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Transfer of an optical frequency over an urban fiber link

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We transferred the frequency of an ultra-stable laser over 172 km of urban fiber. The link is composed of two cascaded 43-km fibers connecting two laboratories, LNE-SYRTE and LPL in Paris area. By implementing a recirculation loop we extend the link length up to 172 km. The link is fed with a 1542-nm cavity stabilized fiber laser having a sub-Hz linewidth. The fiber-induced phase noise is measured and cancelled with an all-fiber-based interferometer using commercial off-the-shelf pigtailed telecommunication components. The compensated link shows an Allan deviation of a few 10^{-16} at 1 s and a few 10^{-19} at 10,000 seconds.

OCIS codes: 060.2360, 120.3930.

1. INTRODUCTION

Transfer of ultra-stable frequencies between distant laboratories is required by many applications in time and frequency metrology, fundamental physics, particle accelerators and astrophysics. Remote clock comparisons are currently performed using satellites, directly by Two-Way Satellite Time and Frequency Transfer, or indirectly through the Global Positioning System carrier phase measurement. However, both methods are limited by instability of 10^{-15} after one day of averaging time [1] and are consequently insufficient to transfer modern cold atom microwave frequency standards having demonstrated frequency stability of a few 10^{-16} at 1 day [2]. The progress on satellite based link will probably lower the floor in the 10^{-16} range at one day and advanced space missions like “ACES” (Atomic Clocks Ensemble in Space) [3] and “T2L2” [4] will allow even better comparisons in the high 10^{-17} at one day. Even in this optimistic view the performance will not be sufficient for the next generation of optical clocks. Optical clocks using a trapped single ion or cold atoms confined in lattice are expected to reach instability level of 10^{-17} or better at 1 day and will consequently require even more stable frequency transfer systems [5,6]. Moreover the assets of the accuracy and stability of the optical clock are critically related to an efficient way to compare remote clocks with short averaging time. Beyond metrology, high resolution clocks comparison is essential for advanced tests in fundamental physics, as for instance test of the fundamental constants stability [7].

To overcome current space link limit, transmission of frequency standards over optical fiber has been experimented for several years [8]. This technique takes advantage of the fiber low attenuation, high reliability and phase noise cancellation achievability.

Microwave frequency transmission using amplitude modulation of an optical carrier demonstrated instability as low as 2×10^{-18} at 1 day over 86 km [9,10,11]. Direct optical frequency transfer [12,13,14] can provide even better stability and be extendable to greater distance. Indeed, optical frequency transfer is less sensitive to the link attenuation, thanks to the heterodyne detection

achievability. In addition, the higher carrier frequency gives much better resolution for measuring link-induced phase noise. In 2007, two pioneering experiments of optical frequency transfer over a fiber link of more than 200 km have been reported [13,14]. Both experiments used fiber spool extension of an urban link and have shown the feasibility of a full optical link with instability in the 10^{-18} range. We report in this paper the results of the transmission of a sub-Hz linewidth optical frequency reference on a fully urban link of 172 km length. After the description of the cavity-stabilized laser used to test the link, we present the scheme of the link-induced phase noise compensation system. The frequency stability performance of an 86-km urban fiber link is then reported and, finally, the link length is extended to 172 km and characterized.

2. LASER SOURCE

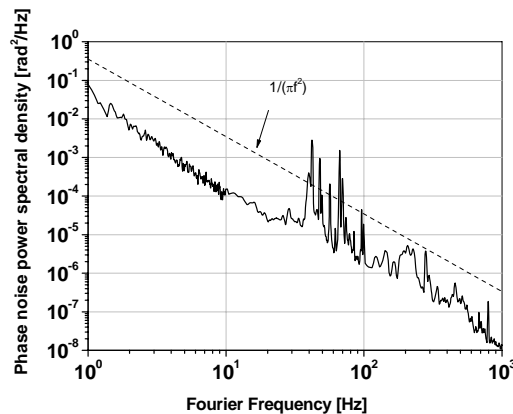


Fig. 1. Phase noise power spectral density versus Fourier frequency of the stabilized laser (solid line) and of a 1-Hz linewidth white frequency noise laser (dashed line)

Two identical ultra low noise laser sources have been developed using 1542-nm 1-2-kHz linewidth commercial fiber lasers stabilized on two identical ultra-stable cavities by the Pound-Drever-Hall method [15]. The cavity consists of a 10-cm ULE spacer and two optically contacted ULE mirrors, giving a measured finesse of $\sim 800,000$. The cavity, specially designed to minimize the vibration sensitivity in all spatial directions [16], is mounted horizontally and sits on four Viton pads. It is placed in a vacuum chamber with pressure below 10^{-7} mbar and the entire system is on a vibration-

isolation platform in an acoustical isolation box. About $2 \mu\text{W}$ of optical power, including $\sim 30\%$ in the phase modulation sidebands, are typically sent onto the cavity with a coupling efficiency better than 60% . A 350-kHz bandwidth locking is achieved using a double-pass acousto-optic modulator with a cat's eye retroreflector. The stabilized output of the laser can provide up to 10 mW of optical power.

