Development of a Prototype Atomic Clock Based on Coherent Population Trapping

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Senior Research Final Talk

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Acknowledgements

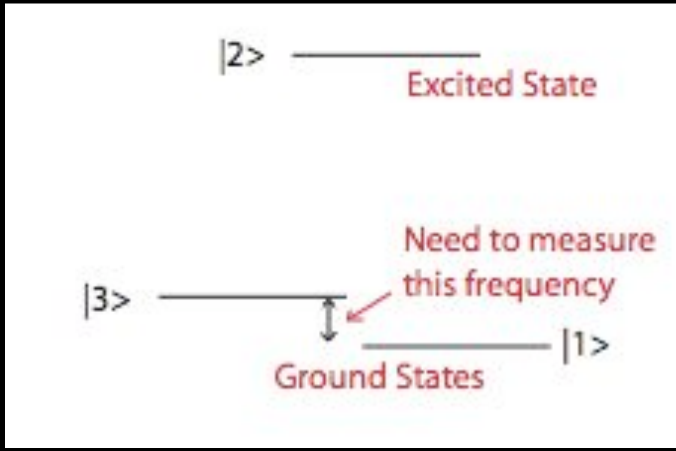
- Prof. Irina Novikova
- Prof. Eugeniy Mikhailov
- Chris Carlin

Outline

- Clocks
- Experimental Setup
- Coherent Population Trapping (CPT)
- Clock Experiment
- Further CPT Studies

What is a second?

- *the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium-133 atom.*

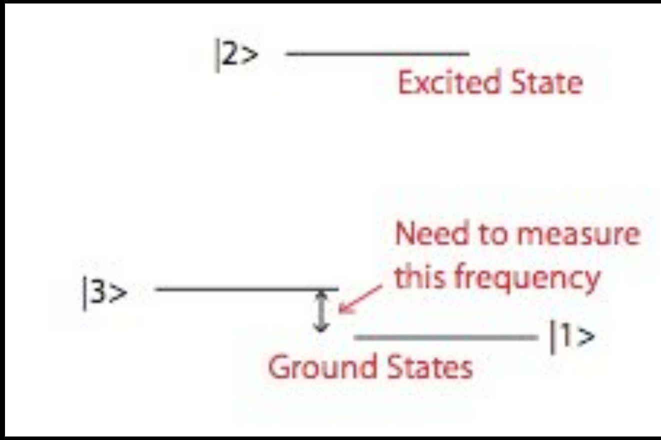


How is a clock made?

- Oscillator provides continuous and stable reference frequency
- Periods of oscillation are counted

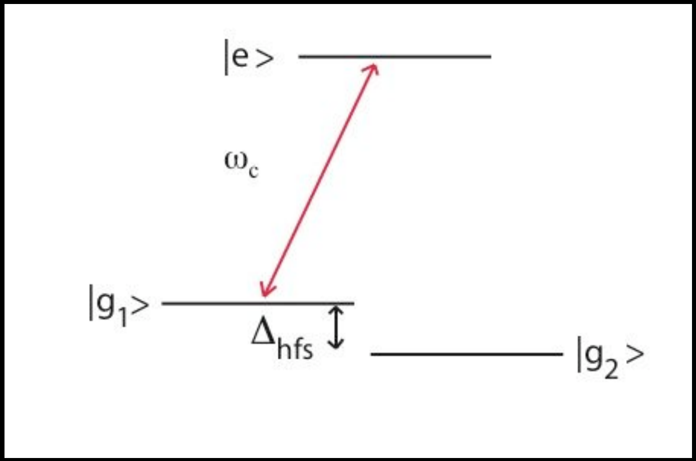
How are atomic clocks made?

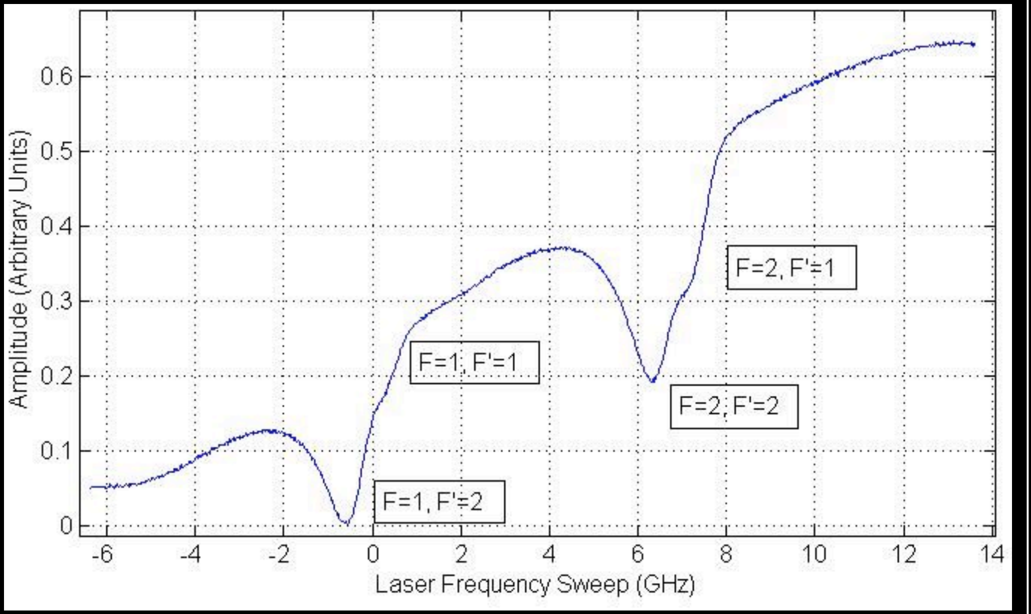
- Use atomic resonance as oscillator
- Counter fed by oscillator
- Have feedback loop to keep counter on atomic resonance



Review of Light Interaction

- When frequency near optical resonance, light gets absorbed



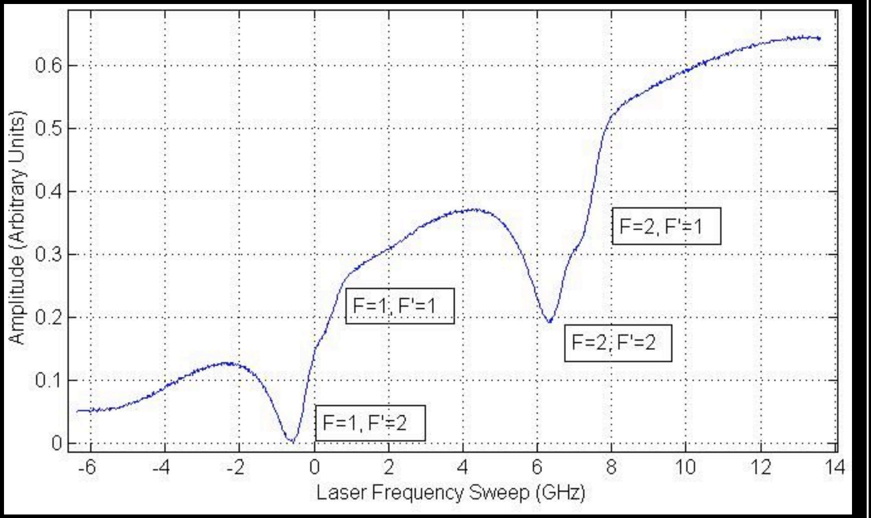


Review continued

$$\hat{H}_0 = \hbar\omega_e |e\rangle\langle e| + \hbar\omega_g |g\rangle\langle g|$$
$$\hat{H}_{int} = \wp_{eg}(E|e\rangle\langle g| + E^*|g\rangle\langle e|)$$

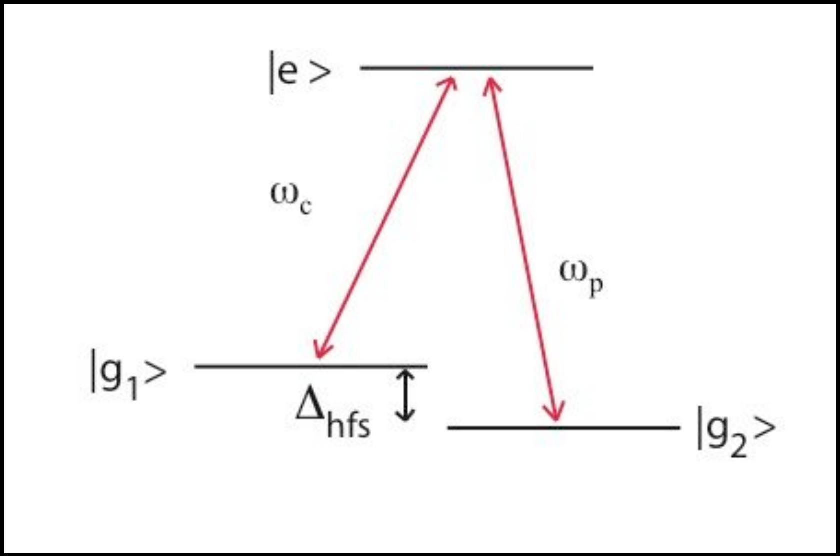
$$\langle g| - e\cdot x|e\rangle = \langle e| - e\cdot x|g\rangle = \wp_{eg}$$
$$\langle g| - e\cdot x|g\rangle = \langle e| - e\cdot x|e\rangle = 0$$

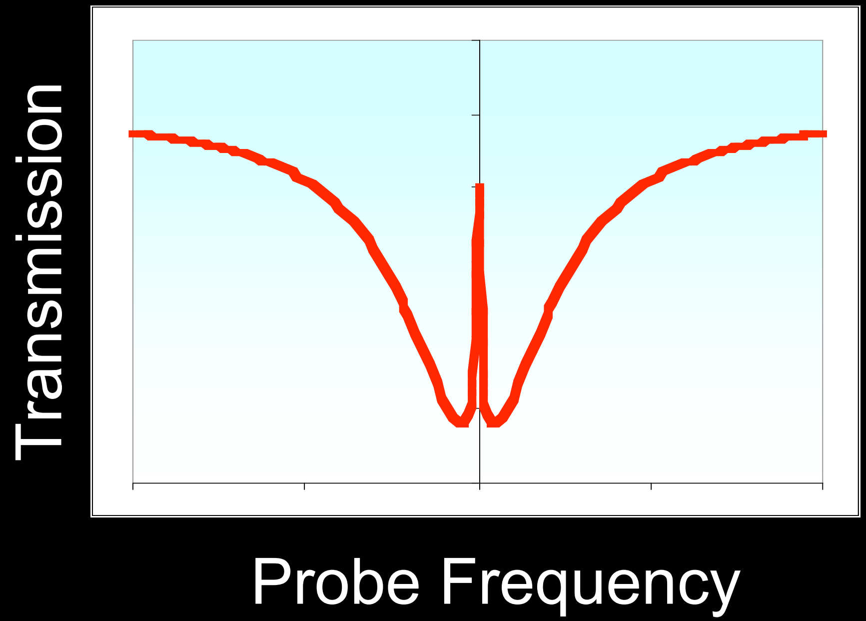
$$\chi(\Delta) = i\frac{N\wp_{eg}^2}{\varepsilon_0\hbar}\frac{\Gamma - 2i\Delta}{\Gamma^2 + 4\Delta^2 + |\Omega|^2}$$



