

Ultra-stable long distance optical frequency distribution using the Internet fiber network and application to high-precision molecular spectroscopy.

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Abstract. We report an optical link of 540 km for ultrastable frequency distribution over the Internet fiber network. The phase-noise compensated link shows a fractional frequency instability in full bandwidth of 3×10^{-14} at one second measurement time and 2×10^{-18} at 30 000 s. This work is a significant step towards a sustainable wide area ultrastable optical frequency distribution and comparison network. Time transfer was demonstrated simultaneously on the same link and led to an absolute time accuracy (250 ps) and long-term timing stability (20 ps) which outperform the conventional satellite transfer methods by one order of magnitude. Current development addresses the question of multiple users distribution in the same metropolitan area. We demonstrate on-line extraction and first results show frequency stability at the same level as with conventional link. We also report an application to coherent frequency transfer to the mid-infrared. We demonstrate the frequency stabilisation of a mid-infrared laser to the near-infrared frequency reference transferred through the optical link. Fractional stability better than 4×10^{-14} at 1 s averaging time was obtained, opening the way to ultrahigh resolution spectroscopy of molecular rovibrational transitions.

1. The challenge of ultrastable frequency dissemination

Frequency metrology has developed considerably over the past ten years and has benefited from scientific advances in the areas of atom laser cooling and frequency comparison with femtosecond laser combs. Today cold atom microwave frequency standards reach routinely a fractional accuracy in the low 10^{-16} and trapped ion or neutral lattice optical clocks have already demonstrated uncertainty of parts in the 10^{17} or better (see for instance [1-5]). This outstanding performance makes them ideal tools for fundamental physics tests of the validity of general relativity on earth and in space. Among them, the comparison of different types of clocks is used to detect possible variations in time of



universal constants of physics. More generally, accurate frequency transfer is essential for the underpinning of the uncertainty of almost every type of precision measurement.

Until recently the conventional means for remote frequency transfer was based on the processing of satellite radio-frequency signals, the Global Navigation Satellite System, or dedicated satellite transfer. Optical fiber links have brought the potential to transfer frequency with much better accuracy and stability thanks to an active compensation of the phase noise added by the fluctuations of the optical length. Direct optical frequency transfer has been developed in order to take full advantage of the optical fiber medium. The link-induced phase noise can indeed be detected with much higher resolution than with a microwave signal frequency and heterodyne detection enables to minimize the effect of link attenuation. In the last five years several experiments all around the world have explored the limits of this method, paving the way to ultrastable optical networks of new generation [6-11]. The latest achievement is an outstanding phase-stabilized 920 km fiber link connecting two German laboratories [10]. A key-question is the capability to extend ultra-stable frequency standard distribution to a larger scale and possibly to any users. In the last four years we have demonstrated optical links using commercial telecommunication fiber networks thanks to wavelength division multiplexing [11-13]. Switching from a dedicated to a public fiber network with data traffic is a major breakthrough for a possible generalization of the concept of optical fiber link frequency distribution. In this paper we demonstrate a robust long distance 540-km phase-stabilized optical link over public telecommunication network for the dissemination of ultra-stable frequency around 1.55 μm . We show that this link can simultaneously be used to transfer accurate timing signal. Then we discuss possible architecture of metropolitan signal distribution and give first results of on-line extraction. We finally show an application of such an optical link to coherent frequency transfer to the mid-Infrared for high resolution molecular spectroscopy.

2. Optical link over public network

We first give the basic principle of an optical link. The frequency reference is an ultra-stable laser emitting around 1.55 μm , which is feeding the optical fiber and transferred to the remote lab. Since the propagation is disturbed by phase noise, due to the thermal and acoustical instabilities of the optical length of the fiber, a correction loop is implemented using the so-called round-trip method. Part of the transferred signal is sent back to local lab and the return signal is compared with the local reference signal to get the instability of the link: the phase difference gives the error signal for the correction loop. Noise compensation is usually applied to an acousto-optic modulator (AOM). The performance of such a link is evaluated by measuring the end-to-end beatnote, which is possible only when the local and remote ends are at the same place. Thus we will show below optical links made of two parallel fibers.

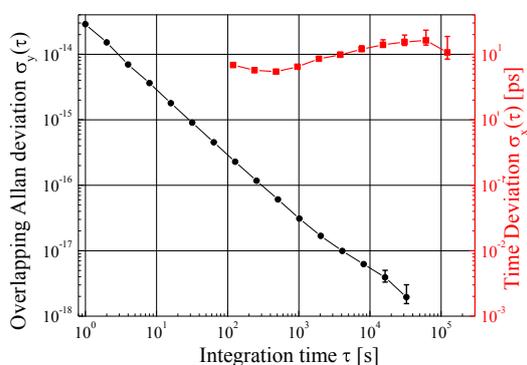


Figure 1. Time (red squares) and frequency (black circles) stability for a 540-km optical link over public network

A multiplexed optical link uses this noise compensation on installed telecommunication fibers [11-13]. The ultrastable frequency reference and the Internet traffic propagate simultaneously in the same fiber but on different frequency channels. Hence, instead of using a dark fiber, we are using a dark channel of existing fibers, thus dramatically reducing the need and cost of fiber infrastructures.

