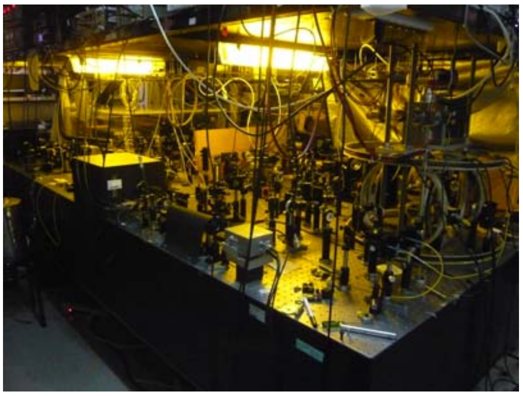
Clock, optical frequency vernier
and quantum control by comb laser



Speaker: Wang-Yau Cheng
Institute of Atomic and Molecular Science, IAMS, Taiwan, ROC

Outline

•Importance and history of human clock

• Comb-CPT freeing from light shift and pressure shift

•Optical frequency vernier

•Astro-comb spectroscopy

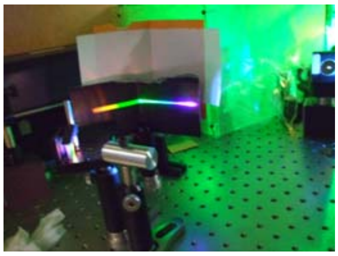
•Future works
– A portable clock
–controlling quantum state of ultracold/BEC atoms

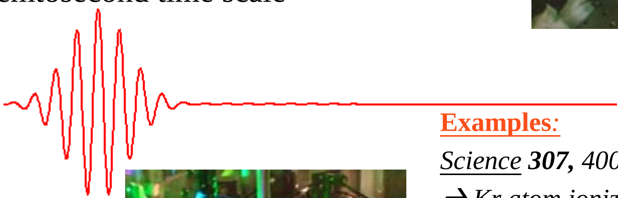
In the viewpoint of time domain:

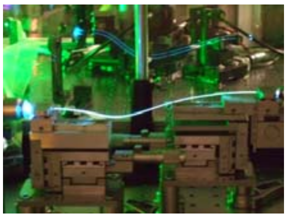
High peak power (compared to CW laser)

Fixed carrier-envelope phase
(good for selective or delicate pumping)

Femtosecond time scale







Examples:

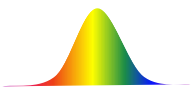
Science ***307,*** *400 (2005)*
→ *Kr atom ionization rate control*

Nature ***436,*** *234 (2005)*
→ *XUV comb*

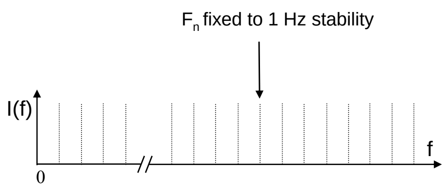
Nature physics ***2,*** *327 (2006)*
→ *Terahertz comb*

In the viewpoint of frequency domain:

Wide-band



High-resolution



Rapid-wideband measurement

Examples:

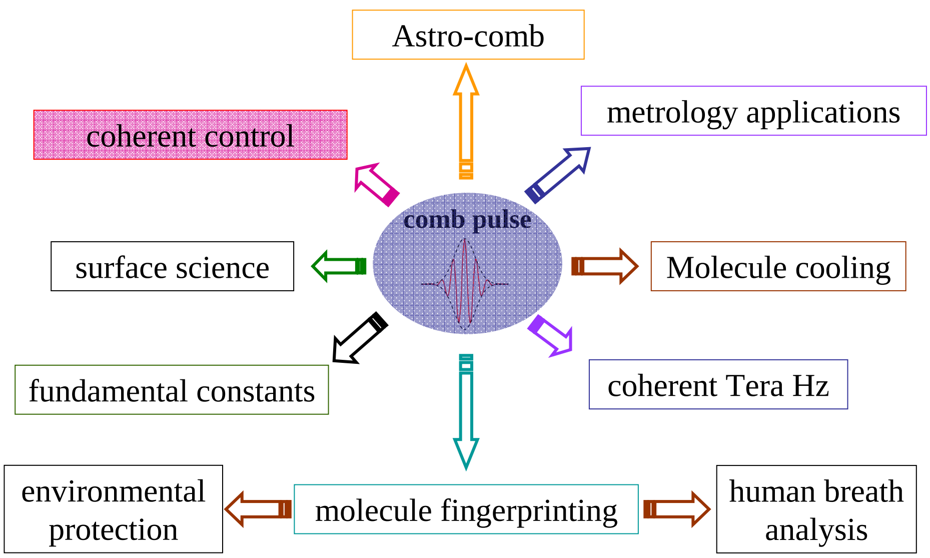
Nature ***445,*** *627 (2007)*
→ *molecular fingerprinting, I_2, span: 16,00,000 MHz (9 nm), resolution: 1 MHz*

Science ***311,*** *1595 (2006)*
→ *comb laser cavity ring down, C_2H_2, H_2O, O_2, NH_3, 210,00 GHz (130 nm), resolution: 25 GHz*

Recent comb laser related reports

[1] *Science* ***321***, *2335 (2008);*
[2] *Nature photonics* ***2***,*712 (2008)*
[3] *Science* ***321***, *1301 (2008);*
[4] *Nature* ***452***,*538 (2008)*
[5] *Nature* ***452***, *06854(2008)*
[6] *Nature* ***445***, *627 (2007)*
[7] *Science* ***311***, *1595 (2006)*
[8] *Science* ***307***, *400 (2005)*
[9] *Nature physics* ***2***, *327 (2006)*
[10] *Science* ***322***, *1595 (2006)*
[11] *Nature photonics* ***1***,*463 (2007)*
[12] *Nature photonics* ***1***,*712 (2007)*
[13] Nature Photonics **1**, 447 - 448 (2007)
[14] Nature Photonics **2**, 355 - 359 (2008)
[15] Nature Photonics **2**, 70 (2008)

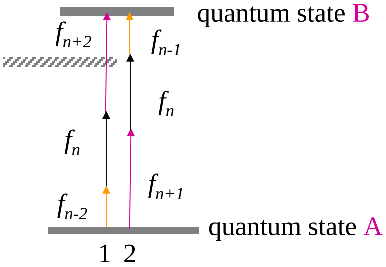
How comb laser opens a new world



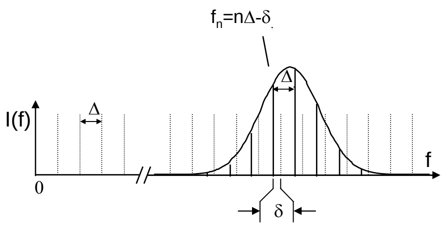
Comb laser for quantum interference

high peak power for nonlinear optics	phase-locked frequencies for coherent control

for example: multi-photon process by comb laser



Our laser is uniquely suited for coherent multi-photon process



$$f_n = n\Delta - \delta$$

Applications of quantum control by comb laser

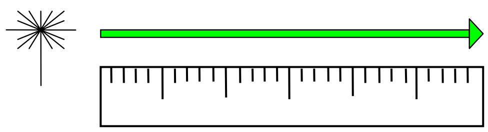
Make a clock !

