A 650 km-Long Optical Fiber Link For Accurate Time and Frequency Metrology

OPTICAL FIBER LINKS FOR ACCURATE TIME AND FREQUENCY METROLOGY

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We report on the status of a new activity towards the realization of the first Italian optical fiber link between the twoinstitutes: Istituto Nazionale di Ricerca Metrologica (INRIM) and University of Firenze (UNIFI). This link will be used to perform remote comparisons between newly developed optical atomic clocks developed in both institutes with resolution better than one part in 10^{18} allowing also for fundamental physics studies.

1. Introduction

Recently, thanks to the advances in the field of quantum optics, the research in the field of atom optics and time & frequency metrology has done a dramatic step forward. Modern techniques of Doppler cooling of atoms with laser radiation, techniques for laser frequency stabilization and the realization of optical frequency synthesizers ("optical frequency combs") give the possibility to perform spectroscopy of optical electronic transition of atoms and single ions (with frequencies of about 10^{14}-10^{15} Hz) at sub-Hz level.
The first optical clocks based on forbidden transitions of alkali-earth atoms and single ions have been realized and the first comparisons among them have already shown the possibility to have relative frequency accuracies at the level of parts in 10^{16} (atoms) – 10^{17} (ions), that is as accurate or even beyond and even beyond of the current primary standards based on a microwave transition of Cs atoms (parts in 10^{16}). The interest for research in this field is related to the tremendous resolution (at this moment 10^{-17}) offered by these systems in measurements of optical frequency ratios of atomic transitions. Other than the general interest in the redefinition of unit of time in the international System (SI) of measurements units, these clocks give the possibility to perform a number of tests of fundamental physics theories at an unprecedented level. Tests of General Relativity can be done for example through measurements of gravitational red-shifts by comparing two clocks in different gravitational potentials or through comparisons between clocks based on optical transitions of different atoms in time; comparisons that could reveal a local tiny dependence on time of fundamental constants of physics, (i.e. the fine structure constant). For these potential applications in fundamental research but also for applications in global satellite positioning systems (GPS, GALILEO) or for deep-Space ranging applications, recently the realization of these systems have also started to attract the attention of Space agencies in Europe (ESA) and in Italy (ASI).
The experimental study of performances and possible future applications needs a first characterization of the frequency stability and accuracy of these new optical frequency

standards. This means that a first comparison with primary Cs microwave standards is requested together with a comparison in the optical domain with other optical frequency standards. To meet this request it is necessary to develop advanced technology that allows remote frequency comparisons at high stability of both microwave and optical standards. Among all the systems known for this task, the best candidate is a technique based on the transfer of an optical carrier (phase locked on the reference atomic clock signal) in phase noise compensated optical fibers (“optical fiber link”).

2. Optical fiber links

During last years, reliability and performances of optical links have been demonstrated over hauls of several hundreds kilometres, allowing remote frequency comparisons with a resolution better than 10^{-19} over few thousands seconds [1,2]. Efforts are being made to realize an optical fiber network that would connect the main European NMIs and research labs. The Italian Institute of Metrology in Torino-INRIM and the European Laboratory for Non Linear Spectroscopy-LENS together with the University of Firenze -UNIFI started a two-year joint project to set up an optical fiber link between them. Both institutes are developing optical clocks: INRIM has two primary Cs atomic fountains and is developing a Yb optical clock, whereas UNIFI has realized a Sr optical clock and is involved in high resolution spectroscopy measurements as well. The forthcoming link will allow remote comparisons between the atomic clocks of the two institutes and an accurate calibration of the UNIFI Sr clock. The outcome of this collaboration will contribute to the study of new frequency standards in the optical domain and of new methods for time and frequency transfer through optical fiber.

The optical link INRIM-UNIFI will use already existing optical fibers to disseminate the optical carrier of an ultra-stable 1542 nm laser. The laser is a laboratory prototype present at INRIM, with a 1 Hz linewidth and a frequency instability as low as few parts in 10^{-15}. At INRIM, the 1542 nm laser frequency is directly measured by use of an optical comb with respect to the INRIM clock ensemble. At UNIFI, the 1542 laser carried by the 450 km optical fiber is compared to a 698 nm ultra-stable laser that is the local oscillator for a Sr optical clock, by use of a second optical comb. In this way, the Sr optical clock is directly compared with INRIM clock ensemble and in particular with the italian realization of the SI second for an absolute measurement of the Sr clock transition at the highest accuracy.

To ensure a good comparison, the 1542 nm ultra-stable laser frequency should not be perturbed by the phase noise added by environmental perturbations along the optical fiber haul. The fiber phase noise is compensated in real time implementing a Doppler noise cancellation technique. This consists of a two-way scheme, where a part of the 1542 nm laser radiation, once at UNIFI laboratory, is reflected back to INRIM. The reciprocal path, along the same fiber, allows to detect the phase noise added by the fiber and to correct that using an Acousto-optic modulator.

To complete the optical link, some amplification stages are required along the fiber haul to compensate for attenuation. Each amplification stage (at least two stages are necessary for the INRIM-UNIFI link, but a conservative approach should suggest about one amplification station each 80-100 km) is composed by a two-way Erbium Doped Fiber Amplifier, with remote GSM control.

