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

Abstracts are in the homepage
http://www.amo.t.u-tokyo.ac.jp/iwcps2016/index.html

iwcps2016 search

Poster NO.	Presentation Title	Name	Affiliation
1	Yb and Sr optical lattice clocks at NMIJ	Kazumoto Hosaka	NMIJ/ AIST
2	Perspective on utilization of optical lattice clock for geodesy	Basara Miyahara	GSI
3	Generation of a time-scale steered by an ^{87}Sr optical lattice clock	Hidekazu Hachisu	NICT
4	The optical ^{88}Sr lattice clocks and stabilized fibre links: a frequency reference for the VLBI system over 20 km link and absolute measurement of the clock transition over 330 km link	Piotr Morzyński	NCU
5	Measuring absolute frequencies beyond the GPS limit via long-haul optical frequency dissemination	Davide Calonico	INRiM
6	^{171}Yb lattice clock at INRIM	Davide Calonico	INRiM
7	Evidence of Orbital Feshbach Resonances and Chiral Edge States in Yb Fermi Gases	Jacopo Catani	LENS/ INO-CNR
8	The ^{87}Sr optical lattice clock at NIM	Ye Li	NIM
9	Compact iodine-stabilized laser using a coin-sized laser module	Takumi Kobayashi	YNU
10	FPGA-based high finesse cavity control for a narrow line-width CW laser	Isao Ito	UTokyo
11	New trapping light source for Sr OLC	Takashi Kubo	UEC
12	Development of a 531-nm frequency-stabilized laser for an astro-comb	Hiroki Yamamoto	YNU
13	Yb:Fibre Frequency Comb for Optical Clock Comparison.	Alissa Silva	UTokyo
14	Optical frequency comb using laser-diode pumped Kerr-lens mode-locked Yb:KYW laser for optical frequency measurement and comparison	Masatoshi Mitaki	Kyoto Univ.
15	Spectroscopy of highly charged holmium ions with an electron beam ion trap	Takayuki Nakajima	UEC
16	Detection of motional sidebands of the $^2S_{1/2}$ - $^2D_{5/2}$ clock transition in single $^{138}Ba^+$ ions	Hiroto Fujisaki	Kyoto Univ.

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

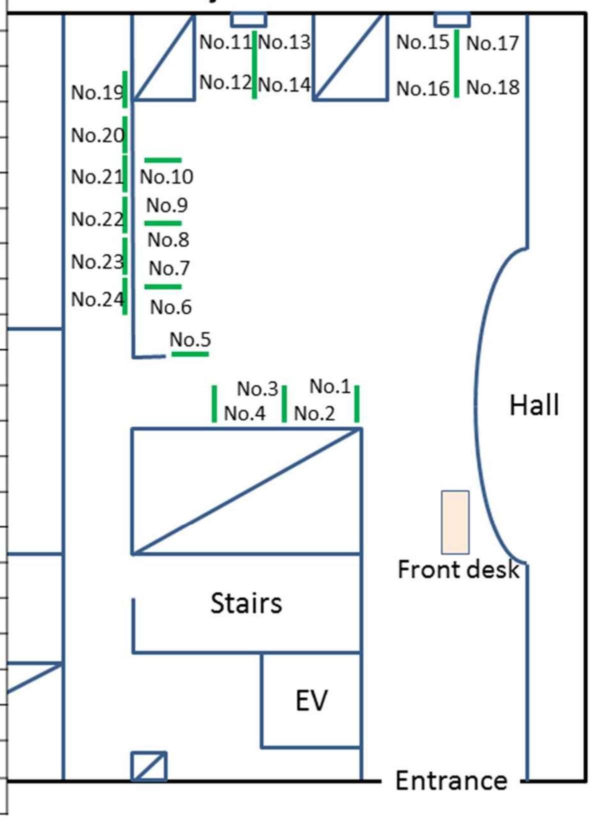
Abstracts are in the homepage
http://www.amo.t.u-tokyo.ac.jp/iwcps2016/index.html