Time and mass are two primary units of all units

for example: Definition of length standard

In 1983

Meter is defined as light travels in vacuum in 1/299792458 sec



for example: Definition of energy

energy (joule) ⇒ **Force** (newton) × **Distance** (meter)

Work- energy theorem

kg

Newton law

⇒ **F=m×a**

m/s

Joule comes from the definition of mass and time

m/s^2

All units come from physical laws

We always need a clock to check physical laws

Therefore, clock is important for

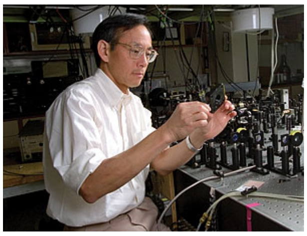
1. verifying physical laws
2. quantum information science
3. GPS (Global positioning system)
4. CPU clock in PC cluster
5. Unification of high precision instruments internationally

(書同文，車同軌)

Clock and Nobel Laureates in atomic physics

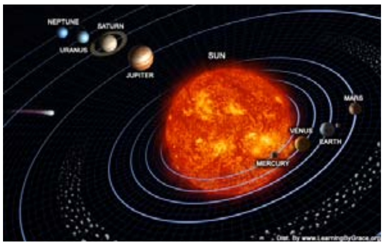
1989-Norman F. Ramsey

1997 - Steven Chu



Evolution of human clock

1. Rotation period of planets



1. The tides

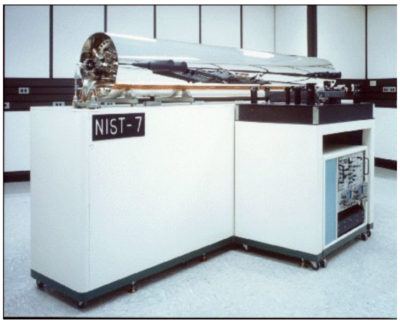

3. sundial

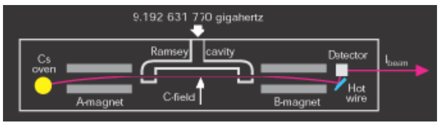
3. Astrolabe clock

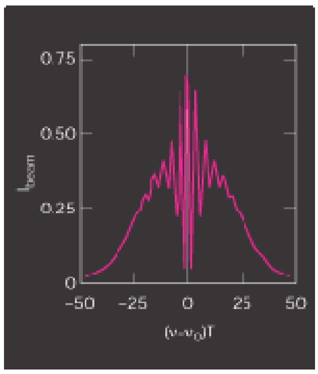
the others:

- water clock
- tower clock
- pendulum clock
- spring-balance-wheel clock
- quartz oscillator clock

Cesium atomic clock using Ramsey fringe





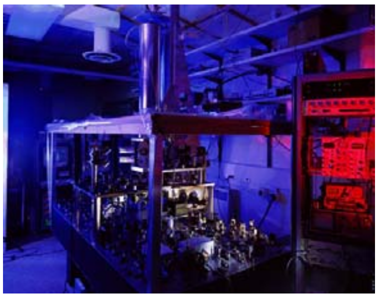


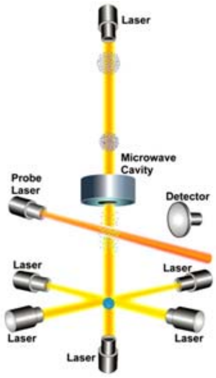
$F = 4$

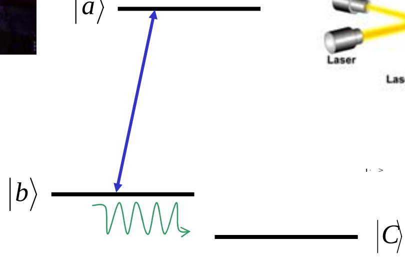
cesium ground state hyperfine transitions
(9.192631770 GHz)

$F = 3$

Cesium fountain clock in NIST







New age of clock: optical clock

1. High stable duty cycle ($\nu/\Delta\nu$ ~10^{17})

2. visible

3. could possibly be used in integrated optics (instead of IC)

1.No direct connection to traditional cesium clock

2. light shift caused accuracy problem (it always happens when you use "light")

3. only be defined in a very narrow wavelength

Hg^+ and Sr clock (optical atomic clock) (narrow linewidth optical transitions)

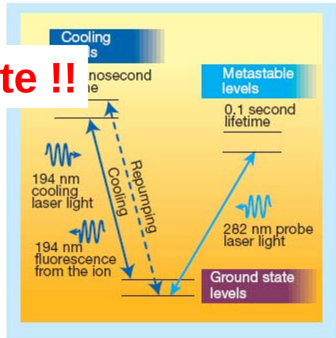
May 2009 (10 second)- JILA optical atomic clock is now t... accurate clock based on neutral atoms. Shining a blue laser onto ultracold strontium atoms in an optical trap tests how efficiently a previous burst of light from a red laser has boosted the atoms to an excited state. Only those atoms that remain in the lower energy state respond to the blue laser, causing the fluorescence seen here. Photo credit: Sebastian Blatt, JILA, University of Colorado[6]

Too complicate !!

Precision measurements

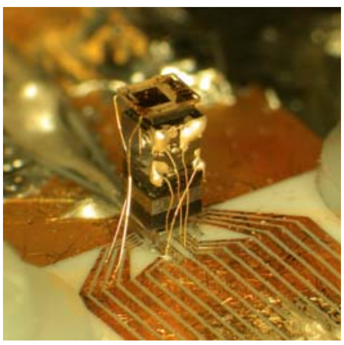
Optical clocks coming of age

Patrick Gill



NATURE | VOL 407 | 5 OCTOBER 2000 | www.nature.com

A portable CPT clock chip



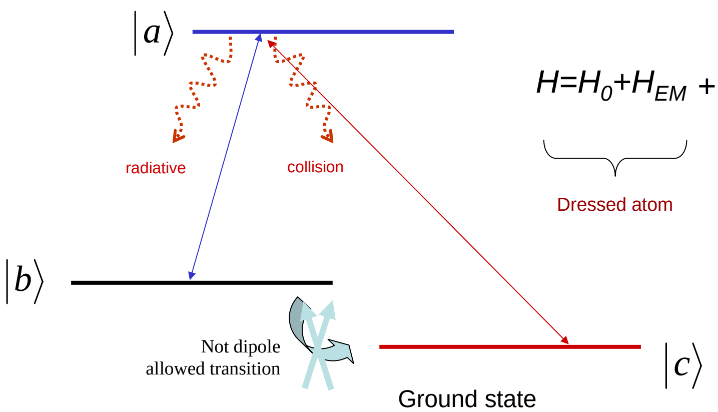
Brief introduction on Coherent Population Trapping (CPT)

$$|\varphi\rangle = \frac{\Omega_{R2}|b\rangle - \Omega_{R1}|c\rangle}{\sqrt{\Omega_{R1}^2 + \Omega_{R2}^2}}$$

$$\boxed{|\varphi\rangle = Cos(\Omega_R t)(|a\rangle + e^{-i\phi}|b\rangle)}$$

Not a stable mixed state

$\Phi\ (\tau)$



$$\underbrace{H=H_0+H_{EM}}_{\text{Dressed atom}} + H_{de}$$

Matrix representation (3 levels)

