Poster List (Poster Session: Jan. 25th - 26th)

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<th>Yb and Sr optical lattice clocks at NMIJ</th>
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</tr>
<tr>
<td>Affiliation</td>
<td>¹ National Metrology Institute of Japan (NMIJ), National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, Ibaraki 305-8563, Japan ² Department of Physics, Graduate School of Engineering, Yokohama National University, Yokohama 240-8501, Japan</td>
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Abstract

Recently, we developed the second optical lattice clock at the National Metrology Institute of Japan (NMIJ). This system can be used as strontium and ytterbium optical lattice clocks, since the oven is filled with strontium and also ytterbium. To share the optical light source with our first ytterbium optical lattice clock, we have newly developed an injection locking system for 399 nm light source, which delivers the light of around 70 mW for each system. We also improved a light source at 578 nm to drive the clock transition in ytterbium. We have developed an external cavity laser diode operated at 1156 nm with the second harmonic generation scheme by using a periodically poled lithium niobate. The laser is stabilised to the optical frequency comb that is tightly locked to a narrow linewidth master laser operated at 1064 nm. Owing to the relatively large servo bandwidth (> 4 MHz), pre-stabilisation is not needed for phase locking to the comb. We have successfully observed the ytterbium clock transitions of about 50 Hz linewidth in the second optical lattice clock system.

In 2014, the frequency of the clock transition in strontium-87 was measured. The absolute frequency was determined as 429 228 004 229 872.0 (1.6) Hz relative to the SI second [1]. At that time the uncertainty of the absolute frequency was mainly limited by the uncertainty of a comparison with UTC(NMIJ). Recently, we carefully evaluate the uncertainties of the
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link between the Sr optical lattice clock and TAI via UTC(NMIJ) using a caesium fountain atomic clock located at NMIJ as a transfer oscillator. In this way, we reduced the final uncertainty to one third that of our previous measurement. The absolute value of the transition frequency is $429\,228\,004\,229\,873.56(49)$ Hz [2].

The frequency ratio of the $^1S_0 - ^3P_0$ clock transitions in ytterbium-171 and strontium-87 is measured by an optical-optical direct frequency link between two optical lattice clocks. In this frequency link, an Nd:YAG laser operating at 1064 nm was used as a master laser to stabilised fibre combs and then the two clock lasers for strontium-87 and ytterbium-171 are phase locked to their respective combs. We determined the ratio to be $1.207\,507\,039\,343\,341\,2(17)$ with a fractional standard uncertainty of $1.4 \times 10^{-15}$ [3].

References
    D. Akamatsu et al., ibid. 22(26), 32199 (2014).
Abstract
Optical lattice clock is an epoch-making device that provides not only ultra-stable time frequency standard but also accurate relative physical heights through detecting variations of clock rates caused by spatially variable geopotential numbers on the earth. Currently, there exist multiple definitions for physical heights. To resolve this issue, the International Association for Geodesy (IAG) has recently adopted a resolution which recommends adopting geopotential numbers for describing physical heights on the earth. However, conventional measurement techniques for relative geodetic elevations such as leveling survey and gravity measurement do not directly provide geopotential numbers, and hence require time-consuming conversion into geopotential numbers that may introduce systematic errors partly due to assumption and approximation involved in the process. On the other hand, geopotential numbers provided by optical lattice clocks is expected to offer bias free relative elevations without any assumption and approximation. In this paper, we will discuss a possibility of utilizing the relative elevations derived from optical lattice clocks for defining and maintaining geodetic reference frame of physical heights, which is fundamental infrastructure for almost all of social and scientific activities.
**Presentation title**  
Generation of a time-scale steered by an $^{87}$Sr optical lattice clock

**Name**  
H. Hachisu, F. Nakagawa, Y. Hanado, and T. Ido

**Affiliation**  
NICT

**Abstract**

Optical clocks have made remarkable progress and surpassed the state-of-the-art microwave clocks in stability as well as accuracy. This fact promotes the discussion about the redefinition of the second. The generation of a time-scale might be an example where the transition from microwave to optical clocks occurs. A few advanced institutes currently maintain their local time-scale by steering the frequency of a hydrogen maser (H-maser) with reference to microwave fountain standards. In this case, continuous operation of fountains is generally required. Due to a high stability of an optical lattice clock, on the other hand, intermittent frequency evaluation might be enough for the “optical” steering. The time-scale at NICT, UTC(NICT), is also maintained likewise by using a H-maser as the source oscillator. However, it is steered by an ensemble time generated from eighteen commercial Cs clocks. The stabilities of the most stable H-masers reach $1 \times 10^{-15}$ at $10^3$ s and stay at $10^{-16}$ level until $10^4$ s. The $^{87}$Sr lattice clock at NICT has an accuracy of $8.6 \times 10^{-17}$ [1]. Therefore, $10^4$ s of frequency measurement with reference to our $^{87}$Sr clock is sufficient to calibrate the time-scale with uncertainty of $1 \times 10^{-15}$ level, by which we can adjust it in real time. In order to confirm this prospect, we operated the lattice clock for $10^4$ s per day on five consecutive days and estimated the possible gain or loss of UTC(NICT). The estimation agreed in sub-ns level with time difference of UTC(NICT)-UTC, which we can obtain one month later in Circular T. Furthermore, numerical investigation using a real log data of Japan Standard Time system showed that the intermittent operations of the $^{87}$Sr lattice optical clock are capable of maintaining a time-scale with a precision of a few ns level.