iwcps2016	search

17	Spectroscopy of the $^2S_{1/2}$ ($F = 0$, $m_F = 0$) – $^2D_{3/2}$ ($F' = 2$, $m_{F'} = 0$) Clock Transition in Single ^{171}Yb Ions Towards Search for Temporal Variation of the Fine Structure Constant	Yasutaka Imai	Kyoto Univ.
18	Coherent optical control of a Bose Einstein condensate on a persistent super-current atom chip	Tetsuya Mukai	NTT
19	Evaluation of the higher order light shift of strontium optical lattice clock	Ichiro Ushijima	ERATO/ RIKEN
20	Narrow line laser cooling of cadmium atoms toward an optical lattice clock	Atsushi Yamaguchi	ERATO/ RIKEN
21	Toward High Performance Mercury Optical Lattice Clocks	Thaned Pruttivarasin	RIKEN
22	Frequency ratio of Yb and Sr clocks by synchronous interrogation	Nils Nemitz	RIKEN
23	Remote frequency comparison of cryogenic Sr optical lattice clocks via an optical fiber link	Tomoya Akatsuka	ERATO/ RIKEN
24	Super-radiance in strontium atoms in a hollow-core fiber	Shoichi Okaba	UTokyo

No.	Name (Affiliation)
1	Kazumoto Hosaka (NMIJ/AIST)
2	Basara Miyahara (Geospatial Information Authority of Japan)
3	Hidekazu Hachisu (NICT)
4	Piotr Morzyński (Nicolaus Copernicus University)
5	Davide Calonico (INRiM)
6	Davide Calonico (INRiM)
7	Jacopo Catani (LENS/INO-CNR)
8	Ye Li (National Institute of Metrology)
9	Takumi Kobayashi (Yokohama National University)
10	Isao Ito (The University of Tokyo)
11	Takashi Kubo (The University of Electro-Communications)
12	Hiroki Yamamoto (Yokohama National University)
13	Alissa Silva (The University of Tokyo)
14	Masatoshi Mitaki (Kyoto University)
15	Takayuki Nakajima (The University of Electro-Communications)
16	Hiroto Fujisaki (Kyoto University)
17	Yasutaka Imai (Kyoto University)
18	Tetsuya Mukai (NTT)
19	Ichiro Ushijima(ERATO/RIKEN)
20	Atsushi Yamaguchi (ERATO/RIKEN)
21	Thaned Pruttivarasin (RIKEN)
22	Nils Nemitz (RIKEN)
23	Tomoya Akatsuka (ERATO/RIKEN)
24	Shoichi Okaba (The university of Tokyo)

Poster layout



Poster No.1

Presentation title	Yb and Sr optical lattice clocks at NMIJ
Name	Takehiko Tanabe[1], Daisuke Akamatsu[1], Takumi Kobayashi[1], Masami Yasuda[1], Hajime Inaba[1], Sho Okubo[1], Feng-Lei Hong[1,2], Atsushi Onae[1], Tomonari Suzuyama[1], Akifumi Takamizawa[1], Shinya Yanagimachi[1], Takeshi Ikegami[1], and Kazumoto Hosaka[1]
Affiliation	[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

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

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 1.4×10^{-15} [3].

References

[1] D. Akamatsu *et al.*, Appl. Phys. Express **7**, 012401 (2014).
[2] T. Tanabe *et al.*, J. Phys. Soc. Jpn. **84**, 115002 (2015).
[3] D. Akamatsu *et al.*, Opt. Express **22**(7), 7898 (2014).
D. Akamatsu *et al.*, ibid. **22**(26), 32199 (2014).

Poster No.2

Presentation title	Perspective on utilization of optical lattice clock for geodesy
Name	Basara Miyahara
Affiliation	Geospatial Information Authority of Japan

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.

