量子情報処理プロジェクト全体会議2011
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光格子時計と光周波数コムによる量子標準の開発
Development of Quantum Standard Using Optical Lattice Clocks and Combs

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Contents

- “Redefinition of the second”
- Yb optical lattice clock
- Sr/Yb dual optical lattice clock
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CIPM recommended laser frequencies

Wavele nght	Laser and reference	Frequency	Uncertainty
237 nm	$^{115}In^{+}$, $5s^2\ ^1S_0$ - $5s5p\ ^3P_0$ transition	1267402452899.92 kHz	3.6×10^{-13}
243 nm	^{1}H, 1S - 2S, 2 photon transition	1233030706593.55 kHz	2.0×10^{-13}
282 nm	$^{199}Hg^{+}$, $5d^{10}6s\ ^2S_{1/2}$ (F=0) - $5d^96s^2\ ^2D_{5/2}$ (F=2) transition	1064721609899145 Hz	3×10^{-15}
436 nm	$^{171}Yb^{+}$, $6s^2S_{1/2}$ (F=0) - $5d^2D_{3/2}$ (F=2) transition	688358979309308 Hz	9×10^{-15}
467 nm	$^{171}Yb^{+}$, $^2S_{1/2}$ (F=0) - $^2F_{7/2}$ (F=3) transition	642121496772657 Hz	6×10^{-14}
532 nm	Nd:YAG laser, $^{127}I_2$, R(56)32-0:a_{10}	563260223513 kHz	8.9×10^{-12}
543 nm	He-Ne laser, $^{127}I_2$, R(106)28-8:b_{10}	551580162400 kHz	4.5×10^{-11}
578 nm	^{171}Yb, $6s^2\ ^1S_0$ (F=1/2) - $6s6p\ ^3P_0$ (F=1/2) transition	518295836590864 Hz	1.6×10^{-13}
633 nm	He-Ne laser, $^{127}I_2$, R(127)11-5:a_{16}	473612353604 kHz	2.1×10^{-11}
657 nm	^{40}Ca, $^1S_0$ - $^3P_1$, $\Delta m_J = 0$	455986240494140 Hz	1.8×10^{-14}
674 nm	$^{88}Sr^{+}$, $5^2S_{1/2}$ - $4^2D_{5/2}$	444779044095484 Hz	7×10^{-15}
698 nm	^{87}Sr, $5s^2\ ^1S_0$ - $5s5p\ ^3P_0$ transition	429228004229873.7 Hz	1×10^{-15}
698 nm	^{88}Sr, $5s^2\ ^1S_0$ - $5s5p\ ^3P_0$ transition	429228066418012 Hz	1×10^{-14}
729 nm	$^{40}Ca^{+}$, $4s\ ^2S_{1/2}$ – $3d\ ^2D_{5/2}$ transition	411042129776393 Hz	4×10^{-14}
778 nm	^{85}Rb, $5S_{1/2}$(F=3) - $5D_{5/2}$(F=5), 2 photon transition	385285142375 kHz	1.3×10^{-11}
1.5mm	$^{13}C_2H_2$, P(16)($\nu_1 + \nu_3$) transition	194369569384 kHz	2.6×10^{-11}
3.39mm	He-Ne laser, CH_4, n_3, P(7), $F_2^{(2)}$	88376181600.18 kHz	3×10^{-12}

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Background

We have demonstrated ^{171}Yb optical lattice clock in 2009.

Applied Physics Express 2 (2009) 072501

One-Dimensional Optical Lattice Clock with a Fermionic ^{171}Yb Isotope

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We demonstrate a one-dimensional optical lattice clock with ultracold ^{171}Yb atoms, which is free from the linear Zeeman effect. The absolute frequency of the $^1S_0(F = 1/2)$–$^3P_0(F = 1/2)$ clock transition in ^{171}Yb is determined to be 518 295 836 590 864(28) Hz with respect to the SI second.

