Optical Frequency Comb:

A Journey for Precision Light

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Mar 10, 2009

Outline

- *Why Precision Light?*
- *Optical Frequency Measurement in Pre-OFC Era*
- *Understanding OFC*
- *NTHU OFC*
- *What can OFC do for us?*

Why Precision Light?

- *Metrology*
  - *Frequency, Time and Length Standard*
  - *Physical Constants*
- *Precision Probe for Small Effects and Internal Structure of Molecules*
  - *Temporal Variation of Physical Constants, QED Test etc.*
- *Practical Applications*
  - *DWDM for Optical Fiber Communication, Quantum Information?*

Optical Frequency Measurement in Pre-OFC Era

Frequency Chain for 40Ca 657 nm

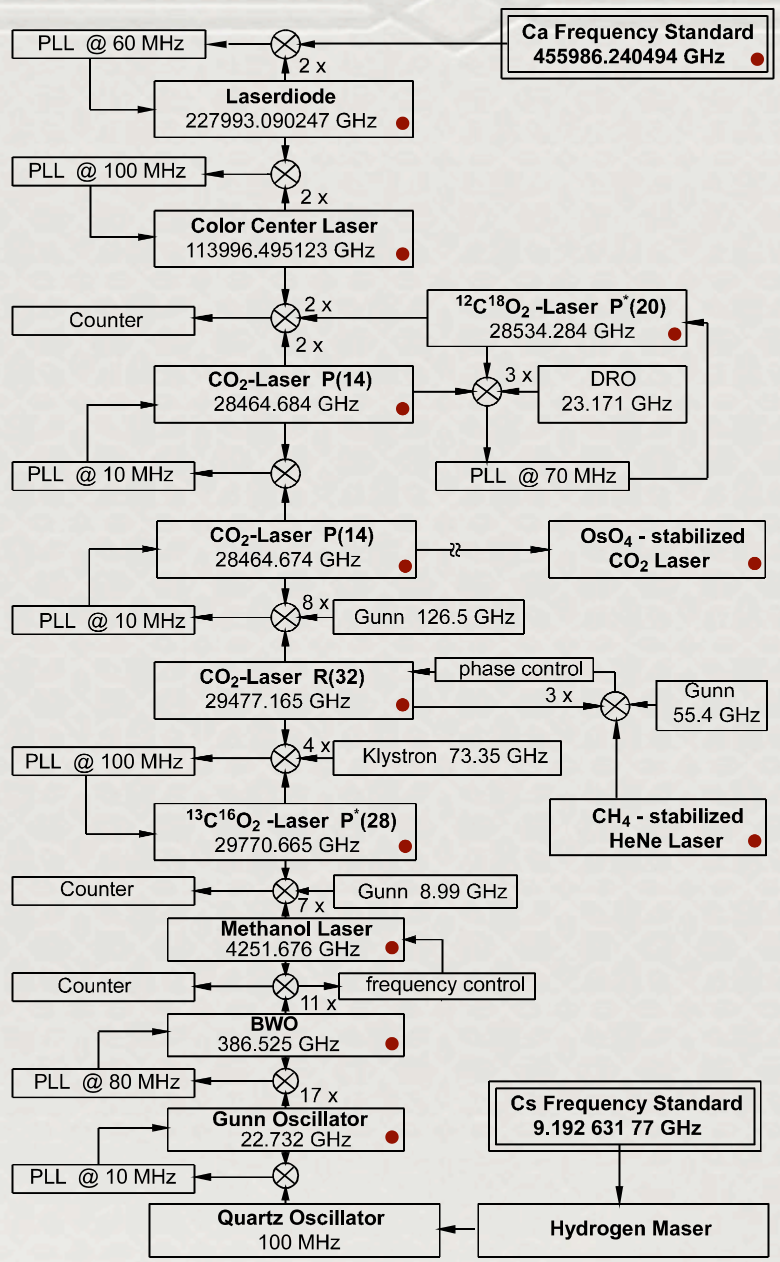
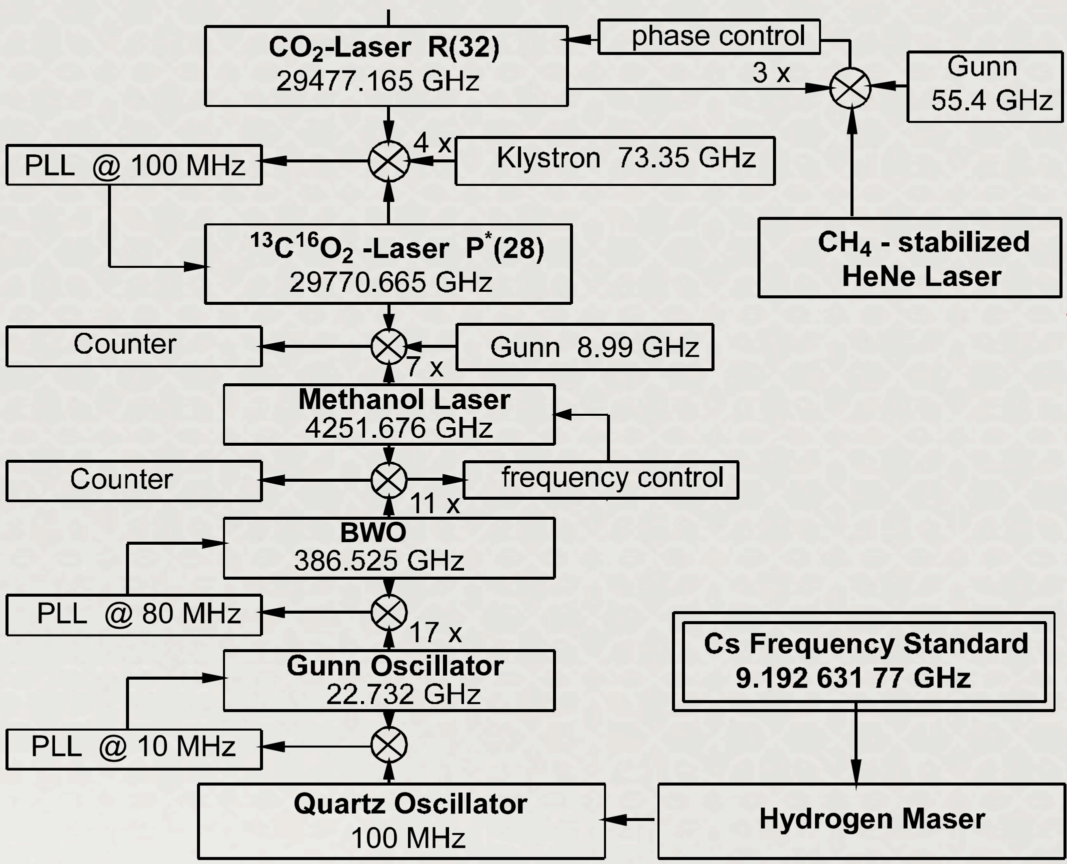


Fig. 17. Frequency-measurement chain to the Ca intercombination line

Frequency Chain for Hydrogen 1S-2S



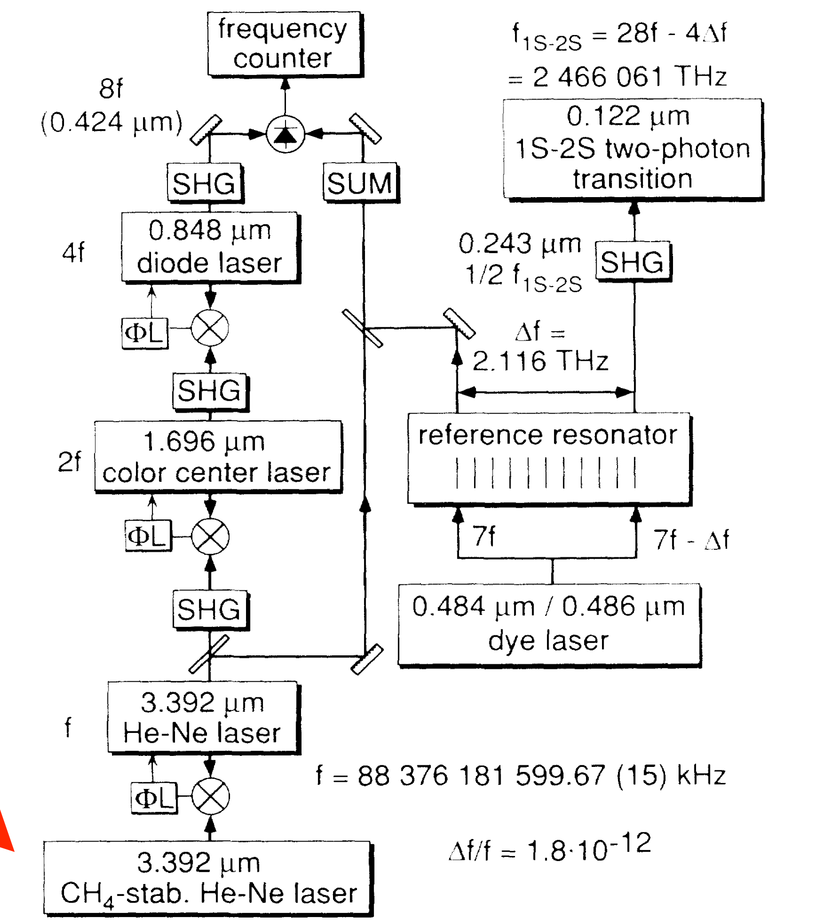
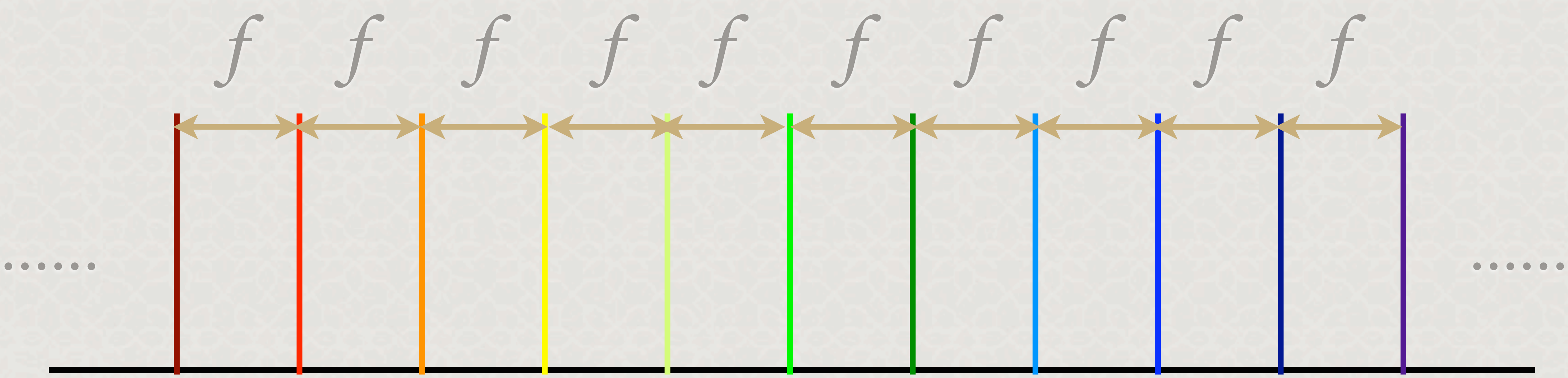


FIG. 2. Experimental setup for the frequency measurement of the 1*S*-2*S* transition in atomic hydrogen (Φ*L*, phase-locked loop: SHG, second harmonic generation).

Laser Shuttle between PTB & Hänsch's Group

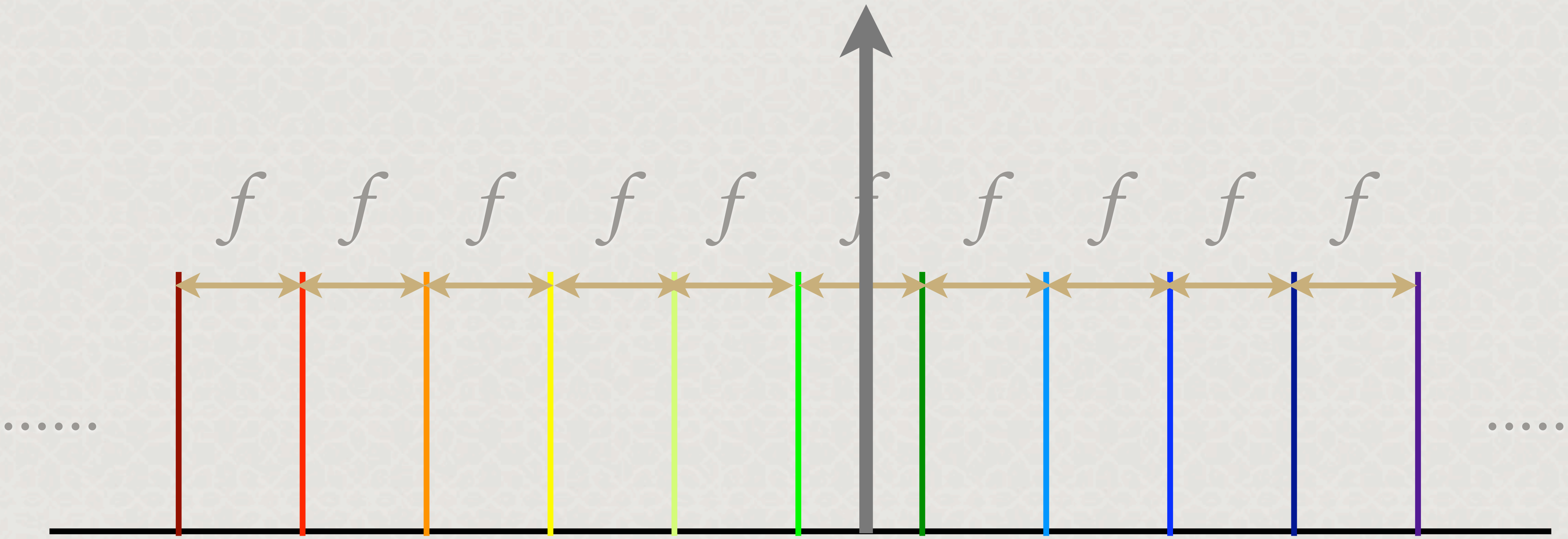
Understanding OFC

What is Optical Frequency Comb



A series of equal-spaced comb lines in frequency domain

What is Optical Frequency Comb



A series of equal-spaced comb lines in frequency domain

How to Build a OFC

How to Build a OFC

- *Cavity Enhanced Phase Modulation*

How to Build a OFC

- *Cavity Enhanced Phase Modulation*
- *Mode-locking Lasers*
  - *Ti:sapphire ($Ti^{3+}:Al_2O_3$): 800 nm*
  - *Cr:forsterite ($Cr^{3+}:Mg_2SiO_4$): 1235 nm*
  - *Er-doped Fiber: 1550 nm*

Cavity Enhanced Phase Modulation

- *Frequency sidebands are generated by phase modulator and enhanced by Fabry-Pérot cavity*
- *Originally constructed for picosecond pulse generation in 1972 and re-implemented by M. Kourogi, K. Nakagawa, M. Ohtsu in 1993 for frequency measurement*

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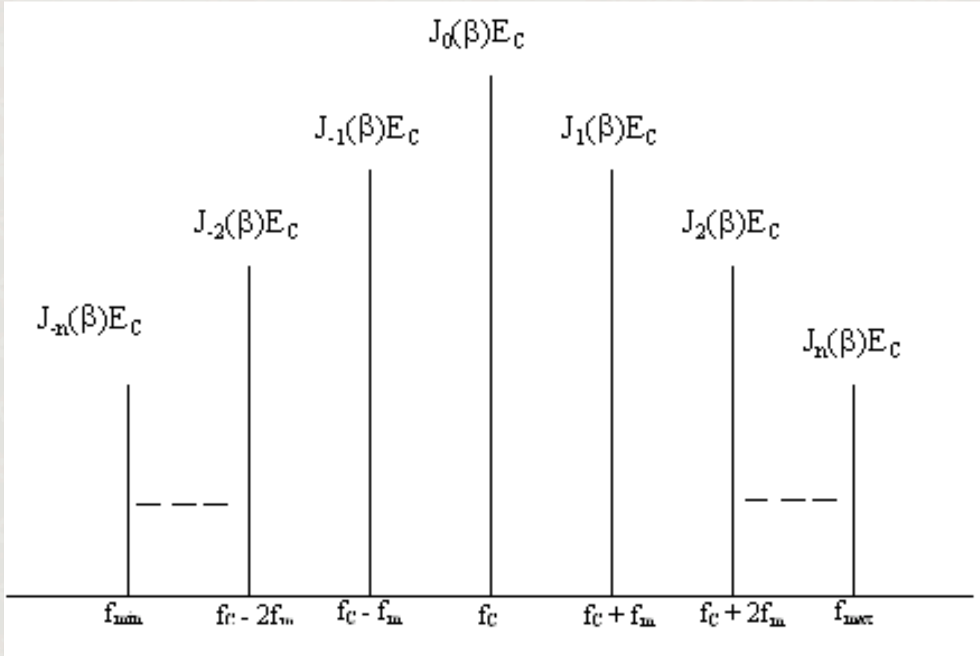