Poster No.3

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 1×10^{-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 8.6×10^{-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 1×10^{-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.

[1] H. Hachisu and T. Ido, Jpn. J. Appl. Phys. **54**, 112401 (2015).

Poster No.4

Presentation title	The optical ^{88}Sr lattice clocks and stabilized fibre links: a frequency reference for the VLBI system over 20 km link and absolute measurement of the clock transition over 330 km link
Name	<u>P. Morzyński</u>[1], M. Bober[1], P. Krehlik[2], Ł. Śliwczyński[2], M. Lipiński[2], M. Pazderski[3], A. Marecki[3], J. Nawrocki[4], P. Ablewski[1], B. Campbell[5], R. Ciuryło[1], M. Zawada[1]
Affiliation	1. Institute of Physics, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University, Grudziądzka 5, PL-87-100 Toruń, Poland 2. Department of Electronics, AGH University of Science and Technology, al. Mickiewicza 30, PL-30-059, Kraków, Poland 3. Centre for Astronomy, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University, Grudziądzka 5, PL-87-100 Toruń, Poland 4. Time and Frequency Department, Astrogeodynamics Observatory of Space Research Center, Borowiec, Drapałka 4, PL-62-035 Kórnik, Poland 5. Joint Institute for VLBI ERIC, Oude hoogeveensedijk 4, 7991 PD Dwingeloo, The Netherlands

Abstract

We report a system of two independent optical lattice standards with ^{88}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 $^1S_0$-$^3P_0$ 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:

[1] P. Morzyński et al., "Absolute measurement of the 1S0-3P0 clock transition in neutral 88Sr over the 330 km-long stabilized fibre optic link", Sci. Rep., **5** 17495 (2015)

Poster No.4

[2] M. Bober et al., “Strontium optical lattice clocks for practical realization of the metre and secondary representation of the second”, Meas. Sci. Tech., **26** 75201 (2015)
[3] J. Azoubib et al., “Independent atomic timescale in Poland – organization and results”, Metrologia, **40** S245 (2003)
[4] Z. Jiang et al., “Comparing a GPS time link calibration with an optical fibre self-calibration with 200ps accuracy”, Metrologia, **52** 384 (2015)
[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)

Poster No.5

Presentation title	Measuring absolute frequencies beyond the GPS limit via long-haul optical frequency dissemination
Name	D. Calonico[1], C. Clivati[1], G. Cappellini[1,2], L. Livi[2], F. Poggiali[2], M. Siciliani de Cumis[1,4], M. Mancini[3], G. Pagano[3], M. Frittelli[1], A. Mura[1], G. A. Costanzo[1,5], F. Levi[1], L. Fallani[3,2], J. Catani[2,4], and M. Inguscio[1,2,3]
Affiliation	1. INRIM Istituto Nazionale di Ricerca Metrologica, Torino, Italy 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, 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.

References

[1] C. Lisdat et al., "A clock network for geodesy and fundamental science," arXiv:1511.07735

[2] D. Calonico et al., High-accuracy coherent optical frequency transfer over a doubled 642-km fiber link. Appl. Phys. B 117, 979-986 (2014).

[3] G. Cappellini et al., Observation of Coherent Interorbital Spin-Exchange Dynamics. Phys. Rev. Lett. 113, 120402 (2014).

Poster No.6

Presentation title	^{171}Yb lattice clock at INRIM
Name	M. Pizzocaro, F. Bregolin, M. Gozzelino, G. Milani, B. Rauf, P. Thoumany, F. Levi and D. Calonico
Affiliation	INRIM Istituto Nazionale di Ricerca Metrologica, Torino, Italy

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 $^1S_0 \rightarrow {}^3P_0$ (Γ = 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 2×10^{-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

[1] I. Ushijima et al., ”Cryogenic optical lattice clocks”, Nature Photonics, 9, 185-189, (2015)

[3] CIPM,”CIPM Recommendation 1(CI-2013): Updates to the list of standard frequencies.”, 2013

