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Mid-infrared laser phase-locking to a remote near-infrared frequency reference for high precision molecular spectroscopy

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Abstract

We present a new method for accurate mid-infrared frequency measurements and stabilization to a near-infrared ultra-stable frequency reference, transmitted with a long-distance fibre link and continuously monitored against state-of-the-art atomic fountain clocks. As a first application, we measure the frequency of an OsO₄ rovibrational molecular line around 10 μm with a state-of-the-art uncertainty of 8×10^{-13} . We also demonstrate the frequency stabilization of a mid-infrared laser with fractional stability better than 4×10^{-14} at 1 s averaging time and a line-width below 17 Hz. This new stabilization scheme gives us the ability to transfer frequency stability in the range of 10^{-15} or even better, currently accessible in the near-infrared or in the visible, to mid-infrared lasers in a wide frequency range.

PACS : 06.20.-f (Metrology), 42.62.Eh (Metrological applications; optical frequency synthesizers for precision spectroscopy), 07.57.Ty (Infrared spectrometers, auxiliary equipment, and technique)

1. Introduction

With their rich internal structure, molecules can play a decisive role in precision tests of fundamental physics. They are for example now being used to test fundamental symmetries [1-3], and to measure either absolute values of fundamental constants [4] or their temporal variation [5-6]. Most of those experiments can be cast as the measurement of molecular frequencies. Ultra-stable and accurate sources in the mid-infrared (MIR) spectral region, the so-called molecular fingerprint region that hosts many intense rovibrational signatures, are thus highly desirable. MIR laser frequency stabilization has been performed for a long time using molecular references such as CH₄ or OsO₄ (see for instance [7-10]). However obtained stability is at least one order of magnitude below those of visible or near-infrared lasers stabilized to ultra-stable cavity. Moreover only a few molecular lines can be used when ultra-high accuracy is needed.

In this paper we present a new method for accurate mid-infrared laser frequency stabilization. The frequency reference is a near-infrared cavity stabilized laser continuously monitored against primary standards and the coherent frequency link between near-infrared and mid-infrared frequencies is obtained by using an optical frequency comb. Moreover we demonstrate this stabilization scheme with a remote near-infrared frequency reference transferred via an optical fibre link from a national metrological institute (NMI). This technique is thus accessible to any laboratory which can be connected to such a NMI with a fibre optical link [11].

Optical frequency combs have proven to be essential for laser frequency measurement and stabilization from the infrared to ultraviolet domain (see for instance [12]). Fractional accuracy and stability (at 10⁴ s averaging time) down to a few 10⁻¹⁶ are potentially reachable when the frequency reference is provided by advanced primary standards. Extension to MIR spectral domain has been demonstrated by comparing the MIR laser frequency to a very high harmonic of the comb repetition rate using sum or difference frequency generation [13-20]. Efforts have also been made towards the development of MIR frequency combs [10, 21-26].

In this paper we first describe the coherent frequency stability transfer between near- and mid-infrared frequencies around 10 μm. Then we demonstrate absolute frequency measurement of a MIR frequency with a fractional resolution of at least 4x10⁻¹⁴. We also report a first application to high resolution molecular

spectroscopy with a fractional uncertainty of 8×10^{-13} on the line centre. Finally we present the mid-infrared laser frequency stabilization against the near-infrared frequency reference leading to state-of-the-art stability.

