Lecture 15. Lidar Architecture (3)

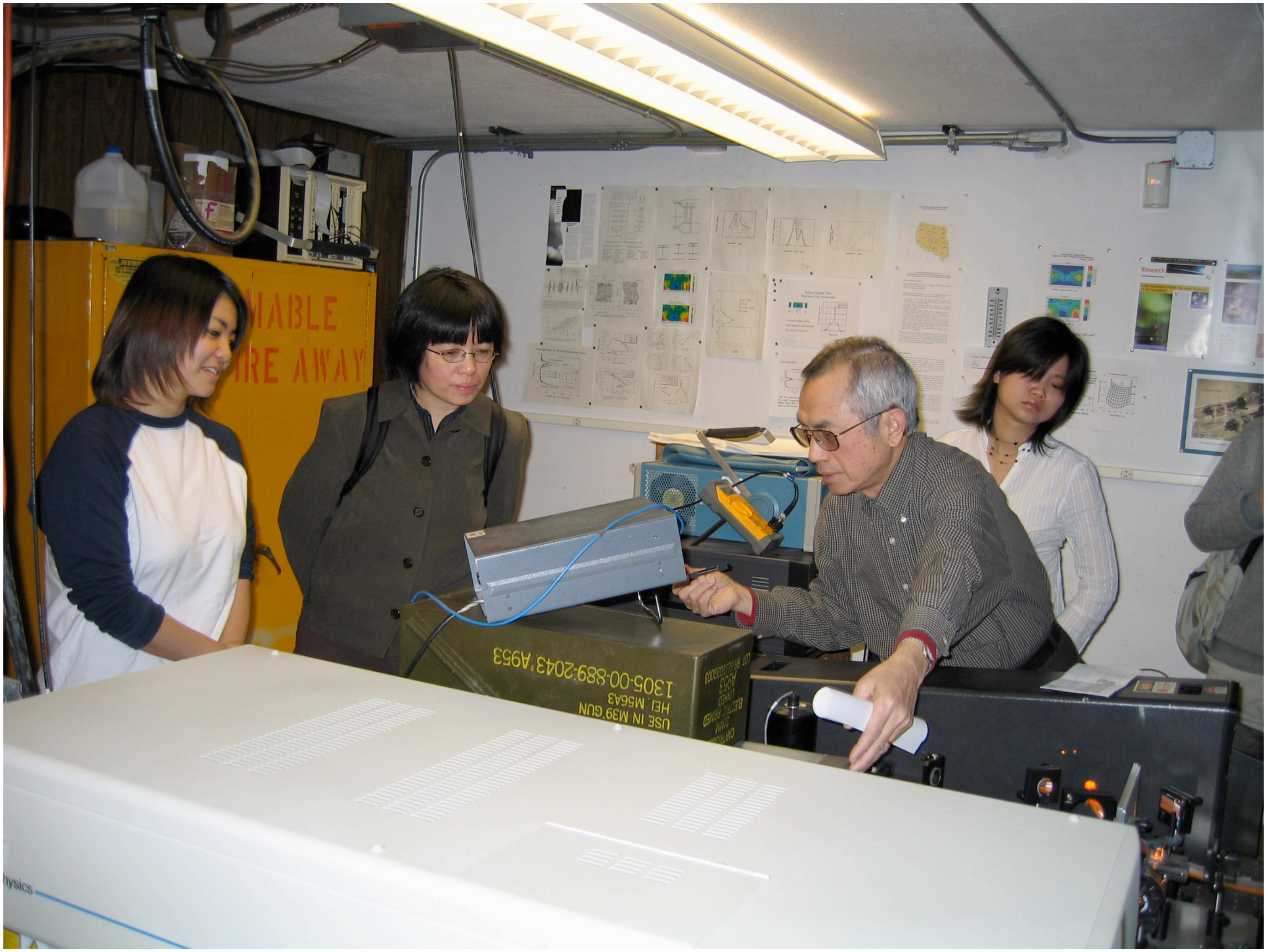
- CSU field trip review
- Lidar Transmitter
  - Dual-Acousto-Optical-Modulator
  - Pulsed Dye Amplification
  - Injection Seeding Nd:YAG laser
- Lidar Receiver
  - Faraday filter
  - Multiple beam interference
  - (F-P etalon and interference filter)
- More laser basics
  - Laser resonator
  - Ring dye laser frequency control