The key point to understand the architecture of a multiplexed optical link is to keep in mind that stable optical signal distribution requires a full bidirectional operation: the optical signal must circulate back and forth on the same fiber for noise compensation. This means that in a single fiber there are two counter-propagating optical

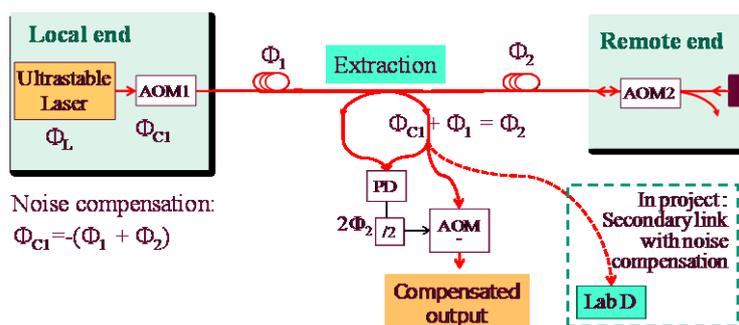
signals whereas standard telecommunication technique enables only one way propagation. Therefore, each telecommunication equipment, such as amplifier or repeater, must be bypassed by the ultrastable signal. For that purpose, we use bidirectional optical add-drop multiplexers (OADM). Such three-port component can insert or extract a specified wavelength from the other wavelengths, with a very good isolation and low losses.

With this technique we demonstrated an optical link of 540-km from LPL to Reims and back to LPL [11], using the fiber network of the French national network for education and research RENATER. This link is composed of different fiber spans and includes 450-km with data traffic on neighbor frequency channels, 0.8 nm and 1.6 nm away from the ultrastable signal frequency. Sixteen OADM are necessary to insert and extract the ultrastable signal from the Internet fibers. We used six bidirectional Erbium-doped fiber amplifiers (EDFA), with a total amplification of about 100 dB, to partly compensate the total end-to-end attenuation of 165 dB due to fiber losses, OADMs and the large number of connectors. Attenuation cannot be compensated due to the parasitic reflections along the link which prevent to increase the gain of bidirectional amplifiers in order to avoid oscillations.

Figure 1 shows the fractional frequency instability (overlapping Allan deviation, black circles) of the 540 km link, measured with a Π -type frequency counter. The Allan deviation is 3×10^{-14} at 1 s averaging time and scales down as $1/\tau$ from 1 s to 30 000 s reaching about 2×10^{-18} . With a measurement bandwidth of 10 Hz, the Allan deviation is about 8 times smaller and reaches 5×10^{-15} at 1 s and 3×10^{-19} at 30 000 s [10]. Moreover the average frequency offset between input and output frequency is 6×10^{-20} compatible with statistical error bars of 3×10^{-19} . This stability is similar to the one obtained with the 920-km German optical link [10], that exhibits a fractional instability (overlapping Allan deviation, Π -data) of 4×10^{-14} at 1 s reaching 5×10^{-18} at 10^4 s. With Λ -data and calculating modified Allan deviation, this stability reaches 5×10^{-15} at 1 s and 10^{-18} in less than 10^3 s.

For many applications, concerning for instance high resolution radio-astronomy and particle physics, frequency transfer is not sufficient and accurate timing is required to precisely synchronize distant experiments. Time transfer consists in comparing the epochs of two distant clocks and not only their frequencies. It demands an accurate calibration of the propagation delay. Using the same 540-km optical link we have demonstrated two-way time transfer [14] simultaneously to the frequency transfer [15]. The ultra-stable laser is carrying both the frequency and timing signals through the fiber. Timestamps signals are consisting in spread spectrum pseudorandom modulation codes and are provided by a pair of two-way satellite time transfer modems, one for each direction. They are encoded on the optical carrier by electro-optic phase modulators. The timing stability (red squares) is below 20 ps for integration time up to 10^5 s (see Figure 1). The time delay variation remains below 50 ps when the fiber length is scaled from 10 m up to 540 km. This method is very robust, with an overall conservative timing error of about 250 ps determined by the measured time delay over several weeks of measurement. These results outperform the satellite techniques by one order of magnitude. They are easily scalable to a wide area network and open the way to a novel approach of precise remote synchronization with the potential to realize even better accuracy.