[4] M. Pizzocaro et al., “Efficient frequency doubling at 399 nm”, Appl. Opt., 53, 3392 (2014)

Poster No.6

[5] M. Pizzocaro et al., “Realization of an ultra-stable 578-nm Laser for an Yb Lattice Clock”, IEEE UFFC, 59, 426-431 (2012)
[6] F. Levi et al., “Accuracy evaluation of ITCsF2: a nitrogen cooled cesium fountain”, Metrologia, 51, 270-284 (2014)

Poster No.7

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 reults 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 Fesbach 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 projeciton 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 whith 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.

Poster No.8

Presentation title	The ^{87}Sr optical lattice clock at NIM
Name	Ye Li
Affiliation	National Institute of Metrology, Beijing, China

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 3×10^{-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 2.3×10^{-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 3.4×10^{-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 lighium 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 detemined 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.

Poster No.10

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 finesses 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.

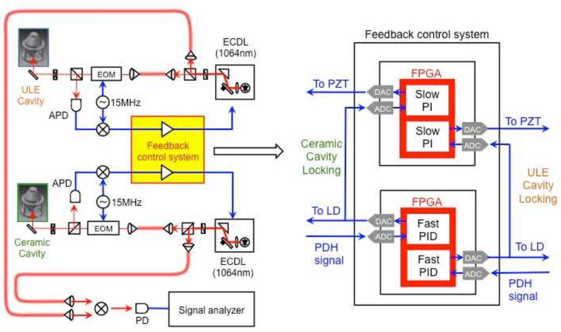


Figure 1. Setup

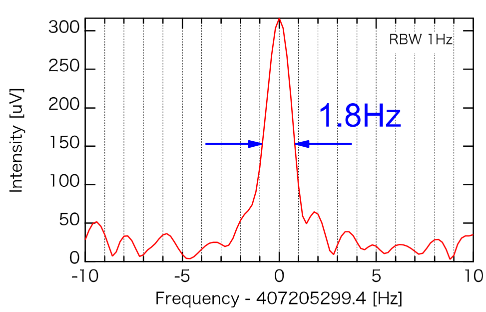


Figure 2. Beat signal

Poster No.11

Presentation title	New trapping light source for Sr OLC
Name	T.Kubo, E.Kajikawa, Y.Takeuchi, M.Musha
Affiliation	Institute for Laser Science, Univ. of Electro-communications

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℃) is much lower than that of silica glass (1500℃). Now we have tried to splice these fibers to realize all-fiber MOPA system.

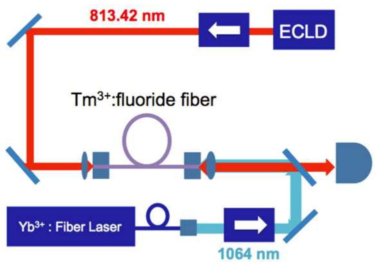


Fig.1

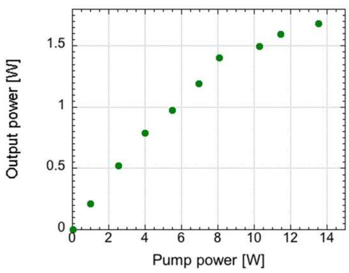


Fig.2

1. E.Kajikawa *et al.*, *Proc.* CLEO-EU2015 CJ-14.4.

Poster No.12

Presentation title	Development of a 531-nm frequency-stabilized laser for an astro-comb
Name	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)
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.

Poster No.13

Presentation title	Yb:Fibre Frequency Comb for Optical Clock Comparison.
Name	Alissa Silva, Akira Ozawa, Isao Ito, Takuma Nakamura, Mamoru Endo, Zhigang Zhao, Shuntaro Tani, Noriaki Ohmae, Hidetoshi Katori, and Yohei Kobayashi.
Affiliation	The Institute for Solid State Physics, The University of Tokyo and RIKEN

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_{beat}) between one comb mode and an optical reference. The carrier-envelope offset frequency (f_{ceo}) beat signal, for phase-locking via the oscillator pump current, was generated by the self-referencing f-$2f$ 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_{ceo} and f_{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_{ceo} and f_{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).