To measure the laser frequency noise power spectral density, the two independent cavity stabilized lasers are mixed on a photodetector, and the down-converted beat-note signal is measured with a dynamic signal analyzer after frequency-to-voltage conversion. The phase noise power spectral density versus Fourier frequency is presented on Fig. 1. Excepted for some spurious peaks between 40 Hz and 100 Hz , it is largely below the phase noise of a 1-Hz linewidth white frequency noise laser (dashed line on Fig. 1). The integrated phase noise from 1 Hz to 10 kHz is below 0.2 rad rms (root mean square). The fractional frequency instability (Allan deviation) was also calculated from the frequency counted beat-note signal and is found less than 2×10^{-15} at 1 s and 10^{-14} at 100 s after a 0.3-Hz/s drift has been removed.

3. COMPENSATED LINK SETUP

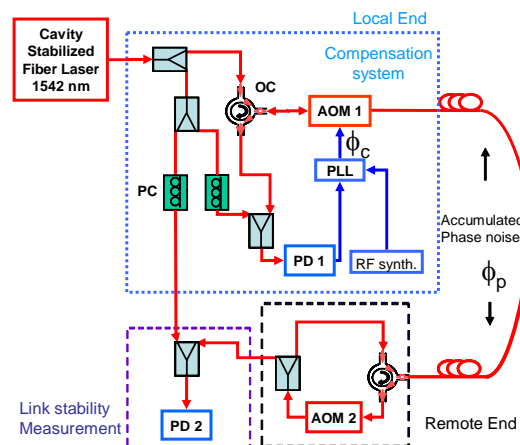


Fig. 2. Full scheme of the optical frequency transfer over fiber; AOM: acousto-optic modulator; PD: photodiode; PLL: phase locked loop; PC: polarization controller; OC: optical circulator; RF synth: Radio-frequency synthesizer.

Fig. 2 shows the scheme of the compensated link based on the principle first described in [17]. The ultra-stable laser light is divided into two parts using a fiber coupler. One arm provides the reference signal for stability measurement and fiber-induced phase noise compensation, while the other arm is connected to the link through an optical circulator (OC) followed by acousto-optic modulator AOM1 (with frequency f_1). To compensate for the phase noise ϕ_p accumulated along the fiber due to acoustical, mechanical and thermal perturbations, part of the signal at the remote end is retraced back to the link through an optical circulator, after frequency shifting by acousto-optic modulator AOM2 (with frequency f_2). This return signal, which passes twice through the link and experienced a phase noise $2\phi_p$, is mixed at the local end with the reference signal on photodiode PD1. The beat note at frequency $2f_1+f_2$ is phase locked to a stable RF synthesizer using AOM1 driven by a voltage controlled oscillator. The phase-lock loop applies the correction $\phi_c=-\phi_p$ to the AOM1 frequency f_1 , thus to the optical signal phase and consequently actively cancels the fiber-induced phase noise at the remote end of the fiber link. To magnify the dynamic range of the servo loop and hence improve its robustness, a digital frequency divider by 40 has been used just ahead of the phase detector. The frequency instability of the link is measured on the beat-note at frequency f_1+f_2 provided by mixing the single trip signal and the reference signal on photodiode PD2. Two polarization controllers are employed for optimizing the beat-note signal amplitudes. The compensation system is entirely fibered and uses only commercial off-the-shelf pigtailed telecommunications components.

4. TRANSMISSION OVER 86 KM

LPL and LNE-SYRTE, located in Paris area, are linked by a pair of 43-km telecommunication fibers. Each fiber is composed of various sections of buried cables of the metropolitan network spliced together. The attenuation of each fiber is about 12 dB. By connecting the two ends of the fibers at LPL, the link length is extended to 86 km with local end and remote end both located in LNE-SYRTE.

