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High Precision Physics using an Optical Fibre Link and Optical Frequency Combs

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SPECTRAL PURITY TRANSFER AT THE 10^{-18} LEVEL

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Ultra-stable lasers are often built at wavelengths where components and spectrally pre-narrowed lasers are available, such as 1064 nm or the telecom C-Band (1530-1565 nm). To apply their stability to optical clocks, it is then necessary to transfer their spectral purity to target metrological wavelengths, such as 698 nm (^{87}Sr) and 1062 nm (^{199}Hg, after frequency quadrupling) in the case of LNE-SYRTE. Lasers with a frequency floor at 1×10^{-17} have been reported [1], which opens the perspective of clock stabilities better than $1 \times 10^{-16}/\sqrt{\tau[\mathrm{s}]}$. Therefore it is all the more important to ensure that laser spectral purities can be transferred with a noise at most in the 10^{-18} range, and with no loss of reliability.

We have assembled two single branch setups based on an Erbium-doped fiber frequency comb. Beatnotes between a single optical amplifier (Erbium-Doped Fiber Amplifier, EDFA) and 3 ultra-stable lasers (1062 nm, 1160 nm and 1542 nm) are formed on the one hand, and between a second EDFA and two ultra-stable lasers (698 nm and 1542 nm) on the other hand. The beatnotes are all formed in free space, uncompensated paths are reduced to a few centimeters, with the possibility of being put under vacuum if necessary.

We will use the transfer oscillator method [2] to carry out the transfer which performance will be assess on a second Erbium-doped fiber frequency comb (where we have duplicated this double single-branch setup). Preliminary results show an out-of-loop instability of 8×10^{-18} at 1s when transferring from 1542 nm to 1062 nm (combination of the contribution of the two combs).

We will present and discuss the results between the various combinations of wavelengths, describe the impact of the various sources of noise, notably the uncompensated paths, the imperfect mode-matching of the beams and the limit imposed by finite signal-to-noise ratios. Finally the results will be compared to the multi-branch (free space as well) and single-branch (fibered version) obtained previously at LNE-SYRTE [3].

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LASER INFRARED SPECTROSCOPY FOR TRACE HYDROCARBON MEASUREMENT

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Compositional analysis of hydrocarbon gas, such as fuel gas quality monitoring or energy content measurement, is of prime importance for various applications in the oil and gas industries. These analyses are also widely used within the hydrocarbon refining industry for process monitoring. In the oil and gas exploration industry, the evaluation of light hydrocarbons enables geologists to characterize reservoir fluid composition while drilling. The prevalent instrumentation technology used to-date is gas chromatography (GC) combined with flame ionization detector (FID). Gas chromatography has a large dynamic range; however, it requires a hydrogen gas supply (i.e. flammable gas), regular maintenance, and frequent calibrations.

In contrast to GC analysis, gas sensors based on mid-infrared optical absorption spectroscopy (3–12 micrometers), enables minimal drift, improved calibration lifetime, and a low level of maintenance. Furthermore, optical infrared sensing allows a fast response time, which brings a better gas measurement resolution by reducing the industry standard GC cycle time from minutes to a few seconds. Recent improvement in miniaturization of infrared components enables the development of compact infrared analyzers inside an explosion-proof case. This analyzer can be deployed as a standalone sensor at a drilling site close to the extraction point.

In this work, we assess the performance of a mid-infrared dual-gas sensor for methane (CH4) and ethane (C2H6) detection developed using a continuous-wave, thermoelectrically cooled, distributed feedback interband cascade laser and a compact Herriott-type multipass gas cell. The performance of the sensor is evaluated using multiple hydrocarbon gas mixtures and two different techniques based on the tunable interband cascade laser: direct absorption spectroscopy (DAS) and second-harmonic wavelength modulation spectroscopy (2f-WMS).

CLONETS - Strategy and Innovation for High Performance Time and Frequency Services over Optical Fibre Networks

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CLONETS (Clock Network Services) [1] is a European funded project, which strives for the creation of a sustainable, pan-European optical fibre-based network providing high-performance time and frequency (T&F) services to Research infrastructures as well as support to a wide range of industrial and societal applications. The project is motivated by recent progress in T&F metrology and the increasing number of applications, which either are in demand for more accurate and stable T&F reference signals than are currently available through satellite techniques, or cannot rely on broadcasted signals due to, for example, security concerns or reception issues. Additionally, the development of high performance T&F dissemination techniques using optical fibre networks has led to a rich range of possibilities for optically connecting national metrology institutes (NMIs) and laboratories in and across Europe.

Optical fibre links have shown excellent performances in transmitting T&F signals on the continental scale. Consequently, they have not only become essential for comparing remote state-of-the-art optical clocks, but also a promising alternative for distributing ultra-stable and accurate T&F reference signals with applications in a wide range of fields including quantum metrology, tests of fundamental physics, atomic and molecular high-resolution spectroscopy, radio astronomy and geodesy. Such high-performance applications often rely on the availability of fibre links between dedicated sites. While some links have been established and are being operated in Europe, they are not yet interconnected.

CLONETS brings together expertise from NMIs, research laboratories, research and education networks (NRENs) and innovative high-technology small and medium enterprises (SMEs) towards creating a unified and sustainable vision of a European optical fibre network providing clock services. We are particularly interested in making contact with potential users of the CLONETS services, and potential partners in developing an optical-fibre infrastructure for specific research applications. In this presentation, we will report on the most recent progress of the project.

[1] www.clonets.eu

System study of heterodyne detection for long baseline infrared interferometry

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Astronomical interferometry has proved to be an extremely powerful tool in order to reach the highest angular resolution, in particular in the near and mid-infrared domain. Its extension to longer baselines and a higher number of telescopes is of major interest for astrophysics, but is still an extremely difficult challenge to be solved, which is addressed in the international collaboration *Planet Formation Imager*[1]. In this context, heterodyne detection has been proposed as a possible detection scheme. Contrarily to direct, Michelson recombination, heterodyne detection - routinely used in radioastronomy - makes the use of a local oscillator (laser in optical domain) to down-convert the incoming astrophysical signal in the RF domain at the level of each telescope, and correlate it electronically. Pioneering work of maser inventor and Nobel Prize C.H. Townes has shown the feasibility of this concept in the mid-infrared ($10\mu m$) on the *Infrared Spatial Interferometer* (ISI, [2]) in the 90s. Although it was the first astronomical interferometer in the mid-infrared domain, such a detection scheme - in this form - is limited to bright astrophysical objects because of its intrinsic quantum noise [3,4].

Here, we will present a signal-to-noise and system study on the use of heterodyne interferometry in the near- and mid-infrared, the relative advantages and drawbacks of such a detection scheme compared to direct interferometry, and the potential tipping point with the emergence of frequency combs. More specifically, two key concerns are : 1) the maximisation of the detection bandwidth with fast detectors and the use, at the level of each telescopes, of multiple local oscillators (frequency-combs) [5,6] to multiply the number of spectral channels and overcome the lack of sensitivity of heterodyne detection 2) the distribution of phase-locked local oscillators between multiple telescopes separated by kilometric baselines with a high stability [7]. Finally, we will open on the short time-scales experiments it could motivate, and their recent start at Institut de Planétologie et d'Astrophysique de Grenoble (IPAG) and Laboratoire Interdisciplinaire de Physique (LIPhy).

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Optical Frequency Standard Dissemination with the REFIMEVE+ project: a tool at hand for ultra-stable and accurate measurements

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Coherent optical fiber links were established over ranges of 1000s of km, enabling unprecedented resolution for clocks comparisons. By opening a new era of optical metrology, coherent optical fiber links also create opportunities for a wide area of application for precise measurements in physical laboratories. To that aim, our groups have explored several dissemination techniques and the way to combine them to improve their reliability in terms of uptime and cycle-slip free operation [1-3].

The REFIMEVE+ project aims to build a wide scale fiber network in France, highly reliable and robust, capable at the same time of comparing the best optical clocks and of disseminating an optical frequency standard to about 20 research laboratories. The long term access to the fiber network and its global supervision is organized through a strong partnership with RENATER, the French network for Education and Research. The deployment, the operation and the maintenance of the network is prepared with a knowledge transfer to industrial partners.

At the conference, we will report on the techniques we developed to move from a point-to-point architecture to an efficient metrological network. We will show that the network performances fulfill the need of clocks comparisons, while disseminating efficiently ultra-stable frequency standard to a large number of end-user laboratories. We will give a focus on a generalization of the repeater laser station (RLS) [4], based on an ultra-low sensitivity multi-branch Michelson interferometer. This Super-RLS enables us to feed five links at once and acts as a metrological node. We will report on the performances of several branches of our optical metrology network over a time period as typically few months [5].

Finally we will present future perspectives, in the frame of the knowledge transfer we organize to SME, so that the equipment and their operation can be commercially available, and made these technologies available to any interested parties.

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Photon-recoil assisted rovibrational spectroscopy of the ^{24}MgH^{+} ion

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Precision spectroscopy of molecules promises a wealth of interesting applications e.g. for better determination of natural constants, for tests of fundamental particle theories, and for qubit realizations. Unfortunately, most molecules do not possess closed transitions for laser cooling, crucial for obtaining temperatures low enough for exploiting these systems. A way to circumvent this issue is to work with a trapped molecular ion, and sympathetically cool its translational degrees of freedom by Coulomb interaction with a co-trapped atomic ion possessing suitable transitions for laser cooling. Doppler laser cooling will lead to the formation of a two-ion Coulomb crystal, which can then be prepared in the ground state of motion via the sideband cooling technique. Having prepared this system, it is possible to detect a change of the internal state of the molecular ion by monitoring the common motional state on the cooling ion, a technique called quantum logic spectroscopy (QLS) first proposed by Schmidt et al. [1]. In our group, an extension of QLS called photon-recoil spectroscopy (PRS) [2], where the target ion absorbs more than one photon, is used. So far we have successfully performed PRS of a dipolar transition in the atomic ion ^{24}Mg^{+} of 280 nm, to verify that the technique works. The light-ion interaction has been modeled by rate equations, and my simulations are in good agreement with our experimental results [3]. The next goal is to perform PRS on the closed rovibrational transition $|v=0, J=1\rangle \leftrightarrow |v=1, J=0\rangle$ in ^{24}MgH^{+} of 6.17 μm, to show the applicability to transitions resulting in very low photon recoil. We have so far modeled this system and produced simulated spectra as guidelines for the ongoing experiments. The ultimate goal is to drive purely rotational transitions in ^{24}MgH^{+}, with energy splittings in the THz range, resulting in photon recoil too low for detection by PRS. The solution is to drive Raman transitions with counter-propagating laser beams, since the effective k-vector is then given by the difference of the two k-vectors driving the transition: $\vec{k}_{Raman} = \vec{k}_1 - \vec{k}_2 \approx 2\vec{k}_1$. The ideal choice of laser for this is a femtosecond frequency comb for two reasons: 1) $\vec{k}_{Raman}$ can be made up of any two k-vectors with the right frequency difference, hence the different teeth of the comb can all work in pairs to drive the transition, and the full power of the comb is exploited. 2) The frequency difference between the teeth is easily changed by tuning the repetition rate, making the comb extremely versatile: Any transition within the spectral bandwidth of the frequency comb ($\sim$ 8 THz) can be driven. Frequency comb driven Raman transitions of 1.8 THz between D-finestructure levels in ^{40}Ca^{+} has recently been demonstrated in our group [4], laying a strong foundation for the future ^{24}MgH^{+} experiments.

