Improved Optical Clocks Comparison via Standard DWDM Optical Networks

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***Abstract*—In this work we propose a solution for improving the stability of optical frequency transfer in standard DWDM networks, which do not support bidirectional transmission in one fiber. The idea is based on the observation that the differential phase noise, resulting from the mismatch between the forward and backward direction fibers, is strongly correlated to the round-trip phase noise, and so may be efficiently compensated for.**

Keywords*—*fiber-optic frequency transfer, DWDM networks, noise cancelation

I. Introduction

A well-established solution for comparing optical clocks over a large distance is based on bidirectional signals exchange in a single optical fiber. Thanks to nearly perfect matching of the phase noise picked-up in the forward and backward directions in the single fiber, the impact of this noise can be canceled out [1].

The possibility of using standard (i.e. not specially modified) DWDM infrastructure for optical clocks comparison is based on a so-called alien wavelength service, when a dedicated wavelength channel in the network is devoted for propagating metrological signals. In this situation, however, the symmetry of bidirectional signals exchange is broken, as the truly bidirectional scheme is substituted with two unidirectional parallel optical paths, consisting of two fibers (in the same cable), and two separate optical paths in network nodes - see Fig. 1. Therefore the stability achieved in optical frequency distribution using DWDM networks, that has been reported till now, is insufficient, being in the range of 1^{-16} to 10^{-15} (for 1000 s and longer averaging) [2].

II. Proposed Improvement

For long observation times, the main factor producing signal phase instability in the fiber is impact of temperature, affecting both the refractive index and physical length of the fiber.

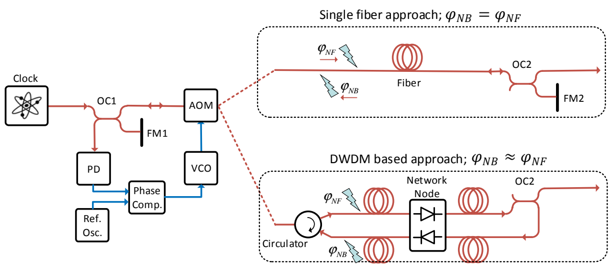

Fig. 1. Actively stabilized frequency transfer in a single fiber and in a DWDM network.

As the pairs of fibers used in DWDM networks are located in the same cable, and even same tube inside the cable, the perfect temperature matching would be expected. In many experiments we observed, however, that some differential phase fluctuations between two fibers in one cable appears. Therefore, we believe that the thermal sensitivity of two fibers may be more or less, but always noticeably, different. Provided that the refractive index and length expansion linearly depend on temperature, this leads to a hypothesis that differential phase fluctuations are proportional (correlated) to the total, round trip fluctuations. We observed such evident correlation in all performed experiments, both with soil-buried and aerial (suspended) fibers - see Fig. 2.

The postulated mismatch between forward and backward fiber may be written in the form: $\varphi_{NB} = (1+m)\varphi_{NF}$, where m is a small mismatch parameter, usually in the range of $\pm1{*}10^{-3}$ ... $\pm3{*}10^{-2}$, (see also Fig. 3). The resulting phase error at the end of the link may be written as:

$$\varphi_{ERR}(t) = [\varphi_{NF}(t) + \varphi_{NB}(t)]\,[m/(2+m)]. \qquad (1)$$

The phase fluctuations φ_{NF} and φ_{NB} are not directly observable, but one may recall that their sum is being compensated for by steering the AOM shown in Fig. 3. Therefore:

$$\varphi_{NF}(t) + \varphi_{NB}(t) = -\varphi_{AOM}(t), \qquad (2)$$

which means that if $\varphi_{AOM}(t)$ is registered, it may be used for compensating $\varphi_{ERR}(t)$, by means of data postprocessing. The challenge is, however, that the mismatch parameter m should be determined in some way, which will be addressed in the next section.

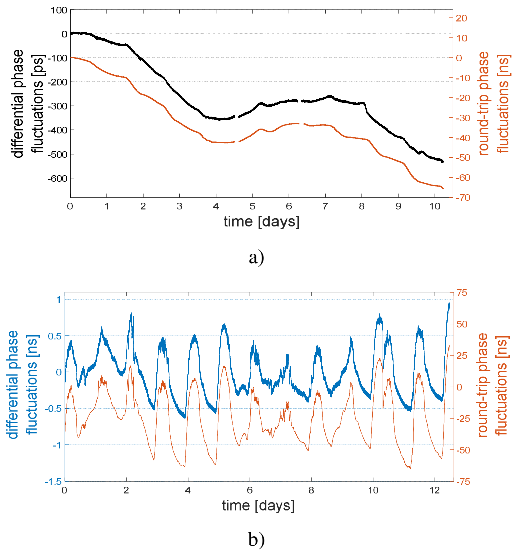

Fig. 2. Correlation between differential and round-trip phase fluctuations for pair of fibers for soil-buried (a), and aerial (b) cables.

