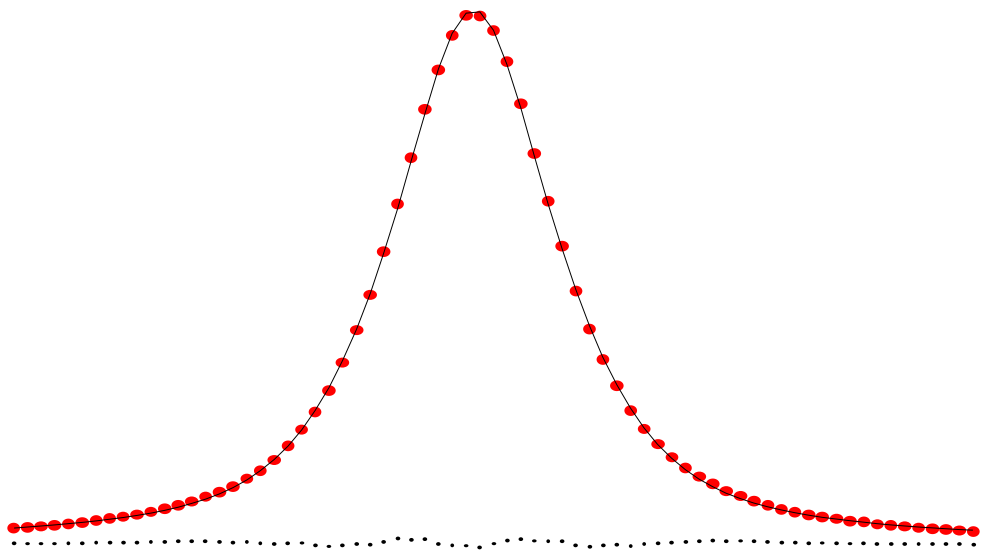
Absolute frequency of cesium 6S-8S hyperfine transition by two-photon interfered spectrum

Chien-Ming Wu, Tze-Wei Liu, Ming-Hsuan Wu, Ray-Kung Lee and Wang-Yau Cheng



Speaker: Wang-Yau Cheng (鄭王曜), Associate Professor

Department of Physics, National Central University

Outline

1. 精密量測如何幫助我們了解物理定律

2. 銫原子能階與物理定律

3.雙光子量子干涉與精密量測

1. 精密量測如何幫助我們了解物理定律

首先，你需要一個穩頻雷射

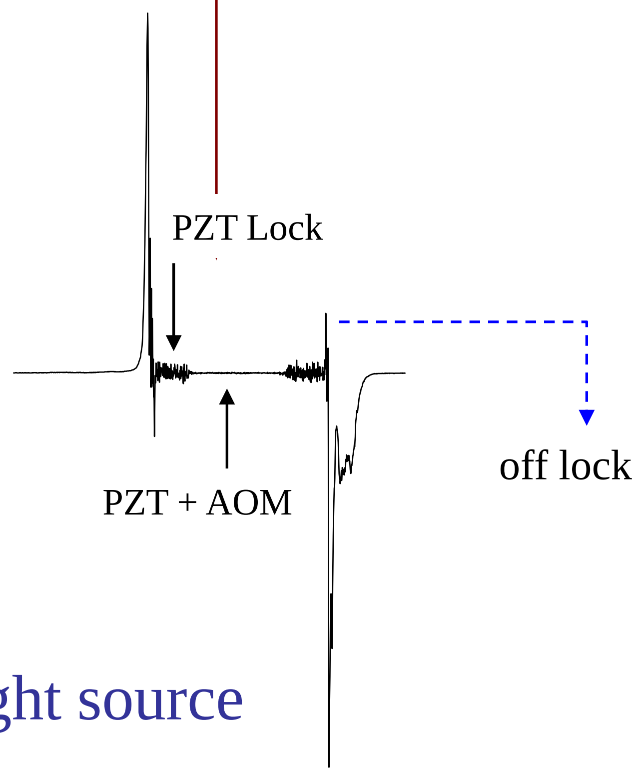
我們的實驗為例

Optical frequency $2.5*10^{-14}$@30 s
*~**150** Hz frequency uncertainty*

cesium 6S-8S
dipole not allowed transition

Opt. lett. **32**, 563 (2007)

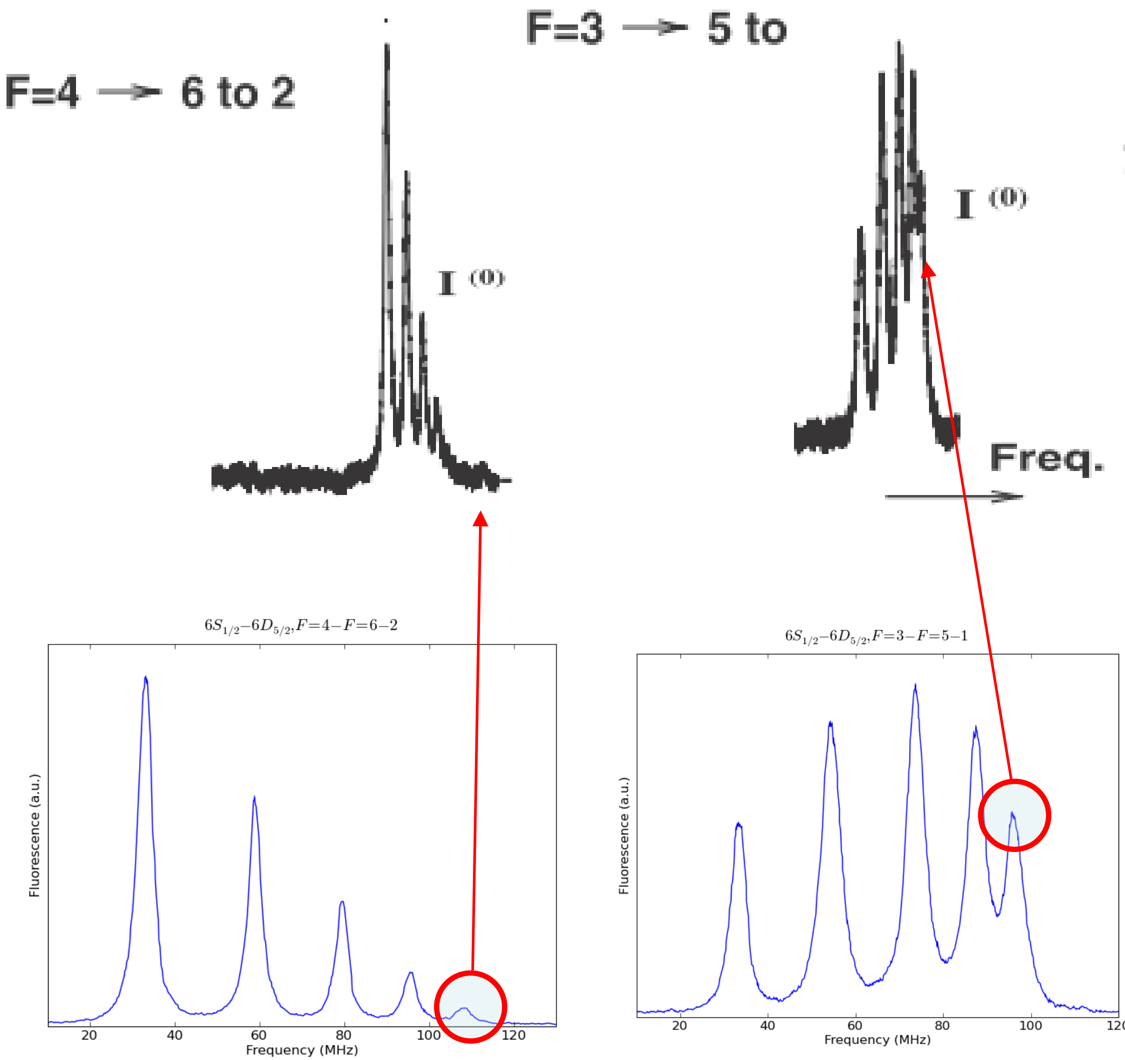
S/N=1800 @ 30 ms



electronics for feedback control

Ultra-high Coherence light source

穩頻雷射的好處：



Journal of the Physical Society of Japan
Vol. 74, No. 9, September, 2005, pp. 2487–2491

雷射功率: 32 W
鈦藍寶石雷射:~300萬台幣
雷射頻率穩定度:
1 MHz
(未穩頻)

Opt. lett. **36**, 76 (2011)

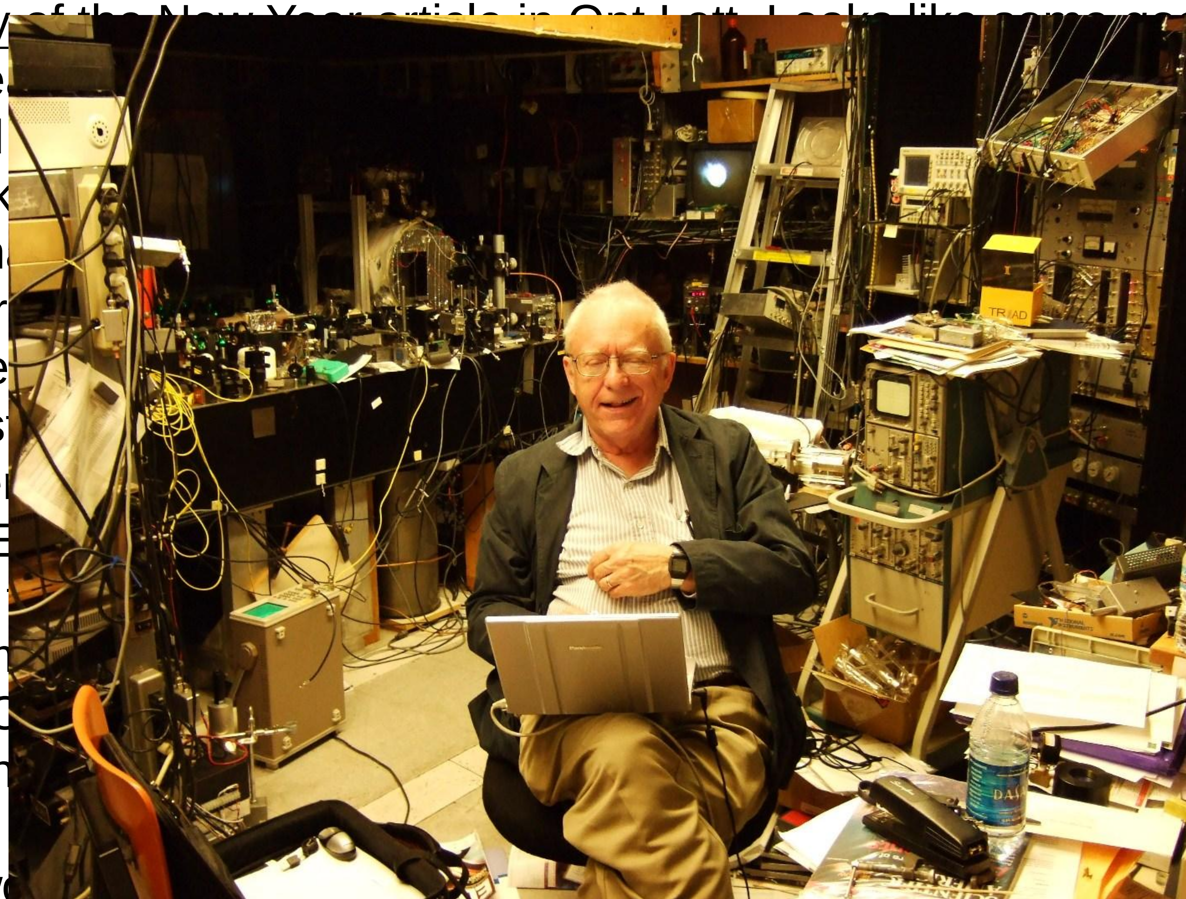
雷射功率: 0.03 W
半導體雷射:~3萬台幣
雷射頻率穩定度:
0.0003 MHz
(穩頻於光學共振腔)

John Hall 看到我們工作的感觸

From: JHall @JILA
To: <wycheng@gate.sinica.edu.tw>
Sent: Wednesday, January 12, 2011 5:22 AM

