Development of single Yb^+ and Ba^+ optical clocks and frequency combs towards search for temporal variation of the fine structure constant

Fundamental Physics Using Atoms 2015

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Katsura-Campus
(since 2003.9)

Coworkers

- Yb^+:

Yasutaka Imai (D)	S-D3/2, -5/2 clock transition
Shunsuke Tomomatsu (M1)	S-F clock transition
Ren Irie (B4)	2nd trap

- Ba^+:

Hiroto Fujisaki (D)	S-D5/2 clock transition
Keisuke Nishida (M2)	Odd isotope
Shinya Kawada (B4)	Clock laser

- Comb:

Masatoshi Mitaki (D)	Solid-state mode-locked laser

Acknowledgement:

Prof. Masao Kitano and Kitano lab.

Outline

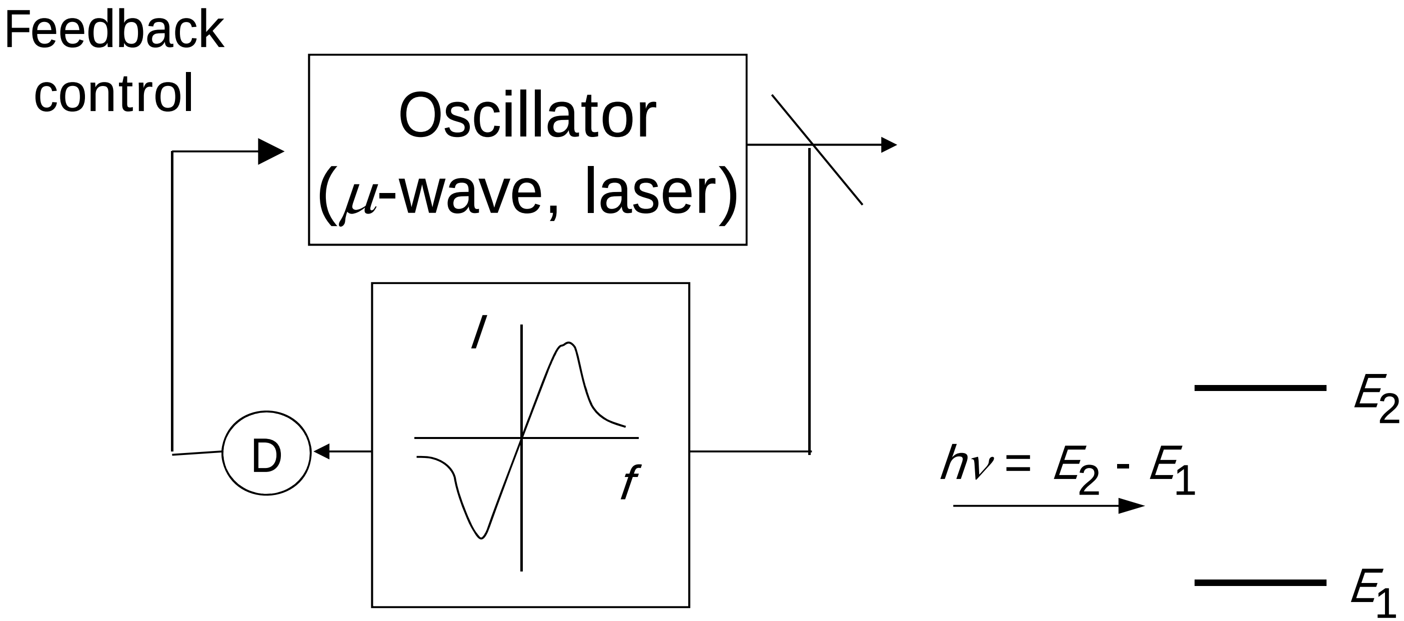
- Introduction
- Progress after the previous FPUA conference
  - Single-ion spectroscopy of $^2S_{1/2}$—$^2D_{3/2}$ in $^{171}Yb^+$
  - Optical frequency comb
    - Phase locking to laser
    - Diode-laser-pumped Yb:KYW laser

Temporal variation of fundamental constant

- A possibility of temporal variation is predicted in the theories unifying gravity to the other three fundamental interactions.
- Dimensionless constant (independent of units, and temporal variation of standards)
  - α , $\mu = m_p / m_e$
- Observation of the past events
  - Absorption in interstellar matter of rf from quasars
    null: J. Bagdonaite *et al.*, Science 339, 46 (2013)
    for: L. K. Webb *et al.*, PRL107, 191101 (2011) (spatial variation?)
  - Observation at one time in the past
  - Model dependent
- Repeatable measurement at present
  - Frequency ratio between atomic clocks of different transitions
    - Requirement: temporal: $<10^{-17}$ /yr $\leftarrow t^{-1}$
      (spatial?: + 10^{-20} annual modulation)

Berengut and Flambaum, EPL 97, 20006 (2012)

(passive) Atomic clock (frequency standard)

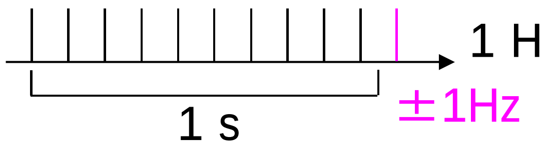


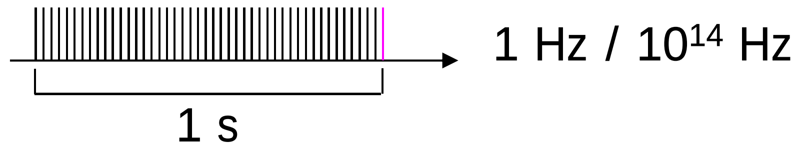
Transition of
atoms, molecules, and ions

Application to search for temporal variation of α, μ

Advantage of optical clock

- Better uncertainty than that of current standard in microwave
  - Higher the frequency,
    better the fractional frequency instability





  - Uncertainty: $<10^{-17}$
    - single-ion clock Al^{+} : 7.0×10^{-18} Chou *et al.*, PRL 104, 070802 (2010)
      Yb^{+} : 3×10^{-18}(?) PTB G., ICOLS 2015
    - optical lattice clock Sr: 7×10^{-18} Ushijima *et al.*, Nat. Photon. 9, 185 (2015)

Advantage of optical clock

- Model independent, concerning α variation

Electronic transition frequency f_E

$$f_\mathrm{E} = \mathrm{const}\cdot\left(R_\infty c\right)\cdot F\left(\alpha\right)$$

Temporal variation of f_E

$$\frac{1}{f_E}\frac{df_\mathrm{E}}{dt} = \frac{1}{R_\infty c}\frac{d\left(R_\infty c\right)}{dt} + K\frac{1}{\alpha}\frac{d\alpha}{dt}, \quad K \equiv \frac{\alpha}{F\left(\alpha\right)}\frac{dF\left(\alpha\right)}{d\alpha}$$

Frequency ratio $f_{\mathrm{E1}}/ f_{\mathrm{E2}}$

$$\boxed{\frac{1}{f_{\mathrm{E1}}/f_{\mathrm{E2}}}\frac{d\left(f_{\mathrm{E1}}/f_{\mathrm{E2}}\right)}{dt} = \left(K_{\mathrm{E1}} - K_{\mathrm{E2}}\right)\frac{1}{\alpha}\frac{d\alpha}{dt}}$$

$F(\alpha)$: Relativistic correction
sensitivity to α depends on the transition

Rydberg-constant ($R_\infty c$ in Hz) variation is the same in all transitions

Sensitivity K to the temporal variation of α

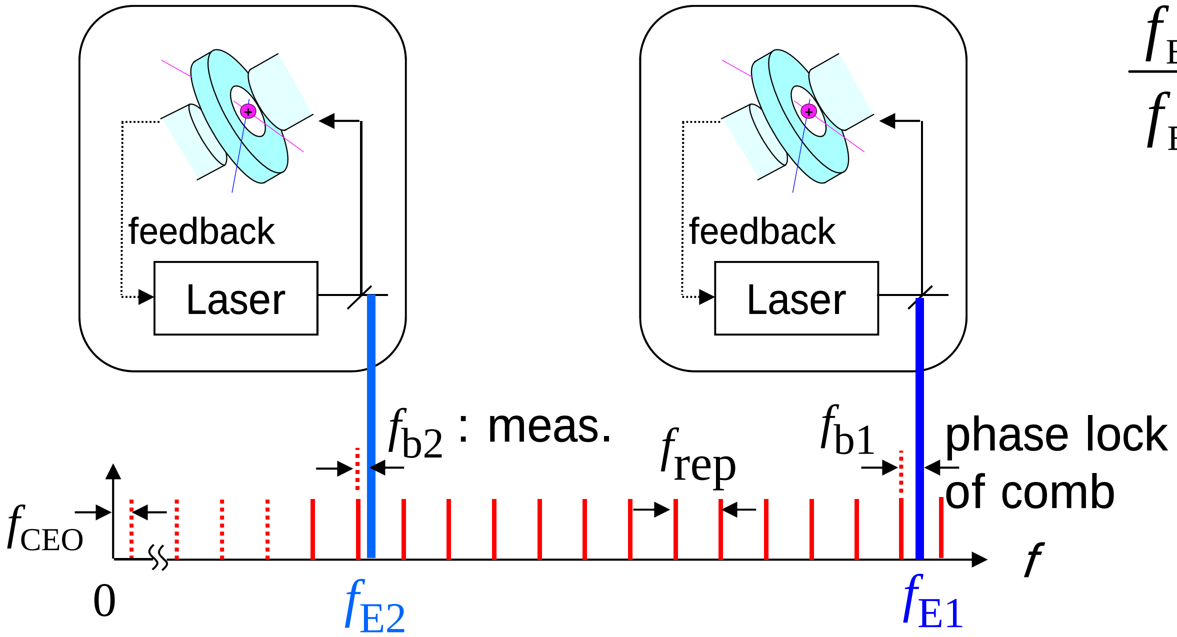
- K : Sensitivity to variation of α
  - Relativistic effect
  - Large interval between fine structure : high sensitivity
    - Scale with $(Z\alpha)^2$
    - Atoms of heavier mass

atom	transition	A
H	$1s_{1/2}$-$2s_{1/2}$	2.4×10^{-5}
Ca	$^1S_0$-$^3P_0$	0.016
Sr	$^1S_0$-$^3P_0$	0.06
Yb	$^1S_0$-$^3P_0$	0.31
Hg	$^1S_0$-$^3P_0$	0.81

ion	transition	K
Al^+	$^1S_0$-$^3P_0$	0.008
In^+	$^1S_0$-$^3P_0$	0.18
Ca^+	$^2S_{1/2}$-$^2D_{5/2}$	0.15
Sr^+	$^2S_{1/2}$-$^2D_{5/2}$	0.43
Ba^+	$^2S_{1/2}$-$^2D_{3/2}$	2.5
	$^2S_{1/2}$-$^2D_{5/2}$	2.4
Yb^+	$^2S_{1/2}$-$^2D_{3/2}$	1.00
	$^2S_{1/2}$-$^2D_{5/2}$	1.03
	$^2S_{1/2}$-$^2F_{7/2}$	-6.0
Hg^+	$^2S_{1/2}$-$^2D_{3/2}$	-1.5
	$^2S_{1/2}$-$^2D_{5/2}$	-2.9