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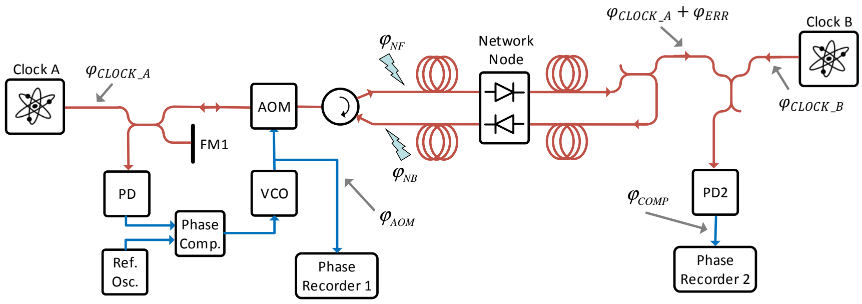

Fig. 3. Clocks comparison exploiting two parallel optical paths in DWDM network. Phase signals used in text marked.

III. Proof-of-Concept Experiment

The experiment was performed in a 1500 km-long link established in a standard DWDM network. The link had a form of geographical loop, with both ends in the same laboratory at AGH University in Krakow. To mimic the real situation of comparison of two optical clocks with slightly different frequencies, we used a single ultra-stable laser, frequency-shifted with two AOMs; by 50 MHz („Clock A") and 50 MHz plus 17 mHz („Clock B"). This is equivalent to $8.76*10^{-17}$ relative frequency difference between the "clocks".

In a real situation we do not know both the offset between the clocks, and the fibers mismatch parameter *m*. These two parameters may be determined by a two-dimensional fitting (optimization), done over a few days measurement record. Basing on previous equations one may write:

$$\Delta\nu_{A-B}\, 2\pi t - \varphi_{AOM}(t)\left[\frac{m}{2+m}\right] = \varphi_{COMP}(t), \qquad (3)$$

where $\Delta\nu_{A-B}$ is difference between clocks frequencies. Both clocks offset and mismatch parameter may be obtained by fitting of the left-hand side of the above equation to actually measured $\varphi_{COMP}(t)$, over the entire measurement period. The fitting is well conditioned when $\varphi_{AOM}(t)$ is not evolving linearly over entire measurement period, which usually may be fulfilled in 5...10-days long measurement session.
The results are presented in Fig. 4. The raw data, recorded by two phase comparators (FXE by K+K), are shown in Fig. 4a. It may be noticed that φ_{COMP}, which basically should reflect the clocks frequency offset, is strongly corrupted by the uncompensated differential phase fluctuation. After performing the abovementioned fitting (optimization), the relative clocks offset is estimated as $(0.8 \pm 0.1)\times 10^{-16}$. The result of the proposed method may be also illustrated by comparing the clocks phase difference evolution estimated with help of the procedure, with its true value, intentionally forced in this experiment (see Fig. 4c). Some discrepancy is visible, but after a few days measurement the offset is clearly visible, in contrast to raw data $\varphi_{COMP}(t)$, presented in Fig. 4a.

IV. Conclusion

In this work we described the new method for improving the stability if optical frequency comparison in DWDM network. The method uses standard alien wavelength service, available in nowadays networks without any physical modifications. The method is efficient for long averaging periods, when fiber temperature changes are the dominant factor limiting transfer stability.

References

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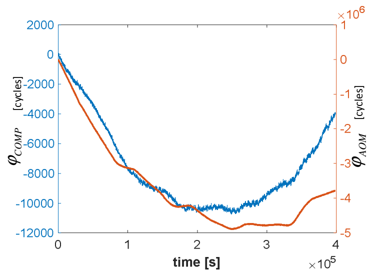
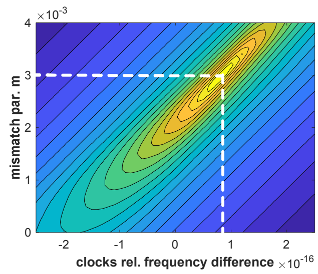
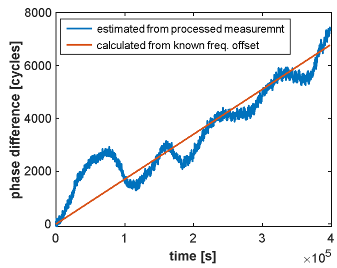


a)



b)



c)

Fig. 4. Illustration of the estimation of phase difference between the clocks; raw data (a), fitting map (b), and corrected phase (c).