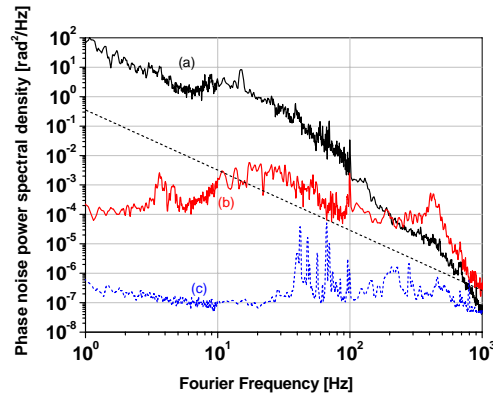


Fig. 3. Phase noise power spectral density versus Fourier frequency of the (a) free running, (b) compensated 86-km link and (c) delayed self-heterodyne beat note. Dashed line represents the phase noise of a 1-Hz linewidth laser.

Fig. 3 shows the 86-km link phase noise power spectral density versus Fourier frequency, without and with compensation. The beat note provided by PD2 is frequency divided by 40 and down mixed to DC, the phase noise power spectral density is then measured with a dynamic signal analyzer. It exhibits a roughly $1/f^2$ roll-off from 1 Hz to 100 Hz with a wide bump between 10 Hz and 100 Hz, and $1/f^4$ behavior above 100 Hz. The integrated phase noise from 1 Hz to 1 kHz is equal to 19.2 rad and 0.4 rad (rms), without and with compensation respectively (corresponding to 15 fs and 0.3 fs rms timing jitter). The phase noise of the transmitted laser is only slightly degraded by the transfer and the laser coherence time is therefore preserved at the output of the compensated link. This is an important point for applications requiring distribution of narrow linewidth sources.

Laser phase noise can corrupt the link-induced phase noise measurement. Indeed, on PD2 are mixed two optical signals coming from the same source but delayed by 430- μ s (due to the 86-km propagation in the fiber). This generates on the beat-note signal a delayed self-heterodyne interferometric phase noise [18] due to the laser phase noise, in addition to the link-induced phase noise to be compensated. This additional phase noise contribution can be calculated from the laser phase noise (shown on Fig. 1) and is displayed in Fig. 3 (c). It shows that the laser phase noise is sufficiently low and does not limit the performance of the stabilization.

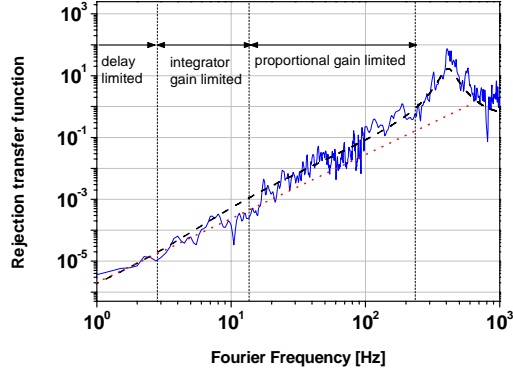


Fig. 4. Fiber noise rejection for 86-km link, experimental data (blue line) and analytical data with proportional gain equal to 2300 and integrator gain equal to 50 (black dashed line). Red dotted line represents the delay-induced rejection floor.

Fig. 4 displays the experimental fiber-induced phase noise rejection for the 86-km link versus Fourier frequency calculated by dividing the phase noise power spectral densities of the compensated and uncompensated links. We have performed the Laplace domain analysis of the compensation scheme and obtain an analytical expression of the rejection transfer function (black dashed line on Fig. 4) [19]. This analysis reveals that the optimum proportional gain is about the inverse of the link single trip time (2300 for an 86-km link) and that the rejection frequency bandwidth is limited to $1/4t_{\text{trip}}$ (~ 600 Hz) where t_{trip} is the one-way trip delay in agreement with [14]. Moreover, this analysis shows that the integrator used in the phase-lock loop improves rejection only in a limited frequency range. Indeed, as already pointed out in [14], at low frequency the rejection is limited by the link delay and scales as $(f \cdot t_{\text{trip}})^2$ (red dotted line on Fig. 4) independently of the loop gain. Our calculations are in good agreement with the measurements as shown on Fig. 4.

For long term frequency stability characterization, the Allan deviation is the most common tool and is typically obtained using frequency counter measurements. The original Allan deviation defined in [20] can only be calculated from frequency samples obtained with a classical, or “ π -type”, counter using a uniform average over the measurement gate time. Indeed, modern enhanced-

resolution, or “ Λ -type”, counters have been shown to lead [21], not to the classical Allan deviation, but to a quantity proportional to the modified Allan deviation [22]. Consequently, we measure the classical Allan deviation of the fractional frequency instability introduced by the link with a four-channel π -type frequency counter. This counter is dead-time free in order to avoid bias in the calculation of the Allan deviation [23]. We measure simultaneously the frequency instability of the compensated link and the frequency instability of the compensation signal (at the voltage controlled oscillator output), which represents the free running fiber frequency noise. The beat-note between the remote end and local end signals provided by PD2 is band limited by a tracking filter based on a low noise quartz oscillator giving a measurement bandwidth of ~ 10 Hz. This bandwidth is larger than the inverse of the gate time.

