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Two wavelength frequency transfer over an optical fiber link

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Abstract. In this paper we present the theory and the experimental setup used to transfer a standard frequency, to synchronize two clocks linked by an optical fiber. In order to verify the accuracy on frequency transfer over fiber link, we prepared an experiment that allows testing the performance of the setup for a variable set of environmental conditions, namely associated to temperature and vibration variations. The experimental setup shows the fiber optic link between one laboratory, where the standard frequency is generated, and another laboratory, where the equipment for simulating temperatures and vibrations are installed. The standard frequency, traceable to UTC(IPQ), is used to modulate two lasers with different wavelength, , injected in the optical fiber. At the end of the optical fiber the signals will be out of phase due to the inherent chromatic dispersion, which is also dependent on the temperature of the propagation media. Measuring the phase variations, caused by temperature gradients in the fiber, we can compensate the frequency transfer and synchronize the clocks. Evaluating all uncertainty components in this model, allows the metrological characterization of the synchronization and obtain the associated uncertainty of this quantity.

1 Introduction

Ultra-stable time and frequency sources, primary time standards or even commercial time standards, that contribute to the realization of the Coordinated Universal Time (UTC), have an important role in fundamental physics and in time and frequency metrology, such as clock evaluation, tests in relativity, work in fundamental constants, among others. Currently, the dissemination in long distances of a standard frequency is achieved using the satellites of the Global Navigation Satellite Systems (GNSS), with a stability in the order of 10^{-15} in one day. This value could be overcome replacing the satellites by optical fiber, being a matter of study in the last decade.
The dissemination of frequency, using optical fiber, is being implemented by most of the National Metrology Institutes (NMI) in Europe.
One method to disseminate frequency consists in modulating the frequency into a light signal, and then injecting the light in an optical fiber. At the end of the fiber, the signal is converted to the microwave domain and can be used as a standard frequency.
Replacing the satellites link by an optical fiber link, made possible the comparison of the best time and frequency standards in short time interval with accuracies 2 order of magnitude better than the observed with the GNSS.
The main goal of this work is to study the transfer a frequency signal, from one laboratory, where the standard frequency is generated, to another laboratory where a setup is mounted to measure the delay of the frequency transfer caused by temperature and vibrations variations. Evaluating all the delays and all the uncertainty components in this transfer will allow the synchronization of two clocks at both ends of the fiber, with the best possible uncertainty.
This paper presents the initial work in this experiment, where temperature variation effect on the frequency transfer accuracy is evaluated. For this purpose, a fiber link of 500 m in length was mounted on the roof top of the laboratory and the environment conditions were recorded.

Although considered for this experiment, vibration tests and their impact on the frequency transfer process are not included in this paper
The work produced by the author follows closely the method and experiment performed in 2010, in Sweden, where two light beams of different wavelength injected in a fiber link were used to evaluate the influence of temperature variations in the frequency transfer process [1].

2 Theory

In general, the frequency stability of an oscillator in free mode, with short integration times, is better than the frequency stability of an oscillator located at the end of a means of transport, due to the noise introduced by it. The inherent stability or the accuracy of the oscillator at the remote location turns out to be irrelevant as the greatest source of uncertainty is caused by the means of transport, in this case by the optical fiber link.
From a physical point of view, the group time delay, τ, is given by the slope of the curve that relates the refractive index to the wavelength. This slope is given by the derivative of the index of refraction as function of the wavelength, which multiplied by the length of the fiber allows to obtain the propagation time of a signal in the fiber.

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$$\tau = \frac{L}{c}\left(n - \lambda\frac{dn}{d\lambda}\right) \quad (1)$$

The delay in the propagation of a beam of light in a fiber can be expressed according to equation 1. The variation in propagation delay can be expressed as a function of temperature (T) using the following expression:

$$\Delta\tau = \frac{L}{c}\frac{\partial n}{\partial T}\Delta T + L\alpha\frac{n}{c}\Delta T + LD\Delta\lambda \quad (2)$$

Where $\alpha = \frac{\frac{\partial L}{\partial T}}{L}$ is the coefficient of thermal expansion of the fiber and $D = \frac{\frac{\partial n}{\partial \lambda}}{c}$ is the chromatic dispersion coefficient of the fiber.