2. Experimental set-up

The experimental setup is shown in figure. 1. The ultra-stable optical reference located at LNE-SYRTE is a 1.54 μm fibre laser locked to a high finesse cavity. Its fractional frequency instability was measured to be lower than 2×10^{-15} at 1 s and 10^{-14} at 100 s (after a 0.3-Hz/s drift was removed) [27]. Its frequency is measured using a fibre fs laser centered around 1.55 μm . The laser repetition rate is phase-locked to the optical reference frequency after removal of the comb frequency offset f_0 . Fast corrections are applied to an intra-cavity electro-optic modulator (bandwidth > 400 kHz) and slower corrections to a piezo-electric transducer (PZT) controlling the laser cavity length (bandwidth ~ 10 kHz) [28]. The absolute frequency of the comb repetition rate 36th harmonic (9 GHz) is continuously measured against the primary standards of LNE-SYRTE, which includes an H-maser, a cryogenic oscillator and Cs-fountains [29-30]. It enables real-time measurement of the ultra-stable laser frequency drift and its correction by applying to the driving frequency of an acousto-optic modulator an opposite linear drift (with a step every ms) updated every 100 s. This makes up an ultra-stable near-infrared reference, the frequency of which is currently traceable to primary standards with a 10^{-14} uncertainty after 100 s.

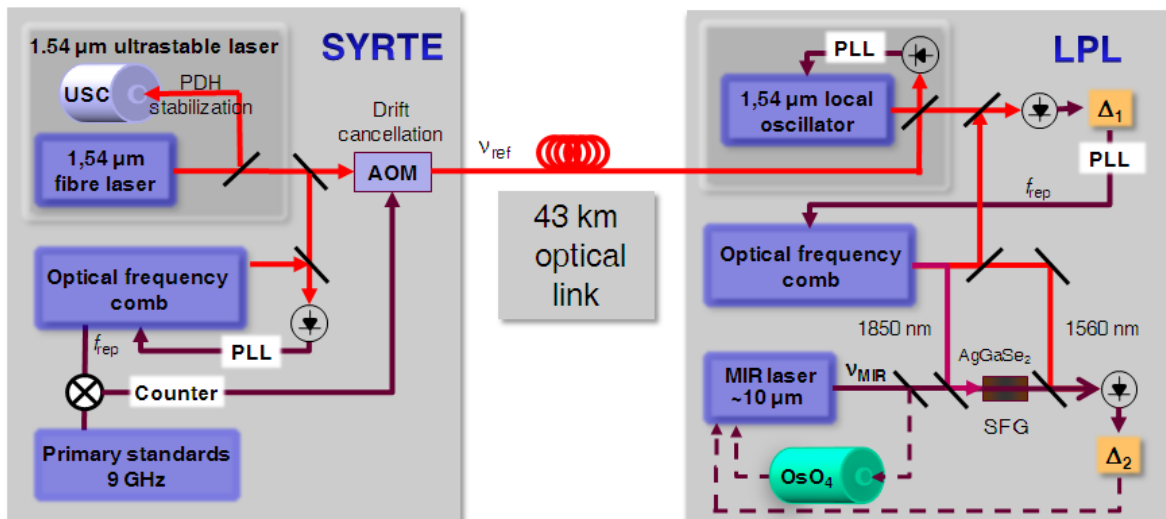


Figure 1. Experimental set-up. The MIR laser frequency can either be controlled with the beat-note Δ_2 or the OsO₄ absorption signal. PLL: phase-lock loop, PDH: Pound-Drever-Hall stabilization, SFG: sum-frequency generation, AOM: acousto-optic modulator, USC: ultra-stable cavity.

This optical reference signal is transmitted to LPL through a 43-km long optical link [27]. The free-running link exhibits a propagation instability of 2×10^{-14} at 1 s and around 10^{-15} between 100 s and 1 day. When compensated, the link instability has been measured to be roughly $10^{-15} \tau^{-1}$ and to reach around 10^{-18} after 10^3 s (see figure 3) [27]. The frequency stability and accuracy of the reference signal are thus preserved at the LPL optical link end.