Review continued

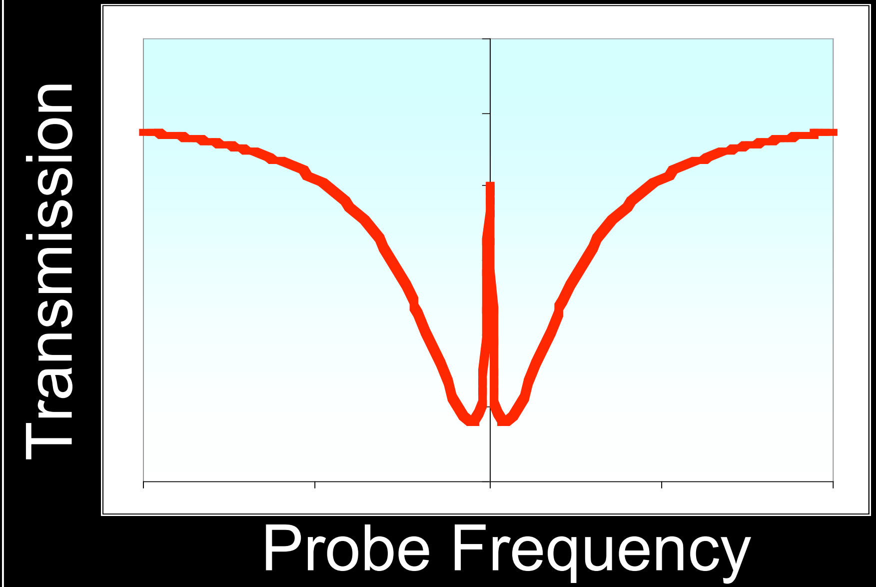
- 3-level absorption and transmission

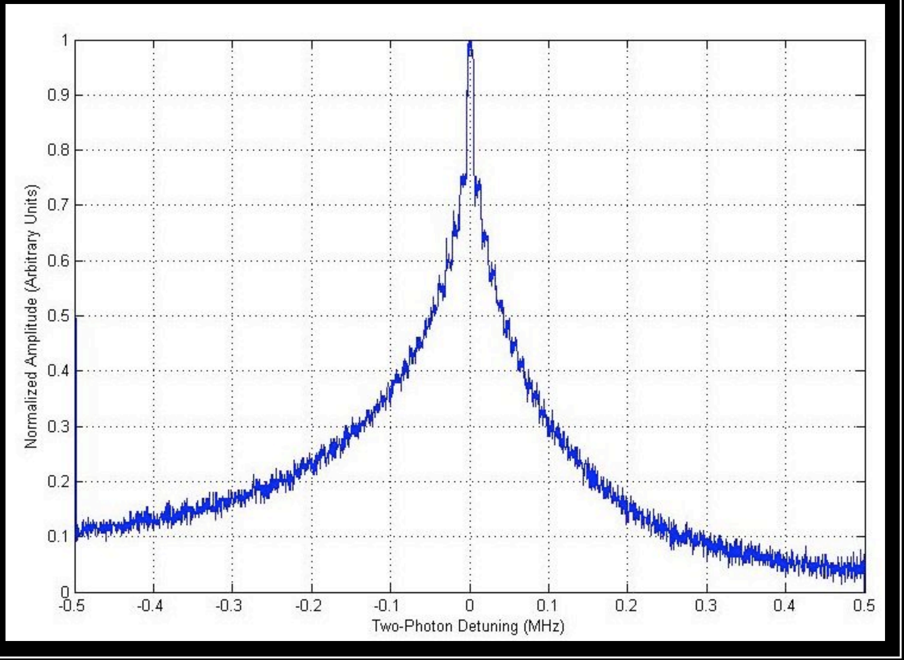




Our Goal

- Get lasers on optical and atomic resonance to achieve maximum transmission





Our Goal's Mathematics

$$\hat{H} = \hbar\omega_e |e\rangle\langle e| + \hbar\omega_{g_2} |g_2\rangle\langle g_2| + \hbar\omega_{g_1} |g_1\rangle\langle g_1|$$

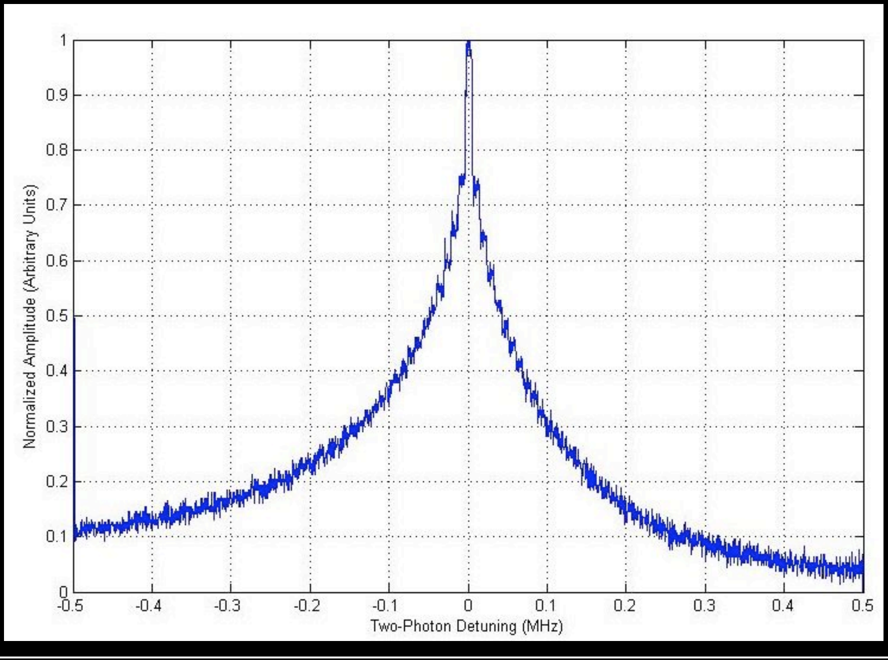
$$\hat{H}_{int} = \wp_{eg}(E_1 |e\rangle\langle g_1| + E_1^* |g_1\rangle\langle e| + E_2 |e\rangle\langle g_2| + E_2^* |g_2\rangle\langle e|$$

$$\Omega_1 = \frac{\wp_{eg_1}\mathcal{E}_1}{\hbar}$$

$$\Omega_2 = \frac{\wp_{eg_2}\mathcal{E}_2}{\hbar}$$

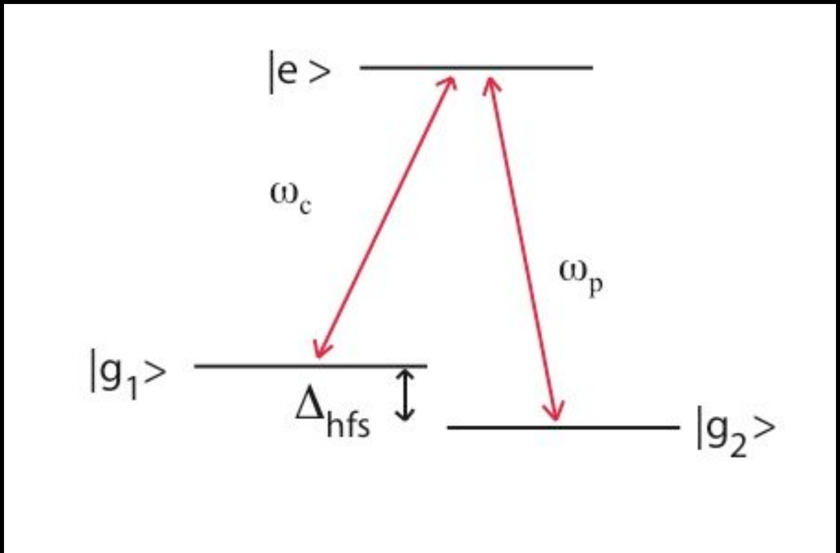
$$|dark\rangle = \frac{\Omega_1 |g_2\rangle - \Omega_2 |g_1\rangle}{\sqrt{|\Omega_1|^2 + |\Omega_2|^2}}$$

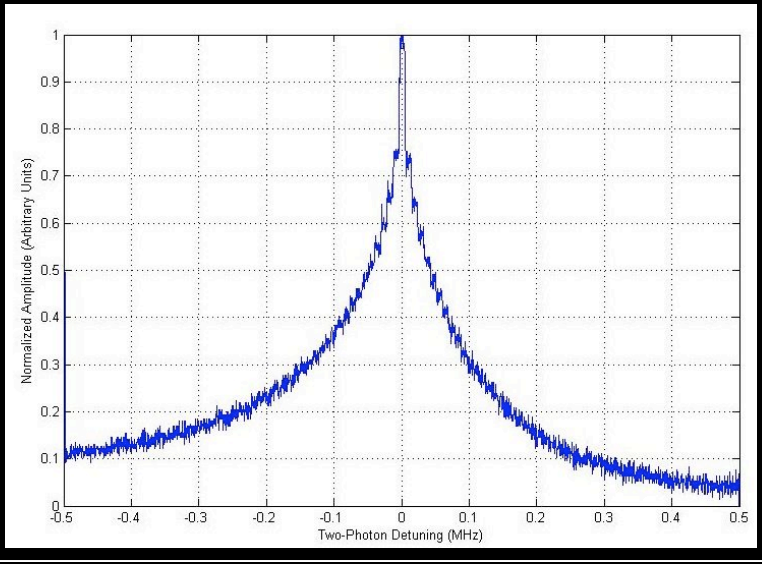
$$\chi(\Delta) = i\frac{n_{Rb}\wp_{eg}^2}{\varepsilon_0\hbar}\frac{(\Gamma_{dark} + i\Delta)}{\Gamma(\Gamma_{dark} + i\Delta) + \Omega^2/4}$$



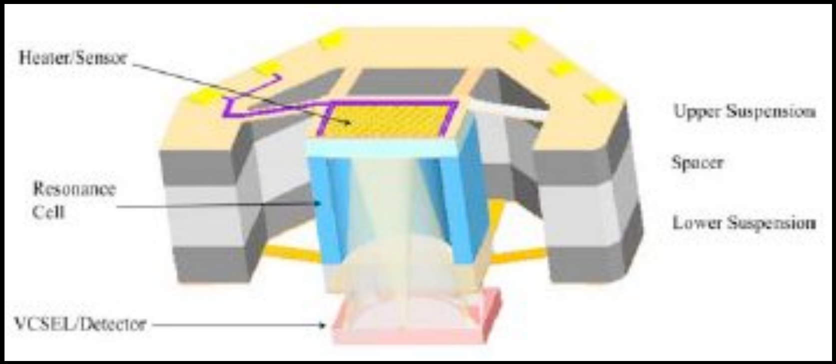
How is our clock made?