Hi Wang-Yau

I like you first day d results
from intensity me
frequency-locked oton
transitions. I think at shot noise
stability level. I h ions about
measuring disper the
Schawlow-Towne But to make
it mechanically s mirror make
an extra little inte s stabilized.
So they have ~1E th averaging.
I'm getting ready f sideband
spectroscopy to n he right
alignment, the EC scratches
on the faces) with a fiber.
After the fiber we onto the
AOM intensity (w o issues



before the stability tests will be definitive. Anyway, it's certainly
fun to play in the labs!
J

把劍磨利，有時勝過千軍萬馬

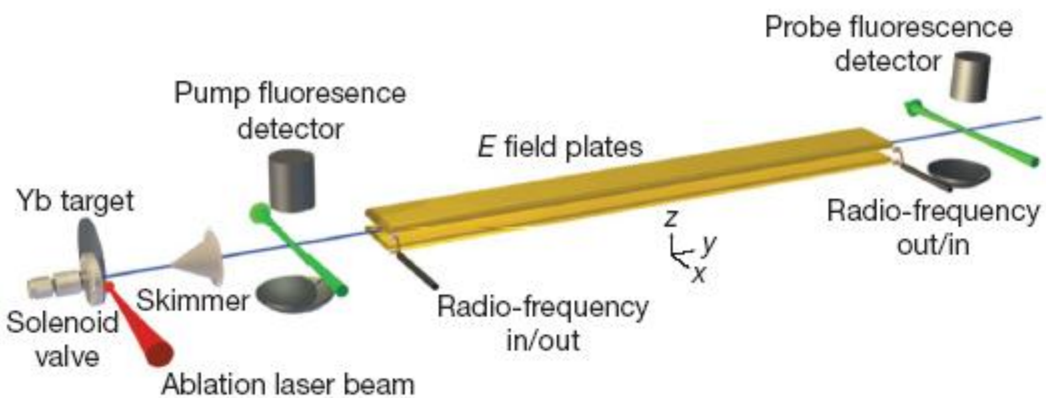
一個很好的註腳

Improved measurement of the shape of the electron

J. J. Hudson[1], D. M. Kara[1], I. J. Smallman[1], B. E. Sauer[1], M. R. Tarbutt[1] & E. A. Hinds[1]

26 MAY 2011 | VOL 473 | NATURE | 493

with 90 per cent confidence. This result, consistent with zero, indicates that the electron is spherical at this improved level of precision. Our measurement of atto-electronvolt energy shifts in a molecule probes new physics at the tera-electronvolt energy scale[2].

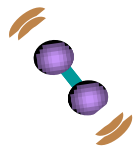


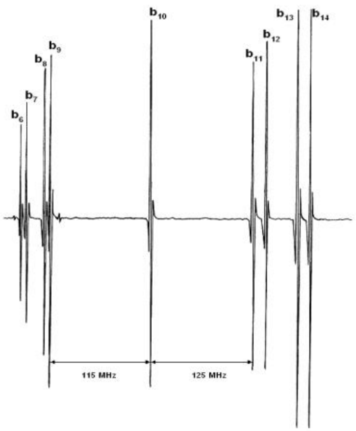
穩頻雷射在基礎科學之貢獻 (小錢做大實驗)

- 電子結構之檢測
  - (Nature **473**, 10104(2011))
- 質子大小之檢測
  - (Nature **466**, 09250(2010))
- 電弱理論之檢測
  - (Science **275**, 1759 (1997))
- 實驗室重力紅移
  - (Nature **463**, 08776 (2010))
- 夸克質量變化之檢測
  - proposed, Phys. Rev. A 79, 054102 (2009)；

穩頻雷射拿來做光鐘

Iodine standard





Linewidth : 23 kHz

strontium clock

Linewidth : mHz

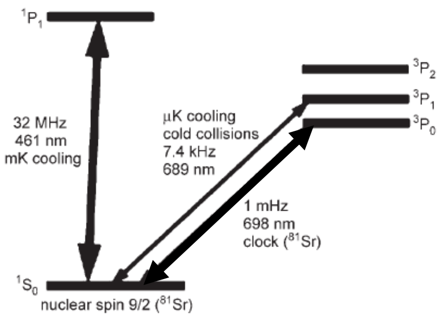
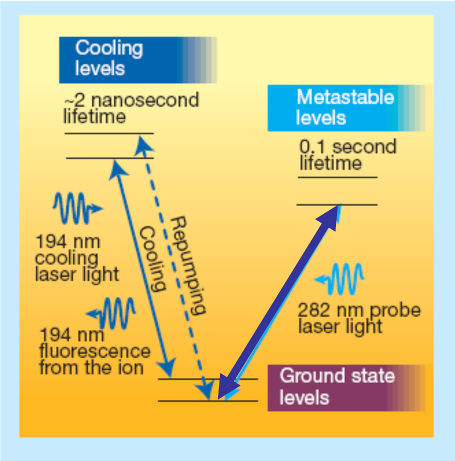


Figure 3. The lowest energy levels of strontium.



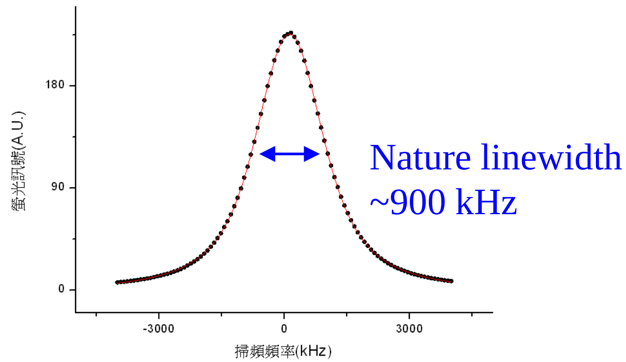
Hg$^+$ clock

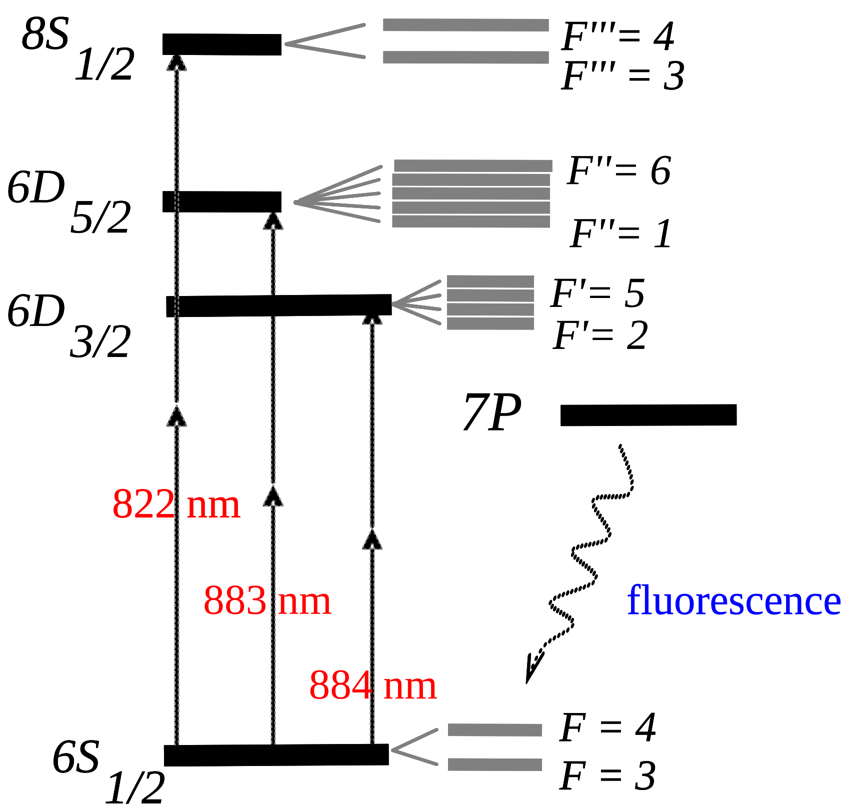
Linewidth : 6.7 Hz

2. 鉋原子能階與物理定律

鉋原子，原子核重而穩定

Cs 6S-8S 躍遷與絕對頻率量測





Cs 6S-8S 躍遷絕對頻率量測之重要性（一）基礎科學

$$\frac{1}{4}\nu_{1S-3S}(\mathrm{H}) = \nu_{6S-8S}(\mathrm{Cs}) + 0.84\ \mathrm{THz},$$

$$\nu_{2^3S_{1/2}-2^3P}(\mathrm{He}) = \nu_{6S-8S}(\mathrm{Cs}) - \nu_{\mathrm{HeNe}/\mathrm{CH_4}} + 0.61\ \mathrm{THz},$$

$$\frac{1}{2}\nu_{^2S_{1/2}-^2D_{5/2}}(\mathrm{Yb}^+) = \nu_{6S-8S}(\mathrm{Cs}) + 0.5\ \mathrm{THz}.$$

clock transition

- 銫原子S-軌域，適合藉由長期觀測絕對頻率，以推測重原子核質量是否隨時間變化 Proposed in Phys. Rev. A **79**, 054102 (2009)
- 銫原子8S-軌域絕對頻率(411-nm)，與Yb+ clock (411-nm)接近，可藉由頻率比對，觀測精細常數α是否隨時間變化。Proposed in Phys. Rev. A **59**, 230 (1999))