Cavity Enhanced Phase Modulation

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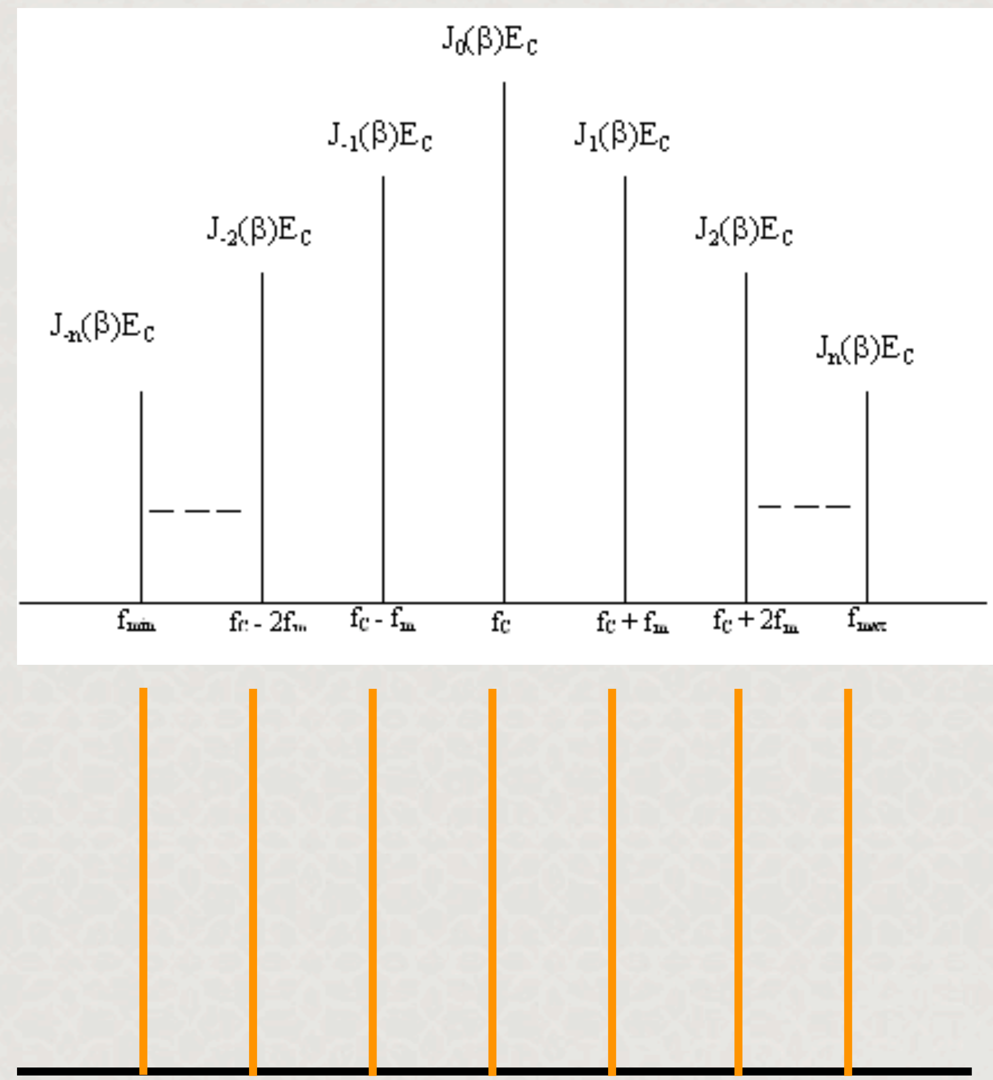


Cavity Longitudinal Modes

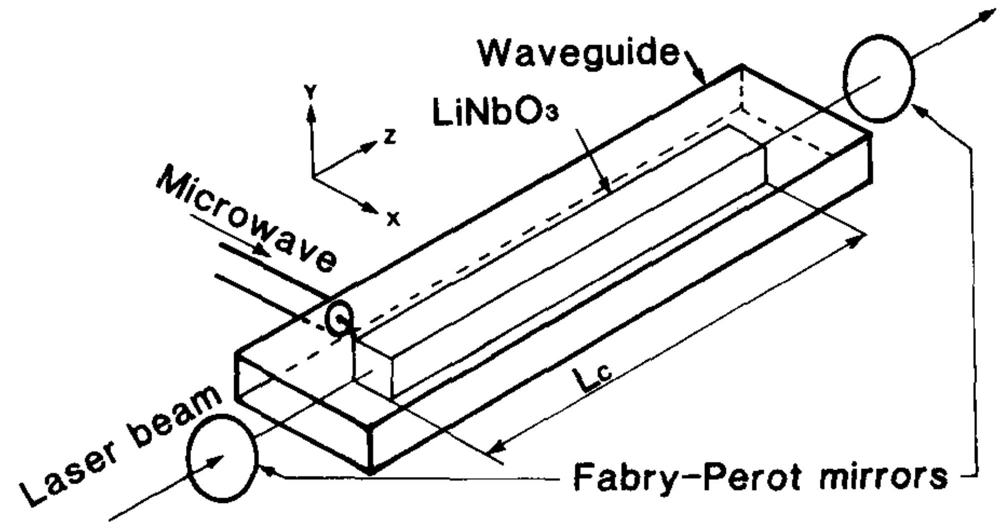
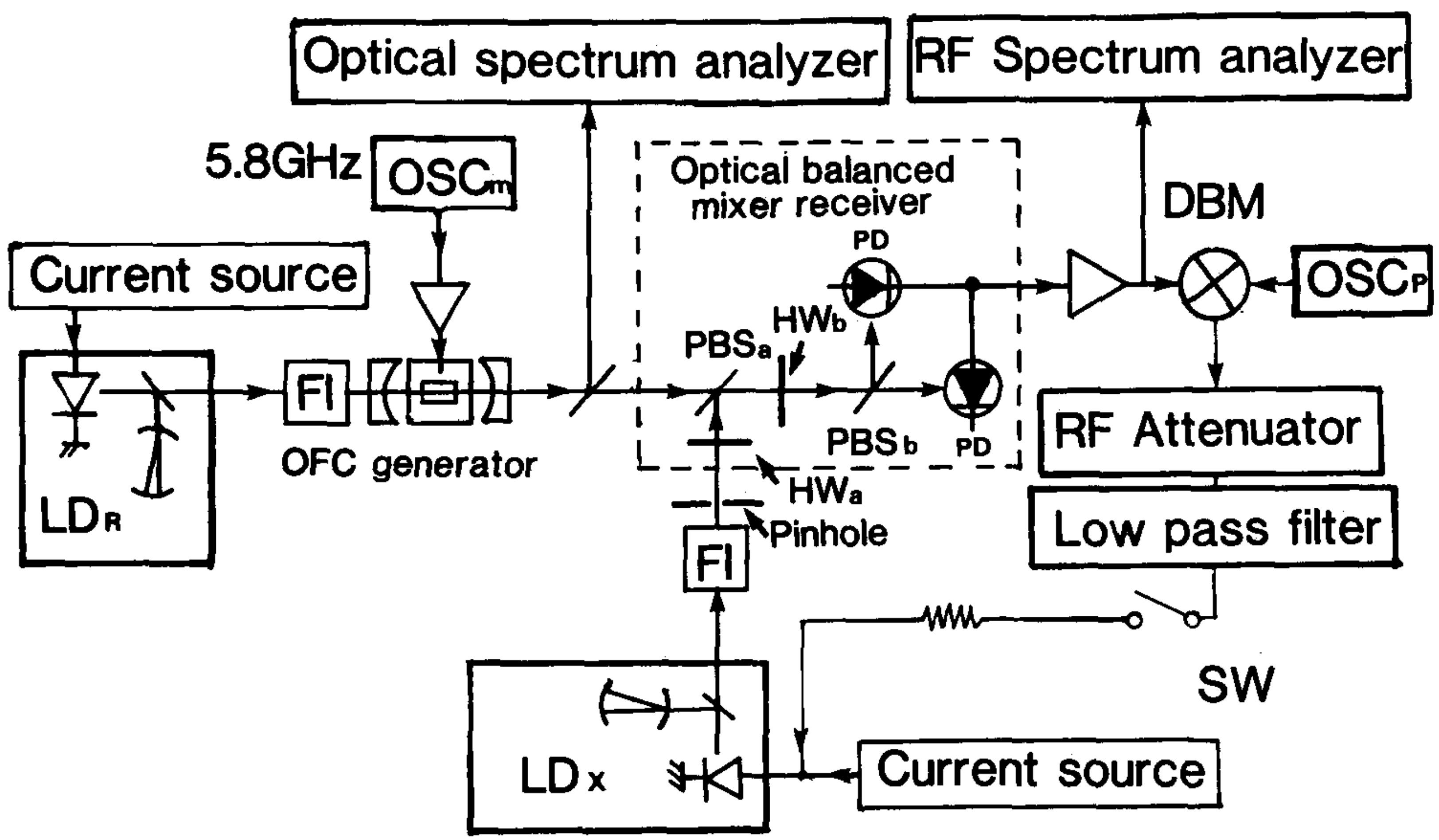
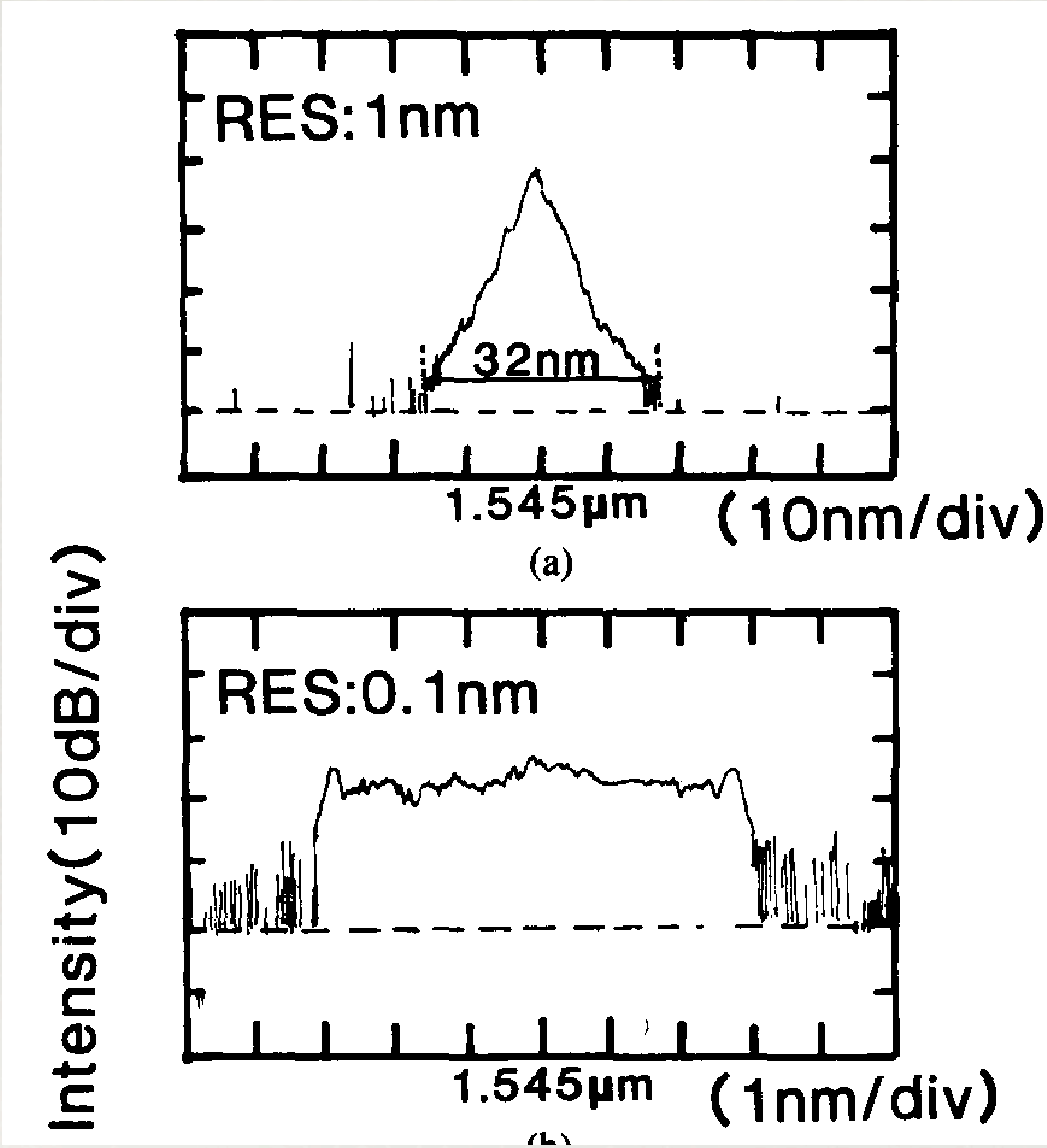


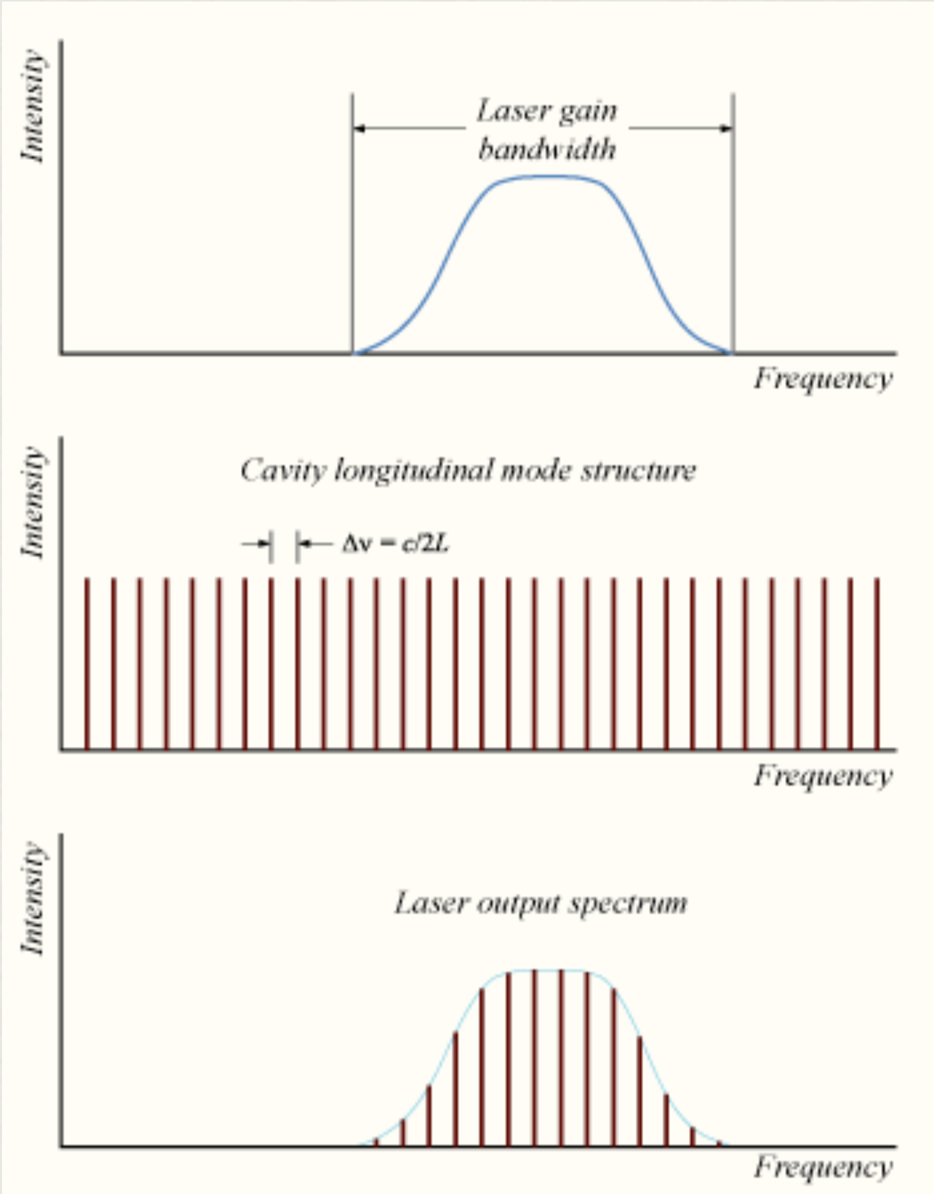
Fig. 2. The construction of the present optical frequency comb generator.

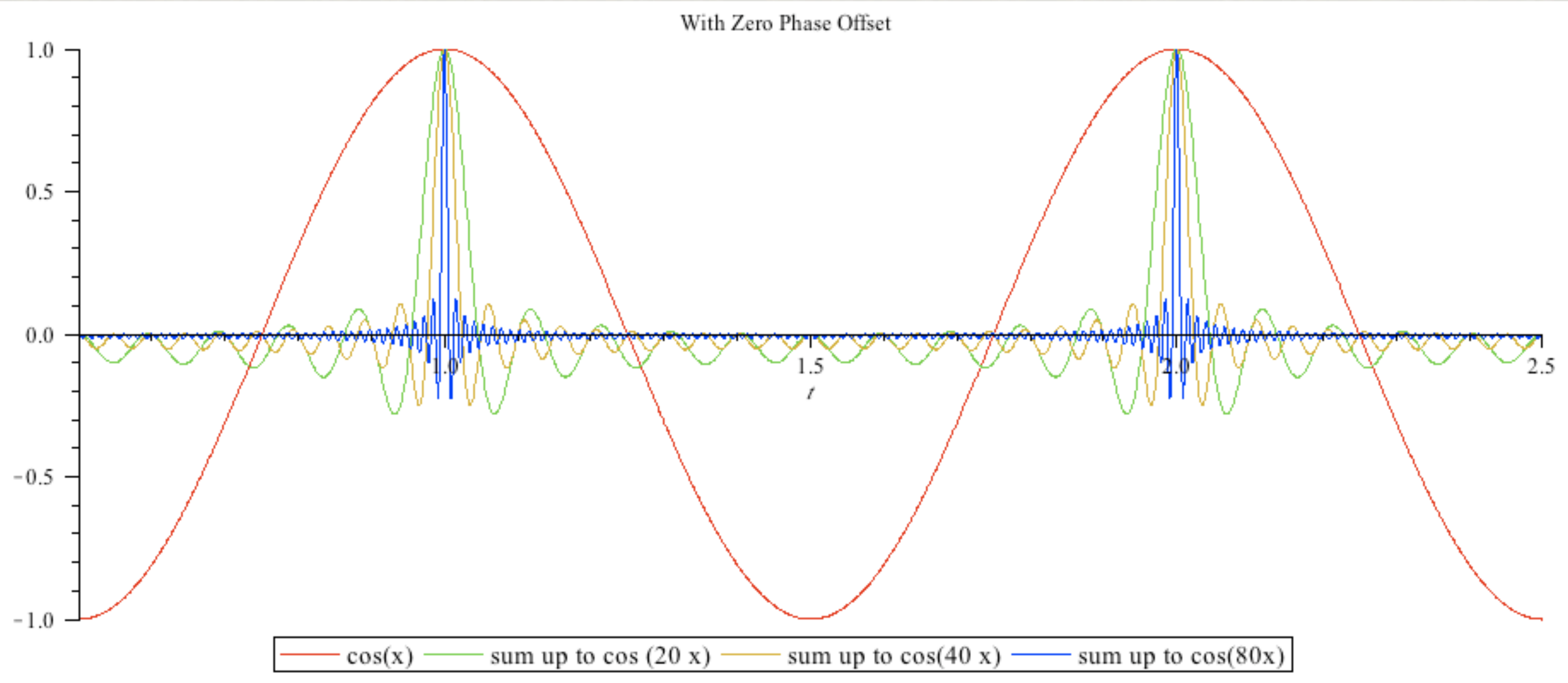



RES:1nm
32nm
1.545μm
(10nm/div)
(a)
Intensity(10dB/div)
RES:0.1nm
1.545μm
(1nm/div)