3. Sr optical lattice clock at LENS-UNIFI

The optical lattice clock built at UNIFI is the first new generation optical clock realized in Italy [3]. This experiment has also been the first one to realize a magneto-optical trap of multiple isotopes of Sr [4,5]. Moreover, one of the first absolute frequency measurement of the intercobination optical transition $^1S_0$-$^3P_1$ in ^{88}Sr and ^{86}Sr isotopes was performed at LENS with the early use of an optical frequency synthesizer [6].

At UNIFI, the spectroscopy on the clock transition at 698 nm has been done on ^{88}Sr atoms by preparing the atomic sample in Lamb-Dicke regime into a light-shift free 1D optical lattice and by employing a static magnetic field to induce the transition [3]. Best resolution achieved is 70 Hz which corresponds to atomic line Q~10^{13}. To deliver the clock laser from the clock laser laboratory to the atomic trap, a 200 m noise compensated fiber link has been used. The short-term frequency stability of this standard is $3*10^{-15}$ at 1 s (tested with a second high finesse optical cavity as a frequency discriminator). The accuracy of this Sr optical lattice clock is currently under evaluation by accurate measurements of all the shifts on the atomic frequency due to external magnetic and electric fields [7]. Moreover, a preliminary estimation of the collisional rate have been evaluated and the experimental study of the effect of collisions on the clock frequency is undergoing [7]. In view of the necessary comparison of this standard with other optical or microwave standard, we have also realized an home built octave spanning optical frequency comb based on a femtosecond Ti:Sapphire laser with a repetition rate of 300 MHz. The two comb free parameters (the offset frequency and repetition rate) have been phase-locked to the 698 nm optical standard at sub-mHz level. In this way the stability of the optical standard has been transferred to each comb teeth spanning in the optical domain from 500 nm to 1 micron. First comparisons of optical standard with respect to the RF standard (quartz oscillator disciplnated to the GPS signal) have shown the instability limit of the RF standard at the level of 10^{-12}

4. Atomic clocks development at INRIM

At INRIM several atomic clocks are continuously operated (like the ITCsF1 Cs laser cooled fountains and a set of three hydrogen masers) while a second cryogenic Cs fountain is now ready to be operated and a Yb optical lattice clock is under development. ITCsF1 is the first primary atomic frequency standard developed in Italy and realizes the definition of the unit of time in the International System of Units at the accuracy level of $5*10^{-16}$ [8]. Up to now, IT-CSF1 has reported to BIPM 23 formal accuracy evaluations (key comparisons) of the International Atomic Timescale (TAI): it has been the first time for the Italian Metrological Institute to give contribution to the realization of the international unit of time at the highest level [9]. Moreover, ITCsF1 has originally contributed to the improvement of the scientific and metrological knowledge, with experiments for the measurement of the Cs sensitivity coefficient to the blackbody radiation, or the study of the role of spurious microwave leakages in primary atomic standards. ITCsF1 and ITCsF2 are Cs fountain frequency standards, then based on the use of ^{133}Cs atoms laser cooled down to 1µK. To improve the accuracy, INRIM has realized a cryogenic fountain, ITCsF2, which structure is maintained at a temperature of about 90 K to reduce the effect of blackbody radiation on the accuracy, one of the main actual limits on fountains. ITCsF2 has an accuracy target of 10^{-16}. INRIM moreover realized and tested the coherent laser source at 1542 nm and the phase noise compensation system [10] that will be used in the link. The optical source is a commercial laser, frequency stabilized on a Fabry-Pérot cavity through the Pound-Drever-Hall technique down to the 10^{-14} level at 1 s, limited by the residual mechanical and temperature noise on the cavity. Preliminary experiments over a 100 km optical link based on fiber spools achieved a fractional frequency instability of 10^{-19} at 1000 s.

Finally, at INRIM it exist an ongoing activity towards the development of an optical lattice clock based on narrow optical transition of neutral Yb atoms [11].

4. Application to fundamental physics and future prospective

The interest in the realization of frequency standards with better short term frequency stability and better accuracy and the development of tool for the dissemination of their ultra-stable signal is manifold. Comparisons between optical frequency standards at 10^{-17} can be important for today's comprehension of fundamental physical theories like General Relativity, or String theory through local tests of time variations of fundamental constants. There is a number of interesting tests to be performed with optical clock comparisons: gravitational redshift tests, test of constancy in time of fine structure constant, test of Lorenz local position invariance and test of couplings of fundamental constants to gravitational fields.

Moreover new optical frequency standards can represent essential tools for all the applications where accurate frequency standards are actually employed. In particular all the applications of satellite positioning and remote ranging in deep Space that are using frequency standards with $>10^{-14}$ uncertainties (hydrogen masers, Cs beam clocks) could improve their performances using new optical standards. In all these applications the huge gain in short-term stability given by optical frequency standards (10^{-15} for 1s integration time) with respect to microwave standards ($>10^{-13}$ at 1s) could give the possibility to precisely measure the position of a remote object in a reduced measurement time interval.

Moreover applications of this new technology are expected in the field of radio-astronomy research and universe observation though VLBI techniques, for which, time syncronization at the highest level of Deep-Space antennas is usually requested.

More recently, experiments in high energy physics revealed the need of high accuracy time and frequency transfer over long distances (see for example the neutrino speed measurement between LNGS and CERN), to which the optical fiber link technology proposed here might represent a way to independently perform a valuable test of neutrino speed even at higher resolution and might be the right tool for further tests on its dependence on other parameter (e.g. energy, spin, etc..).

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