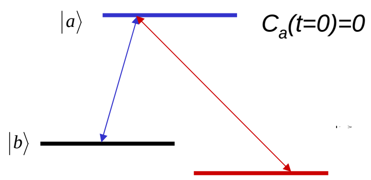
$$H_0 = \begin{array}{cc} & \begin{array}{ccc} |a\rangle & |b\rangle & |c\rangle \end{array} \\ & \begin{pmatrix} \hbar\omega_a & 0 & 0 \\ 0 & \hbar\omega_b & 0 \\ 0 & 0 & \hbar\omega_c \end{pmatrix} \begin{array}{c} |a\rangle \\ |b\rangle \\ |c\rangle \end{array} \end{array}$$

$$H_{EM} = \begin{pmatrix} 0 & \hbar\Omega_{R1} & \hbar\Omega_{R2} \\ \hbar\Omega_{R1}^* & 0 & 0 \\ \hbar\Omega_{R2}^* & 0 & 0 \end{pmatrix}$$

$$\underbrace{H=H_0+H_{EM}}_{\text{Dressed atom}}$$

$$|\varphi\rangle = C_a(t)e^{-iw_a t}|a\rangle + C_b(t)e^{-iw_b t}|b\rangle + C_c(t)e^{-iw_{cb} t}|c\rangle$$

$$i\hbar\frac{\partial}{\partial t}|\varphi\rangle = \hat{H}|\varphi\rangle$$



$$\dot{C}_b(t) = \frac{i}{2}\Omega_{R1}e^{i\phi_1}C_a$$

$$\dot{C}_c(t) = \frac{i}{2}\Omega_{R2}e^{i\phi_2}C_a$$

$$\dot{C}_a(t) = \frac{i}{2}(\Omega_{R1}e^{i\phi_1}C_b + \Omega_{R2}e^{i\phi_2}C_c)$$

$$\langle a|\hat{H}_{EM}|b\rangle \equiv \hbar\Omega_R = \langle a|-\vec{p}\cdot\vec{E}|b\rangle$$

When will the destructive interference happen?

Control the power-relation and phase-difference (ϕ_1-ϕ_2) of radiations

Wait until: $C_b(t) = e^{i\pi}\,C_c(t) = -C_c(t)$

$$|\varphi\rangle = \frac{\Omega_{R2}|b\rangle - \Omega_{R1}|c\rangle}{\sqrt{\Omega_{R1}^2 + \Omega_{R2}^2}}$$

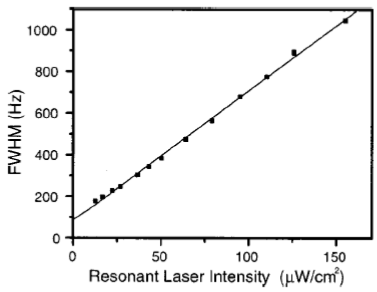
Note that it is a irreversible process

Problems of CPT clocks

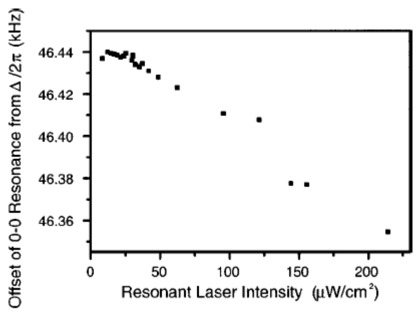
1. light shift always happen
2. need narrow linewidth as a frequency discriminator
3. buffer gas caused pressure shift

$$H_0 = \begin{array}{cc} \begin{array}{ccc} |a\rangle & |b\rangle & |c\rangle \end{array} & \\ \begin{pmatrix} \hbar\omega_a & 0 & 0 \\ 0 & \hbar\omega_b & 0 \\ 0 & 0 & \hbar\omega_c \end{pmatrix} & \begin{array}{c} |a\rangle \\ |b\rangle \\ |c\rangle \end{array} \end{array}$$

$$H_{EM} = \begin{pmatrix} 0 & \hbar\Omega_{R1} & \hbar\Omega_{R2} \\ \hbar\Omega_{R1}^* & 0 & 0 \\ \hbar\Omega_{R2}^* & 0 & 0 \end{pmatrix}$$

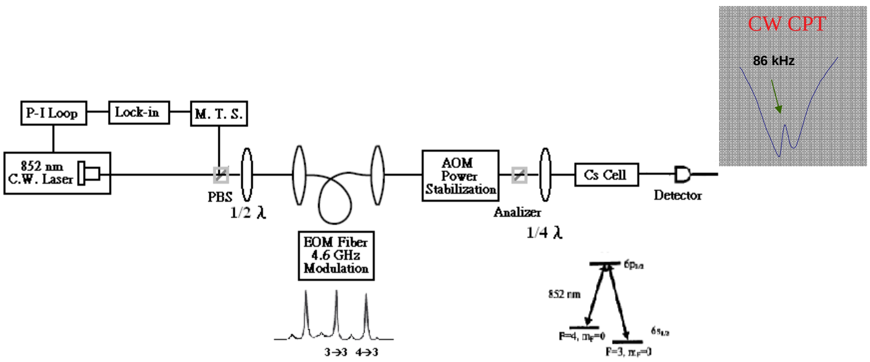


CW-CPT
Power broadening (with buffer gas)



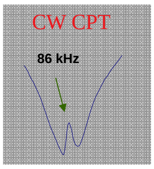
CW-CPT
Light shift (with buffer gas)

Probe CPT signal by CW laser (without buffer gas)



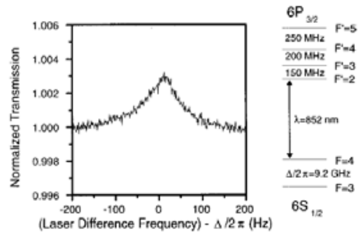
examples

without buffer gas



with Ne buffer gas

1546 J. Opt. Soc. Am. B/Vol. 18, No. 11/November 2001



$F = 4$

cesium ground state hyperfine transitions
(9.192631770 GHz)

$F = 3$

reduce the spin-spin exchange collision

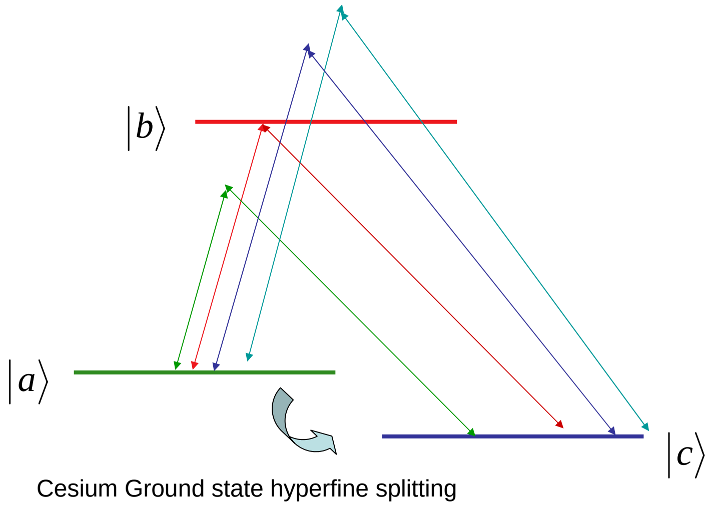
Characterization of coherent population-trapping resonances as atomic frequency references

Svenja Knappe and Robert Wynands
Institut für Angewandte Physik, Universität Bonn, Wegelerstrasse 8, D-53115 Bonn, Germany

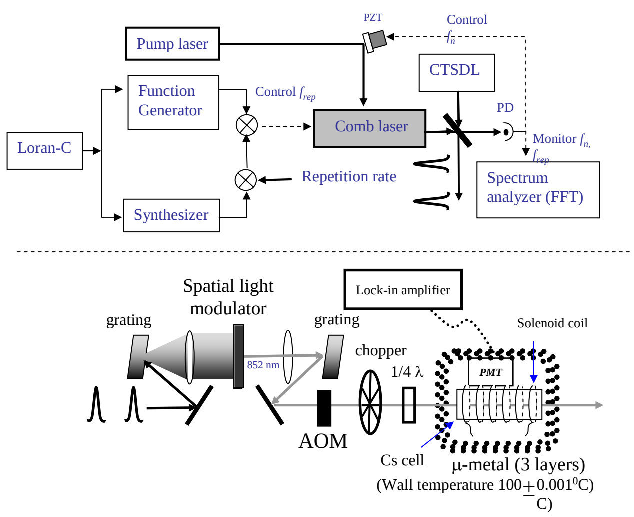
John Kitching, Hugh G. Robinson, and Leo Hollberg
Time and Frequency Division, Mail Stop 847.10, National Institute of Standards and Technology, 325 Broadway, Boulder, Colorado 80303

ceeds the laser linewidth. In addition, the CPT resonance frequency is shifted upward by ~46 kHz by Cs–Ne collisions at this pressure.[20]