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Power stabilization of a laser diode with an acousto-optic modulator in a compact setup for a compact cesium clock

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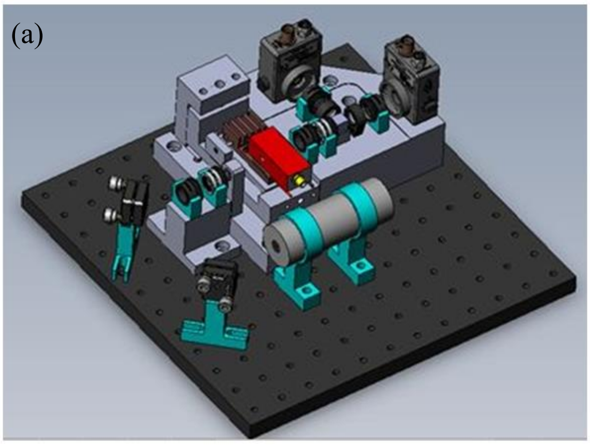
As many other applications, atomic clocks require very stable laser power: low frequency variations of laser power degrade long-term stability [1] and high frequency fluctuations degrade the clock signal-to-noise ratio. Several methods enable improving the stability, e. g. optical isolation of the laser source, feedback loop on the laser gain (temperature or pumping power), and feedback loop on external losses generated with an electro-optic modulator or with an acousto-optic modulator (AOM). Laser power stabilization with an AOM was applied to monomode extended-cavity diode lasers (ECDL) on a cesium clock setup based on Coherent Population Trapping (CPT) where very good performance was demonstrated in the band 1 Hz – 1 MHz [2]. Recently, a compact and portable bench has been designed (Fig. a) to apply this stabilization technique to a dual-frequency dual-polarization Vertical External Cavity Surface Emitting Laser (VECSEL) developed for an industrial CPT clock (ANR project CHoCoLa). Here we report the first performance characterization of the ECDL power stabilization in a compact bench. The performances stand comparison with a similar ECDL stabilized with an operating Cs CPT clock bench[3], and show only small degradation after transport of the compact bench (Fig. b).



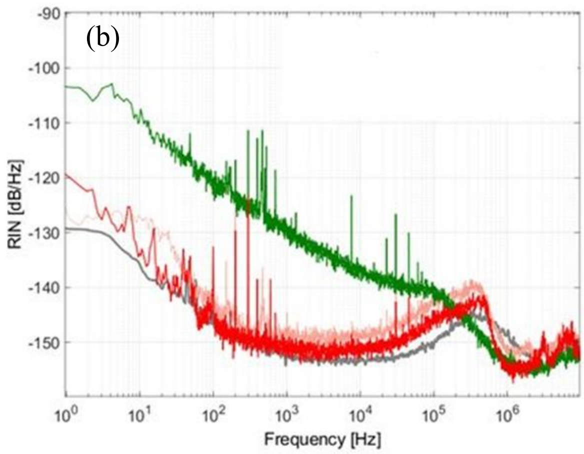


Figure 1: (a) experimental set-up comprising an optical isolator, a half-wave plate and a beam reducer before an AOM (red case), a beam expander and a beam splitter cube before two photodetectors for feedback loop and measurement. (b) Relative Intensity Noise (RIN) measurements: free laser diode (green), laser diode with stabilization (red), laser diode with stabilization after transport (pink), equivalent laser diode stabilized on reference Cs-CPT bench (gray).

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Progress towards an Al$^+$ Quantum Logic Optical Clock

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Clocks are characterized by their statistical and systematic uncertainty. Optical clocks offer an improved statistical uncertainty compared to microwave clocks because of their higher transition frequency. Currently there are different kinds of optical clocks with neutral atoms and with single ions. Here we present our status on the progress towards an Al^+ optical clock. The advantage of aluminum compared to other ions used for clocks is that aluminum has a very low sensitivity to external fields. Al^+ exhibits only nuclear linear Zeeman shifts and a very small blackbody radiation shift which is estimated to be less than 10^{-19} in our trap setup. The trap used in the experiment is a linear Paul trap. Since Al^+ does not have an accessible transition for laser cooling and detection, the Al^+ ion is trapped together with a Ca^+ ion which provides cooling of the Al^+/Ca^+ crystal. The state of the Al^+ ion is read out by mapping it with a few laser pulses to the Ca^+ ion, where it is detected with high efficiency [1]. The scheme as well as the reduction of second order Doppler shifts requires cooling of the crystal close to the motional ground state. For this we use double bright electromagnetic induced transparency cooling (D-EIT) on Ca^+ [2] which is an extension to single EIT. In D-EIT motional modes separated by MHz are cooled at the same time with a high cooling rate (see Figure). Using this technique, we estimate to reach a fractional second order Doppler shift from residual motion of a 2-ion crystal below 10^{-18}. For the experimental realization of D-EIT four electronic levels in Ca^+ need to be coupled by three lasers, one of which has a different frequency and is therefore phase stabilized to the other lasers via a transfer-lock using an optical frequency comb [3]. The transfer-lock is independent of comb repetition rate noise and carrier envelop offset noise.

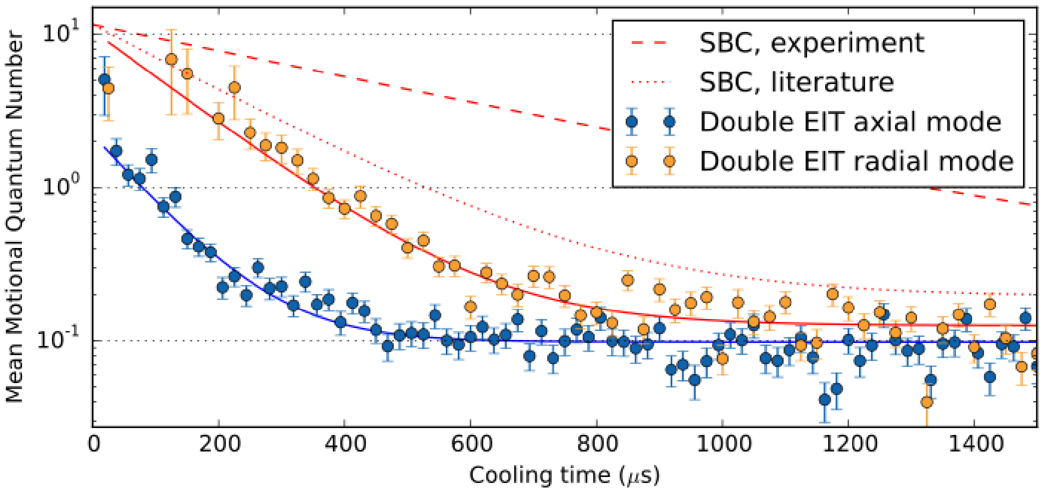

Figure 1: D-EIT reaches a state near the motional ground state in the axial and radial mode much faster than sideband cooling (SBC) which only cools one mode.

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LAMB-DIP SPECTROSCOPY OF BUFFER-GAS-COOLED MOLECULES

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Nowadays, buffer gas cooling represents an invaluable option to produce cold stable molecules, both in view of secondary cooling/trapping strategies towards the achievement of quantum degeneracy and for fundamental studies of complex molecules. From this follows a demand to establish a pool of specialized, increasingly precise spectroscopic interrogation techniques. Here, we demonstrate a general approach to Lamb-dip ro-vibrational spectroscopy of buffer gas-cooled molecules. The saturation intensity of the selected molecular transition is achieved by coupling the probe laser to a high-finesse optical cavity surrounding the cold sample. A cavity ring-down technique is then implemented to perform saturation sub-Doppler measurements as the buffer (He) and molecular gas flux are varied. As an example, the ($\upsilon_1 + \upsilon_3$) R(1) ro-vibrational line in a 20-Kelvin acetylene sample is addressed. By referencing the probe laser to a Rb/GPS clock, the corresponding line-center frequency as well as the self and foreign (i.e. due to the buffer gas) collisional broadening coefficients are absolutely determined. Our approach represents an important step towards the development of a novel method to perform ultra-precise ro-vibrational spectroscopy on an extremely wide range of cold molecules.

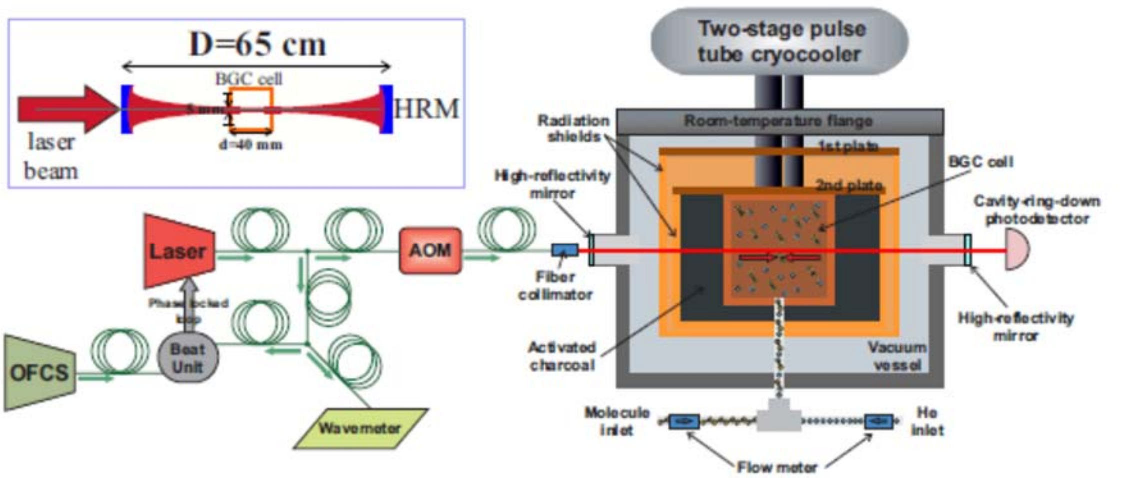

Figure 1 : Schematic layout (not to scale) of the experimental apparatus consisting of two main blocks: the BGC source and the OFCS- referenced probe laser [1]. To keep the pressure inside the radiation shields below 10^{-7} mbar, the internal surface of the inner shield is covered with a layer of activated charcoal which, at cryogenic temperatures, acts as a pump for helium and non-guided molecules. The gas adsorbed by the charcoal is released during warm up of the cryogenic system and then pumped out of the vessel by a turbomolecular pump (not shown). Relevant dimensions of the enahmcement cavity and the buffer cell are given in the inset.