V. Flambaum and V. Dzuba, Can J. Phys. 87 25 (2009)

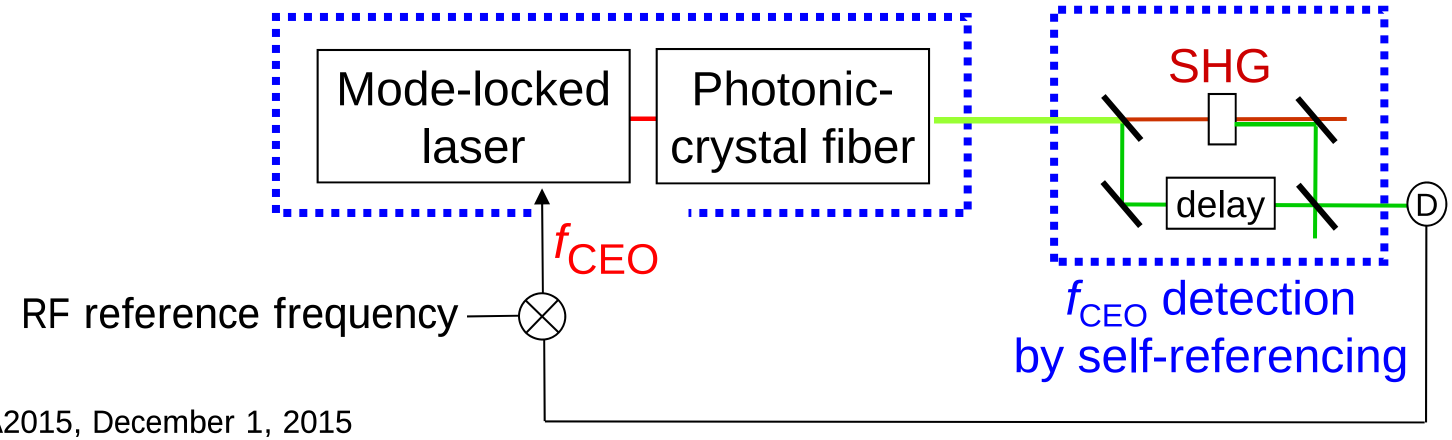
Optical frequency ratio measurement



$$\frac{f_{E2}}{f_{E1}} = \frac{n_2 f_{rep} + f_{CEO} + f_{b2}}{n_1 f_{rep} + f_{CEO} + f_{b1}}$$

- Value of RF reference frequency is not required.
- Stability of 10^{-12} required in RF reference for uncertainty 10^{-18} ($n \sim 10^6$)
- Uniformity of comb spacing is proved in 10^{-19}.

Octave-spanning optical frequency comb



Constraints from comparisons of atomic clocks

$$\boxed{\frac{1}{\alpha}\frac{d\alpha}{dt}}$$

$^{27}Al^{+}/^{199}Hg^{+}$

-1.6(2.3) × 10^{-17} /yr at NIST

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

Please refer to fig. 4 in

R.M. Godun *et al*., PRL 113, 210801 (2014)

incl. $^{171}Yb^{+}E2/^{171}Yb^{+}E3$

-0.7(2.1) × 10^{-17} /yr at NPL

-2.0(2.0) × 10^{-17} /yr at PTB

$$\boxed{\frac{1}{\mu}\frac{d\mu}{dt}}$$

Comparison to Cs hyperfine

incl. $^{171}Yb^{+}E2/^{171}Yb^{+}E3$

0.2(1.1) × 10^{-16} /yr at NPL

-0.5(1.6) × 10^{-16} /yr at PTB

Please refer to fig. 3 in

N. Huntemann *et al*., PRL 113, 210802 (2014)

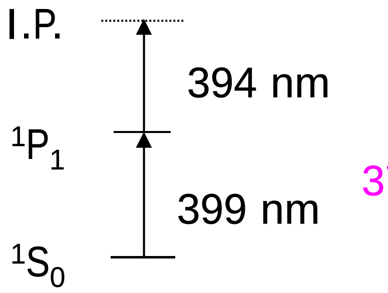
Advantage of Yb^+ and Ba^+ on search for temporal variation of α

- Yb^+:
  - Measurement on one ion in one trap
    - Close investigation of perturbations
    - Cancellation of gravitational effect

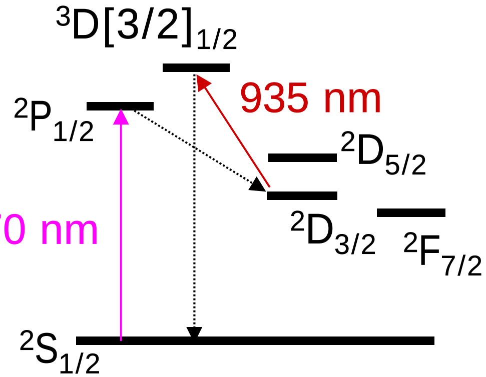
      gravitational red shift: 10^{-18}/cm
  - S-F: sensitivity twice as large as S-$D_{5/2}$ in Hg^+
  - S-$D_{3/2,5/2}$: variation vanished
  - Comparison with other labs (PTB, NPL)
- Ba^+
  - Odd isotope: insensitive to electric quadrupole shift
    - Low uncertainty
    - Increase of number
- Frequency ratio measurement on three transitions in Yb^+ & Ba^+
  - Ratio measurement among three
    - Absolute variation
    - Extract temporal variation of Rydberg constant

	$K_1 - K_2$
$Yb^+(^2S_{1/2}-^2D_{3/2})$ - $Yb^+(^2S_{1/2}-^2D_{5/2})$	-0.03
$Yb^+(^2S_{1/2}-^2D_{3/2})$ - $Yb^+(^2S_{1/2}-^2F_{7/2})$	7.1
$Ba^+(^2S_{1/2}-^2D_{3/2})$ - $Yb^+(^2S_{1/2}-^2F_{7/2})$	8.5
$Ba^+(^2S_{1/2}-^2D_{3/2})$ - $Yb^+(^2S_{1/2}-^2D_{3/2})$	1.5

Yb^+



Neutral Yb
for photoionization



Yb^+

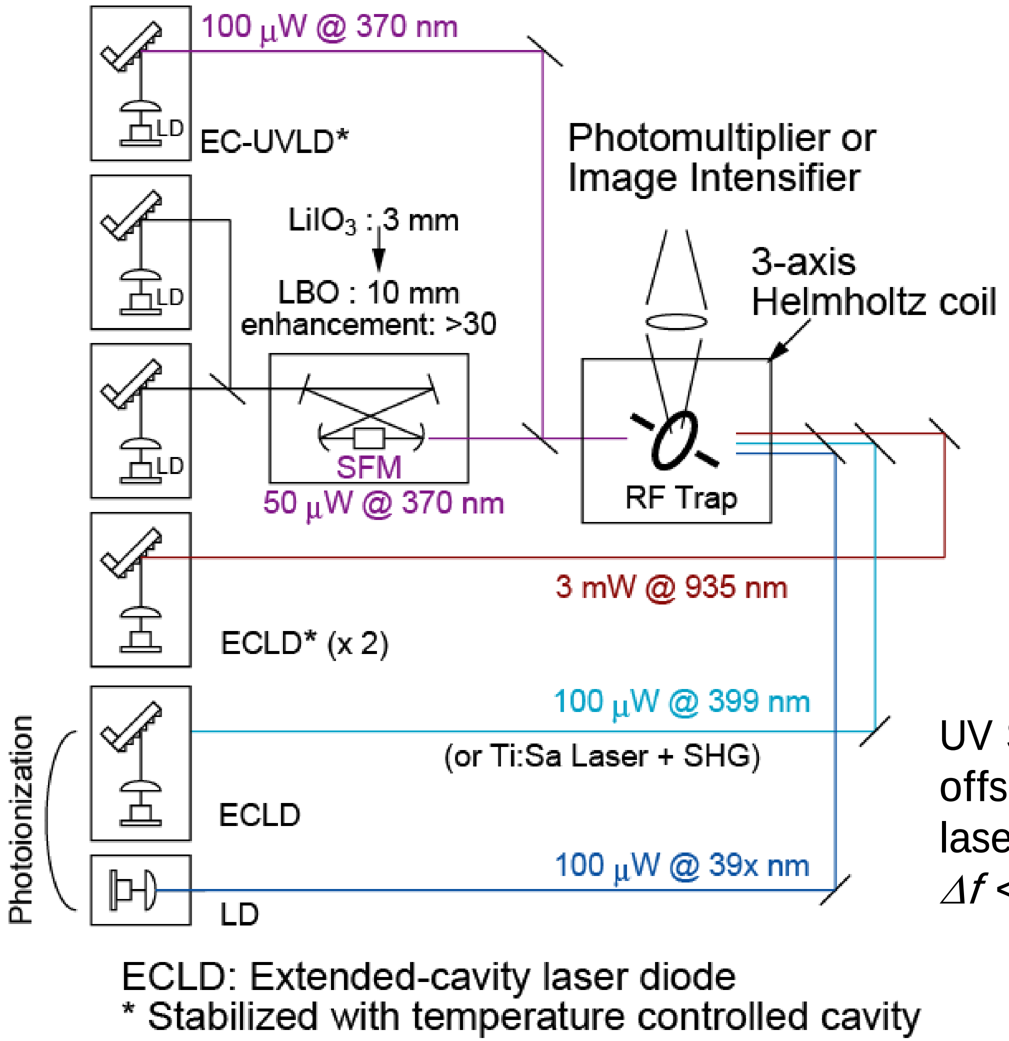
Clock transitions:

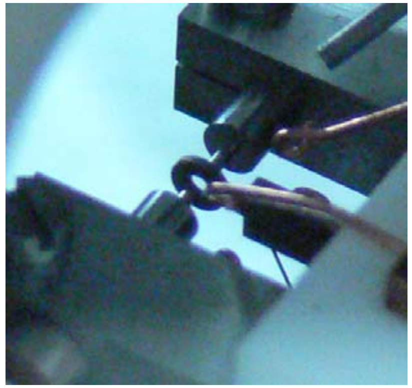
411 nm: $^2S_{1/2} - {}^2D_{5/2}$ $\tau = 7$ ms
435 nm: $^2S_{1/2} - {}^2D_{3/2}$ $\tau = 52$ ms
467 nm: $^2S_{1/2} - {}^2F_{7/2}$ $\tau \sim 4000$ d

Roberts et al PRA60, 2867 (1999)
Tamm et al, PRA80, 043403(2006)
Huntemann et al., PRL 108, 090801(2012)

- Isotope 171 (I=1/2)
  - $m_F=0 \rightarrow m_F'=0$, no 1st-order Zeeman shift
  - simplest hyperfine structure because of I=1/2
  - (only $^{199}Hg^+$ has I=1/2)
- Small system with simple light source
  - Secondary frequency standard
    PTB, NPL
  - Quantum information processing
    U. Maryland, etc.

Setup for laser cooling of Yb$^+$





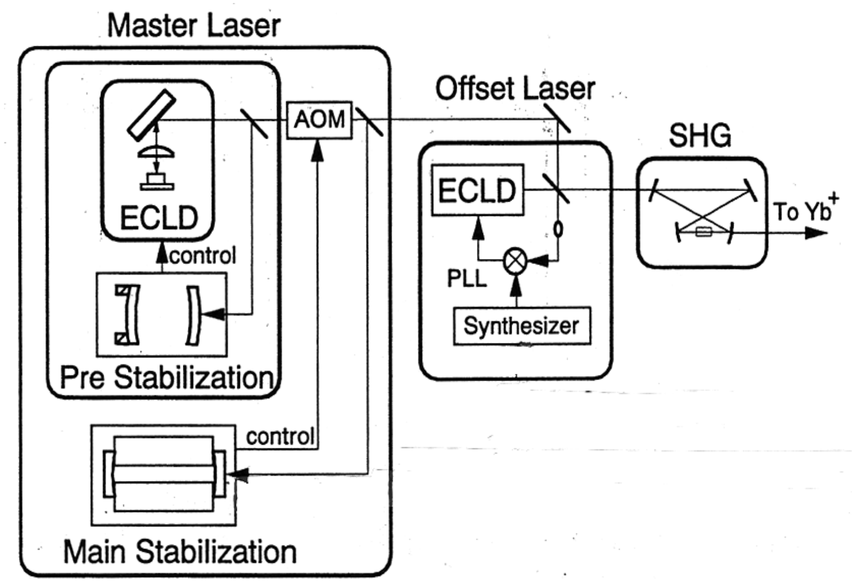
$2r_0$ = 0.8 mm
$\Omega/2\pi$ = 13.5 MHz

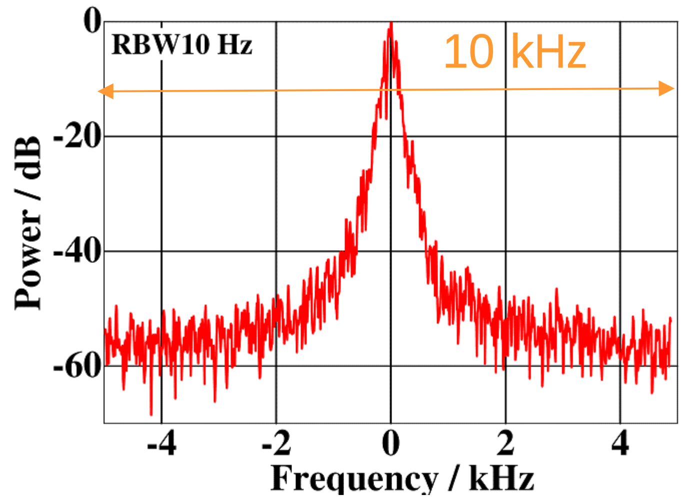
UV SF radiation is frequency stabilized by offset locking of one of the fundamental laser to the clock laser at 822 nm.
$\Delta f < \pm 200$ kHz @ 370 nm

We acknowledge Prof. Kawakami and Nichia Ltd. for providing us UV-LDs.

SFM: Sugiyama et al., Applied Optics, 49, 5510 (2010)
Photoionization: Onoda et al., Applied Physics B (2011)

Spectroscopy of the $^2S_{1/2}$ - $^2D_{5/2}$ clock transition at 411 nm in $^{174}Yb^+$

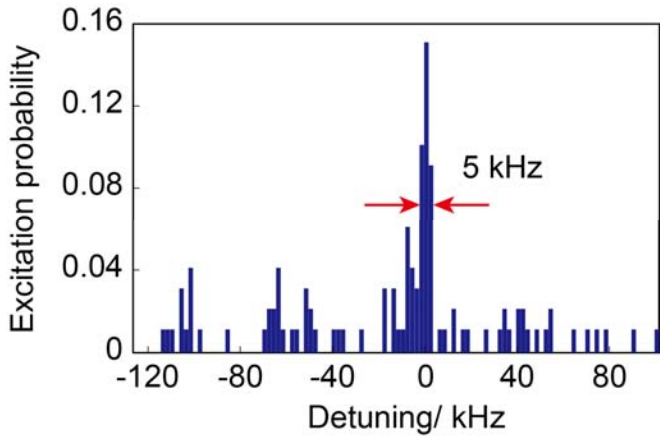




Beatnote of two independent systems
Linewidth < 300 Hz

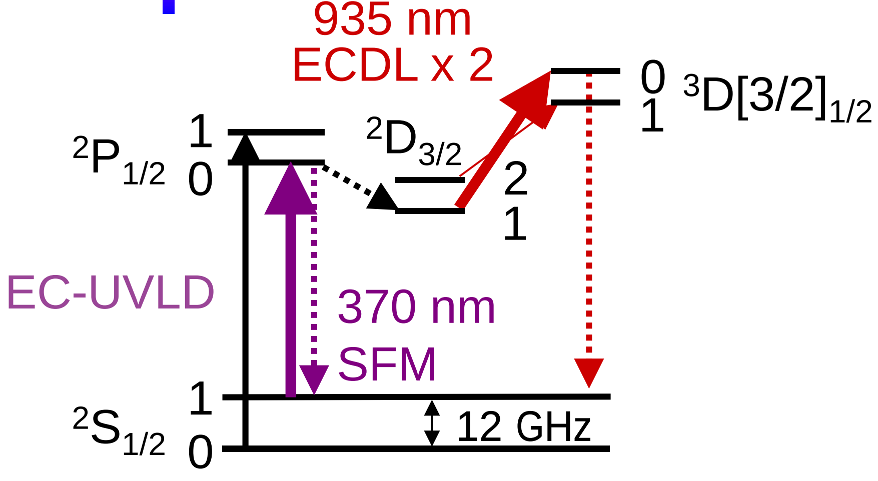
Pre: Δ_{cavity} = 15 MHz (super inver)
Transparent fringe side
fast: current,
slow: PZT

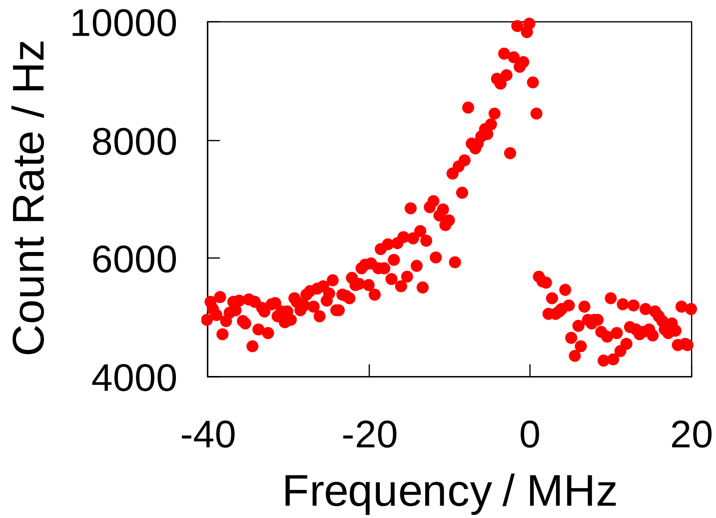
Main: Δ_{cavity} = ~80 kHz (ULE)
FM sideband
fast: AOM
slow: PZT(Pre stab. cavity)