At LPL, a low-noise laser diode (free-running linewidth below 10 kHz) is phase-locked to the incoming signal with a bandwidth of 100 kHz and constitutes the local optical frequency reference ν_{ref} . The repetition rate f_{rep} of a 1.55 μm fibre fs laser is phase-locked to ν_{ref} . To that purpose, the beat-note Δ_1 between ν_{ref} and the N^{th} comb mode ($N \sim 780000$) is used, after removal of the comb frequency offset f_0 :

$$\nu_{\text{ref}} - N f_{\text{rep}} = \pm \Delta_1 \quad (1)$$

Fast and slow corrections are applied to an intra-cavity electro-optic modulator and a PZT respectively as performed at LNE-SYRTE [28]. A second beat-note Δ_2 compares the MIR laser frequency ν_{MIR} around 10 μm and the n^{th} harmonic of the repetition rate with $n \approx 120000$:

$$\nu_{\text{MIR}} - n f_{\text{rep}} = \pm \Delta_2 \quad (2)$$

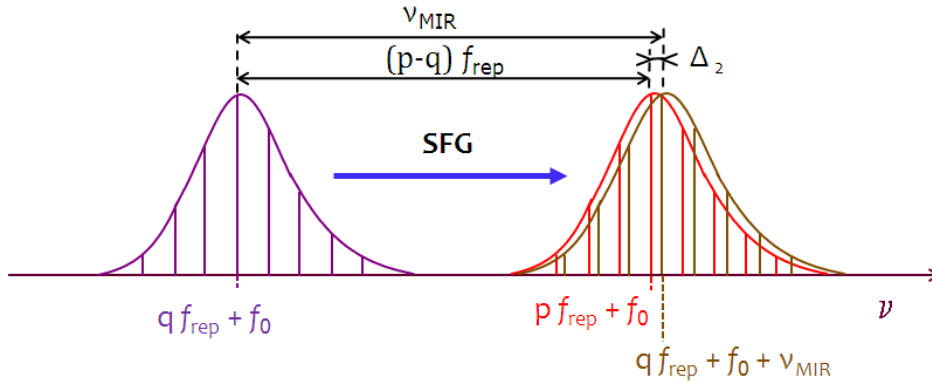


Figure 2. Sum-frequency of a comb output centred at 1850 nm (purple comb), of mode frequencies $q f_{\text{rep}} + f_0$ with q an integer, and the MIR laser (of frequency ν_{MIR} around 10 μm) results in a shifted comb (brown comb) centred at 1550 nm of mode frequencies $q f_{\text{rep}} + f_0 + \nu_{\text{MIR}}$. The beat-note of this shifted comb with the comb main output centred at 1550 nm (red comb), of mode frequencies $p f_{\text{rep}} + f_0$ with p an integer, can be written as $\Delta_2 = \pm q f_{\text{rep}} + f_0 + \nu_{\text{MIR}} - p f_{\text{rep}} + f_0$ which results in $\Delta_2 = \pm \nu_{\text{MIR}} - p - q f_{\text{rep}}$. SFG: sum-frequency generation.

This signal is generated using sum-frequency generation (SFG) of the MIR light and an additional comb output centred on 1.85 μm , generated in a non-linear fibre (figure 2) [14]. This comb output (~ 25 mW) and the MIR laser beam (~ 100 mW) are focused in a 10-mm long crystal of AgGaSe_2 for type I SFG. The measured efficiency is around 0.4 mW/W^2 and phase-matching bandwidth (for the 1.85 μm comb) is about 30 nm (~ 3 THz). The resulting shifted comb, centred on 1.55 μm , is combined with the 1.55 μm fs-laser output. An adjustable delay line enables to control the overlapping of the pulses in the time domain. About 10^4 mode pairs generate the beat-note Δ_2 which shows a signal-to-noise ratio of about 30 dB in a 100 kHz bandwidth. A RF tracking oscillator is phase-locked to this beat-note. Resulting from the frequency difference between two modes of the same comb, Δ_2 is independent of the comb offset f_0 .

Combining (1) and (2), the MIR laser frequency ν_{MIR} is finally obtained as:

$$\nu_{\text{MIR}} = \pm \Delta_2 + \frac{n}{N} \nu_{\text{ref}} \mp \Delta_1 \quad (3)$$

with n/N roughly 0.15. The MIR frequency is thus directly linked to the near-infrared frequency reference, once the integers n and N and the signs have been determined.