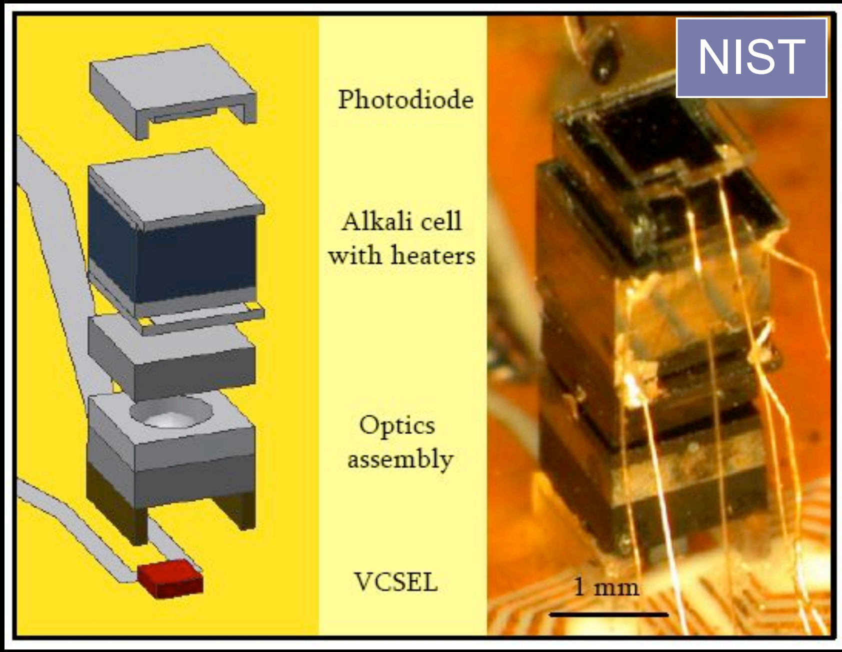
- Use lasers to drive transition between hyperfine levels of ground state
- Use feedback to match lasers to 6.834 GHz



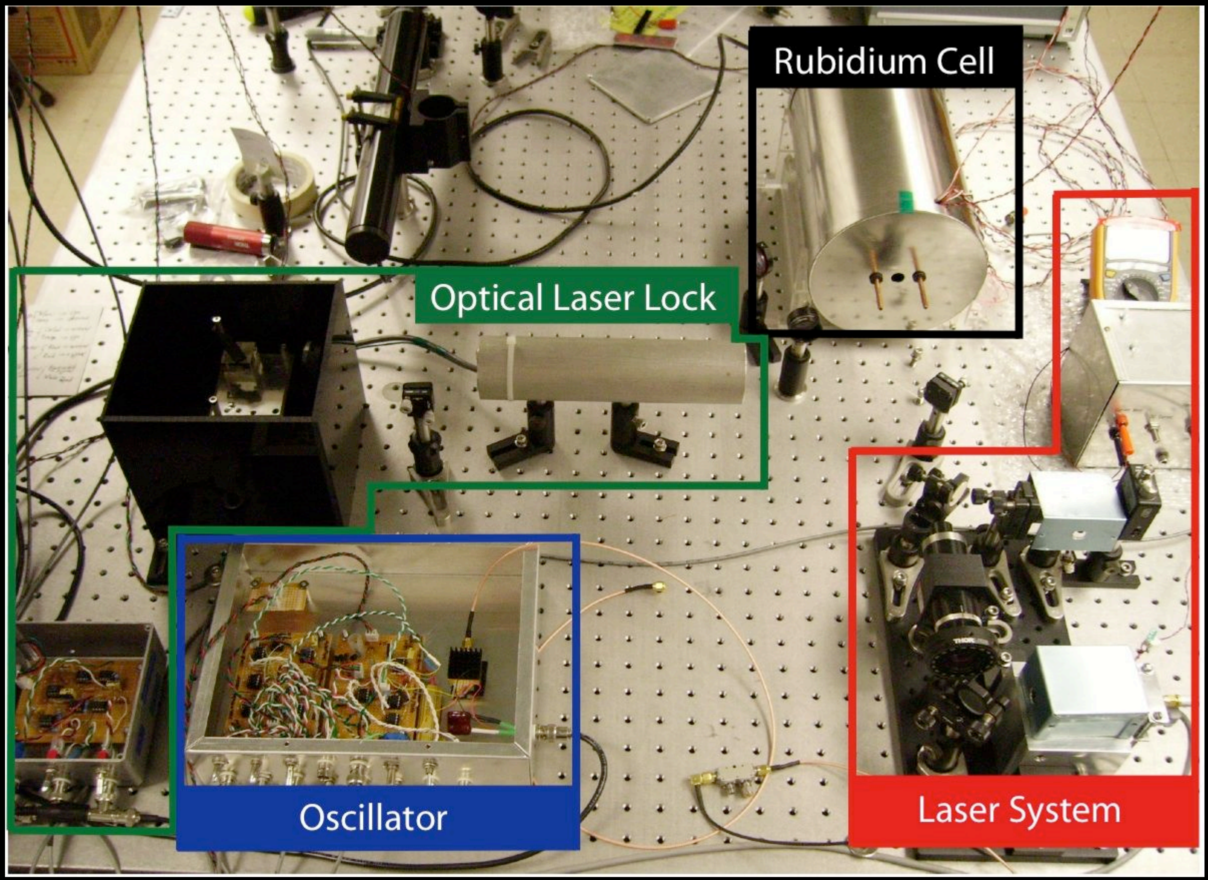


Miniature Atomic Clocks





The Experiment

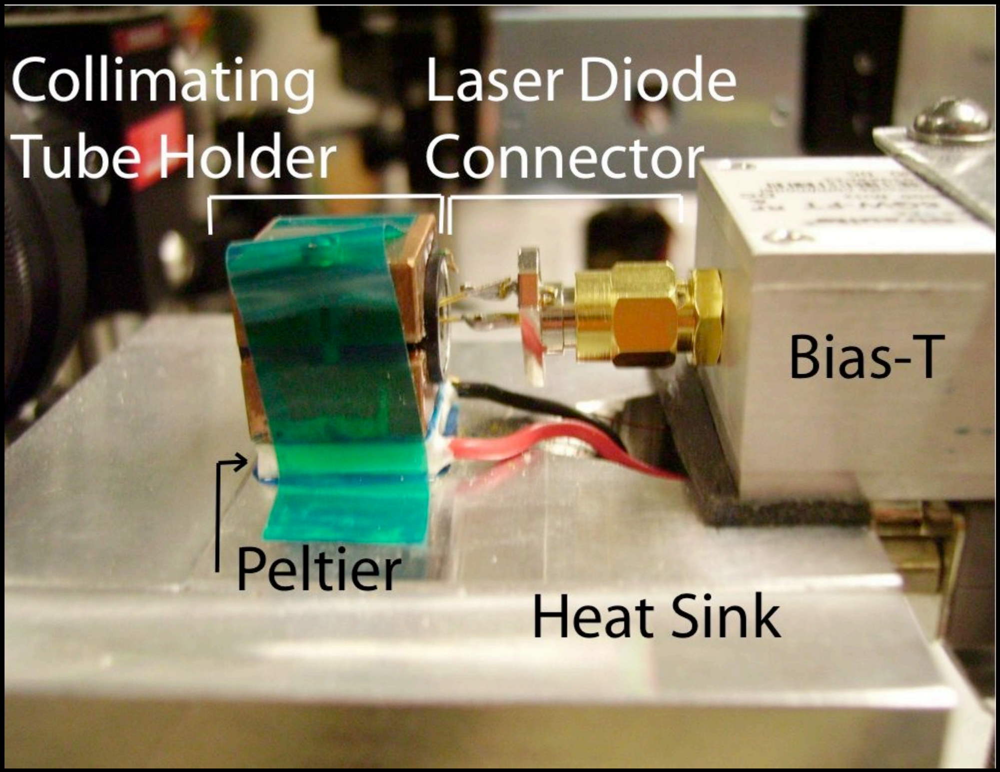


Vertical-Cavity Surface-Emitting Laser (VCSEL)

- VCSELs are good because low power consumption, ease of modulation, use in other applications
- Need two lasers from one physical laser