CSU Field Trip

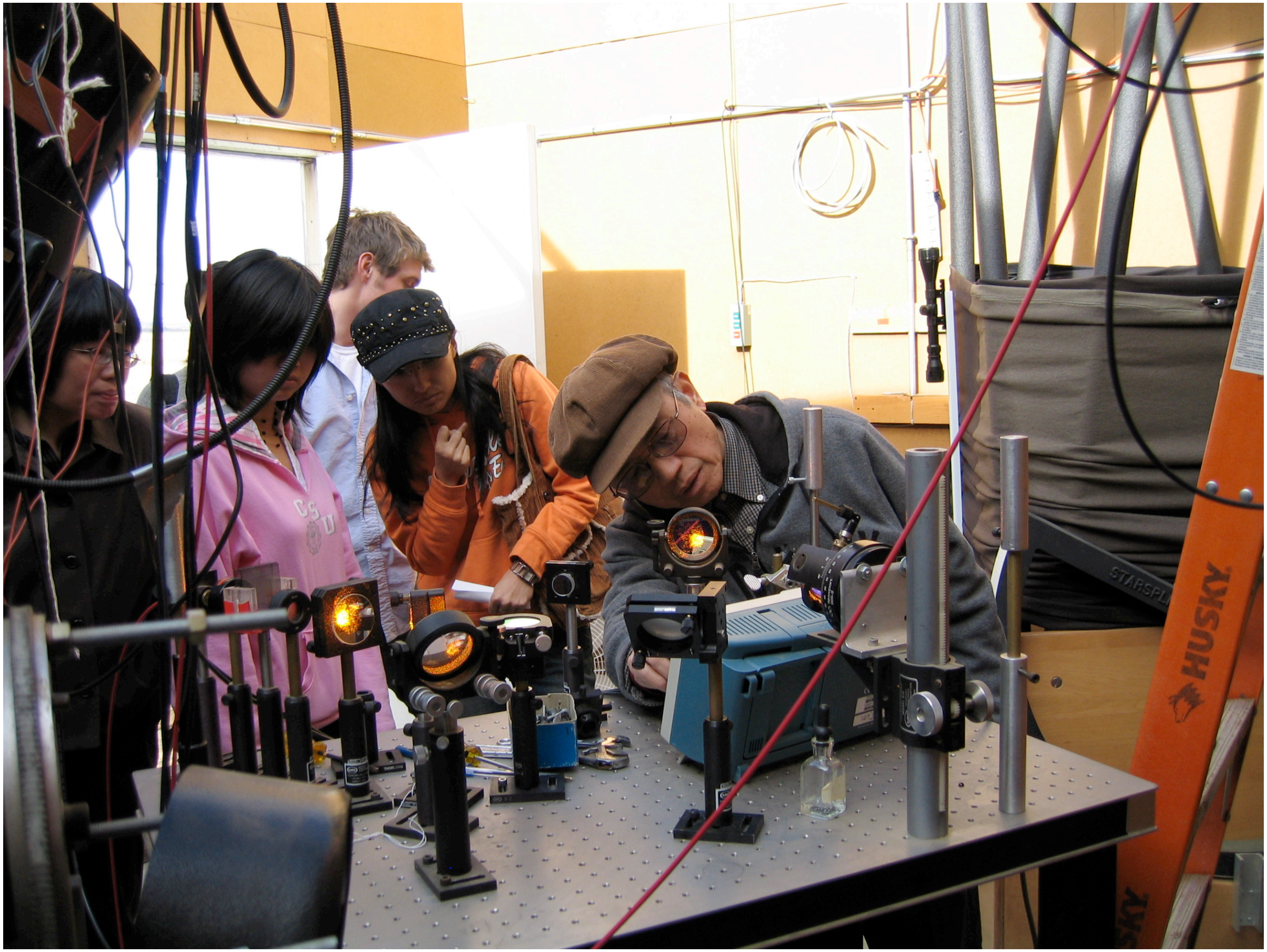
Prof. She Showing Lidar Dual-Beam

Prof. She Explaining Lidar Principle

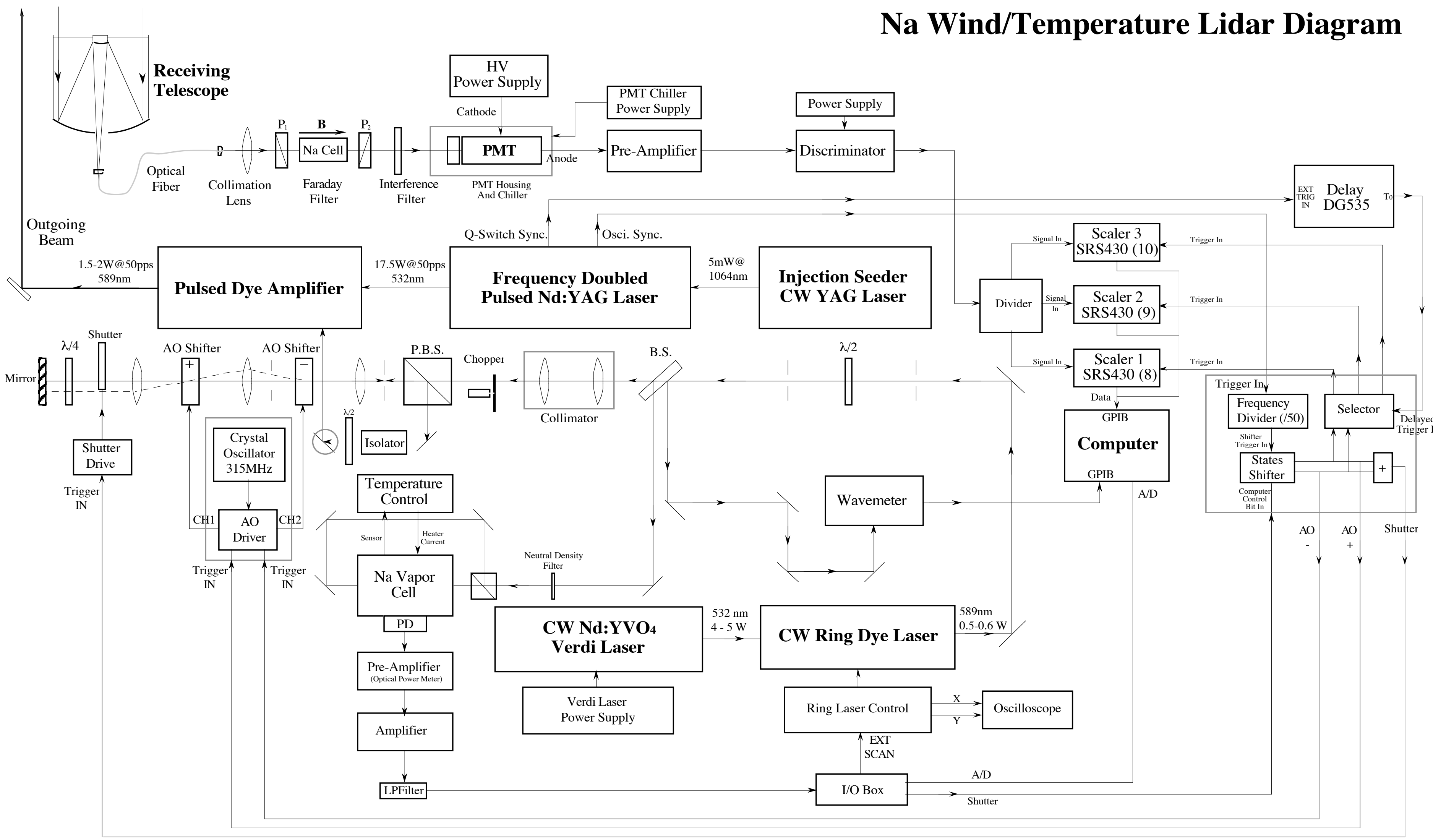
Prof. She Showing Lidar Transmitter



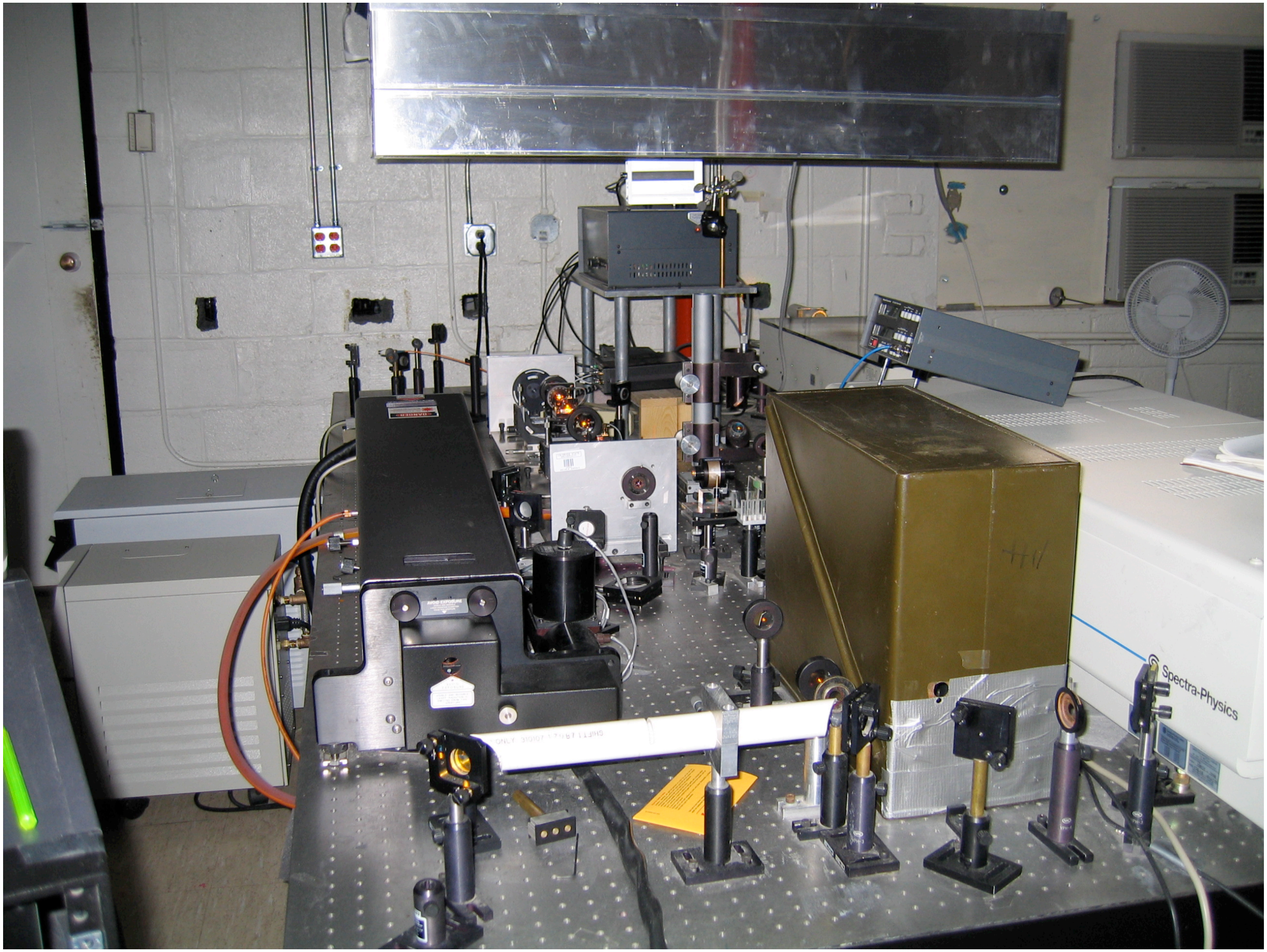
Prof. She Showing Return Signal



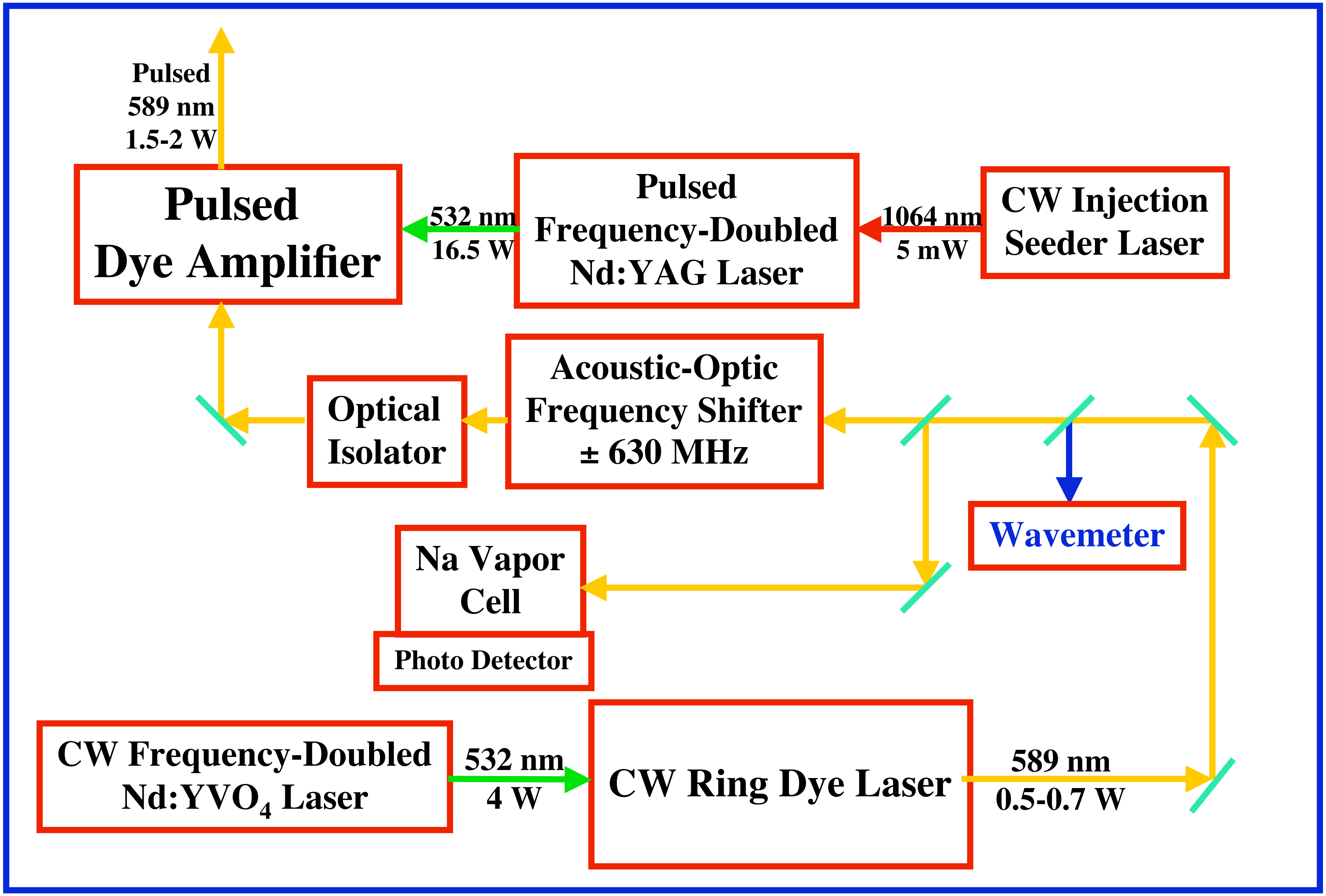
CSU Na Doppler Lidar



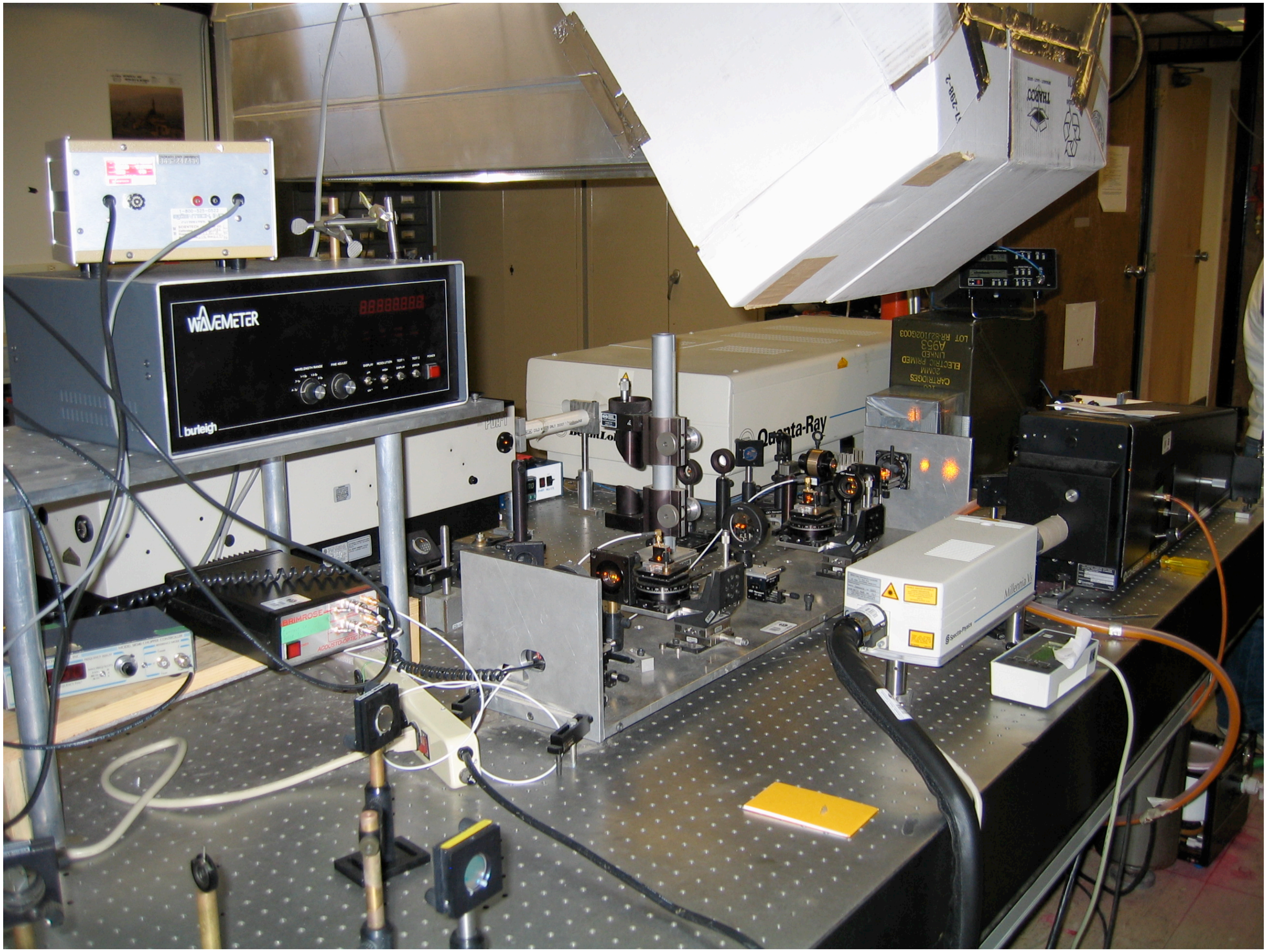
CSU Na Lidar Transmitter



Na Doppler Lidar Transmitter

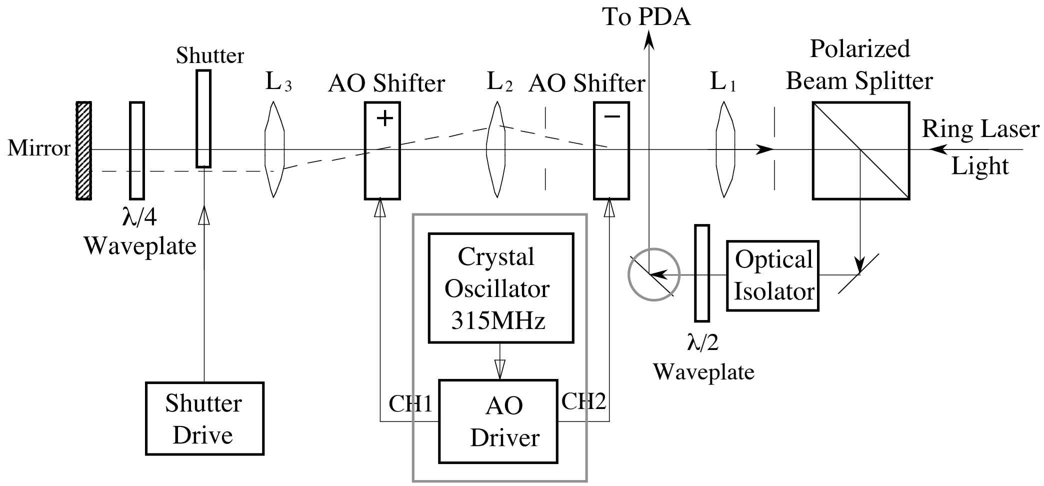


CSU Dual-AOM

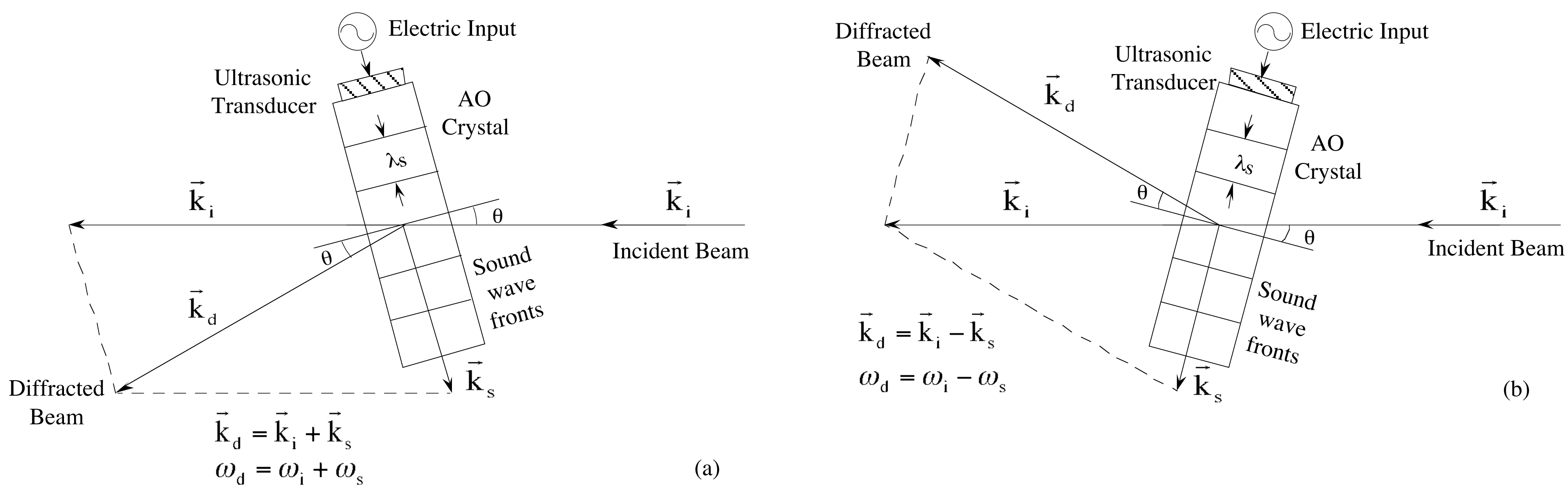


Acousto-Optical Modulator

Hardware



Explanation: Doppler shift or Photon/Phonon Annihilation



Acousto-Optical Modulator

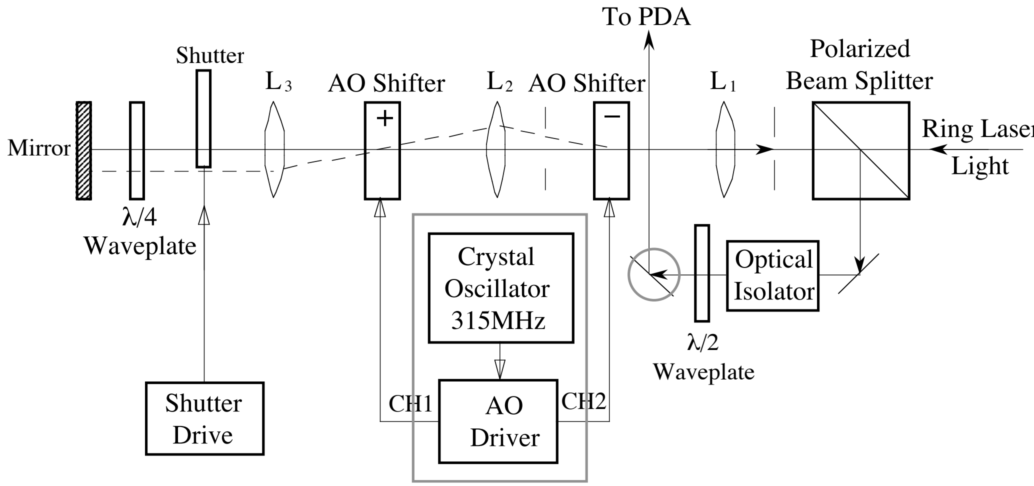