Mode-locked Lasers

- *Multi-longitudinal-mode in frequency domain and pulse operation in time domain*
- *The modes are equal-spaced in frequency and phase-coherent*
- *The frequency of each mode can be written as:*
  $F_n = n \times F_r + F_o$
  - F_r: Repetition Frequency =Longitudinal Mode Spacing
  - F_o: Offset Frequency

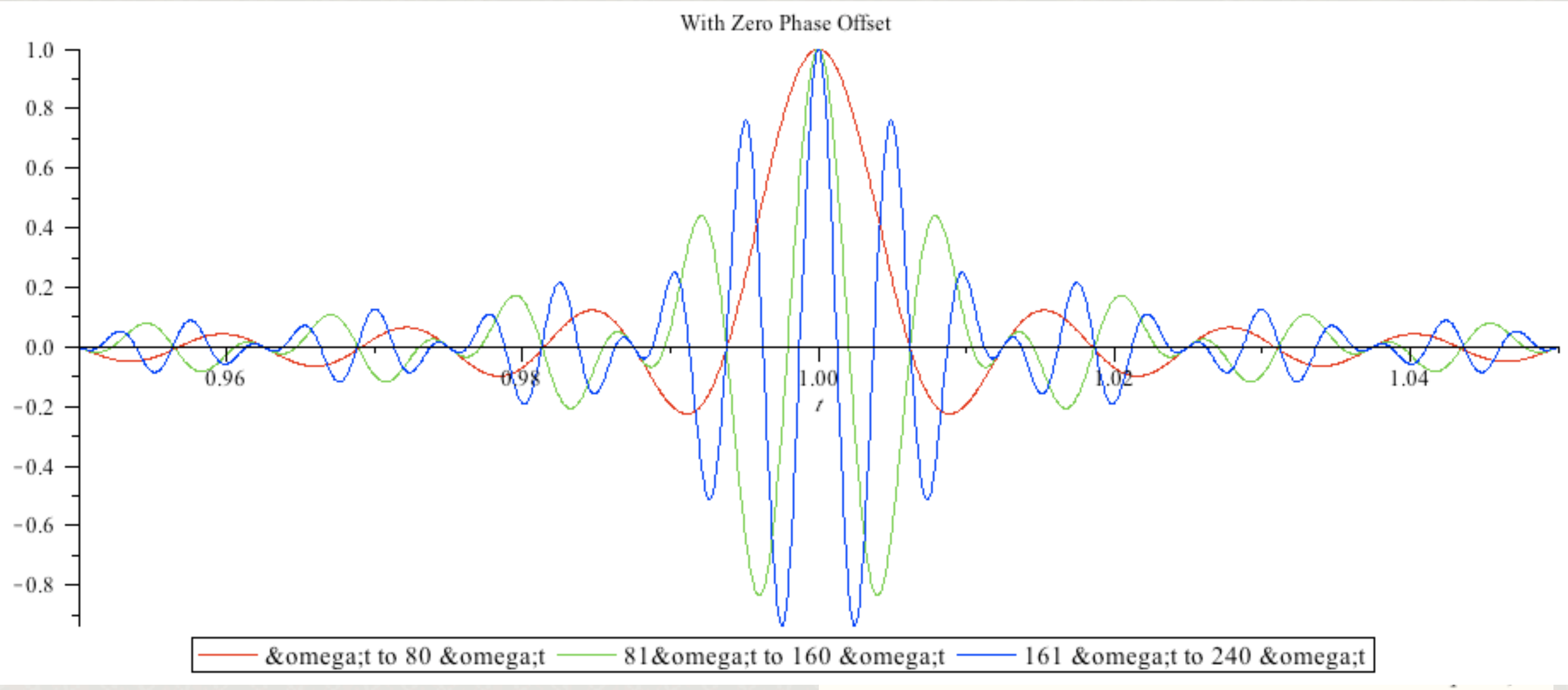




$$\sum_{N=1}^{10} \cos(N\omega t)$$

$$\sum_{N=1}^{20} \cos(N\omega t)$$

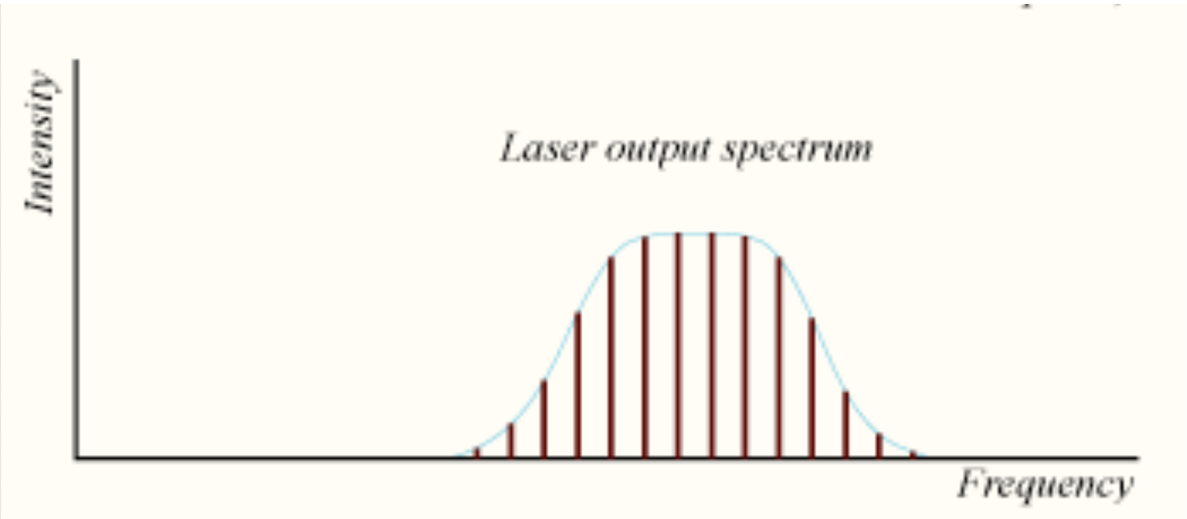
$$\sum_{N=1}^{80} \cos(N\omega t)$$

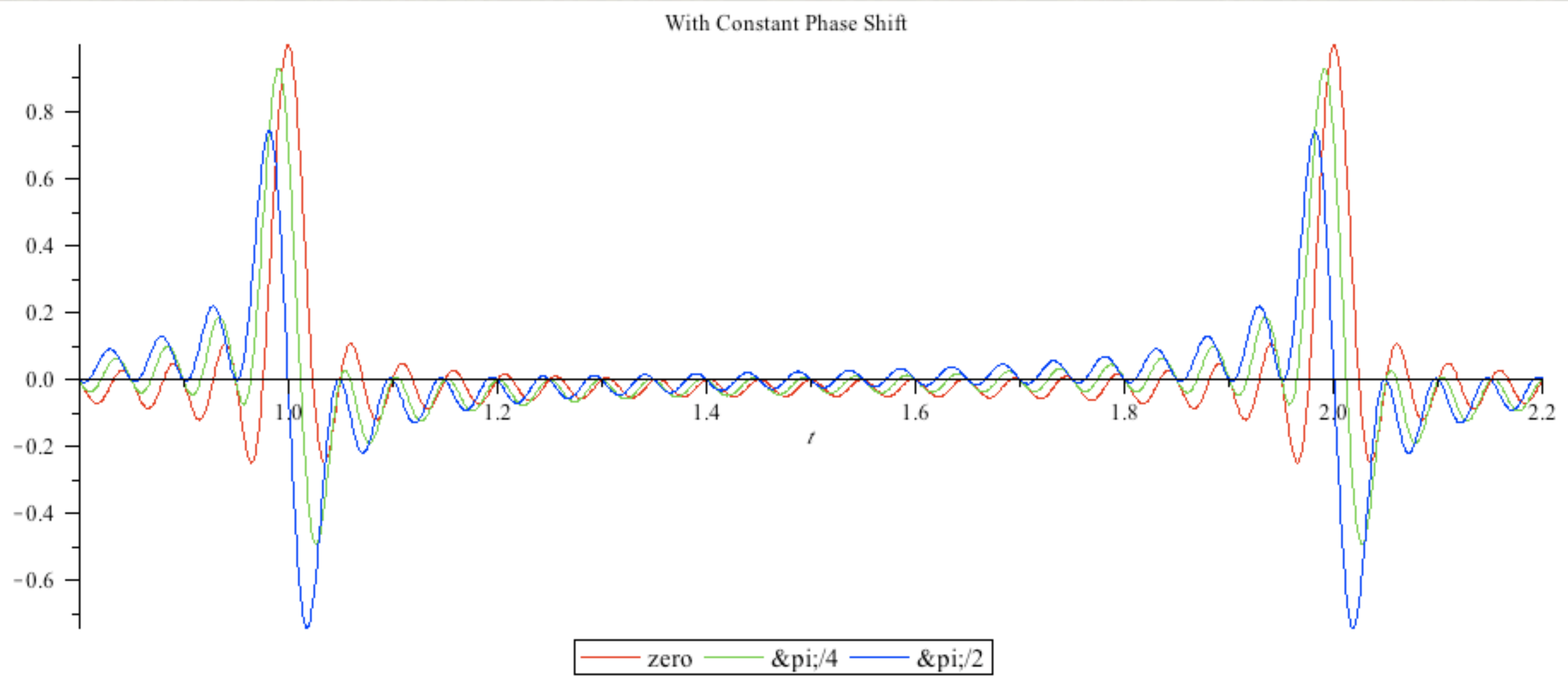


$$\sum_{N=1}^{80} \cos(N\omega t)$$

$$\sum_{N=81}^{160} \cos(N\omega t)$$

$$\sum_{N=161}^{240} \cos(N\omega t)$$

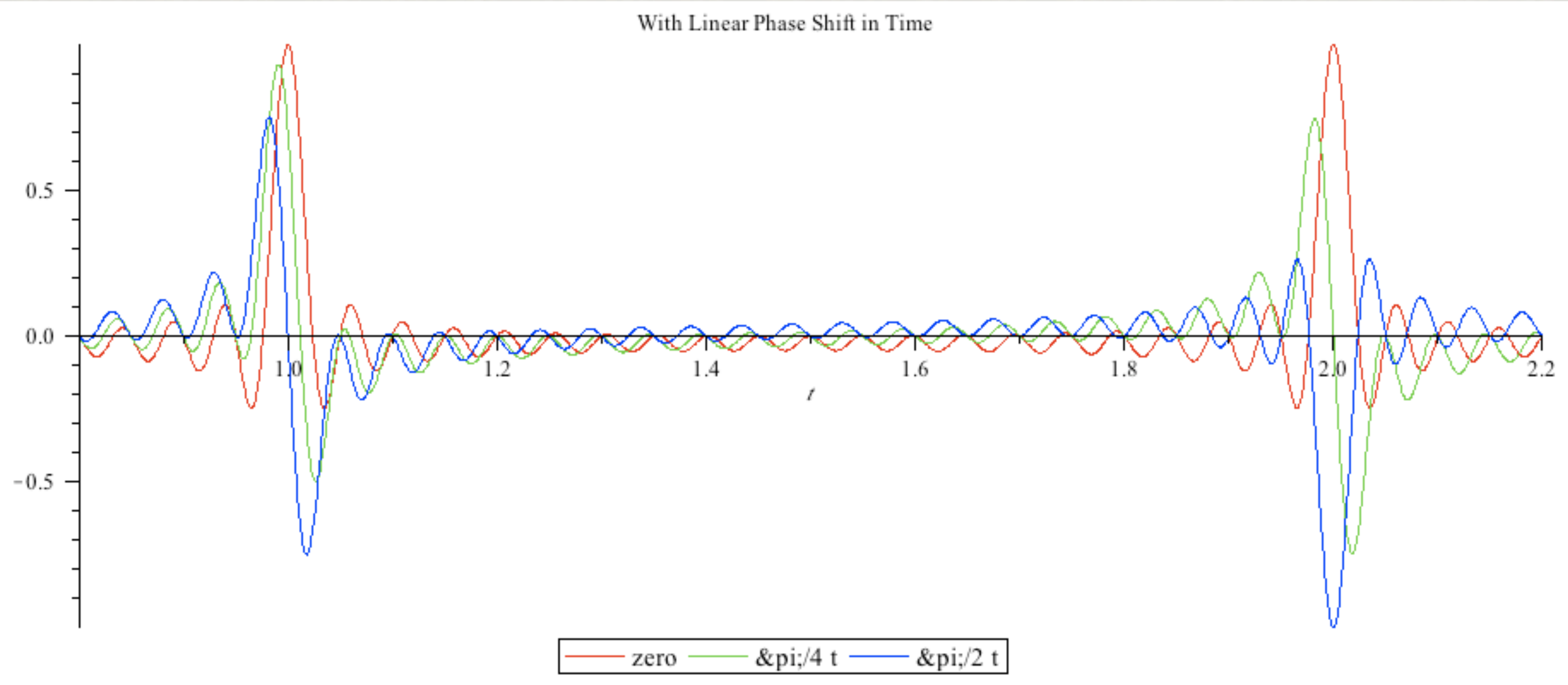




$$\sum_{N=1}^{20} \cos(N\omega t)$$

$$\sum_{N=1}^{20} \cos(N\omega t + \frac{\pi}{4})$$

$$\sum_{N=1}^{20} \cos(N\omega t + \frac{\pi}{2})$$

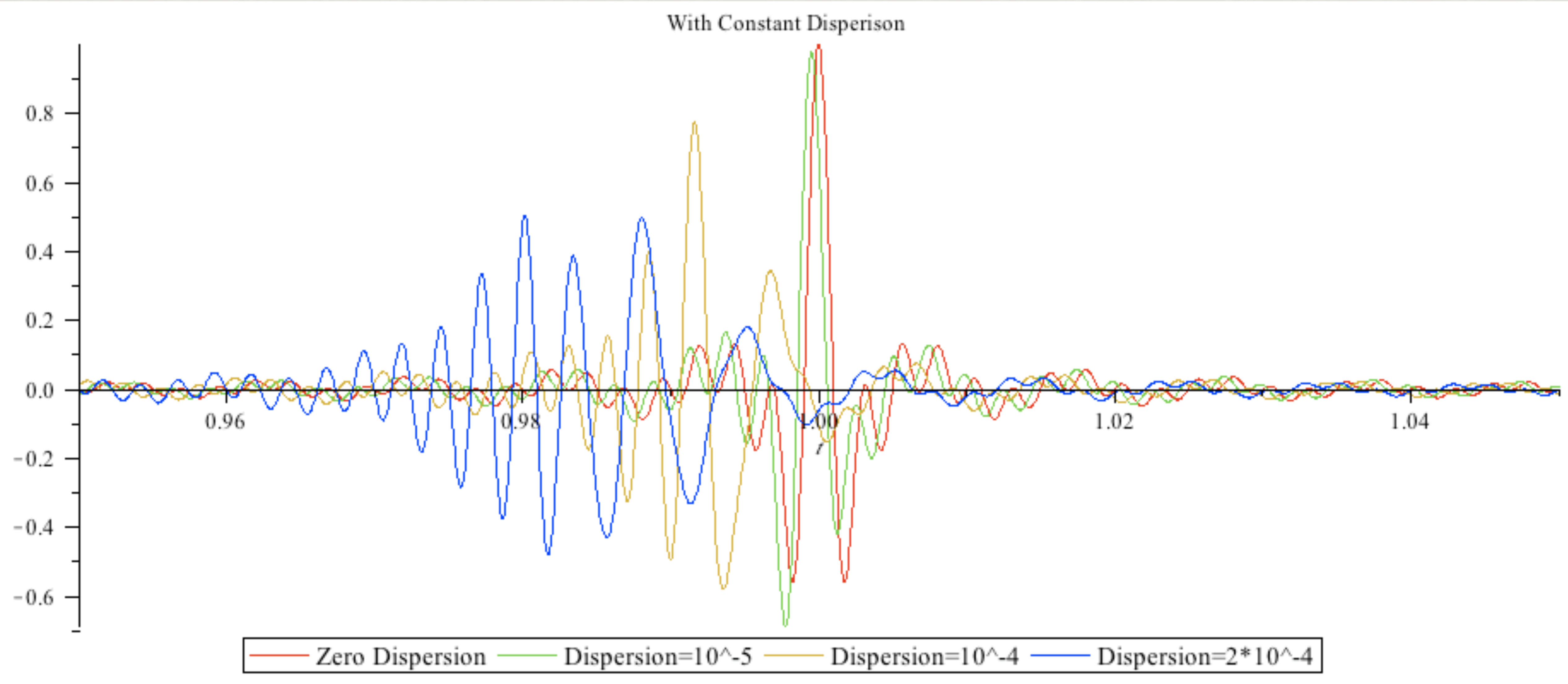


$$\sum_{N=1}^{20} \cos(N\omega t)$$

$$\sum_{N=1}^{20} \cos(N\omega t + \frac{\pi}{4} t)$$

$$\sum_{N=1}^{20} \cos(N\omega t + \frac{\pi}{2} t)$$

$$\begin{aligned} f &= \frac{d\phi}{dt} \\ \omega_1 &= \omega, 2\omega, \cdots, 20\omega \\ \omega_2 &= \omega + \frac{\pi}{4}, 2\omega + \frac{\pi}{4}, \cdots, 20\omega + \frac{\pi}{4} \\ \omega_3 &= \omega + \frac{\pi}{2}, 2\omega + \frac{\pi}{2}, \cdots, 20\omega + \frac{\pi}{2} \end{aligned}$$