3. MIR frequency measurement and stabilisation

To characterize the phase-coherent link between the near-infrared frequency reference and the MIR frequency, we used this setup to measure the absolute frequency of a CO_2 laser stabilized onto an OsO_4 saturated absorption line. Such a OsO_4 -stabilized CO_2 laser constitutes the current state-of-the-art MIR secondary reference standard [7-8]. In this work, the CO_2 laser was locked either to the P(55) line of $^{190}\text{OsO}_4$ near the 10.55 μm P(16) CO_2 laser line or to the R(67) line of $^{192}\text{OsO}_4$ near the 10.25 μm R(20) CO_2 laser line. Corrections are applied to a PZT controlling the laser cavity length with a stabilization bandwidth of about 400 Hz limited by the PZT actuator. The obtained fractional frequency stability, shown in figure 3 (red circles and blue squares), is 4×10^{-14} at 1 s, reaches 10^{-14} after 100 s of integration, and degrades at longer times due to a frequency drift of the CO_2/OsO_4 frequency reference. We checked that this stability was limited by the CO_2/OsO_4 reference since changing the CO_2 laser locking parameters induced a variation of the obtained stability. This stability is consistent with previous measurements obtained by comparing either two identical stabilized CO_2 lasers [7-8] or one of such lasers to a titanium-sapphire (Ti:Sa) frequency comb referenced to a microwave frequency [13].

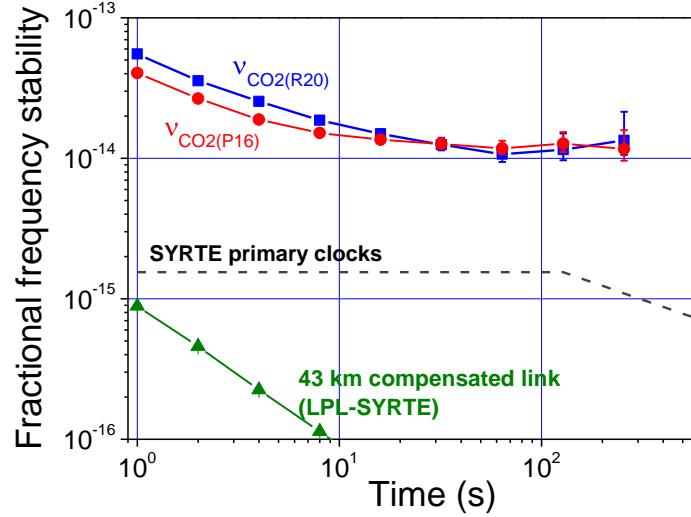


Figure 3. Frequency stability of a CO₂ laser locked on two different OsO₄ saturated absorption lines: the P(55) line of ¹⁹⁰OsO₄ near the 10.55 μm P(16) CO₂ laser line (red circles ●) and the R(67) line of ¹⁹²OsO₄ near the 10.25 μm R(20) CO₂ laser line (blue squares ■). The propagation instability of the compensated LPL-SYRTE fibre link (green up-triangles ▲) and the SYRTE primary standards stability (dashed line) are shown for comparison. .

This demonstrates the capability of the system to measure the stability of the best MIR frequency sources to date without any degradation. We expect the optical link and the frequency comb to contribute a few 10^{-15} at 1 s to the frequency instability [27-28].

The relationship of equation (3) between the frequency of the 1.54 μm LNE-SYRTE reference laser and that of the MIR laser is ensured by means of coherent phase-lock loops. Thus the accuracy of the MIR frequency measurement only depends on the uncertainty of the near-infrared frequency reference. The latter is known with an uncertainty of about 10^{-14} after 100 s averaging time, when only steered with the H-maser which is sufficient for this experiment. The 3×10^{-16} Cs fountain accuracy [30] can ultimately be reached and then transferred from the optical reference to the MIR frequency.