- Piezoelectric transducer attached to an AO crystal coverts RF EM wave to acoustic energy. The vibration produces a traveling acoustic wave across the AO crystal.
- The variation of density causes change in refraction index, and forms partially reflecting plane mirrors.
- According to the first-order Bragg diffraction condition, if the incident laser beam, the acoustic wave, and the angle θ satisfy the following equations (n is the AO refraction index):

$$k_s = 2k_i \sin\theta \qquad 2\lambda_s \sin\theta = \lambda_i / n$$

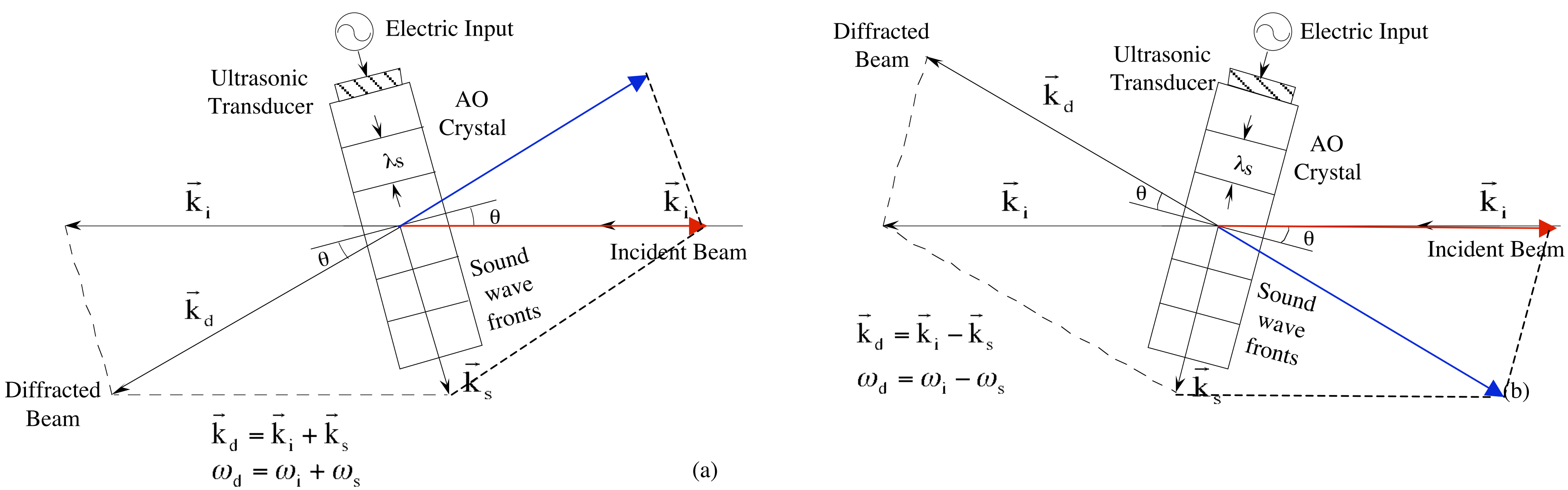
- then part of the incident laser beam will be diffracted by the acoustic wave and exit the AO with the same angle θ on the other side of the AO crystal.
- The diffracted beam will experience a Doppler frequency shift due to the moving acoustic wave.