Cs 6S-8S 躍遷絕對頻率量測之重要性（二）計量學的應用

- 150-Hz 光頻率穩定度已實現
Opt. Lett., **32**, 536 (2007) -- Wang-Yau Group

- 光梳雷射手掌大小之參考雷射已實現
Opt. lett. **36**, 76 (2011) -- Wang-Yau Group

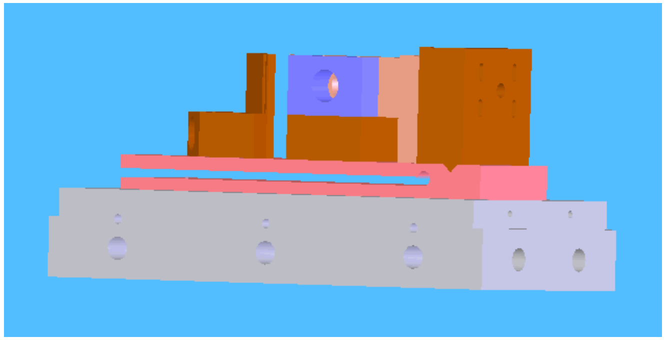
若量得絕對頻率，有機會成為手掌大小、便宜的二級光頻標準

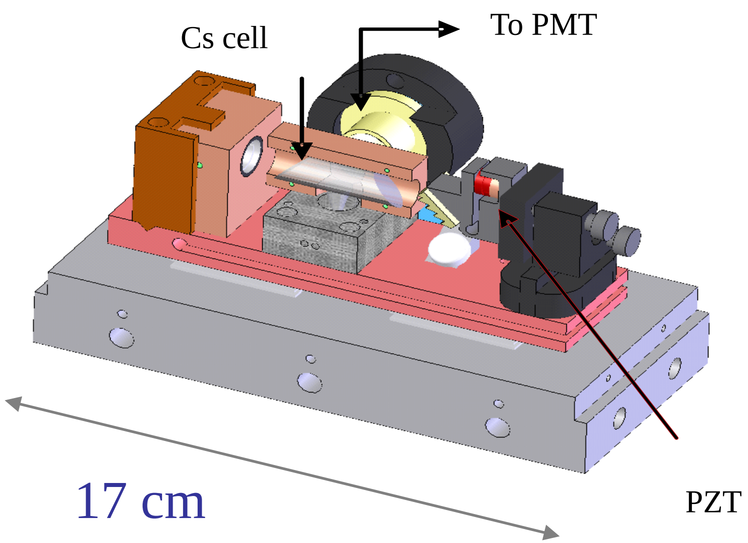
專利申請中

Ti:sapphire 雷射之參考雷射
Applied Physics B **92**, 13 (2008) -- Wang-Yau Group

Hand-size laser system is realized

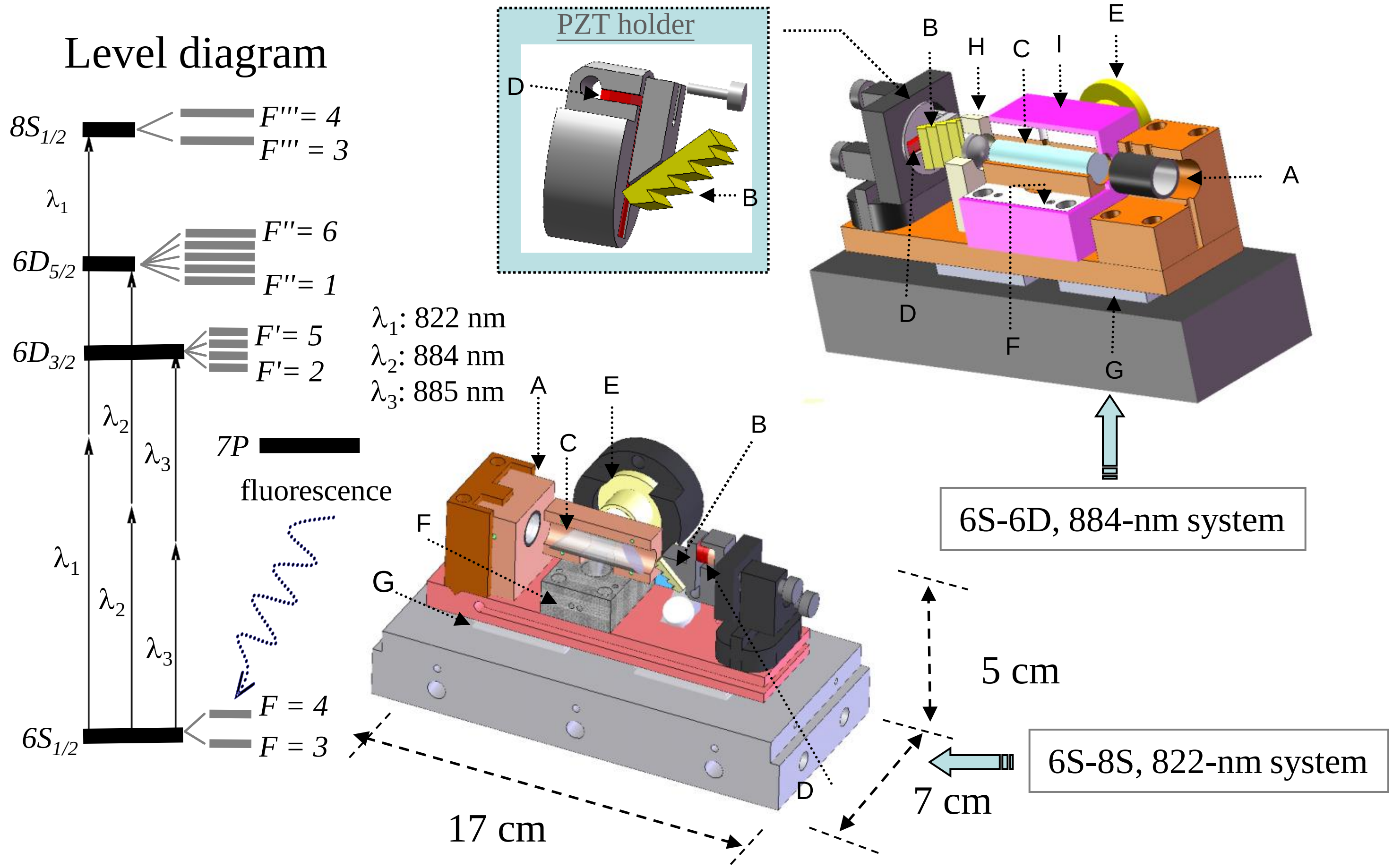
Opt. Lett **36**, 76 (2011)



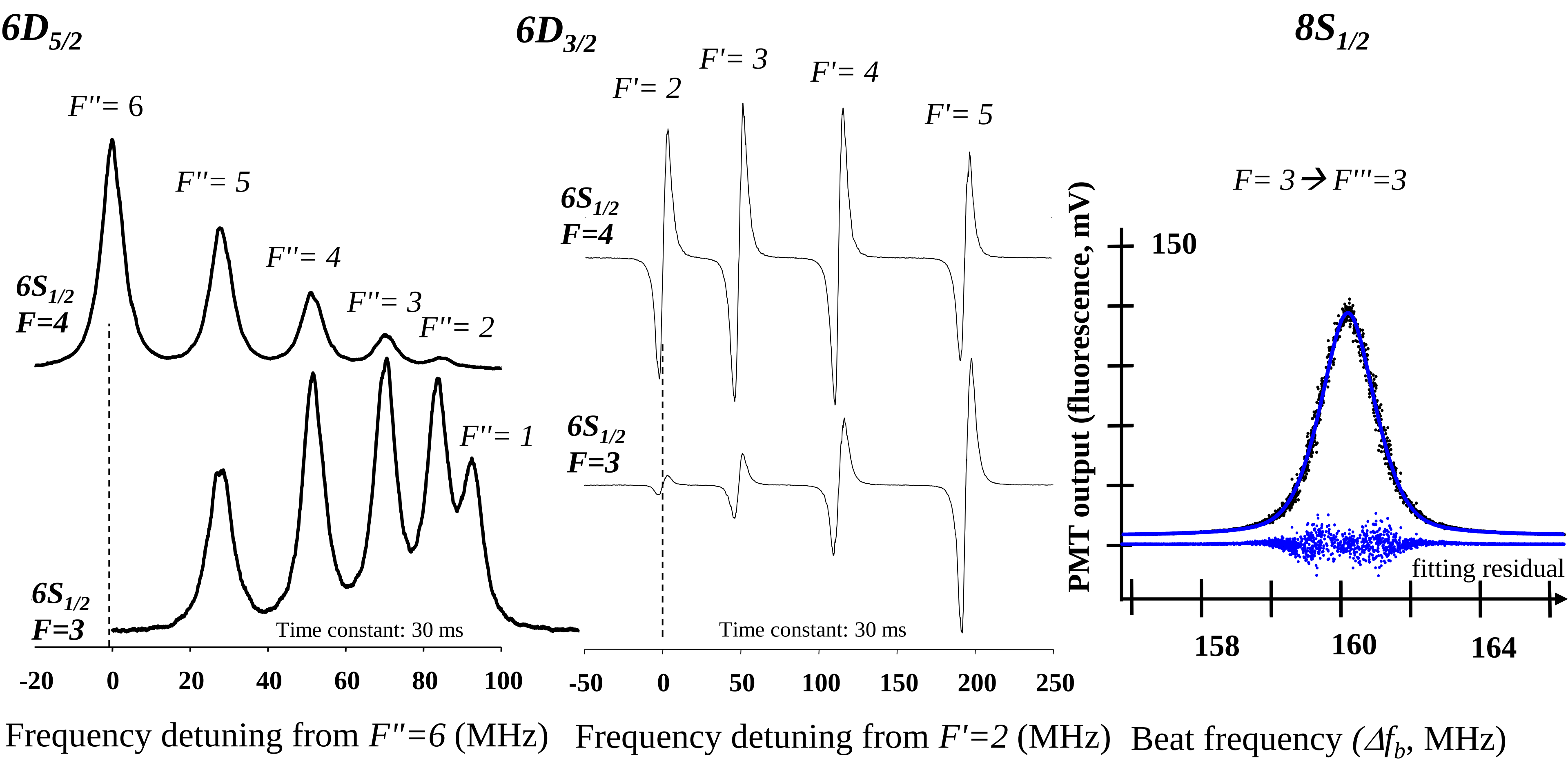


Extended-cavity
diode laser

pattern is applied



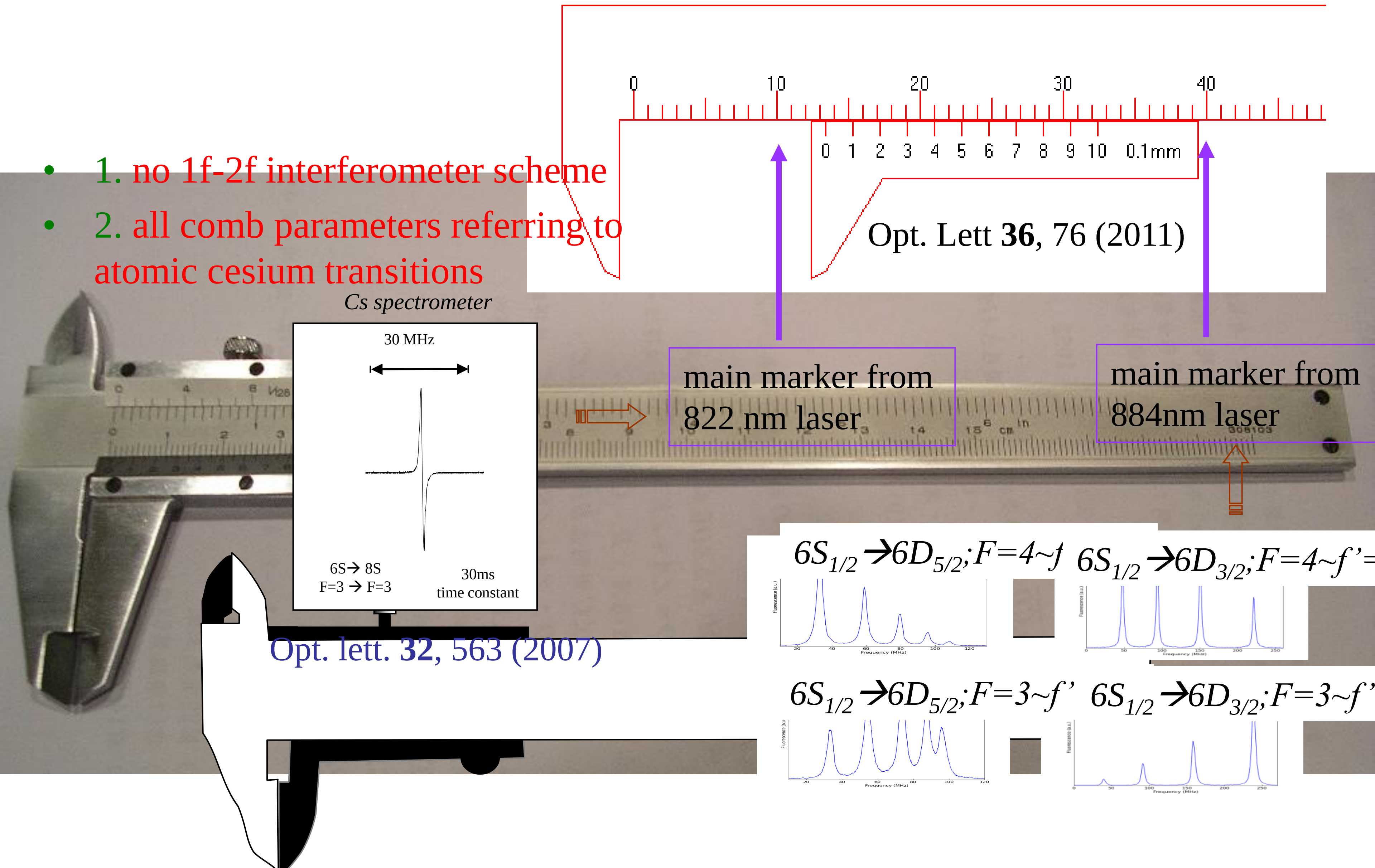
Level diagram
$8S_{1/2}$
$F''' = 4$
$F''' = 3$
λ_1
$6D_{5/2}$
$F'' = 6$
$F'' = 1$
$6D_{3/2}$
$F' = 5$
$F' = 2$
λ_2
λ_3
$7P$
fluorescence
λ_1
λ_2
λ_3
$6S_{1/2}$
$F = 4$
$F = 3$
λ_1: 822 nm
λ_2: 884 nm
λ_3: 885 nm
PZT holder
A
B
C
D
E
F
G
H
I
6S-6D, 884-nm system
5 cm
17 cm
7 cm
6S-8S, 822-nm system