Poster No.14

Presentation title	Optical frequency comb using laser-diode pumped Kerr-lens mode-locked Yb:KYW laser for optical frequency measurement and comparison
Name	Masatoshi Mitaki, Kazuhiko Sugiyama, Yasutaka Imai , and Masao Kitano
Affiliation	Grad. School of Electronic Science and Engineering, Kyoto Univ.

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_{CEO} by self-referencing technique [5]. We phase lock f_{rep} and f_{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.

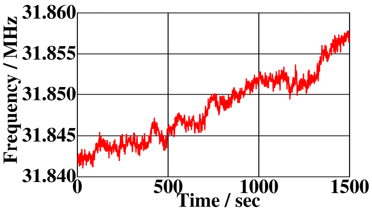


Fig 1 Frequency counting of beat signal at 871 nm (Gate 1s)

References

[1] T. Rosenband *et al.*, Science **319**, 1808 (2008).

[2]S. Meyer, *et al.*, Eur. Phys. J. D **48**, 19 (2008).

[3]I. Inaba, *et al.*, Opt. Exp **14**, 5223(2006).

[4]S. A. Diddams, *et al.*, Phys. Rev. Lett. **84**, 5102 (2000).

[5]D. J. Jones, *et al.*, Science **288**, 635(2000).

[6]M. Mitaki, *et al.*, Advanced Solid State Lasers, AM5a.27 (2014).

Poster No.15

Presentation title	Spectroscopy of highly charged holmium ions with an electron beam ion trap
Name	Takayuki NAKAJIMA[1], Taichi SHIMAYA[1], Kunihiro OKADA[2], Michiharu WADA[3], Noriaki Ohmae[3,4,5], Hidetoshi KATORI[3,4,5], and Nobuyuki NAKAMURA[1]
Affiliation	[1]The University of Electro-Communications, [2]Sophia University, [3]RIKEN, [4]ERATO, [5]The University of Tokyo

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 Ho^{14+} 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 Ho^{14+}, whose ground state configuration is $4f^6 5s$, 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 Ho^{14+}. 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 Ho^{14+} have been observed. The analysis of the spectra through the comparison with theoretical calculations is given.

[1] Berengut, Dzuba, and Flambaum, Phys. Rev. Lett. 105 (2010) 120801

[2] Dzuba, Flambaum, and Katori, Phys. Rev. A 91 (2015) 022119

[3] Nakamura el al., Rev. Sci. Instrum. 79 (2008) 063104

Poster No.16

Presentation title	Detection of motional sidebands of the $^2S_{1/2}$ - $^2D_{5/2}$ clock transition in single $^{138}Ba^+$ ions
Name	Hiroto Fujisaki, Yasutaka Imai, Masatoshi Mitaki, Keisuke Nishida, Masao Kitano, and Kazuhiko Sugiyama
Affiliation	Graduate school of Electronic Science and Engineering, Kyoto University

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 $^2S_{1/2}$ - $^2P_{1/2}$ 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 $^2S_{1/2}(F = 2; m_F = 0)$ - $^2D_{3/2}(F = 0; m_F = 0)$ 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.

