# Ultra-Accurate Time Dissemination in a Hybrid Fiber-Optic System with Frequency-Synchronized Lasers and λ-Swapping

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***Summary*— The accuracy of the wavelengths of lasers used in a fiber optic long-distance time transfer systems need to be at the level of some tens of MHz, if the transfer uncertainty at the level of picoseconds is expected at the distances spanning hundreds of kilometers. Such level of accuracy is difficult to obtain using a typical technology exploiting telecom-grade wavelength lockers based on Fabry-Perot etalons. We propose to solve this problem in a hybrid fiber optic transfer system, where the lasers used for time transfer are frequency-locked to a stable optical carrier, which also is simultaneously transmitted in the same fiber. Proposed method makes the time transfer uncertainty practically unaffected by the chromatic dispersion of the fiber link.**

***Keywords—time transfer, fiber optic, optical frequency, laser synchronization***

## I. INTRODUCTION

For an ultra-accurate long distance fiber optic time transfer, where the accuracy in the order of a few ps is considered, the problem of the relative accuracy of the wavelengths of the lasers used to convey timing information becomes important. This is caused by the chromatic dispersion of the fiber, which results in a correction factor that need to be determined when performing the link time calibration. The uncertainty of this correction appears to increase almost linearly with the link length, approaching 100 ps for 1000 km link when standard laser wavelength stabilization techniques are used (based, e.g. on a Fabry-Perot etalon) [1].

The approaches proposing to use the same wavelength for the forward and backward directions [2], apart from calling for extra countermeasures to overcome Rayleigh backscattering, does not, solve the uncertainty problem as it is inherently related to the wavelength accuracy of the lasers used.

A possible approach can exploit a relative synchronization of the lasers frequencies between the local and remote terminals of the time transfer system by keeping the frequency of the beat note between the local and remote lasers constant [3]. Some drawback of this idea is that the optical power available for laser synchronization is low, being only a fraction of the received and modulated optical signal, which

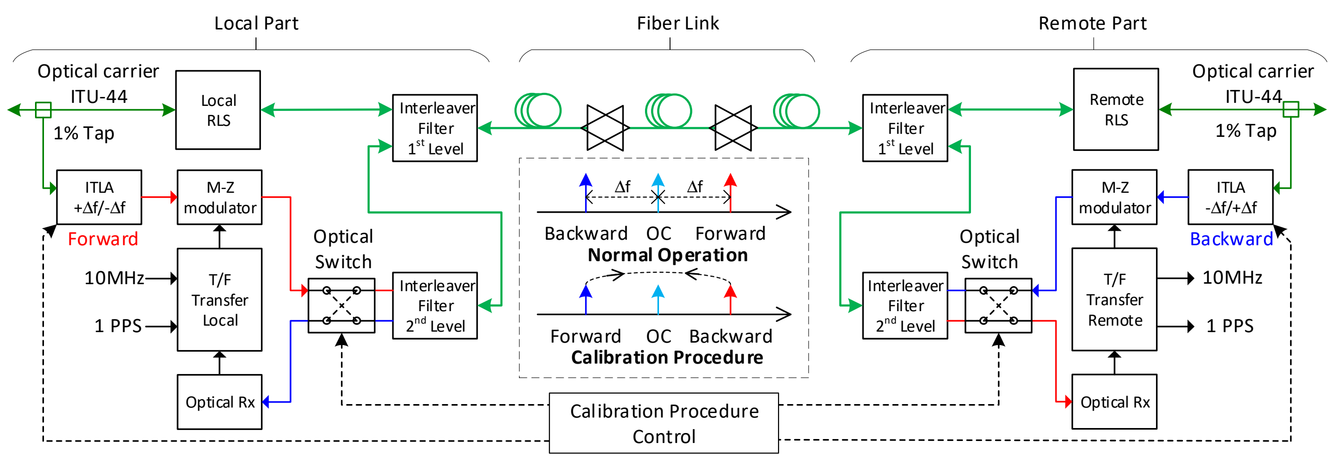


Fig. 1. Block diagram of the setup. Position of the forward and backward lasers frequencies with respect to the optical carrier during the normal setup operation and during the calibration procedure are shown in the inset.

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can result in a systematic frequency synchronization error [4]. In addition, some form of adaptive polarization control is necessary to avoid the beat note fading due to unpredictable polarization changes occurring in optical fibers.

