes of the group refractive index, represented by the first term in eq. 1 with the resulting thermal coefficient $(1/L)(\partial\tau_{FIB}/\partial T)$ around 38-40 ps/(km·°C) **[6]**. The influence of two other terms, taking into account thermal lengthening of the fiber and the interaction of the fiber chromatic dispersion with the thermally induced shift of the laser wavelength, is either very weak or may be quite easily reduced using stabilization of the laser wavelength. The seasonal variations of τ_{FIB} on the scale of nanoseconds in the link a few dozen of km long may be expected, even when the fiber cable is buried underground. Usually the Allan deviation of such links is not better than $5 \cdot 10^{-15}$ at 1 day, and does not improve for longer averaging times **[0]**. This makes a unidirectional fiber optic frequency transfer scheme suitable only for short distances, preferably with the fiber placed entirely indoors in a thermally stable environment.

In order not to degrade the accuracy of the frequency signal from the atomic standard, some method of compensation of the fluctuations of the fiber propagation delay must be applied. This way, the “virtual atomic clock” may be created at the distant end, with long-term performance inherited from the “master” clock. Some implementations of such systems known from the literature exploit either bulky optical delay lines (e.g., exploiting variations of the propagation delay occurring in the fiber span affected by temperature or mechanical stress **[0-0]**) or phase conjugators **[0,0,0]**. The Allan deviation reported for such systems varies depending on the frequency used as the “carrier” for the transfer (typical values are

100 MHz, 1 GHz, and 10 GHz), the particular implementation, and the technical means used; nevertheless, values on the order of 10^{-17}-10^{-18} are possible. The frequency transfer systems discussed above are rather complex installations, suited rather for laboratory experiments, and not necessarily for widespread use.

Thus, we designed and developed a novel frequency distribution system making use of electronic variable delay lines. This way, the size of the transmission equipment and its power consumption may be substantially reduced, along with the complexity of the frequency transfer system.

DELAY STABILIZATION USING ELECTRONIC DELAY LINES

The simplified schematic diagram of our frequency transfer system is shown in Fig. 2. The signal from the reference (in experiments, we used a 5 MHz signal derived from a 5071A cesium clock) is passed through the forward delay line τ_{DF} and drives the forward transmitter TX_F with distributed feedback (DFB) semiconductor laser operating at 1551.2 nm. The optical signal is launched to the transmission fiber through fiber circulator and delivered to the remote end, where the second circulator is used to direct the signal to the forward receiver RX_F, based on a transimpedance amplifier with an avalanche photodiode. This signal is the output from the system. The same signal drives the backward transmitter TX_B (using a slightly different wavelength to avoid beating of the backscattered signal from the fiber with the desired signal) and transmitted via the same optical fiber at the opposite direction. A circulator directs this signal to the backward receiver RX_B at the local end that drives the backward delay line τ_{DB}. Both forward and backward delay lines are controlled by the signal obtained from the phase comparator, producing a signal proportional to the phase shift between the reference signal from the atomic clock and that fed back from the remote end. The entire system forms a delay-locked loop (DLL) with the equilibrium when the phases of the signals in points A and B are the same.

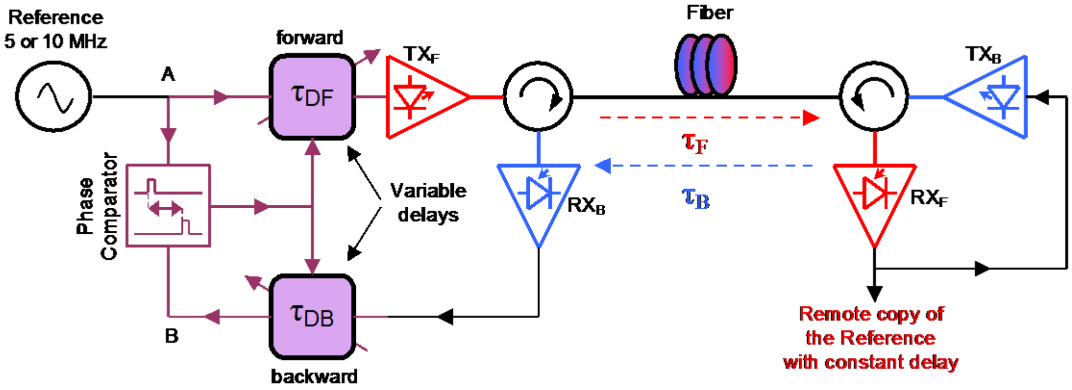


Figure 2. Simplified diagram of the frequency transfer system using electronic variable delay lines.