Laser Setup continued

- Temperature stability



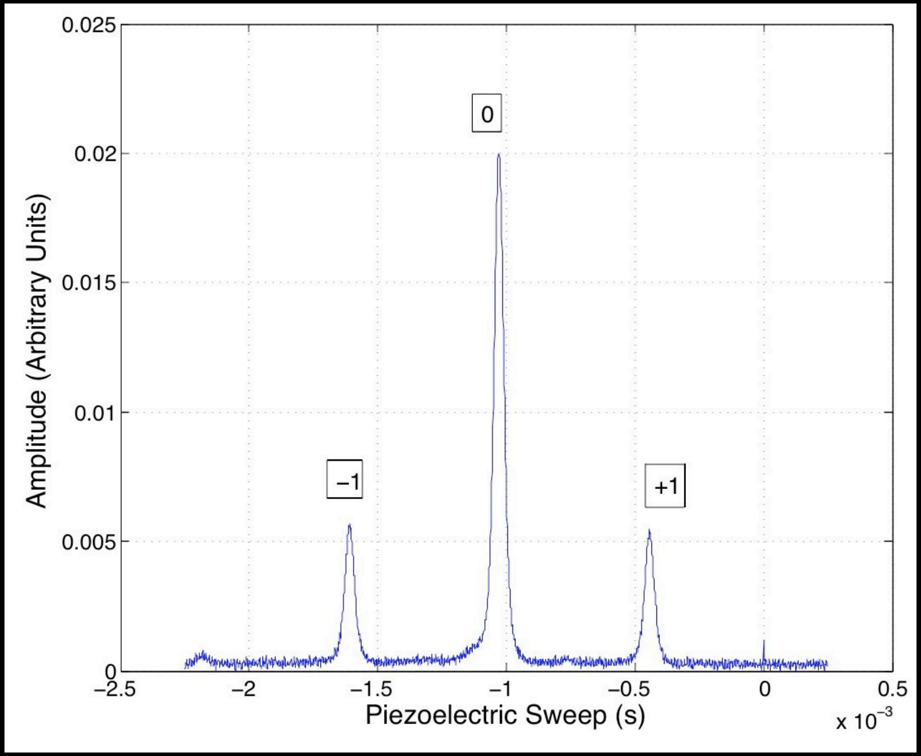
Phase Modulation

- Apply rf field to laser, create carrier and sideband comb

$$E = E_0 e^{ikx - i\omega t + i\varphi(t)}$$

$$\varphi(t) = \varepsilon sin(\omega_m t)$$

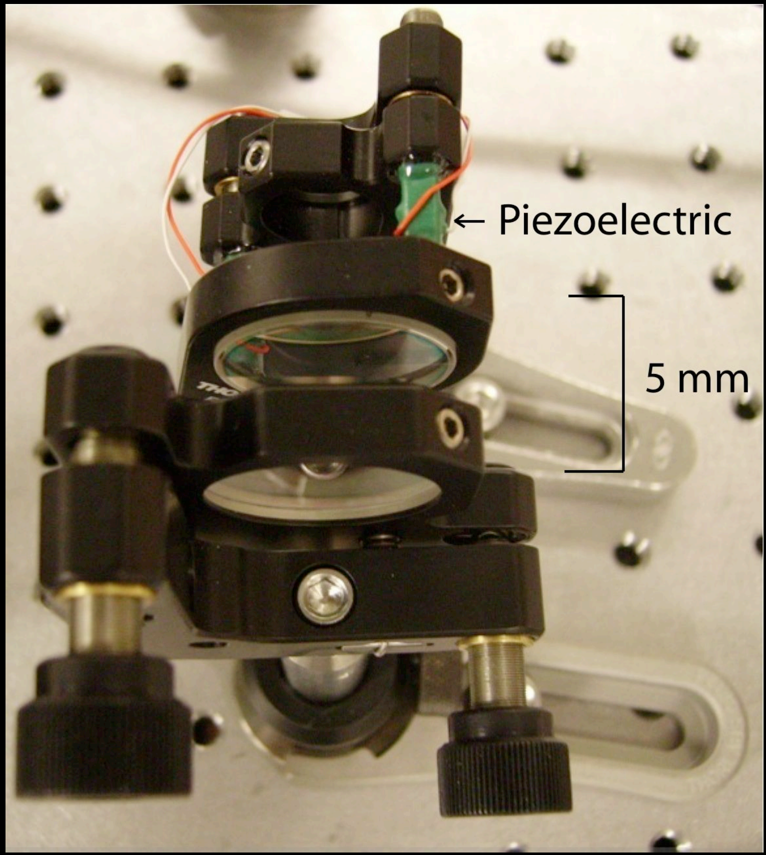
$$E = \sum_{n=0}^{\infty} E_0 J_n(\varepsilon) e^{ikx - i(\omega - n\omega_m)t}$$



Phase Modulation continued

- Fabry-Perot cavity
- Second mirror moved by piezoelectric
- Piezoelectric controlled by voltage source, with low frequency modulation

$$\Delta \nu = \frac{c}{2L}$$

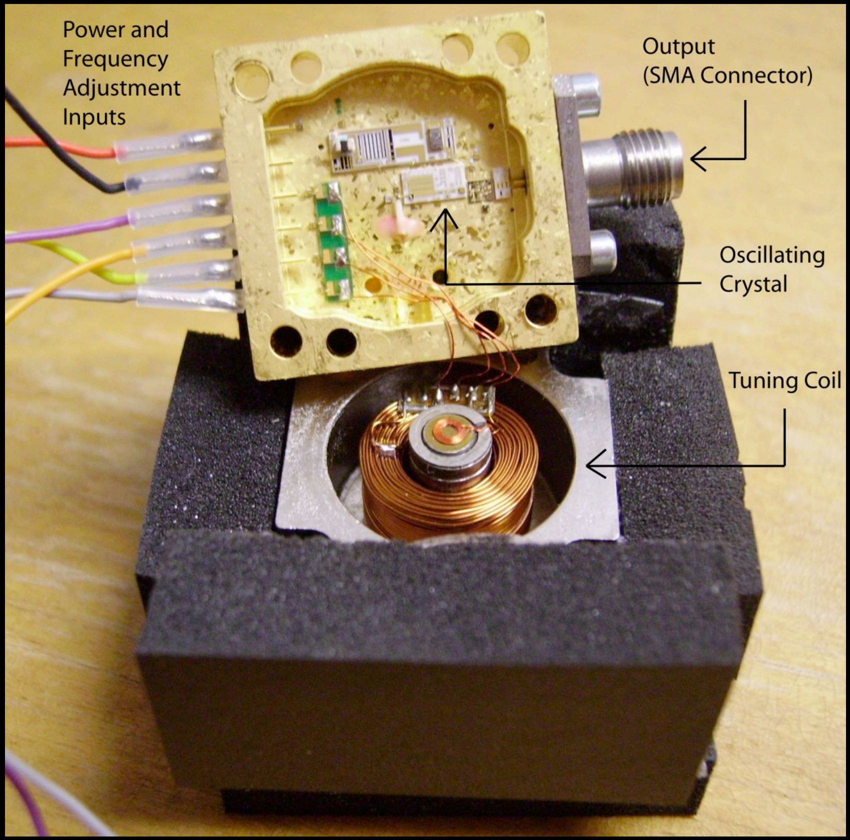


Phase Modulation continued

- Modulators
  - Commercial digital synthesizer (Agilent E8275D)
    - Up to 14 dBm of power at very precise frequencies
  - Stellex Mini-YIG crystal oscillator
    - Current controlled tunable crystal with frequencies ranging from 5.95 GHz to 7.15 GHz at 15 dBm