$$\sum_{N=101}^{400} \frac{1}{300} \cos(N\omega t)$$

$$\sum_{N=101}^{400} \frac{1}{300} \cos(N\omega t + 10^{-5}\omega^2)$$

$$\sum_{N=101}^{400} \frac{1}{300} \cos(N\omega t + 10^{-4}\omega^2)$$

$$\sum_{N=101}^{400} \frac{1}{300} \cos(N\omega t + 2 \times 10^{-4}\omega^2)$$

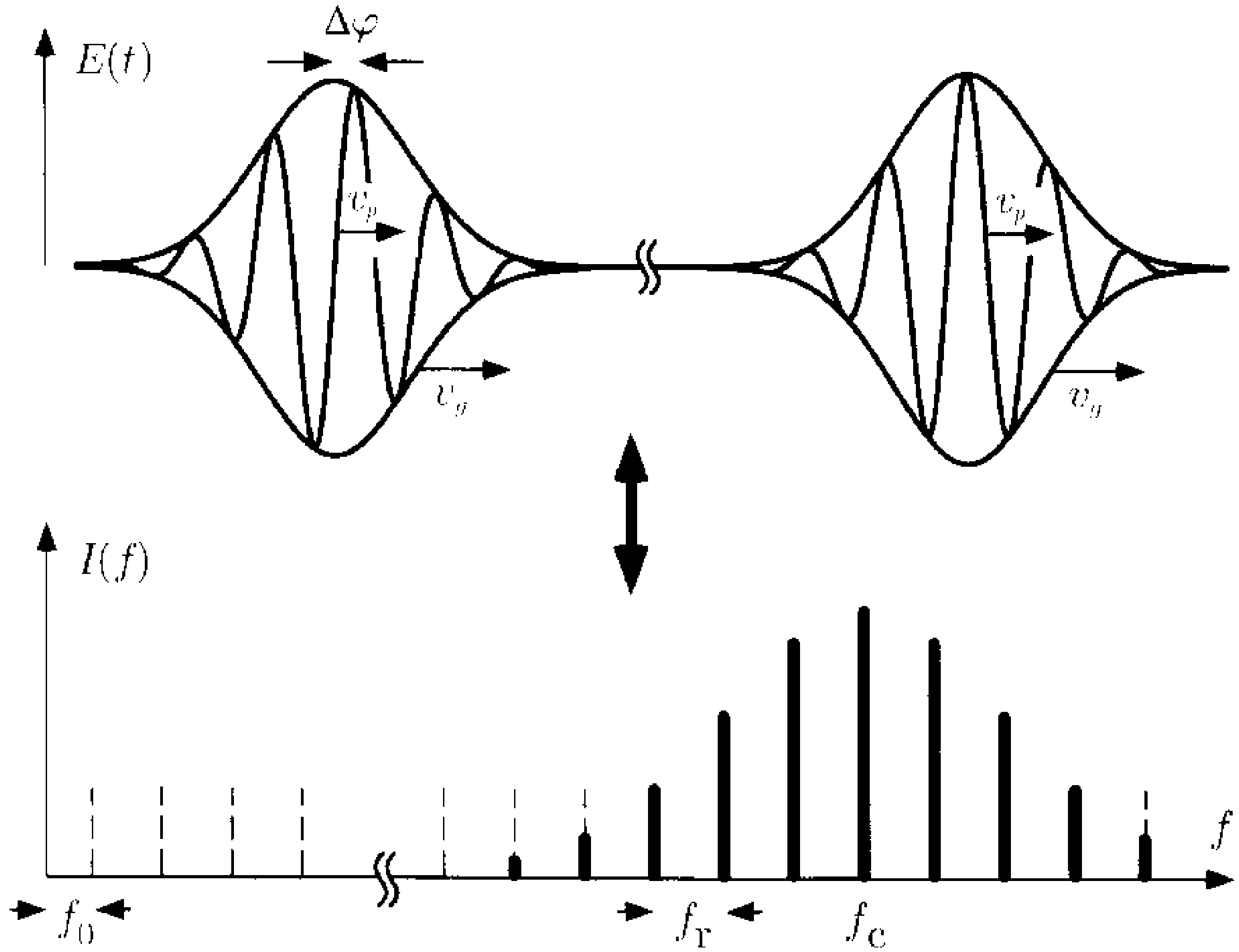
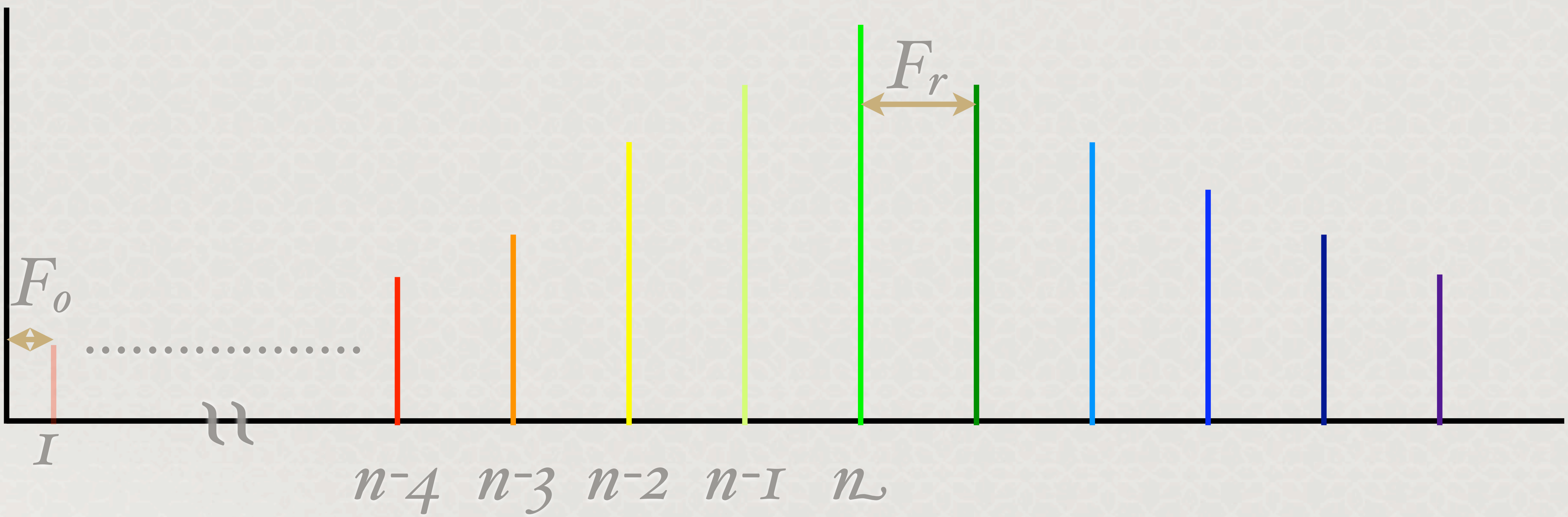


Fig. 1. Two consecutive pulses of the pulse train emitted by a mode-locked laser and intensity spectrum of the train. Within the cavity, the envelope is traveling with the group velocity v_g which, in general, differs from the phase velocity of the carrier v_p. The carrier phase relative to the envelope changes from pulse to pulse by $\Delta\varphi$. The modes are offset from being integer multiples of the pulse repetition rate f_r by $f_0 = (\Delta\varphi/2\pi)f_r$.

J. Reichert et al. Opt. Comm. 172, 59(1998)

Controlling Frequency of Mode-locked Laser

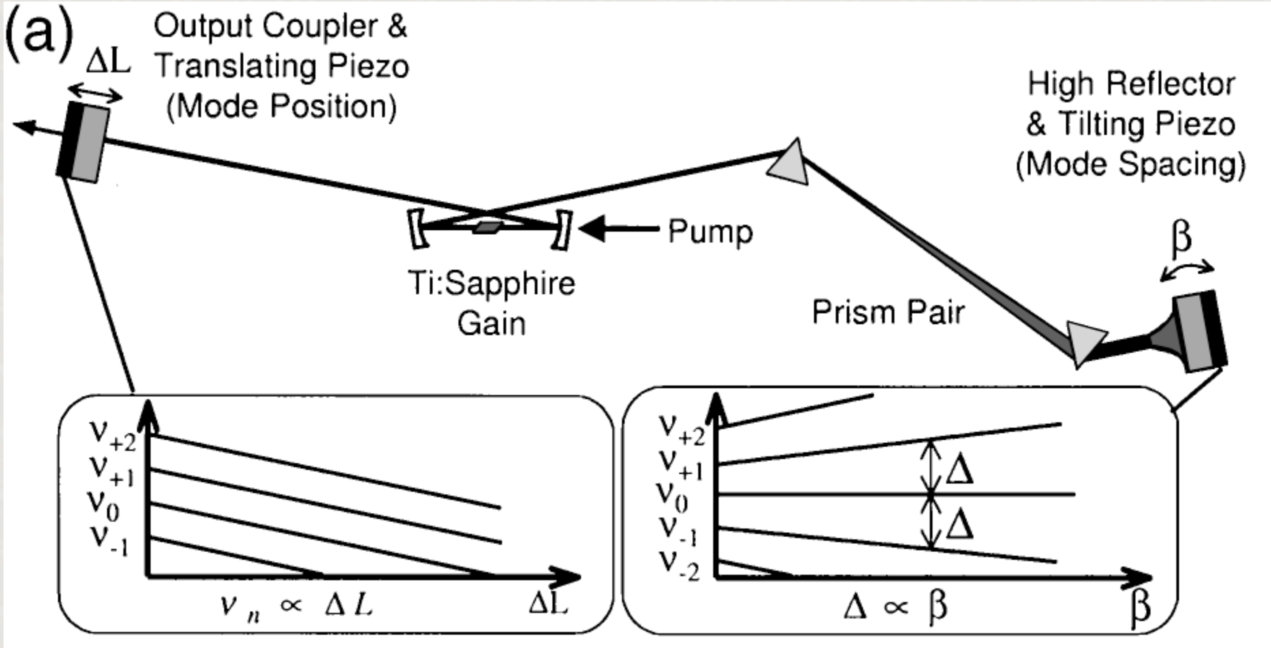


$F_n = n \times F_r + F_o$

Controlling F_r and F_o, F_n is fixed

Controlling Frequency of Mode-locked Laser

- *Repetition frequency Fr, equal to longitudinal mode spacing, can be controlled via round-trip path length*
- *Controlling the phase revolution to fix offset frequency*