We report a system of two independent optical lattice standards with $^{88}\text{Sr}$ probed with a single shared ultra-narrow laser [1,2]. We achieve frequency stability (frequency between two standards) of $7 \cdot 10^{-17}$.

The 20 km-long stabilized fibre optic link between KL FAMO and Toruń Centre for Astronomy made possible to use the optical clocks as a frequency reference for the 32 m precise parabolic antenna of the radio telescope in the Toruń Centre for Astronomy participating in the VLBI networks.

The absolute frequency of the clock transition can be measured by the use of an optical frequency comb referenced to the UTC(AOS) and UTC(PL) [3,4] via the 330 km-long distance stabilized fiber optic link of the OPTIME network [5].

We present current status of the KL FAMO optical lattice clocks, including their frequency stability, the uncertainty budget and the measured absolute frequency of the $^{1}\text{S}_0-^{3}\text{P}_0$ clock transition. The value of the absolute frequency of the clock transition was verified by series of measurements on two independent optical lattice clocks and agrees with recommendation of Bureau International des Poids et Mesures.

References:
Poster No.4

[5] Ł. Śliwczyński et al., “Dissemination of time and RF frequency via a stabilized fibre optic link over a distance of 420 km”, Metrologia, 50 133 (2013)
Measuring absolute frequencies beyond the GPS limit via long-haul optical frequency dissemination

D. Calonico¹, C. Clivati¹, G. Cappellini¹,², L. Livi³, F. Poggiali², M. Siciliani de Cumis¹,⁴, M. Mancini³, G. Pagano³, M. Frittelli¹, A. Mura¹, G. A. Costanzo¹,⁵, F. Levi¹, L. Fallani³,², J. Catani²,⁴, and M. Inguscio¹,²,³

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2. LENS European Laboratory for Nonlinear Spectroscopy, Sesto Fiorentino, Italy
3. Department of Physics and Astronomy, University of Florence, Sesto Fiorentino, Italy
4. INO-CNR Istituto Nazionale di Ottica CNR, sez. Sesto Fiorentino, Italy

Abstract

Coherent fiber links are the best method available for continental remote clocks comparisons [1] and their exploitation can also move forward present metrology in the quest for new physics. Another relevant application is the optical dissemination of frequency standards to non-metrological laboratories with an unprecedented level of stability and accuracy. In Italy, a 650-km long coherent optical fiber link disseminates a Cs fountain clock to relevant research centers [2], as the European Laboratory for Non-Linear Spectroscopy (LENS) in Florence. We exploited the coherent fiber link to measure the frequency of the forbidden transition $^1S^0-^3P^0$ of $^{173}$Yb, in an ultracold gas used for quantum simulation [3]. We demonstrated the coherent optical link as a tool for high-precision spectroscopy, at a level that standard techniques cannot obtain. We also report an improvement of two orders of magnitude in the accuracy on the clock transition frequency reported in literature. At the conference, we will report on the experimental set-up, on the results obtained and on the future developments.

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<tr>
<td>Affiliation</td>
<td>INRIM Istituto Nazionale di Ricerca Metrologica, Torino, Italy</td>
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Abstract

Optical clocks are outperforming the present primary frequency standard based on Cs by one or more orders of magnitude in accuracy as well as in stability [1]. BIPM has recognized the $^1S_0 \rightarrow ^3P_0$ forbidden transition in neutral Ytterbium as a secondary representation of the second [3]. At INRIM, an optical lattice clock based on neutral $^{171}$Yb is under operation and currently the metrological characterization of the standard is ongoing. The dipole trap at the magic wavelength of 759 nm collects up to $10^4$ atoms in about 200 ms, starting from a double stage MOT at 399 nm and 556 nm. The captured atoms are then spin-polarized using the $^1S_0 \rightarrow ^3P_1$ transition, and then the clock transition $^1S_0 \rightarrow ^3P_0$ ($\Gamma = 10$ mHz) at 578 nm is probed by a laser stabilized to an ultra-stable cavity (Finesse $F = 150.000$). The cycle duration sums up to about 350 ms. The light generation at 399 nm [4], 556 nm and 578 nm [5] is based on infrared lasers and sum- or double-frequency generation in nonlinear crystals, while the lattice light is being obtained directly via a Ti:Sa laser.