Acousto-Optical Modulator

Hardware

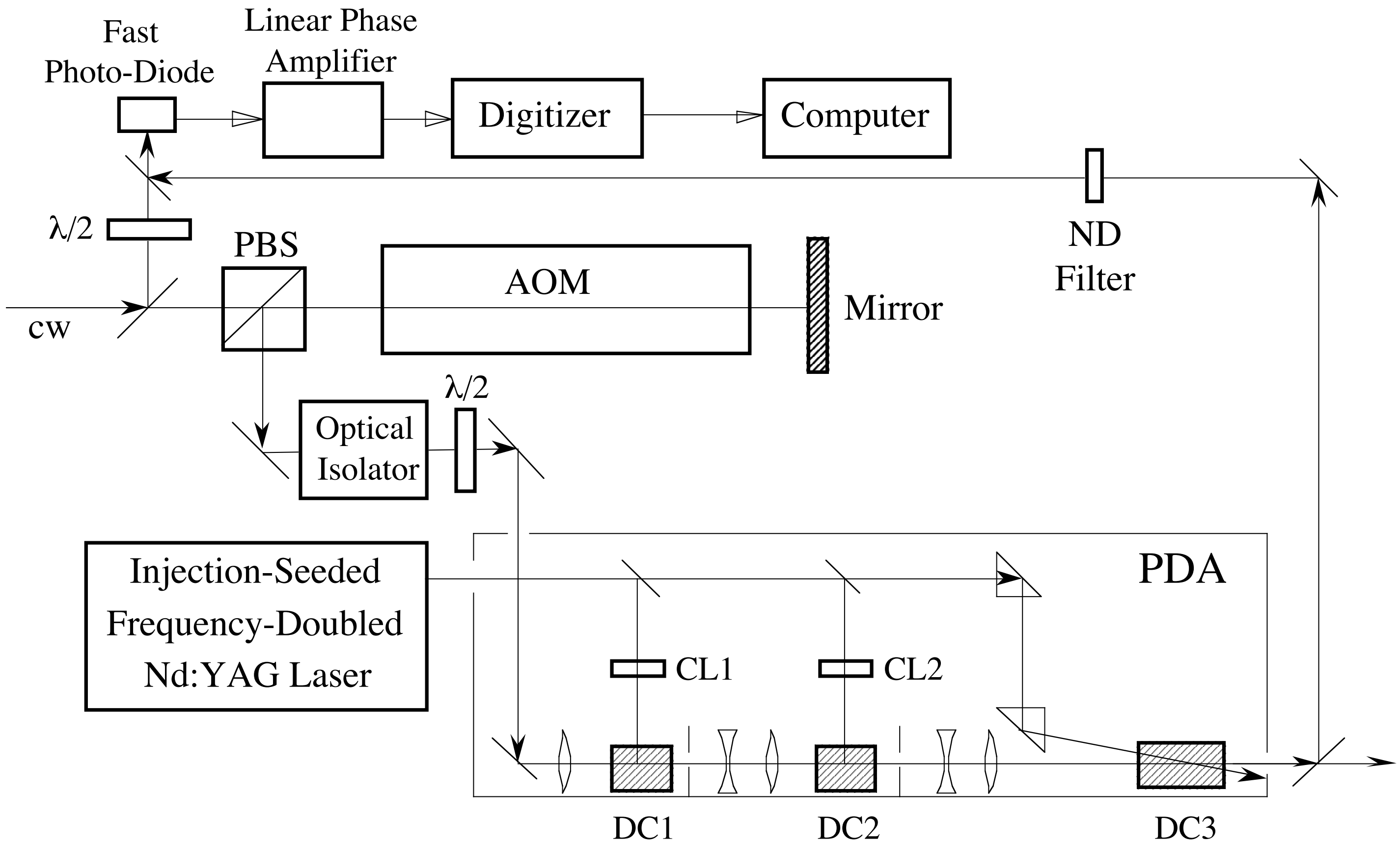


Explanation: Doppler shift or Photon/Phonon Annihilation



Pulsed Dye Amplifier in Na Lidar

Pulsed Amplification



1. **Amplified Spontaneous Emission (ASE)**
2. **Injection-seeded Nd:YAG laser**
3. **PDA chirp caused by pulsed amplification**

Dye Laser

- Due to the numerous rotational-vibrational states of the organic dye molecules, energy levels turn into energy bands, which enable the tuning of laser frequency.

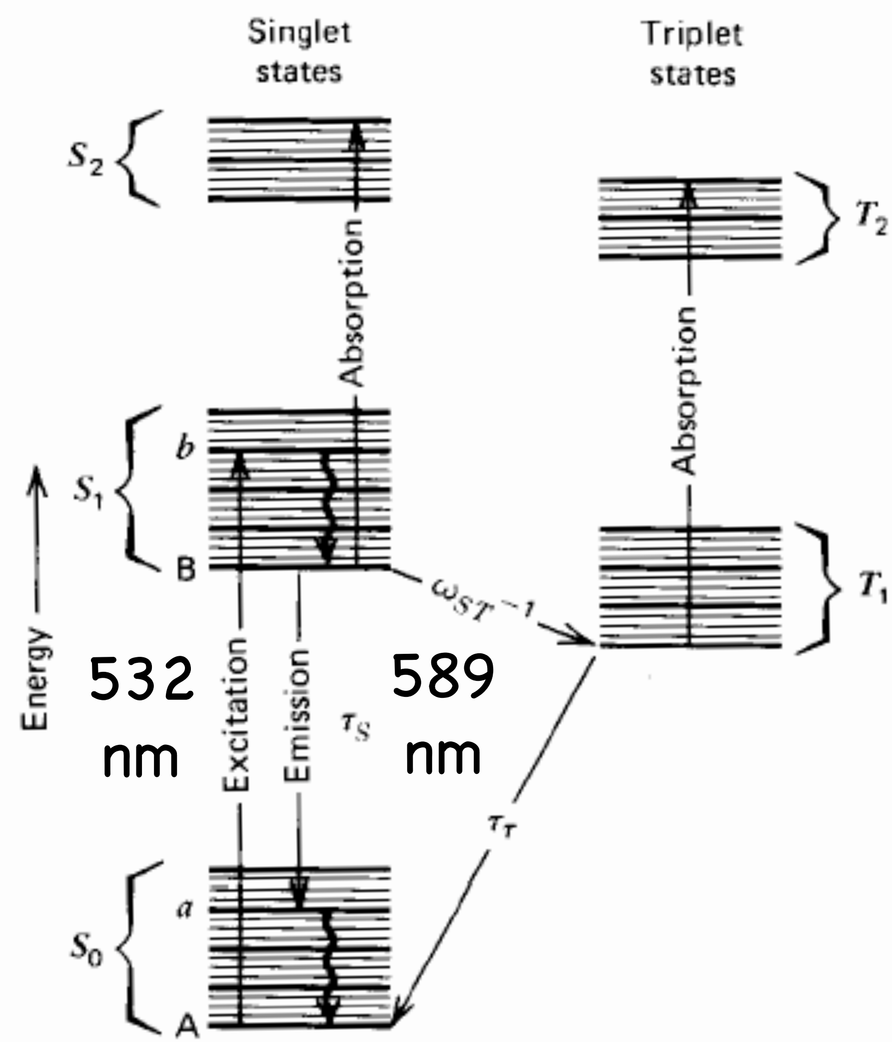
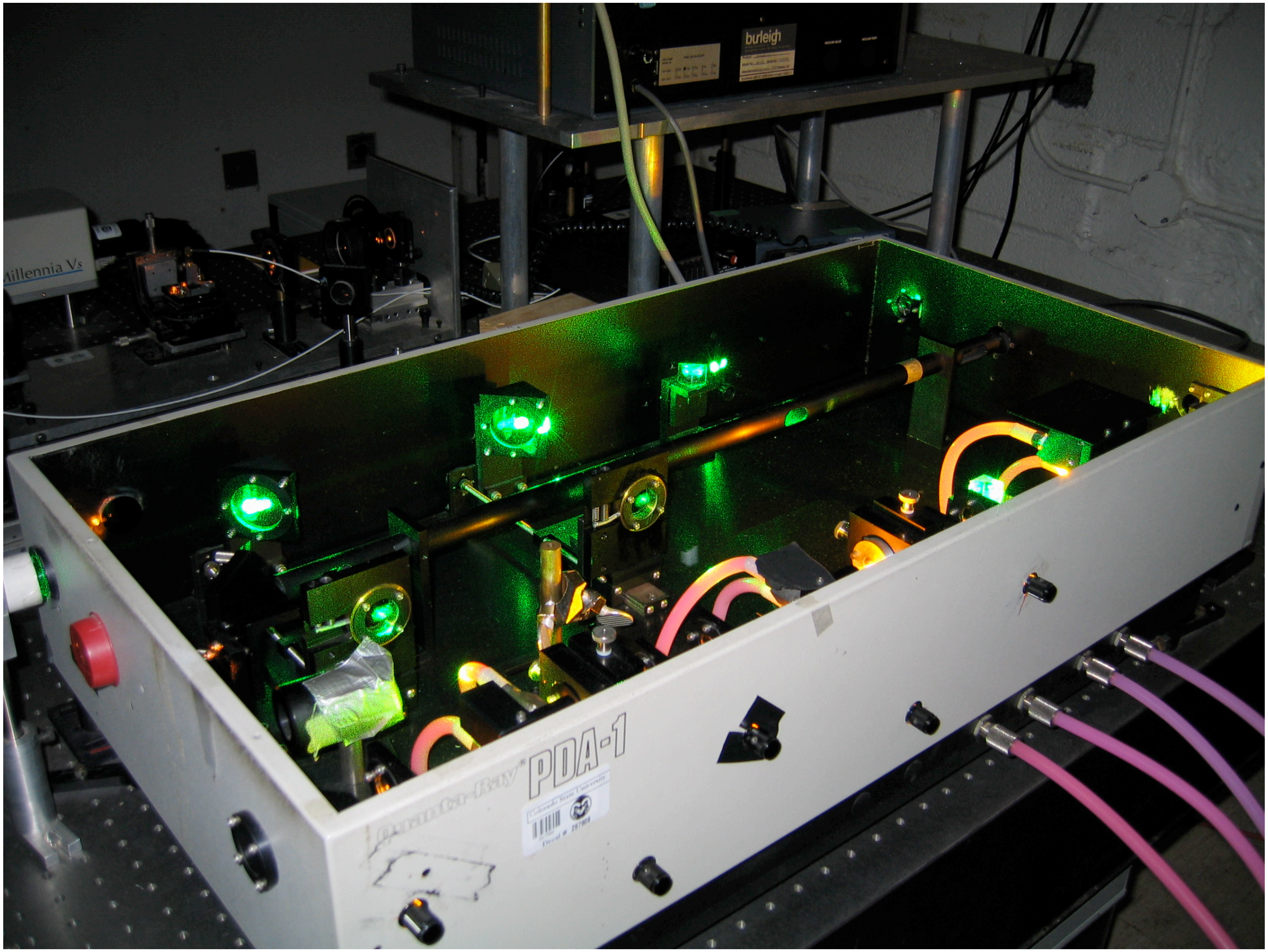