J. Ye et al., Opt. Lett. 25, 1675(2000)

Another Way to Control Offset Frequency

High intensity within the cavity of mode-locked laser

↓

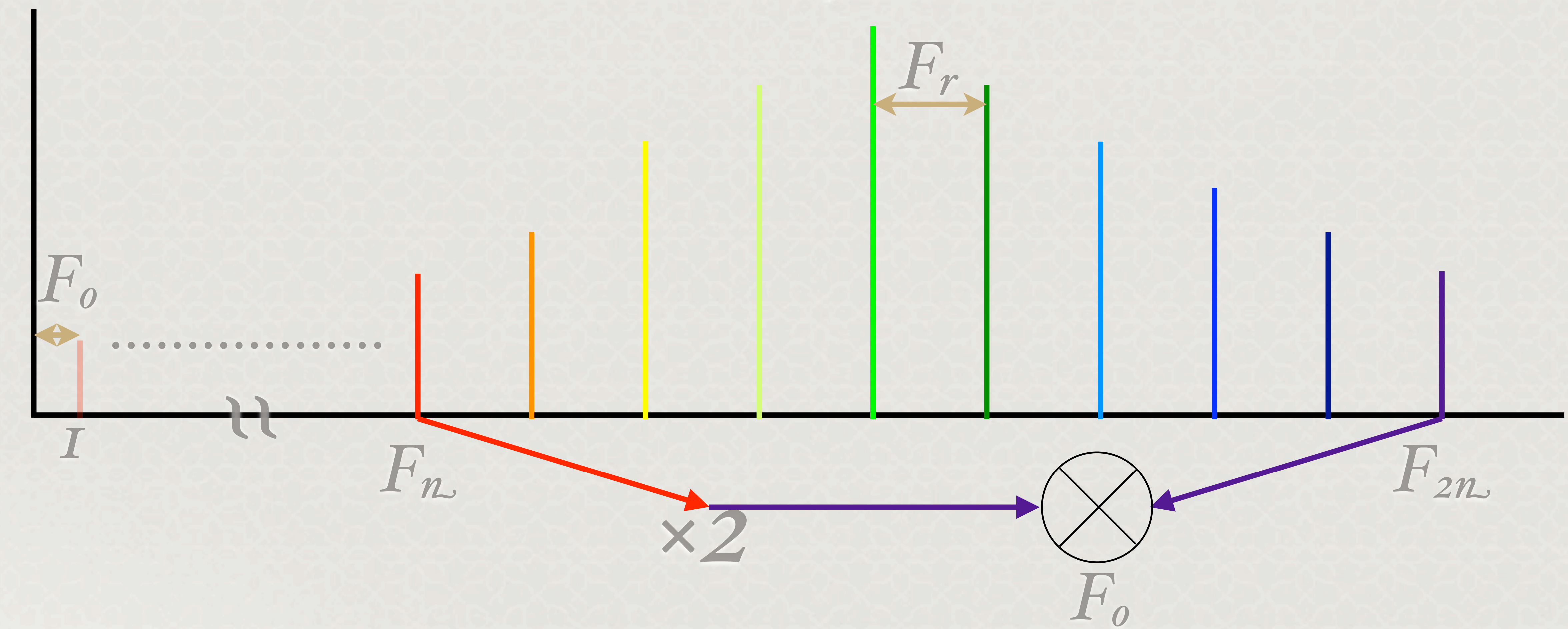
Optical Kerr Effect, $n=n_0+n_2I$

↓

Change intracavity intensity to control the offset frequency

J. Stenger et al., Opt. Lett. 25, 1553(2000)

Detecting Offset Frequency: f-2f Self-Referencing



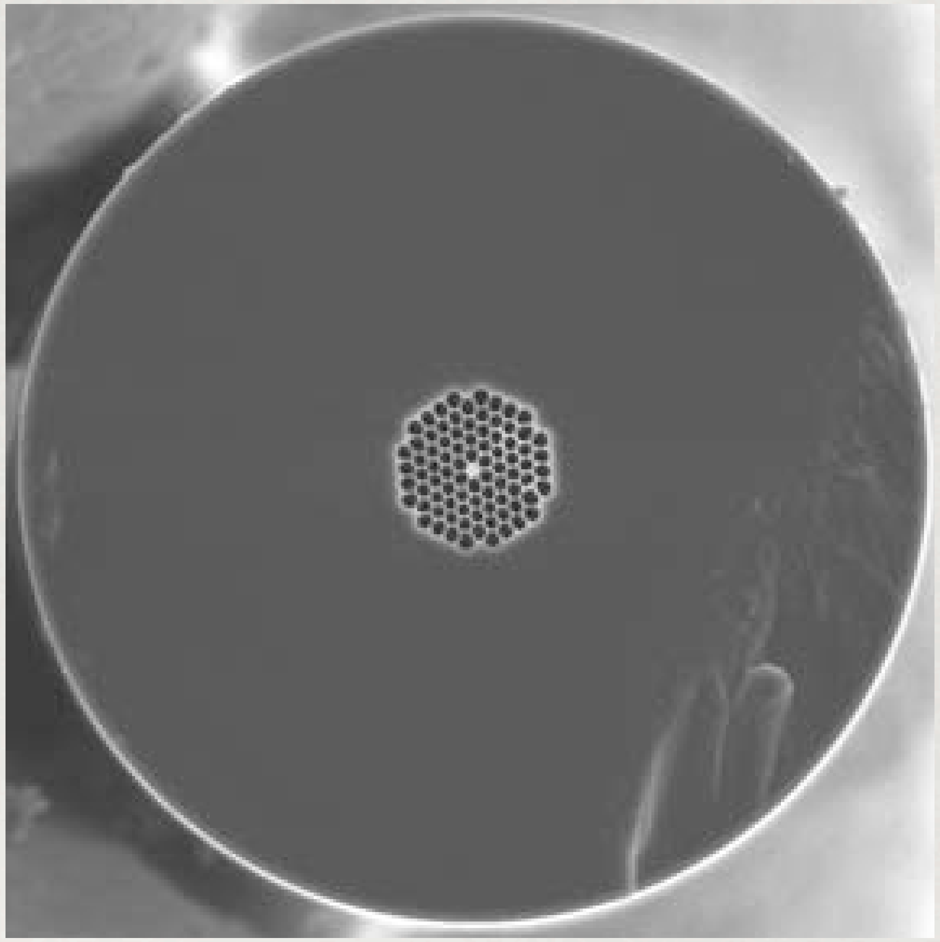
$F_n = n \times F_r + F_o$

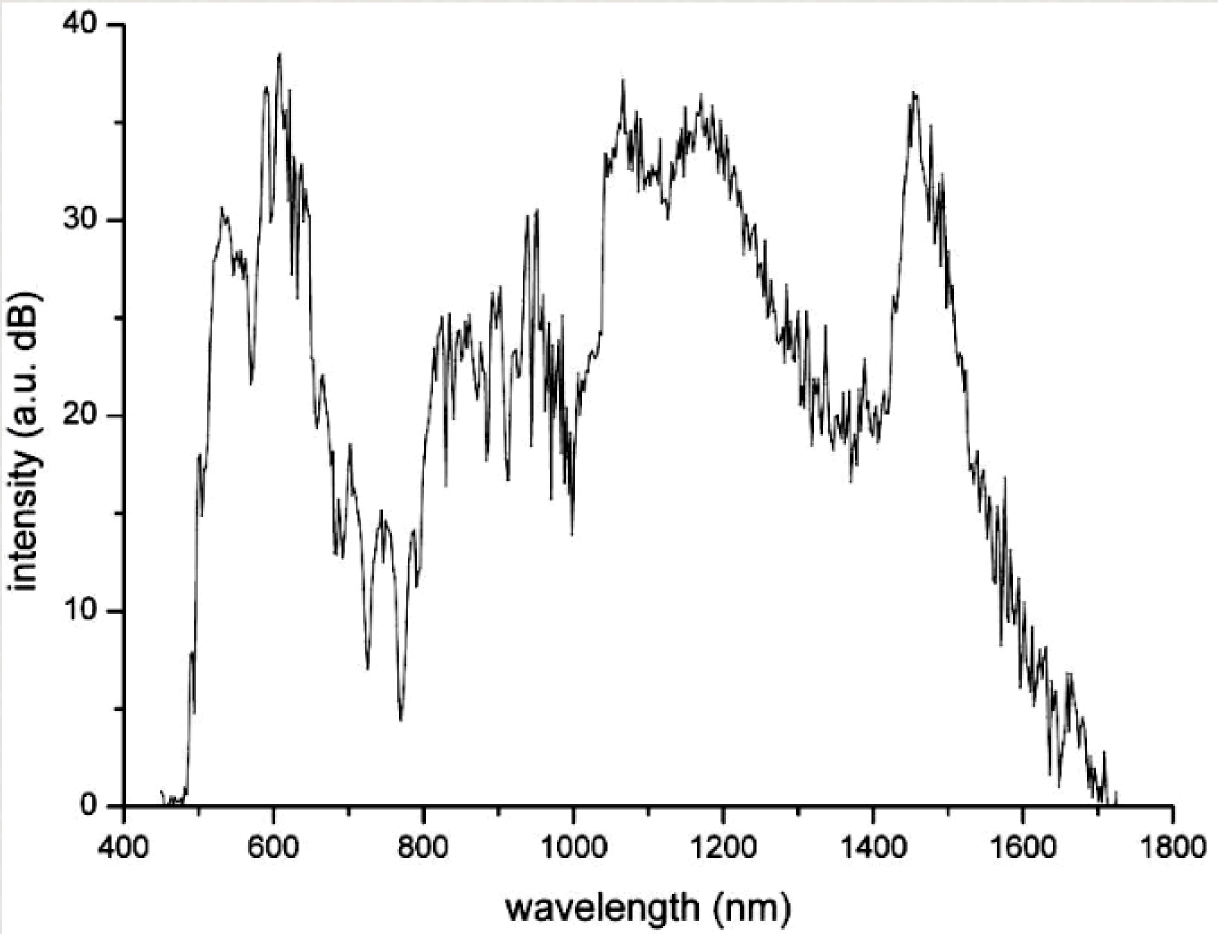
$F_{2n} = 2n \times F_r + F_o$

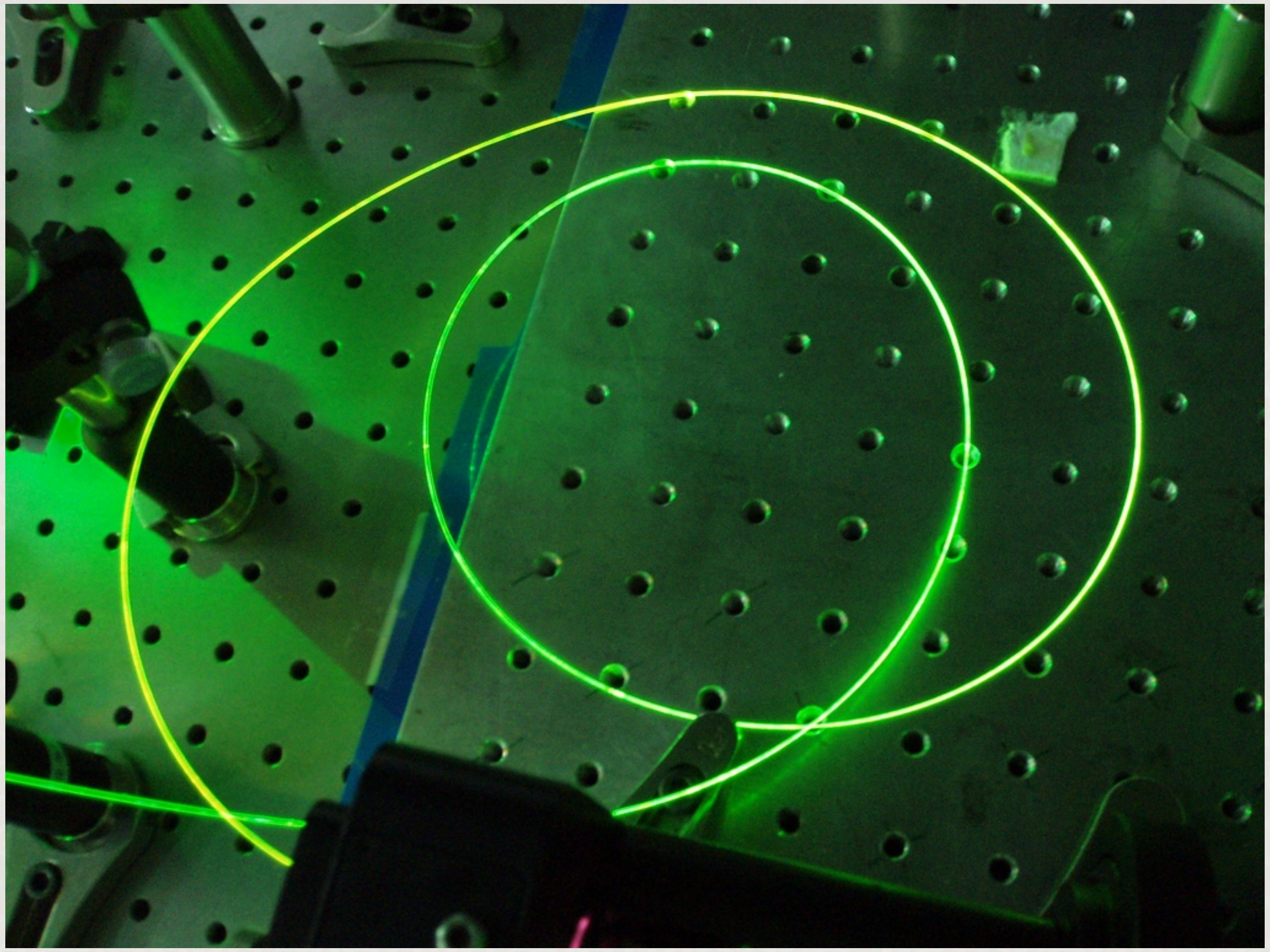
$F_n \times 2 - F_{2n} = 2 \times (n \times F_r + F_o) - (2n \times F_r + F_o) = F_o$

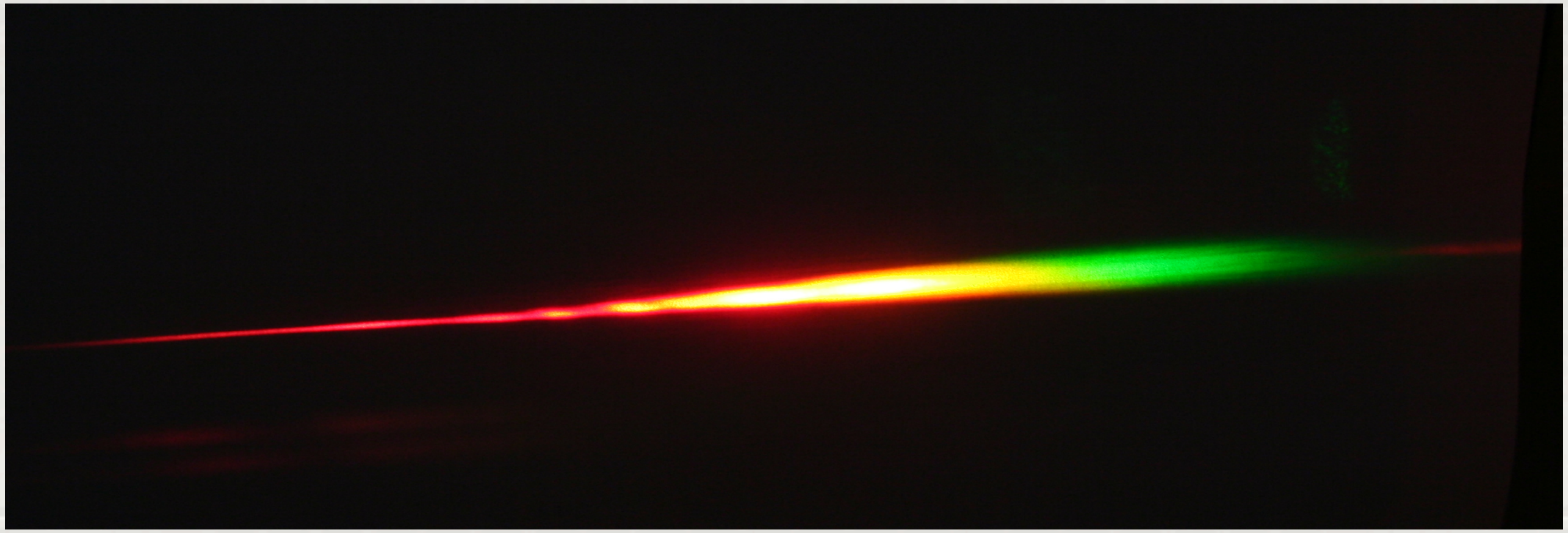
J. Reichert et al., Opt. Comm. 172, 59(1999)

Spectrum Broadening via Microstructure Fiber

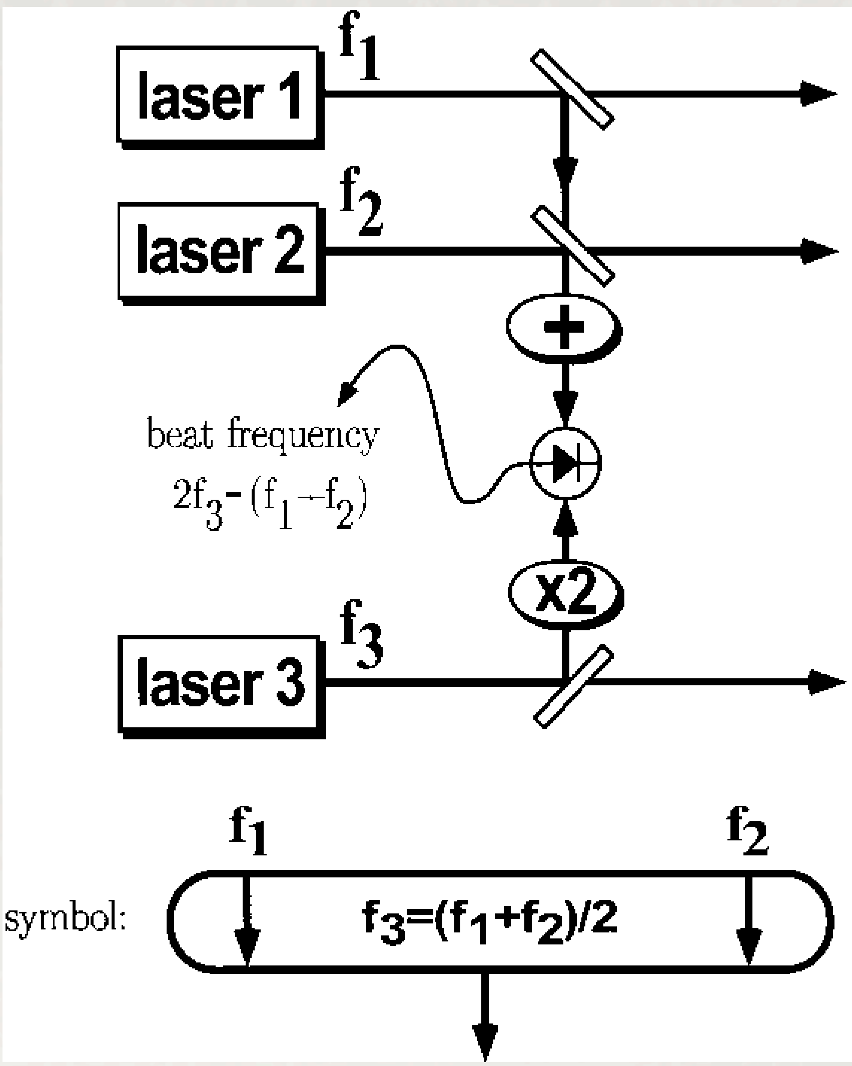


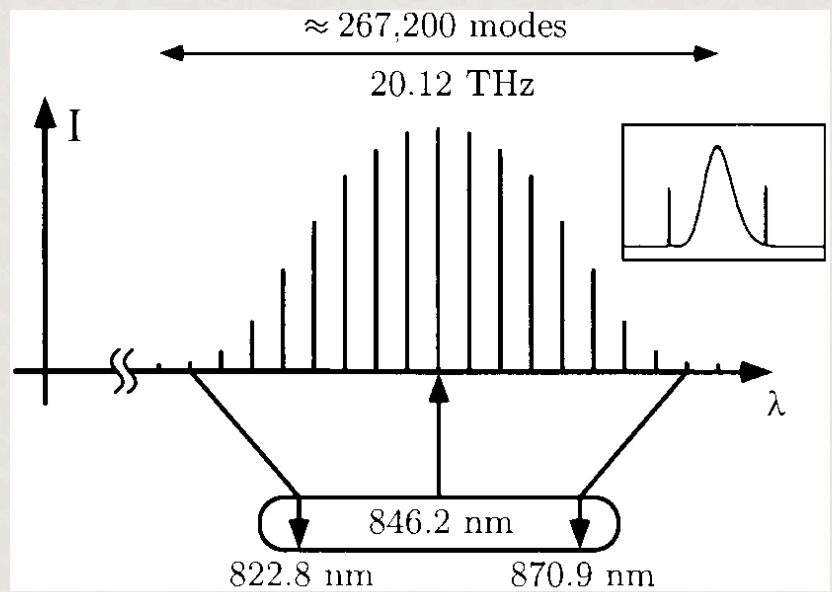


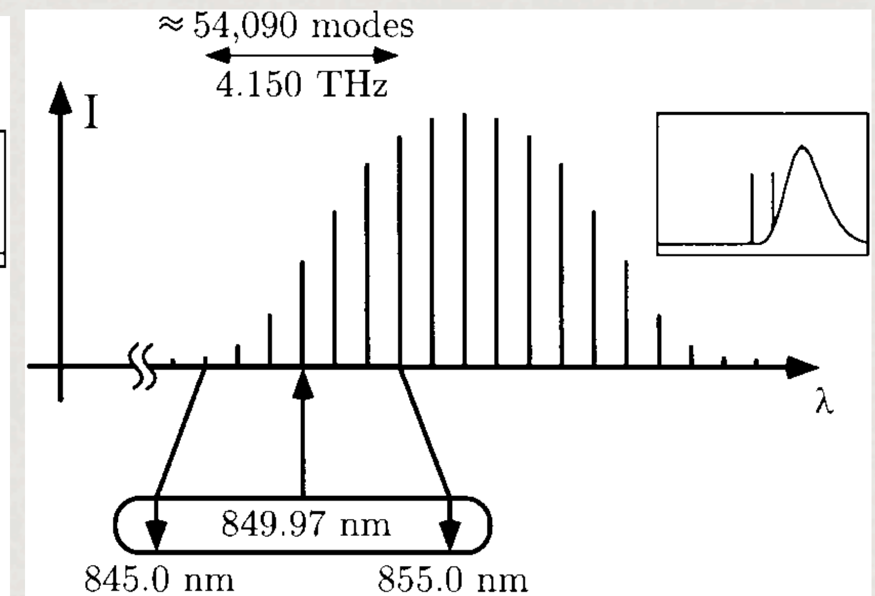




Uniformity of OFC Mode Spacing







Uniformity is within the experimental limit 6×10^{-16}

Th. Udem et al., Opt. Lett. 24, 881(1999)