At the conference, we present the first characterization of the clock, the absolute frequency measurements towards the INRIM cryogenic Cs fountain (accuracy $2 \times 10^{-16}$) [6]. Moreover, we describe the ongoing activities involving the Yb clock, in particular a relativistic geodesy experiment within the European project International Timescale with Optical Clocks.

References

Presentation title | Evidence of Orbital Feshbach Resonances and Chiral Edge States in Yb Fermi Gases
---|---
Name | Jacopo Catani
Affiliation | LENS & INO-CNR – Florence (ITALY)

**Abstract**

In this poster I report on recent results obtained in two different sets of experiments exploiting both nuclear and orbital degrees of freedom in a quantum degenerate gas of fermionic Yb. Firstly, I report on the evidence of Feshbach scattering resonances which are observed in the open channel involving different electronic orbitals (tagged by the ground-state and the 3P0 metastable state). The metastable state is loaded by a coherent manipulation of the 1S0 transition via an ultranarrow laser. The universal behavior which is observed in the position of resonance centers as a function of the relative spin projection of the scattering particles reflects the SU(N) character of interactions in the Yb atom. The strong interacting regime is achieved by tuning the scattering length via this novel kind of resonance.

Secondly, I report on the observation of edge states in an atomic Hall ribbon, implemented by exploiting the concept of “synthetic dimensions” envisioned in the controllable, internal nuclear degree of freedom. Combining this technique with standard optical lattices, we create a 2D ribbon on which we overlay a strong artificial magnetic flux realized through a Raman phase. Atoms hence acquire a topological phase across a “synthetic” plaquette. Similarly to the behavior of electrons in a Hall system, edge states are observed, as long as their “skipping” trajectories, bouncing off the geometrical edges of the atomic systems. Such edge states show a true chiral behavior, whereas inner bulk states of the systems are shown not to take part to the chiral transport.
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<td>Ye Li</td>
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<td>Affiliation</td>
<td>National Institute of Metrology, Beijing, China</td>
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**Abstract**

An optical lattice clock based on $^{87}$Sr is being built at the National Institute of Metrology (NIM). After two stages of laser cooling, the temperature of the atoms was cooled to ~3 μK. The 813 nm lattice beam is focused to the center of the magneto-optical trap (MOT) and then retro-reflected by a dichroic mirror to form a standing wave optical lattice. About 10,000 atoms are trapped in the horizontally oriented 1-dimensional optical lattice. The 698 nm clock laser is an external-cavity diode laser (ECDL) locked to a high finesse 10-cm reference cavity with the Pound-Drever-Hall (PDH) technique. The short term stability (<10 s) of this clock laser is measured to be $3 \times 10^{-15}$. The clock laser beam is precisely co-aligned with the 813 nm lattice laser from the opposite direction using the dichroic mirror mentioned above. The Rabi excitation linewidth is as narrow as 3 Hz with a 320 ms clock laser probe pulse after the atoms were spin-polarized. The normal running of the clock uses 80 ms probe pulse (the Fourier-limited Rabi linewidth is ~10 Hz) for the robustness of the atomic lock. Two independent digital servos are used to lock the clock laser time-multiplexed to the two stretched state transitions. The average of the two digital locks gives the center frequency of the Sr lattice clock.

The first systematic shifts evaluation of our $^{87}$Sr clock has been done. The self-comparison method is performed to evaluate the systematic shifts uncertainties. Two independent atomic servos that share the same physical apparatus are compared in a time-interleaved way. The zero shift frequency of the optical lattice is determined to be 368 554 672(44) MHz. The total systematic uncertainty of our Sr clock is evaluated to be $2.3 \times 10^{-16}$.

The absolute frequency of the Sr clock is traced to NIM5 Cs fountain. A 50-km fiber link with active fiber noise cancellation (FNC) is applied to transfer the NIM5 calibrated H-maser frequency from the time keeping lab to the Sr lab. The absolute frequency of the clock is measured to be 429 228 004 229 873.7(1.4) Hz with the measurement uncertainty of $3.4 \times 10^{-15}$. 
Poster No.9

**Presentation title**  
Compact iodine-stabilized laser using a coin-sized laser module

**Name**  
Takumi Kobayashi\(^1,2,3\), Daisuke Akamatsu\(^2\), Kazumoto Hosaka\(^2,3\), Hajime Inaba\(^2,3\), Sho Okubo\(^2,3\), Takehiko Tanabe\(^2\), Masami Yasuda\(^2\), Atsushi Onae\(^2,3\), and Feng-Lei Hong\(^1,2,3\)

**Affiliation**  
1 Yokohama National University  
2 Advanced Industrial Science and Technology  
3 ERATO, MINOSHIMA Intelligent Optical Synthesizer Project