m_j = +1/2 → +5/2
Step: 2 kHz

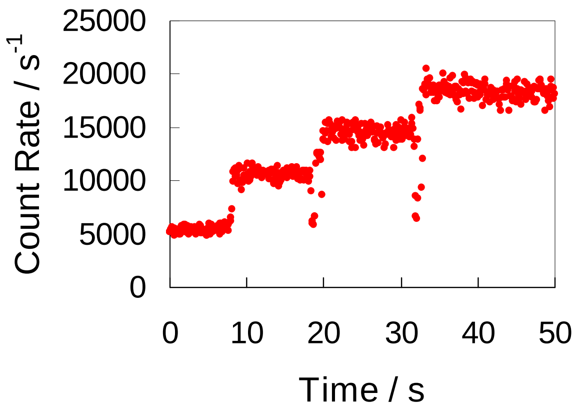
Laser cooling of single $^{171}Yb^+$





Spectrum of cooling transition

Temperature: ~13 mK



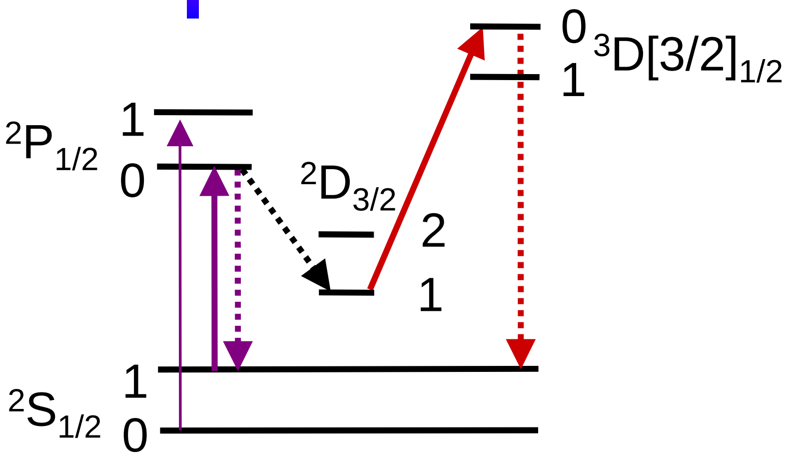
One-by-one loading with photoionization

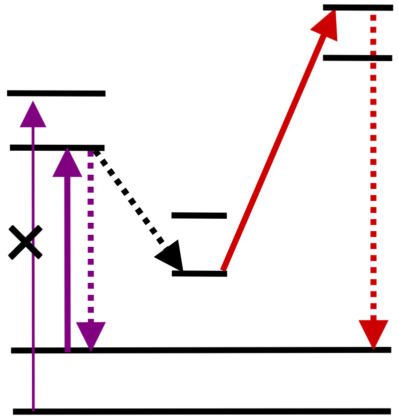
~6000 cps/ion

- Micromotion minimization by elimination of stray DC field
  ← rf-photon cross correlation detection
  Berkeland et al., JAP 83, 5025 (1998)
- Elimination of dark states
  ← Appropriate magnetic field and laser polarization
  Berkeland et al., PRA 65, 033413 (2002)

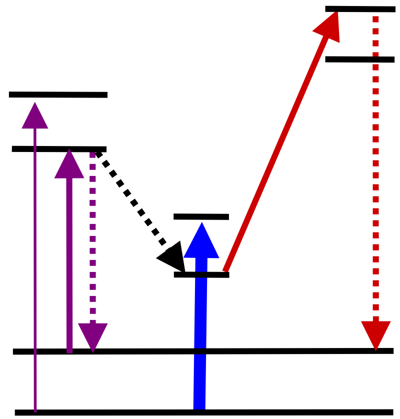
Driving of the $^2S_{1/2}$ - $^2D_{3/2}$ clock transition at 435 nm

Imai

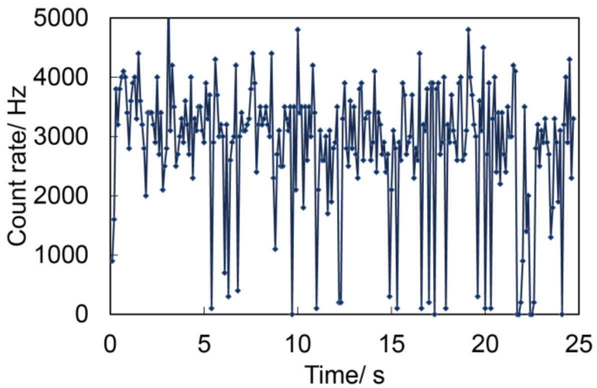




Initialization to $S_{1/2}$ F=0

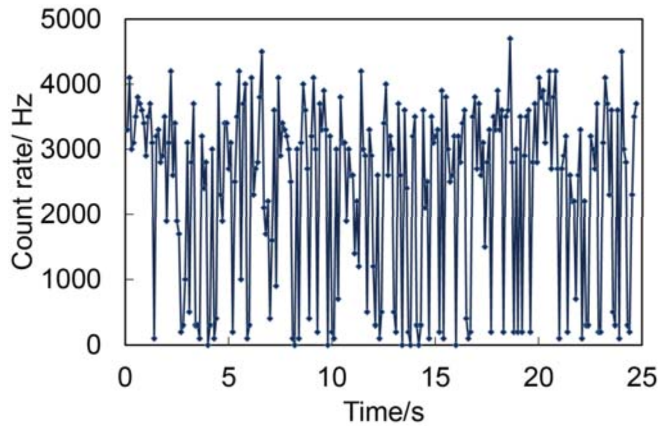


Clock irradiation
/Detection



without sub-repumping
($D_{3/2}$ F=2 ─ $[3/2]_{1/2}$ F=1)

spontaneous decay
from $P_{1/2}$ F=1 to $D_{3/2}$ F=2

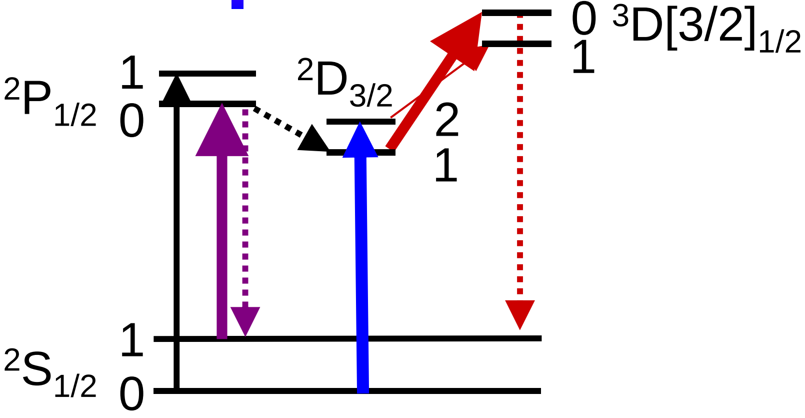


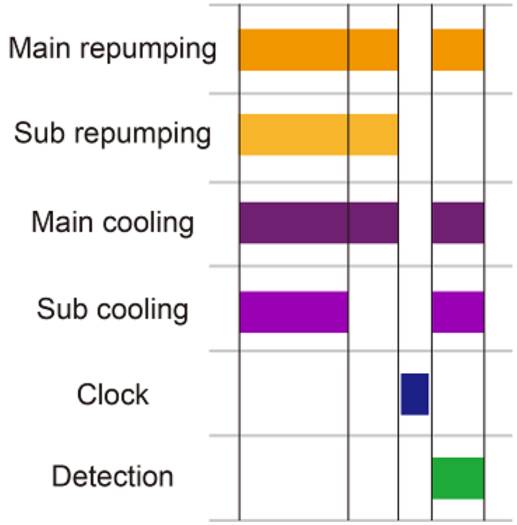
Clock : 10 ms
Detection: 10 ms

Quantum jumps with clock transition

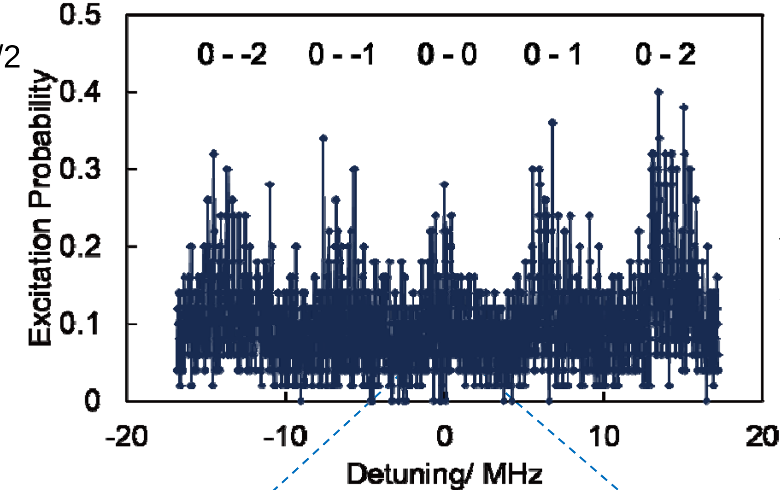
Ref. D. Engelke and C. Tamm, Europhys. Lett. 33, 347 (1996)
V. Buehner and C. Tamm, Phys. Rev A61, 061801(R)(2000)

Spectra of $^2S_{1/2}$ (F=0) – $^2D_{3/2}$ (F=2) transition in single $^{171}Yb^+$



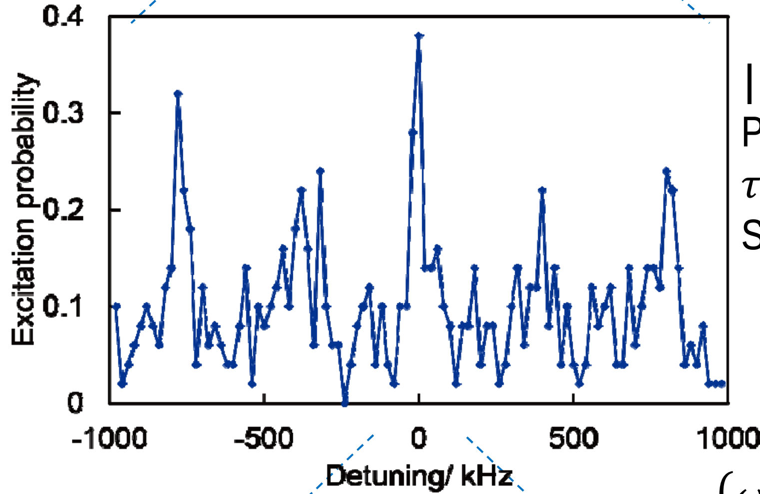


Initialization :	10 ms
Clock irradiation :	10 ms
Detection:	10 ms
Averaging	50 traials