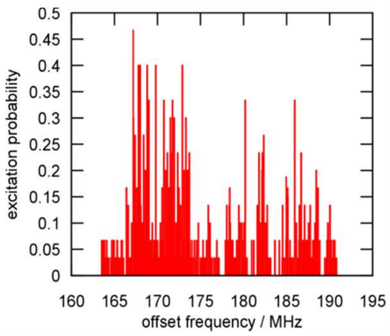


Figure 1: spectroscopy of the clock transition

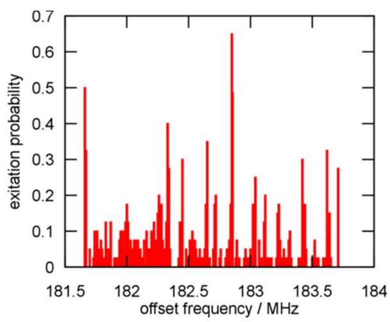


Figure 2: detection of the motional sidebands

[1] J. Sherman, *et al.*, 2015 Digest of the LEOS Summer Topical Meetings, p.99
[2] N. Kurz, *et al.*, *Phys. Rev. A*, **82**, 030501(R) (2010)
[3] W. Nagourney, *et al.*, *Opt. Commun.*, **79**, 176 (1990)
[4] B. Appasamy, *et al.*, *Appl. Phys. B*, **60**, 473 (1995)
[5] L. Slodička, *et al.*, *Phys. Rev. A*, **85**, 043401 (2012)

Poster No.17

Presentation title	Spectroscopy of the $^2S_{1/2}$ ($F = 0$, $m_F = 0$) – $^2D_{3/2}$ ($F' = 2$, $m_{F'} = 0$) Clock Transition in Single ^{171}Yb Ions Towards Search for Temporal Variation of the Fine Structure Constant
Name	Yasutaka Imai, Kazuhiko Sugiyama, Ren Irie, and Masao Kitano
Affiliation	Graduate School of Electronic Science and Engineering, Kyoto University

Abstract

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

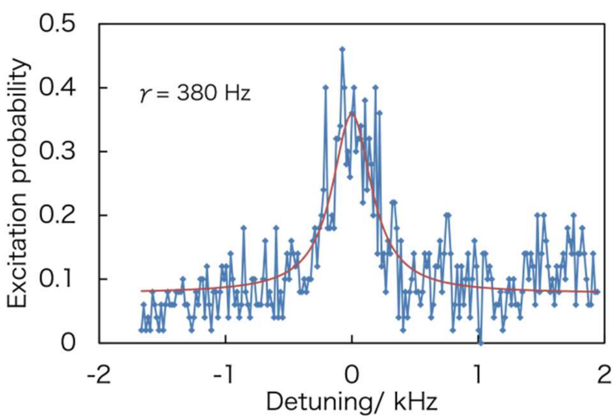


Fig 1. Carrier spectrum of the $^2S_{1/2}$ ($F = 0$, $m_F = 0$) – $^2D_{3/2}$ ($F' = 2$, $m_{F'} = 0$) in single ^{171}Yb ion.

[1]. R. M. Godun *et al.*, Phys. Rev. Lett. **113**, 210801 (2014).

[2.] N. Huntemann *et al.*, Phys. Rev. Lett. **113**, 210802 (2014).

Poster No.18

Presentation title	Coherent optical control of a Bose Einstein condensate on a persistent super-current atom chip
Name	Tetsuya Mukai
Affiliation	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.