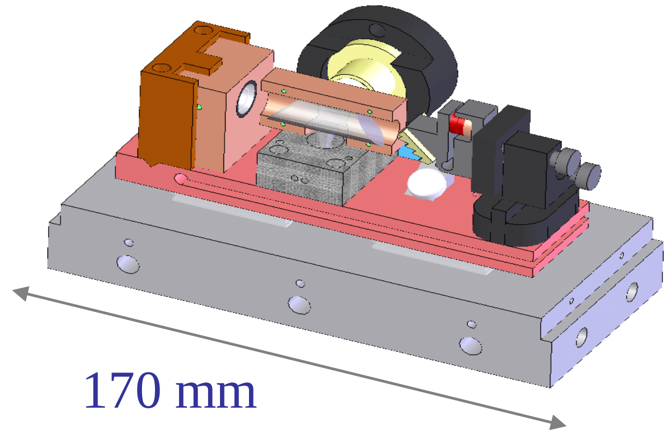
6D5/2
F''= 6
F''= 5
F''= 4
F''= 3
F''= 2
F''= 1
6S1/2 F=4
6S1/2 F=3
Time constant: 30 ms
-20
0
20
40
60
80
100
Frequency detuning from F''=6 (MHz)
6D3/2
F'= 2
F'= 3
F'= 4
F'= 5
6S1/2 F=4
6S1/2 F=3
Time constant: 30 ms
-50
0
50
100
150
200
250
Frequency detuning from F'=2 (MHz)
8S1/2
F= 3 → F'''=3
PMT output (fluorescence, mV)
150
fitting residual
158
160
164
Beat frequency (Δfb, MHz)

光學游標尺

- 1. no 1f-2f interferometer scheme
- 2. all comb parameters referring to atomic cesium transitions



Moveable comb clock is now under construction

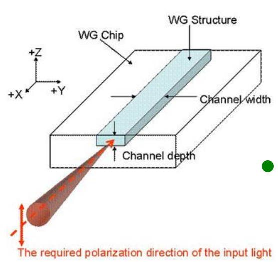


- criteria:
  - 1. stable and small reference laser
  - 2. small Ti:sapphire laser

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 + MgO:PPLN

- +



- 10*30 mm

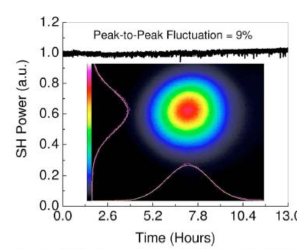
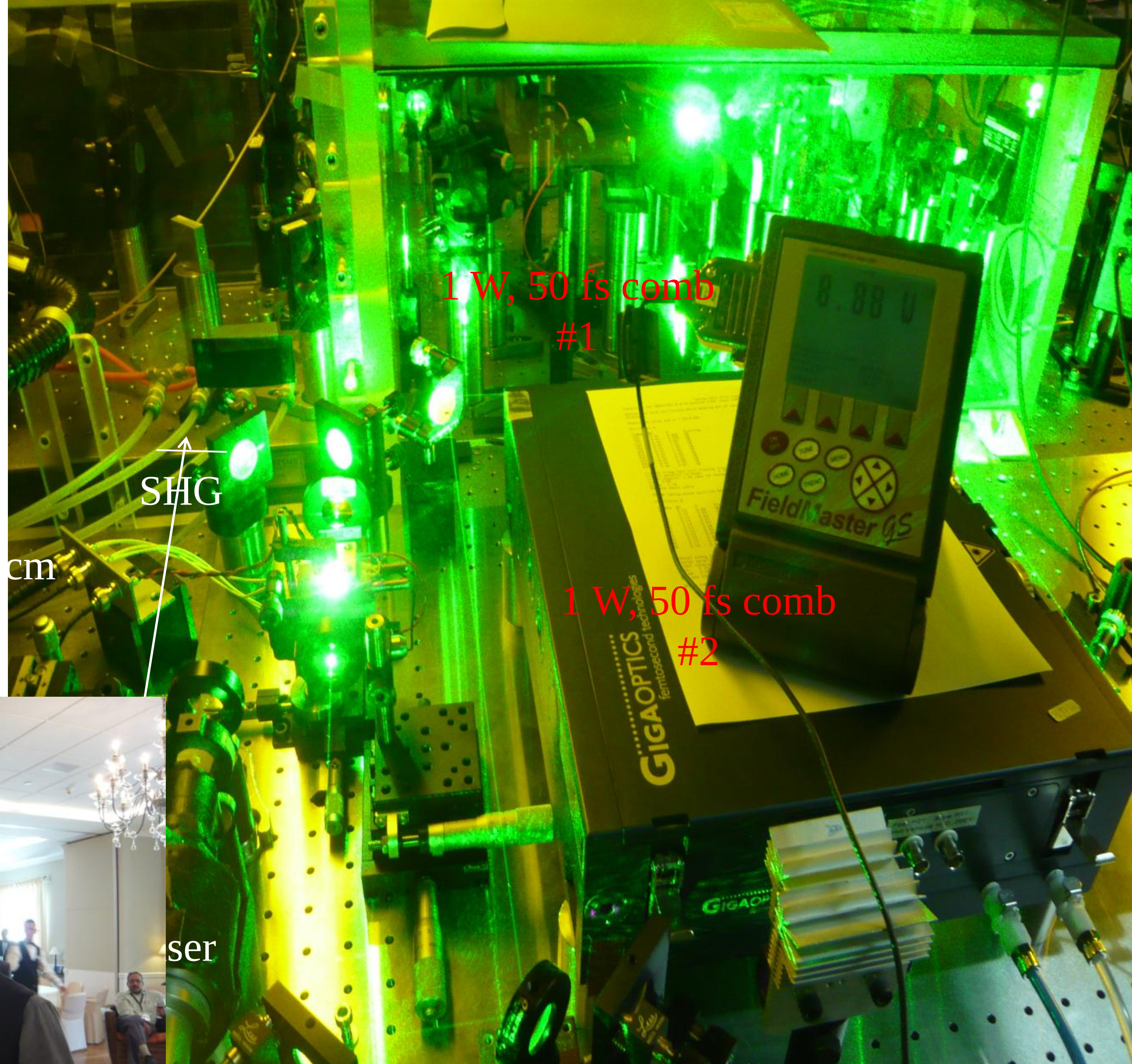
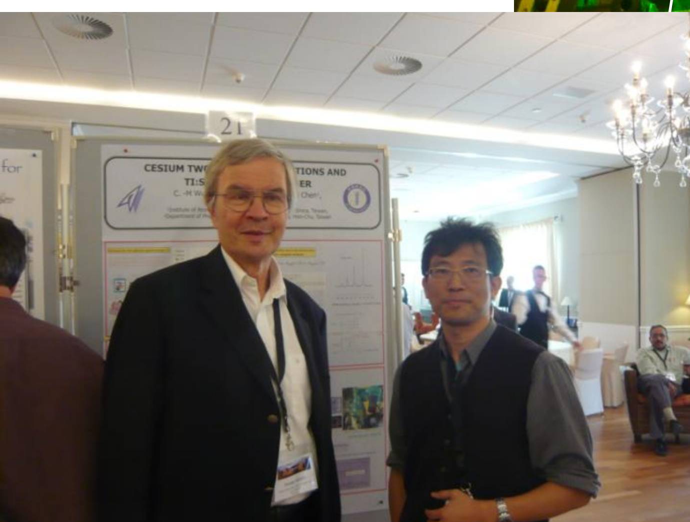


Fig. 4. (Color online) Green output power stability at 9.64 W over 13 h and (inset) far-field TEM_{00} energy distribution and intensity profiles of the generated green beam.

fiber laser based two Ti:sapphire lasers which were presented in the conference of ICOLS



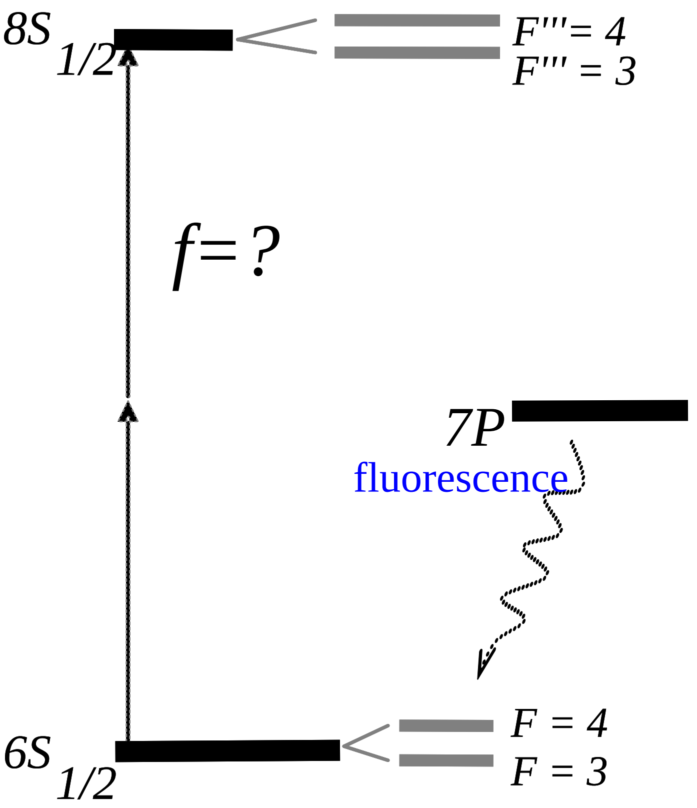


55 cm

green power: 8.88 W

Three approaches on determining the absolute frequency of cesium atom 8S hyperfine levels

^{133}Cs level diagram



1. By frequency comparison with standards (1999)

Accurate measurement of the frequency of the 6S–8S two-photon transitions in cesium

G. Hagel, C. Nesi, L. Jozefowski, C. Schwob, F. Nez *, F. Biraben

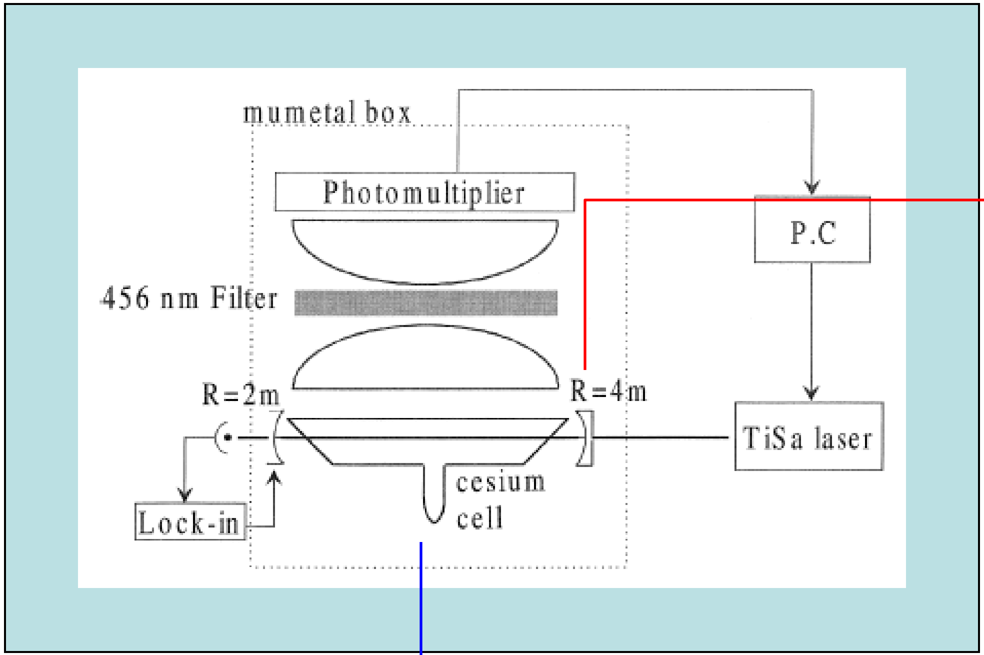
Laboratoire Kastler Brossel, ENS, Université Pierre et Marie Curie, Case 74, Laboratoire Associé au CNRS URA 18, 4, Place Jussieu, T12, E1, 75252 Paris Cedex 05, France

Optics Communications 160 (1999) 1–4

用了四個頻率標準躍遷來決定822 nm 頻率

Value was double checked by
H 750- nm $2S_{1/2}$-$6D_{5/2}$ transition

Finally, we have adopted a conservative 100 kHz uncertainty for the absolute frequencies on cesium transitions.