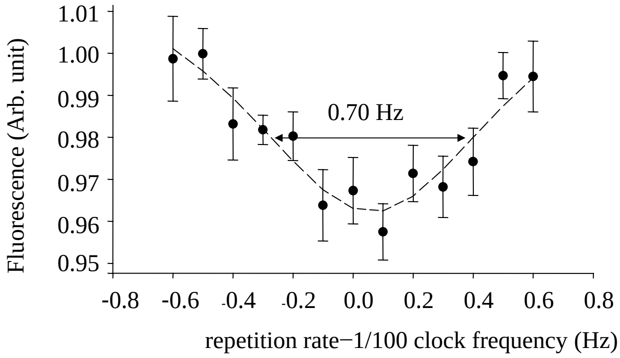
With a comb laser?

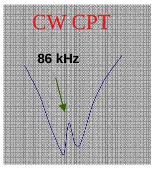


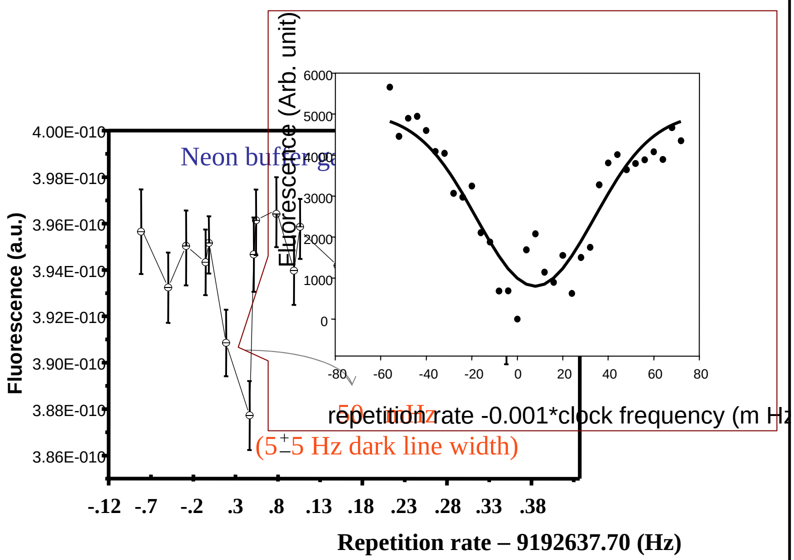
Cesium Ground state hyperfine splitting
→ Clock frequency

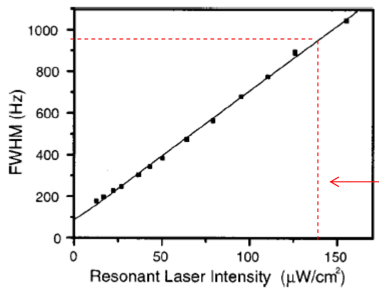


experimental results

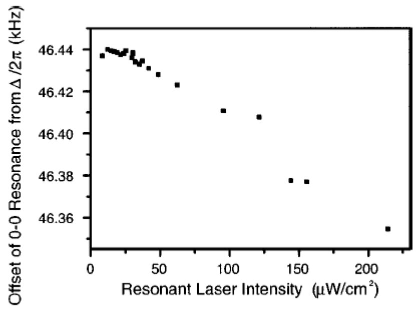






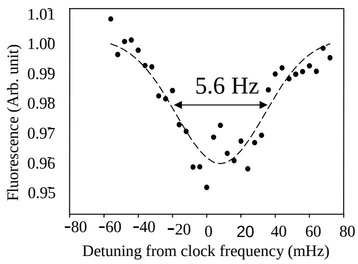


CW-CPT
Power broadening (with buffer gas)



CW-CPT
Light shift (with buffer gas)

Comb-CPT (with buffer gas)
2-order of magnitude narrower
No light shift
No pressure shift



comments from PRL reviewer

These results are very interesting and probably with applications in different fields. However, some points, described below, should be clarified.

1. Could the authors give some hint why no pressure shift was observed?

2. The authors should discuss the contribution of the two effects attributed to the observed linewidth (exceptionally narrow).

Why reviewers concern about those features?

1. Light intensity is an important parameter during light-matter interaction. It causes linewidth broadening and it can shift clock frequency

Why comb laser is immune from the broadening and shiftting?

2. Pressure shift is inevitable if buffer gas is applied

(Buffer gas can efficiently reduce the decoherence of the mixed quantum state)

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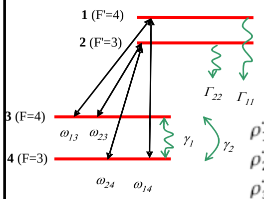
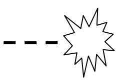
5. Theoretical analysis on comb laser-matter interaction

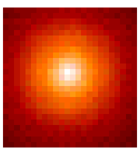
⇨ *Develop the theory background*

4-level density matrix

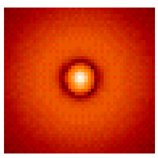


$$\dot{\rho}_{11} = -\Gamma_1\rho_{11} - \mathrm{Im}[\Omega_{13}\delta_{31}] - \mathrm{Im}[\Omega_{14}\delta_{41}]$$
$$\dot{\rho}_{22} = -\Gamma_2\rho_{22} - \mathrm{Im}[\Omega_{23}\delta_{32}] - \mathrm{Im}[\Omega_{24}\delta_{42}]$$
$$\dot{\rho}_{33} = \Gamma_{13}\rho_{11} + \Gamma_{23}\rho_{22} - \gamma_1(\rho_{33} - \rho_{44}) + \mathrm{Im}[\Omega_{13}\delta_{31}] + \mathrm{Im}[\Omega_{23}\delta_{32}]$$
$$\dot{\rho}_{44} = \Gamma_{14}\rho_{11} + \Gamma_{24}\rho_{22} - \gamma_1(\rho_{44} - \rho_{33}) + \mathrm{Im}[\Omega_{14}\delta_{41}] + \mathrm{Im}[\Omega_{24}\delta_{42}]$$
$$\dot{\rho}_{21} = -\frac{1}{2}(\Gamma_1 + \Gamma_2)\rho_{21} + \mathrm{i}\omega_{12}\rho_{21} + \frac{\mathrm{i}}{2}(\Omega_{23}\delta_{31} - \Omega_{31}\delta_{23} + \Omega_{24}\delta_{41} - \Omega_{41}\delta_{24})$$
$$\dot{\delta}_{31} = -\frac{1}{2}\Gamma_1\rho_{31} - \mathrm{i}(\nu_L - \omega_{13})\delta_{31} + \frac{\mathrm{i}}{2}[\Omega_{31}(\rho_{11} - \rho_{33}) + \Omega_{32}\rho_{21} - \Omega_{41}\rho_{34}]$$
$$\dot{\delta}_{41} = -\frac{1}{2}\Gamma_1\rho_{41} - \mathrm{i}(\nu_L - \omega_{14})\delta_{41} + \frac{\mathrm{i}}{2}[\Omega_{41}(\rho_{11} - \rho_{44}) + \Omega_{42}\rho_{21} - \Omega_{31}\rho_{43}]$$
$$\dot{\delta}_{32} = -\frac{1}{2}\Gamma_2\rho_{32} - \mathrm{i}(\nu_L - \omega_{23})\delta_{32} + \frac{\mathrm{i}}{2}[\Omega_{32}(\rho_{22} - \rho_{33}) + \Omega_{31}\rho_{12} - \Omega_{42}\rho_{34}]$$
$$\dot{\delta}_{42} = -\frac{1}{2}\Gamma_2\rho_{42} - \mathrm{i}(\nu_L - \omega_{24})\delta_{42} + \frac{\mathrm{i}}{2}[\Omega_{42}(\rho_{22} - \rho_{44}) + \Omega_{41}\rho_{12} - \Omega_{32}\rho_{43}]$$
$$\dot{\rho}_{43} = -\gamma_2\rho_{43} + \mathrm{i}\omega_{34}\rho_{43} + \frac{\mathrm{i}}{2}(\Omega_{41}\delta_{13} - \Omega_{13}\delta_{41} + \Omega_{24}\delta_{41} - \Omega_{23}\delta_{42})$$