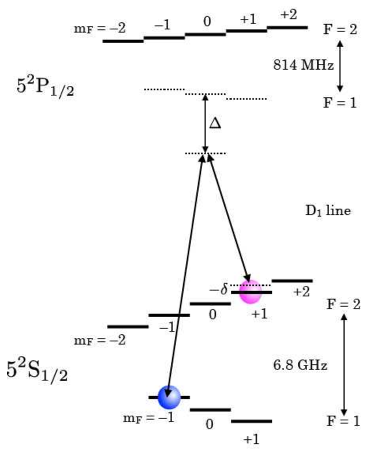


Figure 1 | Relevant energy level of ^{87}Rb

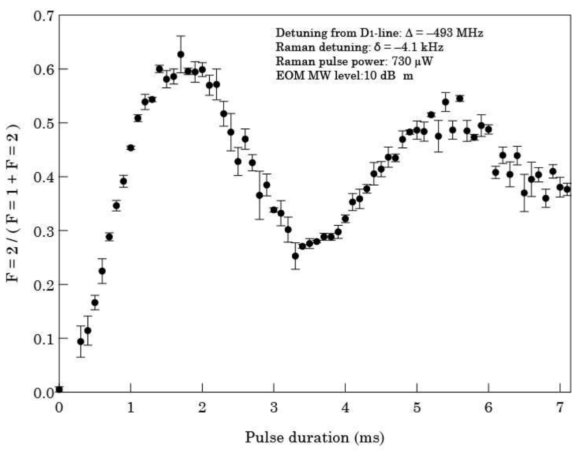


Figure 2 | Measured Rabi oscillation

Poster No.19

Presentation title	Evaluation of the higher order light shift of strontium optical lattice clock
Name	Ichiro Ushijima[1,2,3], Manoj Das[1,2,3], Masao Takamoto[1,2,3] and Hidetoshi Katori[1,2,3,4]
Affiliation	[1]Innovative Space-Time Project, JST-ERATO [2]Quantum Metrology Laboratory, RIKEN [3]RIKEN Center for Advanced Photonics [4]Department of Applied Physics, the University of Tokyo

Abstract

Cryogenic strontium optical lattice clocks[1], 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 $\Delta\alpha_{\mathrm{E1}} I$, where $\Delta\alpha_{\mathrm{E1}}$ 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[2,3]. 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:

[1] I. Ushijima et al., Nature Photon. 9, 185 (2015).

[2] P. G. Westergaard et al., Phys. Rev. Lett. 106, 210801 (2011).

[3] H. Katori et al., Phys. Rev. A 91, 052503 (2015).

Poster No.20

Presentation title	Narrow line laser cooling of cadmium atoms toward an optical lattice clock
Name	Atsushi Yamaguchi[1,2,3] and Hidetoshi Katori[1,2,3,4]
Affiliation	[1] Katori Innovative Space-Time Project, JST-ERATO [2] Quantum Metrology Laboratory, RIKEN [3] RIKEN Center for Advanced Photonics [4] Department of Applied Physics, Graduate School of Engineering, The University of Tokyo

Abstract

The accuracy of recent strontium (Sr) optical lattice clocks reaches to 10^{-18} level[1]. 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 μK) 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) μK and 5.2 (6) μK, respectively. We discuss details of the experiment and the future prospects.

1. I. Ushijima *et al.*, Nat. Photonics 9, 185 (2015).
2. Y. Kaneda *et al.*, accepted to Opt. Lett.
3. H. Katori *et al.*, Phys. Rev. Lett. 82, 1116 (1999).

Poster No.21

Presentation title	Toward High Performance Mercury Optical Lattice Clocks
Name	Thaned Pruttivarasin[1], Yosuke Sato[2], Noriaki Ohmae[2,3], Masao Takamoto[1,3,4] , and Hidetoshi Katori[1,2,3,4]
Affiliation	[1] Quantum Metrology Laboratory, RIKEN [2] Department of Applied Physics, Graduate School of Engineering, The University of Tokyo [3] Katori Innovative Space-Time Project, JST-ERATO [4] RIKEN Center for Advanced Photonics

Abstract

The value of the fine-structure constant α 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 α at a long time scale, laboratory-based measurements provide a complementary insight into a possibility of a variation of α in a much shorter time scale. An optical clock based on mercury (Hg) atoms is suitable as a probe for a α variation due to its better stability compared to a single-ion clock and larger sensitivity to α -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 α

We have recently attained the uncertainty of the Hg/Sr frequency ratio at the level of 8.4x10^{-17}, limited by the uncertainty of the frequency shift due to the optical lattice light in the Hg clock system at 6.1x10^{-17} [3]. We are currently developing a 2^{nd} 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 α at a level competitive to current best measurements [5,6].

References:

[1] Webb, J. K. *et al.*, Phys. Rev. Lett. 87, 091301 (2001).