**Abstract**  
We demonstrate a compact iodine-stabilized laser emitting at 531 nm using a coin-sized light source consisting of a 1062-nm distributed-feedback diode laser and a periodically poled lithium niobate for second harmonic generation. A hyperfine transition of molecular iodine is observed using the light source with saturated absorption spectroscopy. The light source is stabilized to the observed iodine transition and achieves frequency stability at the 10\(^{-12}\) level. The absolute frequency of the compact laser stabilized to the a\(_1\) hyperfine component of the R(36)32-0 transition is determined as 564 074 632 419(8) kHz. The iodine-stabilized laser can be used for various applications including interferometric measurement of gauge blocks, the calibration of a wavemeter, a laser gravimeter, and an absolute frequency marker for an astro-comb.
**Presentation title**  
FPGA-based high finesse cavity control for a narrow line-width CW laser

**Name**  
Isao Ito, Yohei Kobayashi

**Affiliation**  
ISSP, Univ. Tokyo, JST-ERATO

**Abstract**

A narrow line-width CW laser is one of the most important tools in Atomic, Molecular and Optical Physics. One of the methods that realizes the narrow line-width CW laser is high finesse cavity locking. Here, we have developed a Field Programmable Gate Array (FPGA)-based servo for high finesse cavity locking. FPGA is an integrated circuit that can be reconfigured by a software. FPGA makes high finesse cavity locking technique more flexible. This feature is the greatest benefit of digital technique.

Figure 1 shows the setup of the FPGA-based servo. We lock an ECDL output to a high finesse cavity (F=300,000) by PDH method. An ADC (14bit, 100MS/s) samples the PDH signal and the PID circuit on FPGA (50MHz) processes the PDH signal, and then a DAC (14bit, 100MS/s) outputs a control signal to the ECDL. Feedback bandwidth of the FPGA-based servo is up to about 1MHz (limited by 500ns total latency). So an analog proportional circuit supports higher feedback bandwidth than 1MHz. FPGA enables our narrow line-width CW laser to realize automatic and remote operation.

Additionally, we have succeeded to lock two ECDLs to two independent high finesse cavities using two circuits in one FPGA. Several digital circuits on FPGA can work in parallel. So it is easy for the FPGA-based servo to expand multi cavity locking. Figure 2 shows beat spectrum between two narrow line-width CW lasers controlled by one FPGA-based servo. The FPGA-based servo realized 1.8Hz beat line-width of two CW lasers. It is good enough for some Atomic, Molecular and Optical applications.

![Figure 1. Setup](image1)

![Figure 2. Beat signal](image2)
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<td>Name</td>
<td>T.Kubo, E.Kajikawa, Y.Takeuchi, M.Musha</td>
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<td>Affiliation</td>
<td>Institute for Laser Science, Univ. of Electro-communications</td>
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Abstract

The trapping laser for Sr OLC has some optical requirements: the high power of more than 1 W, the narrow linewidth of less than 1 MHz, the wavelength of 813.42 nm. Though Ti:sapphire laser is currently used as 800 nm light source, it is not suitable for light source of the optical clock due to its short stable continuous operation time. Therefore we have developed the fiber MOPA (Master Oscillator Power Amplifier) system for the trapping light source of next-generation Sr OCL. The Master oscillator is an ECLD (External-cavity laser diode) whose output power is amplified by Tm$^{3+}$-doped fibers. The ordinary Tm$^{3+}$-doped silica fiber cannot amplify light source at 810 nm regions due to its short upper-state lifetime. Replacing host material from silica to fluoride fiber extends the upper-state lifetime. Therefore we use Tm$^{3+}$-doped fluoride fiber as a fiber amplifier, which is core-pumped by Yb$^{3+}$-doped fiber laser (1064-nm upconversion pumping).

First, we demonstrated the fiber MOPA in free-space set up (Fig.1), and obtained the maximum power of 1.68 W (Fig.2) with the wavelength of 813.42 nm and the linewidth of less than 200 kHz, whose optical properties satisfy the requirements of Sr OLC [1]. As a next step, we have tried to develop all-fiber MOPA system that is indispensable for stable continuous long-term operation. The all-fiber system requires splicing silica fiber with fluoride fiber. The fluoride fiber is hard to be spliced with silica fiber, because the melting point of fluoride glass (260°C) is much lower than that of silica glass (1500°C). Now we have tried to splice these fibers to realize all-fiber MOPA system.