As a first application to high-precision spectroscopy, we determined the absolute frequency of the P(55) line of ¹⁹⁰OsO₄ by measuring the OsO₄-stabilized CO₂ laser frequency. Eleven measurements were performed between December 2011 and April 2012. The beat-note Δ_2 , the repetition rate f_{rep} and the frequency ν_{ref} were counted with a gate time of 1 s. Δ_2 and ν_{ref} were combined using equation (3) to calculate the CO₂/OsO₄ frequency. Signs in Eq. 3 and values of n and N were unambiguously deduced from f_{rep} and the value $\nu_{OsO_4/1999} = 28\,412\,648\,819\,596\,(45)$ Hz of the CO₂/OsO₄ frequency obtained by combining two independent measurements reported in the literature [31-32]. The mean value over 600 measurements of 1 s of the CO₂/OsO₄

frequency gives one data point. For each data point, we correct the frequency of the LNE-SYRTE H-maser using the data published by Bureau International des Poids et Mesures (BIPM) [33]. Between each measurement the OsO₄ absorption cell was pumped and filled again or the whole experiment was switched off and on. We obtained $\nu_{\text{OsO}_4/2012}=28412648819588$ (24) Hz where the uncertainty is the weighted 1- σ deviation of the data points. It is -8 Hz from the value $\nu_{\text{OsO}_4/1999}$ and +8 Hz from another measurement performed in 2004 with a microwave-referenced Ti:Sa frequency comb with an uncertainty of 58 Hz [13]. Within 1- σ error bars the present result agrees with the previous measurements and confirms the very high accuracy of the measurement setup. The factor of 2 improvement of the uncertainty obtained in the measurement reported here, still limited by the molecular reference, is due to a better control of the OsO₄ pressure and optimization of the CO₂ laser locking parameters.

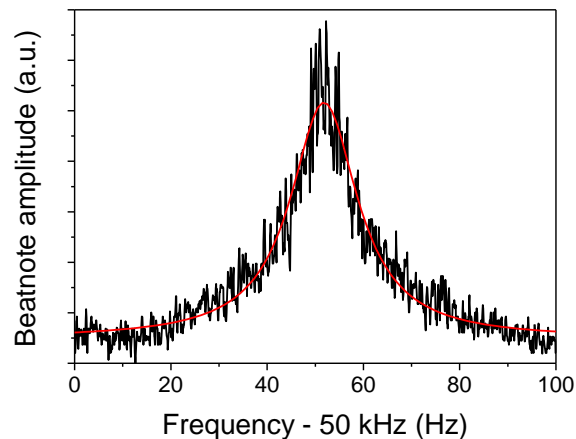


Figure 4. Down-converted beatnote of two independent CO₂ lasers, one stabilised on an OsO₄ resonance line, the other phase-locked to a comb repetition rate high-harmonic; red line is a Lorentzian fit of linewidth 17 Hz

From the previous results, we conclude that the coherent frequency chain is a viable and potentially much better alternative to an OsO₄ molecular transition for frequency stabilization of a MIR source. This was investigated by locking the CO₂ laser frequency to the optical comb: the beat-note of the free-running CO₂ laser with the comb repetition rate n^{th} harmonic, Δ_2 , was phase-locked onto a stable frequency synthesizer with a 400 Hz bandwidth. The obtained CO₂ laser frequency stability is characterized by measuring the beat-note Δ_3 with a second independent CO₂ laser stabilized onto OsO₄. Figure 4 displays this beatnote signal, fitted with a Lorentzian of linewidth 17 Hz (full width at half maximum). In the case of a Lorentzian lineshape, the contribution of each laser linewidth adds [34] and we deduce a linewidth between 8.5 and 17 Hz for each laser,

the state of the art for a CO₂ laser [7]. Figure 5 displays Δ_3 's frequency noise power spectral density (PSD) (red trace). Using the beat-note Δ_2 with the local frequency comb, the frequency noise PSD of the OsO₄-stabilized CO₂ laser was also measured (figure 5, blue trace). The two PSD almost perfectly overlap as expected from efficient phase stabilization. Together with the above results, it shows that the comb-stabilized MIR laser frequency noise is at least as low as the one of the OsO₄-stabilized laser. The former is most probably much lower, potentially compatible with the frequency noise of the optical frequency reference which inferred PSD (including noise added by the link) is displayed in figure 5 (dotted black line). This noise level is the lowest reachable with our stabilization scheme.