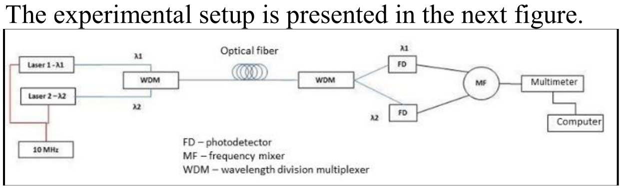
Deriving equation 1 in order of temperature and calculating the difference in propagation time between two different wavelengths, we obtain:

$$\left.\frac{d\tau}{dT}\right|_{\lambda_1-\lambda_2} = \frac{1}{c}\left(\frac{dL}{dT}\left(\left(n_{\lambda_1} - n_{\lambda_2}\right) + \lambda_2\frac{dn_{\lambda_2}}{d\lambda_2} - \lambda_1\frac{dn_{\lambda_1}}{d\lambda_1}\right) + L\frac{d}{dT}\left(\left(n_{\lambda_1} - n_{\lambda_2}\right) + \lambda_2\frac{dn_{\lambda_2}}{d\lambda_2} - \lambda_1\frac{dn_{\lambda_1}}{d\lambda_1}\right)\right) \quad (3)$$

Equation 3 reflects the influence of temperature in the refractive index of two wavelengths, being able to determine the variation in the propagation time.

3 Experimental and reference set up

The experimental setup is presented in the next figure.



The lasers used are diode lasers with 1310 nm and 1550 nm wavelength, modulated with the 10 MHz reference frequency, from one Caesium clock (Cs8), used in the realization of the national reference time scale, UTC(IPQ). The stability of Cs8 is 6.00×10^{-13} in 100 s. The optical signals from the lasers, after modulation, go to a Wavelength Division Multiplexing (WDM), where they are injected into a 500 m optical fiber. At the end of the fiber both signals go back to a WDM where they are divided by wavelength and sent for detectors, to be converted in microwave. The microwave from the detectors goes to a frequency mixer, to be used as a phase detector [2], and the voltage is measured in a multimeter.

Part of the optical fiber link were installed in the rooftop of the building and is exposed to daily temperature gradients. Several temperature sensors were installed along the optical fiber path, in order to observe the temperature to which the fiber is subjected along the day.

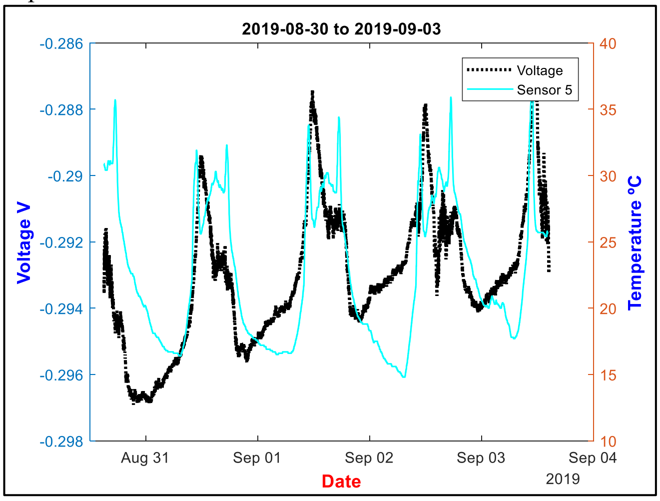
Two stet of measurements were made, in July 2019 and September 2019.

As a result, we have the variation of voltage and temperature across several days.

4 Results

Initially was analysed the stability of the 1550 nm and 1310 nm signals, after passing through the 500 m of optical fiber link. Subsequently the Modified Allan Variation was calculated for both signals, and a decrease about two order of magnitude in stability was observed.

The results from the frequency mixer working as phase detector, are extracted from a dataset of 5 days, collected in September 2019.



A similar behaviour can be observed by the temperature and voltage (with the information of phase difference between the two channels) which can indicate that changes in the temperature of the fiber in the rooftop can cause a phase variation, in accordance with the theory.

5 Conclusion

There is a decrease in the stability of the reference signal after its transmission in the fiber.

The collected data allows the conclusion that there is an influence of the temperature in the frequency transfer, although it wasn't observed in a categorical way a relation between the variations of the voltage in function of the temperature for this optical fiber path because all sensors presented different values of temperature along the day. It can be considered that, despite being a short path of optical fiber, it is a good example of a real connection, in which different parts of the fiber are at different temperatures.affecting cumulatively the stability of the frequency transfer.

A real implementation, with an optical fiber link of several kilometers is being studied and will allow the synchronization of two clocks, and in this way disseminate the second with the lowest possible uncertainty value.

References

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