All Zeeman components

|B| ~ 830 μ T
P_{clock} = 60 μW
τ = 10 ms
Step: 20 kHz

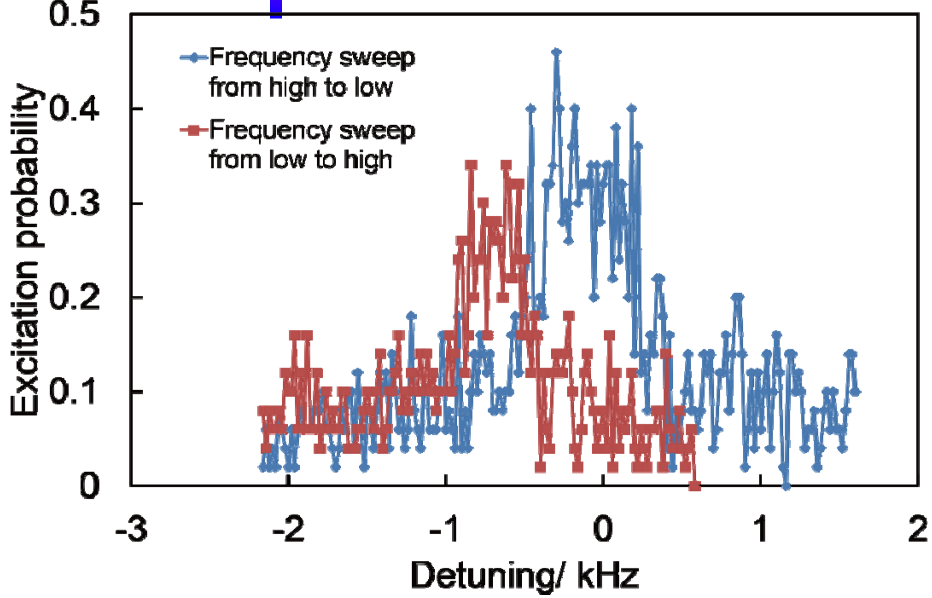


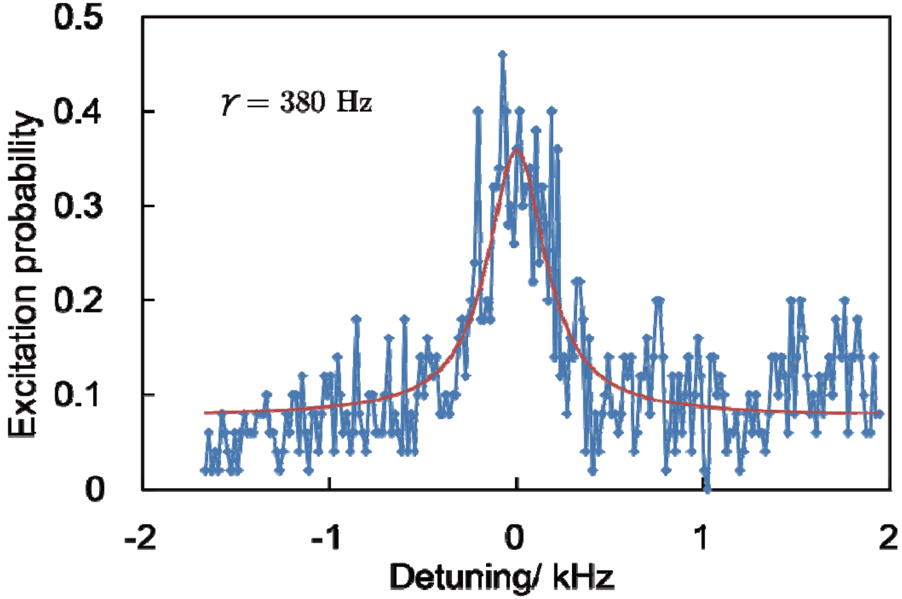
|B| ~ 830 μ T
P_{clock} = 60 μW
τ = 10 ms
Step: 20 kHz

mF=0 – 0 transition with motional sidebands

$$\begin{cases} \omega_{\mathrm{rad}} \cong 370\ \mathrm{kHz} \\ \omega_{\mathrm{ax}} \cong 760\ \mathrm{kHz} \end{cases}$$

High-resolution scanning of carrier spectrum





$m_F = 0$ - $m_{F'} = 0$ carrier spectrum

Feed forward compensation of drift of clock laser: +32 Hz/s

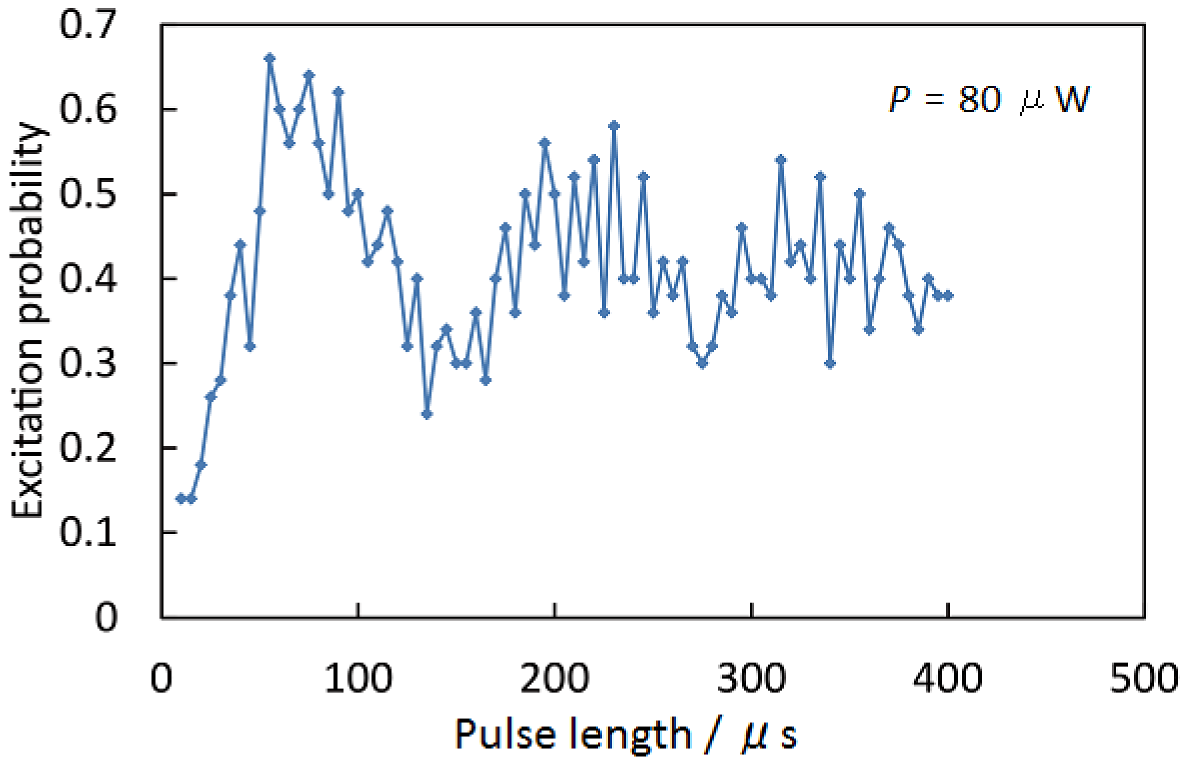
Sweep direction:
Red: low to high
Blue: high to low