DOI: 10.1143/APEX.2.072501

Effect	Correction (Hz)	Uncertainty (Hz)
Blackbody radiation shift	+ 1.32	0.13
Gravitational shift	- 1.19	0.03
2nd order Zeeman shift	+ 0.4	0.05
Scalar light shift	0	14
Clock laser light shift	- 0.04	< 0.01
Paper lock error	0	23
UTC (NMIJ)	0	5
Total	+ 0.49	27

$^1S_0(F = 1/2)$-$^3P_0(F = 1/2)$ transition in ^{171}Yb

***f* = 518 295 836 590 864 (28) Hz**

(Fractional uncertainty 5.4×10^{-14})

CIPM Recommended frequency list
(June, 2009)

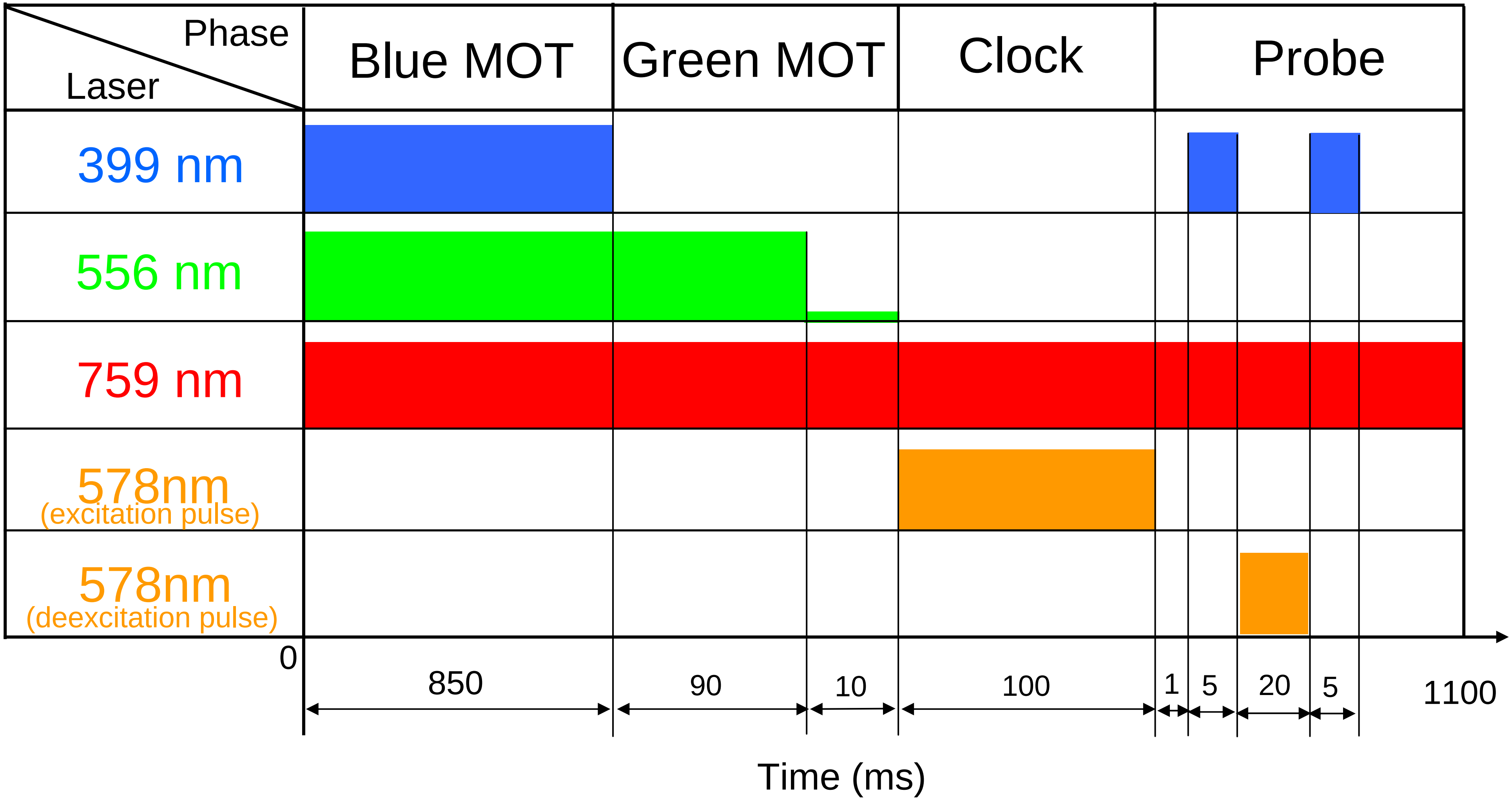
cf. NIST group's GREAT result:
N. D. Lemke *et al.*, "Spin-1/2 Optical Lattice Clock"
Phys. Rev. Lett., vol. 103, pp. 063001, August 2009
***f* = 518 295 836 590 865.2(0.7) Hz**
(Fractional uncertainty 1.4 x 10^{-15})

Yb OLC can be so good!