FIGURE 10.23 Schematic representation of the energy levels of an organic dye molecule. The heavy horizontal lines represent vibrational states, and the lighter lines represent the rotational fine structure. Excitation and laser emission are represented by the transitions $A \rightarrow b$ and $B \rightarrow a$, respectively.

CSU Pulsed Dye Amplifier

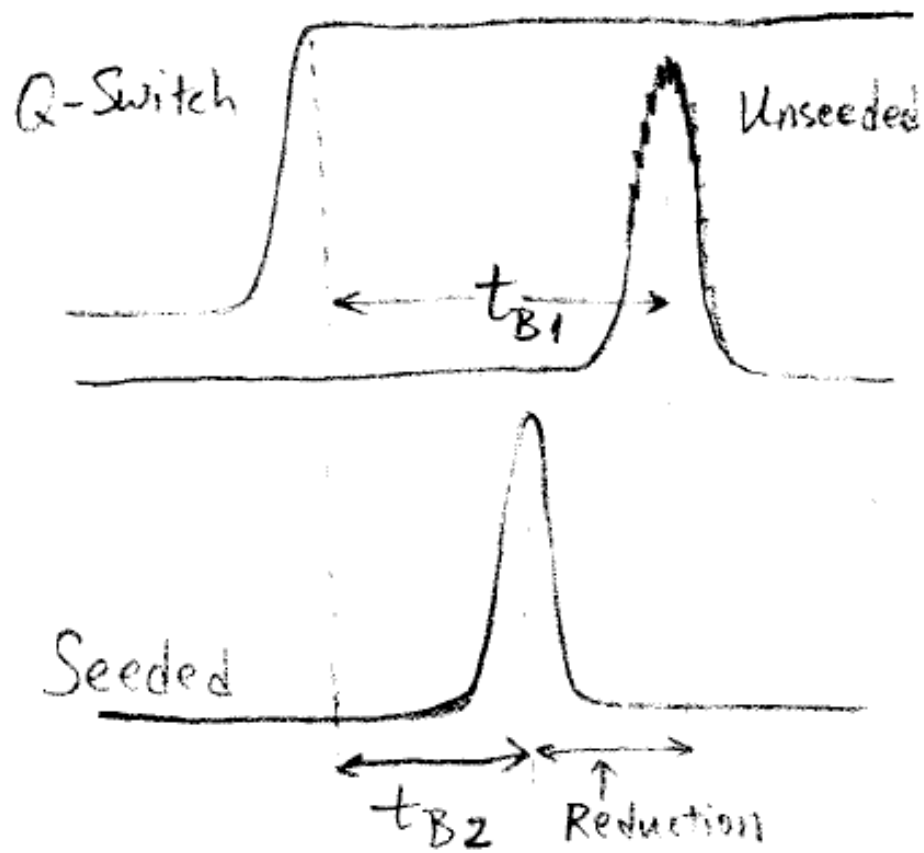


Injection-Seeded Nd:YAG Laser

- When the Nd:YAG laser is unseeded, many modes can be excited in the YAG laser cavity. The mode beating causes the YAG laser pulse (in time domain) has unsmooth shape. This causes the PDA output pulses to have numerous large side bands, so much wider than Fourier transform limit.
- The injection-seeding at fundamental wavelength 1064nm significantly reduces the possible number of modes that can lase and makes the Nd:YAG laser pulses to have nearly pure Gaussian shape with stable width and height.
- The resulting PDA output spectrum is nearly Fourier transform limited and highly reproducible.
- Injection seed photons also help the laser pulse to build up faster, as the intensity is many order of magnitudes larger than spontaneous emission photons.

Injection-Seeded Nd:YAG Laser

- Buildup-time reduction of the Nd: YAG laser pulse is used to monitor the injection seeding status.



PDA Output Frequency

- Actual PDA output not only has a broadened linewidth (larger than the Fourier transform-limitation) but also has a shifted central frequency. These effects are mainly caused by three factors:

(1) Amplified spontaneous emission (ASE)

(2) Unseeded Nd:YAG laser pulses

(3) Nonlinear effects during pulsed amplification – chirp!

- Frequency chirp is variation of instantaneous frequency with time, like a bird chirp.
- Chirp is mainly caused by the optical phase perturbation during pulsed amplification process.

PDA Frequency Chirp Issue

- Main causes for optical phase distortion include

(1) Heating of the dye solvent - cooling it

(2) Intensity dependence of the refraction index

(3) Time dependence of the gain

- Changing excited-state population

  → the time-varying susceptibility of the dye solution

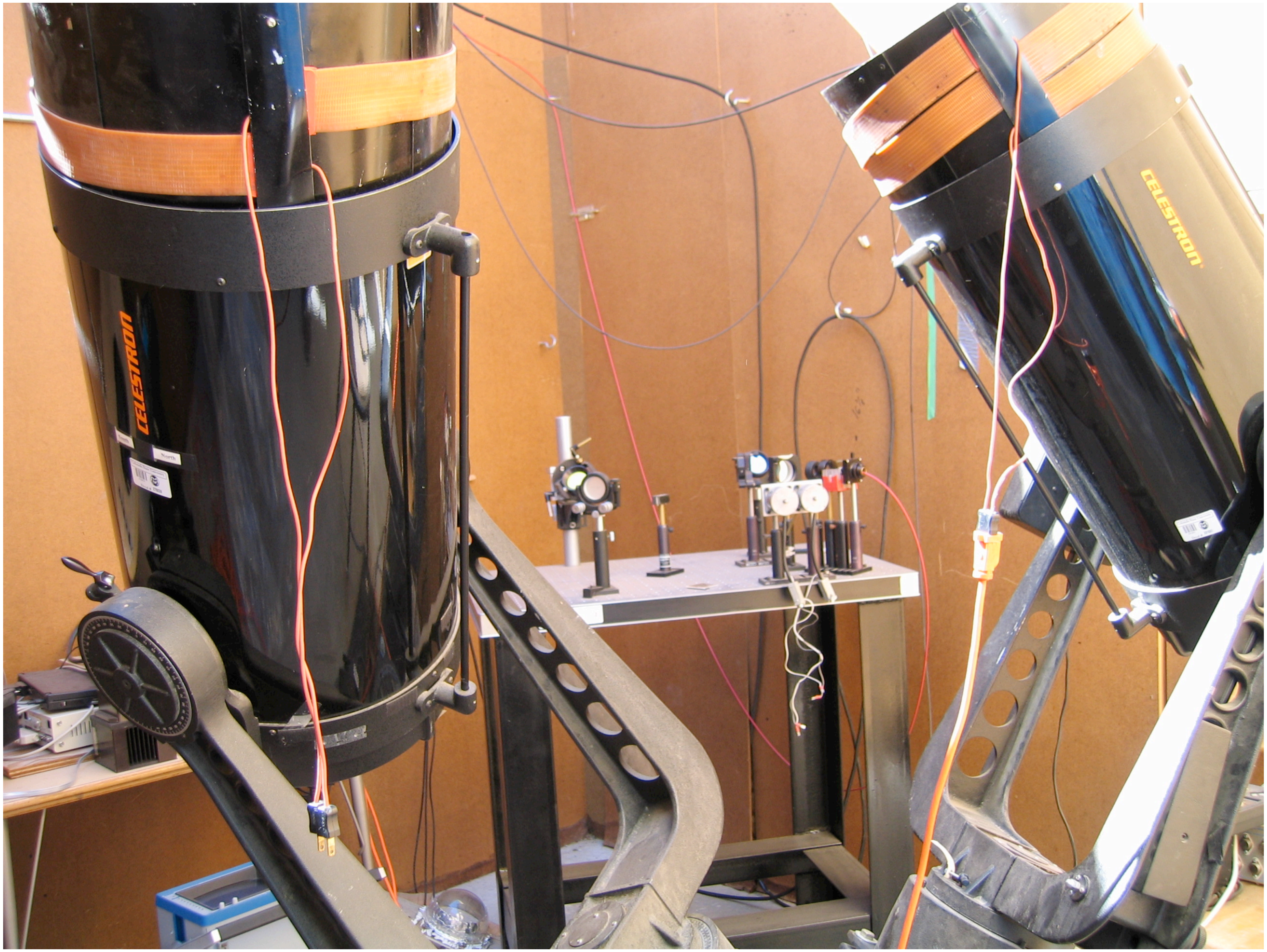
  → the change of refraction index

  → optical phase distortion

  → frequency variation with time during pulse buildup

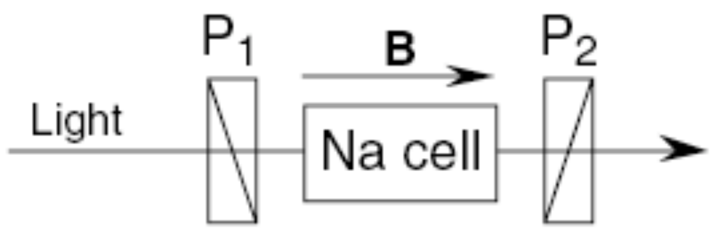
  → broadened linewidth and shifted central freq