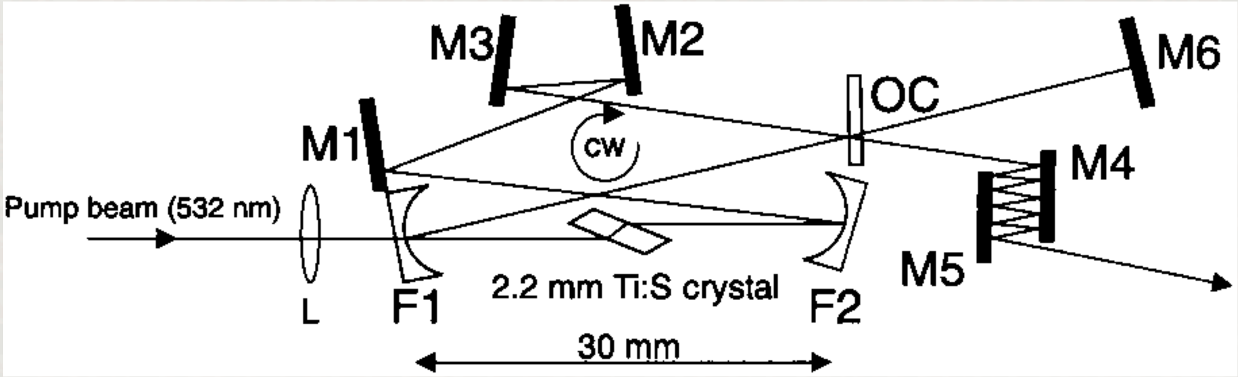
OFC in NTHU

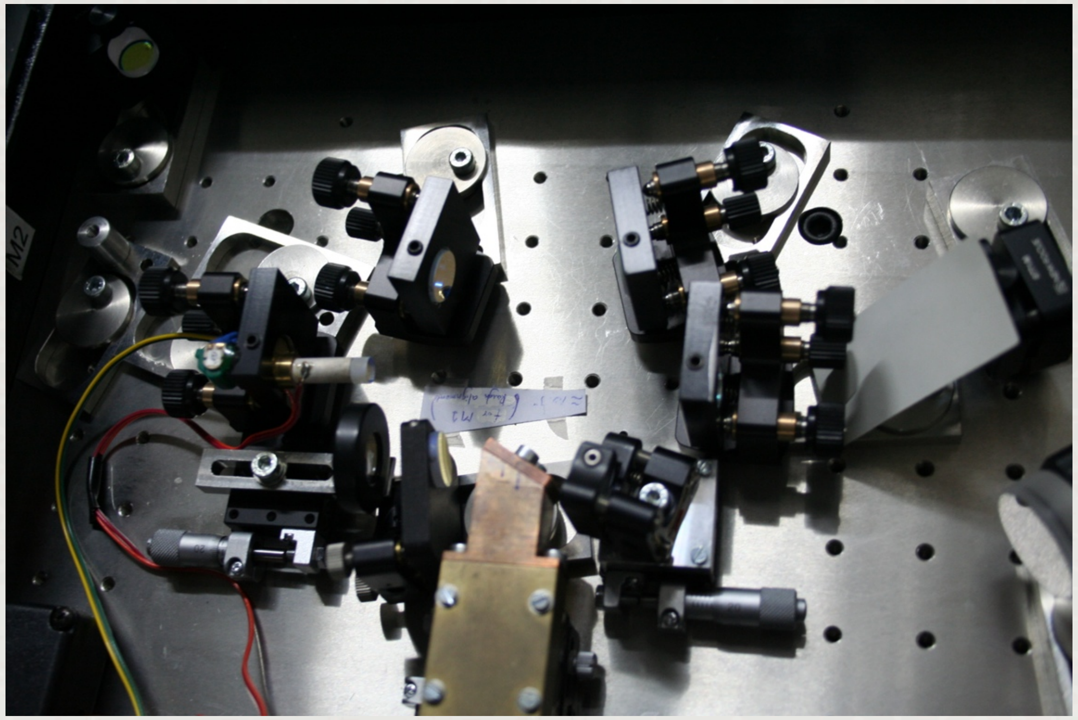
Brief of NTHU OFC

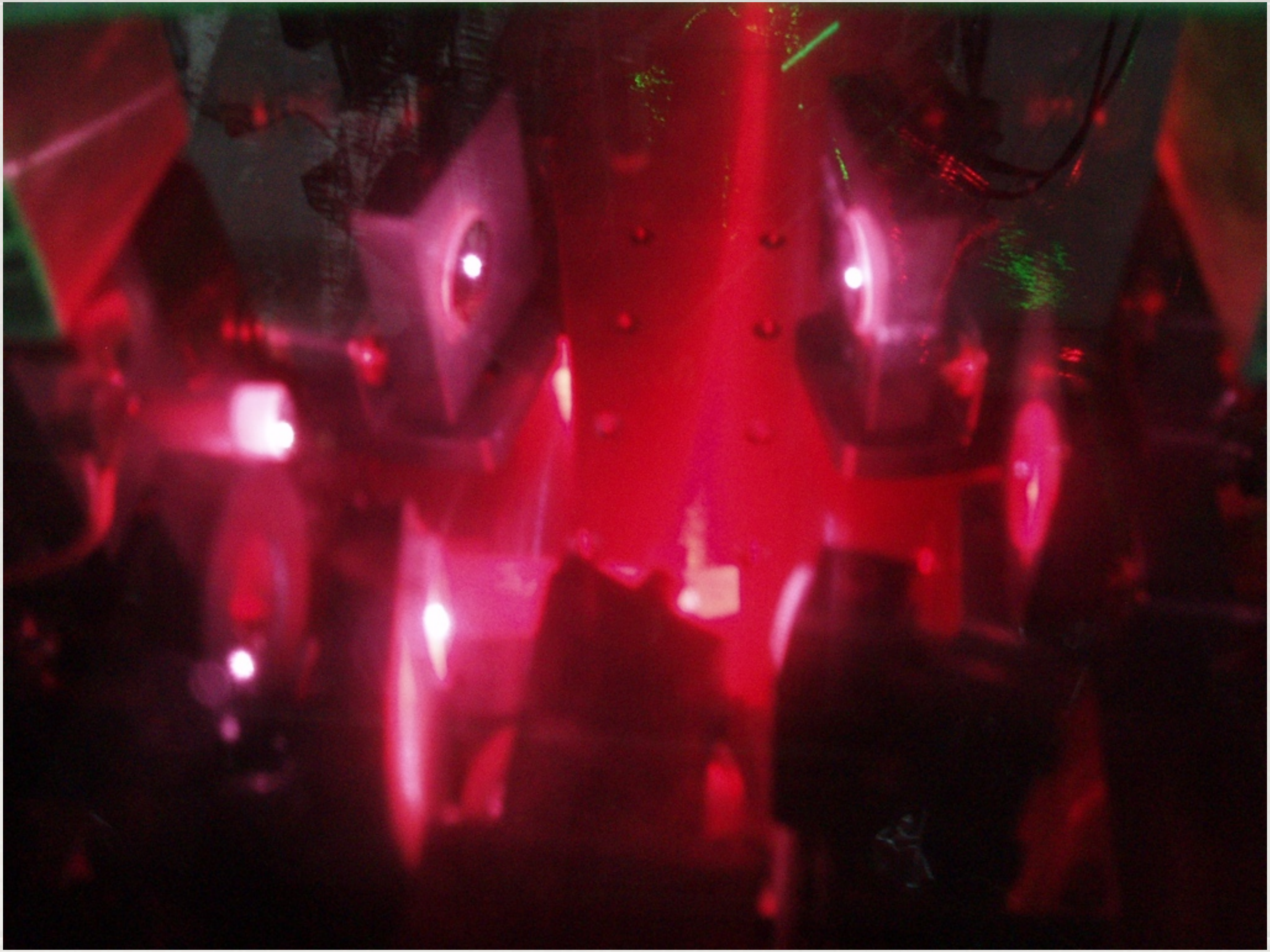
- *Based on 1 GHz repetition frequency Kerr-lens mode-locked Ti:sapphire laser*
- *Spectrum broadened by a polarization maintaining microstructure fiber; coverage: 500-1650 nm*
- *f-2f self-referencing scheme for offset frequency stabilization*

1-GHz KLM Laser

- *Ring cavity, soft aperture*
- *Chirped mirror dispersion compensation*
- *1 GHz repetition frequency*
- *> 730 mW @ 5 W 532 nm pumping, mode-locked operation*

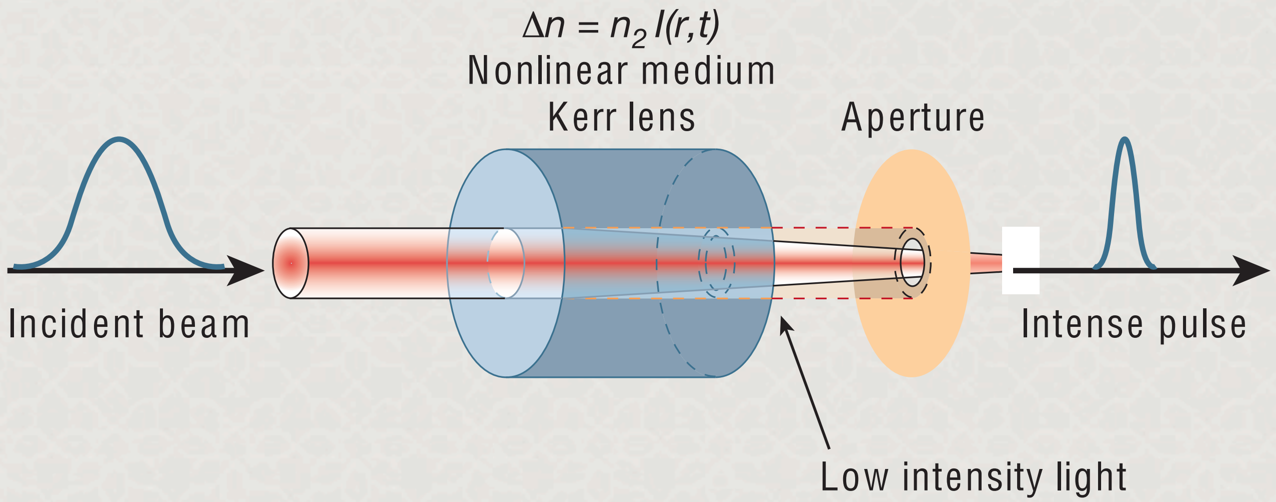


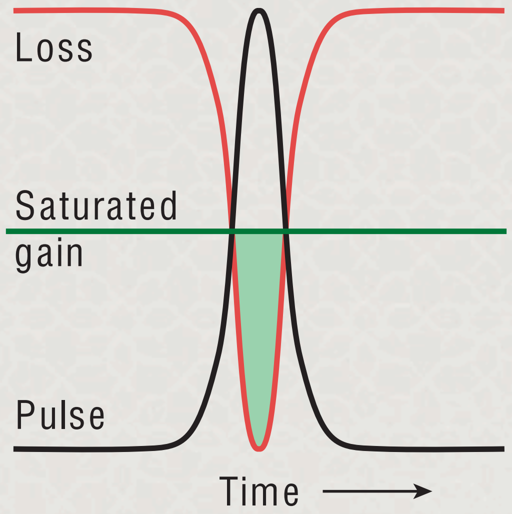


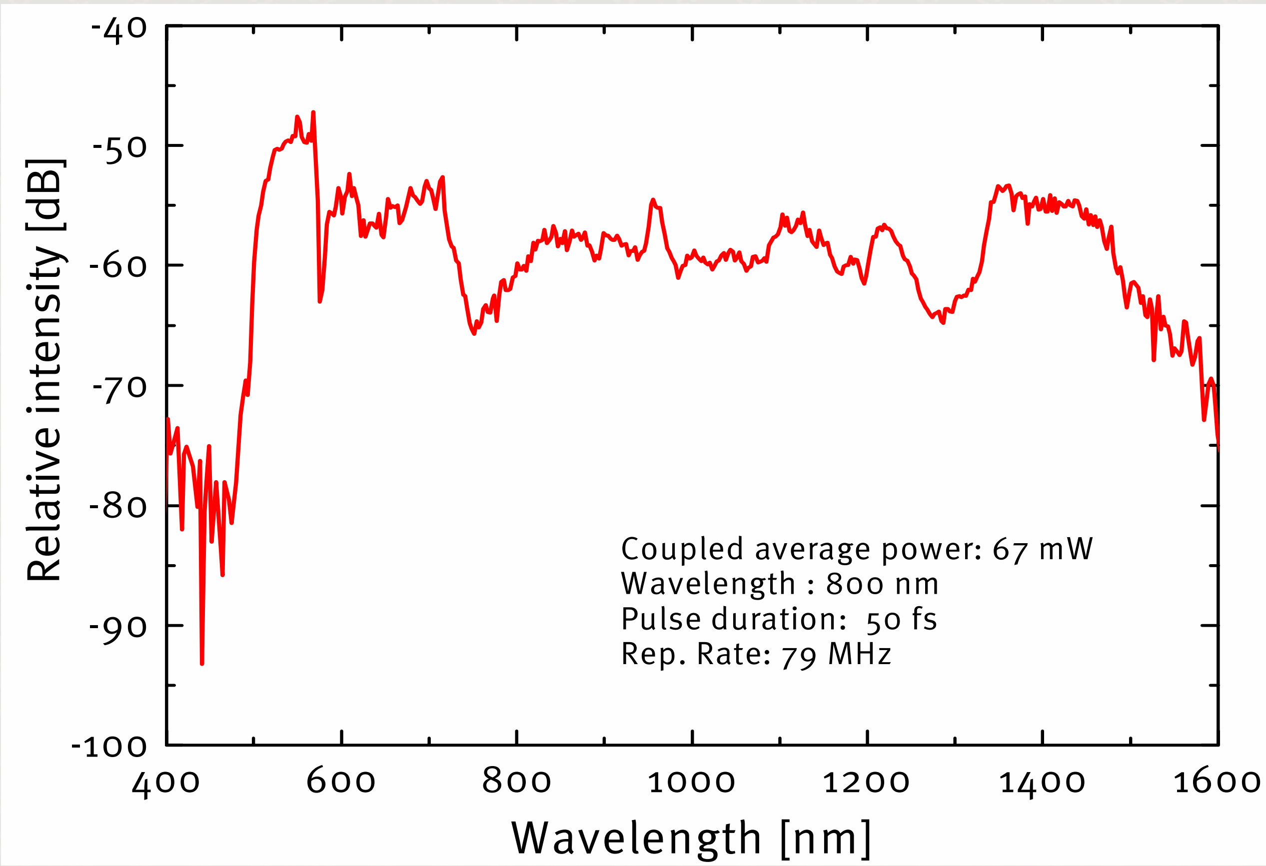


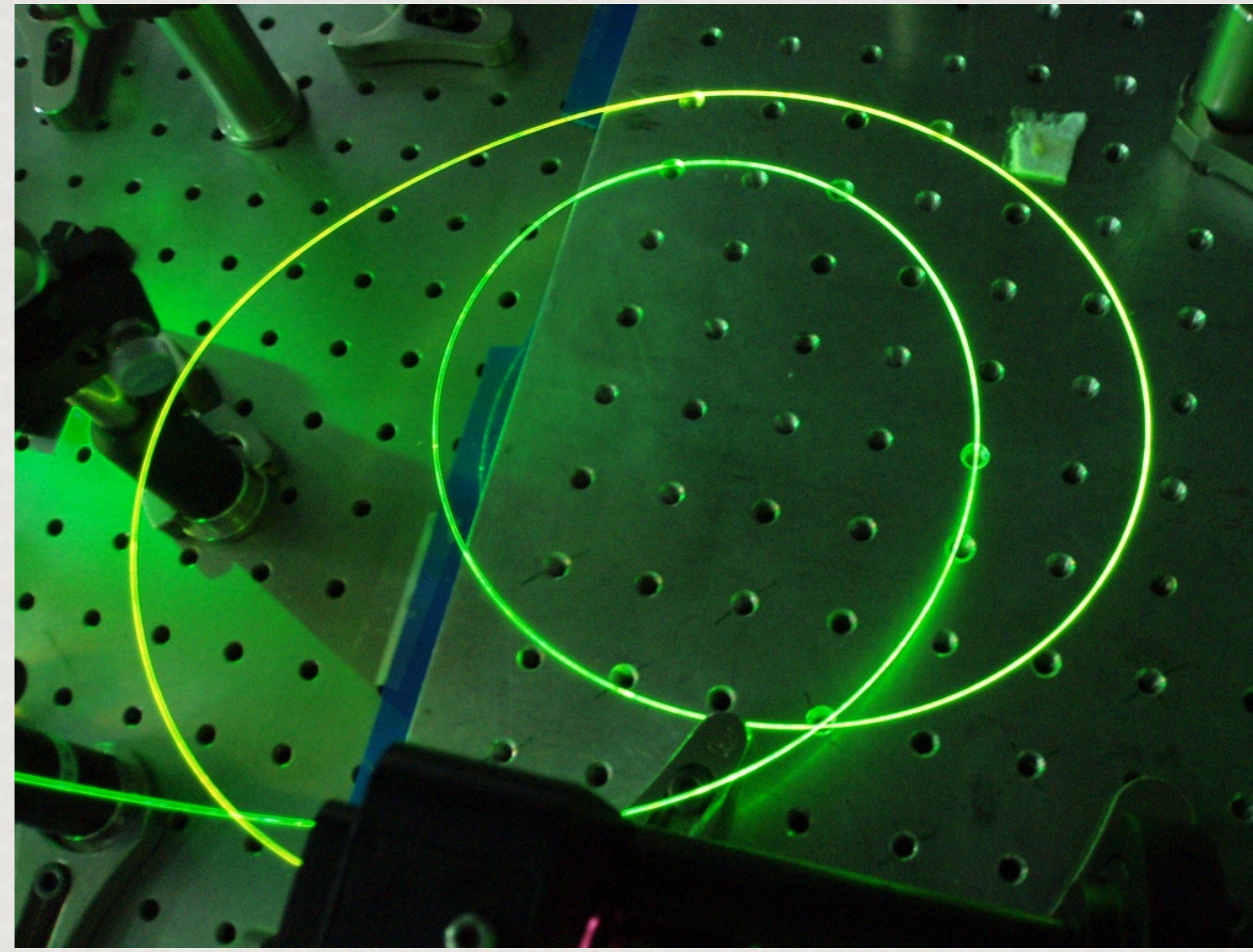
Kerr-lens Mode-locking

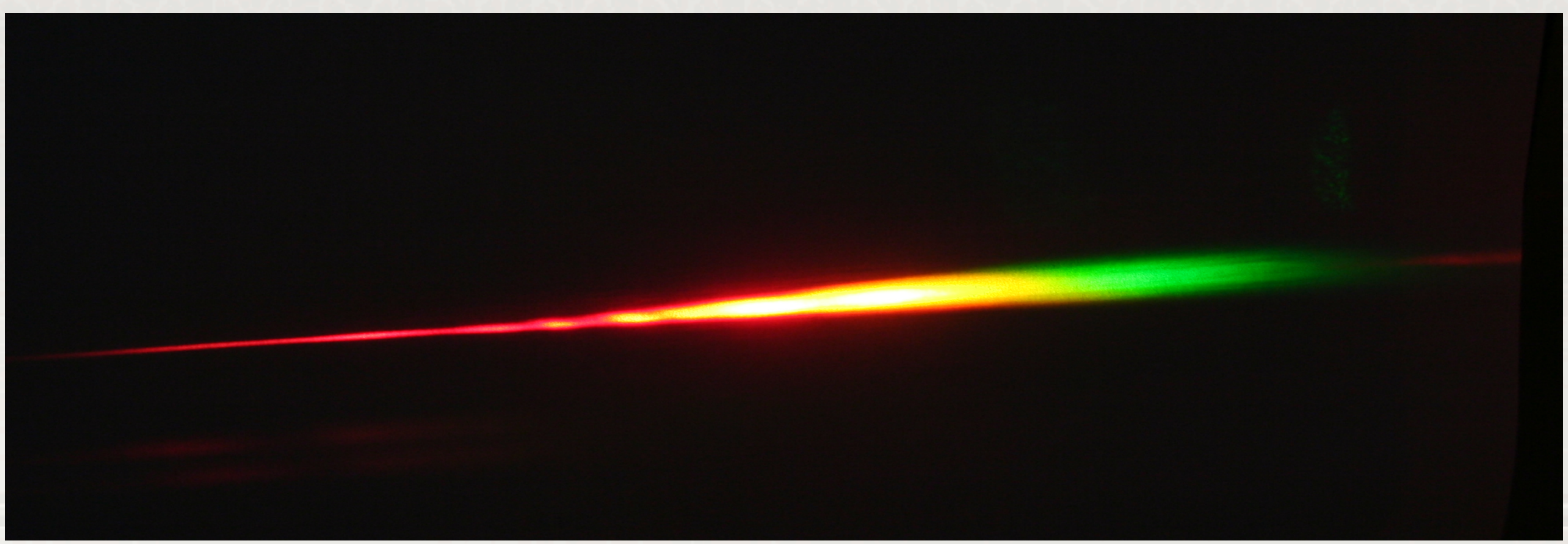
- *No mode-locking → Weak Kerr effect → High cavity loss → Power decrease*
- *Mode-locking → Strong Kerr effect → Low cavity loss → Power increase*
- *Kerr medium: Ti:sapphire laser crystal*
- *Aperture: Pump beam spot*





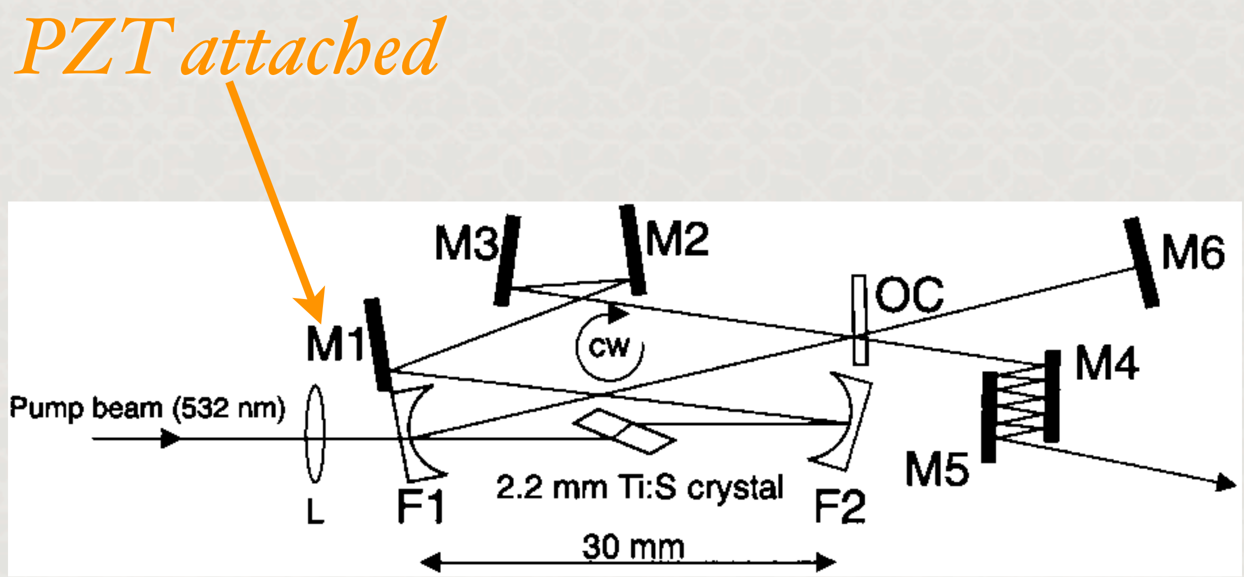

Relative intensity [dB]
-40
-50
-60
-70
-80
-90
-100
400
600
800
1000
1200
1400
1600
Wavelength [nm]
Coupled average power: 67 mW
Wavelength : 800 nm
Pulse duration: 50 fs
Rep. Rate: 79 MHz