cavity length was stabilized by 633-nm iodine-stabilized He-Ne laser

mode number was traced by
Rb 778-nm 5S-5D standard

offset frequency was checked
H 750- nm 2S-12D transition

power: 0.1~2 W; 0.38 mm waist

2. By direct frequency comb spectroscopy (2007)

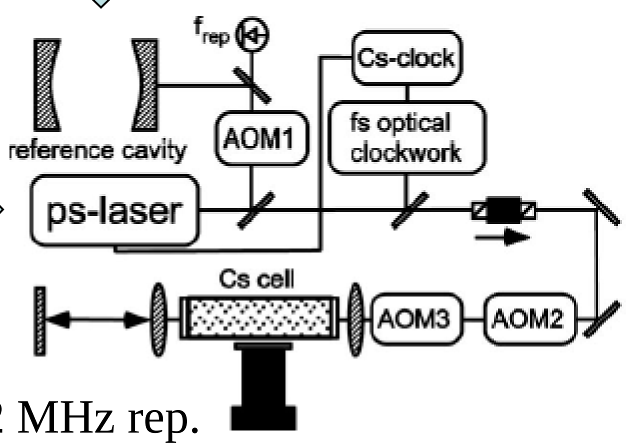
March 15, 2007 / Vol. 32, No. 6 / OPTICS LETTERS 701

Two-photon frequency comb spectroscopy of the $6s$–$8s$ transition in cesium

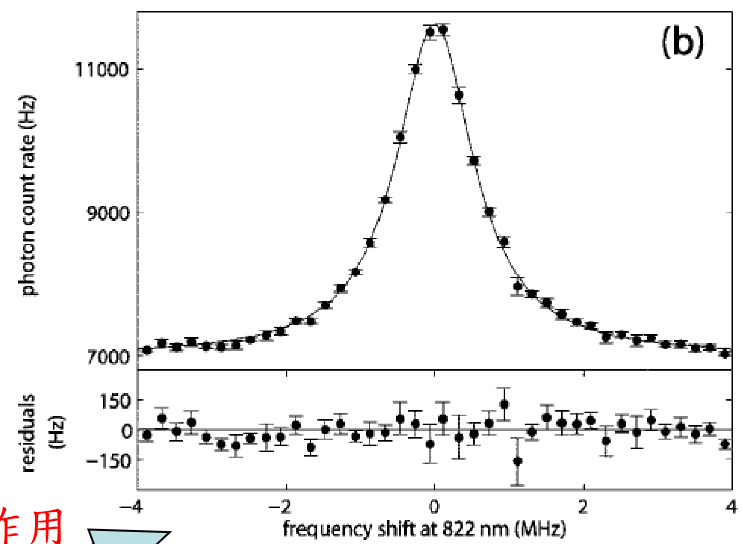
P. Fendel, S. D. Bergeson, Th. Udem, and T. W. Hänsch
Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, 85748 Garching, Germany

改善ps laser絕對頻率之jitter

減少中間態(6P)之影響
延長交互作用時間to ps



82 MHz rep.



直接與原子作交互作用

ps-laser+cavity+Cs clock

校正

self-reference comb laser

Fig. 2. (a) Fluorescence measurement showing both hyperfine components of the Cs $6s-8s$ transition. Because of the comb structure, the signal repeats itself every $f_{rep}/2$. (b) $F'=3$ to $F=3$ hyperfine component of the $6s-8s$ transition fitted to a Lorentzian line profile. These data are an average of nine separate scans, each measured at 450 mW laser power, a Gaussian waist of 0.72 mm, and a 1 s integration time per data point. The bottom panel shows the plot residuals as a percentage of the background-subtracted Lorentzian peak height.

Table 1: Absolute frequencies of ^{133}Cs 6S-8S hyperfine transitions

***+364507238000 kHz; ** +364503080000 kHz;**

	***F=3 (kHz)**	****F=4 (kHz)**	**hyperfine constant (kHz)**
Approach 1	**417 (15)**	**351 (15)**	**219124 (7)**
	↕ 97 kHz	↕ 91 kHz	
Approach 2	**320 (100)**	**260 (100)**	**219120 (10)**

Finally, we have adopted a conservative 100 kHz uncertainty for the absolute frequencies on cesium transitions.

3. By quantum interfered spectroscopy (2012)

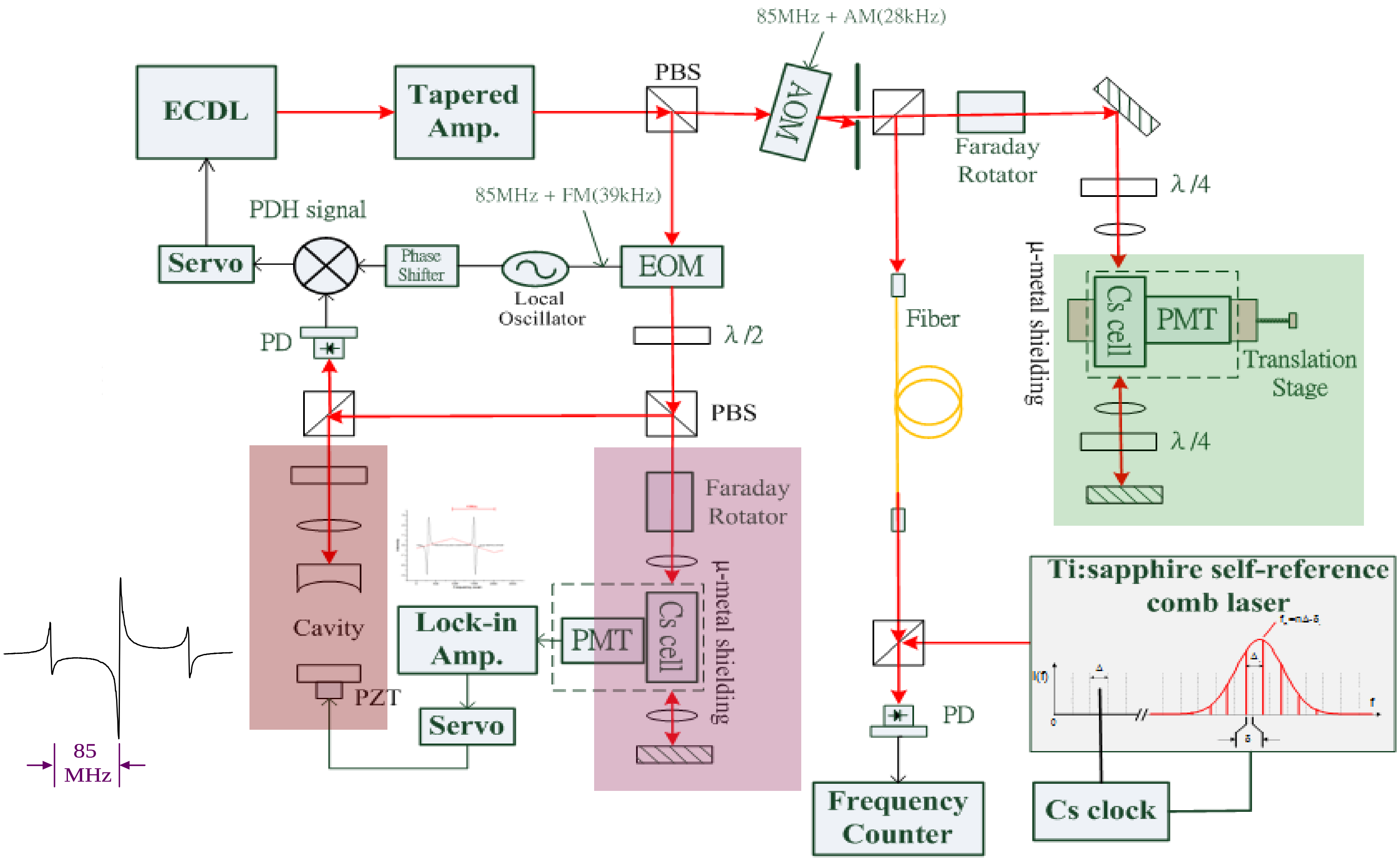
submitted to Optics Letters

Table 1: Absolute frequencies of ^{133}Cs 6S-8S hyperfine transitions

	*F=3 (kHz)	**F=4 (kHz)	hyperfine constant (kHz)
Approach 1	**417 (15)**	**351 (15)**	**219124 (7)**
Approach 2	**320 (100)**	**260 (100)**	**219120 (10)**

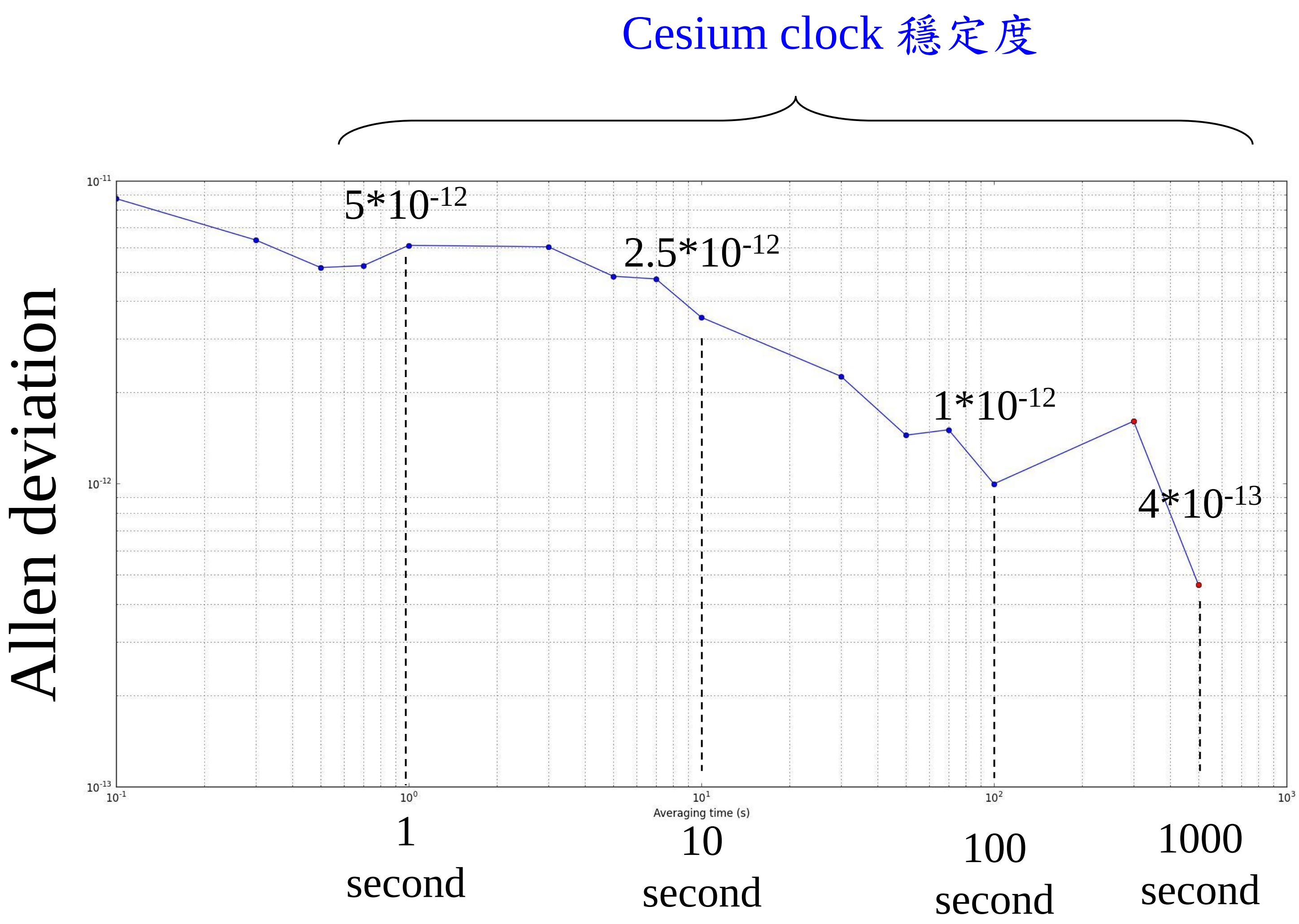
***+364507238000 kHz; ** +364503080000 kHz;**