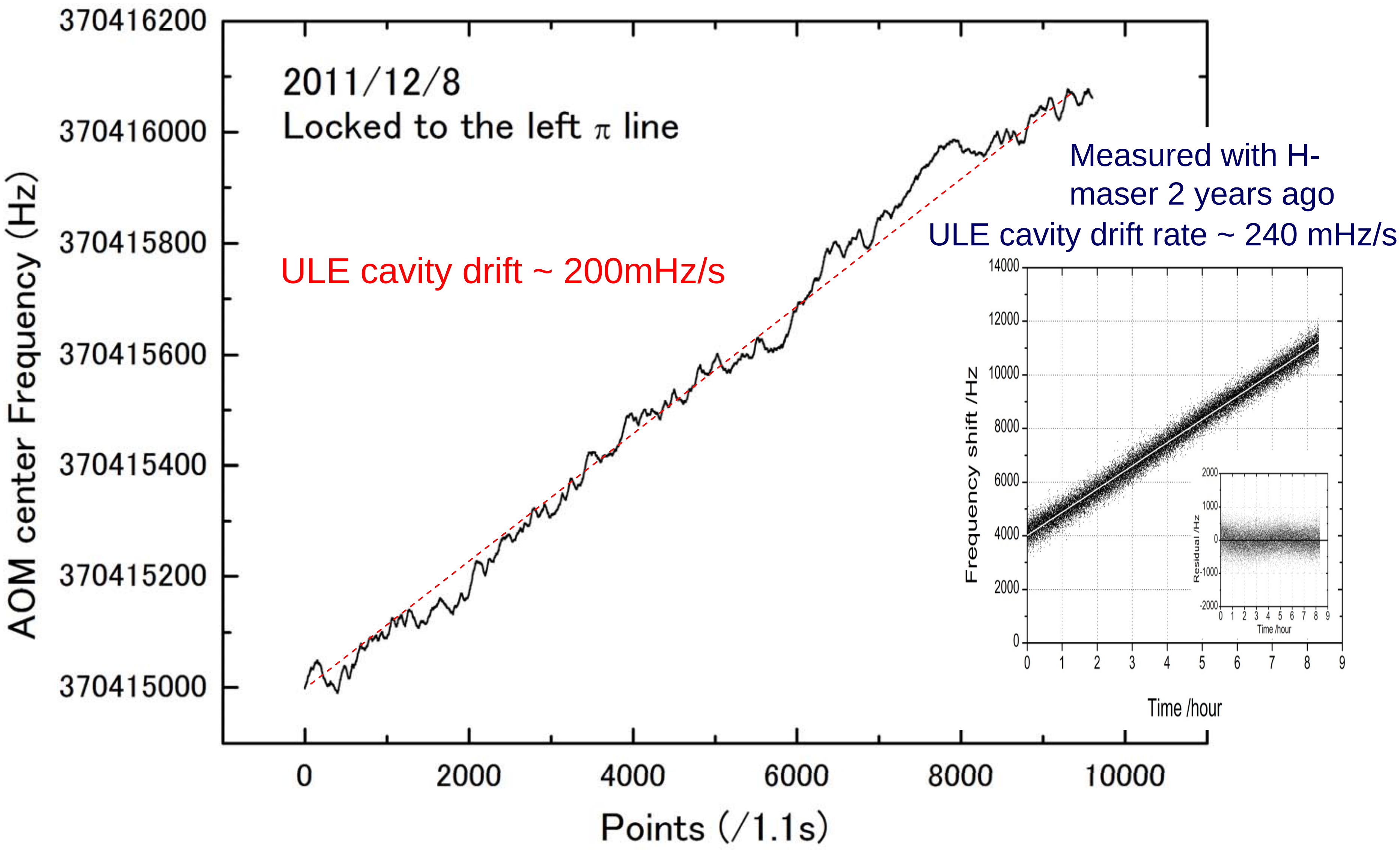
To reduce the uncertainty,
we have to lock the clock laser to the clock transition.

We improve the spectroscopy signal by normalizing the atom number.

Timing chart of the spectroscopy w/ atom # normalization



Locking to the atomic transition



Future Prospects

- Lock the clock laser to the center of σ (π) transitions
- Next absolute frequency measurement in a few month.

(the result will be limited by our Cs clock.)