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A robust clock transition on $^{40}Ca^{+}$ with a continuous dynamical decoupling scheme

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Dynamical decoupling is a promising approach for protecting an optical clock transitions against dominant environmental shifts. By applying continuous radio frequency (rf) fields, we generate a decoherence-free subspace in form of a pair of dressed states with largely suppressed field shifts. In particular, it is possible to remove inhomogeneous line shifts in large crystals of ions, enabling the operation of an optical frequency reference with many ions and correspondingly reduced statistical uncertainty. We present predictions and limitations for the achievable linewidths and residual shifts, using this scheme [1]. A transfer beat with an optical frequency comb will be later used to transfer this stability to the clock laser of an absolute frequency reference. In first experiments spectroscopic measurements for a trapped $^{40}Ca^{+}$ ion were performed for which the $4S_{1/2}$ and the $5D_{5/2}$ Zeeman states were dressed, resulting in a reduction of linewidth broadening of the 729 nm clock transition. The final scheme will involve four rf fields to realize doubly-dressed states, protecting the system against power fluctuations of the first driving fields, Zeeman-, quadrupole-, and tensor ac-Stark shifts from the rf driving field of the Paul trap. We will present first measurements on this doubly-dressed states.

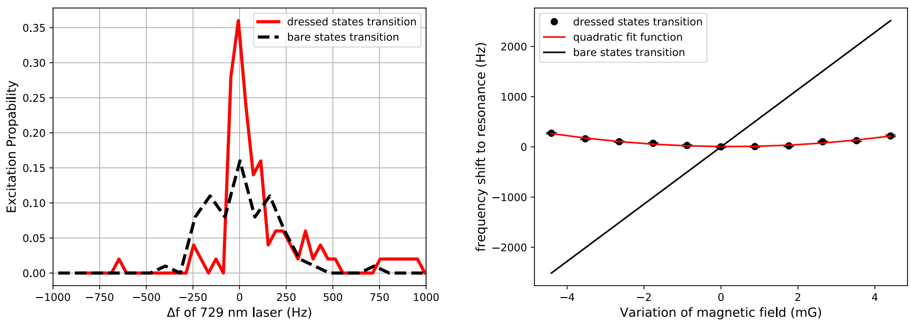

Figure 1. The decoherence and linewidth broadening of the clock transition is supressed for the spectroscopy between the radiofrequency dressed systems. In first order the clock transition is insensitive against magnetic field variations.

[1] Nati Aharon, Nicolas Spethmann, Ian D. Leroux, Piet O. Schmidt, Alex Retzker arXiv:1811.06732v1 (2018)

Time Transfer over Optical Fibre Links: Motivations, Evolution, & Opportunities

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Over the last decade, optical frequency standards and associated frequency transfer has been a very active field The stabilized optical carrier method associated with fibre links has been widely adopted, and has improved tremendously [1].Surprisingly when considering the Time Transfer, the range of methods is broader, but a few exhibit a high maturity level such as ELSTAB and WhiteRabbit [2]

The stakes of Time Transfer are as various as range, topology, service level, industrial integration, costs, and last but not least, access the telecommunications networks [3]. In this contribution, we will describe a cascaded long-range White Rabbit experiment over 500 km ,[4]By using a unidirectional optical transmission scheme these experiments are made compatible with most legacy optical telecommunication WDM networks, which eases and fastens their deployment thanks to shared infrastructure and OAM costs, standardized off the shelf components, and particularly co-existence with legacy data traffic Despite this apparent trade off (as ideally the fibre delay is best compensated using bidirectional propagation we will show that the measured stability performances outperforms the ones of GNSS methods by up to order of magnitudes Finally hierarchy of the time transfer, in the sense of *Primary Reference Clock*, *Boundary Clock* etc is also to be considered for offering a robust and resilient service.

However the afore mentioned techniques are not the best choices when aiming at ultra long reaches such as it the case for submarine transmissions. Indeed recent development of coherent high bit rate ($>$100Gbit/s) telecommunication networks pave the way of new perspectives, which will be discussed in the poster.

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Ultra-stable heterodyne detection in the mid-infrared spectral range

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A very wide range of scientific and technological applications relies on the availability of mid-infrared (MIR, 2 - 20 μm) coherent sources and large bandwidth detectors [1]. Quantum cascade lasers (QCL) are now compact and reliable sources providing MIR radiation at room temperature [2] and are already available commercially. However, MIR metrological applications, requiring entering a lower noise regime, demands a better control of the laser frequency stability, in particular narrower linewidths. Moreover, because of smaller photon energy, MIR detectors are less performing than their shorter wavelength counterparts [3].

We report preliminary results from the realization of a heterodyne detection scheme (see Figure 1.a) where the beating of two MIR QCL's (at 8.6 μm), a local oscillator (LO) and a signal, is detected by a quantum-well infrared photodetector (QWIP). A beatnote linewidth of about 2 MHz and a signal-to-noise ratio (SNR) of 40 dB is obtained with a resolution bandwidth (RBW) of 300 kHz when both the LO and signal are free running (Figure 1.b), while phase locking the LO to the signal, resulting in a far narrower beatnote linewidth of 2 Hz, allowed for a 75 dB SNR with a RBW of 1 Hz (Figure 1.c). In this stabilized scheme, a signal power three orders of magnitude weaker could be detected compared to the free running operation, exploiting the full detector sensitivity and paving the way towards detection at the single photon level.

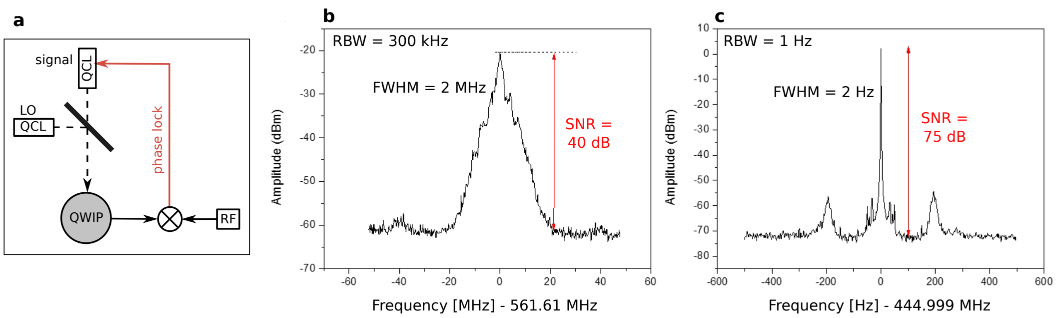

Figure 1. **a**: schematic view of the heterodyne setup. The two QCL's (LO and signal) are beaten onto a QWIP whose output is mixed down with a RF source at the beatnote frequency, providing an error signal for the phase locking of the LO to the signal. **b**: Beatnote profile in free running operation. **c**: Beatnote profile with the phase lock scheme.

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A DEEP-ULTRAVIOLET ABSORPTION SPECTROMETER FOR TEMPERATURE METROLOGY

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We report on the development of a comb-assisted laser absorption spectrometer for frequency metrology and precision spectroscopy in the deep-UV region. The spectrometer combines the technology of optical frequency combs in the visible and near-infrared regions with the most advanced nonlinear mixing techniques for the generation of coherent UV radiation. We intend to probe the shape of the $6^1S_0 \rightarrow 6^3P_1$ transition of mercury atoms at 253.7 nm with an unprecedented level of spectral fidelity. One of the aims of the work is the development of a new primary thermometer based on Doppler-broadened atomic spectroscopy for the practical realization of the new definition of unit kelvin [1,2].

The generation of the UV light is carried out using a pair of single-mode visible diode lasers. One of them is an external-cavity diode laser (ECDL) emitting at the wavelength of 402 nm with a maximum output power of 64 mW. The other one is based on a diode laser mounted in ECDL configuration injecting a tapered amplifier to provide an output beam at 689 nm with a power level as high as 150 mW. Sum-frequency generation has been performed through a single pass in a 12-mm-long beta-barium borate (BBO) crystal implementing the type I critical phase matching configuration. The measured UV power amounts to about 70 nW.

I will describe the set-up and report on the results of a linearity test of a silicon carbide (SiC) photodiode.

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Experimental Demonstration of a Terahertz Frequency Reference based on CPT in a Trapped Ion Cloud

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Recent works [1] in our group have demonstarted the existence of a highly resolved line referenced to a magnetic dipole transition at 1.82~THz in the singly-ionised atomic ion Ca^+. This line is observed by the study of a dark resonance in the laser induced fluorescence of a cloud of calcium ions. For that pupose, it is necessary to phaselock three visible radiations at wavelength 729, 794 and 866 nm. The experimental protocol is based on the transfer of stability via an offset-free frequency comb from a local clock laser at 729 nm to both other lasers at 866 and 794 nm [2]. The arrival of the metrological optical fiber signal (Refimeve) later in the current year opens the door for high resolution spectroscopy of this terahertz reference.

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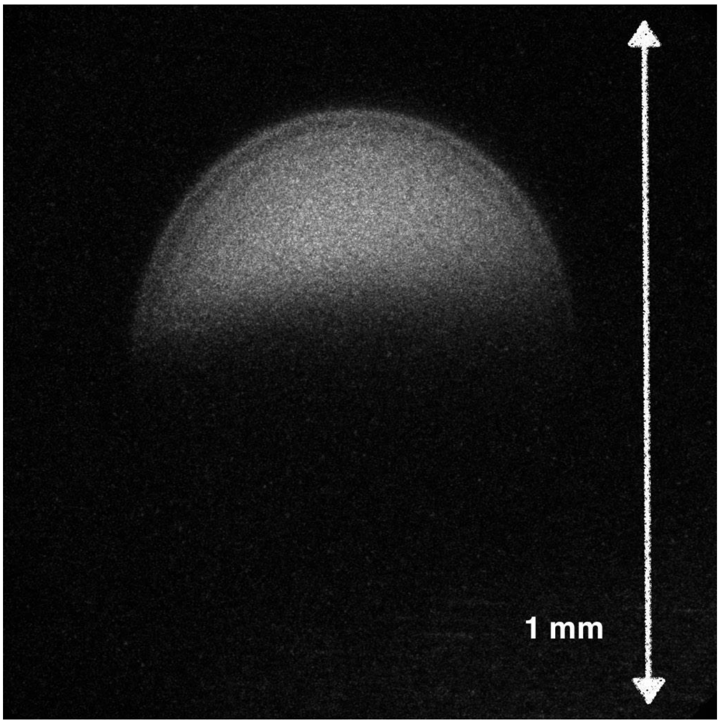

Figure 1 : picture of the Ca^+ cloud taken while scanning over the three-photon CPT process, showing that the sympathetic cooling is maintaining the cloud in the liquid phase, despite the radiation pressure which tends to separate the dark and bright ions

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TELECOM LASER LOCK ON ACETYLENE LINE FOR APPLICATIONS IN COLD ATOMS EXPERIMENTS

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Cold atom experiments require single frequency narrow linewidth lasers in order to address specific transitions. It is mandatory to lock the lasers to fixed references, because due to environmental fluctuations, drifts change the laser frequency outside of the acceptable range, which for the fundamental transition of alkaline atoms corresponds to the linewidth of 6 MHz.