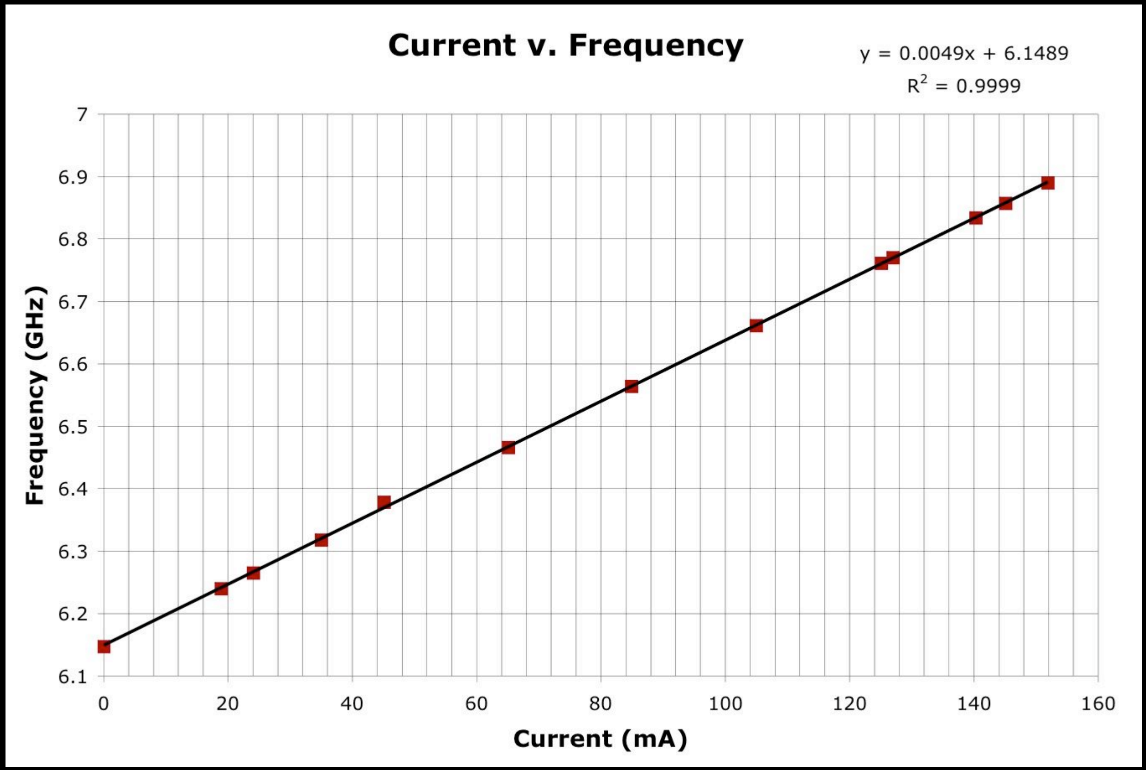
Phase Modulation continued

- Inside of Stellex oscillator

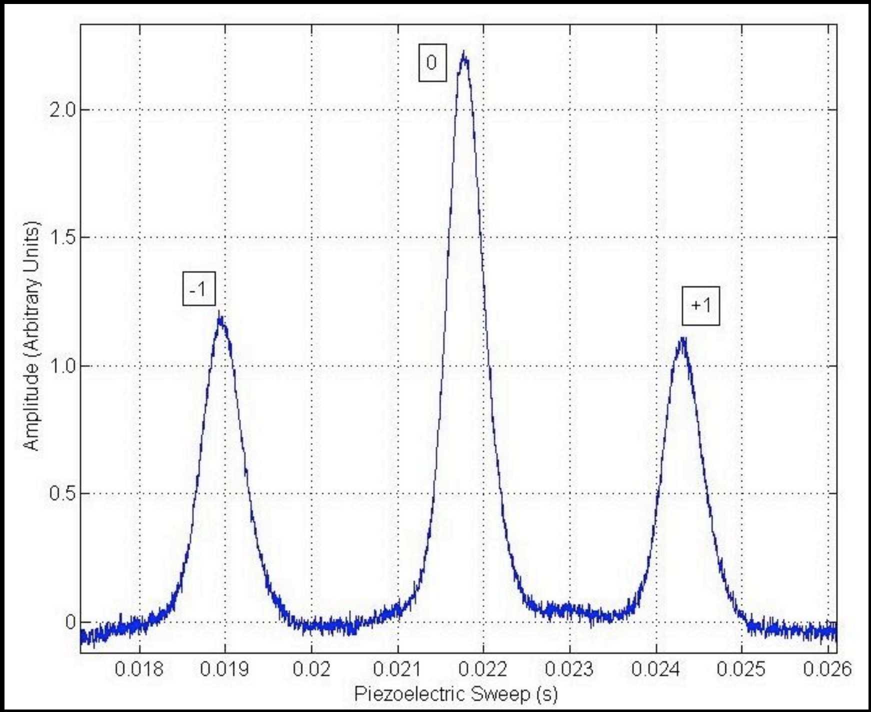


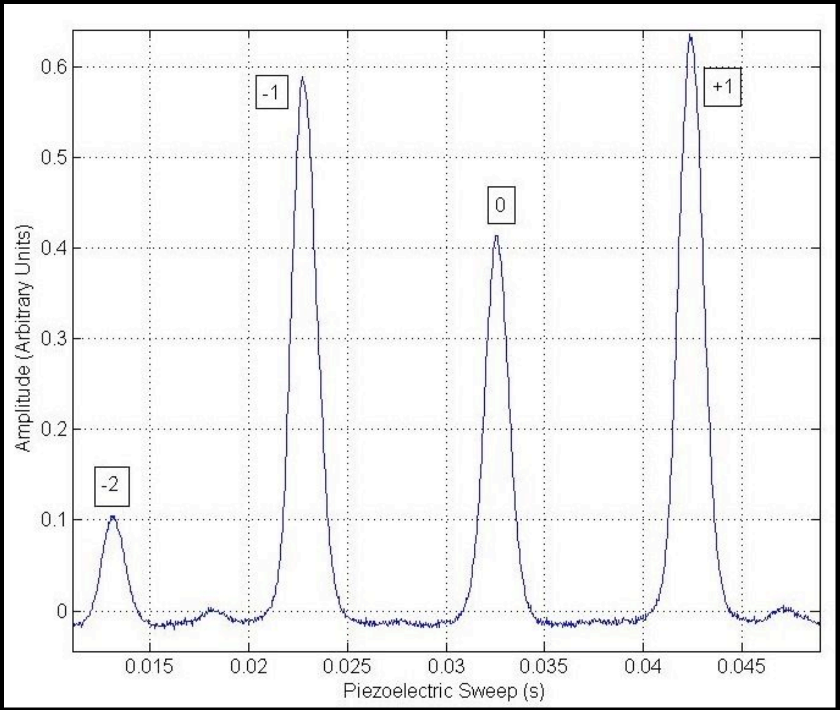
Phase Modulation continued

- Stellex oscillator calibration measurements

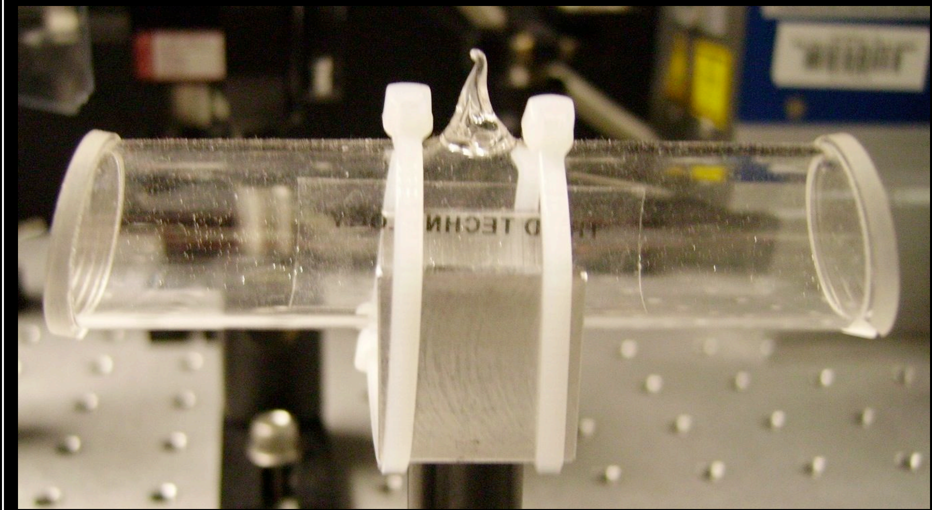


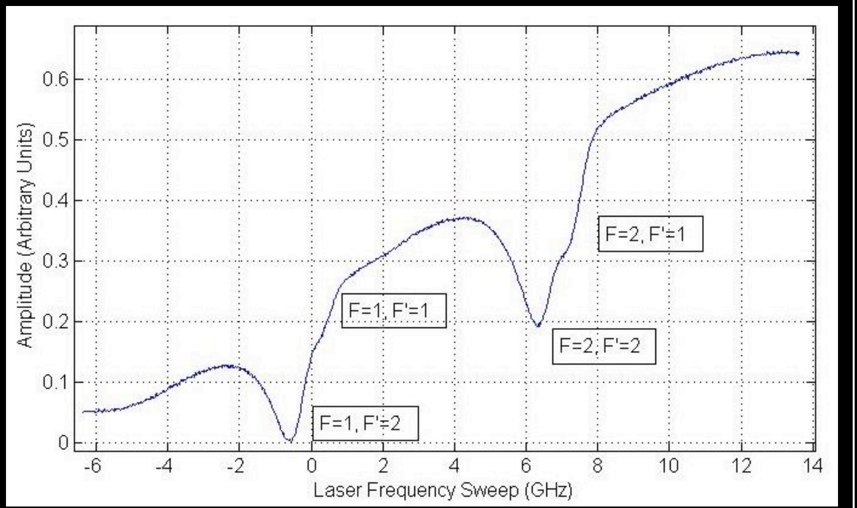