Control Repetition Frequency of OFC

- *Detect the repetition frequency by fast silicon PD and lock the frequency to the signal from 1-GHz RF synthesizer by analog phase-locked loop*
- *PZT controls cavity length*



Control Offset Frequency of OFC

- *Detect the offset frequency via f-2f self-referencing scheme and lock the frequency to the frequency form low frequency synthesizer by digital phase-locked loop*
- *AOM controls pumping power*

Pump Power Controlled by AOM

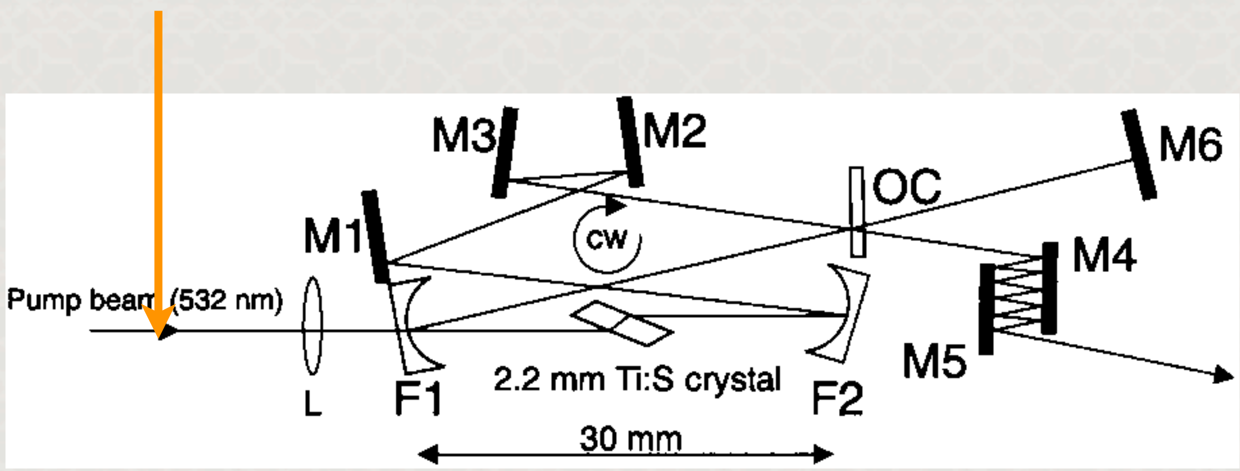
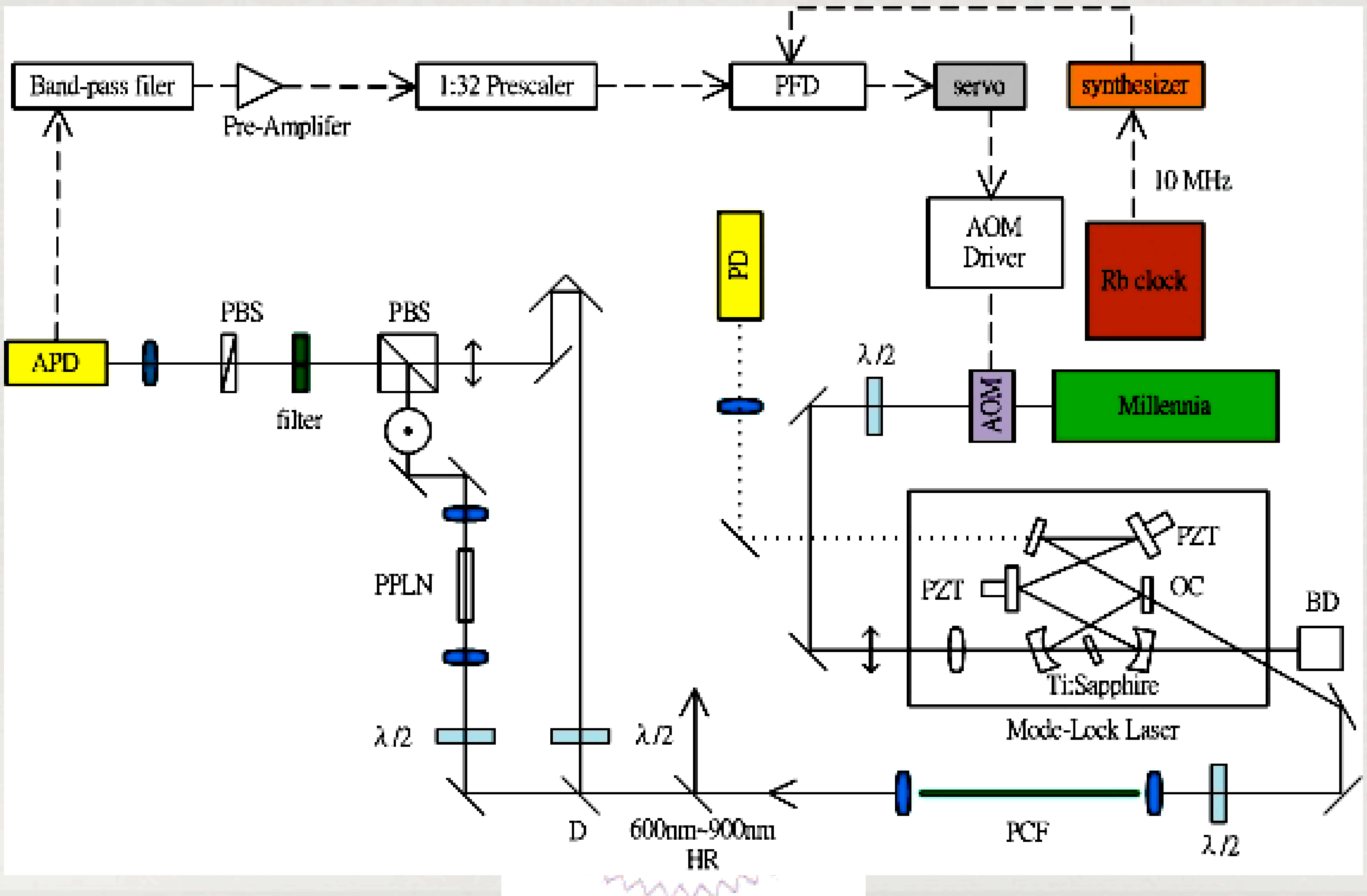


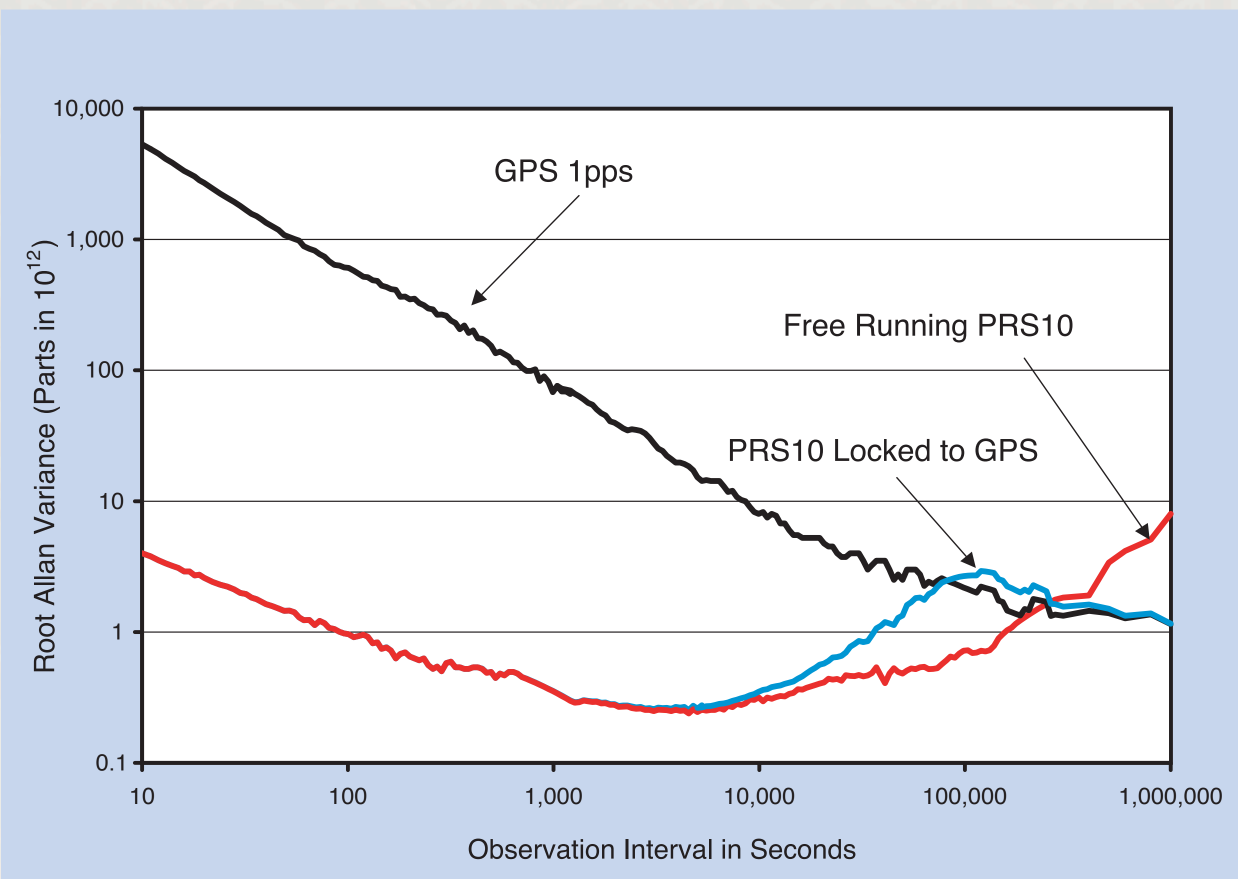
Diagram of NTHU OFC

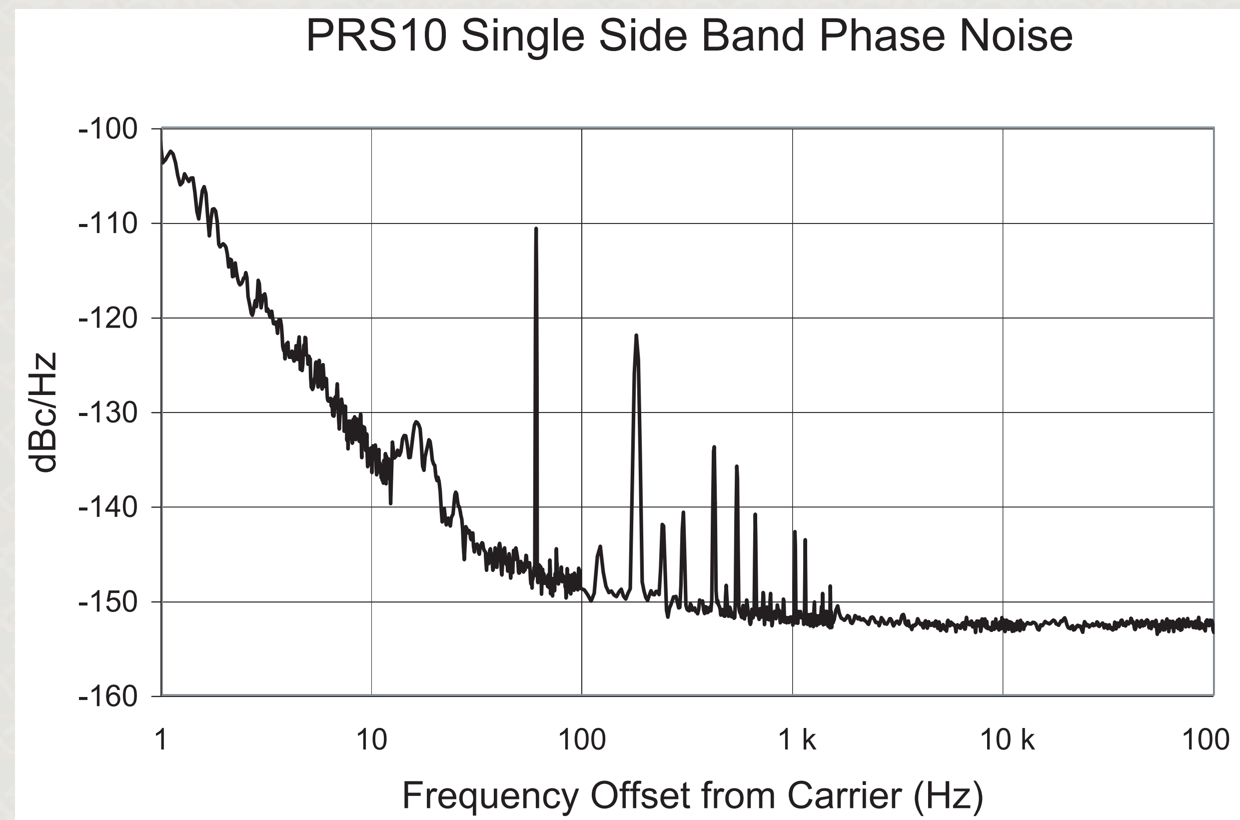


High Precision Local Oscillator

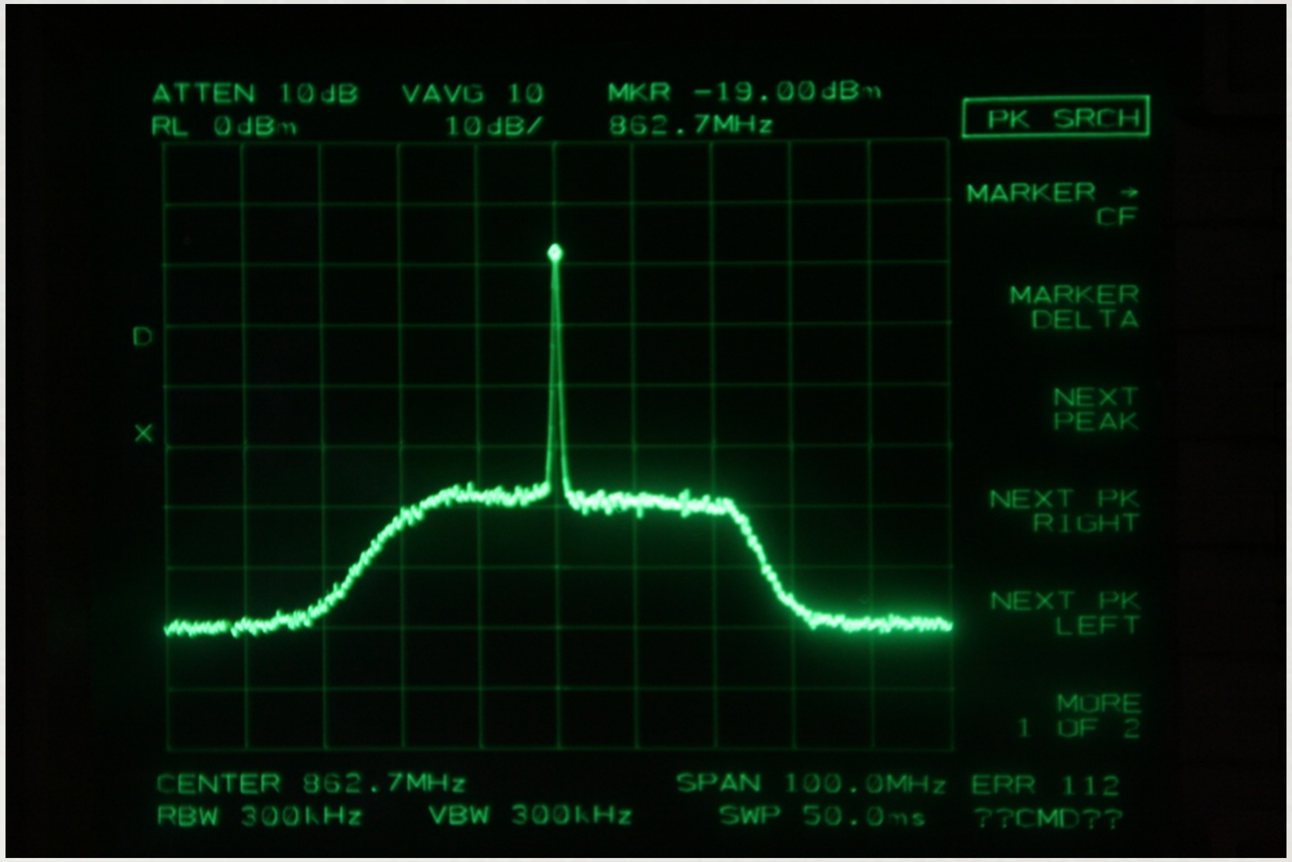
- *GPS Disciplined Rb Frequency Standard*
- *Allan variance: 2×10^{-12}@1000 s*