Up to now, for Potassium, Rubidium and Caesium, the lasers systems were composed of a laser diode directly emitting at the atomic wavelengths seeding a solid state tapered amplifier. But in the past years, new kinds of lasers were developed from telecom technologies. Indeed, ultranarrow fibred laser diodes can be amplified up to Watt levels using fibred amplifiers. Then thanks to a doubling stage, it is possible to produce high power radiation in the near infrared range.

Up to now, the absolute reference used are bulk cells containing a vapor of the desired atom. Thanks to a saturated absorption setup it is possible to realise a Doppler free spectroscopy of the different hyperfine atomic transitions. Nevertheless, this scheme reaches its limits for Potassium atoms, because the different hyperfine lines are separated of less than their linewidth (3 MHz between the F'=0 and F'=1 of the D2 transition of ^{39}K at 767 nm). It is thus hard to determine on which transition the lock takes place, which impacts the efficiency of the cooling mechanisms. In this context, it is interesting to develop a new kind of laser lock, directly in the telecom domain.

There are no atomic transitions in this wavelength range, but acetylene possesses very narrow linewidths (natural linewidth of 5 Hz) of vibrational transitions between 1515 and 1545 nm, on which one can realise saturated absorption. We propose a laser architecture meant for a cold Potassium experiment, locked on the P(14) line of $^{12}C_2H_2$, which is 7 GHz away from the D2 lines of Potassium.

The absorption is low, which means that one needs either high pressure cells or long paths. But, molecules present numerous non-radiative decay channels, and effect such as collisions broadens the lines really fast (6 MHz for 200 mTorr). Moreover, the saturation intensity is proportional to the square of this linewidth. It is thus important to work at low pressure, with long paths. We study geometries to reach a good stability while keeping the setup compact, working both with bulk cells and functionalized hollow core fibres.

MID-IR FREQUENCY MEASUREMENTS FOR H_2^+ SPECTROSCOPY

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We have developed an experimental setup to perform high resolution spectroscopy of H_2^+ ions in the mid-IR. We have achieved theoretical predictions including relativistic and QED corrections at the 7.6 10^{-12} relative inaccuracy level and should reach 3. 10^{-12} in the near future. We aim at measuring Doppler-free rovibrational transitions on state selected sympathetically cooled H_2^+ ions at the 10^{-12} level using a quantum cascade laser phase locked to CO_2 laser, referenced to a stabilized femtosecond comb.

Optical modulation and demodulation of a PRN code

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It is demonstrated that optical frequency standards are able to reach better instabilities and uncertainty budgets than that of primary frequency standards [1], [2]. Since they are not yet working continuously, there are several attempts to steer a time scale with a such new generation of clocks [3], [4]. From these prospects one can expect that the stability of the optical time scales reaches the level of 10s of ps. Comparing optical time scales at this level of accuracy is a big challenge. Nowadays only a few techniques are capable of comparing these ultra stable time scales - in fiber [5], optical methods based on combs [6] and in laser pulses [7].

In this work, we are investigating new methods for ultra high performance time dissemination and time comparison over a bi-directional fiber network. In the context of REFIMEVE we are looking for a method that can be combined with coherent frequency transfer. We will show an experiment based on imprinting a simple phase pulse to a narrow bandwidth laser, that is demodulated optically after propagation with a Mach Zehnder interferometer [8]. We report on progresses made on this experiment to record longer data sets - from 1 day up to about 5 days. We will also report on our latest results when imprinting a PRN-code on this laser. These methods could serve as an alternative to current technology, with the possibility of transmitting data in addition to time transfer, and also lowering the cost of implementation due to being independent of bi-directional traffic.

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Towards spin-squeezing in a strontium optical lattice clock

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Optical lattice frequency standards have demonstrated world leading fractional frequency instabilities and uncertainties [1]. The stability of lattice clocks are close to the limit imposed by the quantum projection noise (QPN), associated with measurements on independent atoms [2]. Our proposal to overcome this limitation is to provide a a high degree of spin-squeezing via optical dressing of the clock state to a highly excited Rydberg state [3]. For the strontium lattice clock set-up this requires an additional laser for Rydberg excitation. We have developed such a tunable, narrow-linewidth source of UV light for excitation to the triplet Rydberg states in strontium [4]. Using this system we have then successfully Rydberg dressed a narrow intercombination line in ^{88}Sr, with dressed-state lifetimes > 1 ms [5]. We showed that this scheme can be used to implement laser cooling of the dressed state, opening up new possibilities in the control and manipulation of atomic samples with long-range interactions.

As single-atom control provides advantages for optical clock systems, we have recently developed methods to trap single strontium atoms in a 532 nm optical tweezer. In the last few months, single divalent atoms such as Sr [6, 7] and Yb [8] were isolated in tweezer arrays for the first time. Our experiment is based on a long working distance (37 mm) in vacuo aspheric objective that has a numerical aperture that is a factor of two lower (NA = 0:26) than that used in previous single atom experiments. Along with a transparent conductive coating, this provides an environment compatible with precision spectroscopy of Rydberg states. We are presently performing high precision Rydberg spectroscopy of the 5s5p ^{3}P$_0$ to 5sns ^{3}S$_1$ transitions, using an optical frequency comb. We have shown that the absolute frequency of the line center is determined with a statistical uncertainty of just 4 kHz [9], where the next challenge is to control systematic frequency shifts at a similar level. Additionally we are currently moving to an 813 nm magic wavelength lattice, as the reduction in differential AC Stark shift is required for the spin squeezing protocol in an optical lattice clock.

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Photonic Microwave generation at NTSC

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Abstract—We report on a photonic microwave generation with an Er:fiber-based optical frequency combs phase locked to a ultra-stable continuous wave laser. The frequency instability of 9.6 GHz microwave signals is 3×10^{-15}@ 1s, and this signal is then synthesized to 9.192 GHz, with an instability of 6.7×10^{-15} @1s, for fountain clock experiment. Further improvement is undergoing.

Keywords—microwave sources; optical frequency comb; ultra-stable laser;

I. INTRODUCTION

Atom fountain clocks provide the most accurate realization of the SI second and define the accuracy of the widely used international atomic time. Highly performance fountain clocks reached frequency uncertainty of low level in 10^{-16}, exhibiting $1\sim3\times10^{-14}/\tau^{1/2}$ for short term stabilities limited only by quantum project noise. However, most of fountain clocks shows $10^{-13}/\tau^{1/2}$ frequency instabilities due to the Dick effect[1]. Ultra-stable photonic microwaves are one solution for eliminating Dick effect.

In this paper, we report on the progress of ultra-stable photonic microwave generators[2] developed at NTSC. Preliminary results show that the microwave generators exhibit a frequency instability of well below 1E-14@ 1s, which is enough for suppressing the Dick effect.

II. EXPERIMENTAL SETUP

Our experimental setup comprises 3 parts. The first part is generating a low-noise and continuously operated constant optical continuous wave (CW) reference by an our homemade ultra-stable CW laser at 1555 nm[3]. The second part is photonic microwave generation by two Er:fiber-based optical frequency combs and measurement system by using down conversion technique. The last one is special designed ultra-low phase noise frequency synthesizers to realize microwave signals at about 9.192 GHz and the instability measurement system.

Finally we get two microwave signals near 9.192 GHz. Then we design the measurement system for evaluating the frequency stability, and the results are showing in Fig. 1.

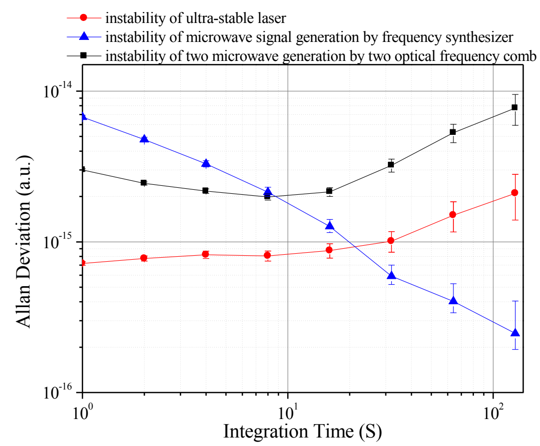

Fig. 1 Circles: fractional frequency instability of ultra-stable CW laser (characterized by the allan standard deviation). Squares: fractional frequency instability of the microwave signal generated by the fiber-based optical frequency combs at 9.6 GHz. Triangles: fractional frequency instability of 9.192GHz shifting by frequency synthesizer.

III. CURRENT RESULTS

We demonstrate a homemade photonic microwave generation with an Er:fiber-based optical frequency comb phase locked to a ultra-stable continuous wave laser. The instability of 9.6 GHz microwave signals is 3×10^{-15}@ 1s, and the instability of synthesized 9.192 GHz signal is about 6.7×10^{-15} @ 1s.

ACKNOWLEDGMENT

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TWO-way optical time and frequency transfer based on BOC

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We demonstrate optical time and frequency transfer over free space via two-way exchange between stable frequency combs, each phase-locked to the local optical oscillator. The variation of optical path-length between sites due to atmospheric turbulence fluctuates the time-of-flight (TOF) of pulse trains of optical frequency combs is obtained based on Balanced optical cross-correlation and compensated with servos.