Phase Modulation continued



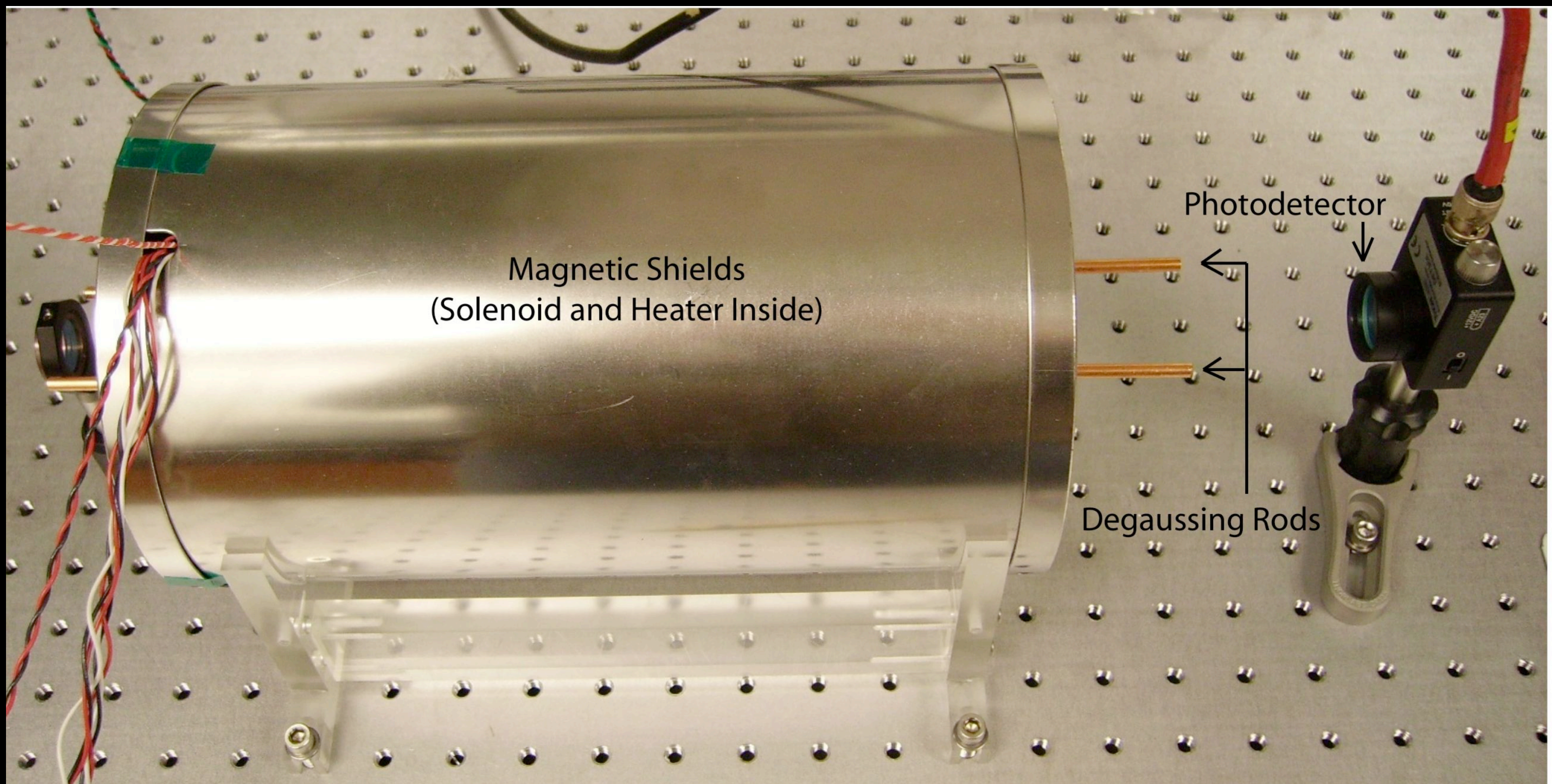


Rubidium Cell



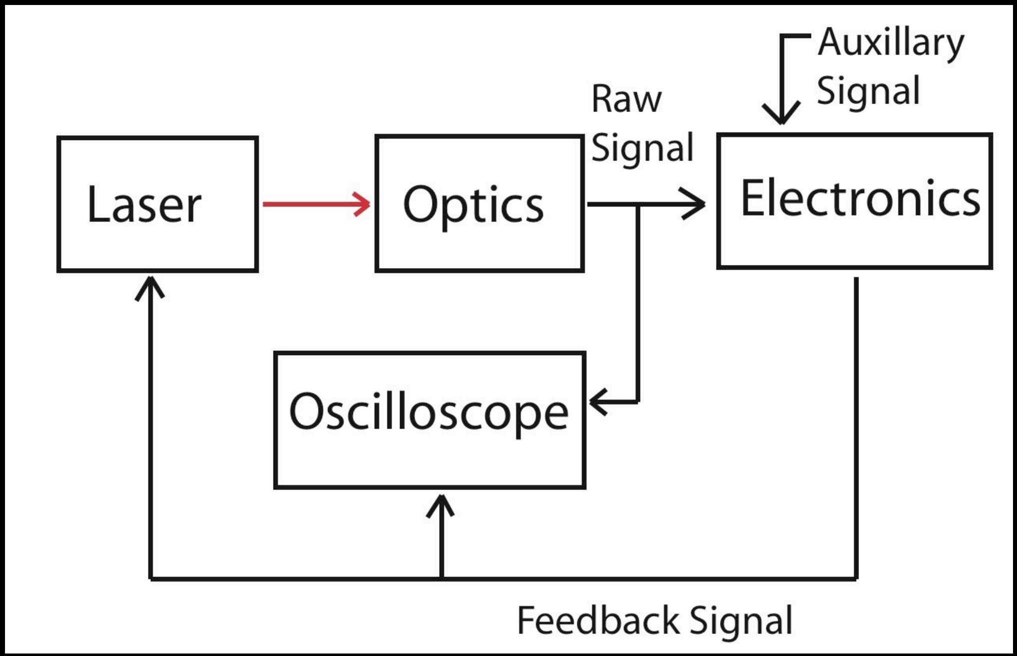


Solenoid and Shields



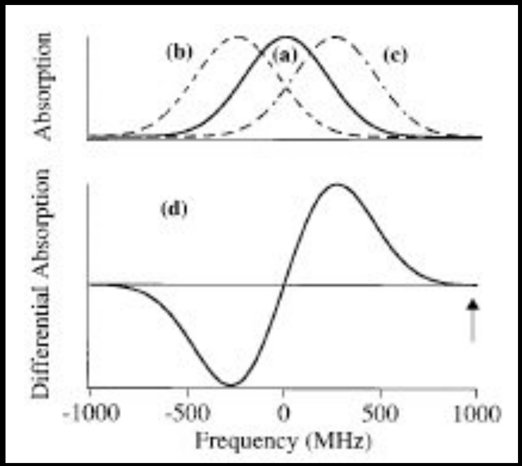
DAVLL

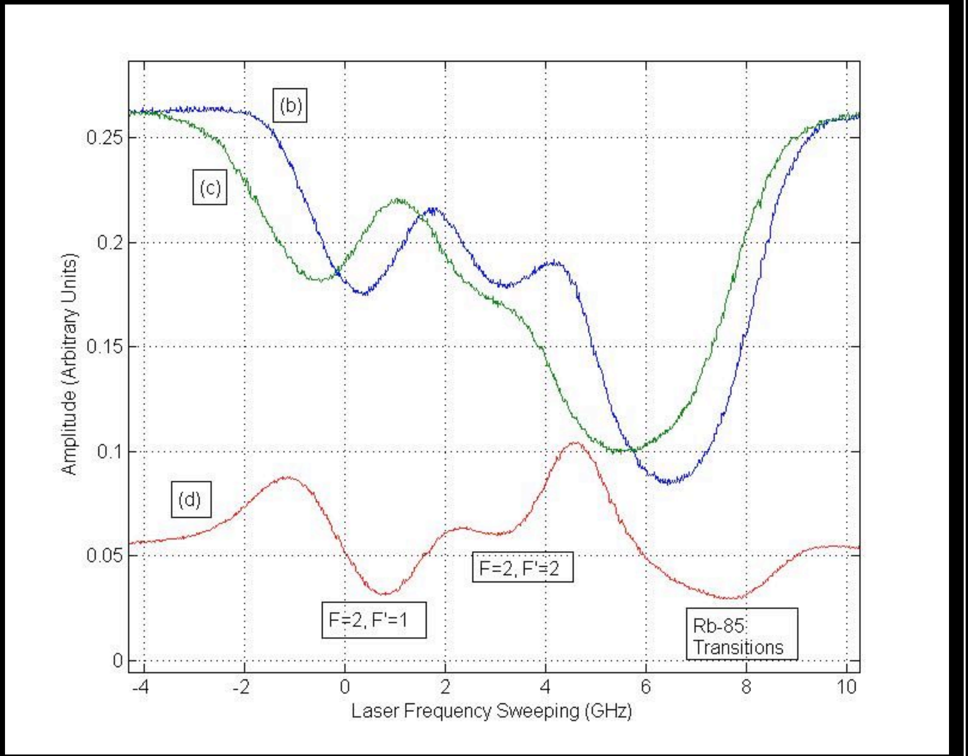
- Allows locking of frequency of VCSEL to specific rubidium resonance frequency