It follows from the operation of the feedback loop that the delay lines must compensate any variations of the propagation delay of the fiber; thus:

$$\Delta\tau_{DF} + \Delta\tau_F + \Delta\tau_B + \Delta\tau_{DB} = 0 \tag{2}$$

where $\Delta\tau_{DF}$, $\Delta\tau_{DB}$ stand for changes of the propagation delays of the forward and backward delay lines and $\Delta\tau_F$, $\Delta\tau_B$ represent variations of the forward and backward propagation delays of the fiber. To have the copy of the reference signal at the remote end, we require also that the propagation delay between input and output of the system must be constant; thus, we need to fulfill the condition:

$$\Delta\tau_{DF} + \Delta\tau_F = 0 . \tag{3}$$

Combining eqs. 2 and 3, it follows that the condition for constant propagation delay requires having $\Delta\tau_{DB} + \Delta\tau_B = 0$ as well. Because in practice it may be assumed that $\Delta\tau_F \approx \Delta\tau_B$, this finally leads to the condition:

$$\Delta\tau_{DF} = \Delta\tau_{DB} \tag{4}$$

which means that variation of the propagation delay versus the control signal must be the same in both delay lines. Because, in practice, external temperature influences the delay introduced by any electronic circuit, it is essential for successful operation of the DLL described herein to have both forward and backward delay lines fabricated in close proximity on the single substrate of the integrated circuit. As no of-the-shelf components of this type are available, we designed an application-specific integrated circuit (ASIC) using an Austria Microsystem AMS 0.35 μm CMOS process **[1]**. The fabricated circuit features a delay variation range around 90 ns and a mismatch between the delay lines in the range of 30 ps **[0]**. Assuming seasonal temperature variations of the fiber around 25°C and taking the propagation delay thermal coefficient of about 40 ps/(km·°C), such a range of delay variations are able to sufficiently stabilize a link up to more than 50 km long.

EXPERIMENTAL SETUP

In order to verify the metrological parameters of the developed DLL system, the experimental setup, shown in Fig 3, was configured, consisted of an A7-MX Phase and Standard Frequency Comparator and an SR620 Time-Interval Counter steered with PC computers. The input of the DLL system was fed with a 5 MHz standard frequency signal taken from an HP5071A Opt. 001 cesium clock or, alternatively, a VCH-1005 active hydrogen maser. As a transmission line for the DLL system, 20 km of optic fiber on the spool was used, which was located outside the laboratory and exposed to sunlight and external temperature variations. All the remaining parts of experimental setup were maintained inside the laboratory in an air-conditioned room. The A7-MX was used to measure phase-time between the 5 MHz DLL input and output signals of the DLL transmitter and receiver respectively, and, supplementarily, the SR620 was used to measure phase-time between 1 pps signals obtained directly from the 5 MHz DLL input and DLL output signals. The results of phase-time measurements allowed calculating the Allan deviation and determining the range of phase-time variations. The measurements were performed between April and July 2010, so the optical fiber on the spool was exposed to relatively big daily variations of the temperature – more than 20 degrees Celsius.

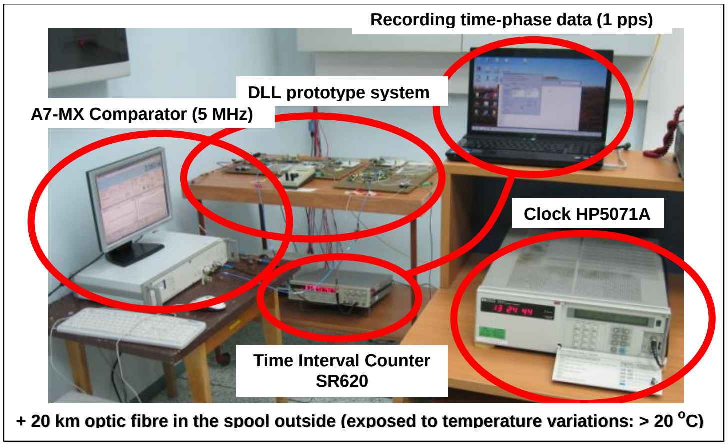


Figure 3. The experimental setup.