The scheme is as follows, in site A the fluctuation ($\delta T1$) of the TOF of pulse trains from site B originates from COMB B (δT_{COMB_B}) and the variation of path-length (δT_{Link}) is obtained by BOC 1 and compensated by the servo 1 and MD. On the other hand, in site B fluctuation $\delta T2$ of the TOF of pulse trains from site A is precompensated with the ($-\delta T1$) and obtained by BOC 2 . Therefore, by elimination the $\delta T2$ through the servo 1 we can realize the synchronization of the two combs in two sites.

$$\delta T1 = \delta T_{Link} + \delta T_{COMB\_B} \tag{1}$$

$$\delta T2 = \delta T_{COMB\_B} - (\delta T_{Link} - \delta T1) = 2\delta T_{COMB\_B} \tag{2}$$

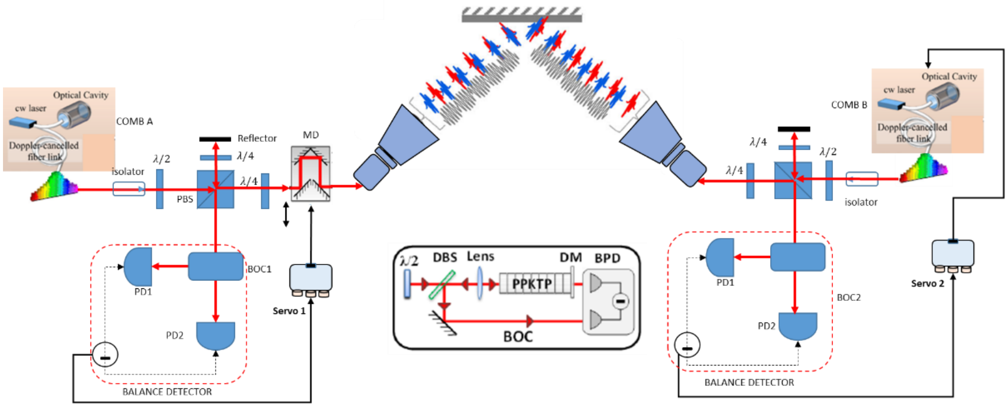

Figure 1. The scheme of two-way optical time and frequency transfer based on BOC. MD: motorized delay; PPKTP, periodically poled KTiOPO4; DBS, dichroic beam splitter; DM, dichroic mirror; λ/4: quarter-wave plate, λ/2: half-wave plate; PD: photodetector; PBS: polarization beam splitter

ACTIVITIES FOR TIME AND FREQUENCY DISSEMINATION USING OPTICAL FIBER LINKS IN SOUTH KOREA

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The activities for the national standard time and frequency dissemination over optical fiber links in South Korea during the last decade are presented. In the early stage, the applications at a short distance are investigated, such as the reference signal transmission from a H-maser to a receiver cabin in radio telescopes [1], and the fiber-optic dissemination of time and frequency between two buildings in KRISS [2]. In 2015, we transferred 1-GHz radio-frequency (RF) to Cheongju using 112-km-long dark fiber, which is a part of Korea Research Environment Open Network (KREONET) operated by Korea Institute of Science and Technology Information (KISTI) [3]. The fractional frequency instability after noise compensation was 5×10^{-14} at an averaging time of 1 s and 1.2×10^{-16} at 1000 s. A long-distance transfer for very-long-baseline interferometry (VLBI) is planned in the next few years. The Korean VLBI Network consists of three radio telescopes at Seoul, Ulsan, and Jeju as in Fig. 1. Transfer of a common reference RF for radio-telescopes is expected to make the VLBI result rapid by reducing the time required for the correlation analysis for the simultaneous observation. RF transfer will also provide a method to evaluate and backup the commercial clocks at remote sites. In 2019, as a test bed for this plan, KRISS reference time and frequency will be transferred to Sejong, which is located 24 km away (straight-line distance). In addition, a satellite laser ranging (SLR) facility is located at Sejong, by which a frequency comparison of KRISS Yb optical clock is possible. Also, the national standard time (UTC(KRIS)) transfer to Korea Electric Power Corporation using White Rabbit is scheduled in 2019 for the reference time design for the electric power utility.

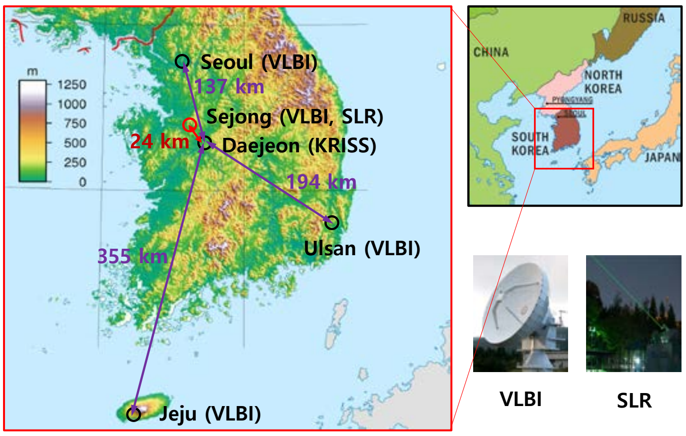

Figure 1 : The VLBI radio telescope locations and the SLR facility at Sejong.

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Coherent Control of Addressable Rydberg Atoms for Hybrid Quantum Information Processing

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Neutral atoms provide an excellent resource for quantum information processing, combining the long atomic coherence times of the hyperfine ground-state with strong dipole-dipole interactions of highly excited Rydberg states for generating deterministic entanglement between qubits separated by $< 10\ \mu$m [1]. Scalable long-range interactions can be obtained by coupling the atomic array to a superconducting microwave cavity enabling hybrid quantum information processing where the cavity-mediated entanglement allows atoms to be coupled over cm length scales. We present the first steps towards such an experiment incorporating high fidelity readout using an sCMOS camera [2] and the ability to drive fast, optically addressable rotations of the hyperfine-encoded qubits to the Rydberg state. Using our sub-kHz cavity-stabilised laser system [3] we demonstrate coherent control of single Rydberg atoms, performing Ramsey spectroscopy to determine coherence time and to generate entanglement between a pair of atoms separated by 6 μm with long ground-Rydberg coherence times [4]. Combining this excitation scheme with our ground-state Raman lasers we show progress towards the implementation of a mesoscopic Rydberg gate based on electromagnetically induced transparency (EIT) offering robust entanglement of multi-atom ensembles [5].

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Testing the parity symmetry in chiral molecules using comb- and fiber-link-assisted precise vibrational spectroscopy

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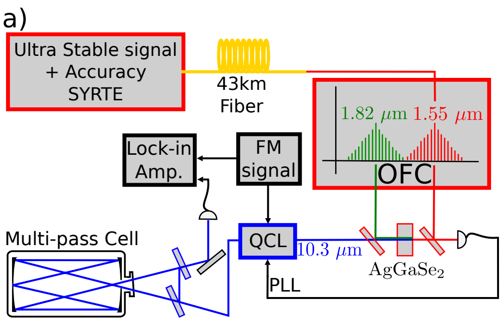
Unlike the other fundamental interactions, the weak interaction is known to violate the parity symmetry, i.e. the symmetry under spatial inversion. It was experimentally demonstrated using nuclear and atomic systems and in high energy physics. However, despite being theoretically predicted, parity-violation (PV) was never measured in molecules. In particular for a chiral molecule, i.e. a molecule non-superimposable to its mirror image, it is expected to lead to energy differences between the left- and right-handed enantiomers, and in turn to frequency differences in their rovibrational spectra potentially measurable using precise mid-infrared spectroscopy. Those PV frequency shifts are however predicted to be extremely small, in the mHz to Hz range [1] depending on the species considered for vibrational transitions at ~ 30 THz. Measuring this allows several fundamental questions to be addressed, from the limit of the standard model in the low-energy regime to the still unexplained origin of biomolecular homochirality, while it can also serve as a benchmark in relativistic quantum chemistry calculations. In this context, I will in particular present ultra-high resolution spectroscopic measurements using a quantum cascade laser (QCL, $\lambda \sim 10$ μm) stabilized at the sub-Hz level,via an optical frequency comb (OFC), on an ultra-stable near infrared reference signal provided by a fiber link to the French metrology institute (LNE-SYRTE) [2]. This allows rovibrational frequencies to be determined at record uncertainties, with traceability to primary frequency standards.



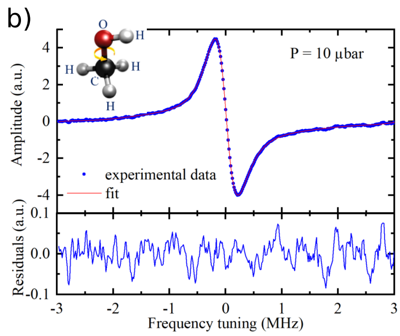


Figure 1. a) Stabilized QCL rovibrational spectroscopy setup. b) Saturated absorption spectrum of a ro-vibrational line of methanol, recorded using frequency modulation and first-harmonic detection.

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RUBIDIUM SPECTROSCOPY FOR PRECISION MEASUREMENT OF HIGH MAGNETIC FIELDS

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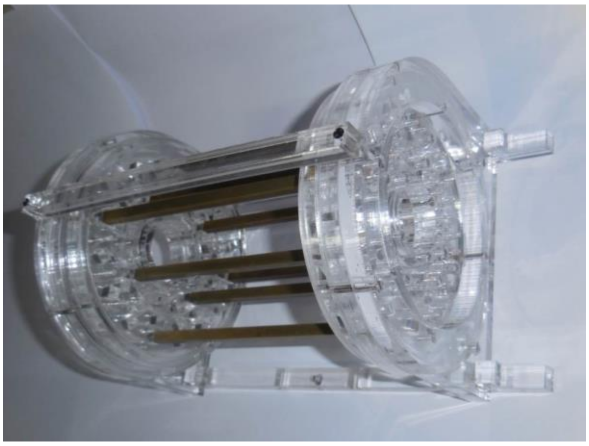
We use alkaline atoms saturated absorption spectroscopy as an accurate measurement technique for magnetic fields in the intermediate (0.1T) or strong regime (several 10T).

For low field magnetometry (B<1T) a new setup is developed with ten-fold increased accuracy (down to few 10ppm) using the beatnote with a reference laser technique. As a side benefit, we will provide soon a better estimate of the Rubidium excited state Landé factor. A similar experiment is planned for Cesium and, in a near future, the possibility of using both elements simultaneously.

For absolute calibration, we have started a collaboration with Steffen Kraemer in LNCMI-Grenoble. A new fiber sensor is being built to compare with in-situ NMR steady field measurements (B<35T). Excited state Landé factors, diamagnetic and core effect will be measured with unprecedented accuracy allowing testing state-of-the art calculations of bound states realized in Hélène Bolvin group (LCPQ-Toulouse).

Finally, the MegaGauss facility in Toulouse (B~150T, 2µs) offers the possibility to investigate a new spectroscopic regime in which the energy levels evolve faster than the internal atomic degrees of freedom (non-adiabatic regime).



