TIME AND FREQUENCY COMPARISONS WITH OPTICAL FIBER LINKS

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ABSTRACT. For the last 5 years, ultra-stable optical fiber links have been successfully developed in order to enable ultra-stable and accurate frequency transfer between the best modern atomic clocks whose accuracy are below 10^{-15}. Optical fiber links exhibit fractional frequency stability in the range of 10^{-18} after only 3 h of measurement and frequency accuracy of a few 10^{-19}, with a range of a few 100 km up to 1800 km [12]. Recently, time transfer through optical fiber link was demonstrated, simultaneously with frequency transfer by the LPL-SYRTE group. Time deviation of the time transfer is below 20 ps, and the accuracy of the link is below 250 ps. These results overcome the capabilities of satellite based comparisons and could play a key role for geodesy, high-resolution radio-astronomy, and modern particle physics.

1. INTRODUCTION

Frequency metrology community witnesses for 20 years the impressive improvements of frequency standards, their accuracy being dropped down by 2 order of magnitude within 2 decades [1,2]. The stability and uncertainty of primary frequency standard are even surpassed by the optical lattice clocks, where the clock frequency does not belong anymore to the microwave domain but to the optical domain. Indeed, given the same interrogation time, and neglecting the noise of the local oscillator, the ratio of the line-width of the atomic fringes to the clock laser frequency is much smaller. These optical clocks demonstrate frequency stability as low as a few 10^{-16} at 1 second integration time. Systematic effects are much better controlled and the uncertainty budgets are in the low 10^{-17} range [3,4,5]. Their performances are even more interesting that they are operated with a variety of atom species, that make their comparisons a stringent test of the temporal variation of fundamental constants [6]. Moreover the gravitational shift is about 10^{-16}/m, so that an accurate knowledge of the geodetic potential is required for accurate remote comparisons of optical lattice clock. As prerequisite to these exciting prospects is the ability to compare 2 or more distant clocks at this level of precision.

In this paper we will briefly describe the technical limitations of coherent link and the state-of-the art frequency transfer abilities. We will present the REFIMEVE+ network for frequency standard dissemination in France and its connection at the borders. In a second part, a novel method to simultaneously disseminate an ultra-stable optical frequency and accurate timing over a public telecommunication network will be shown.

2. FREQUENCY TRANSFER

Actually clocks are compared with satellite based methods using a carrier in the microwave domain, as Global Navigation Satellite Systems (GNSS) and 2-way satellite time and frequency transfer (TWSTFT). The resolution of such means of comparisons is about 10^{-11} at one second and about 10^{-15} at 1 day integration time [7,8]. In order to reach better stability and uncertainty, one idea is to increase the carrier

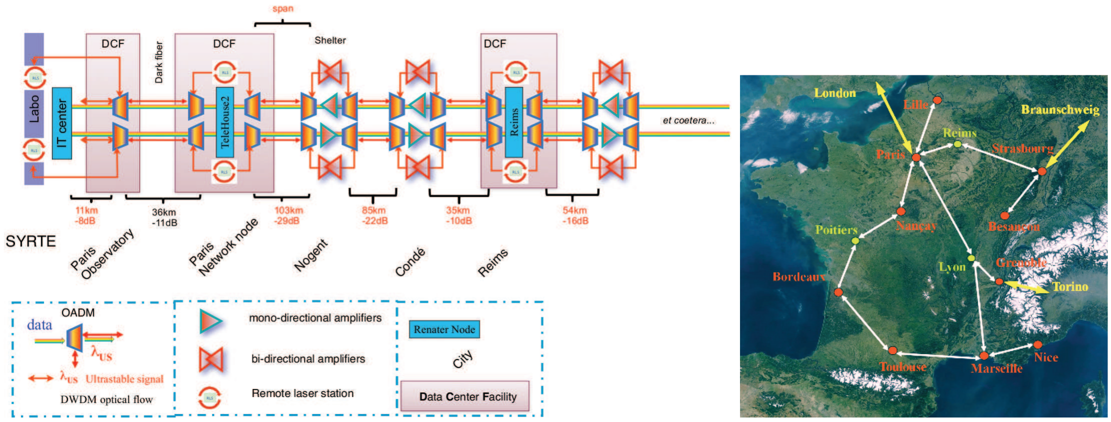

Figure 1: Left : Topology of coherent long haul link with parallel data traffic. OADM are inserted to bypass the uni-directionnal amplifiers. Bi-directional amplifiers are used instead of. After a number of spans, the metrological signal is regenerated to keep a large enough bandwidth of correction and to clean up the optical signal to noise ratio. Right : Map of the spots connected by the REFIMEVE+ project. The green and red dots corresponds to the places where at least 2 remote laser stations will be set up. The users of REFIMEVE will be connected to the red dots. Bi-directionnal amplifiers are omitted. The yellow arrows show the cross boarder links envisioned to connect to Germany, Italy, and UK.