![Diagram](image1)

**Fig.1**

![Diagram](image2)

**Fig.2**

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<td>Hiroki Yamamoto(1,2,4), Sho Okubo(2,4), Takumi Kobayashi(2,4), Atsushi Onae(2,4), Hajime Inaba(2,4), Kaoru Minoshima(3,4), Kazumichi Yoshii(1,4), Feng-Lei Hong(1,2,4)</td>
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</table>
| **Affiliation**    | 1: Department of Physics, Graduate School of Engineering, Yokohama National University(YNU)  
|                    | 2: National Metrology Institute of Japan(NMIJ), National Institute of Advanced Industrial Science and Technology(AIST)  
|                    | 3: Department of Engineering Science, Graduate School of Informatics, The University of Electro-Communications(UEC)  
|                    | 4: JST, ERATO, Intelligent Optical Synthesizer(IOS) Project |

**Abstract**

Laser frequency combs for astronomical observations (astro-combs) have been installed in several observatories for calibrating the spectrographs used to measure the cosmological redshift of distant objects. We are now establishing an astro-comb including an iodine-stabilized reference laser that will be used to lock the comb and optical cavities for realizing larger comb spacing. The astro-comb will be installed in Okayama Astrophysical Observatory, NAOJ, in the first quarter of the next year.
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</table>

**Abstract**

A ytterbium (Yb):fibre frequency comb was developed to complement and come in support of Erbium:fibre and titanium:sapphire frequency combs currently used as the means to establish optical clock frequency ratios. Frequency combs based on Yb-doped fibre laser systems have shown the ability for low phase noise operation using transducers, namely intracavity electro-optic phase modulators, for high servo feedback bandwidths. The work presented proposes a laser system which maintains the low residual phase noise of previous similar Yb:fibre-based frequency combs, and through the combination of elements borrowed from various schemes, extends this full phase stabilisation ability from the short term to the long term. The frequency comb is an amplified Yb:fibre femtosecond mode-locked laser system with an electro-optic modulator and a slower speed piezoelectric transducer both placed inside the oscillator cavity to maintain the repetition frequency through the phase-stabilisation of a heterodyne beat signal ($f_{\text{beat}}$) between one comb mode and an optical reference. The carrier-envelope offset frequency ($f_{\text{ceo}}$) beat signal, for phase-locking via the oscillator pump current, was generated by the self-referencing $f2f$ interferometer in a collinear scheme using a fan-out periodically poled magnesium-oxide-doped stoichiometric lithium tantalite quasi phase-matched nonlinear crystal. Signal-to-noise ratios exceeding 40 dB (at 100 kHz resolution bandwidth, RBW) were observed for both beat signals when the frequency comb was free-running and of 33 dB and 45 dB (at 1 kHz RBW), for $f_{\text{ceo}}$ and $f_{\text{beat}}$ respectively, during full phase stabilisation. This lead to an in-loop phase noise of 0.682 rad and 0.212 rad (integrated over 1 Hz-1 MHz), for $f_{\text{ceo}}$ and $f_{\text{beat}}$ respectively, which translates to a timing jitter of 235 and 121 as, respectively. Full phase stabilisation of the Yb:fibre frequency comb was reproducibly achieved for periods of up to 6 hours, in excess of the time necessary for optical clock frequency ratio measurements (10,000 s).
Optical frequency comb using laser-diode pumped Kerr-lens mode-locked Yb:KYW laser for optical frequency measurement and comparison

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Abstract

Frequency-ratio measurement of different optical clocks is essential for evaluation of the reproducibility of the optical clocks and search for a temporal variation of the fine structure constant [1]. We investigate optical frequency combs (OFCs) based on ytterbium-doped potassium yttrium tungstate (Yb:KYW) lasers [2]. The Yb:KYW laser can be oscillated by pumping with a relatively low-power laser diode (LD), and has a small quantum defect. Therefore, the OFC based on the Yb:KYW laser has a potential in stable long-term continuous operation with a low running cost similar to that on the fiber laser [3]. In additions, the similar methods used for frequency control of the OFC based on the titanium-doped sapphire laser [4] may be applicable.

We realize soft-aperture Kerr-lens mode-locking of a Yb:KYW laser of the output power of 360 mW from the pump LD power of 750 mW. We obtain a spectrum over one octave by using a photonic-crystal fiber. We detect the $f_{\text{CEO}}$ by self-referencing technique [5]. We phase lock $f_{\text{op}}$ and $f_{\text{CEO}}$ to a radiofrequency reference by controlling the cavity length and the injection current of the pump LD, respectively [6]. We measure the beat frequency between a mode of the OFC and a clock laser for the transition in Yb$^+$ at 871 nm as shown in fig 1.

References


Fig 1 Frequency counting of beat signal at 871 nm (Gate 1s)
Poster No.15

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<th>Presentation title</th>
<th>Spectroscopy of highly charged holmium ions with an electron beam ion trap</th>
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<tr>
<td>Name</td>
<td>Takayuki NAKAJIMA¹, Taichi SHIMAYA¹, Kunihiro OKADA², Michiharu WADA³, Noriaki Ohmae³,⁴,⁵, Hidetoshi KATORI³,⁴,⁵, and Nobuyuki NAKAMURA¹</td>
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<td>Affiliation</td>
<td>¹The University of Electro-Communications, ²Sophia University, ³RIKEN, ⁴ERATO, ⁵The University of Tokyo</td>
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</table>