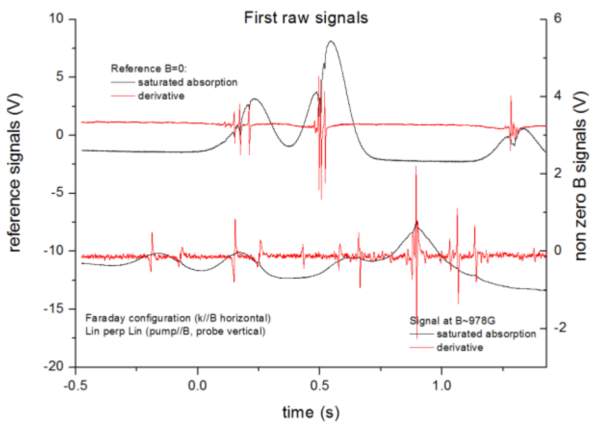


Figure 1 : Left : triple Halbach cell producing highly homogeneous B-field tunable between 0.01 and 0.15T. Typical signals. An experimental run consists in 6 frequency scans for 5 polarizations schemes. More than a hundred of line is recorded, each line several times for statistical treatment.

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HIGH SENSITIVITY MOLECULAR SPECTROSCOPY ASSISTED WITH A FREQUENCY COMB

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LAME team from LIPhy has large experience in developing and using cavity enhanced spectroscopic techniques for state of the art spectroscopic studies. These techniques (in particular CRDS) have produced a lot of data for molecules of atmospheric and planetary interest, which are now included in databases like HITRAN and GEISA. Since few years, we have at disposal an auto-referenced frequency comb that we are using in different ways. Hence, comb-assisted CRDS spectra are recorded with *on the fly* measurement of the absolute frequency of the laser source (Distributed feedback laser diodes or External Cavity diode lasers) through the beat note between the laser and the comb teeth [1]. This allows determining line positions with uncertainty down to 100 kHz in Doppler-limited regime and reducing the amplitude noise due to frequency noise on the edges of the absorption lines. With home-made sub-kHz laser sources coupled into a high-finesse cavity [2], saturated absorption can be done leading to absolute position determination at the kHz level from Lamb-dips [3]. The optical comb can also be used to transfer the phase coherence from these ultrastable master lasers to our much broader (~2 MHz) DFB lasers [4].

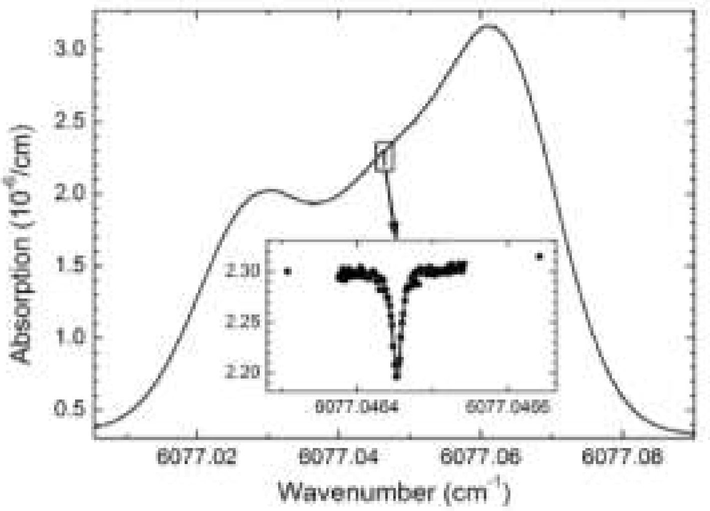

Figure 1 (From Ref. [4]): CRDS absorption spectrum of pure methane. One Lamb dip appears as an illustration of the narrow source linewidth. It belongs to the central line of the triplet and is made visible by using 50 kHz scanning steps locally. The other two expected Lamb dips are not visible given the 5 MHz steps used elsewhere.

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Narrow Linewidth InGaN Laser Diode Based on a Fiber Bragg Grating

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The first InGaN-based LDs were reported in 1996 by Nakamura and co-workers [1] and commercialized from 1999 by the Nichia Corporation. Since then, huge efforts have been devoted to the optimization of the epitaxial layers (doping, defect concentration, shortening of the radiative lifetime, etc.). Nowadays, blue laser diodes emitting hundreds of mW are commercially available but they often exhibit multimode behaviors for both transverse and longitudinal directions. At telecom wavelengths, a mature approach to force the laser diode in a single frequency regime consists in using an external feedback by means of Fiber Bragg Grating [2]. Nevertheless, to our knowledge, such a compact design has not been proposed for blue laser diodes yet.
In this paper, we demonstrate the possibility to reach single mode emission from a Fabry Perot

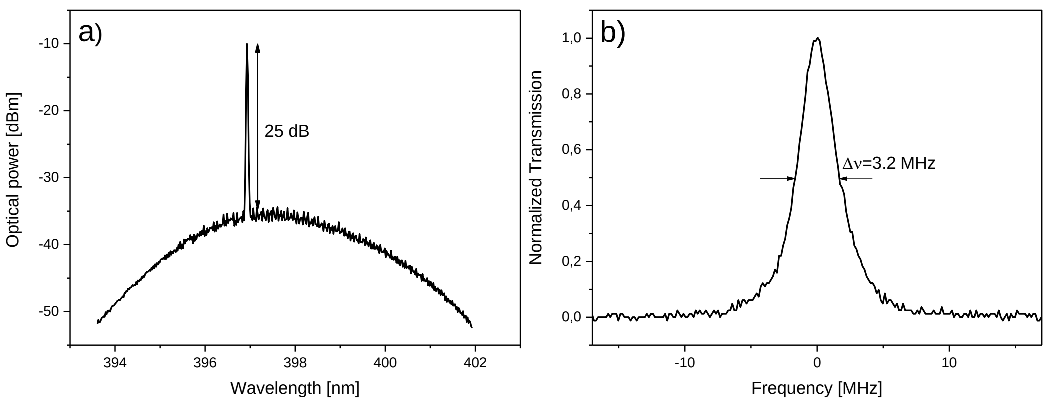

Fig. 1 a) Optical spectrum of the Fiber Bragg Grating external cavity Laser diode (FGL) centered at 396.9 nm b) Resolution limited measurement of the FGL in the single frequency regime measured with a Fabry-Perot Analyser.

(FP) InGaN laser diode [3], emitting around 400 nm, by optical feedback using a Fiber Bragg Grating (FBG). A phase-mask based Talbot interferometer arrangement is used to side write the FBG in the photosensitive fiber, single mode at the operating wavelength. It has a uniform profile with 60 % reflectivity centered at 396.9 nm with a 35 pm bandwidth sufficiently narrow to select one mode of the diode laser cavity.
Single frequency operation with 25 dB side mode suppression ratio and a linewidth of less than 3.2 MHz is demonstrated.
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CESNET FIBRE INFRASTRUCTURE FOR NEW DEMANDING APPLICATIONS

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CESNET has been working with fibre optic links since 1999, connecting two major cities in Czech republic at 2.5 Gb/s speed. Today CESNET has almost 5830 km of fibres, including 1360 km single fibre lines for special applications and economical savings, with data transmission rates at 10 Gb/s and 100 Gb/s [1]. CESNET also tested new equipment with speeds up to 400 Gb/s as part of its international activities in GEANT between Praha and Wien. New application, accurate time transfer, was tested in 2010 and is in production state since 2012, comparing Caesium clocks in Praha and Wien. Ultra stable frequency transfer is another new application using standard telco fibres and is used for monitoring of critical infrastructures like containment of nuclear powerplants. These new applications are not focused on highest data rates but sensitive to parametres like jitter, stable temperature and no vibrations. Even relativistic effects must be taken into account for the highest possibly accuracy and stability [2]. Of course in the real world only real fibres are available, with parasitic effects disturbing optimal performance and every fibre provider must deal with these conditions.

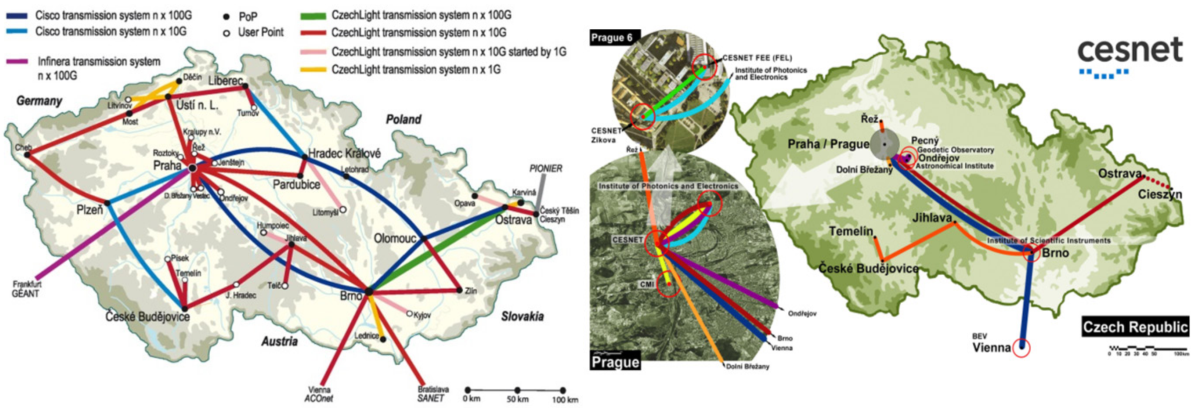

Figure 1 : CESNET fibre network and time and frequency fibre infrastructure in 2019

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Development of a Fibre-Based Acetylene Optical Frequency Standard at 1.5 µm

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Optical frequency standards are essential for various applications in metrology. Our work focus on the devloppement of a compact frequency laser stabilized on a Doppler-free acetylene absorption at 1542nm, using standard fibre-optic components.The frequency stability achieved so far is about of 4.10-13 at 4000s.

SATELLITE-TO-GROUND QUANTUM-SECURE TIME TRANSFER

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High-precision time transfer can establish time synchronization between two remote parties [1], which are not only very important for fundamental science research, but also have many applications in industry, military and social life. Unfortunately, the time synchronization protocols widely used today, such as the Global Navigation Satellite Systems (GNSS) have many security risks and may bring huge losses. Here we propose a novel quantum-secure time transfer scheme based on two-way quantum key distribution (QKD), which can ensure the time data and time synchronization signals with information-theoretic security [2]. To show the feasibility of this scheme, we have implemented demonstration experiment of satellite-to-ground secure time transfer based on the Micius quantum satellite [3]. A high-precision of 30 ps of time transfer and 1 cm ranging precision is obtained, which shows that sub-ns secure time transfer between satellite and ground is possible. It is feasible and efficient to establish a satellite-based quantum-secure time transfer network based on the quantum communication network in space.