After further adjustment to agree the spectra obtained by two sweep directions

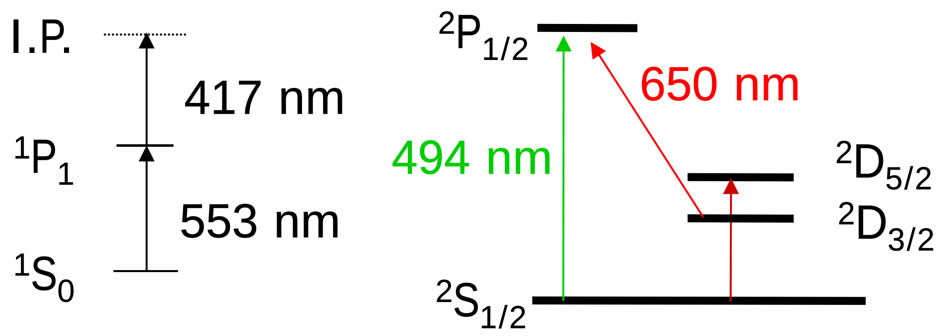
FWHM ～380 Hz
limited by laser linewidth

$|B| \sim 830\ \mu$T, $P_{clock} = 10\ \mu$W
τ = 10 ms, Step: 20 Hz

Finding π pulse



Ba^+



Neutral Ba
for photoionization

Ba^+

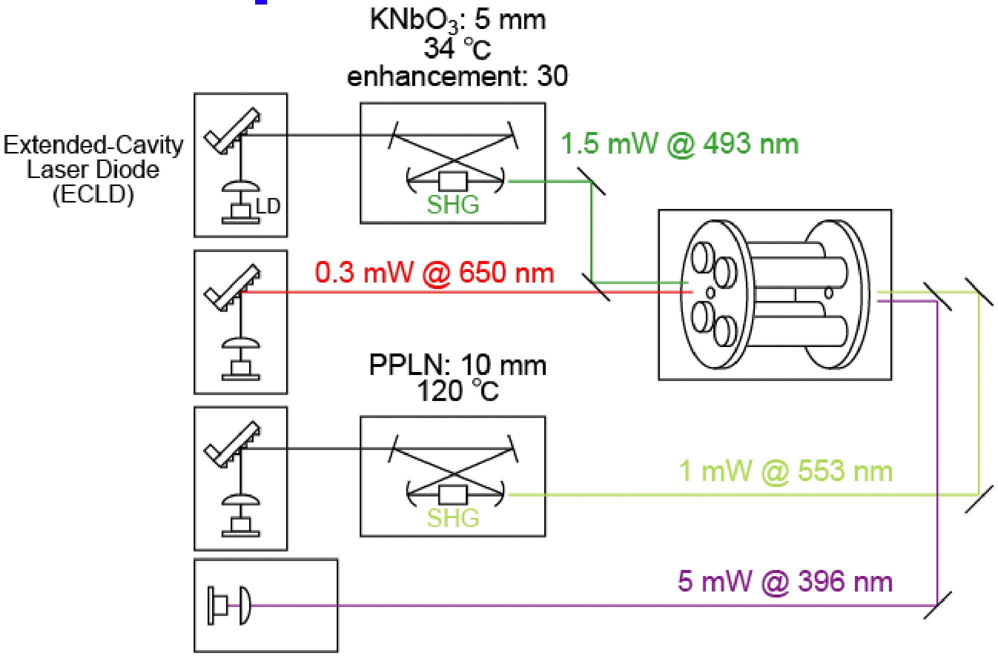
- Clock transitions
  1.762 μm: $^2S_{1/2} - {}^2D_{5/2}$ τ = 30 s
  2.052 μm: $^2S_{1/2} - {}^2D_{3/2}$ τ = 17 s

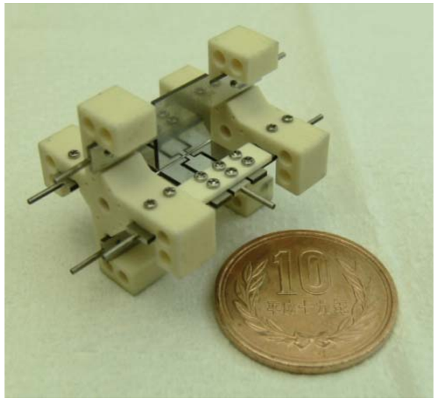
ECLD, DFM
DFM

- Isotope 135, 137（I=3/2）
  - $^2D_{3/2}$, F=0: very small electric quadrupole moment (largest factor of uncertainty in ions with alkali-metal like level scheme)
  - $m_F=0 \rightarrow m_F'=0$, no 1st-order Zeeman shift

Blinov Gr. & Fortson Gr. (U. Washington)
Blatt Gr. (U. Insbrueck)
U. Groningen, U. Singapole

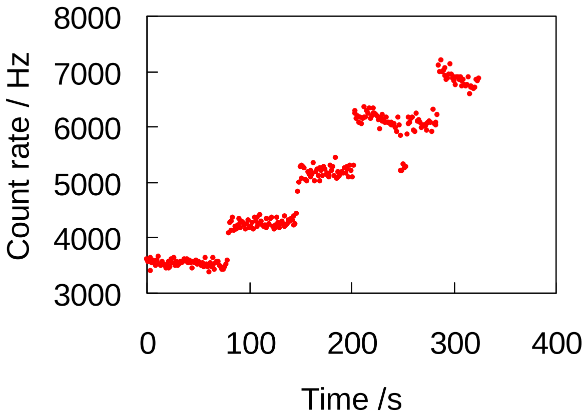
Setup for laser cooling of Ba⁺



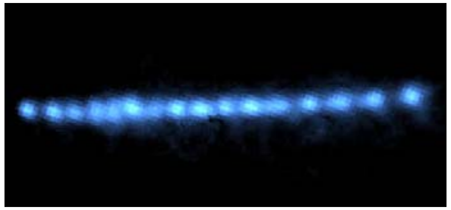


$2r_0$ = 0.8 mm, $2z_0$ = 1.0 mm

Segmented-electrode linear RF trap
(acknowledgement: Prof. Urabe (U.Osaka), Dr. Hayasaka (NICT))



One-by-one loading of $^{138}Ba^+$ with photoionization



String of 16 $^{138}Ba^+$ ions

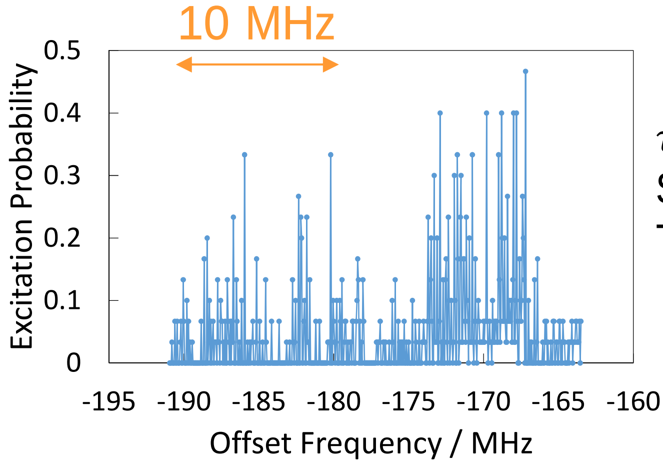
Single $^{138}Ba^{+}$ spectroscopy of the $^{2}S_{1/2} - {}^{2}D_{5/2}$ transition at 1762 nm

Fujisaki

- **Clock laser**

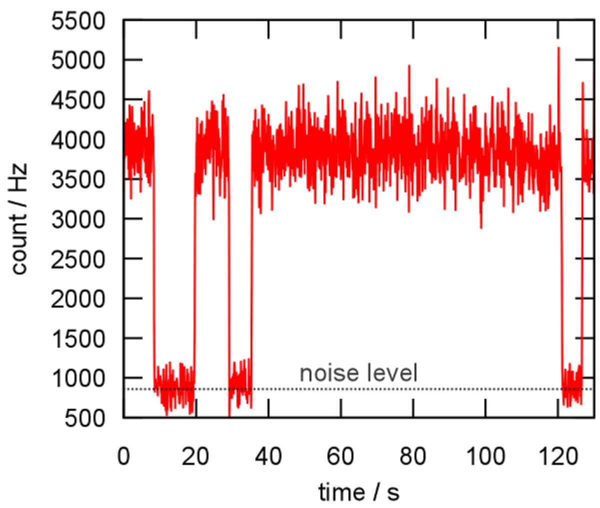
  1) ECLD at 881 nm locked to a high-finesse cavity
     relative linewidth ~ 10 Hz
     comparison with comb <200 Hz

  2) Phase locking of ECLD at 1762 nm using second-harmonics.

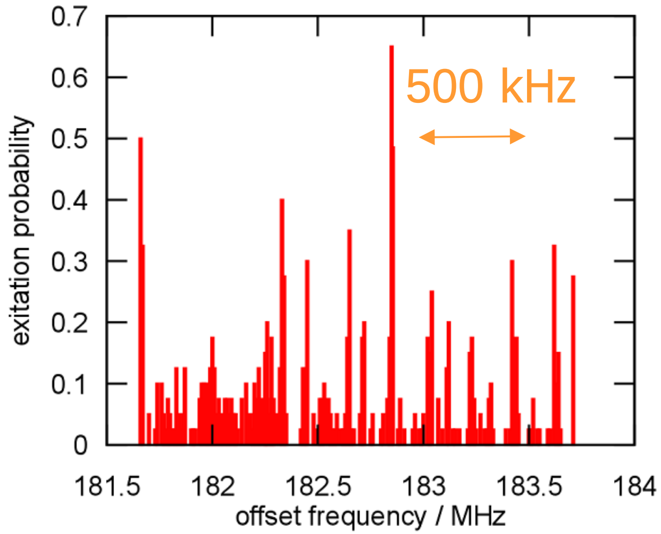


τ = 100 ms
Step: 50 kHz
Trial: 30

Zeeman components?



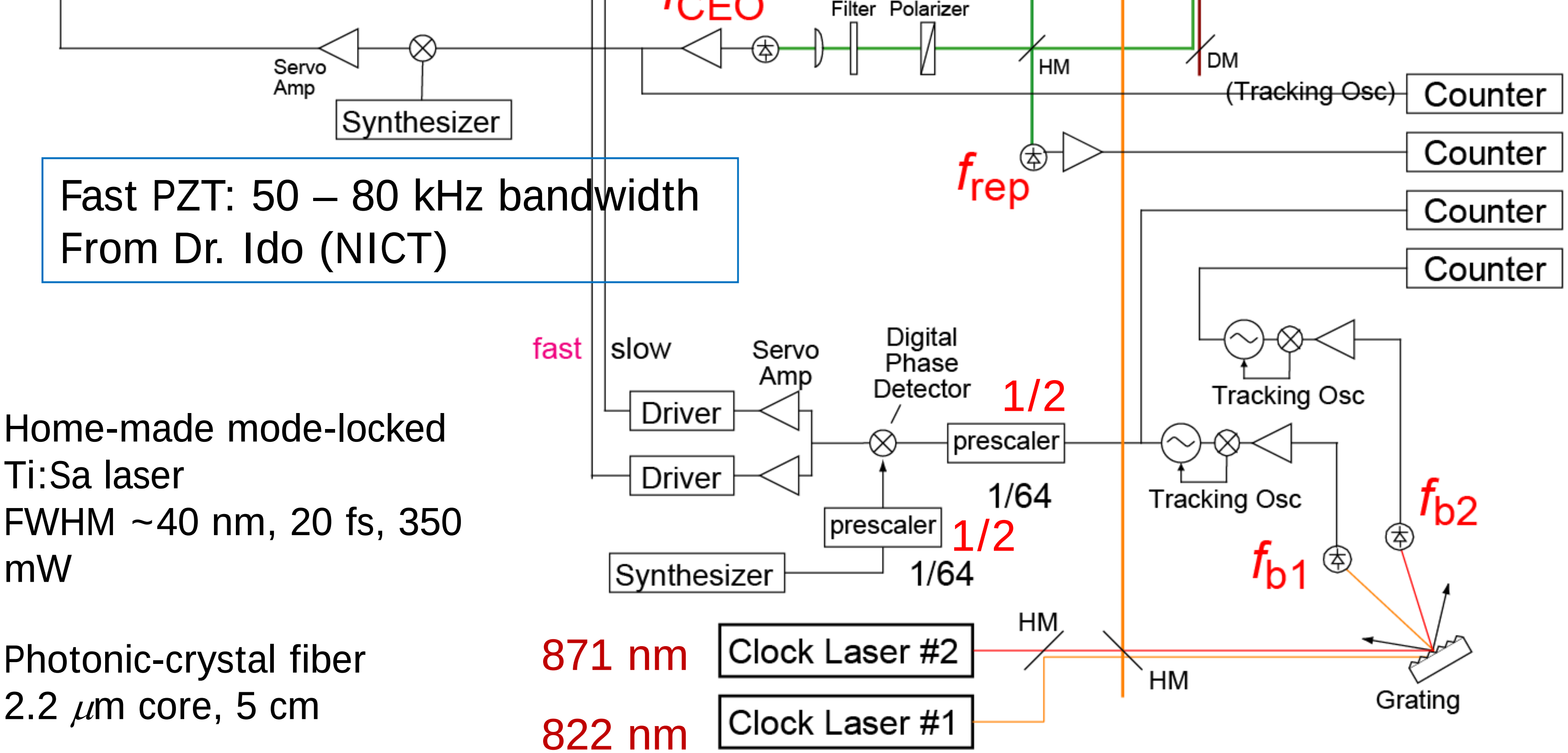
Quantum jumps of single $^{138}Ba^{+}$ by using linenarrowed 1762-nm ECLD