^{171}Yb clock uncertainty	$\times 10^{-16}$	How to tackle?
BBR	2.5	Cooling the environment
Lattice polarizability	2.0	Well-define the lattice laser. (Freq., Power. Pol.)
Density	0.8	Further cooling atoms -> Collision suppression
Hyperpolarizability	0.7	Further cooling atoms -> Less lattice laser power

(excerpt from “Spin-1/2 Optical Lattice Clock”, PRL **103**, 063001 (2009))

Sr optical lattice clock project has been started.

→ opt.-opt. comparison beyond our Cs-limit

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Dual Optical Lattice Clock

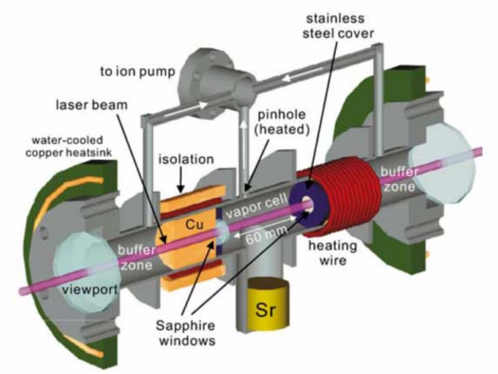
Yb OLC and Sr OLC in a same chamber

1) Contribution to the Sr lattice clock community;
2) As a second optical clock to be used for the evaluation of the Yb lattice clock;
3) Measurement of the Sr/Yb frequency ratio with an uncertainty beyond the Cs limit;
4) Contribution to the experimental demonstration of alpha variation;
5) Demonstration an atomic clock with suppressed BBR shift.

A diode laser for intercombination cooling

The frequency of the cooling laser has to be locked to a frequency reference.

The linewidth has to be sub-kHz to cool the atoms down to μK level.