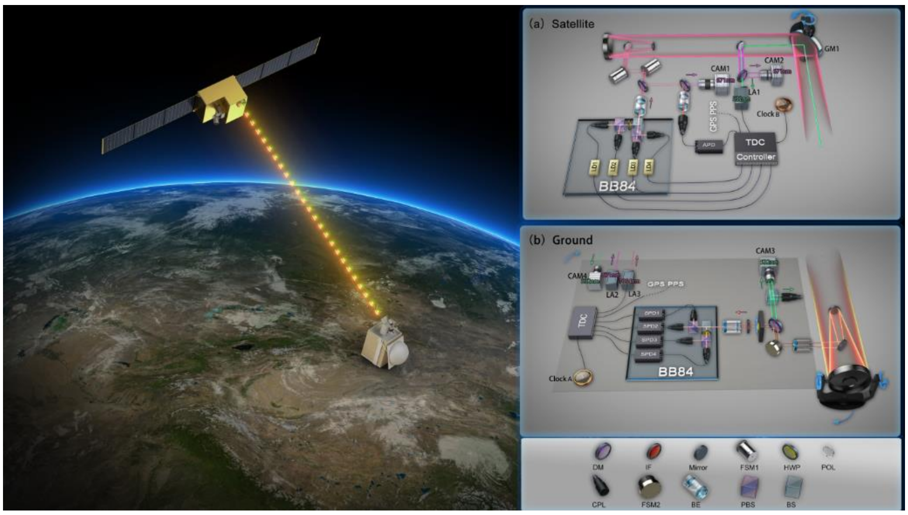

Figure 1 : Illustration of the secure time transfer experimental setup based on Micius satellite.

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CLOCK SYNCHRONIZATION OVER METROPOLITAN FIBER NETWORKS

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We demonstrate synchronization between two clocks via distribution of photon pairs generated from a correlated source and identifying the temporal coincidences [1]. The photon pairs are created at telecom O-band (1310 nm) via spontaneous parametric downconversion (SPDC), and are efficiently seperated using a wavelength division demultiplexer. The seperated photons are routed to deployed fibre links and are detected at the terminals of the links.

The arrival times of photons are recorded with two timestamping modules disciplined by local clocks. The two sets of timestamp records are shared to obtain a cross-correlation histogram. The identification of a peak in the cross-correlation histogram allows the pairing of corresponding detection events and measures the time differences between the two clocks. Using this method we can reliably achieve sub-nanosecond clock synchronization over a metropolitan scale fibre network (up to 100 km), limited only by fibre dispersion and timing jitter of single photon detectors. In our more recent work, we also show that this timing uncertainty can be further reduced by introducing nonlocal dispersion compensation over the fibre link [2].

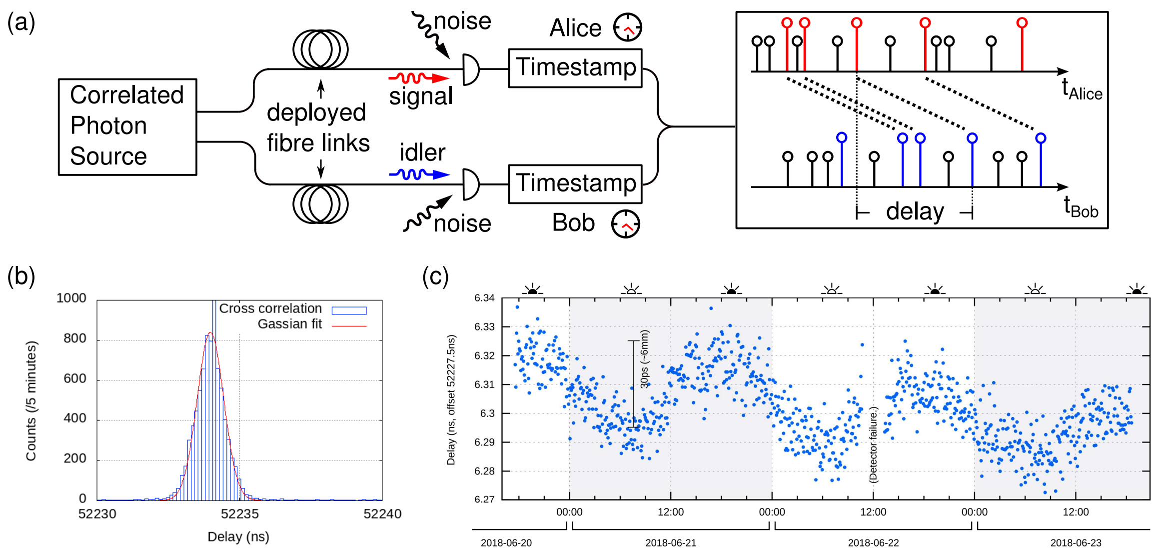

Figure 1. (a) Clock synchronization between Alice and Bob via coincidence identification of correlated photon pairs. (b) Timing correlation obtained with one photon propagates across a 10 km fibre link, while the other photon being detected locally. (c) Changes in delay time due to thermal expansion of fibre, measured over a period of 54 hours.

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Precision molecular spectroscopy using a network for distribution of the Swiss primary frequency standard

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Recent progress in laser technology, frequency metrology and molecule optics have enabled ultra-precise measurements of molecular frequencies [1 - 3]. We are developing a complete experimental and theoretical toolbox for non-destructive spectroscopy of single molecular ions using quantum-logic techniques [4 - 7]. In a first stage, we target relative measurement accuracies of order 10^{-14} – 10^{-15}; an improvement of several orders of magnitude in comparison to the present state of the art of 10^{-9} [1, 2]. These advancements will pave way for using molecules as new high-precision frequency standards and clocks, for addressing fundamental physical problems such as the proton-radius puzzle and a possible temporal variation of fundamental physical constants [8, 9] and for precision tests of quantum electrodynamics. It will also enable the observation and control of chemical reactions of single particles on the quantum level.

The dramatic advancement in measurement accuracy targeted here will be enabled by the implementation of new spectroscopic methodologies based on quantum technologies, by the development of ultra-narrow quantum-cascade laser sources tailored to the present needs, and in particular through the implementation of a fibre-optical network for the distribution of the Swiss primary frequency standard [10] maintained by the Federal Institute of Metrology METAS to spectroscopy laboratories in Basel and Zurich. By means of Optical Frequency Combs (OFCs), this network will enable the absolute stabilization, calibration and frequency comparison of the laser sources employed in our measurements at a level of up to 10^{-15}.

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IR TO UV ULTRA-STABLE OPTICAL OSCILLATOR TRANSFER FOR PRIMARY THERMOMETRY

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In 2018, the International Committee for Weights and Measures (CIPM) established T measurements in terms of the thermal energy of the particle system, $K_B T$, with K_B exactly known. Consequently, recalibration of T scale is requested, for eliminating any artifact or material dependency and ensure the long term stability of the SI unit. Doppler-Broadened Spectroscopy has been recognized as an independent method for relating the temperature scale to absolute measures of optical frequencies, making the Doppler-Broadened Thermometry (DBT) a primary thermometer. This method consist in retrieving the Doppler width of an atomic [1] absorption line in a rarefied gas sample at thermodynamical equilibrium. The intercombination Hg transition at 253.7 nm seems to be an ideal candidate to perform DBT. To this aim, a coherent UV source is required, with a linewidth narrower than 1 kHz, a tunability of at least 6 GHz and directly traceable to the primary frequency standard. We plan to adopt a frequency quadrupled scheme to transfer all these spectral requirements from near infrared (near-IR) to the UV region. An Extended Cavity Diode Laser (ECDL) at 1014.8 nm, is the source used to generate the UV radiation and it will be frequency stabilized against to a very stable ultra-narrow linewidth (30Hz) single mode CW laser at 1540 nm, using slave-master heterodyne technique.

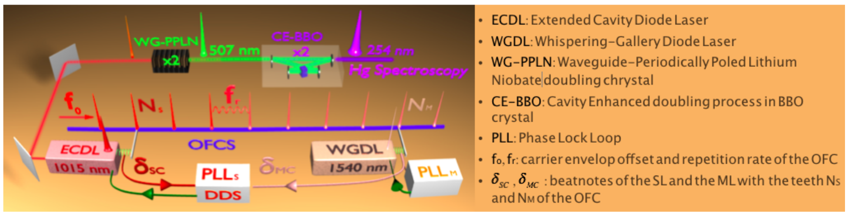

Figure 1. Experimental set-up of the UV laser source for Hg spectroscopy at 253.7 nm.

Direct Digital Synthesis (DDS) uses an Optical Frequency Comb (OFC) as an optical bridge to transfer phase fluctuations of the laser at 1540 nm to the ECDL through the beatnotes of these sources with the nearest OFC tooth [2]. A 1-s stability of 6x10^{-13} or 10^{-14} and absolute accuracy of 2x10^{-12} or 10^{-15} for the UV frequency is expected, depending if the OFC is disciplined against to Quartz-Rb-GPS oscillator or to a fiber-link provided optical primary standard, respectively. Here, we present the implementation of such precise frequency chain and preliminary results in terms of spectral characterization of both the laser sources in order to validate the spectral requirements of the DBT spectroscopy of Hg.

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Ultra-stable laser based on cryogenic silicon Fabry - Perot cavity

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Ultra-stable lasers are key instruments in Optical Frequency Metrology. Their very low frequency instability in the short term allows the operation of cold atomic optical clocks, or the generation of microwave signals with very low phase noise via the use of optical frequency combs. In practice, a frequency stabilized laser is constituted by a continuous laser whose frequency is locked by a correction circuit, in a resonance mode of a Fabry - Perot cavity with a very high finesse. In order to reduce the laser frequency noise, the laser frequency can be stabilized to a more stable external reference. The world's best ultra-stable lasers today have relative frequency stability below 10^{-16}. The aim of the project is to build a laser frequency-stabilizing system with a monocrystalline silicon cavity operated at a very low temperature. In order to realize a temperature-stable and quiet environment at less than 17 K, we used a cryocooler system with helium recondensation as well as a thermal isolation stainless steel shield to keep the cavity at the desired temperature. We used a passive and active vibration isolation system for reducing the effect of seismic motion and vibration from the refrigerator. In addition, several noise-reduction system such as Doppler noise cancellation, laser power stabilization, etc., were installed. We evaluated the performance of our system quantitatively. The instability is lowest around 1 second using an optical cavity operated at a very low temperature. Moreover, we evaluated any noise contributions for the frequency instability due to various effects, such as seismic motion, temperature fluctuation.

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Towards the supervision and the scientific data processing of a fiber network for optical frequency transfer

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The development of coherent optical fiber links have led to many different applications, as clock comparisons [1], HR spectroscopy [2], geodesy and tests of special relativity [3]. This will be even further enhanced in the context of the French REFIMEVE+ project, where 20 partner laboratories with experts in different fields of physics will benefit from a metrological optical signal, as well as in the context of the European OFTEN project for clock comparisons. This growing network will demand appropriate supervision and assessment of the performance of the fiber links. This also results in large amounts of data, where new physics is waiting to be discovered.