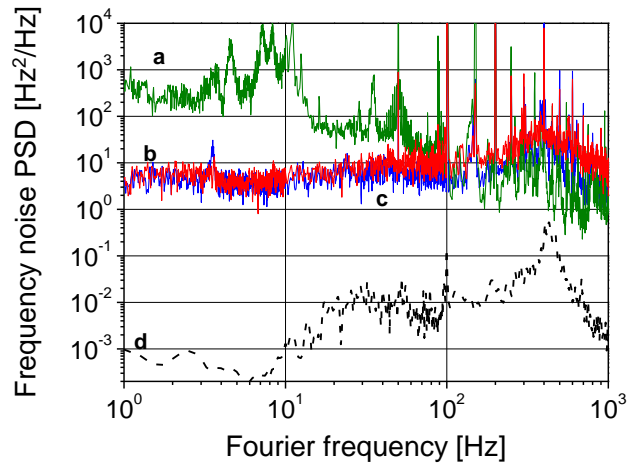


Figure 5. Frequency noise PSD of (a) the free-running CO₂ laser (green trace), (b) the beat-note between the CO₂ laser stabilized onto the frequency comb and an independent OsO₄-stabilized CO₂ laser (red trace), (c) the OsO₄-stabilized CO₂ laser measured with the comb (blue trace), and (d) the optical reference (dotted black line). The free-running CO₂ laser PSD has been measured using the beat-note Δ_2 with the local frequency comb and is given for comparison.

4. Conclusion

We have demonstrated a coherent frequency chain linking a remote ultra-stable 1.54 μm frequency reference and a MIR source, leading to the control of the absolute MIR frequency. It uses reliable commercially available fibre-based frequency combs and an optical reference potentially available to any laboratory connected to a fibre network [11]. Stability below 4×10^{-14} at 1 s was demonstrated, and we expect it to be in the 10^{-15} range. Using a

state-of-the-art near-infrared ultra-stable laser [35] may reduce this value even further. The 3×10^{-16} accuracy of the LNE-SYRTE Cs fountains is potentially within reach.

Frequency tuning of such a stabilized MIR laser source, required for high resolution spectroscopy, is achievable by scanning the near-infrared frequency referencing the comb. Tuning the frequency offset between the LNE-SYRTE optical reference and the LPL laser diode of frequency ν_{ref} (see equation (3)) would result in a tuning range of a few GHz.

This setup enables to stabilize MIR laser sources in a much wider spectral range than is currently possible using the OsO₄ molecular standard. With the present setup the 9-11 μm range is accessible, limited by the non-linear crystal and the central frequency of the auxiliary 1.85 μm comb output used in the sum-frequency generation. Nevertheless, it can easily be extended to the whole 5-20 μm range with proper comb spectrum and crystal optimization. Orientation-patterned GaAs would for instance ensure a wide tunability [36]. Our stabilization technique is thus particularly well-suited to quantum cascade lasers that have achievable wavelengths covering the whole MIR region [37]. Moreover, the ongoing work on dissemination of optical reference through Internet fibre networks over a continental scale [11] will eventually enable many laboratories to access an ultra-stable optical reference. Thus such ultra-stable and accurate MIR sources could benefit a very wide molecular spectroscopy community.