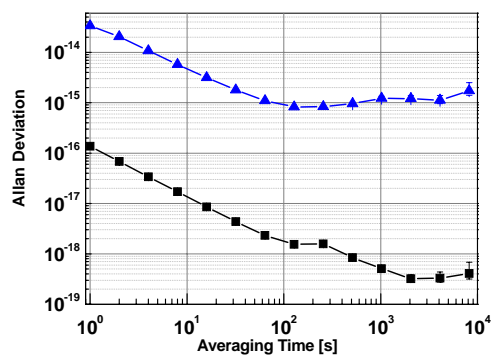


Fig.5. Fractional frequency instability of the 86-km free running link (blue triangle) and compensated link (black squares), versus averaging time. The measurement frequency bandwidth is 10 Hz.

Fig. 5 shows the fractional frequency overlapping Allan deviation of the 86-km link with and without compensation for several days of continuous operation. The Allan deviation scales down with a $1/\tau$ slope from 1 s to 100 s. The bump at 250 s, which corresponds to the half cycle time of the air conditioning system, is due to thermal effects in the sections of the interferometric system that are not actively compensated. After 1000s of averaging time, the Allan deviation levels off in the low 10^{-19} range probably also limited by the uncompensated section of the system. Without

filtering, the Allan deviation is 10 times higher. This is consistent with the fact that the Allan deviation of a white phase noise is proportional to the square root of the noise bandwidth.

5. TRANSMISSION OVER 172 KM

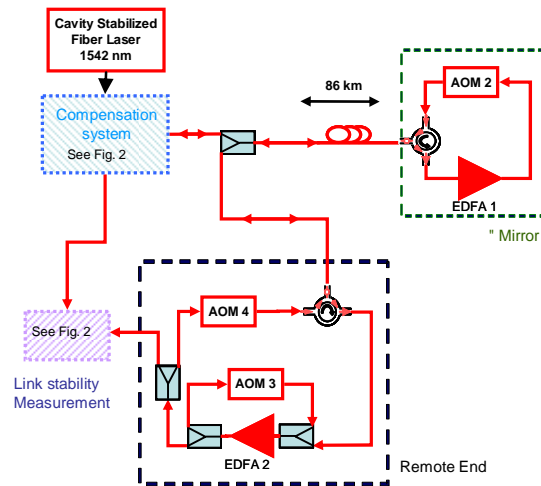


Fig. 6. Scheme of the 172-km link (EDFA : Erbium Doped Fiber Amplifiers, AOM, PD, see Fig.3.)

Previous extended link results have been demonstrated by adding spooled fiber to an urban link [13,14]. To simulate a longer link more realistically, we devised a new scheme, represented in Fig. 6, to pass twice through the 86-km link leading to a full urban link of 172 km. The optical signal is fed into the 86-km link through an optical coupler. At the end of the 86-km link, a “frequency shifter mirror” is connected. This “mirror” consists of a unidirectional loop based on an optical circulator and an acousto-optic modulator. An Erbium doped fiber amplifier (EDFA1) with 17-dB gain is also implemented in order to compensate for losses due to recirculation (12 dB due to the double pass combiner losses, 5 dB due to the optical circulator and AOM2 losses). As a result, this is equivalent to a 172-km span link without intermediate optical amplifier and the resulting phase noise is equivalent to the noise of a real 172-km telecom network link. A second optical amplifier (EDFA2) was added at the remote end to amplify the return signal. Temperature variations in EDFAs induce phase fluctuations, which degrade the long-term frequency stability. In order to

correctly compensate for this effect, the output optical signal should pass once through the EDFAs when the round trip signal should pass twice. This is naturally the case for EDFA1, but not for EDFA2. This is overcome by adding a recirculation loop around EDFA2. To easily identify the output and round trip signals AOM3 is inserted in this loop. At the output of PD1 the beat-note signal at frequency $2(f_1+f_2)+f_3+f_4$ is appropriate for link compensation while at the output of PD2 the beat-note signal at f_1+f_2 is used to derive the link stability (f_i is the frequency of the AOM i). This set-up could be simplified by using a bi-directional EDFA.