We will present a global data processing software, sized for a network at regional, national and European scale. This scientific tool enables supervision of the network as well as measurements examining fundamental physics with coherent optical fiber links. We will demonstrate the use of the software for the REFIMEVE+ project, where it gives the users the tools needed to validate the performance of the metrological signal. In the context of OFTEN, we will also present the last results of the performances of the current fiber network during a European clock comparison campaign using this software.

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High-precision spectroscopy on molecular beam of CO

Maurizio Verde

February 21, 2019

We use high-precision spectroscopy on molecular beams to address theoretical topics of fundamental physics, such as the existence of the electron dipole moment for elementary particles or the variation of natural constants, for instance the electron to proton mass ratio and the fine structure constant. Indeed, molecules are highly sensitive probes as their complex spectra can fully reflect these tiny effects better than atoms, whose energetic structure is too much simple. To observe these spectra variations, is still now an hard task. We approach high-precision molecular spectroscopy, exploiting a very complex setup based on a supersonic beam of CO molecules. Our setup is essentially based on three laser beams, interacting with CO molecules; the first prepares them in a definite quantum state, the second enables their vibrational transition, while the third is used for their detection. Specifically, we prepare CO molecules in the $a^3\Pi_1$ electronically-excited metastable state by using an Optical-Parametric-Oscillator generating a pulsed radiation around 206 nm. Then, the vibrational transition is driven by a continuos-wave Quantum-Cascade-Laser in the mid-infrared, which can be referenced, through a complex locking chain, to an Optical Fibre Link delivered in Florence and coming from Turin. Finally, the higher vibrational state population can be measured through a Resonance Enhanced Multiphoton Ionization, as performed by a pulsed laser at 283 nm. The excitation and the detection pulsed lasers have to be spatially well separated to select a single class of speed in order to reduce, as much as possible, the Doppler broadening. We reached a precision and an accuracy of 11 significant digits for the vibrational frequency, where the main limitation came from the residual Doppler broadening. Now, we are attempting to overcome this limit, by developing Doppler-free measurements based on two-photons transitions.

Spectral Hole Burning for Ultra-stable Lasers and Atomic-scale Force Sensors

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High precision spectroscopy measurements using the spectral hole burning technique can be used in time-frequency metrology and related applications. Spectral hole burning in rare-earth doped crystals can provide frequency references using the optical transitions of the dopant ions [1], making it possible to improve laser frequency stabilization. The fundamental limit of this novel technique is unknown, but early studies have estimated it to be below 10^{-18}in relative frequency stability at 1 s [2], well below techniques based on standard Fabry-Perot cavities, which are limited by thermodynamic noise at a few 10^{-16}at 1 s. At the SYRTE laboratory, an experimental setup using an $Eu^{3+}: Y_2SiO_5$crystal has been constructed at cryogenic temperatures (below 7 K). In this matrix, the $^7F_0 \rightarrow {}^5D_0$ transition of the europium ions has a linewidth that can be as low as 1 kHz, and some measurements indicate a value reaching a few 100Hz at 1K [3]. In our experimental setup, the master laser is pre-locked on a Fabry Perot cavity and the slave laser is locked to the spectral hole. This scheme provides the possibility to create a new generation of ultra-stable lasers. The first demonstration of laser stabilization yields a relative frequency stability at a few 10^{-15}around 1 s. On the other hand, the strain sensitivity of the spectral holes allows us to perform such experiments in micro-mechanical resonators, with the possibilities to realize atomic-force sensors with rare-earth doped crystals.

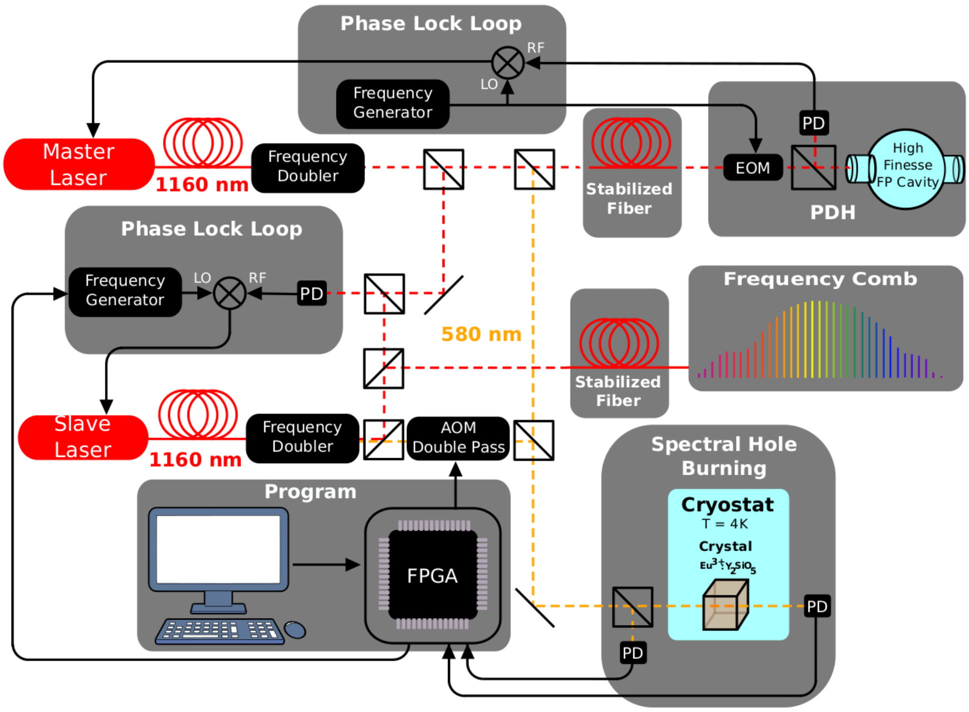

Figure 1 : Experimental Set-up

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PROGRESS ON DEVELOPMENT OF OPTICAL FREQUENCY COMBS AT NTSC

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Optical frequency comb is a frequency-controlled femtosecond laser, which has been widely used in many applications[1, 2]. Robust mode-locked laser and capability of its frequency control are critical in some cases. In this paper, we demonstrate two techniques to improve performance of Er:fiber frequency combs at NTSC[3, 4].

The first technique is to obtain a low noise and robust mode-locked laser. As we know, the nonlinear polarization evolution (NPE) mode-locked laser is the most widely employed type of the erbium fiber lasers for its low noise and narrow pulse width. However, the drawback of the NPE laser is sensitivity to temperature and difficult to start mode locking. On the other hand, polarization-maintaining lasers based on nonlinear amplifier loop mirrors (NALM) can self-starting by introducing a nonreciprocal phase bias in the cavity and insensitive to the environmental perturbation**.** To obtain self-start and low noise mode-locked laser, we design a hybrid laser incorporating NPE and NALM mechanisms. The system can self-start and work normally after being unpowered six months, and the noise level is similar to the pure NPE.

The second technique is to control mode-locked laser frequency with broad bandwidth and large range. Usually, combining control techniques have to be used for this[5], because high bandwidth control technique has insufficient dynamic control range to conquer long term frequency drift. We propose a method that rotates of a NPR mode-locked laser the polarization state to steer laser`s frequencies. By taking advantage of birefringence of the whole laser cavity, this approach can tune frequencies in a broadband width and over a large dynamic range. Compared with other high bandwidth frequency control techniques, the control range of this approach is at least 10 times larger.

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MICROWAVE FREQUENCY DISSEMINATION AT NTSC

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We report on the development and characterization of novel simple-architecture microwave frequency dissemination via optical fiber using microwave phase compensation. A 10 GHz signal is transferred through a 50 km optical fiber spools with a fractional frequency instability of 3E-14 at 1 s integration time and 5.5E-18 at 40000 s integration time.

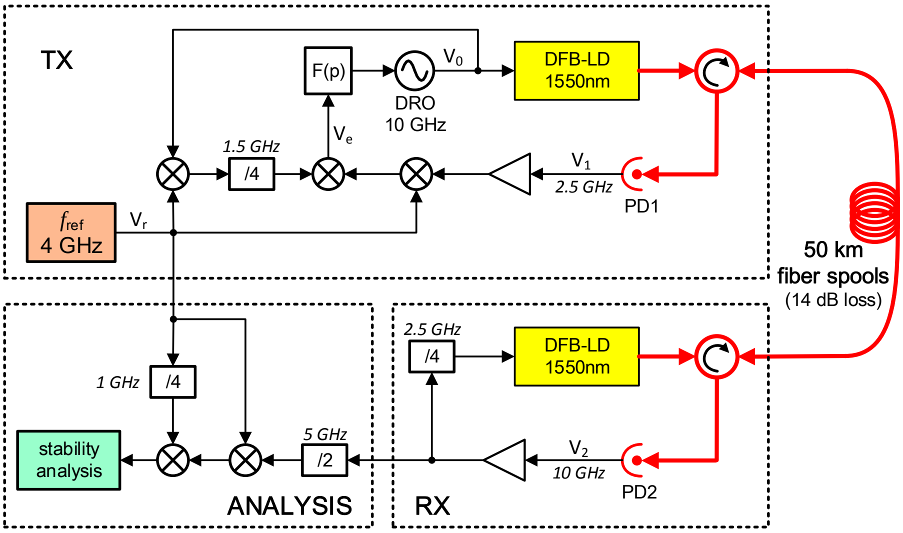

Fig. 1. Schematic of the microwave frequency dissemination system. DRO: dielectric resonator oscillators; DFB-LD: distributed feedback laser diode;

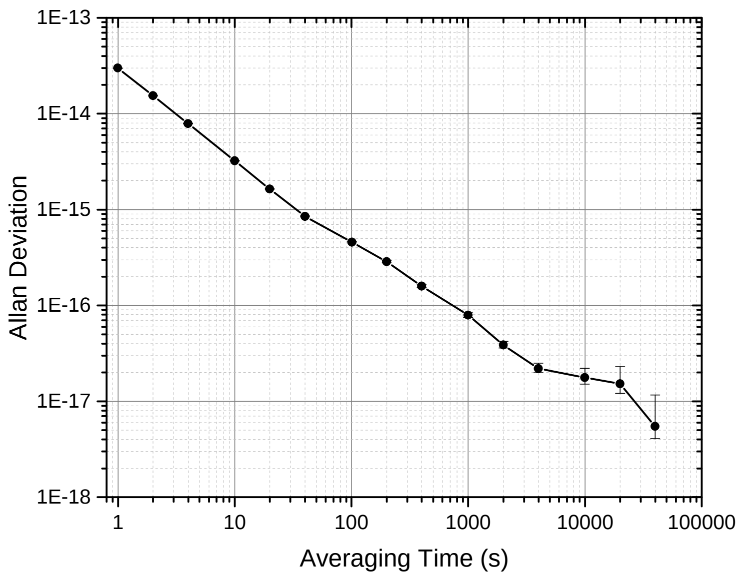

Fig. 2. Fractional frequency instability of the compensated link at 10 GHz