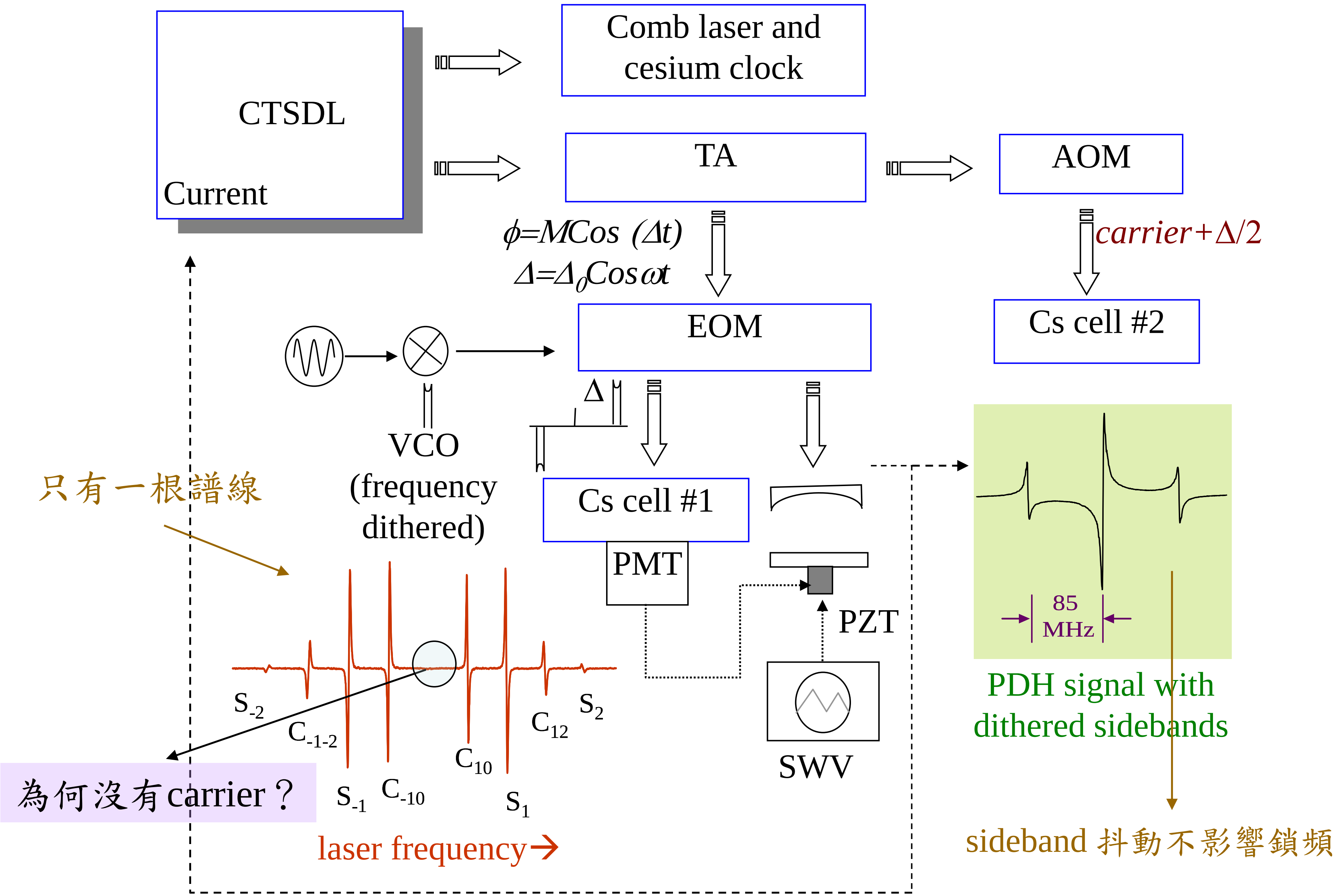
用一個EOM



85MHz + AM(28kHz)
ECDL
Tapered Amp.
PBS
AOM
Faraday Rotator
λ /4
PDH signal
85MHz + FM(39kHz)
Servo
Phase Shifter
Local Oscillator
EOM
μ-metal shielding
Cs cell
PMT
Translation Stage
Fiber
PD
λ /2
PBS
λ /4
Faraday Rotator
Cavity
PZT
Lock-in Amp.
PMT
Cs cell
μ-metal shielding
Servo
Ti:sapphire self-reference comb laser
85 MHz
PD
Frequency Counter
Cs clock

Comb laser與CW laser 拍頻

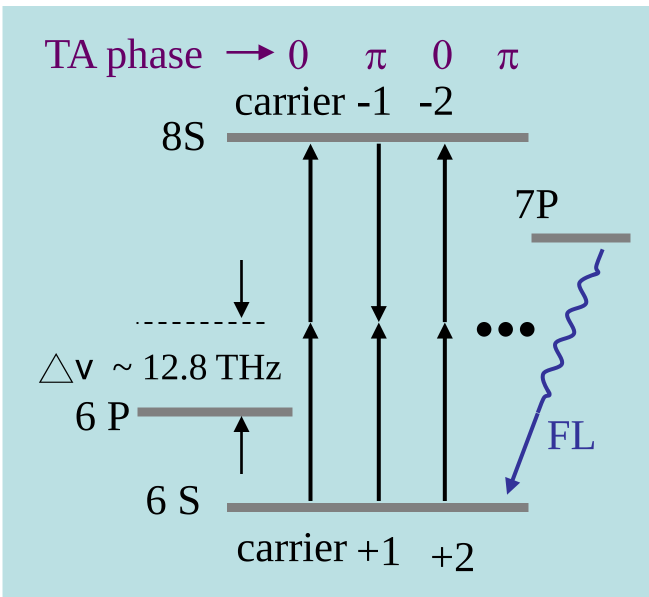


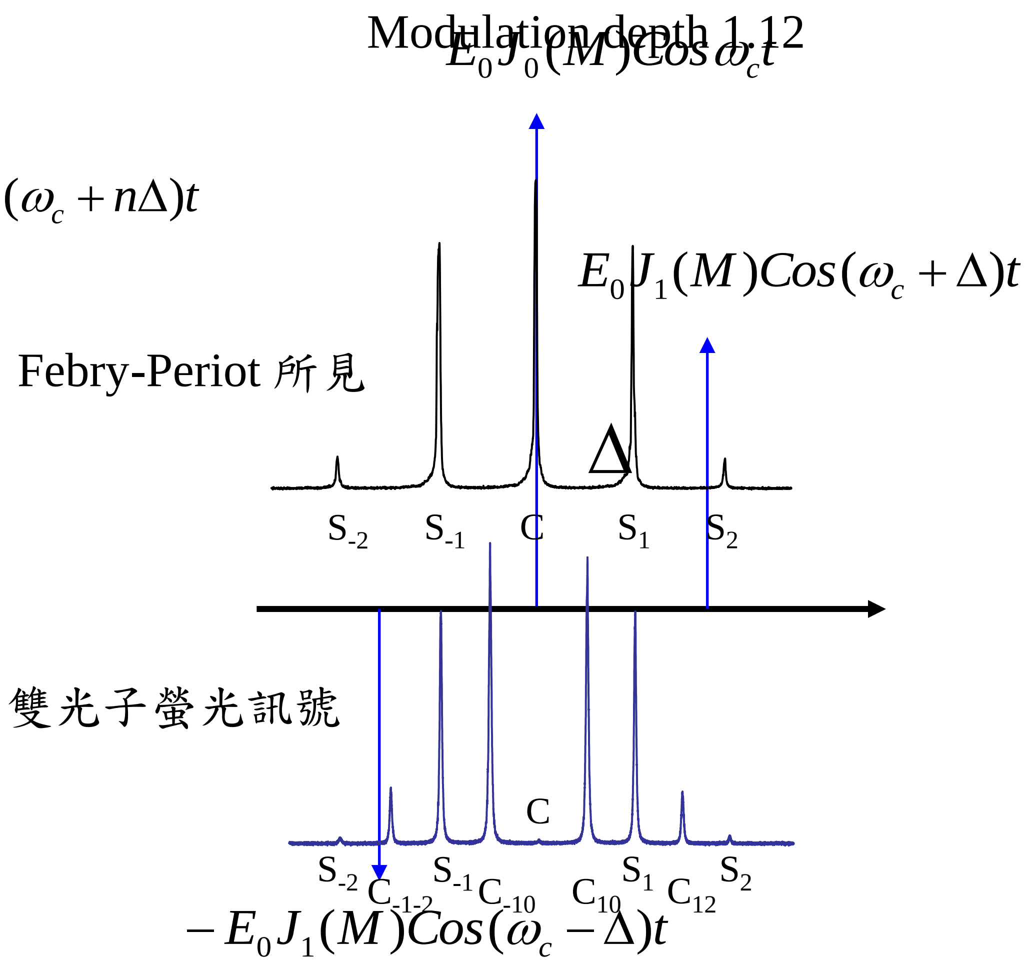


CTSDL
Current
Comb laser and cesium clock
TA
AOM
φ=MCos (Δt)
Δ=Δ0Cos ωt
carrier+Δ/2
EOM
Cs cell #2
Δ
VCO
(frequency dithered)
Cs cell #1
PMT
PZT
SWV
只有一根譜線
S-2
C-1-2
S-1
C-10
C10
S1
C12
S2
為何沒有carrier？
laser frequency→
85 MHz
PDH signal with dithered sidebands
sideband 抖動不影響鎖頻

Principle of quantum interfered two-photon spectroscopy

$$E = E_0 Cos(\omega_c t + \phi)$$
$$= E_0 Cos(\omega_c t + MCos\Delta t)$$
$$= E_0 \times \sum_{n=-\infty}^{n=\infty} (-1)^n J_n(M) Cos(\omega_c + n\Delta)t$$