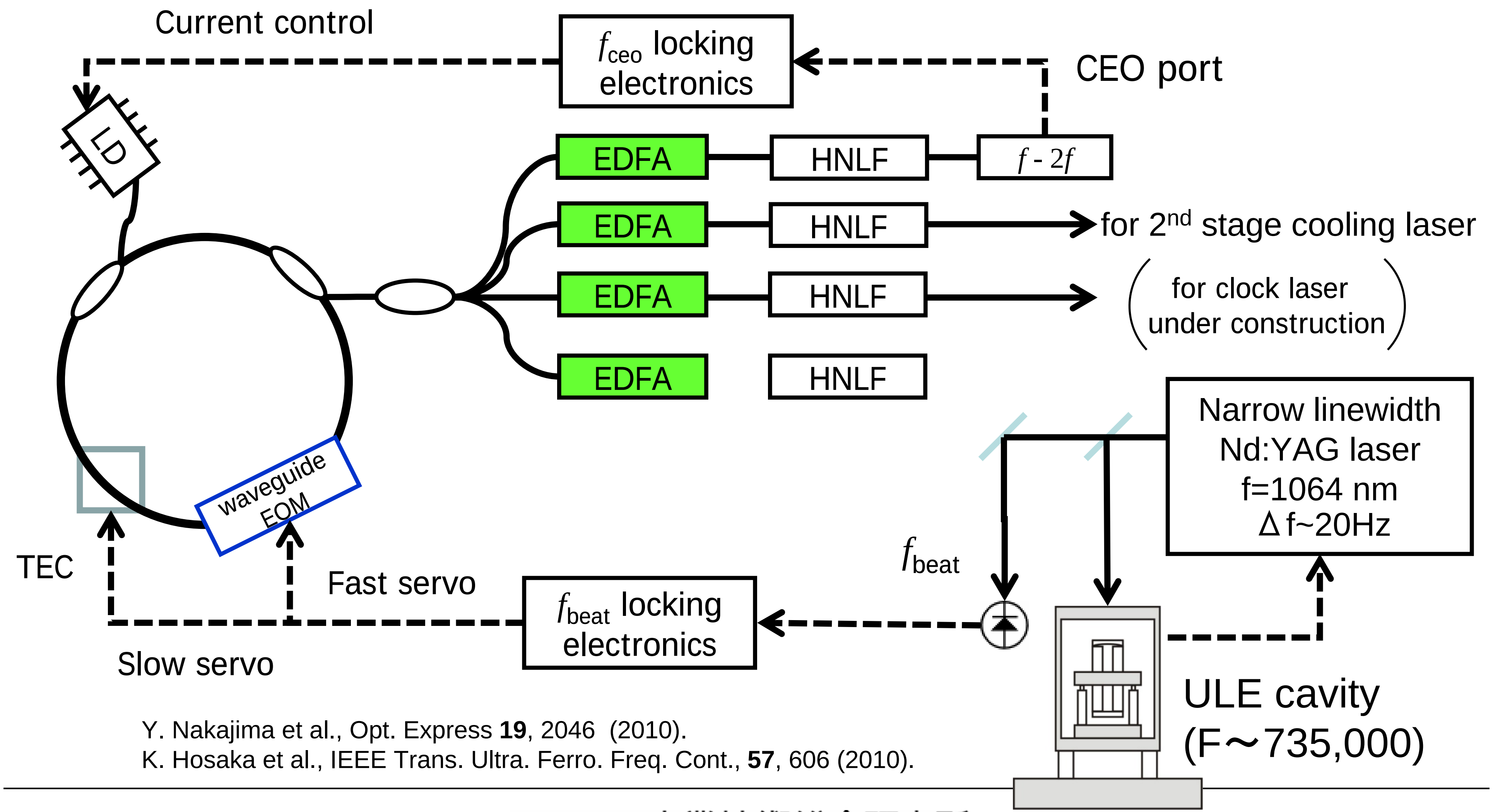


Y. Li et al., Appl. Phys. B **78**, 315

a heat pipe and a high finesse cavity
are conventionally used for narrowing the linewidth.

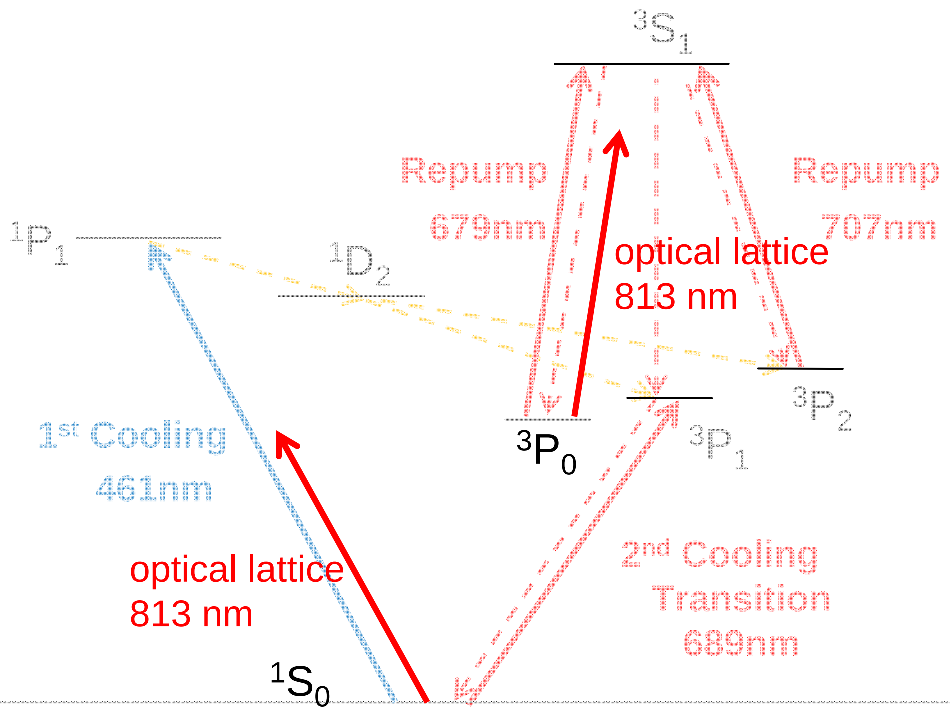
We employ "a linewidth transfer method" with optical freq. comb.