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REFERENCES

- [1] DeMille D., Cahn S.B., Murphree D., Rahmlow D.A. and Kozlov M.G. 2008 Using Molecules to Measure Nuclear Spin-Dependent Parity Violation *Physical Review Letters* **100** 023003
- [2] Darquié B. et al 2010 Progress toward a first observation of parity violation in chiral molecules by high-resolution laser spectroscopy *Chirality* **22** 870-884
- [3] Hudson J.J., Kara D.M., Smallman I.J., Sauer B.E., Tarbutt M.R. and Hinds E.A. 2011 Improved measurement of the shape of the electron *Nature* **473** 493
- [4] Koelemeij J.C.J., Roth B., Wicht A., Ernsting I. and Schiller S. 2007 Vibrational spectroscopy of HD⁺ with 2-ppb accuracy *Physical Review Letters* **98** 173002
- [5] Shelkownikov A., Butcher R.J., Chardonnet C. and Amy-Klein A. 2008 Stability of the Proton-to-Electron Mass Ratio *Physical Review Letters* **100** 150801
- [6] Hudson E.R., Lewandowski H.J., Sawyer B.C. and Ye J. 2006 Cold molecule spectroscopy for constraining the evolution of the fine structure constant *Physical Review Letters* **96** 143004
- [7] Bernard V., Daussy C., Nogues G., Constantin L., Durand P.E., Amy-Klein A., van Lerberghe A. and Chardonnet C. 1997 CO₂ laser stabilization to 0.1 Hz level using external electrooptic modulation *IEEE J. Quantum Electron.* **33** 1282-1287
- [8] Acef O. 1997 Metrological properties of CO₂/OsO₄ optical frequency standard *Optics Communications* **134** 479-486
- [9] Gubin M. A., Tyurikov D. A., Shelkownikov A. S., Koval'chuk E. V., Kramer G. and Lipphardt B. 1995 Transportable HeNe/CH₄ optical frequency standard and absolute measurements of its frequency *IEEE J. Quantum Electron.* **31** 2177
- [10] Foreman S.M., Marian A., Jun Ye J., Petrukhin E.A., Gubin M.A., Mücke O.D., Wong F.N.C., Ippen E.P. and Kärtner F.X. 2005 Demonstration of a HeNe/CH₄-based optical molecular clock *Optics Letters* **30** 570-572
- [11] Lopez O., Haboucha A., Chanteau B., Chardonnet C., Amy-Klein A. and Santarelli G. 2012 Ultra-stable long distance optical frequency distribution using the Internet fiber network *Optics Express* **20** 23518
- [12] Cundiff S. T., Ye J. and Hall J. L. 2001 Optical frequency synthesis based on mode-locked lasers *Review of Scientific Instruments* **72** 3749
- [13] Daussy C. et al 2005 Long-distance frequency dissemination with a resolution of 10⁻¹⁷ *Physical Review Letters* **94** 203904
- [14] Amy-Klein A., Goncharov A., Guinet M., Daussy C., Lopez O., Shelkownikov A. and Chardonnet C. 2005 Absolute frequency measurement of a SF₆ two-photon line by use of a femtosecond optical comb and sum-frequency generation *Optics Letters* **30** 3320