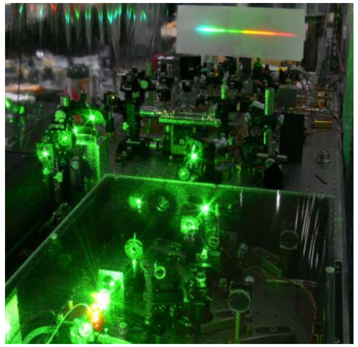


τ = 50 ms
Step: 10 kHz
Trial: 40

Motional sideband

Setup for frequency ratio measurement using Ti:Sa laser





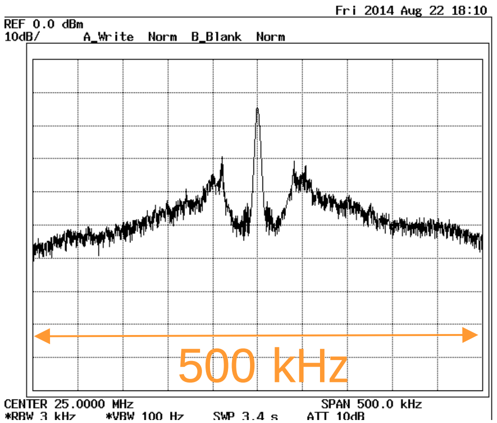
Fast PZT: 50 – 80 kHz bandwidth
From Dr. Ido (NICT)

Home-made mode-locked Ti:Sa laser
FWHM ~40 nm, 20 fs, 350 mW

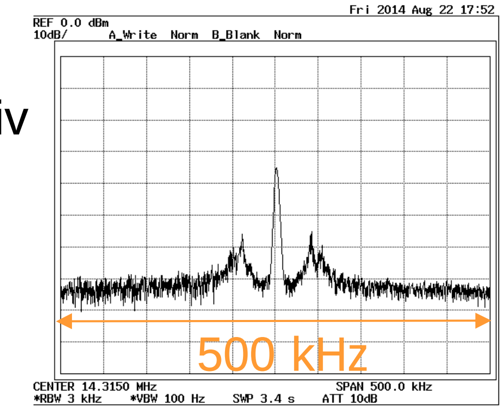
Photonic-crystal fiber
2.2 μm core, 5 cm

Phase locking of comb to laser

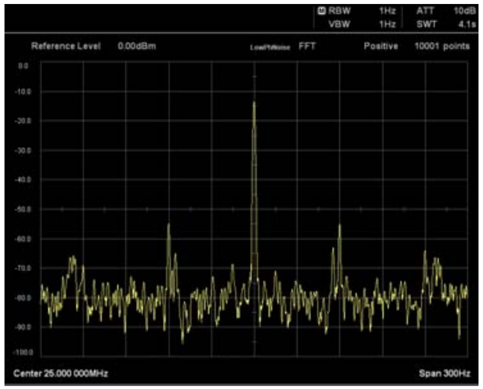
Hatanaka

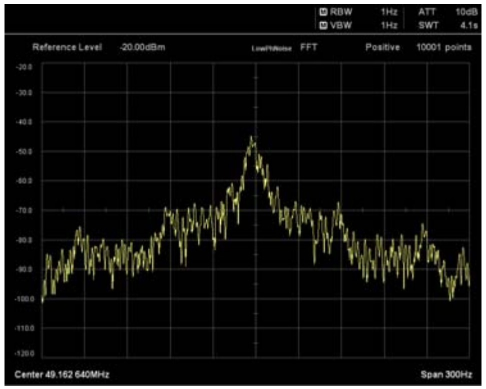


y: 10 dB/div



Span: 500 kHz, RBW: 30 Hz





FWHM:
<10 Hz

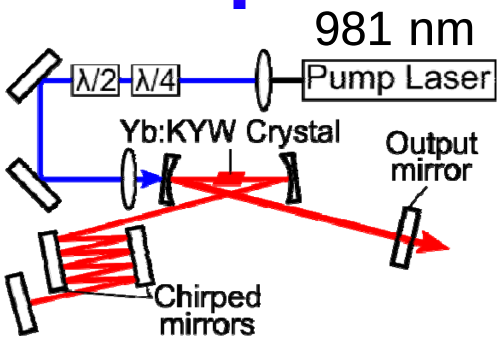
Span: 300 Hz, RBW: 1 Hz

822 nm : Phase locked   871 nm : measured

Power concentration to carrier: 92 %
Residual phase noise: 0.32 rad (10 Hz - 1 MHz)

Laser-diode pumped Kerr-lens mode-locked Yb:KYW laser

Mitaki



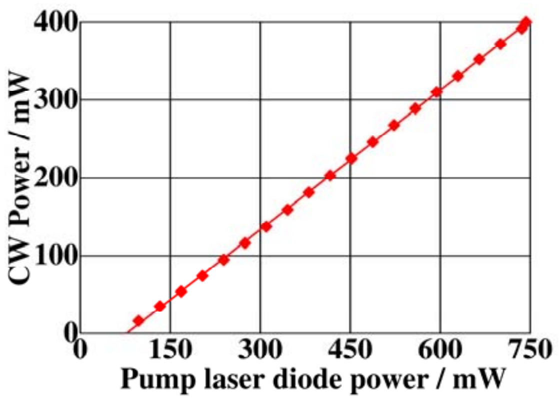
Goal:

- Long-term continuous operation with low running cost
- Alternative to fiber laser

Advantage:

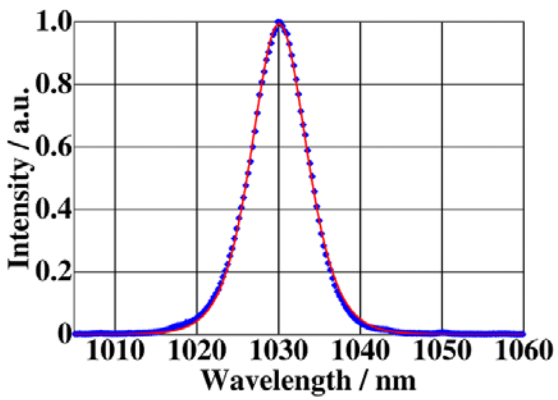
- Low heat generation

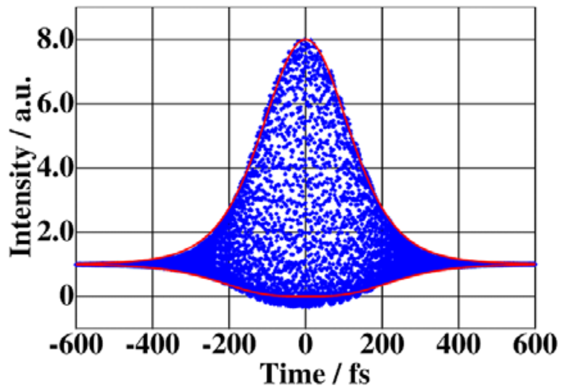
Comb: Meyer *et al*., Appl. Phys. B 112, 5765 (2013).
High frep: Endo *et al*., Opt. Express, 20, 12191 (2012).