Linewidth transfer for Strontium OLC

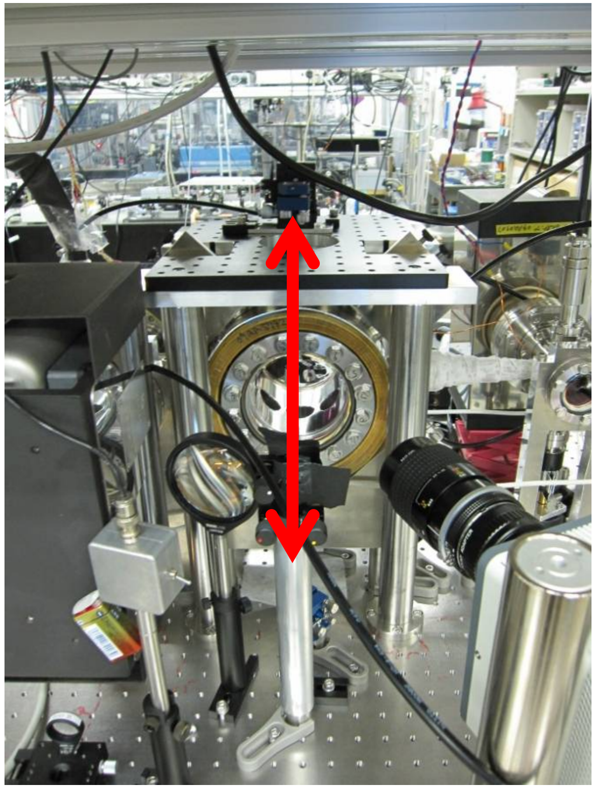


Y. Nakajima et al., Opt. Express **19**, 2046 (2010).
K. Hosaka et al., IEEE Trans. Ultra. Ferro. Freq. Cont., **57**, 606 (2010).