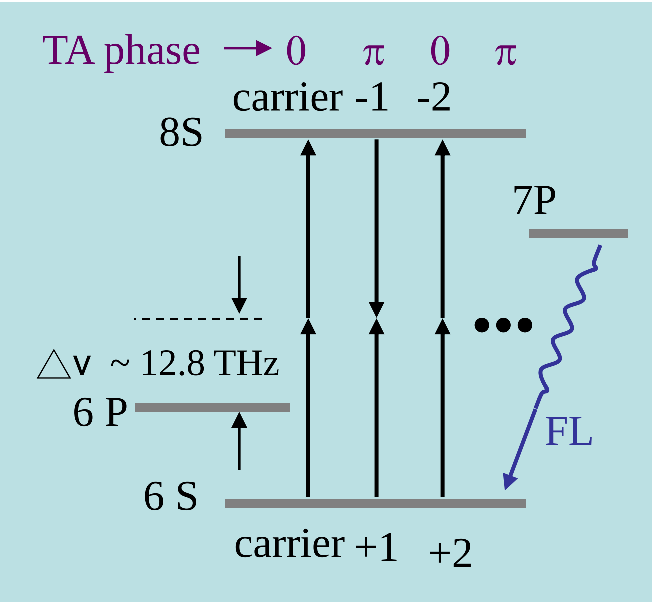


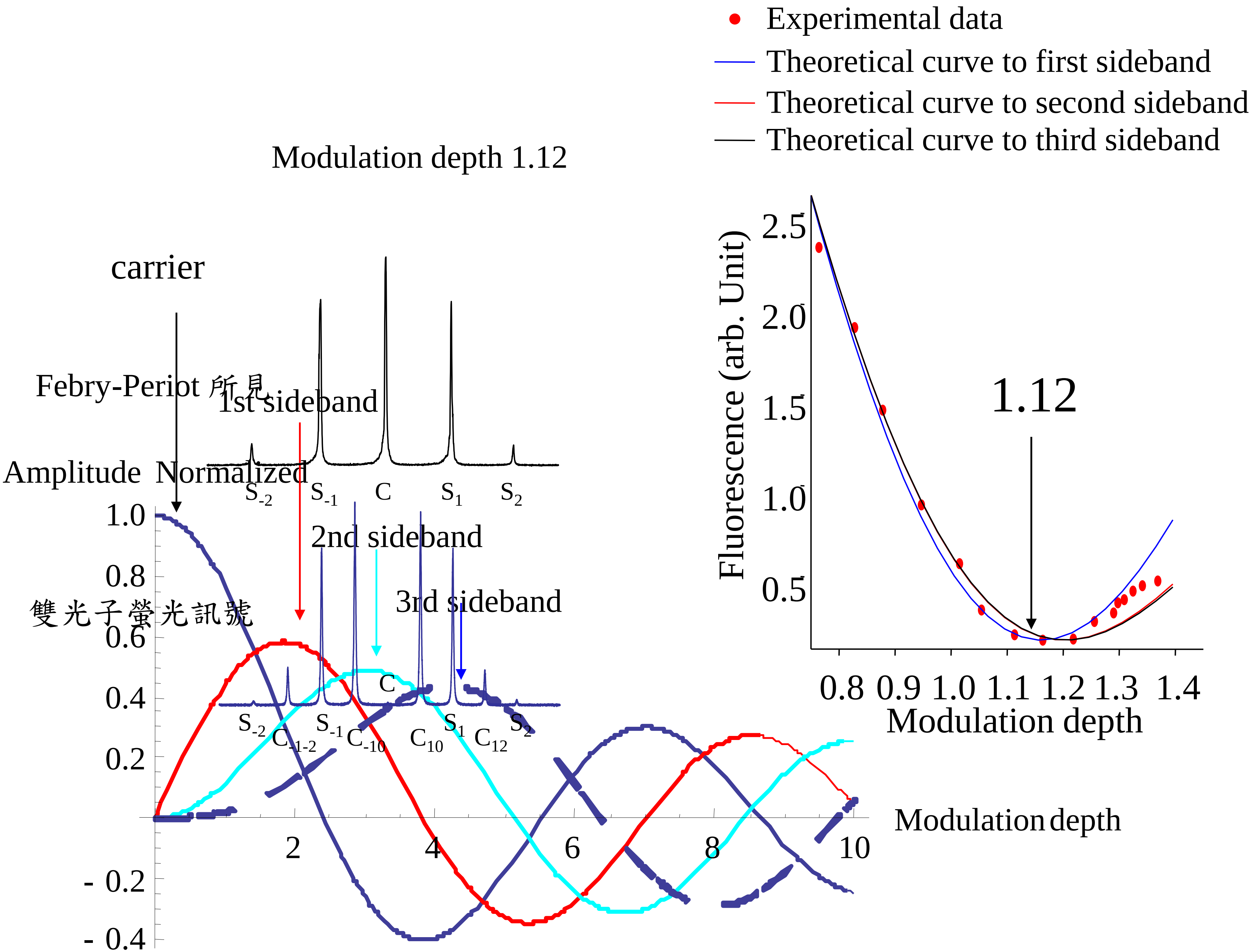
Principle of quantum interfered two-photon spectroscopy

$$E = E_0 Cos(\omega_c t + \phi)$$

$$= E_0 Cos(\omega_c t + M Cos \Delta t)$$

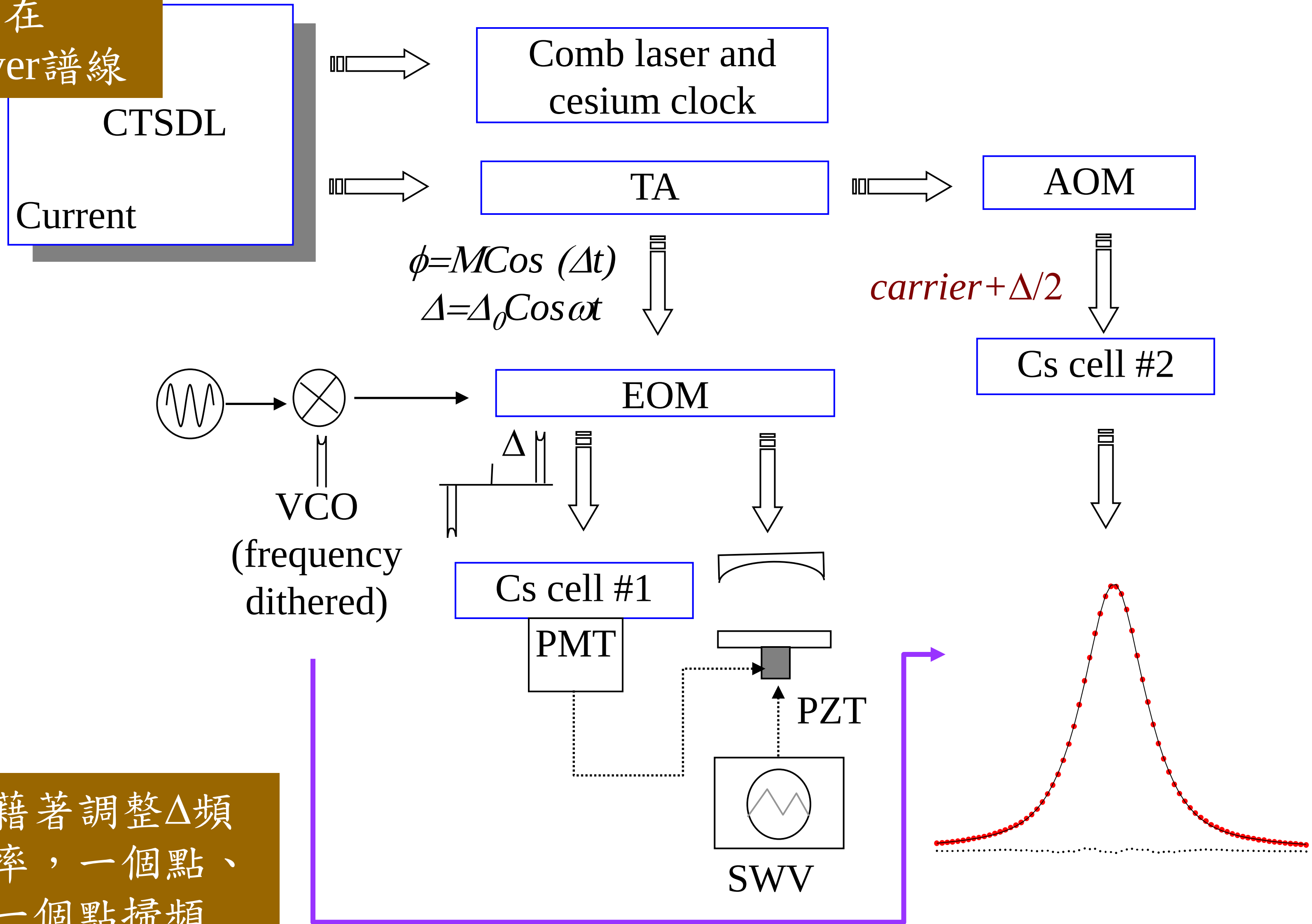
$$= E_0 \times \sum_{n=-\infty}^{n=\infty} (-1)^n J_n(M) Cos(\omega_c + n\Delta)t$$





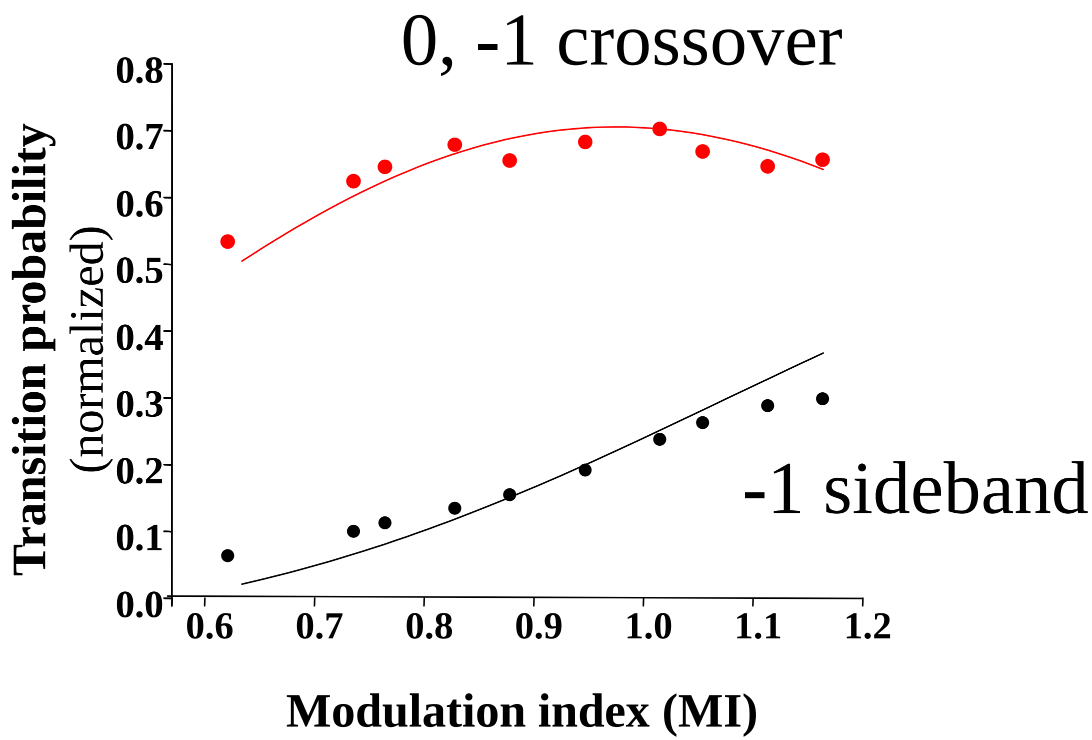
Experimental data
Theoretical curve to first sideband
Theoretical curve to second sideband
Theoretical curve to third sideband
Modulation depth 1.12
carrier
Febry-Periot 所見
1st sideband
Amplitude Normalized
S_{-2} S_{-1} C S_1 S_2
2nd sideband
3rd sideband
雙光子螢光訊號
C
S_{-2} C_{-1-2} S_{-1} C_{-10} C_{10} S_1 C_{12} S_2
1.0
0.8
0.6
0.4
0.2
- 0.2
- 0.4
2 4 6 8 10
Modulation depth
Fluorescence (arb. Unit)
2.5
2.0
1.5
1.0
0.5
1.12
0.8 0.9 1.0 1.1 1.2 1.3 1.4
Modulation depth