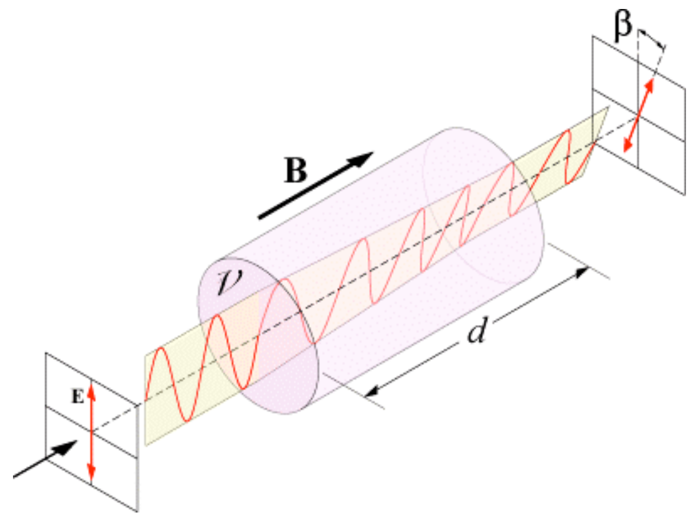
CSU Na Lidar Receiver



Faraday Effect

- Faraday effect is the rotation of light polarization by some media under magnetic field.





- Refraction index n of dilute Na vapor

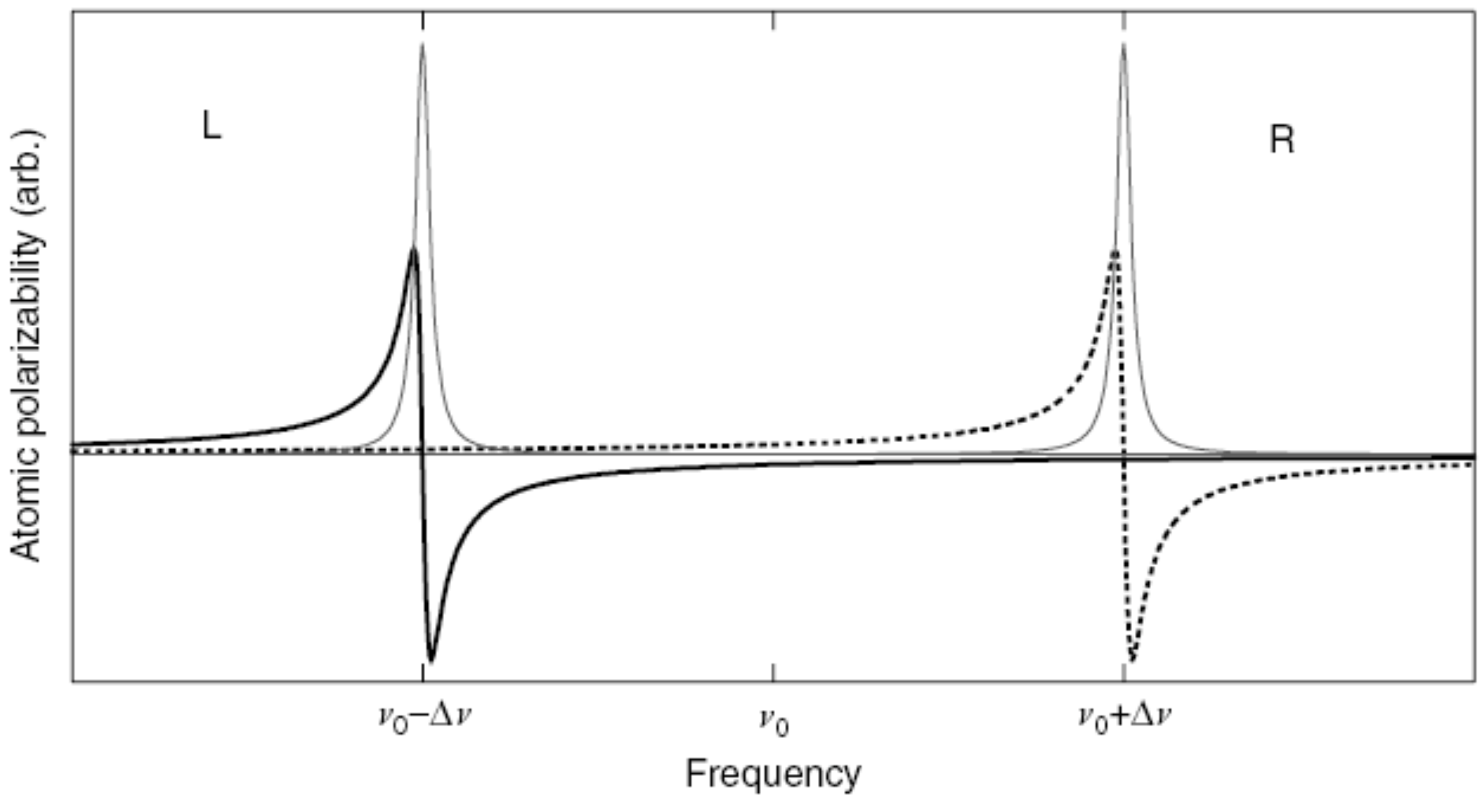
$$n = \sqrt{1+\chi} \cong 1 + \frac{1}{2}\chi = 1 + \frac{1}{2}\chi' - \mathrm{i}\frac{1}{2}\chi'' \qquad (5.74)$$

χ is the electric susceptibility of Na vapor

Faraday Effect under Zeeman Splitting

$$\chi' = \frac{Ne^2 f}{2m\omega\epsilon_0} \frac{\omega_0 - \omega}{(\omega_0 - \omega)^2 + (\gamma/2)^2}$$ Dispersion

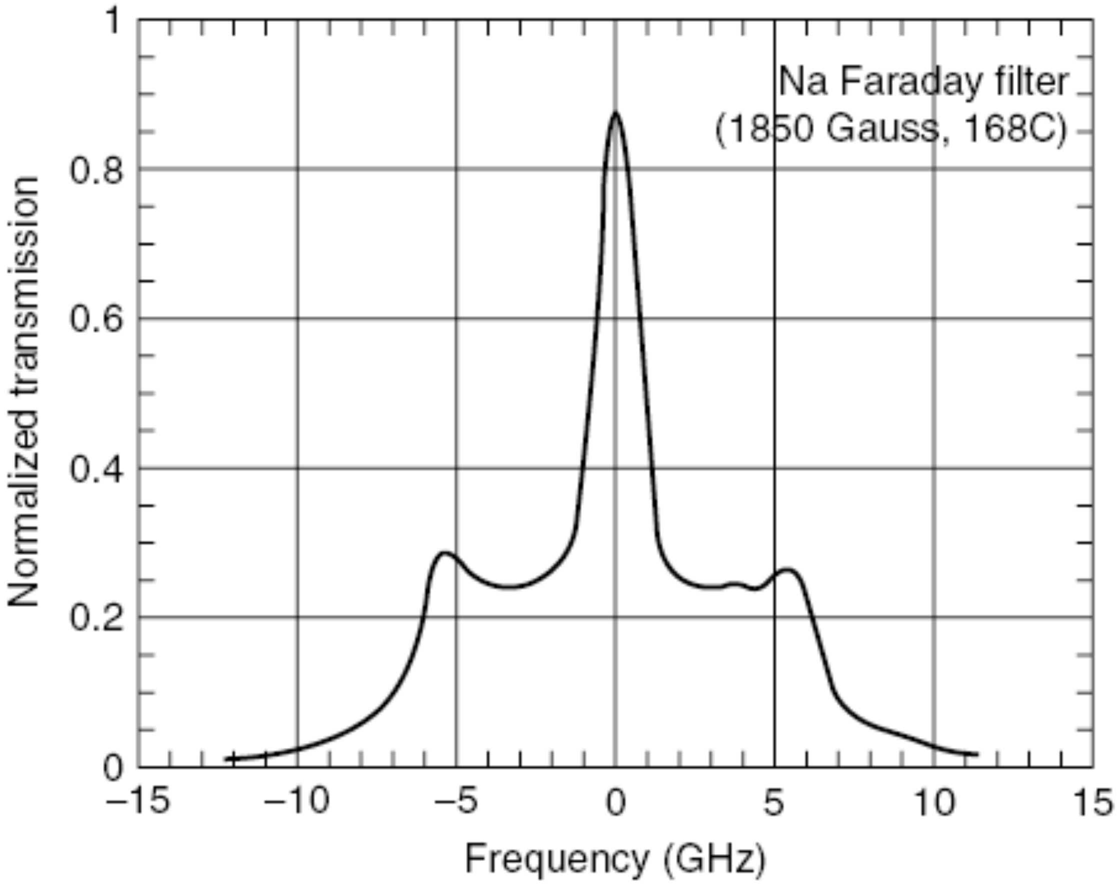
$$\chi'' = \frac{Ne^2 f}{2m\omega\epsilon_0} \frac{\gamma/2}{(\omega_0 - \omega)^2 + (\gamma/2)^2}$$ Resonance absorption



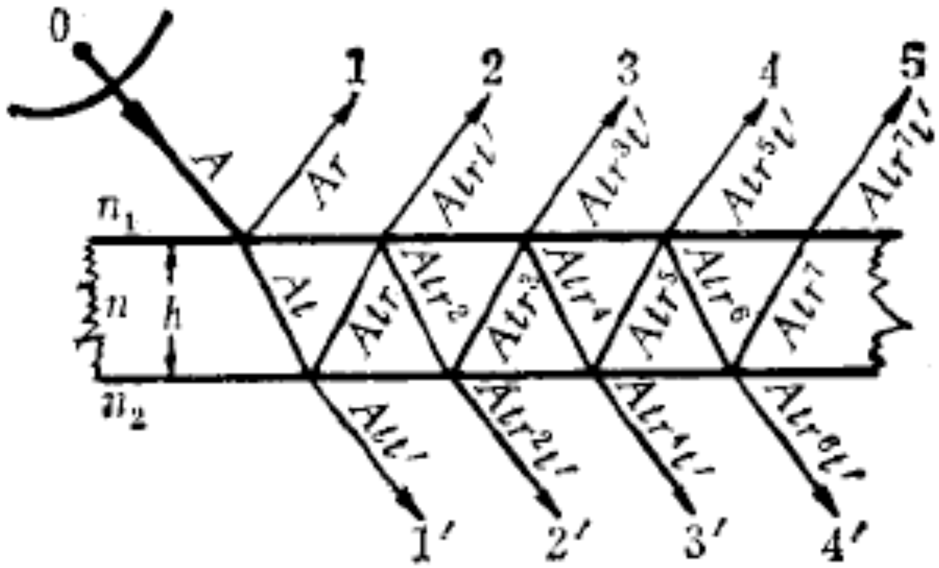
Faraday Filter

- Phase shift between two circular polarizations

$$\Delta\varphi = 2\pi \frac{l\Delta n}{\lambda}$$



Multiple Beam Interference



- Phase difference between two adjacent beams is given by

$$\delta = \frac{2\pi}{\lambda}\Delta L = \frac{2\pi}{\lambda} 2nh\cos i$$

- In the figure, t and r are the amplitude-transmission and reflection coefficients. Intensity transmission and reflectivity are the square of t and r, i.e., $T = t^2$ and $R = r^2$.