- [15] Bielsa F., Djerroud K., Goncharov A., Douillet A., Valenzuela T., Daussy C., Hilico L. and Amy-Klein A. 2008 HCOOH High resolution spectroscopy in the 9.18 μ m region *Journal of Molecular Spectroscopy* **247** 41–46
- [16] Vainio M., Merimaa M. and Halonen L. 2012 Frequency-comb-referenced molecular spectroscopy in the mid-infrared region *Optics Letters* **36** 4122
- [17] Bressel U., Ernsting I. and Schiller S. 2012 5 μ m laser source for frequency metrology based on difference frequency generation *Optics Letters* **37** 918
- [18] Borri S. et al 2012 Direct link of a mid-infrared QCL to a frequency comb by optical injection *Optics Letters* **37** 1011
- [19] Mills A.A., Gatti D., Jiang J., Mohr C., Mefford W., Gianfrani L., Fermann M., Hartl I. and Marangoni M. 2012 Coherent phase lock of a 9 μ m quantum cascade laser to a 2 μ m thulium optical frequency comb *Optics Letters* **37** 4083-4085
- [20] Galli I. et al 2013 Comb-assisted subkilohertz linewidth quantum cascade laser for high-precision mid-infrared spectroscopy *Applied Physics Letters* **102** 121117
- [21] Schliesser A., Picqué N. and Haensch T.W. 2012 Mid-infrared frequency combs *Nature Photonics* **6** 440-449
- [22] Adler F., Cossel K.C., Thorpe M.J., Hartl I., Fermann M.E. and Ye J. 2009 Phase-stabilized, 1.5 W frequency comb at 2.8-4.8 μ m *Optics Letters* **34** 1330-1332
- [23] Baumann E., Giorgetta F.R., Swann W.C., Zolot A.M., Coddington I. and Newbury N.R. 2011 Spectroscopy of the methane ν_3 -band with an accurate midinfrared coherent dual-comb spectrometer *Physical Review A* **84** 062513
- [24] Hugi A., Villares G., Blaser S., Liu H.C. and Faist J. 2012 Mid-infrared frequency comb based on a quantum cascade laser *Nature* **492** 229-233
- [25] Coluccelli N., Gambetta A., Sala T., Gatti D., Marangoni M., Laporta P. and Galzerano G. 2012 Frequency-stabilized 1 W optical comb at 2.2-2.6 μ m by Cr²⁺:ZnSe multipass amplification *Optics Letters* **37** 4440
- [26] Gambetta A., Coluccelli N., Cassinero M., Gatti D., Laporta P., Galzerano G. and Marangoni M. 2013 Milliwatt-level frequency combs in the 8-14 μ m range via difference frequency generation from an Er: fiber oscillator *Optics Letters* **38** 1155
- [27] Jiang H. et al 2008 Long-distance frequency transfer over an urban fiber link using optical phase stabilization *J. Opt. Soc. Am. B* **25** 2029
- [28] Zhang W., Lours M., Fischer M., Holzwarth R., Santarelli G. and Le Coq Y. 2012 Characterizing a fiber-based frequency comb with electro-optic modulator *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control* **59** 432
- [29] Chambon D., Bize S., Lours M., Narbonne F., Marion H., Clairon A., Santarelli G., Luiten A. and Tobar M. 2005 Design and realization of a flywheel oscillator for advanced time and frequency metrology *Review of Scientific Instruments* **76** 094704-094704-5

- [30] Guena J. et al 2012 Progress in atomic fountains at LNE-SYRTE *IEEE Trans. on Ultras. Ferro. and Frequ. Contr.* **59** 391-410
- [31] Chardonnet C. and Bordé C.J. 1994 Hyperfine Interactions in the ν_3 Band of Osmium Tetroxide: Accurate Determination of the Spin-Rotation Constant by Crossover Resonance Spectroscopy *Journal of Molecular Spectroscopy* **167** 71-98
- [32] Acef O., Michaud F. and Rovera G.D. 1999 Accurate determination of OsO₄ absolute frequency grid at 28/29 THz *IEEE Transactions on Instrumentation and Measurement* **48** 567-570
- [33] see publication of the clocks' rates relative to TAI on <ftp://ftp2.bipm.org/pub/tai/publication/>
- [34] Elliott D.S., Roy R. and Smith S.J. 1982 Extracavity laser band-shape and bandwidth modification *Physical Review A* **26** 12-18
- [35] Kessler T., Hagemann C., Grebing C., Legero T., Sterr U., Riehle F., Martin M.J., Chen L. and Ye J. 2012 A sub-40-mHz-linewidth laser based on a silicon single-crystal optical cavity *Nature Photonics* **6** 687-692
- [36] Eyres L.A., Tourreau P.J., Pinguet T.J., Ebert C.B., Harris J.S., Fejer M.M., Becouarn L., Gerard B. and Lallier E. 2001 All-epitaxial fabrication of thick, orientation-patterned GaAs films for nonlinear optical frequency conversion *Applied Physics Letters* **79** 904
- [37] Yao Y., Hoffman A.J. and Gmachl C.F. 2012 Mid-infrared quantum cascade lasers *Nature Photonics* **6** 432