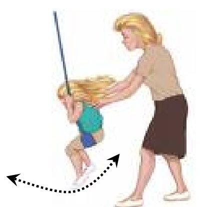


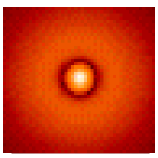
Cesium
ground state



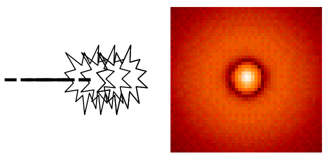
become
mixed state
(dressed)

Periodic-driven swing

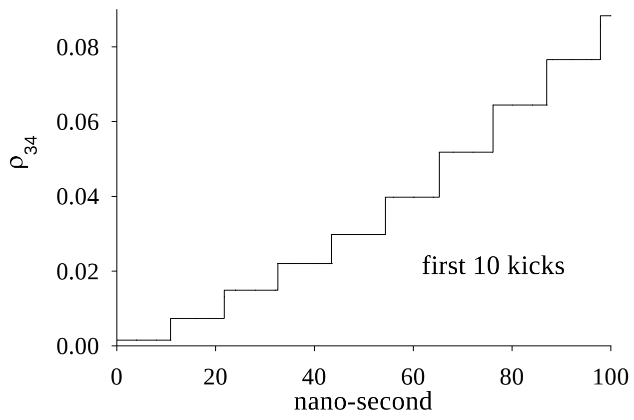


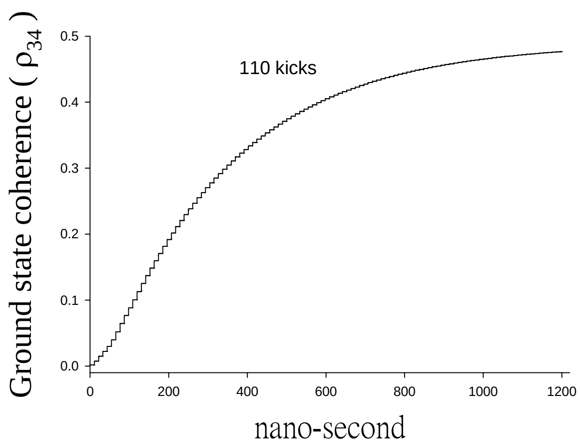


The wavefunction of mixed state decays with a quantum beat (clock frequency)

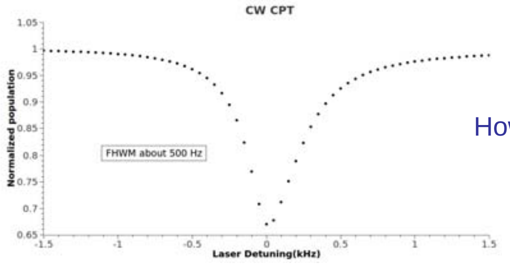


When the repetition rate and carrier-envelop phase of pulse matched that of the quantum beat, then stable mixed state was built up

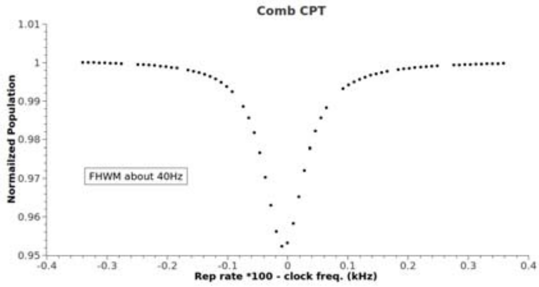

0.08
0.06
0.04
0.02
0.00
ρ34
0
20
40
60
80
100
nano-second
first 10 kicks


Ground state coherence (ρ34)
0.5
0.4
0.3
0.2
0.1
0.0
0
200
400
600
800
1000
1200
nano-second
110 kicks

Theoretical simulation



How the narrowing happens



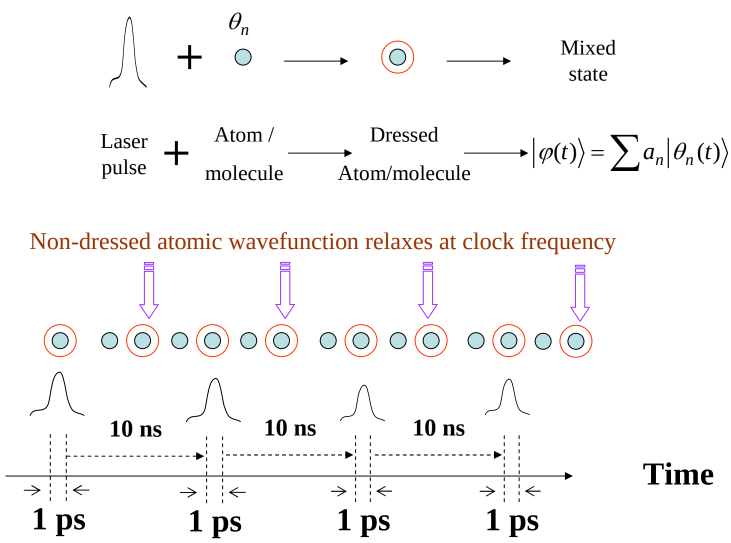
How the frequency shift happens

$$H_0 = \begin{array}{cccc} |a\rangle & |b\rangle & |c\rangle & \\ \multicolumn{3}{c}{\begin{pmatrix} \hbar\omega_a & 0 & 0 \\ 0 & \hbar\omega_b & 0 \\ 0 & 0 & \hbar\omega_c \end{pmatrix}} & \begin{array}{c} |a\rangle \\ |b\rangle \\ |c\rangle \end{array} \end{array} \qquad H_{EM} = \begin{pmatrix} 0 & \hbar\Omega_{R1} & \hbar\Omega_{R2} \\ \hbar\Omega^*_{R1} & 0 & 0 \\ \hbar\Omega^*_{R2} & 0 & 0 \end{pmatrix}$$

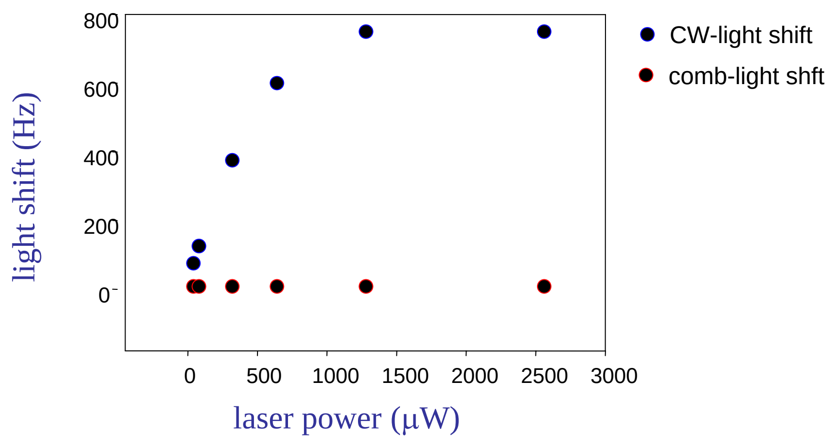
$$\hbar\Omega = \hbar\Omega(\tau)$$

τ of our comb laser is just 1 ps

Principle



Power insensitive character of comb-CPT (1)



Can the traditional comb laser modes become numerous optical clocks?