Optical Dipole Trapping of Sr at a magic wavelength

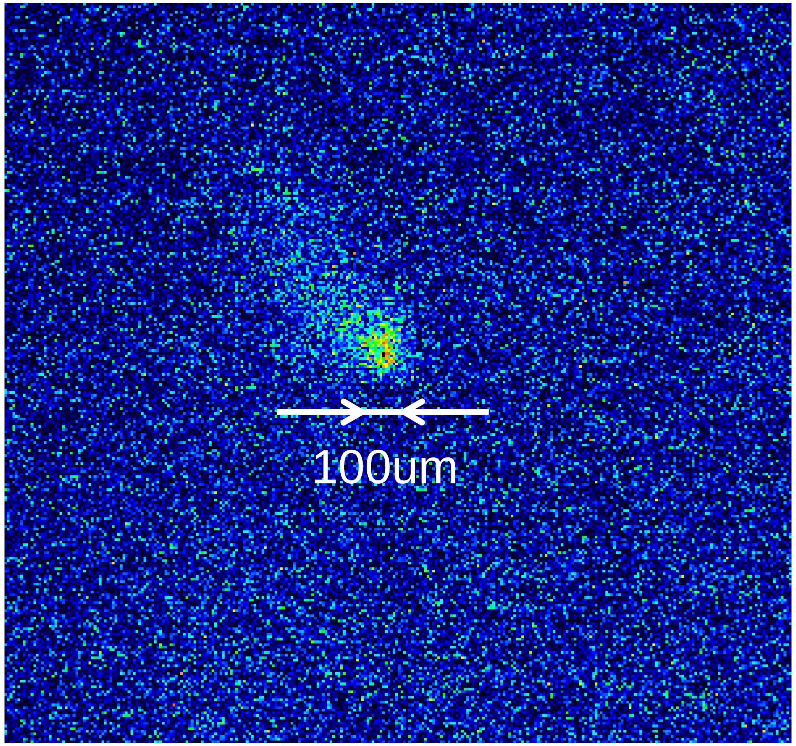


Optical Dipole Trap of ^{88}Sr



813.4nm (magic wavelength)
120mW

g



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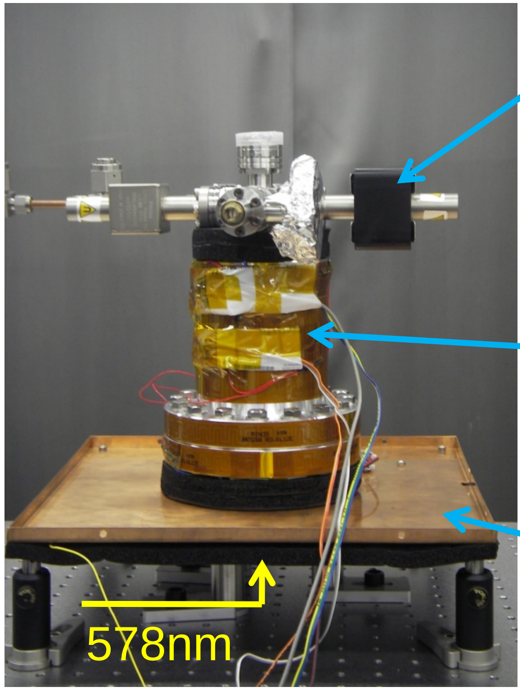
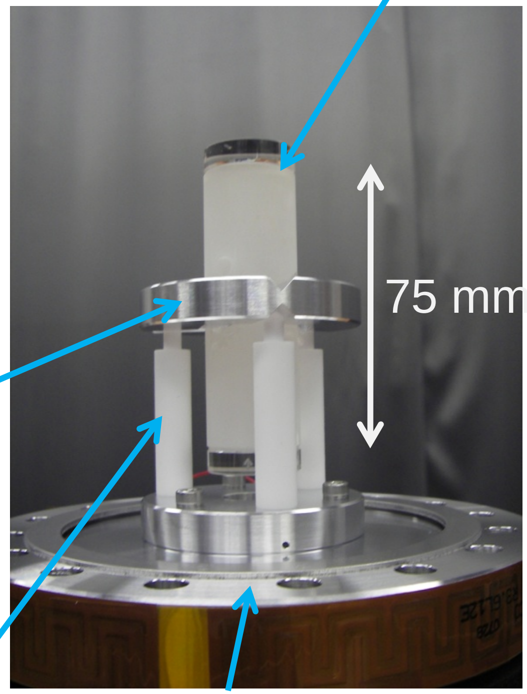
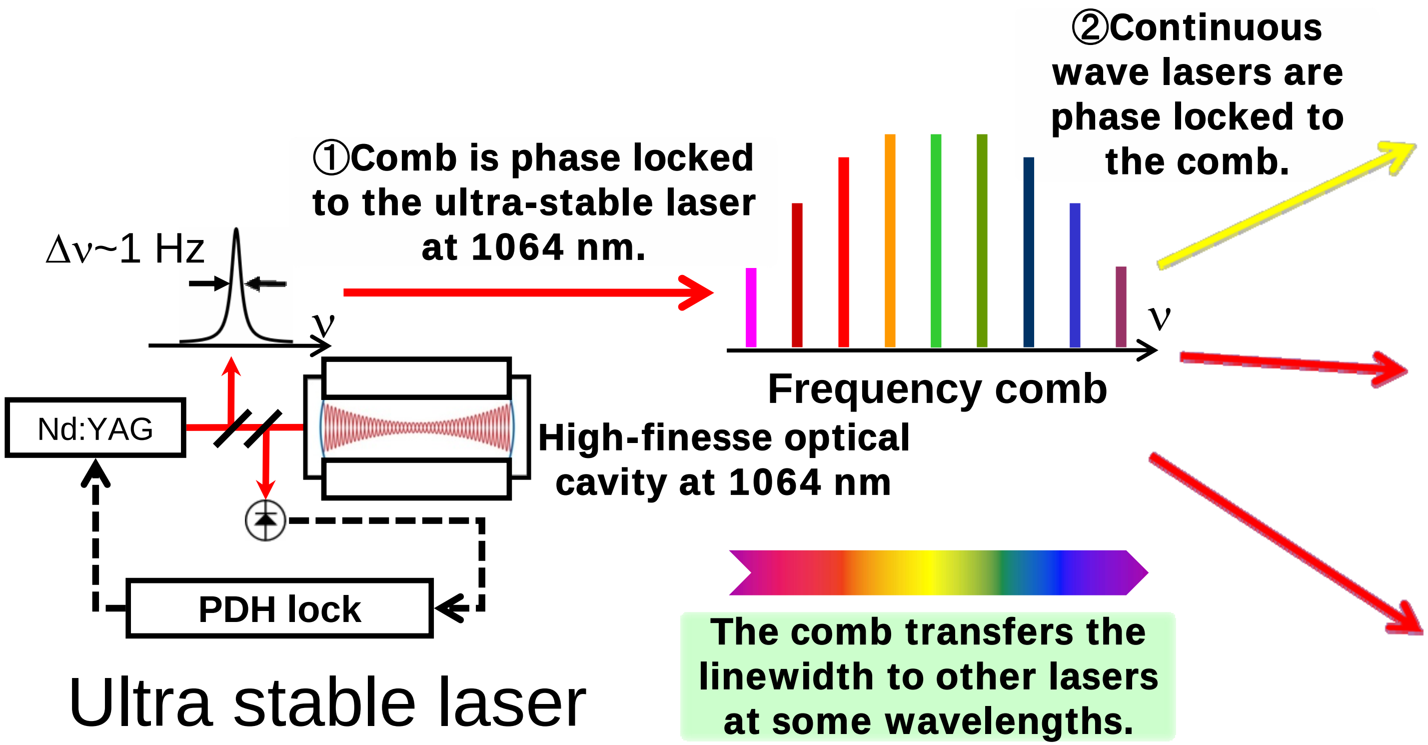
578 nm & 1064 nm reference cavities