frequency up to the optical domain, using an optical fiber as the medium of propagation.

The best optical frequency transfer is achieved so far by injecting a low phase noise laser into a single mode fiber. The frequency signal consists then of the frequency of the carrier laser. The fiber propagation noise is detected by an optical interferometer comparing the phase of the local laser with the one of the light that travelled forth and back through the same fiber [9]. In the case of fully bi-directional operation, one assumes that the accumulated phase noise is equal forth and back, and one can actively compensate the fiber noise.

There is mainly 3 technical challenges to overcome. First comes the attenuation, about 0.25 dB/km in average. This is partially compensated by the use of bi-directional amplifiers. As they are not isolated from back and stray reflections, the experimental gain must be set below about 15 dB to prevent it from self oscillations. With typical span length of 100 km, the losses are most often not compensated. As the input power must be below 5 mW, in order to avoid stimulated Brillouin scattering, the detected power in the interferometer is low (as low as 1 nW for the link described in [10]). In addition the detected noise power is very high, due to spontaneous emission, scattering processes and stray reflections. The necessary high signal to noise ratio needed by the phase lock loops is obtained by narrow filters and delicate signal treatment. The second technical challenge is to use a laser with a coherent length longer than the double length of the link. Typically a line width equal to 1 kHz is just enough for a 25 km long link only. The third and most severe limitation comes from the propagation delay and the finite velocity of light in the medium. Typically a 1000 km link will have a round trip delay of 5 ms. This limits the bandwidth of the correction to 25 Hz, which means that the acoustic noise is left almost uncompressed. It determines also the residual noise power at Fourier frequency lower than the cut off frequency [11]. In order to overcome all these limitations, we developed remote laser stations, that are able to transmit the metrological signal in a cascaded way (see figure 1).

The last, but not least, difficulty is actually to access the fiber. The rental cost of a fiber is quite prohibitive for most of the research institute. The alternative strategy we developed is to benefit from the existing telecommunication networks to broadcast the metrological signal. We use Optical Add-Drop Multiplexers (OADMs) to extract and insert the science signal into the telecommunication fibers. The price to pay is to use techniques compatible with data traffic, and additional losses penalty that arise from the insertion losses of the OADMs. Fiber Brillouin amplifiers as such used in Germany are prohibited in such networks for instance [12]. Despite these technical challenges, we successfully transfer an optical frequency over telecommunication network in parallel with data traffic over a link made of 5 spans with a total length of 540 km [10]. In this long haul link, the total end-to-end attenuation is in excess of 165 dB. With the help of six bidirectional EDFAs and a total amplification of about 100 dB, the net optical

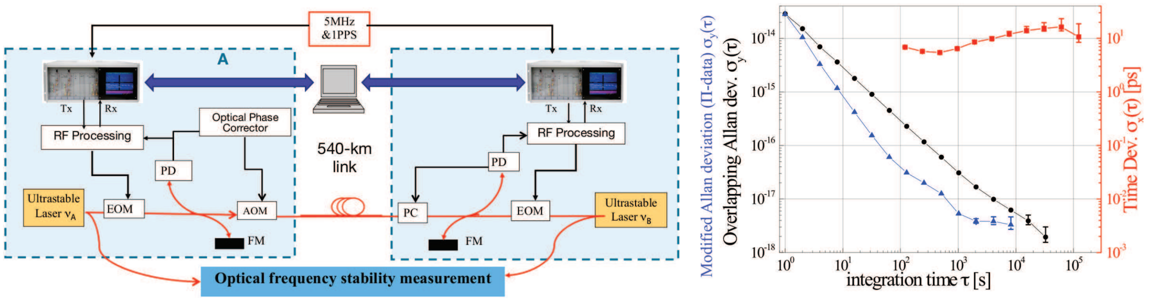

Figure 2: Left : Sketch of the experimental set up. Right : Relative frequency stability and time stability, represented in overlapping, modified and time deviation recorded versus 30 000 s integration time, for a simultaneous time and frequency transfer.