Performance of GPS Disciplined Rb Frequency Standard

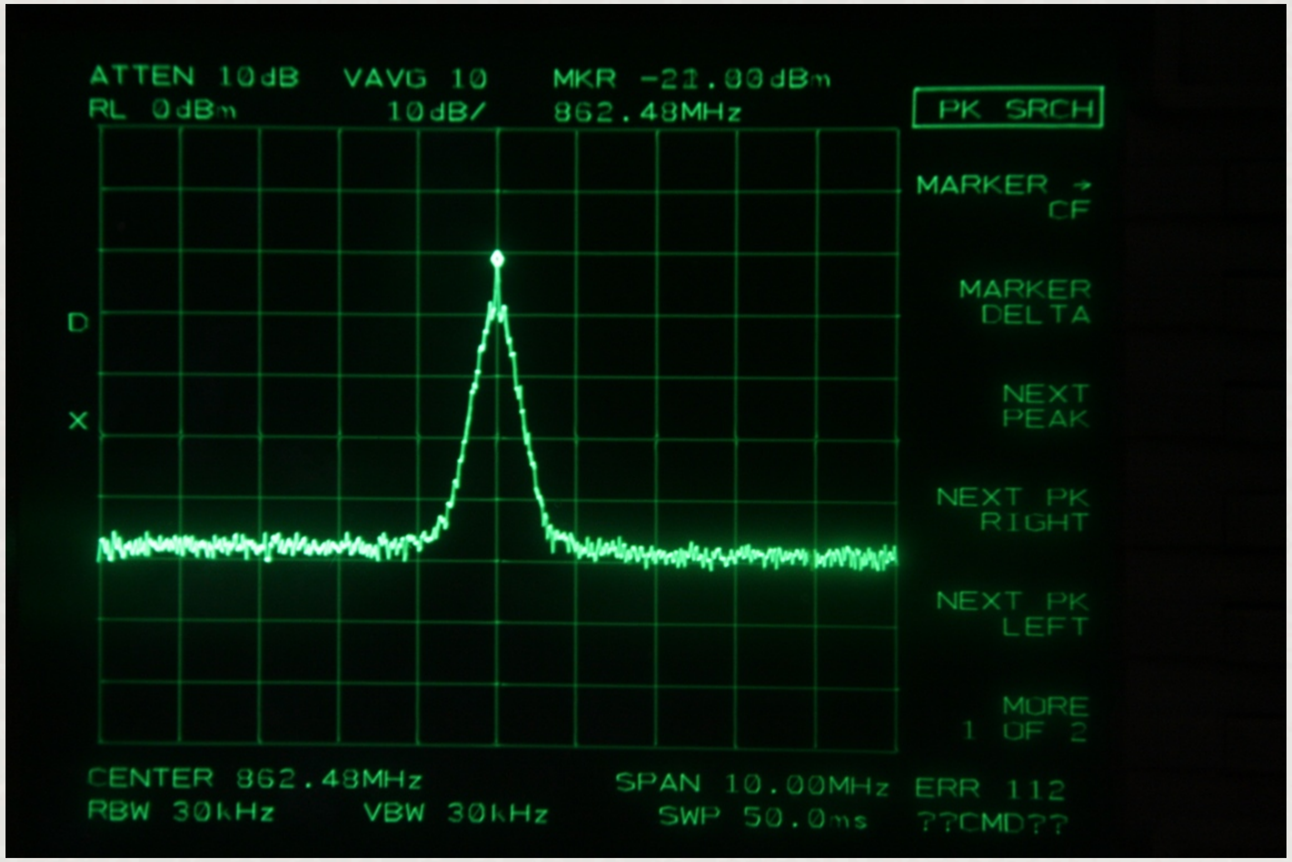




Signal of Offset frequency



Span: 100 MHz



Span: 10 MHz

CO_2 Transitions Absolute Frequency Measurement

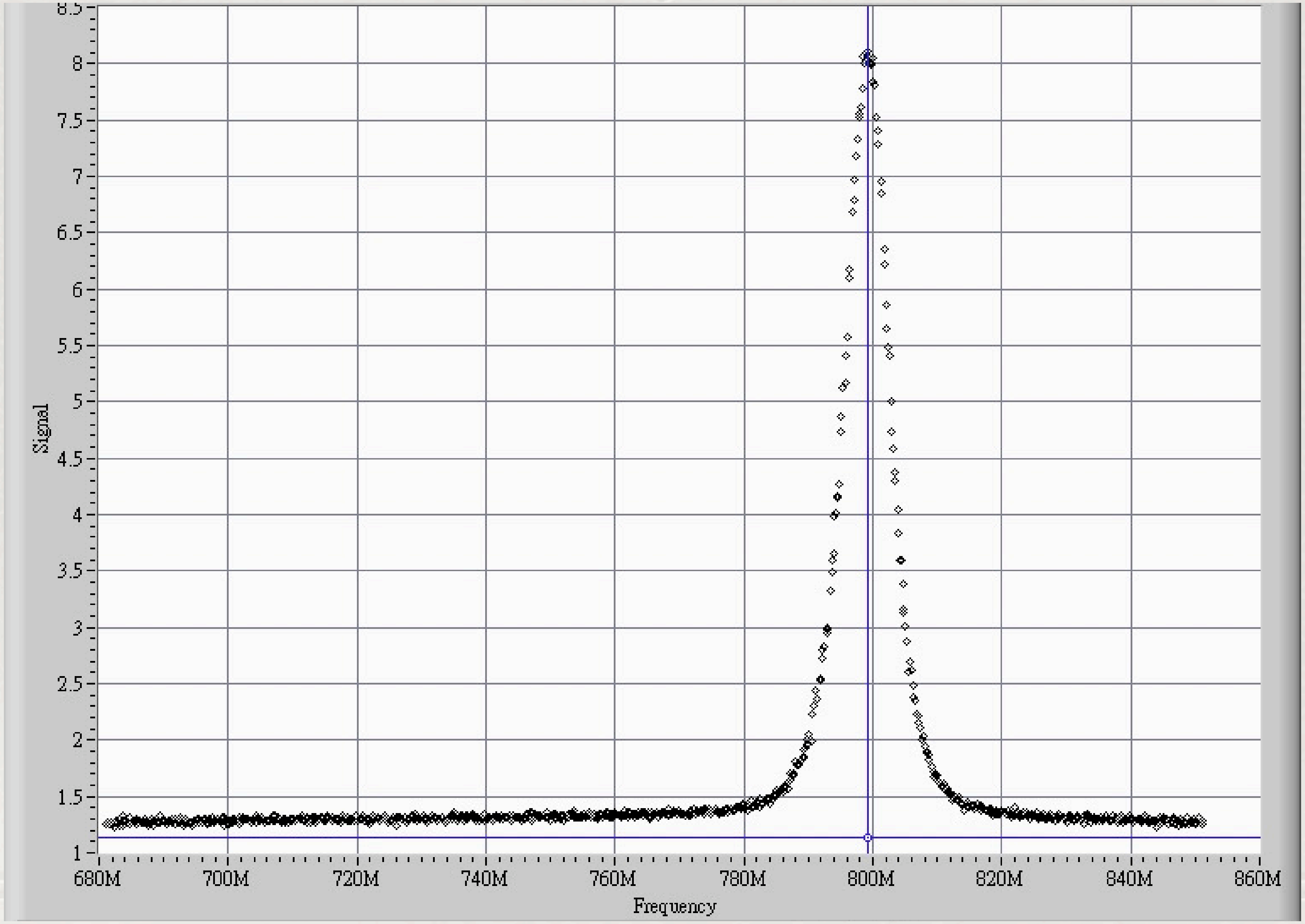
Table 4.4: Measured P-branch lines on $(00^01\text{-}00^00)$ band

P branch line	Gas pressure (mTorr)	Present result (kHz)	HITRAN04 (MHz)	difference (kHz)
$P(56)$	40	68 834 038 921(15)	68 834 039(3)	-775
$P(54)$	40	68 900 642 151(11)	68 900 642(3)	-667
$P(52)$	40	68 966 529 482(10)	68 966 530(3)	-463
$P(50)$	30	69 031 700 054(9)	69 031 700(3)	-184
$P(48)$	30	69 096 152 910(9)	69 096 153(3)	81
$P(46)$	30	69 159 887 185(9)	69 159 887(3)	338
$P(44)$	30	69 222 902 134(9)	69 222 901(3)	652
$P(42)$	30	69 285 196 804(10)	69 285 196(3)	937
$P(38)$	30	69 407 621 923(9)	69 407 620(3)	1459
$P(36)$	2	69 467 750 707(9)	69 467 749(3)	1709
$P(34)$	2	69 527 155 865(11)	69 527 154(3)	1972
$P(30)$	2	69 643 791 832(10)	69 643 789(3)	2334
$P(28)$	2	69 701 020 989(10)	69 701 019(3)	2490
$P(26)$	2	69 757 523 218(12)	69 757 521(3)	2655
$P(22)$	2	69 868 343 412(10)	69 868 341(3)	2828
$P(20)$	2	69 922 659 782(9)	69 922 657(3)	3130
$P(18)$	2	69 976 245 898(12)	69 976 243(3)	2963
$P(16)$	2	70 029 101 083(14)	70 029 098(3)	3089
$P(14)$	2	70 081 224 268(12)	70 081 221(3)	3068
$P(12)$	2	70 132 614 878(10)	70 132 612(3)	3075
$P(10)$	2	70 183 272 067(10)	70 183 269(3)	3103
$P(8)$	2	70 233 195 001(10)	70 233 192(3)	3098
$P(4)$	2	70 330 835 136(10)	70 330 832(3)	3108
$P(2)$	30	70 378 550 790(10)	70 378 548(3)	3135

Table 4.5: Measured R-branch lines on $00^01 \leftarrow 00^00$ band

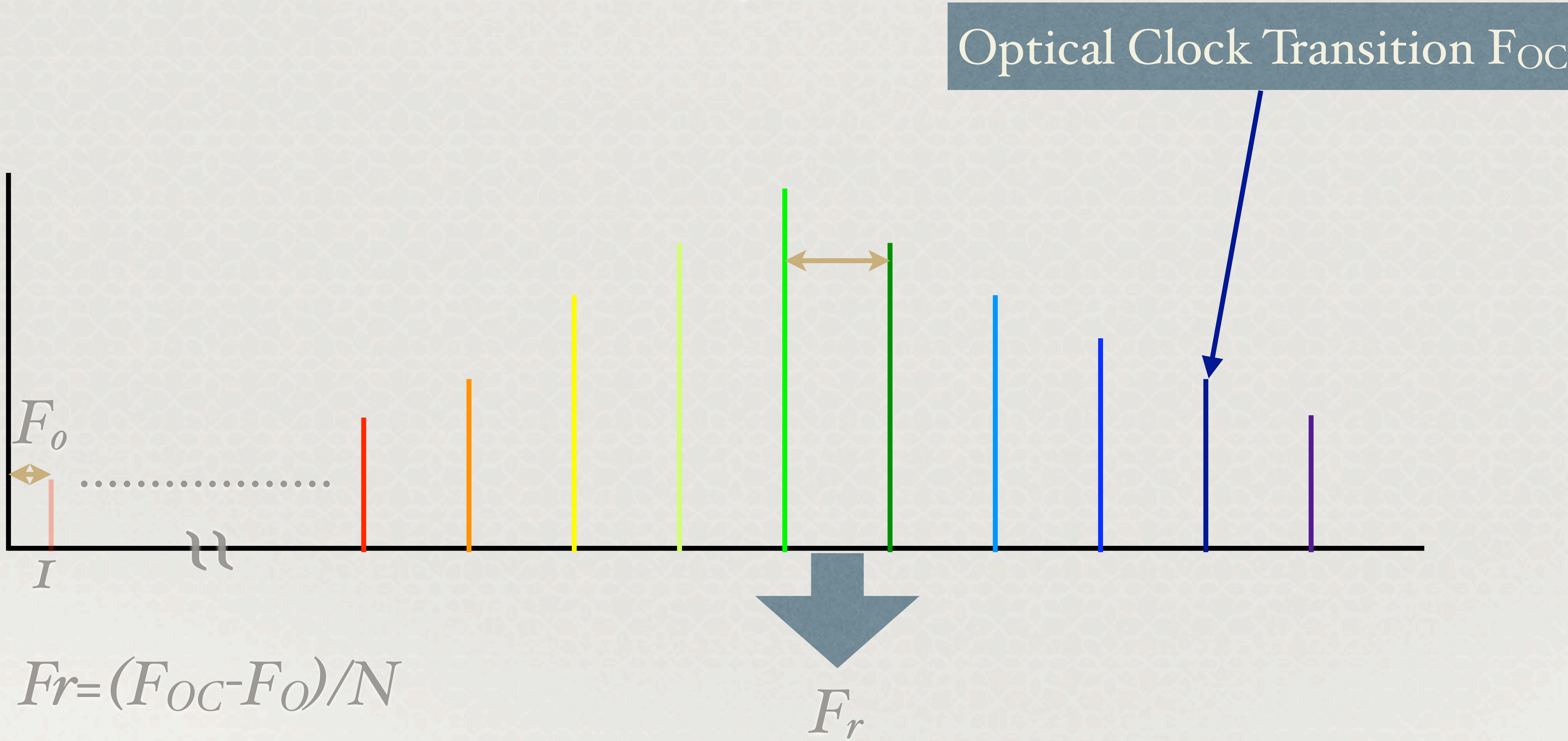
R branch line	Gas pressure (mTorr)	Present result (kHz)	HITRAN04 (MHz)	difference (kHz)
$R(62)$	40	71 523 708 501(11)	71 523 709(3)	-386
$R(60)$	40	71 500 327 965(15)	71 498 830(3)	-620
$R(58)$	40	71 476 187 894(11)	71 476 189(3)	-710
$R(56)$	40	71 451 288 976(10)	71 451 290(3)	-695
$R(54)$	40	71 425 631 898(11)	71 425 632(3)	-516
$R(52)$	40	71 399 217 159(10)	71 399 217(3)	-331
$R(50)$	20	71 372 045 466(11)	71 372 046(3)	-125
$R(48)$	20	71 344 117 501(10)	71 344 117(3)	126
$R(46)$	20	71 315 433 898(9)	71 315 434(3)	365
$R(44)$	20	71 285 995 348(10)	71 285 995(3)	655
$R(42)$	20	71 255 802 495(10)	71 255 802(3)	920
$R(40)$	20	71 224 856 328(8)	71 224 855(3)	1489
$R(38)$	20	71 193 156 751(9)	71 193 155(3)	1577
$R(36)$	2	71 160 704 945(10)	71 160 703(3)	1705
$R(34)$	2	71 127 501 715(12)	71 127 500(3)	1928
$R(32)$	2	71 093 547 578(17)	71 093 545(3)	2135
$R(30)$	2	71 058 843 255(10)	71 058 841(3)	2327
$R(28)$	2	71 023 389 424(10)	71 023 387(3)	2462
$R(26)$	2	70 987 186 808(9)	70 987 184(3)	2603
$R(24)$	2	70 950 236 211(9)	70 950 233(3)	2776
$R(22)$	2	70 912 538 109(9)	70 912 535(3)	2826
$R(20)$	2	70 874 093 451(11)	70 874 091(3)	2953
$R(18)$	2	70 834 903 061(8)	70 834 900(3)	3262
$R(16)$	2	70 794 966 952(8)	70 794 964(3)	3016
$R(14)$	2	70 754 286 639(8)	70 754 284(3)	3040
$R(12)$	2	70 712 862 655(9)	70 712 860(3)	3119
$R(10)$	2	70 670 695 563(9)	70 670 692(3)	3095
$R(8)$	2	70 627 786 288(10)	70 627 783(3)	3145
$R(6)$	2	70 584 135 435(12)	70 584 132(3)	3093
$R(4)$	2	70 539 743 863(9)	70 539 741(3)	3109
$R(2)$	2	70 494 612 370(8)	70 494 609(3)	3212
$R(0)$	20	70 448 741 463(8)	70 448 738(3)	3130

^{6,7}Li 2S-3S Two-photon Transitions



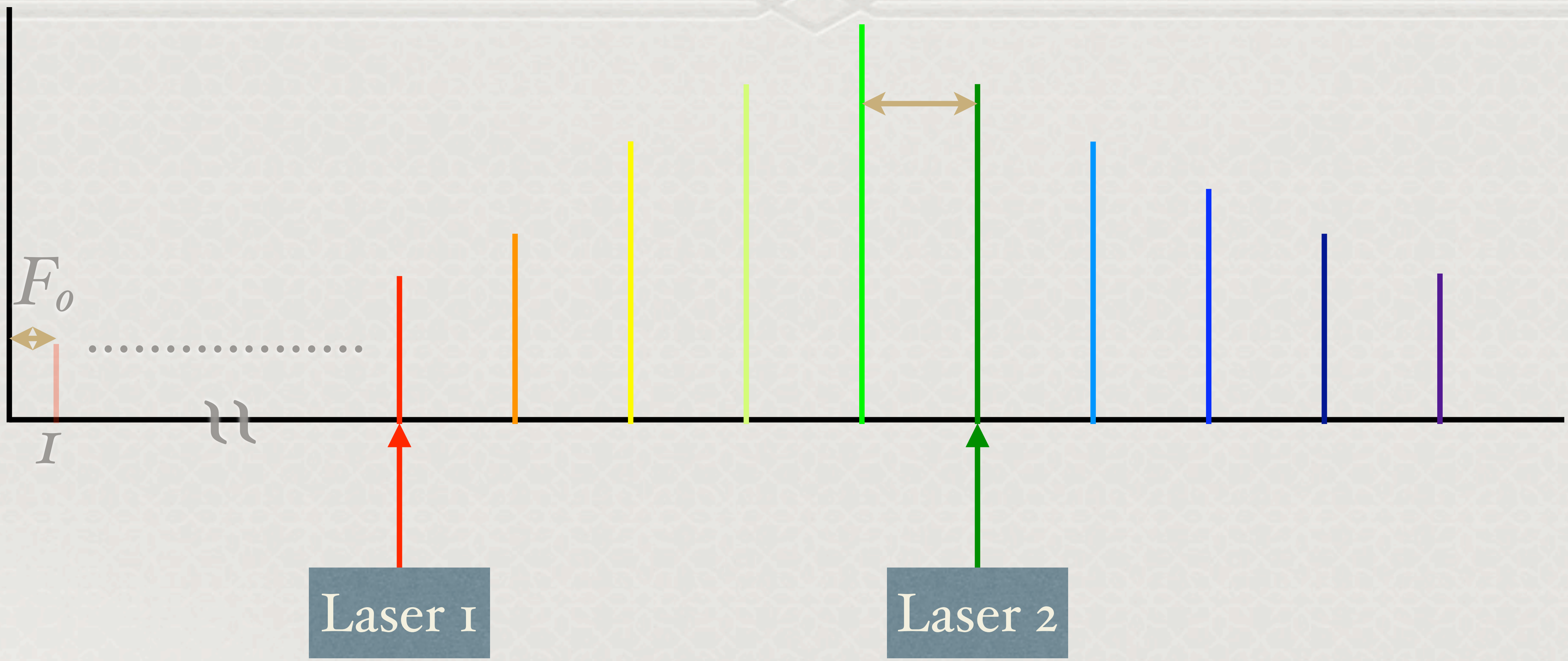
What can OFC do for us?

Optical Clock



$Fr = (F_{OC} - F_O)/N$

Coherence Link between Far Separated Lasers



Potential Applications: EIT, CARS, DFG, OPO

Direct Frequency Comb Spectroscopy (DFCS)

- *Direct absorption spectroscopy*
- *Cavity enhanced spectroscopy*
- *Cavity ringdown spectroscopy*
- *Two-photon spectroscopy*

References

- *Laser Physics at the Limits, Ed. by H. Figger, D. Meschede, and C. Zimmermann, Springer 2002*
- *Femtosecond Optical Frequency Comb: Principle, Operation and Applications, Ed. by J. Ye and S. T. Cundiff, Springer 2004*