**Abstract**

We present visible spectra of highly charged Ho ions observed with a compact electron beam ion trap (EBIT). Recently, an optical clock using highly charged ions has been proposed as a potential candidate for an accurate and stable clock that has an excellent sensitivity to the time variation of the fine structure constant[1]. Dzuba et al.[2] have proposed to use Ho¹⁴⁺ and predicted several optical transitions which are useful for cooling and observation. However, the uncertainty in the predicted frequency is rather large as 10,000 cm⁻¹ since Ho¹⁴⁺, whose ground state configuration is ⁴f⁶⁵s, has dense and complex energy levels arising from configuration interaction among a huge number of fine structure levels. It is thus important to determine the transition wavelength experimentally for designing and constructing the clock using Ho¹⁴⁺. The compact EBIT[3] at The University of Electro-Communications is useful device to observe and identify previously-unreported transitions in highly charged ions. In the present study, several transitions of Ho¹⁴⁺ have been observed. The analysis of the spectra through the comparison with theoretical calculations is given.

Abstract

We aim at realization of an optical frequency standard with barium ions (Ba\(^+\)). Ba\(^+\) has a transition of short lifetime suitable for laser cooling, i.e., the \(^2S_{1/2} - ^2P_{3/2}\) at 493 nm, and two clock transitions of long lifetime, i.e., \(^2S_{1/2} - ^2D_{5/2}\) and \(^2S_{1/2} - ^2D_{3/2}\). The \(^2S_{1/2}(F=2;m_F=0) - ^2D_{5/2}(F=0;m_F=0)\) transition in \(^{135}\)Ba\(^+\) or \(^{137}\)Ba\(^+\) is insensitive to quadrupole electric field[1]. Therefore, it is possible to improve the frequency stability by increase of the number of ions without degradation of uncertainty.

As a first step, we are developing an optical clock by using the \(^2S_{1/2} - ^2D_{5/2}\) transition at 1.76 μm in \(^{138}\)Ba\(^+\). We realize a light source based on external-cavity diode lasers (ECDLs) for driving of the transition. So far, this transition has been observed by using other lasers[2-5]. We linenarrow an ECDL at 881 nm to a resonance of a reference cavity, and the ECDL at 1.76 μm is phase locked to the ECDL at 881 nm by using second harmonic. We measure the linewidth of the ECDL at 881 nm to be narrower than 200 Hz from the beatnote with an optical frequency comb phase locked to the other linenarrowed ECDL.

We confine and laser cool single \(^{138}\)Ba\(^+\) ions in a linear RF trap. We detect the fluorescence of the photon counting rate of 3 kHz for single \(^{138}\)Ba\(^+\) ions. We obtain the spectra of the clock transition by using single \(^{138}\)Ba\(^+\) ions. We observe Zeeman splitting as shown in Fig.1. Then we resolve motional sidebands, as shown in Fig.2, by high-resolution frequency scanning.

We are developing optical clocks based on single $^{171}\text{Yb}^+$ ions. $^{171}\text{Yb}^+$ has $m_F = 0 - m_{F'} = 0$ clock transitions, which are not disturbed by 1st order Zeeman shifts in low magnetic field. $^{171}\text{Yb}^+$ has relatively simple hyperfine structures because of the nuclear spin of 1/2. A large difference in the sensitivities to the variation of $\Delta$ between the quadrupole and octupole clock transitions enables us to search for a temporal variation of $\Delta$ by using only $^{171}\text{Yb}^+$ [1, 2].

We conducted spectroscopy of the $m_F = 0 - m_{F'} = 0$ component of the $^2S_{1/2}$ ($F = 0$) – $^2D_{3/2}$ ($F' = 2$) clock transition and resolved motional sidebands. We probed the carrier spectrum by frequency sweep of the clock laser by 20-Hz intervals as shown in Fig. 1. In order to measure and cancel a linear frequency drift in the clock laser, we detected the spectra two times by switching the sweep direction of the clock laser frequency. We obtained a spectrum of a full width at half maximum of 380 Hz. This is limited by the linewidth of the clock laser.


Fig. 1. Carrier spectrum of the $^2S_{1/2}$ ($F = 0$, $m_F = 0$) – $^2D_{3/2}$ ($F' = 2$, $m_{F'} = 0$) in single $^{171}\text{Yb}$ ion.
Coherent optical control of a Bose Einstein condensate on a persistent super-current atom chip

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NTT Basic Research Laboratories