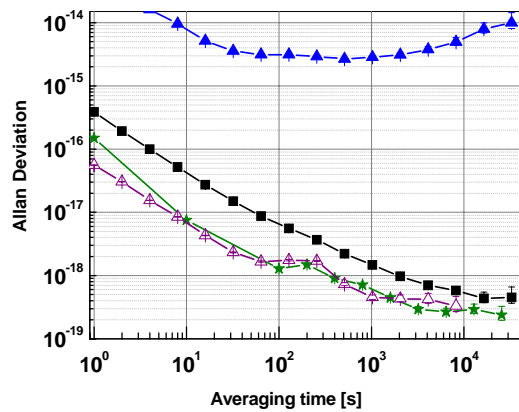


Fig. 7. Fractional frequency instability of the 172-km free running link (blue triangle), compensated link with 10-Hz measurement bandwidth (black squares), and with Λ -type counter (green stars). Empty triangles correspond to the experimental set-up floor (see text).

Fig. 7 shows the fractional frequency instability of the 172-km link. The Allan deviation is about 4×10^{-16} at 1 second and in the range of 10^{-19} at 1 hour with a 10-Hz measurement bandwidth. The system floor is measured by replacing the urban fiber with an optical attenuator having the equivalent attenuation.

In addition to data obtained with π -type counter we have used a Λ -type counter, without the 10-Hz filter, to allow comparison with the results of [14] obtained with 76 km of urban fiber, 175 km of spooled fiber and four in-line EDFA. To avoid dead-time, the gate time of the counter was set equal to the averaging time for averaging time ≤ 100 s. Data obtained with Λ -type counter are shown with green star points on Fig. 7. They are better than with π -type counter, due to an

additional filtering of the phase noise. The Allan deviation is calculated for every averaging time with the classical formula and not with the modified Allan deviation (as in reference [14] for averaging time >10 s). Indeed, when original Allan deviation formula is used, Λ -type counters report directly a quantity similar to the modified Allan deviation. For comparison, the use of the modified Allan deviation would lead in our case to a reduction factor of $2/3$ on the Allan deviation for averaging time above 100 s. For averaging time below 100 s, results are found similar to the data presented in [14]. Data obtained with longer averaging times show that frequency instability keeps falling off until 5000 s and reach 3×10^{-19} with the Λ -type counter at 3000 s.

6. CONCLUSION AND DISCUSSION

We have demonstrated a long-distance link for optical frequency transfer over a fiber installed in an urban environment. Frequency transfer was demonstrated with instability of 1.5×10^{-16} at 1 s and integrates down to the range of 10^{-19} at 500 s over 86 km. We have simulated a link at twice this distance via recirculation in the fiber to represent the phase noise of a 172-km urban link. It shows instability of 4×10^{-16} at 1 second and a few 10^{-19} at 10,000 seconds, which is below the anticipated performance of optical clocks.

Attenuation of longer link (> 200 dB for 1000 km) makes mandatory in-line bidirectional amplifiers in order to provide sufficient power at the output and allow phase locking at the local end.

For extension of the link to continental distance, attention must be paid to the delay effect. In a single segment configuration, for $1/f^2$ free-running fiber induced phase noise, Allan deviation scales as $t_{trip}^{3/2}$, due to the quadratic decrease of the rejection [14] and assuming a linear increase of the accumulated fiber induced phase noise power. This would lead to an Allan deviation of 6×10^{-15} at 1 second for a 1000-km single segment link in a 10-Hz measurement bandwidth. Alternatively long-distance link can be divided in a few shorter distance compensated links. This multiple segments approach allows to increase the correction bandwidth and enhance the resolution and the

reliability but with a significant increase of complexity. This alternative approach would allow to transfer the coherence of the laser itself.

A long-distance link of 1000 km connecting several German research laboratories has been set last year using dedicated fibers from the German research network (Deutsches Forschungsnetz). This is the first milestones towards a pan-European ultra-stable network for clocks comparisons. For a wider extension of such long-distance links, the challenge is to use the existing communication network. The research and education network, such as RENATER in France, can provide the infrastructure to link frequency metrology laboratories in Europe. The use of a non-dedicated fiber link network imposes to transfer the ultrastable signal on a dedicated channel in the standard telecommunication grid by wavelength division multiplexing. Although appealing, this solution raises a few difficult points. The optical telecommunication network operates in a unidirectional way, whereas the compensation needs a two-way approach. Moreover, the coexistence with standard internet traffic on the network imposes a flawless operation of the ultra-stable frequency transfer. We aim to implement this original approach in collaboration with the French research and education network RENATER.

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