CW oscillation

Max. power
(output coupler: 90%):
400 mW @ 750 mWpump
Slope efficiency: 59 %





Mode-locked oscillation

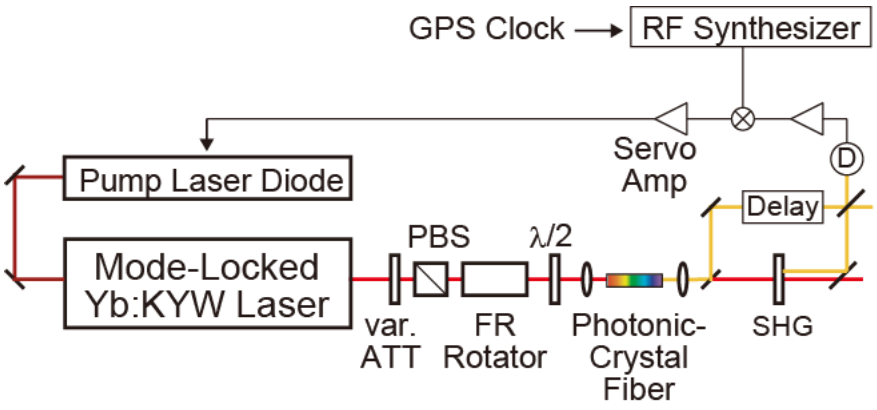
Output coupler 92.5 %, frep ~90 MHz

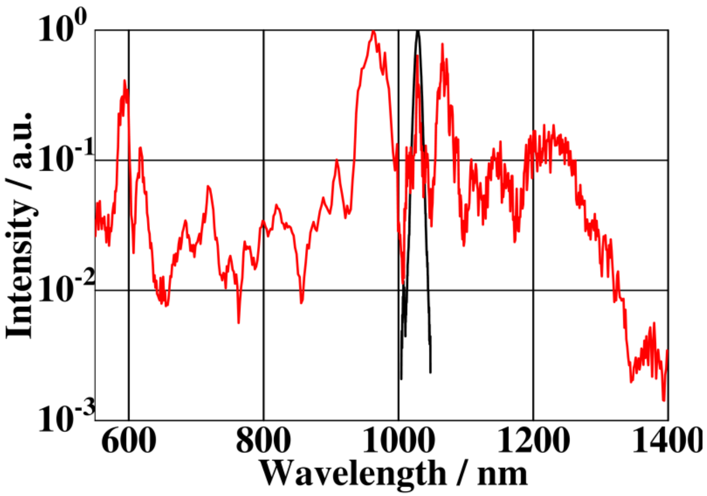
Spectral width:
8.0 nm@360 mW

Pulse duration:
165 fs @360 mW

Continuous mode-locking ~1 month
with temperature-controlled base plate

Detection of f_{CEO} with self-referencing technique





Self-referencing technique

Second-harmonic of low-frequency wing

$$2f(n) = 2 \text{ x } (n\ f_{rep}) + 2f_{CEO}$$

high-frequency wing of fundamental

$$f(2n) = 2n\ f_{rep} + f_{CEO}$$

→ beat frequency $= f_{CEO}$

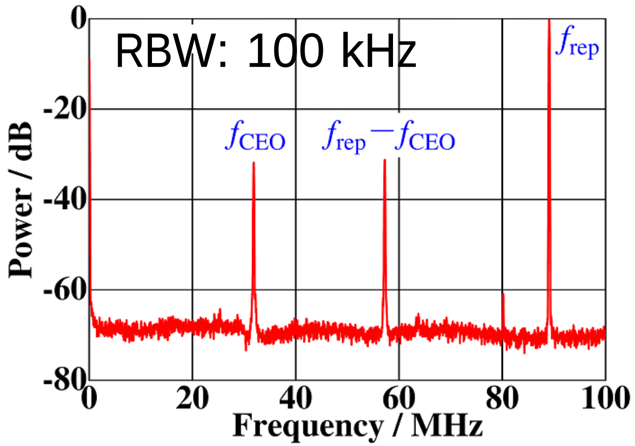
Jones *et al*., Science 288, 635 (2000)

Spectral broadening with photonic-crystal fiber

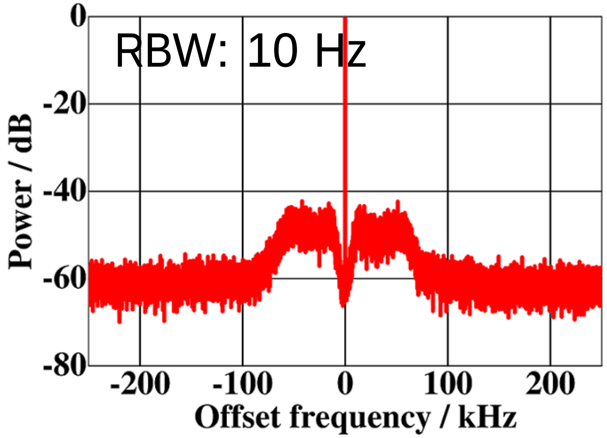
Core: 3.3 μm, Length: 5 cm,
Input: 360 mW
Output: 200 mW

Fiber amplifier not required

Phase locking of f_{CEO}



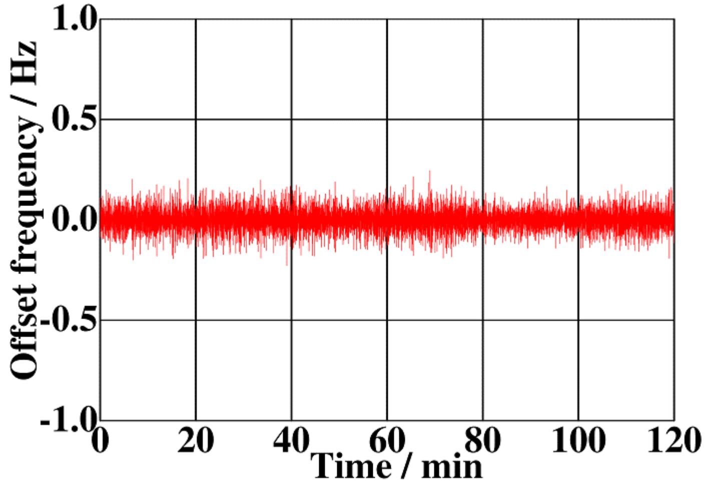
Free running



phase-locked

Beat at fCEO

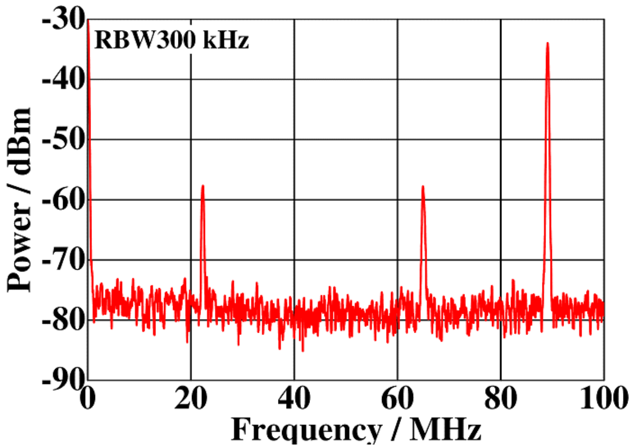
- Residual phase noise:
  0.48 rad (1 Hz—1 MHz)
- Concentration in carrier:
  90 % in 25-Hz BW
  within 250-kHz span

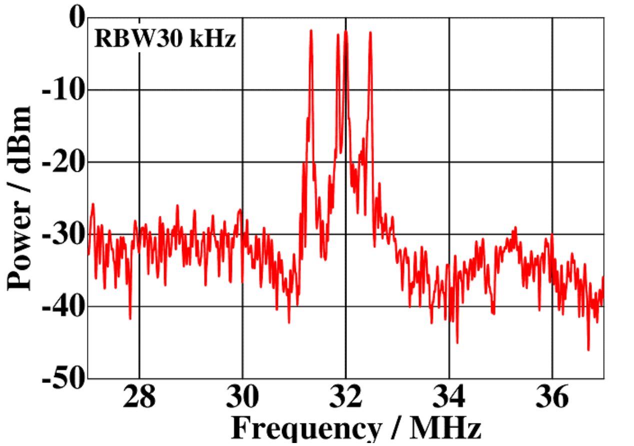


Frequency counting of fCEO

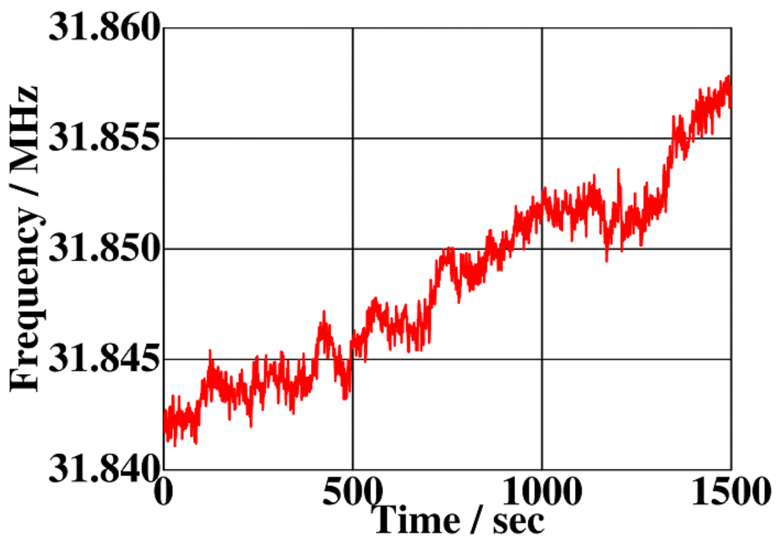
Continuous locking: 2 hours
Gate: 1 s

Frequency measurement





Beat with
a clock laser at 871 nm



<u>Frequency counting of fbeat</u>

Gate: 1 s

Drift: 10 Hz/s,   Fluctuation: 3×10^{-12}

Summary

- Development of single Yb^+ and Ba^+ ion optical clock, and frequency comb
  - Application: search for temporal variation of the fine structure constant

Current status

- Single-ion spectroscopy: $^{174}Yb^+$ S-$D_{5/2}$ and $^{171}Yb^+$ S-$D_{3/2}$ transition
  - Resolution: 380 Hz, laser-linewidth limit (<300 Hz)
- Ba^+: single-ion spectroscopy of 1.76 μm S-$D_{5/2}$ transition
- Comb: Ti:Sa: phase locking to laser completed
  Yb:KYW laser : frequency measurement system

Next step

- ✸ Single $^{171}Yb^+$ spectroscopy
  - Improvement of linewidth and stability of clock lasers → higher resolution
  - S-F transition
- ✸ Second system → Comparison between same or different transitions
- Ba^+: single-ion spectroscopy improved, Better cooling of odd isotopes
- Comb: Yb:KYW: phase locking to laser