3. On-line-extraction



The extension of the ultrastable frequency signal dissemination to a large number of laboratories asks the question of the network architecture. For long-distance transfer, cascaded optical links have already been proposed and demonstrated [7, 13]. Here we address the question of multiple users distribution. In

Figure 2. On-line extraction scheme on a main compensated link.
 AOM : acousto-optic modulator, PD : photodiode

that case, a point-to point network needs a lot of fibers and is not the optimum solution. On-line extraction, as first proposed three years ago by G. Grosche [16], enables a more flexible distribution: the signal is extracted from the main link and either directly distributed to a lab or fed to another secondary link. Figure 2 displays a schematic scheme of the link architecture. The noise compensation of the main link leads to an overcorrection at the extraction point. In order to compensate this overcorrection, both extracted signals are recombined to get the relative phase. After division by two, this signal is driven an AOM in order to correct for the over-noise. With that scheme, the phase noise due to the main link is compensated.

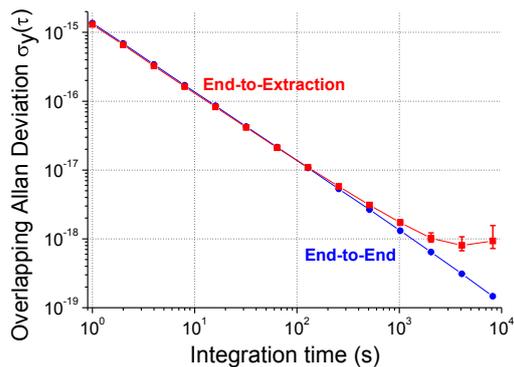


Figure 3. Fractional frequency stability for a 92-km link on dedicated fibers (blue circles) with noise compensation, and for on-line extraction after 86-km (red squares).

This set-up has been tested on an optical link of 92-km dedicated fiber from the telecommunication network in the Parisian metropolitan area. Both ends are at LNE-SYRTE, together with the extraction, which occurred after 86-km of the main link. Figure 3 displays the end-to-end frequency stability of the main link (blue circles) with noise compensation. On the same graph is given the extracted signal stability (red squares), which is the stability of the beatnote between the extracted signal and the local signal. It is below 2×10^{-18} at 10^3 s integration time thus providing the stability performance at the same level than with a simple link. However the stability degrades around 10^3 s due to temperature fluctuations

of the extraction set-up. There are indeed still some uncompensated sections of fiber at the extraction end, mainly between the AOM and the user.

To improve the noise compensation, we are now implementing an upgraded extraction scheme. A short secondary link is implemented just after the extraction. Its noise compensation is added to the previous compensation in order to compensate both the noise of the main link and the local noise. This will give the possibility to distribute an ultrastable signal in a wide metropolitan area.

4. Coherent frequency transfer to the mid-infrared

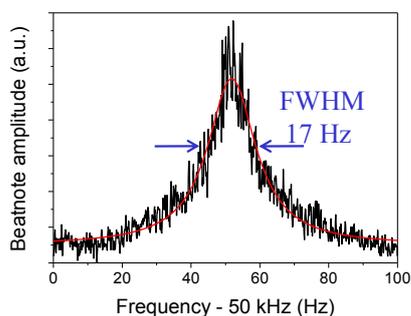


Figure 4. Down-converted beatnote of two independent CO₂ lasers, one stabilised on an OsO₄ resonance line, the other phase-locked to a comb repetition rate high-harmonic; red line is a Lorentzian fit of linewidth 17 Hz

10 μ m and obtained a linewidth below 17 Hz (see Figure 4), at the state-of-the art. Stability below

4×10^{-14} at 1 s was demonstrated, and we expect it to be in the 10^{-15} range, at the level of the near-infrared frequency reference [20]. The 3×10^{-16} accuracy of the LNE-SYRTE Cs fountains is potentially within reach. Tunability is also possible by scanning the near-infrared frequency referencing the comb. Extension to Quantum Cascade Laser frequency stabilization is under progress. Such a stabilized laser gives the possibility to perform ultra-high resolution spectroscopy of molecules and test fundamental symmetries such as parity [21].

5. Perspectives

To conclude, we have established an optical link of 540-km which uses an optical telecommunication network simultaneously carrying Internet data. We demonstrate joint frequency and time transfer over this link with frequency instability integrating down to 2×10^{-19} after 30000 s. This result is a first step towards an extension of the fiber network in France and Europe using several cascade optical links connected by stations.

These development opens the way to very fascinating applications of optical links. Transcontinental optical links will give the opportunity to compare the best primary and optical clocks in different countries. We plan also to take advantage of fiber links to evaluate the performance of satellite links, such as the microwave link of the ACES space mission. At LPL, we are currently taking advantage of the ultrastable frequency transfer to test fundamental symmetries with high resolution spectroscopy of molecules. Finally optical links open the way to numerous new high precision experiments, as for instance ultra-precise atomic and molecular spectroscopy, measurement of fundamental constants or fundamental tests of physics like the search for space-time variations of fundamental constants. And the number of these applications will grow with the extension of the fiber network.

Acknowledgments

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