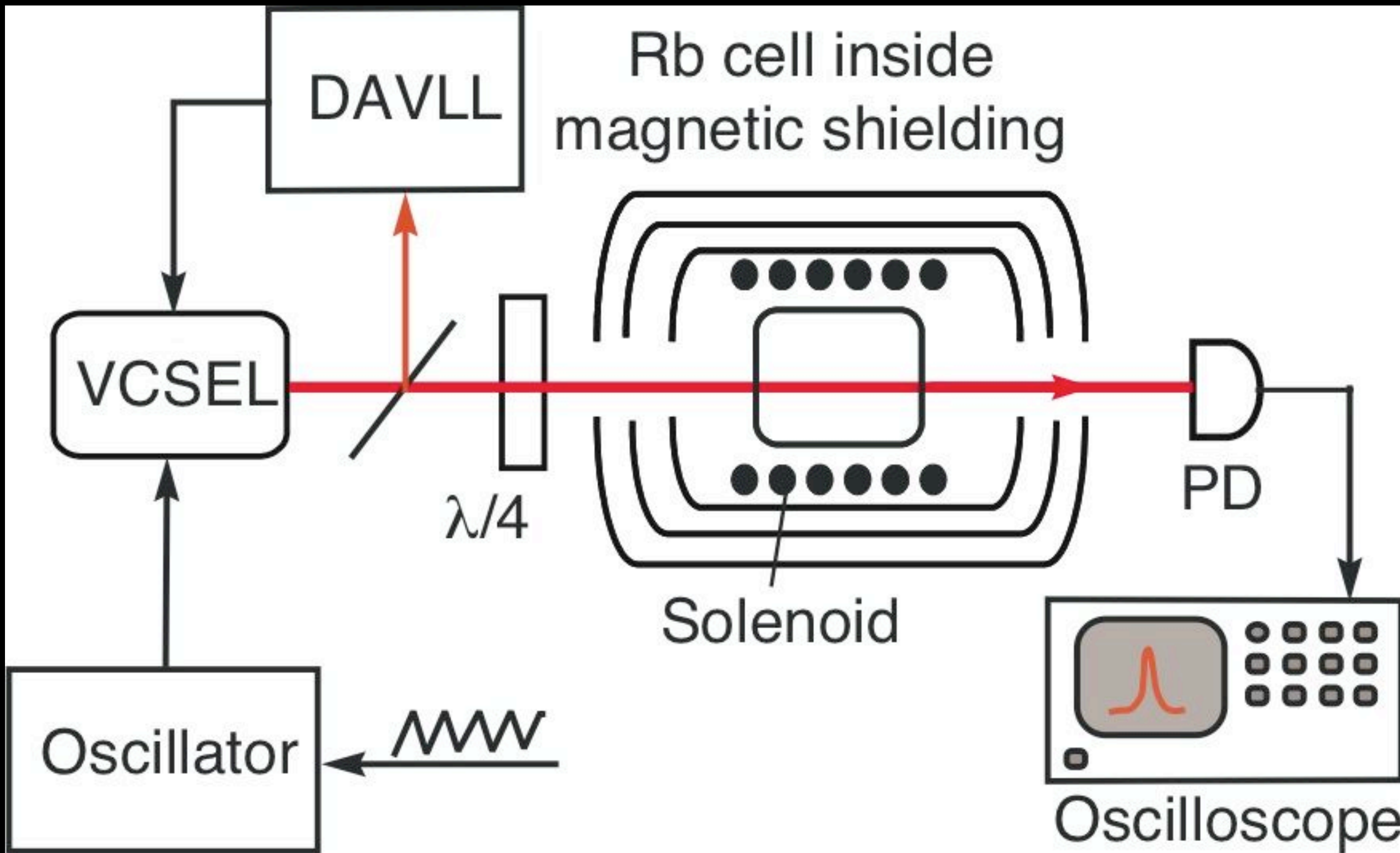
DAVLL continued

- Absorption and differential spectra



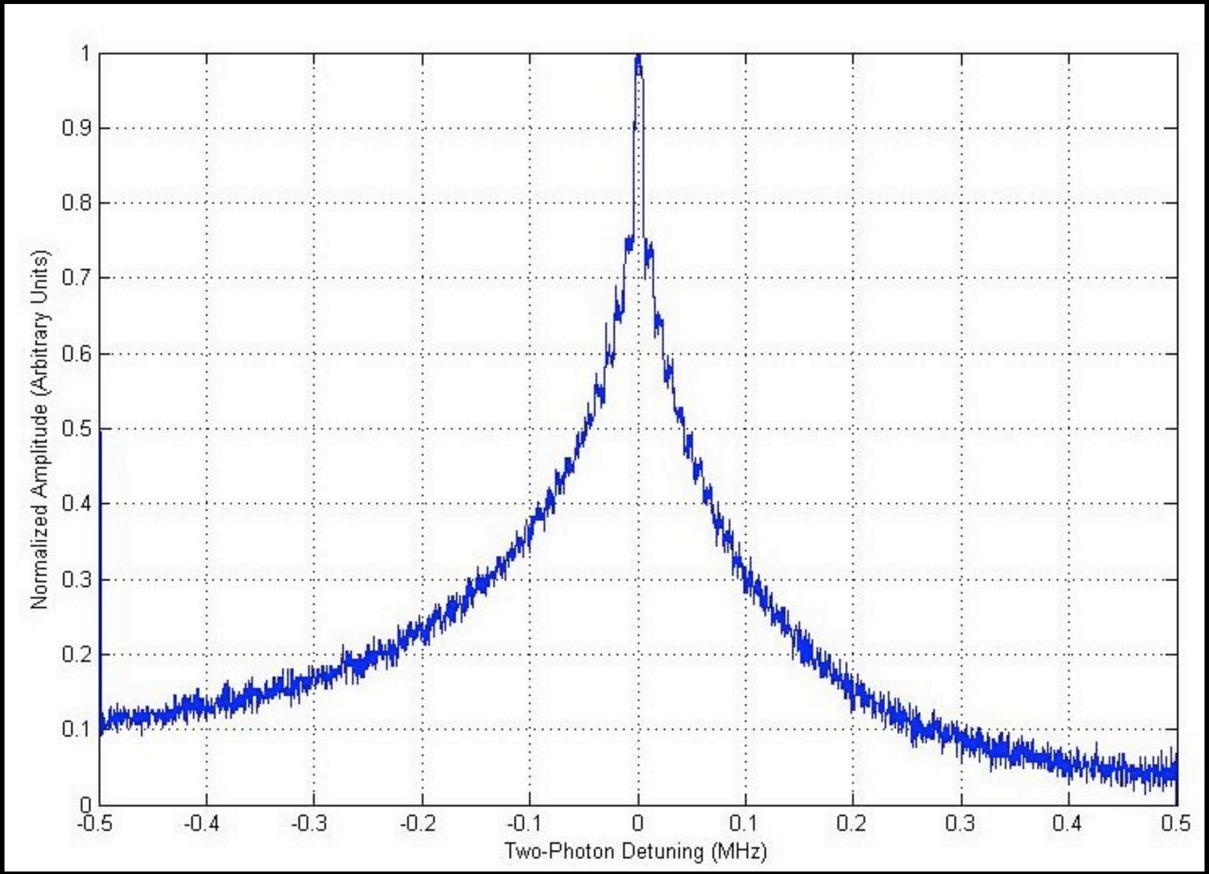


CPT Experiment

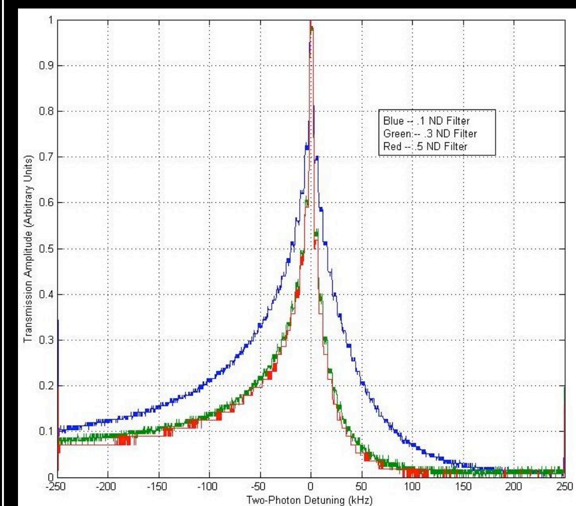


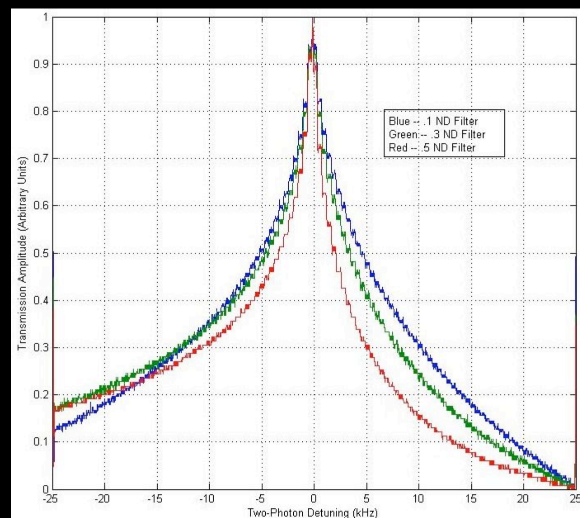
CPT Experiment continued

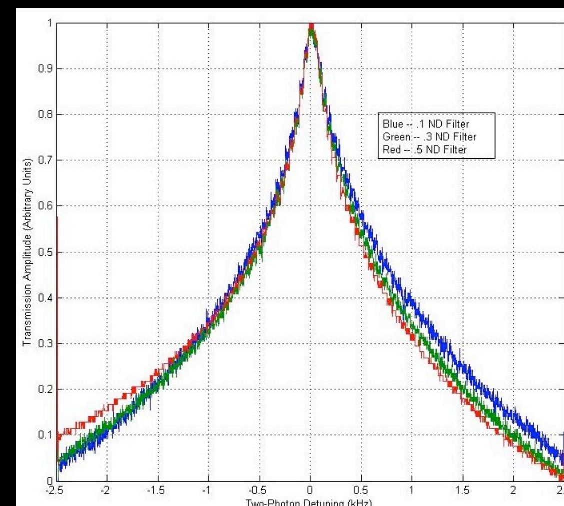
$$|dark\rangle = \frac{\Omega_1 |g_2\rangle - \Omega_2 |g_1\rangle}{\sqrt{|\Omega_1|^2 + |\Omega_2|^2}}$$



CPT Experiment continued



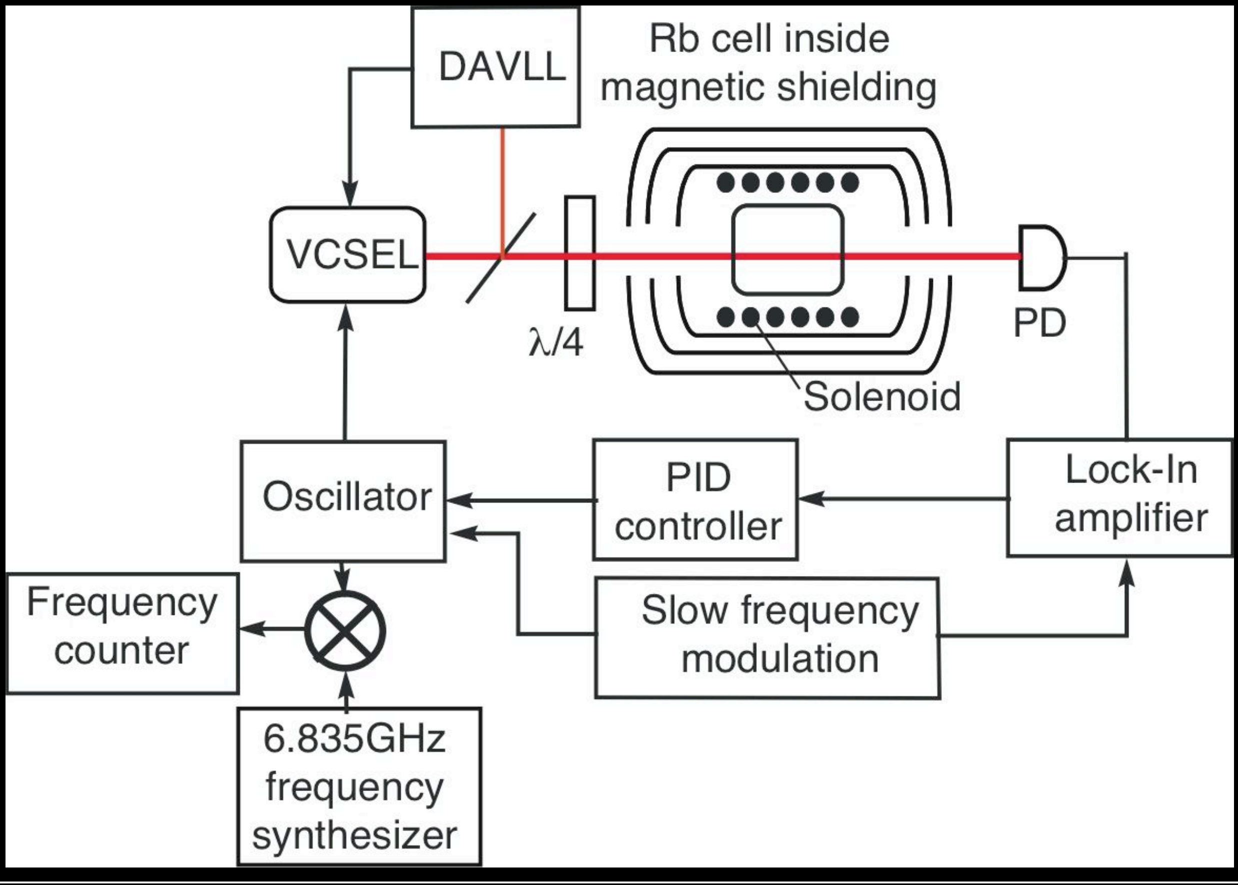




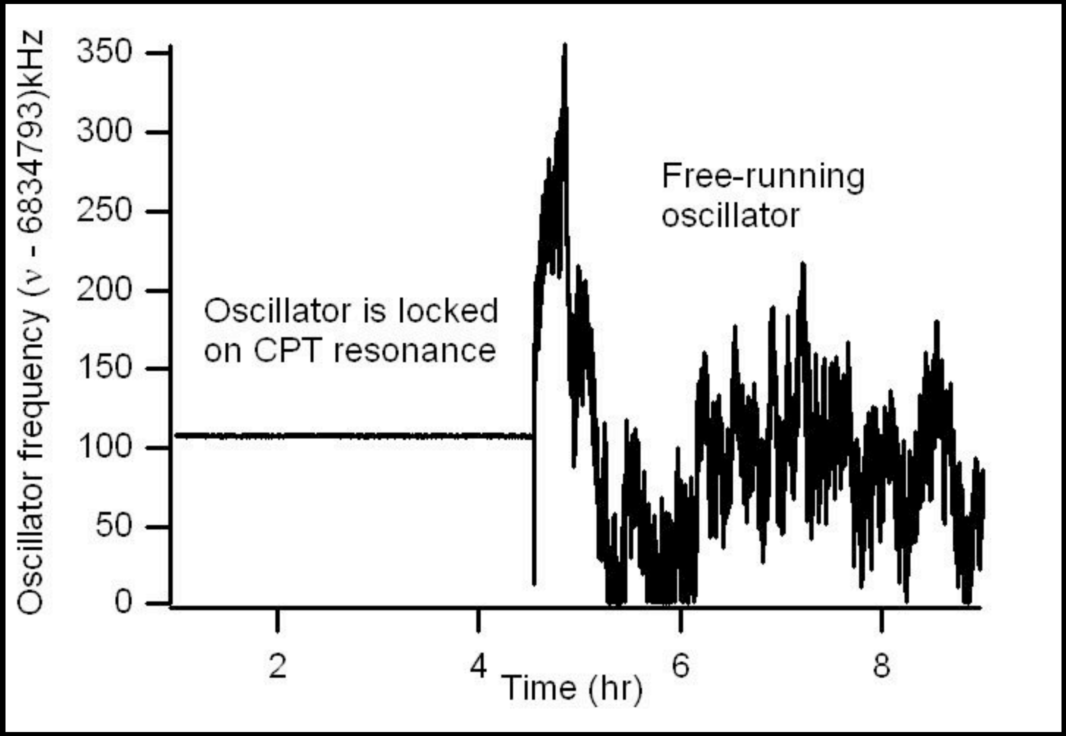
Two-Photon Detuning: 500 kHz, 50 kHz, 5 kHz