Abstract

Ultra-cold atom is a practical candidate of quantum resource. Under the ideal conditions, the internal quantum state of atoms can be controlled with electromagnetic field. However, the practical implementation of atomic system into quantum devices with long coherence time, large scalability, and independent controllability needs special technologies to tackle the system de-coherence. So far quantum state control of a trapped atomic cloud or a Bose-Einstein condensate (BEC) in a magnetic potential are demonstrated with microwave and radio frequency electromagnetic field, however, the technique is poor in spatial resolution. To achieve addressability on an atom chip system, we studied coherent optical control of a BEC on a persistent super-current atom chip with stimulated Raman transition. In experiment, the weak field seeking Zeeman sublevels in the $5^2S_{1/2}$ grand state of rubidium-87 atoms, $|F, m_F >= |1, -1 >$ and $|2, 1 >$, are connected via an excited sublevel $|1, 0 >$ in $5^2P_{1/2}$ with a $D_1$ line transition (Fig.1). With this configuration we can choose large detuning to the excited level, and the suppression of de-coherence for the resonance and spontaneous emission is highly expected. Figure 2 shows a preliminary result of the measured Rabi oscillation of a BEC on an atom chip. The feasibility of this technique as a resource for the atomic quantum device will be discussed.
Abstract
Cryogenic strontium optical lattice clocks, where the atoms are interrogated in a cryogenic environment, reduce the major source of uncertainty due to blackbody radiation (BBR) below $10^{-18}$ level. As progress of clock continues towards the total uncertainty of $10^{-19}$ level, the next major uncertainty arises from higher-order lattice light shifts.

When we consider only the electric-dipole (E1) polarizability of atoms, the lattice light shift can be expressed by $\Delta a_{E1} I$, where $\Delta a_{E1}$ is the E1 polarizability difference of the ground and excited states of the clock transition and $I$ is the intensity of lattice laser. So far, lattice clocks have been operated with lattice laser tuned to a frequency, where the lattice light shift is insensitive to the intensity variation in the intensity range used for the experiment, assuming that the shift is proportional to $I$. However, to reduce the lattice light shift uncertainty, it is necessary to include the contributions from magnetic-dipole (M1) and electric-quadrupole (E2) polarizabilities and hyperpolarizability. If we take all the contributions into account, the light shift can be written by the terms proportional not only to $I$ but also to $I^{1/2}$, $I^{3/2}$ and $I^2$. We have evaluated higher order terms of lattice light shift by measuring the dependence on intensity of lattice laser and vibrational levels of atoms. In this poster, we will discuss the latest experimental results.

References:
Abstract
The accuracy of recent strontium (Sr) optical lattice clocks reaches to $10^{-18}$ level. The light shift caused by the black body radiation has been a major source of uncertainties of Sr optical lattice clocks, but now is suppressed by making use of atoms trapped in cryogenic environment. In contrast, the resonance frequency of the clock transition in cadmium (Cd) is intrinsically insensitive to the black-body radiation. This feature of Cd enables a precise optical lattice clock without the arrangement of the cryogenic environment. Such advantage makes it possible to build a compact and portable optical lattice clock.

Aiming towards a Cd-based optical lattice clock, we demonstrate narrow line laser cooling of Cd atoms. Cd atoms are first trapped in a MOT on the $^1S_0 - ^1P_1$ transition (Doppler temperature: 2.2 mK) at 229 nm [2]. For further cooling of atoms, the MOT transition is switched to the narrower $^1S_0 - ^3P_1$ transition (Doppler temperature: 1.6 $\mu$K) at 326 nm. This two-stage laser cooling scheme, which was originally developed for cooling of Sr atoms [3], allows us to cool both the bosonic ($^{112}$Cd) and fermionic ($^{113}$Cd) isotopes down to the temperature of 4.2 (9) $\mu$K and 5.2 (6) $\mu$K, respectively. We discuss details of the experiment and the future prospects.

2. Y. Kaneda et al., accepted to Opt. Lett.
Abstract
The value of the fine-structure constant $\alpha$ might be allowed to change space-wise and time-wise in some theories beyond the Standard Model [1]. While astronomical measurements look into a variation of $\alpha$ at a long time scale, laboratory-based measurements provide a complementary insight into a possibility of a variation of $\alpha$ in a much shorter time scale. An optical clock based on mercury (Hg) atoms is suitable as a probe for a $\alpha$-variation due to its better stability compared to a single-ion clock and larger sensitivity to $\alpha$-variation compared to strontium (Sr) atoms [2]. Hence, by monitoring the frequency ratio of the clock transitions between Hg and Sr, we directly probe any new physics that might cause a change in the value of $\alpha$.

We have recently attained the uncertainty of the Hg/Sr frequency ratio at the level of $8.4 \times 10^{-17}$, limited by the uncertainty of the frequency shift due to the optical lattice light in the Hg clock system at $6.1 \times 10^{-17}$ [3]. We are currently developing a 2nd Hg-clock for the purpose of investigating the lattice light shift with an ability to further increase the intensity and tune the polarization of the lattice light, as suggested in Ref. [4]. We aim to reduce the total uncertainty of the Hg/Sr frequency ratio to below $10^{-17}$, which will enable us to probe the variation of $\alpha$ at a level competitive to current best measurements [5,6].