losses exceed 65 dB. Many technical details are given in [10]. We recorded a relative frequency stability of 4×10^{-14} at one second integration time, scaling down as τ^{-1} down to 10^{-18} after 40,000 s integration time. This excellent results give birth to the the REFIMEVE+ project, aiming at broadcasting the optical reference elaborated at SYRTE to 20 laboratories in France on the RENATER network, thanks to 85 bi-directional amplifiers and 48 remote laser stations (see fig. 1). The technologies are now being transferred to an industrial partner, IDIL [14]. The metrological network is expected to be built in 2016.

3. TIME TRANSFER

The upcoming challenge is to transfer not only frequency but also time. Time transfer and accurate timing is also important for numerous applications, from modern particle physics to communication network's synchronization. Long distance accurate time dissemination is usually based on GNSS signals, or geostationary telecommunication satellites, with an accuracy about 1 ns, and time deviation of few 100th of ps after one day averaging at best [7,8,13].

We introduced recently a novel method to transfer time simultaneously with frequency. We followed the general approach of satellite 2-way comparison that we transposed as phase modulation of an optical carrier [15]. The experimental set up is sketch in Fig. 2. A detailed description is reported in [17]. The method consists of relating the phase of a pseudorandom noise modulation carried on a radio frequency intermediate carrier signal (50-80 MHz) to the one-pulse-per-second (1PPS) and a 10 MHz reference signal from a common clock. The SATRE modem correlates the received signal and the local replica, and measures the time of arrival of the received signal with respect to the local clock. The time of arrival of both modems are afterwards collected, and the differential time delay is computed. At each link end the time signal is encoded on the laser as phase modulation with a fiber pigtailed electro optical modulator. A low modulation depth of 1% is used in order to keep the frequency transfer without degradation. The time signals are detected by an optical heterodyne beat-note of the local laser with the incoming signal. After several stage of delicate filtering and frequency mixing (parasitic signals due to stray reflections are 40 dB larger than the useful signals), the time signals are processed by the modems and sent to the computer. The frequency transfer stability and the timing stability/jitter are simultaneously measured and are plotted in Fig. 2. The frequency stability of the link reaches a resolution of 10^{-18} at 30 000 s averaging time, which is almost identical to the one reported in [10]. The timing stability shows a noise of less than 20 ps for all measurement time. We perform in addition a preliminary calibration campaign, in order to estimate the uncertainty of the time link, following standard calibration procedure in time and frequency metrology [16]. We vary the length of the link by setting "shortcuts" in the accessible places along the long-haul optical link, while keeping the overall link attenuation constant within ± 2 dB. We vary therefore the link length from 10 m to 94 km, 400 km to the total of 540 km. The measured differential time delay variation is smaller than 50 ps. The sensitivity to power fluctuation was checked by changing the power of the signals from the optical detection up to the modem input. We found a coefficient below 15 ps/dB. Fiber chromatic dispersion is also very low, as the signals are quite narrow, and was estimated below 25 ps. Polarization mode dispersion plays also a minor role with contribution to the error budget below 20 ps. As both time measurements are collocated in this experiment the Sagnac effect is zero. The preliminary conservative accuracy budget of 250 ps is actually mainly dominated by scarce phase jumps of about 50-80 ps that we believe to be due to technical imperfections. The system is quite robust and operates over many days with time variations below the above stated accuracy.

4. CONCLUSIONS AND OUTLOOK

We have presented the REFIMEVE+ metrological network that aims at transferring optical frequency standard at the French scale. We have shown that simultaneous time transfer was also possible on telecommunication network with an excellent level of stability, competitive with the satellite-based methods, and much better at short integration time. The accuracy of the time transfer is now limited by our calibration capability of all instrumental delays. In a near future, we hope to perform comparisons of means of comparison, in order to check the consistency of the methods and the stability of the calibration campaigns. These tests could also be used to measure Sagnac effect, and probe general relativity on giant Sagnac loops.

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