BACKGROUND

The initial measurement, performed with the usage of a digital oscilloscope, showed short-term changes of phase-time of the DLL output signal at a level of below 20 ps with reference to the DLL input signal. So the measurement instruments, used for verifying metrological parameters of the DLL system, should meet high requirements in phase-time or time-interval measurement. The SR620 Universal Time-Interval Counter cannot be sufficient, because its single shot rms resolution is specified as 25 ps for time-interval measurement typically **[16]**, although, in practice, about 10 ps is observed. Next, the relative accuracy of the SR620 is specified as 100 ps for time-interval measurement typically **[16]** and it can be the main limitation of this instrument. However, the A7-MX Phase and Standard Frequency Comparator allows for observation phase-time changes with a 1 fs resolution. The auxiliary measurements of the internal noise of the A7-MX, performed with the same 5 MHz split signal put onto both the reference and the measurement inputs of the A7-MX directly (Fig. 4), are consistent with the A7-MX specification **[17]** and constitute a background and the main reference to the essential measurements performed with the DLL system.

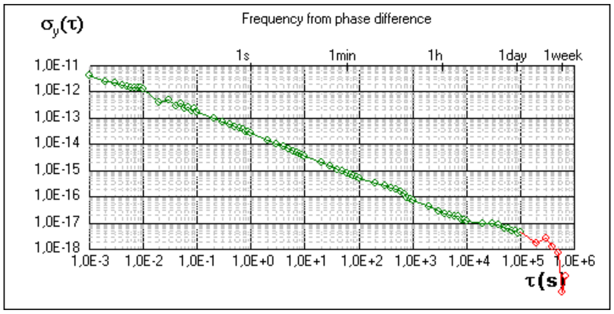


Figure 4. Internal noise of the A7-MX. Allan deviations were calculated from relative phase measurements with the same 5 MHz split signal put onto both the reference and the measurement inputs of the A7-MX (graph obtained automatically with the A7-MX software for 18.5 days of continuous measurements with a sampling time of 1 ms).

MEASUREMENT RESULTS

The results of the essential measurements performed in experimental setup are shown in Figs. 5 and 6. Results of measurements performed with the SR620 (Fig. 5) and related to results obtained with the A7-MX (Fig. 6 a,b) confirmed the insufficiency of the SR620 for verifying the stability of the DLL system and, at the same time, the existence of variations of the SR620 covering the full range of the specified relative accuracy for time-interval measurement, which were observed also at repeated measurements of the same time interval.

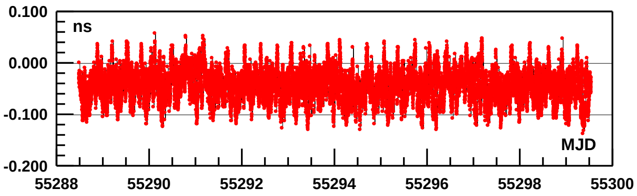
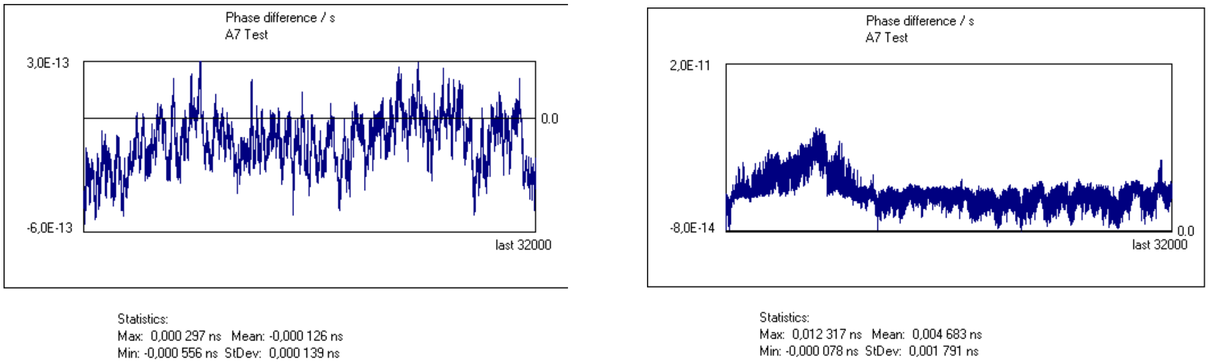
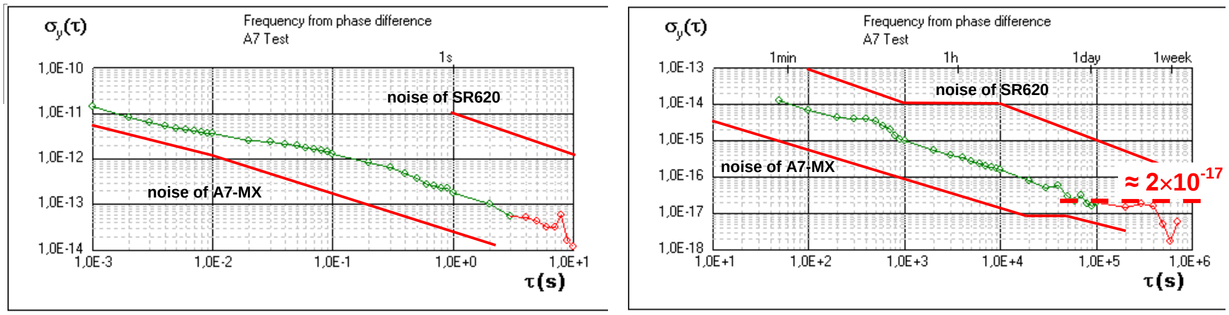