References:
**Presentation title**  
Frequency ratio of Yb and Sr clocks by synchronous interrogation

**Name**  
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\(^4\) RIKEN Center for Advanced Photonics

**Abstract**

With optical atomic clocks approaching uncertainties of \(10^{-18}\), full frequency descriptions are now far beyond the reach of the SI second. Frequency ratios of such super clocks, on the other hand, are not subject to this limitation. They can therefore verify consistency and overall accuracy for an ensemble of clocks, an essential step towards a redefinition of the second. However, with the measurement stabilities so far reported for such frequency ratios, a confirmation to \(1\times10^{-18}\) uncertainty would require an averaging time of multiple months.

Optical lattice clocks offer an intrinsic advantage for achieving a greater stability due to the low quantum projection noise when probing hundreds or thousands of atoms. By employing the technique of synchronous interrogation to take full advantage of this, we realize a frequency ratio measurement with a much reduced instability of \(4\times10^{-16} \ (\nu/s)^{-1/2}\). This will ultimately allow \(1\times10^{-18}\) uncertainty with only two days of measurement time.

At this point, the final uncertainty is limited by the evaluation of systematic effects in the Yb clock, for which we present the latest uncertainty budget. We find \(R = 1.207 \ 507 \ 039 \ 343 \ 337 \ 749(55)\) for the Yb/Sr ratio, with a fractional uncertainty of \(4.6\times10^{-17}\).
**Poster No.23**

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<tr>
<th>Presentation title</th>
<th>Remote frequency comparison of cryogenic Sr optical lattice clocks via an optical fiber link</th>
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<tr>
<td><strong>Name</strong></td>
<td>Tomoya Akatsuka\textsuperscript{1,2,3}, Tetsushi Takano\textsuperscript{1,4}, Masao Takamoto\textsuperscript{1,2,3}, Ichiro Ushijima\textsuperscript{1,2,3}, Noriaki Ohmae\textsuperscript{1,2,4}, Atsushi Yamaguchi\textsuperscript{1,2,3}, and Hidetoshi Katori\textsuperscript{1,2,3,4}</td>
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<td>\textsuperscript{1} Innovative Space-Time Project, JST-ERATO \textsuperscript{2} Quantum Metrology Laboratory, RIKEN \textsuperscript{3} RIKEN Center for Advanced Photonics \textsuperscript{4} Department of Applied Physics, Graduate School of Engineering, The University of Tokyo</td>
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</table>

**Abstract:**

We report a remote frequency comparison of two cryogenic Sr optical lattice clocks located at RIKEN and the University of Tokyo (UTokyo), 15 km apart with 15 m height difference (Fig. 1). The two clocks are connected by a 30-km-long optical fiber link based on a transfer laser at 1397 nm which is the subharmonic of the clock transition. After 11 measurements carried out over 6 months, frequency difference between the two clocks is determined to be 0.7095(2) Hz originating from the gravitational red shift. Corresponding height difference of the two clocks can be determined with an uncertainty of 5 cm. Such a highly accurate remote clock comparison enables many applications in relativistic geodesy, for example, monitoring movement of the Earth’s crust and searching underground resources.

![Frequency comparison between two distant optical lattice clocks via an optical fiber link.](image)

Fig. 1 Frequency comparison between two distant optical lattice clocks via an optical fiber link.
Poster No.24

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<th>Presentation title</th>
<th>Super-radiance in strontium atoms in a hollow-core fiber</th>
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<tr>
<td>Name</td>
<td>Shoichi Okaba&lt;sup&gt;1,2&lt;/sup&gt;, Tetsushi Takano&lt;sup&gt;1,2&lt;/sup&gt; and Hidetoshi Katori&lt;sup&gt;1,2,3,4&lt;/sup&gt;</td>
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</table>
| Affiliation        | 1 Department of Applied Physics, Graduate School of Engineering, The University of Tokyo  
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                      3 Quantum Metrology Laboratory, RIKEN  
                      4 RIKEN Center for Advanced Photonics |

Abstract

We report our experiments on super-radiance phenomenon [1] in strontium atoms confined in an optical lattice inside a hollow-core photonic crystal fiber (HC-PCF).

The HC-PCF can extend the trap volume arbitrarily and prepare atoms with high optical depth and long coherence time [2]. This atomic ensemble, sharing a common fiber mode, is an ideal system for observing their cooperative effects. The investigation of super-radiance in this system paves the way for future applications, such as lasing with ultra-narrow linewidth [3].

In our experiment, ultra-cold Sr atoms are loaded into the HC-PCF and excited to \(^3P_1\) state by a 500 ns-long-\(\pi\)-pulse. We have observed a burst of radiation and its ringing, cooperatively emitted from the excited atoms. The frequency of the radiated photons, measured by heterodyne detection with a known frequency reference, is hardly influenced by that of the excitation pulse and that is resonant to Sr atoms.

We have also measured the coupling efficiency of the radiated photons to the fiber guided mode. It increases with the atom number \(N\) and reaches near 100%. This indicates cooperatively emitted photons, which increase with \(N\), are efficiently coupled to the guided mode, while independently emitted ones hardly couple to it.