Blue = .1 ND filter, Green = .3 ND filter, Red = .5 ND filter

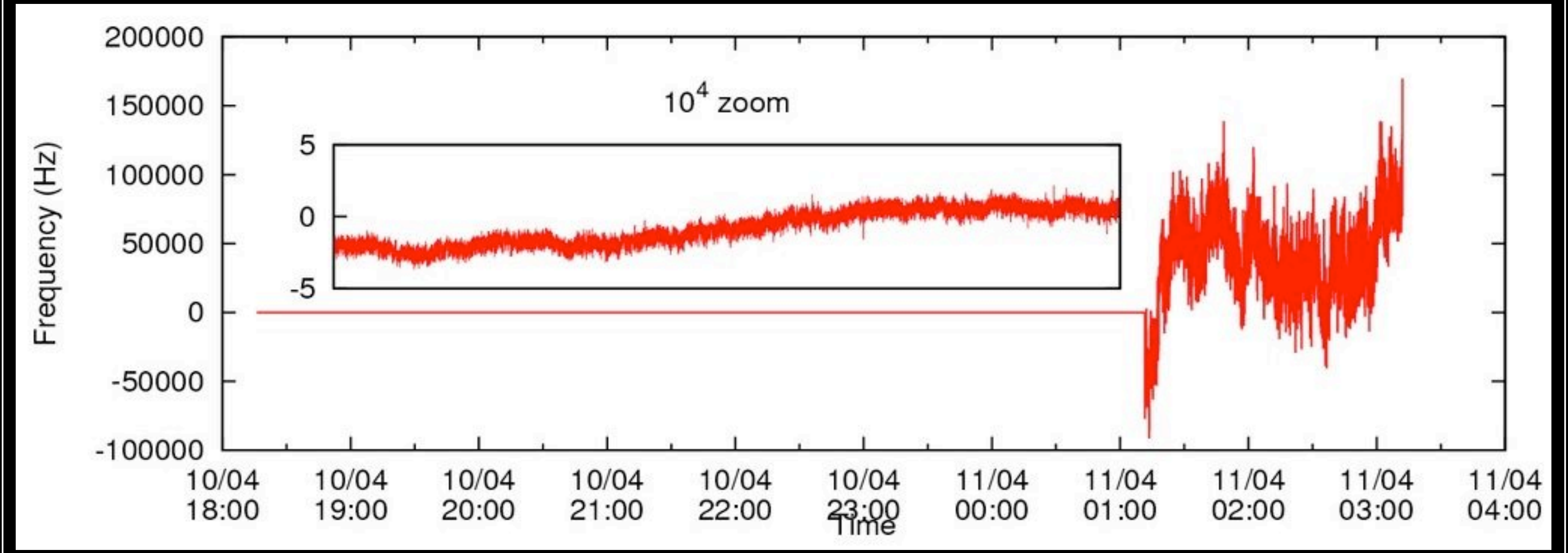
Clock Experiment



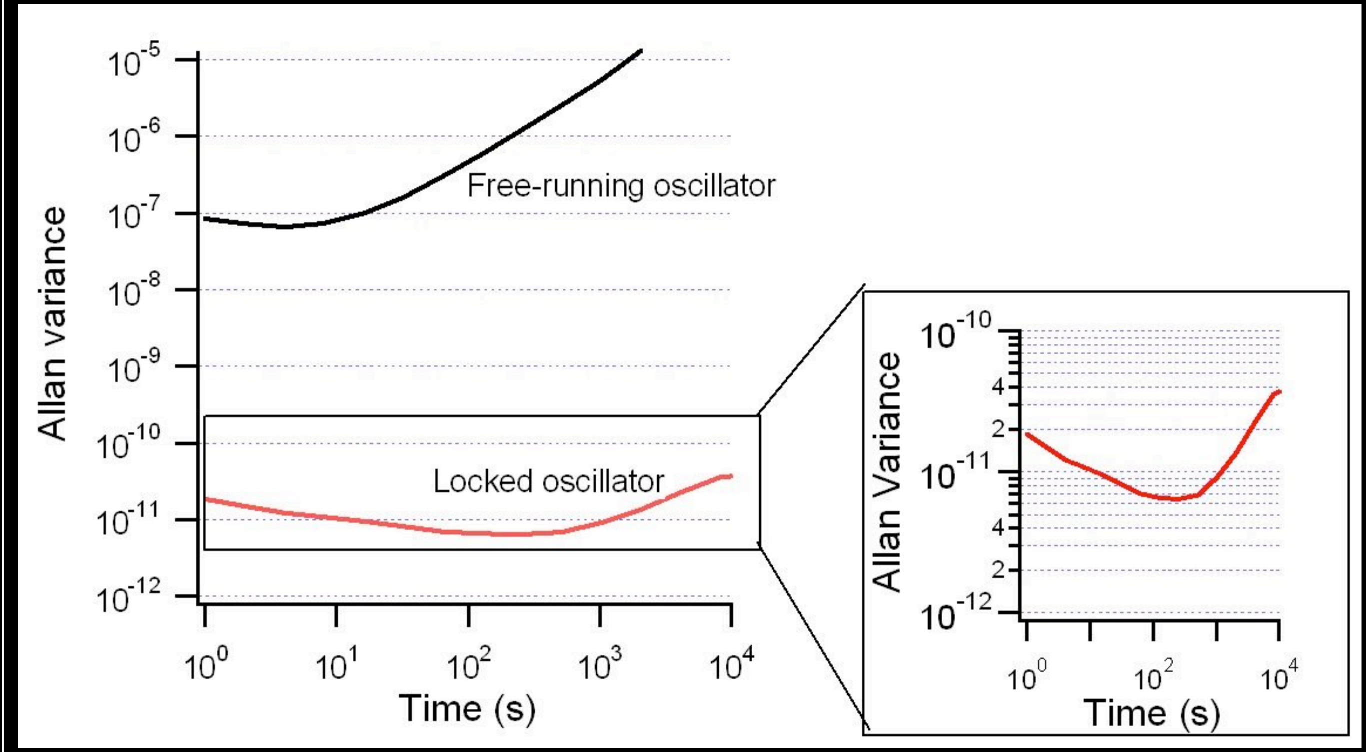
Clock Experiment continued



Clock Experiment continued

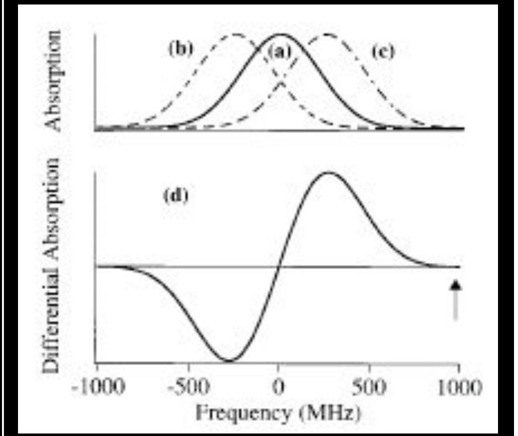


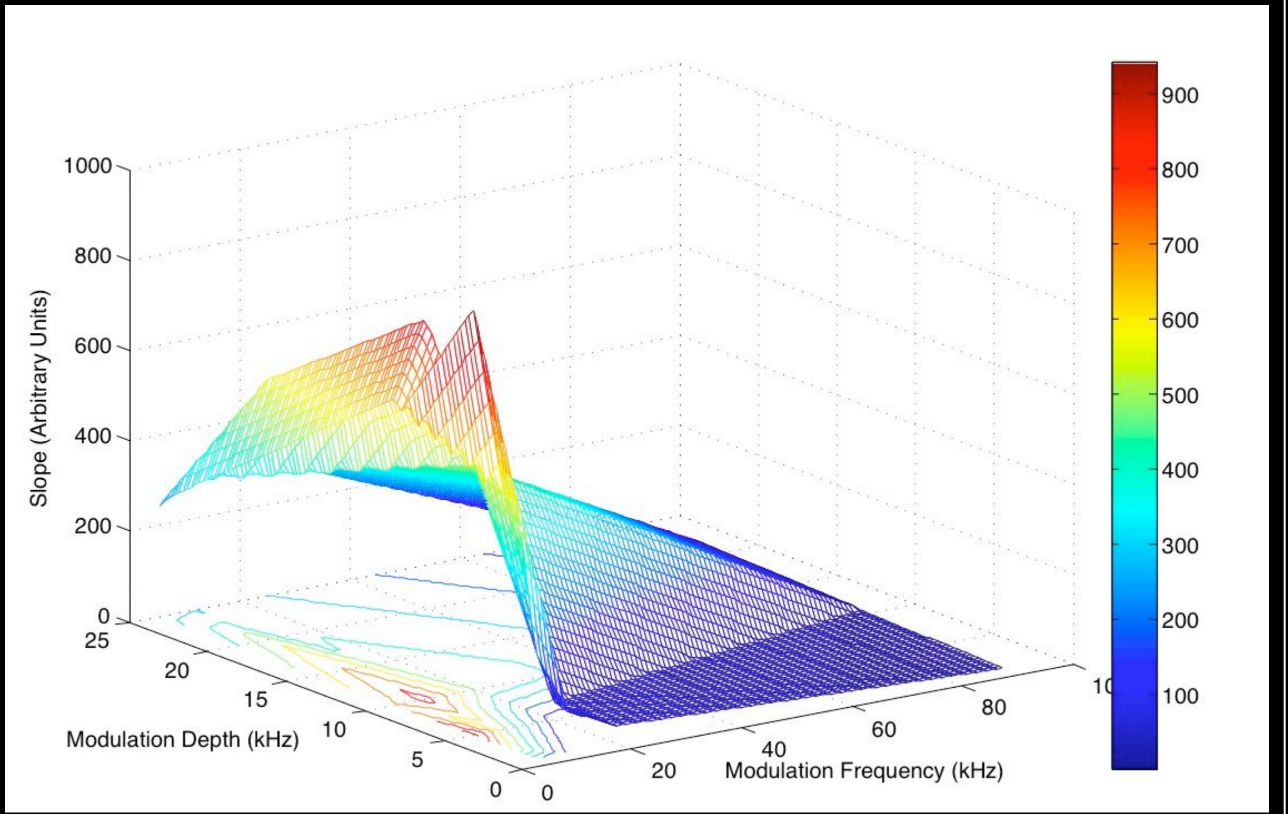
Clock Experiment continued



$$\sigma_\nu^2(\tau) = \frac{1}{2}\left\langle \nu^2 \right\rangle$$

Clock Experiment continued





Clock Experiment continued

- Find right lock-in amplifier slope
- Modify circuits that form PID controller
- Improvements in DAVLL locking
- Hardware upgrades
  - Counter
  - Reference frequency
  - Lock-in amplifier
- Temperature stabilized DAVLL and rubidium cell

Further CPT Studies

- Change locking point from F =1 to F’ =2 to F = 2 to F’ = 1
- Driven by two linearly polarized fields instead of two circularly polarized fields
- Study effects of laser power on CPT
- Effects of applied magnetic field