## II. Idea of a Hybrid System with Synchronized Lasers

An elegant and effective approach, which is considered in this paper, exploits an optical frequency dissemination link with repeater laser stations (RLS) [5], where the transmitted highly accurate optical carrier acts simultaneously as a frequency reference for the lasers used for time transfer. In such a hybrid system (i.e. the system where both optical and electrical reference signals plus time are disseminated simultaneously in single fiber and in a relatively narrow slice of the optical spectrum) all the above mentioned negative aspects are removed. The optical power that can be tapped from the RLS and use as a reference can be high enough not to cause a risk of the systematic frequency error, and stable polarization state of the internal RLS laser removes the necessity of additional active polarization control. In addition, as the lasers used for the time transfer are relaxed from simultaneously providing the reference for synchronization, they can be modulated with high extinction, increasing the available signal to noise ratio (SNR) for the time transfer system.

A block diagram of the considered experimental setup is provided in Fig. 1. It is composed of a local and remote parts equipped with two levels of interleaver-based optical filters, which are used to distribute the optical signals among the relevant parts of the system. The optical signals required for the synchronization of the time transfer lasers are tapped from the local and remote RLSs, which are then used to steer the frequencies of two integrated tunable lasers (ITLA). In the setup we used in the experiments the offset between the optical carrier and the time transfer lasers is kept at $\Delta f$ =12.5 GHz, being positive for the local part and negative for the remote one. These optical signals are further modulated by the external Mach-Zehnder modulators, receiving their driving signals from a pair of local/remote time and frequency transfer modules that stabilize the propagation delay of the fiber link using electronic variable delay lines.

Using the optical interleavers as the multiplexing and de-multiplexing devices gives the opportunity to exchange the optical frequencies between the local and remote time transfer modules during the time calibration procedure. This so-called λ-swapping technique gives a huge frequency step (equal twice the separation between the forward and backward directions, i.e. 50 GHz in the considered scheme) used for determining the chromatic dispersion correction. This allows substantial reduction of the calibration uncertainty [4] and enables picosecond-accurate long-distance fiber optic time transfer. To implement this idea in an operational system it is not enough to change the frequencies of the lasers, but also to switch the connections between the transmitter, receiver and the 2nd level interleaver. This is done in the described scheme by two cross-bar optical switches.

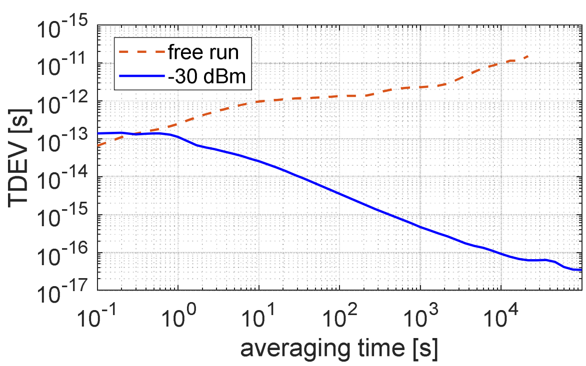


Fig. 2. Stability of the synchronized laser frequency assuming 1000 km long fiber link with the accumulated chromatic dispersion of 17000 ps/(nm·km).

## III. Experimental results

In a first step we undertake an extensive tests of the circuits for the offset-synchronizing the ILTA lasers. We determined that the circuit can work reliably with the power of the synchronizing optical signal well below -50 dBm, although care have to be taken to avoid the mentioned systematic frequency error, which will affect the time transfer uncertainty. To avoid this problem we decided to operate the circuit with much a more power, at the level of -30 dBm, as such a power level can be easily accessed from the RLS laser. In Fig. 2 the deterioration of the time transfer TDEV due to the instability of the synchronized laser frequency is shown. As the TDEV curve is below 100 fs for the averaging times greater than 1 s the contribution of the synchronized laser stability can be regarded as negligible when compared to typical results achieved in fiber optic time transfer experiments (TDEV better than a few hundred fs).

In the next step thee experimental setup from Fig. 1 was tested in the laboratory for more than a month using both spooled and outdoor fibers. In this part of the experiments we were searching for any system malfunction, observing no any synchronization loss or other unusual system behavior.

In the last part of the experiments we performed verification of the link calibration. For estimating the chromatic dispersion correction $\Delta\tau_{CD}$ the λ-swapping technique was used. The details of the optical spectra in both the nominal and calibration modes of the transfer system are shown in Fig. 3. The close-up in the spectral range occupied by the ultra-accurate optical frequency reveals two pikes, which corresponds to the signals propagating in the forward and backward directions between two RLSes. In case of our experimental setup they are separated by 70 MHz. The local and remote lasers of the time transfer part are synchronized to the respective optical frequencies with the offset of 12.5 GHz, which results in a total offset between the forward and backward lasers equal to 25.070 GHz in case of normal operation and 24.930 GHz during the link calibration procedure. During the λ-swapping procedure the total frequency change is thus 50 GHz.