Multiple Beam Interference

- Total amplitude is the sum of multiple beam amplitudes

$$\tilde{U}_T = Att'(1 + r^2 e^{i\delta} + r^4 e^{2i\delta} + \dots) = \frac{Att'}{1 - r^2 e^{i\delta}}$$

- Thus, the transmission intensity is

$$I_T = \tilde{U}_T \tilde{U}_T^* = \frac{A^2 (tt')^2}{\left(1 - r^2 e^{i\delta}\right)\left(1 - r^2 e^{-i\delta}\right)} = \frac{I_0 (1 - r^2)^2}{1 - 2r^2 \cos\delta + r^4}$$

- Recall R = r^2, therefore, we have

$$I_T = \frac{I_0}{1 + \dfrac{4R\sin^2(\delta/2)}{(1-R)^2}}$$

Multiple Beam Interference

- When $\delta = 2k\pi$, the transmission light reaches maximum, which determines the transmission wavelength or frequency.
- If incident angle i = 0, transmission wavelengths and frequencies are determined by

$$2nh = k\lambda_k$$

$$\nu_k = \frac{c}{\lambda_k} = \frac{kc}{2nh}$$

- Thus, the frequency spacing or Free-Spectral-Range is

$$FSR = \frac{c}{2nh}$$

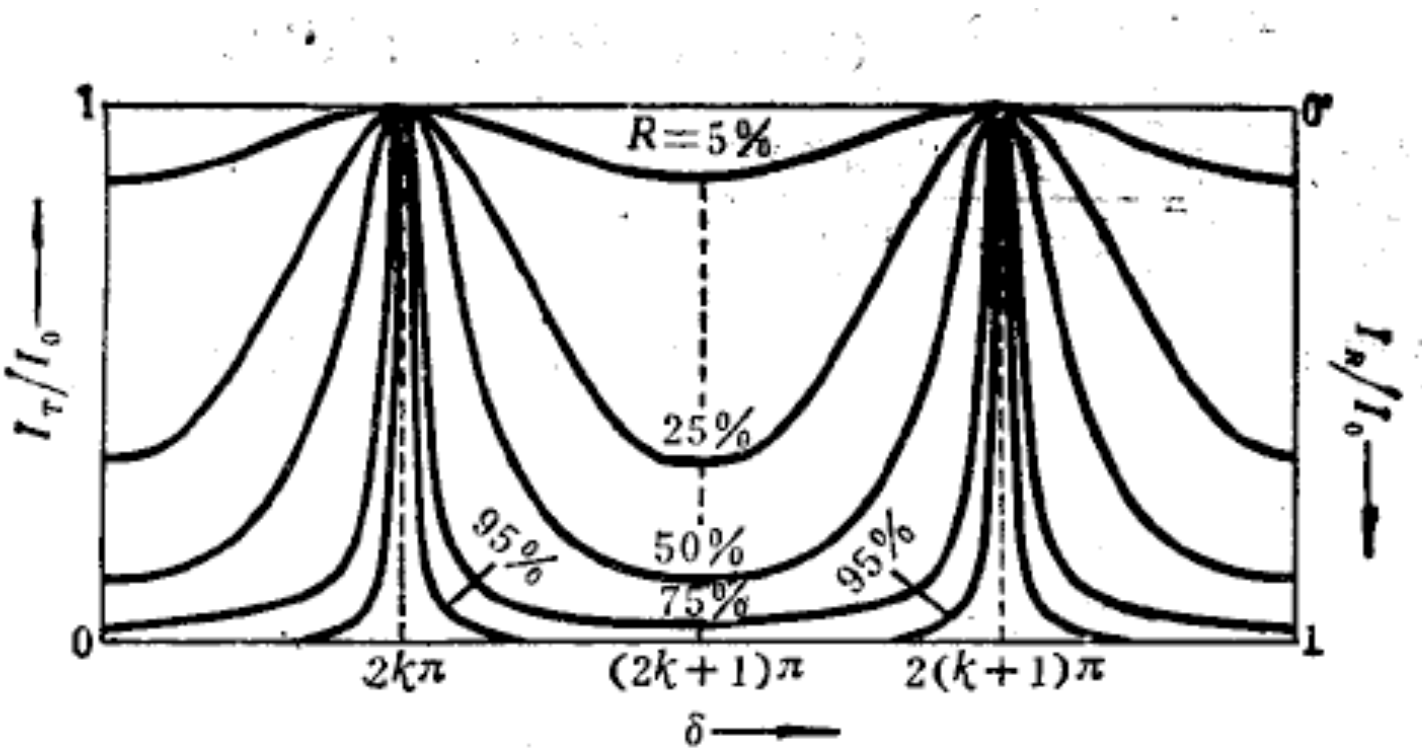
- Full-Width-at-Half-Maximum for each transmission line is

$$\Delta\nu_k = \frac{1-R}{\pi\sqrt{R}} \cdot \frac{c}{2nh}$$

- Finesse is defined as

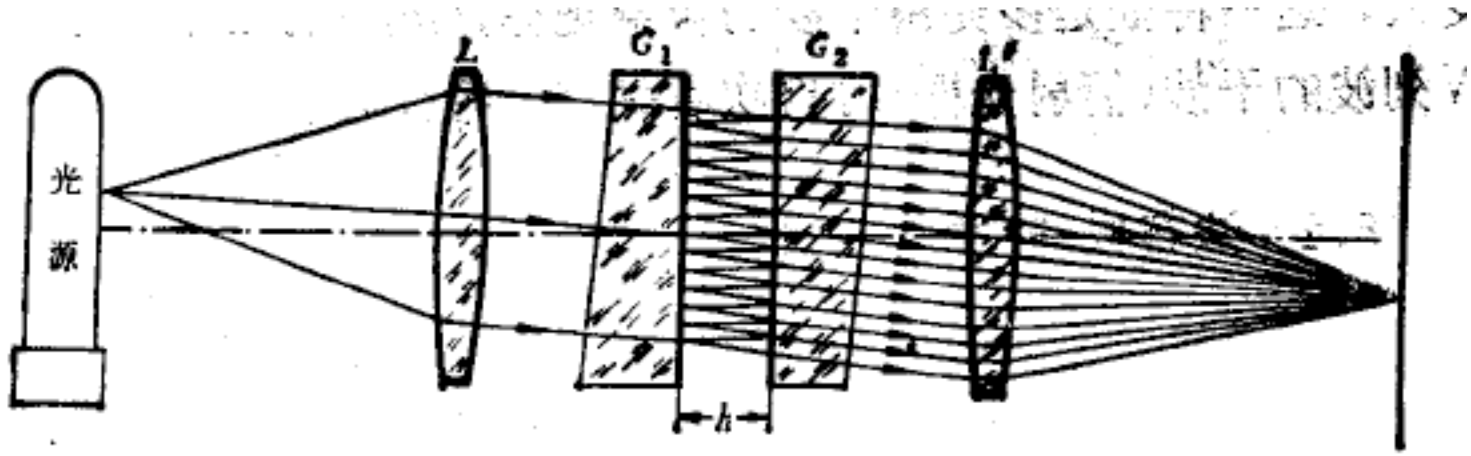
$$F = \frac{FSR}{\Delta\nu_k} = \frac{\pi\sqrt{R}}{1-R}$$