Self-reference → $f_m = m\Delta + \delta$

m~10^6

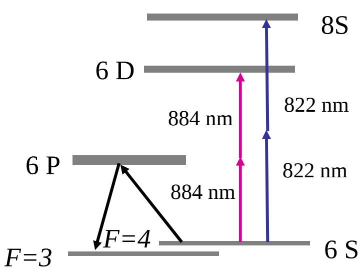
LOCKED LOCKED

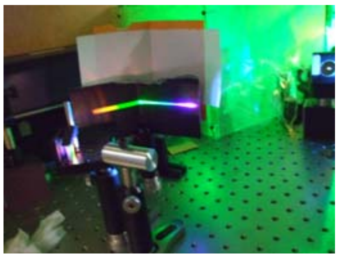
When Δ~2 mHz instability→ f_m~ 2 kHz instability

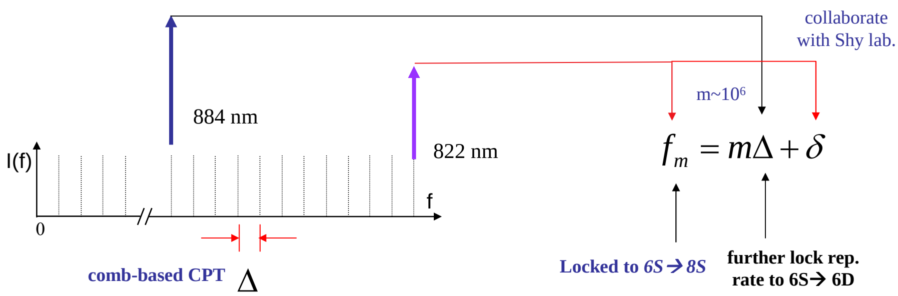
Due to inaccurate repetition rate, the comb modes were actually NOT coherently presented

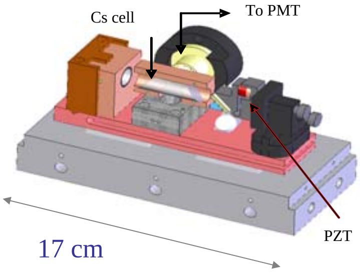
---

An idea optical clock**s** from 1500 nm to 400 nm

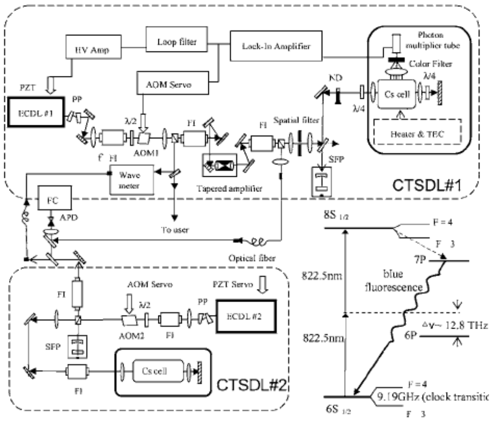








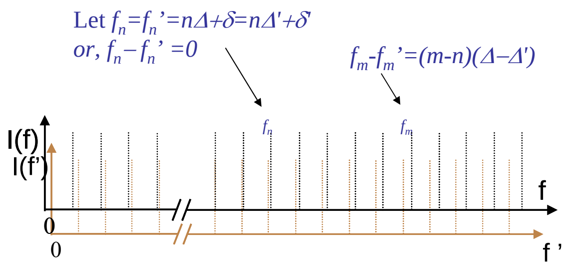
Extended-cavity
diode laser



2. Kerr gas lensing free

On-going works

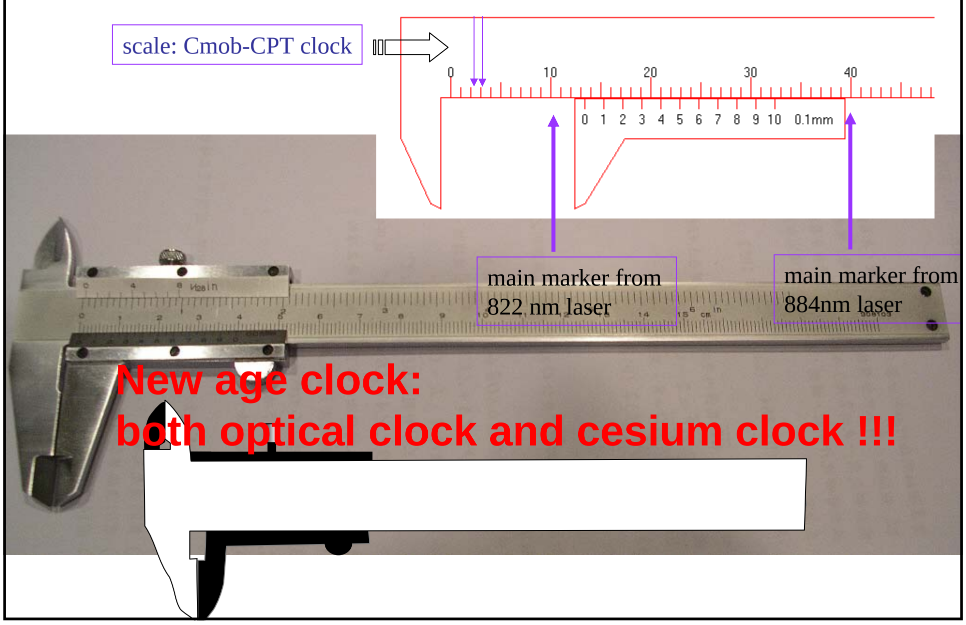
Frequency vernier for wideband high-resolution laser spectroscopy
(Collaborate with Dr. Yen-Chu Hsu's group)



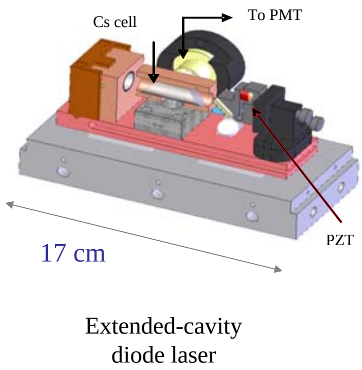
Beat notes increase with mode number

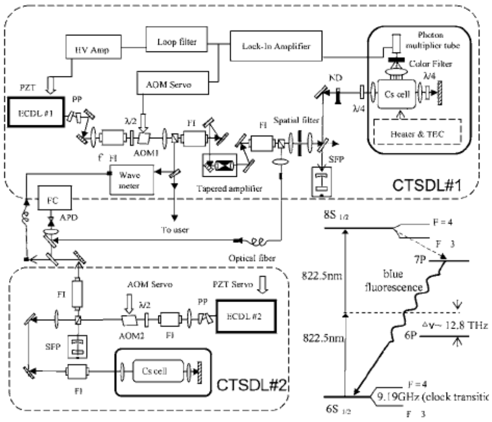
One can get absorption spectra by checking the FFT in RF region
(even the change of index of refraction can be perceived)