Figure 5. Exemplary results of phase-time measurements performed with the usage of the SR620 for 1 pps signals obtained directly from the DLL input and DLL output 5 MHz signals. The DLL system was connected to 20 km of optical fiber on a spool.



a) phase measurements with sampling time of 1 ms b) phase measurements with sampling time of 50 s



c) Allan deviation with sampling time of 1 ms d) Allan deviation with sampling time of 50 s

Figure 6. Results of relative phase measurements and Allan deviations calculated from phase difference performed with the usage of the A7-MX for frequency transfer with the developed DLL system connected to 20 km of optical fiber on a spool (graphs obtained automatically with the A7-MX software for 32 seconds and 18.5 days of continuous measurements with sampling times of 1 ms and 50 s respectively).

For short-time measurements (here arbitrary: up to 32 s – a consequence of the usage of the A7-MX software revision, which allows a storage maximum of 32000 data points for a minimum of 1 ms of sampling time), we typically observed phase-time variation below 1 ps and an Allan deviation of frequency transfer below $5 \cdot 10^{-13}$ for 1 s of averaging time.

For about 18.5 days of continuous measurements (32000 data points for 50 s of sampling time), maximum phase-time variations below 15 ps and Allan deviations of frequency transfer in the range about between $2 \cdot 10^{-17}$ and $3 \cdot 10^{-17}$ for 24 hours of averaging time were observed. Small deviations (little "humps") from linearity of the Allan deviations for averaging times of about 500 s and 12 hours follow probably from small time-inertia temperature variations inside the laboratory with periods of 15 min (relating to the periodic operation of the air-conditioning system) and of 24 hours (relating to diurnal changes of characteristics of air collected from outside by the air-conditioning system). In the whole range of averaging time, the Allan deviation is about 10 times bigger than the background noise of the A7-MX.

At a similar level of stability and accuracy, results of measurement were obtained with the spool of optical fiber replaced with about a 38-km-long fiber that was part of a telecommunication urban network.

CONCLUSIONS

The outstanding metrological characteristics of the developed DLL system, e.g. the stability of frequency distribution at the level of about $2 \cdot 10^{-17}$, determined from Allan deviations with an averaging time longer than 24 hours, and the stability of the propagation delay at a level below 15 ps, determined as maximal peak-to-peak fluctuations of phase-time during continuous measurements, show that such systems are suitable for distributing the frequency from atomic clocks or even primary frequency standards at distances spanning tens of km directly. In the future, such systems can distribute frequency in the microwave range for comparison of optical clocks. The range of the system can be extended for longer distances by multiplication of electronic delay lines and special amplification of optical signals. Currently, we are also considering transfer of a 100 MHz frequency reference signal from a hydrogen maser and transfer of a 1 pps time signal with stabilized constant propagation delay.

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