[2] Angstmann, E. J *et al.*, V. V., Phys. Rev. A **70**, 014102 (2004).

[3] Yamanaka, K. *et al.*, Phys. Rev. Lett. **114**, 230801 (2015).

[4] Katori, H. *et al.*, Phys. Rev. A **91**, 052503 (2015).
[5] Rosenband, T. *et al.*, Science **319**, 1808 (2008).
[6] Godun, R. M. *et al.*, Phys. Rev. Lett. **113**, 210801 (2014).

Poster No.22

Presentation title	Frequency ratio of Yb and Sr clocks by synchronous interrogation
Name	Nils Nemitz[1], Takuya Ohkubo[1,2,3], Masao Takamoto[1,2,4], Ichiro Ushijima[1,2,4], Manoj Das[1,2,4], Noriaki Ohmae[1,2,3], Hidetoshi Katori[1,2,3,4]
Affiliation	[1] Quantum Metrology Laboratory, RIKEN [2] Katori Innovative Space-Time Project, JST-ERATO [3] Department of Applied Physics, Graduate School of Engineering, The University of Tokyo [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 1×10^{-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 $4\times10^{-16}\,(\tau/\mathrm{s})^{-1/2}$. This will ultimately allow 1×10^{-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 $\mathcal{R}$ = 1.207 507 039 343 337 749(55) for the Yb/Sr ratio, with a fractional uncertainty of 4.6×10^{-17}.

Poster No.23

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

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(25) 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.

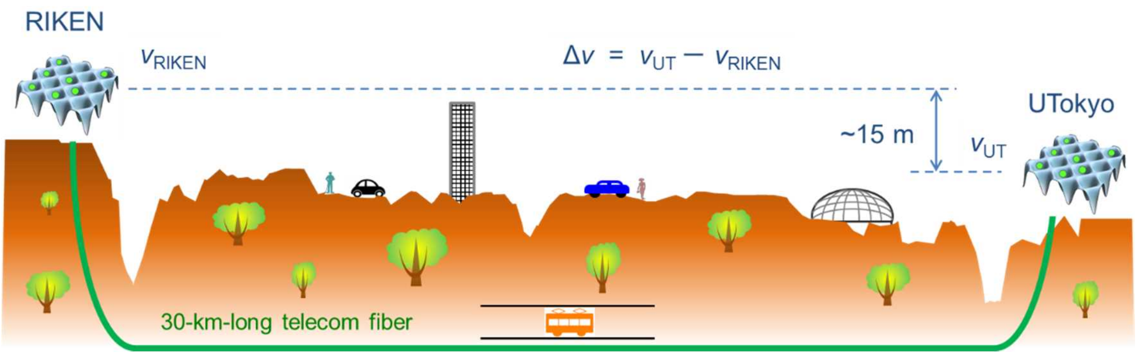


Fig. 1 Frequency comparison between two distant optical lattice clocks via an optical fiber link.

Poster No.24

Presentation title	Super-radiance in strontium atoms in a hollow-core fiber
Name	Shoichi Okaba[1,2], Tetsushi Takano[1,2] and Hidetoshi Katori[1,2,3,4]
Affiliation	[1] Department of Applied Physics, Graduate School of Engineering, The University of Tokyo [2] Katori Innovative Space-Time Project, JST-ERATO [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-π-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.

[1]R. H. Dicke, “Coherence in Spontaneous Radiation Processes,” *Phys. Rev.*, vol. 93, no. 1, pp. 99–110, 1954.
[2]S. Okaba, et. al., “Lamb-Dicke spectroscopy of atoms in a hollow-core

photonic crystal fibre.," *Nat. Commun.*, vol. 5, p. 4096, 2014.
[3]J. G. Bohnet, et. al., "A steady-state superradiant laser with less than one intracavity photon.," *Nature*, vol. 484, pp. 78–81, 2012.