An analogy to traditional vernier

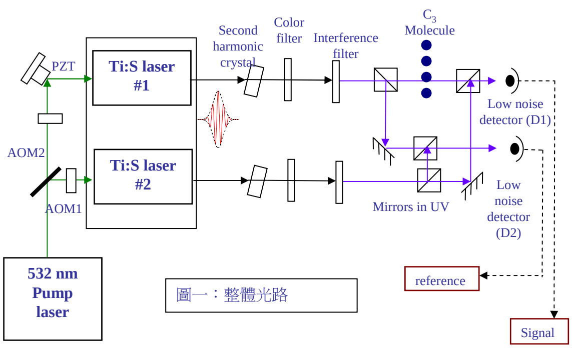


marker can be hand-size

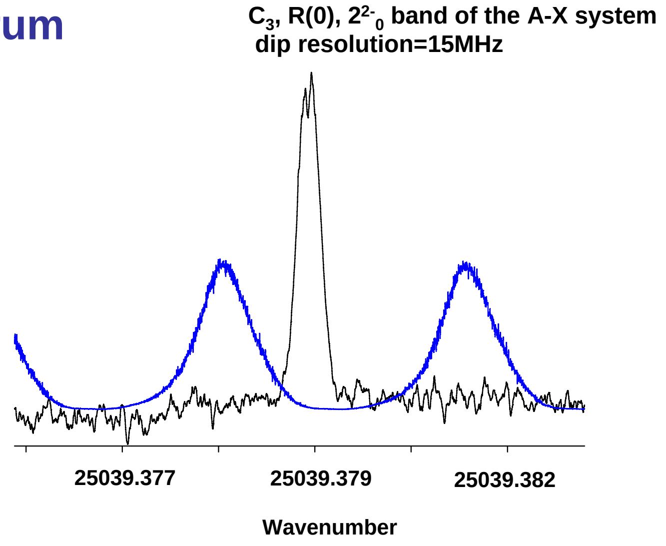




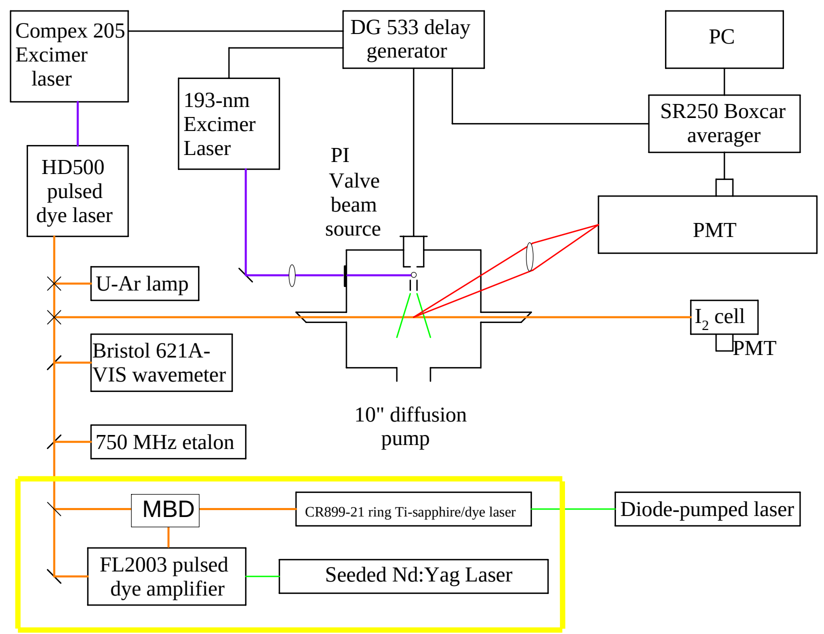
2. Kerr gas lensing free



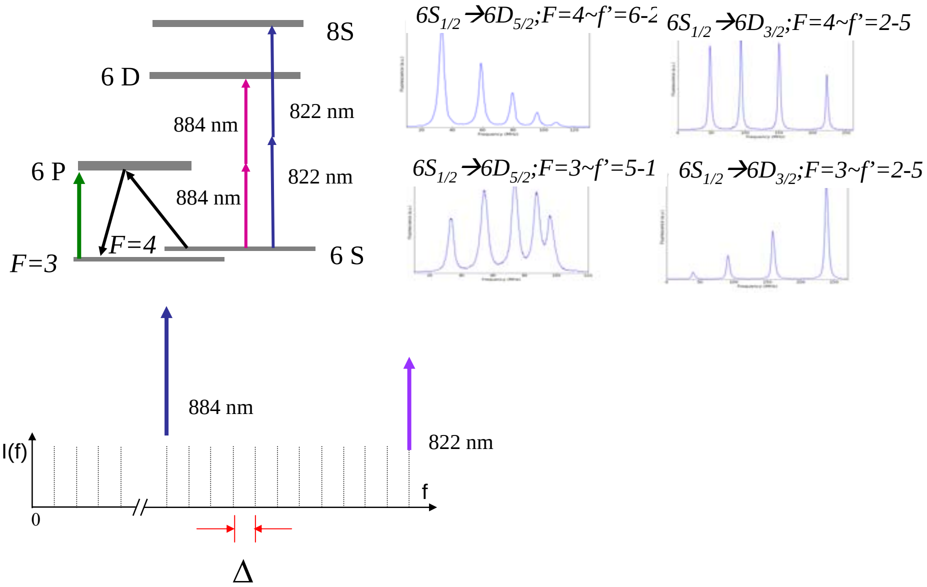
Typical C3 spectrum



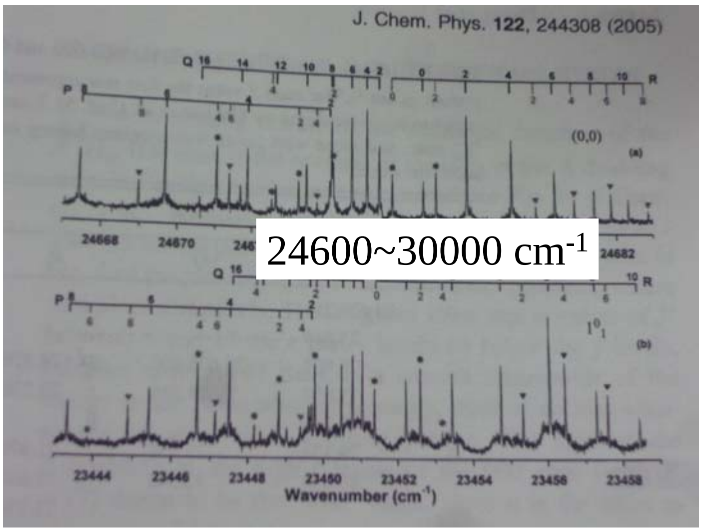
Supersonic jet-cooled molecular beam apparatus



We already have several atomic transitions as the references of Ti:sapphire laser



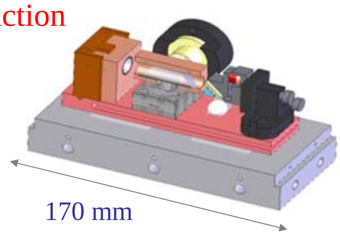
With C3 molecules– UV comb references



portable comb clock is now under construction

criteria:

1. stable and small reference laser



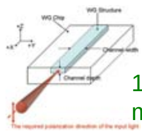
2. small Ti:sapphire laser

pulse duration after appropriate extracavity pulse compression optics (not included, see item 4 of this quotation), typical uncompressed at output is 50 fs.	≤ 30 fs
average output power @ 5.5 W pump power with TEM_{00} beam @ 532 nm (equivalent to Coherent Verdi™)	≥550 mW
central wavelength preset value will be fixed within a range of +15/-10nm around specified value	810nm
M^2	≤1.2
Dimensions	$250x160x107\ mm^3$

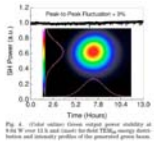
3. small pump laser

fiber laser + waveguide crystal

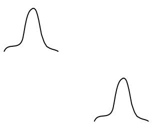
+



10*30 mm



Optics letters **34,** *1561 (2009)*



It is a team work !