- Ultra-low expansivity glass (ULE) etalon
- Length : 75 mm
- Finesse : ~400,000 (+/- 150,000)
- The cavity was bonded to an Al disc using silicon RTV
- Turning point of thermal expansivity is around room temp
- Two-layer temperature control (± 1 mK)
- Vacuum : ~10^{-5} Pa





Applications to optical lattice clocks using narrow linewidth combs



Ultra stable laser at 1064 nm

Yb lattice clock
Clock laser
(578 nm) OK!

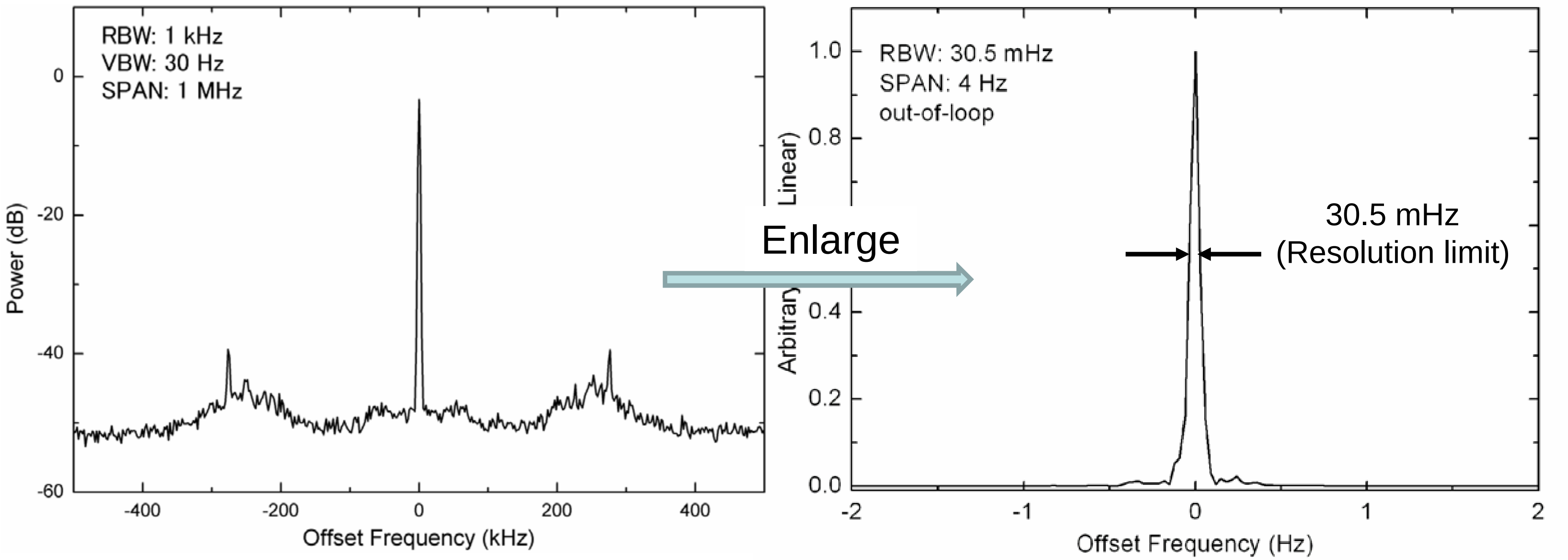
Sr lattice clock
Clock laser
(698 nm) Soon

Sr lattice clock
2nd cooling
laser (689 nm)
OK!

Linewidth transfer using narrow linewidth combs

Fiber combs are not only very reliable for long-term operation but also useful to transfer linewidth and frequency stability from one wavelength to another.

Out-of-loop beat signal of 2 fiber combs commonly phase-locked to a narrow linewidth laser



The energy concentration to the coherent carrier is 99 %

Relative linewidth < 30 mHz

Conclusion: frequency combs can be used to transfer laser linewidth at mHz level!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