The measurement setup used for the link calibration verification is shown in Fig. 4. The estimation of the

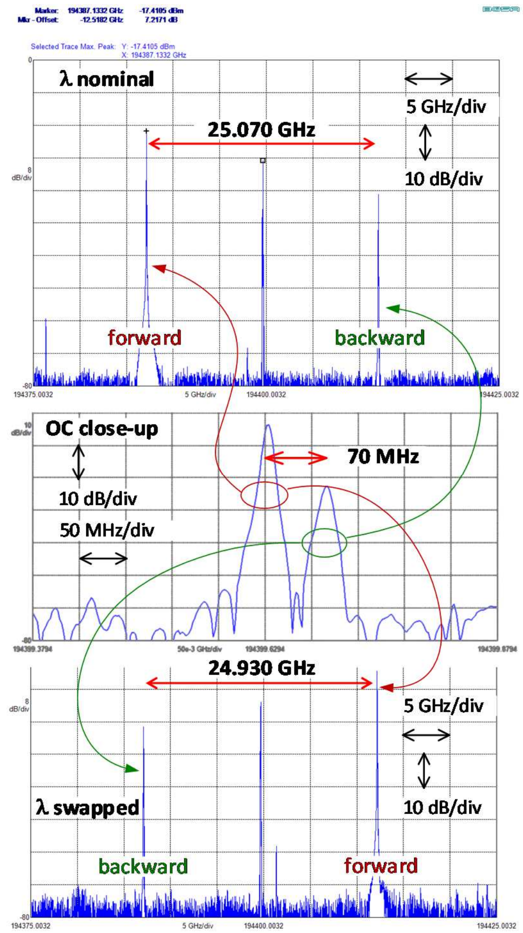


Fig. 3. Optical spectra during normal system operation and after λ-swapping with reference to the ultra-stable optical frequencies.

propagation delay between the reference input of the local module and the output of the remote module is equal to:

$$\tau_{REF\to OUT}^{estimated} = \frac{1}{2}(\quad _{RB} + \tau_C + \Delta\tau_{CD}), \qquad (1)$$

where $T_{RT}$ is the round-trip propagation delay measured at the $PPS_{RET}$ port of the local module and $\tau_C$ is the internal asymmetry between the local and remote modules. For the equipment we used for the experiments we estimated $\tau_C$ as equal to 7725±8 ps.

The value of $\Delta\tau_{CD}$ was calculated from the formula:

$$\Delta\tau_{CD} = (\Delta\tau_M - \tau_{CDA})\frac{\Delta\lambda_{A\to}}{\Delta\lambda_M}, \qquad (2)$$

where $\tau_{CDA}$ is the asymmetry related to the optical cross-point switches used in the setup. Its value was estimated to be equal to 1401±8 ps.

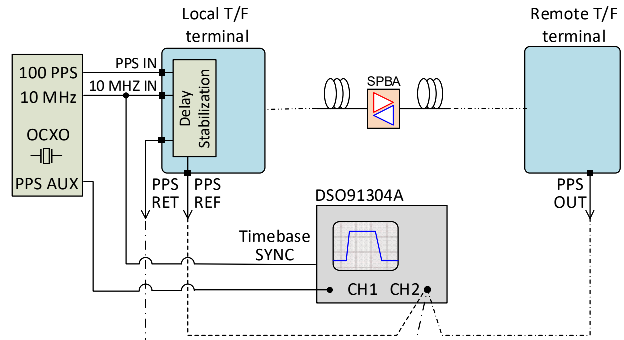


Fig. 4. The measurement setup used for the link calibration verification.

The verification tests were performed for three different lengths of the fibers connecting the local and remote modules equal to 50 km, 150 km and 300 km. The results collected in Table 1 show a very good agreement between the measured and estimated propagation delay of the link, which does not exceed 2 ps.

## CONCLUSION

The accuracy of time transfer in a hybrid system exploiting the λ-swapping technique is substantially improved comparing to the links where the wavelengths accuracy of the lasers used for time transfer are derived from the references based on Fabry-Perot wavelength lockers. Proposed and experimentally verified transfer techniques solves the problem of uncertainty component resulting from fiber chromatic dispersion, resulting in calibration uncertainty at the level of a few ps, limited in practice by the uncertainty of related to the time interval measurement.

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Table 1. Results of link calibration verification.

| № | length [km] | [ps] | [ps] | [ps] | [ps] | difference [ps] | comments |
|---|---|---|---|---|---|---|---|
| 1 | 50 | 497170754±8 | 67±8 | 248589273±8 | 248589273±8 | 0±11 | 1 spool: 1×G.655 |
| 2 | 150 | 1488300751±8 | 205±8 | 744154338±8 | 744154340±8 | +2±11 | 3 spools: 1×G.652 + 2×G.655, 2×SPBA |
| 3 | 300 | 2975210748±8 | 506±8 | 1487609489±8 | 1487609490±8 | +1±11 | 6 spools: 2×G.652 + 4×G.655, 3×SPBA |