雷射鎖在
crossover譜線



藉著調整Δ頻
率，一個點、
一個點掃頻

為何把雷射鎖在crossover上再掃頻？

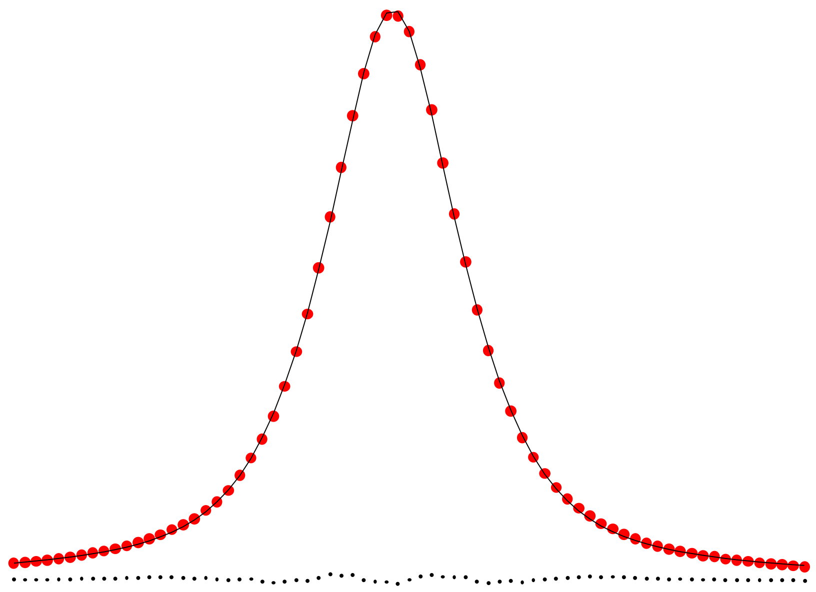


1. 在 modulation 小的時候，訊噪比比 1st sideband好
2. 對modulation depth 不敏感

雷射穩頻技術與高精密光譜

Laser Stabilization and High-resolution Spectroscopy

AMO summer school 2012



Speaker: Wang-Yau Cheng

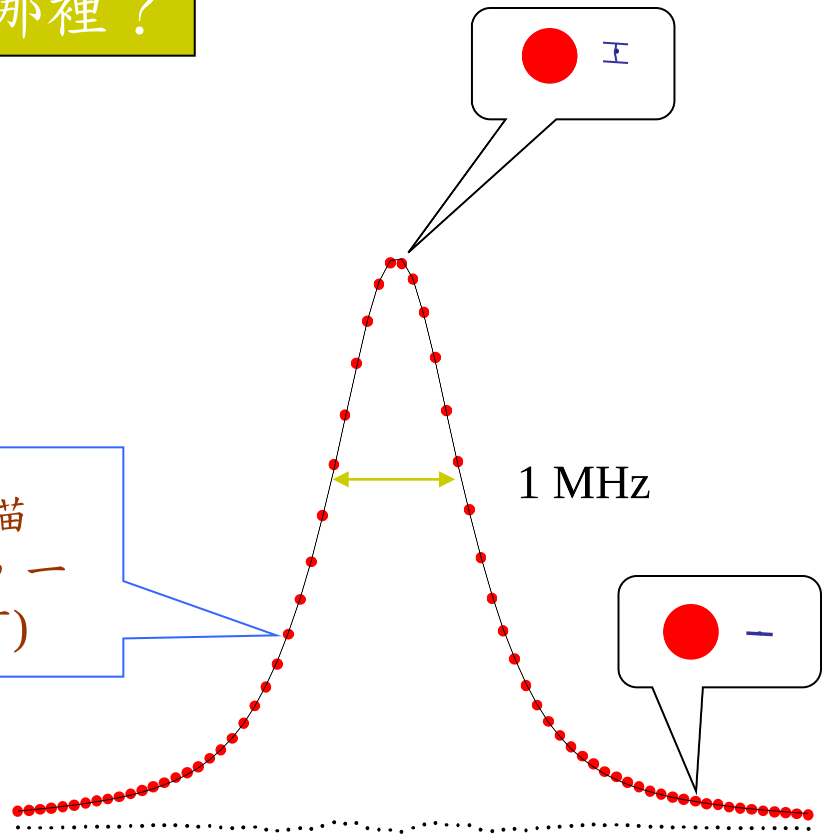
Department of Physics, National Central University

精研高解析光譜就像是在畫一幅畫

中心頻率不準度: 900 Hz

吳建明作品美在哪裡？

將畢業之博士生



一小點一小點的描
(目前每步100 kHz，一
步 30 Hz亦無不可)

高度對稱的fitting殘餘

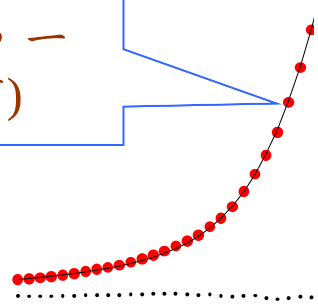
10^{-2}的fitting殘餘

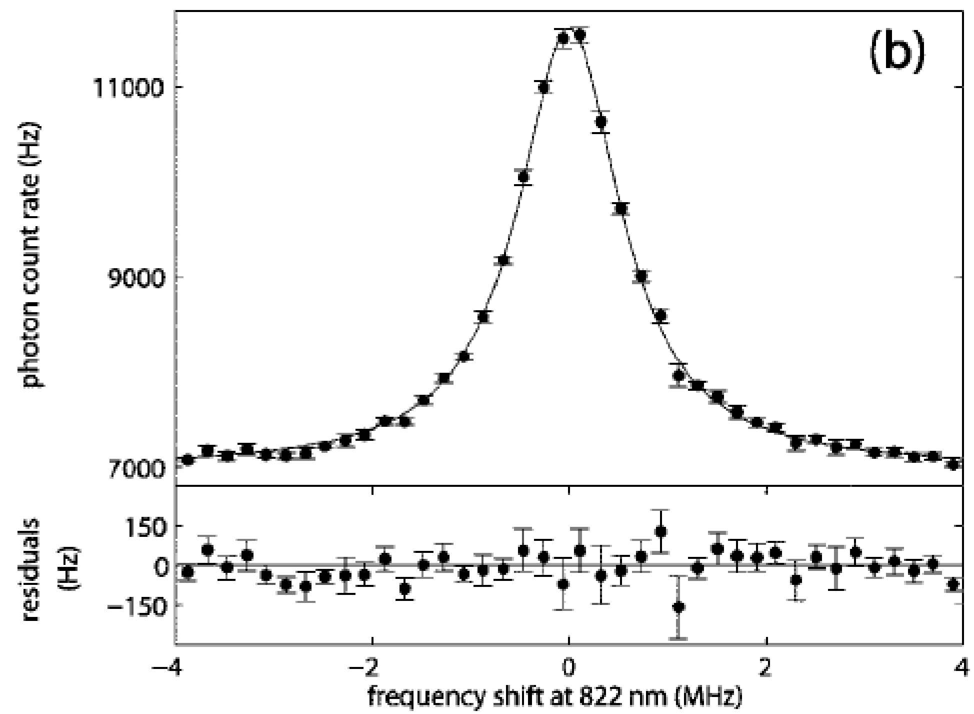
中心頻率不準度: 900 Hz

我們與另外一份畫作的比較(同一條譜線)

將畢業之博士生

一小點一小點的描
(目前每步100 kHz，一步30 Hz亦無不可)

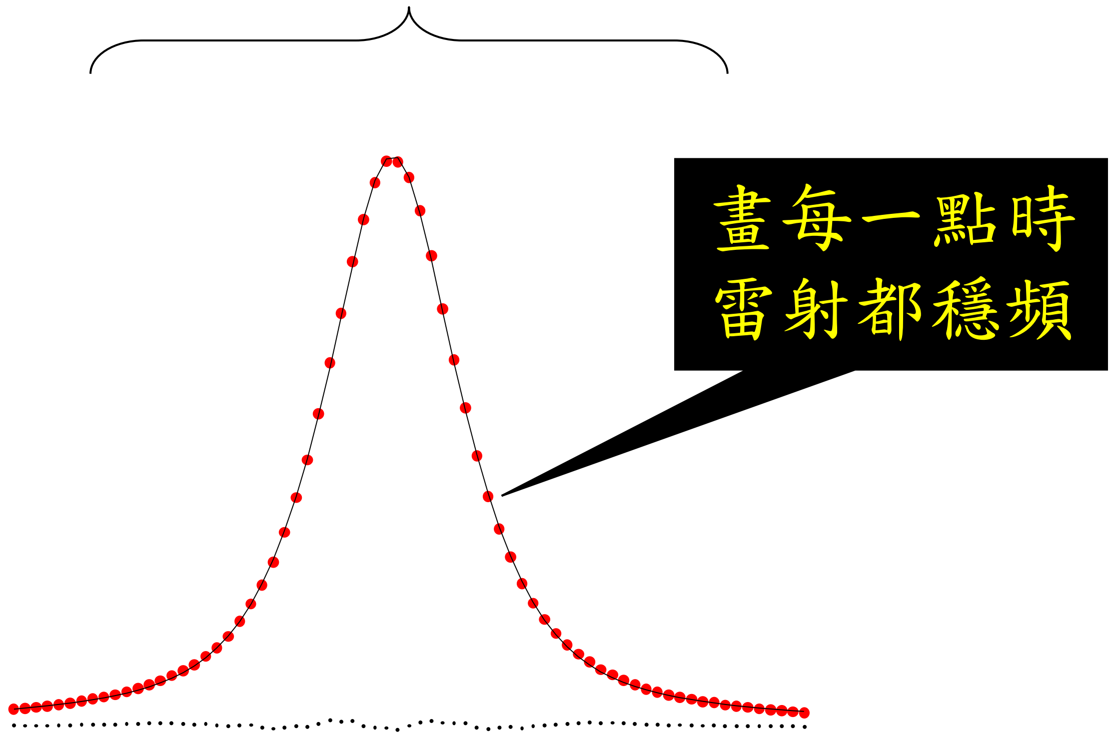




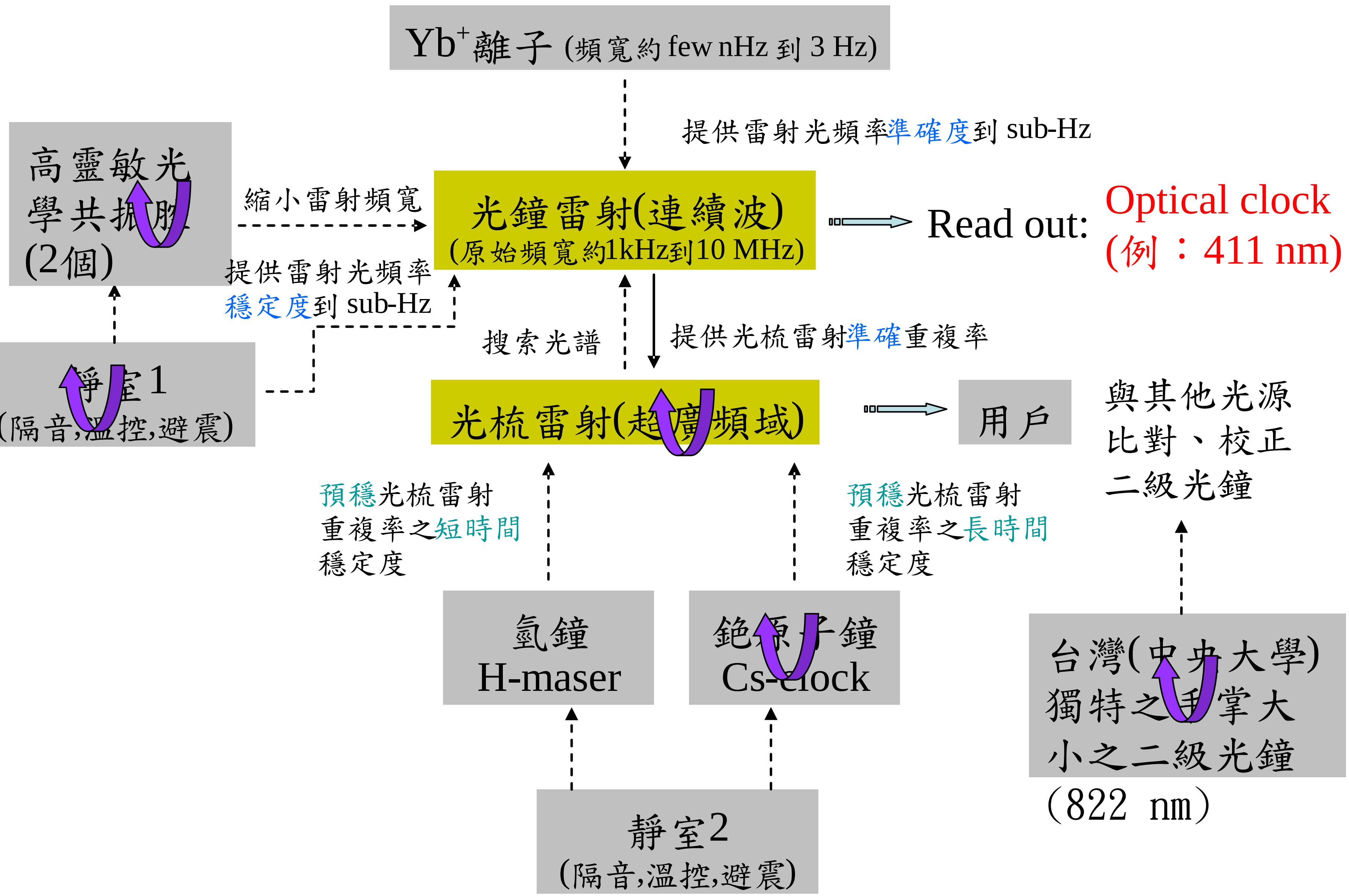
高度對稱的fitting殘餘

10^{-2}的fitting殘餘

最後得到高解析光譜



有助於未來光鐘的實現，雖然目前沒有錢，沒有人



Acknowledgement:

National Science Council (國科會)

Telecommun. Labs. (中華電信研究所)

- It is a team work !

822 nm standard

子維

建宏 **comb laser** 宗翰

建明

theory modeling

彥龍

Cs MOT

Gergly

建中 **884 nm spectra**

郁菁

麗晶

Hand-size laser

宥寰

聖輝

芝佑 **852 nm CPT**