Thanks for your attention

A dream for time standard in home

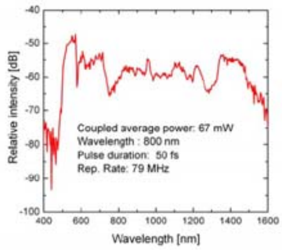
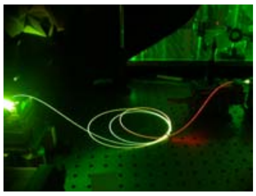


Figure 8 Octave-spanning supercontinuum generated in 1 m NL-PM-750 fiber.



Comb laser

Repetition rate
= clock transition

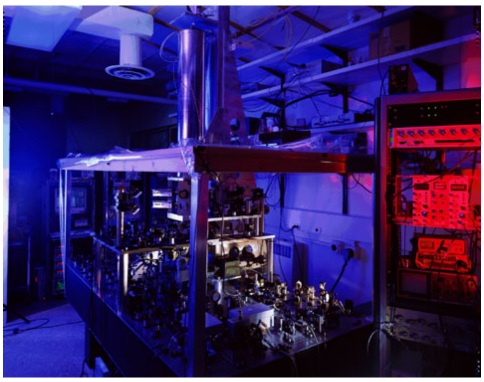
1.5 μm fiber amplifier

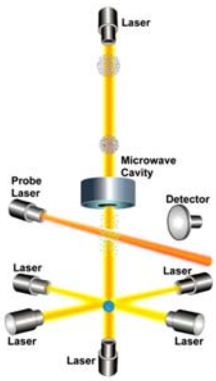
Error signal from
dark state linewidth

User

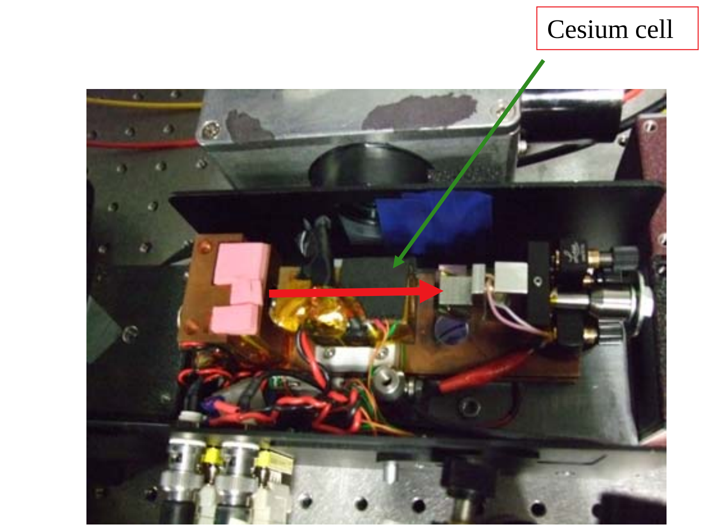
100*Repetition rate
= clock transition

Cesium clock in NIST

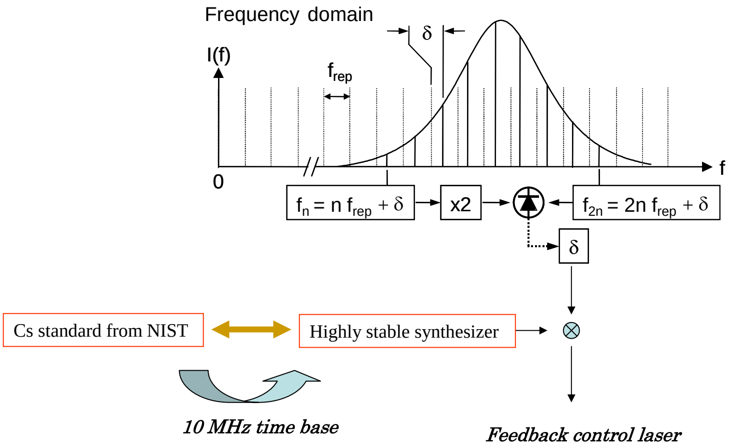




How can this be in your home !

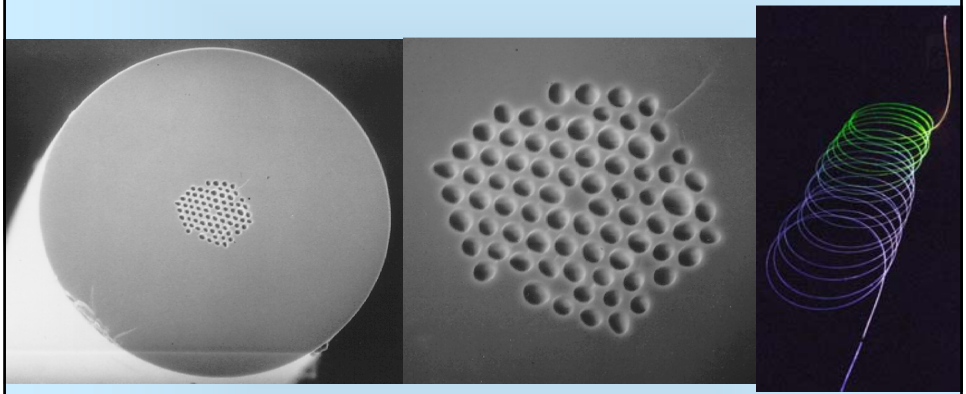


Cesium cell



Frequency domain
I(f)
f_{rep}
δ
0
f
$f_n = n f_{rep} + \delta$
x2
$f_{2n} = 2n f_{rep} + \delta$
δ
Cs standard from NIST
Highly stable synthesizer
10 MHz time base
Feedback control laser

Honeycomb Microstructure Optical Fiber



May, 1999

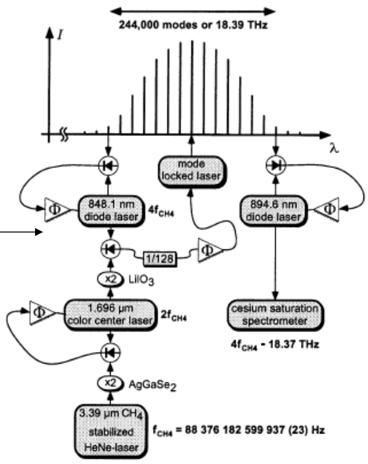
courtesy of Jinendra Ranka

Lucent Technologies
Bell Labs Innovations

Two kinds of combs

Self-reference by J. Hall

Reference to frequency standard by T. Hansch



Recent comb laser related reports

[1] *Science* ***321***, *2335 (2008);*
[2] *Nature photonics* ***2***,*712 (2008)*
[3] *Science* ***321***, *1301 (2008);*
[4] *Nature* ***452***,*538 (2008)*
[5] *Nature* ***452***, *06854(2008)*
[6] *Nature* ***445***, *627 (2007)*
[7] *Science* ***311***, *1595 (2006)*
[8] *Science* ***307***, *400 (2005)*
[9] *Nature physics* ***2***, *327 (2006)*
[10] *Science* ***322***, *1595 (2006)*
[11] *Nature photonics* ***1***,*463 (2007)*
[12] *Nature photonics* ***1***,*712 (2007)*
[13] Nature Photonics **1**, 447 - 448 (2007)
[14] Nature Photonics **2**, 355 - 359 (2008)
[15] Nature Photonics **2**, 70 (2008)

How comb laser opens a new world