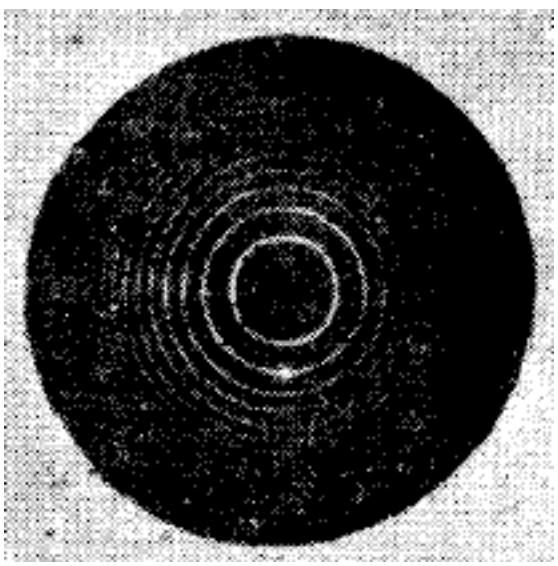
Interference Fringes

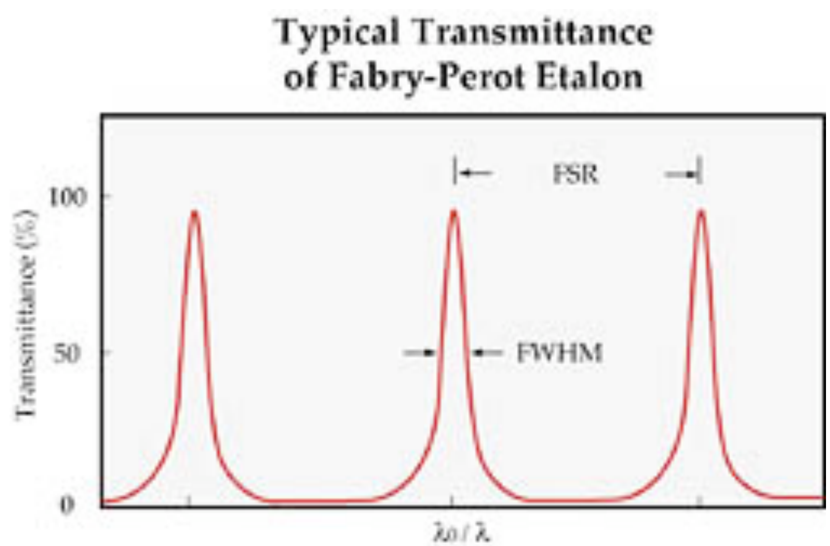


- Periodic transmission lines

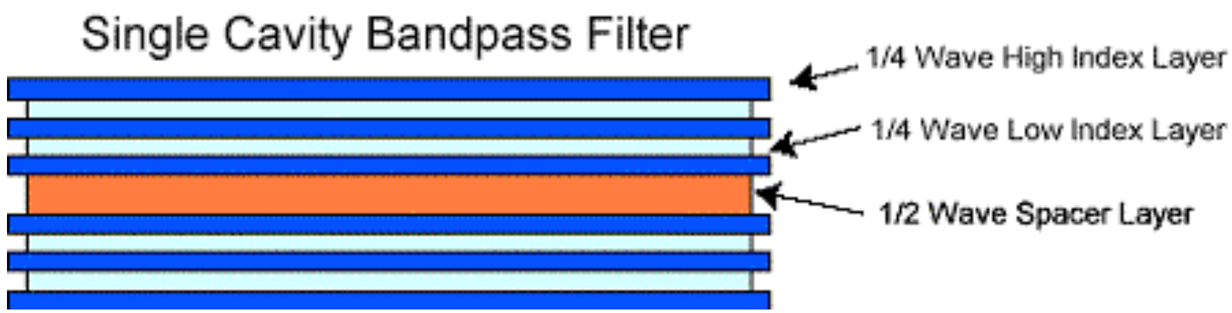
Fabry-Perot Etalon

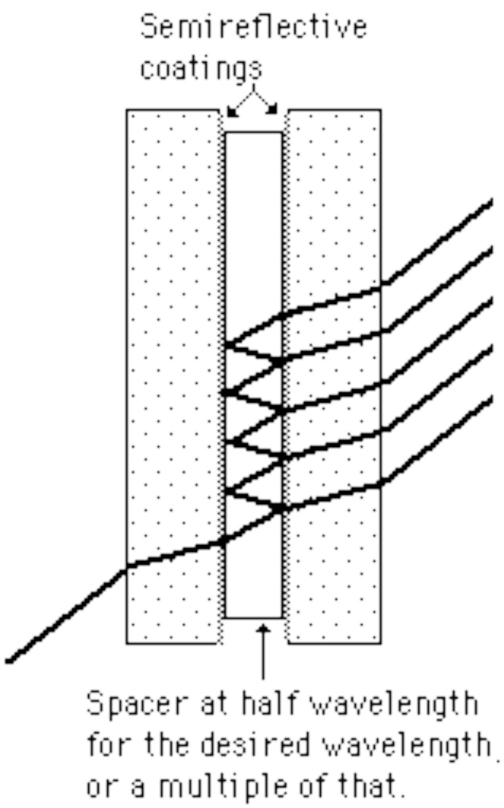






Interference Filter

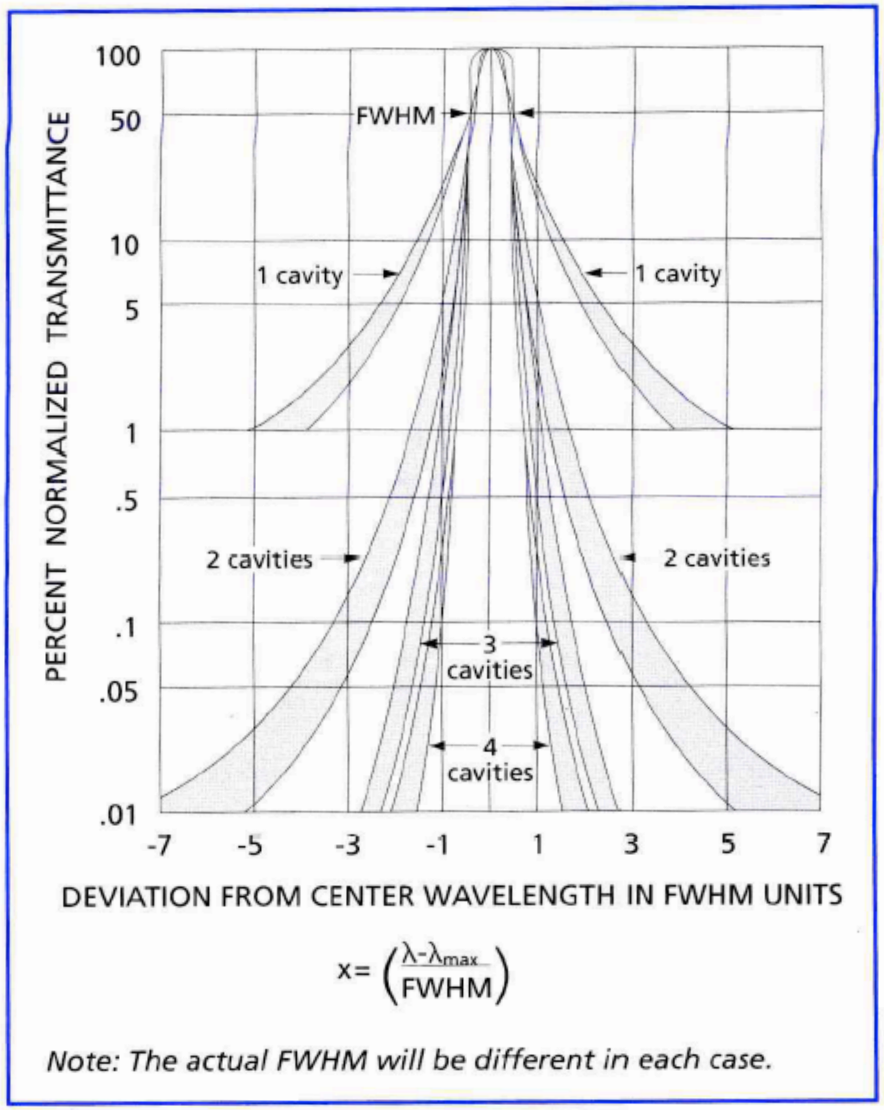




- Interference filters are multilayer thin-film devices, based on Fabry-Perot interferometer.
- Constructive interference at the desired wavelength (spacer $d = \lambda_0/2$) - round trip $2d = \lambda_0$
- Destructive interference at other wavelengths to block them.

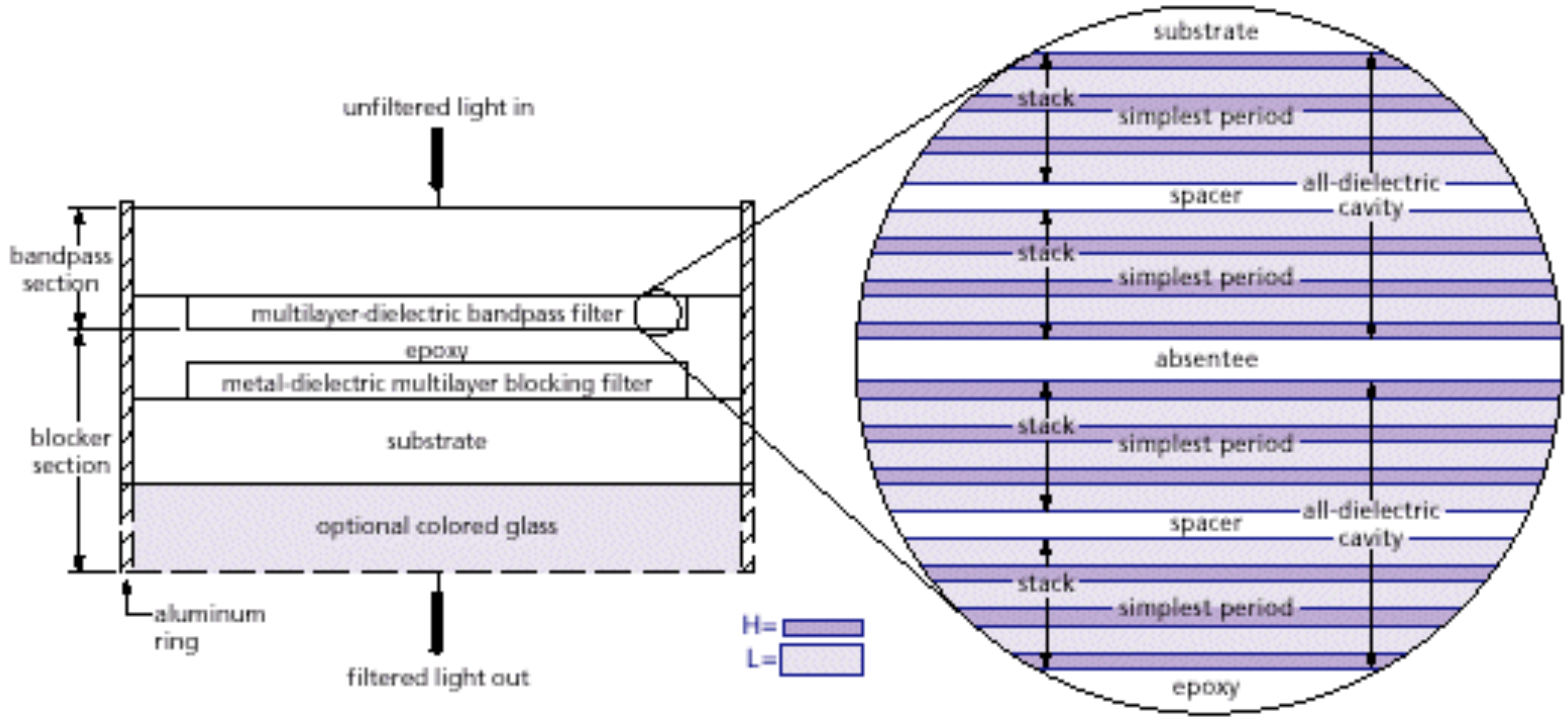
Multi-Cavity Interference Filter

- Multi-cavity interference filter gives better rejection to wavelength other than desired wavelength



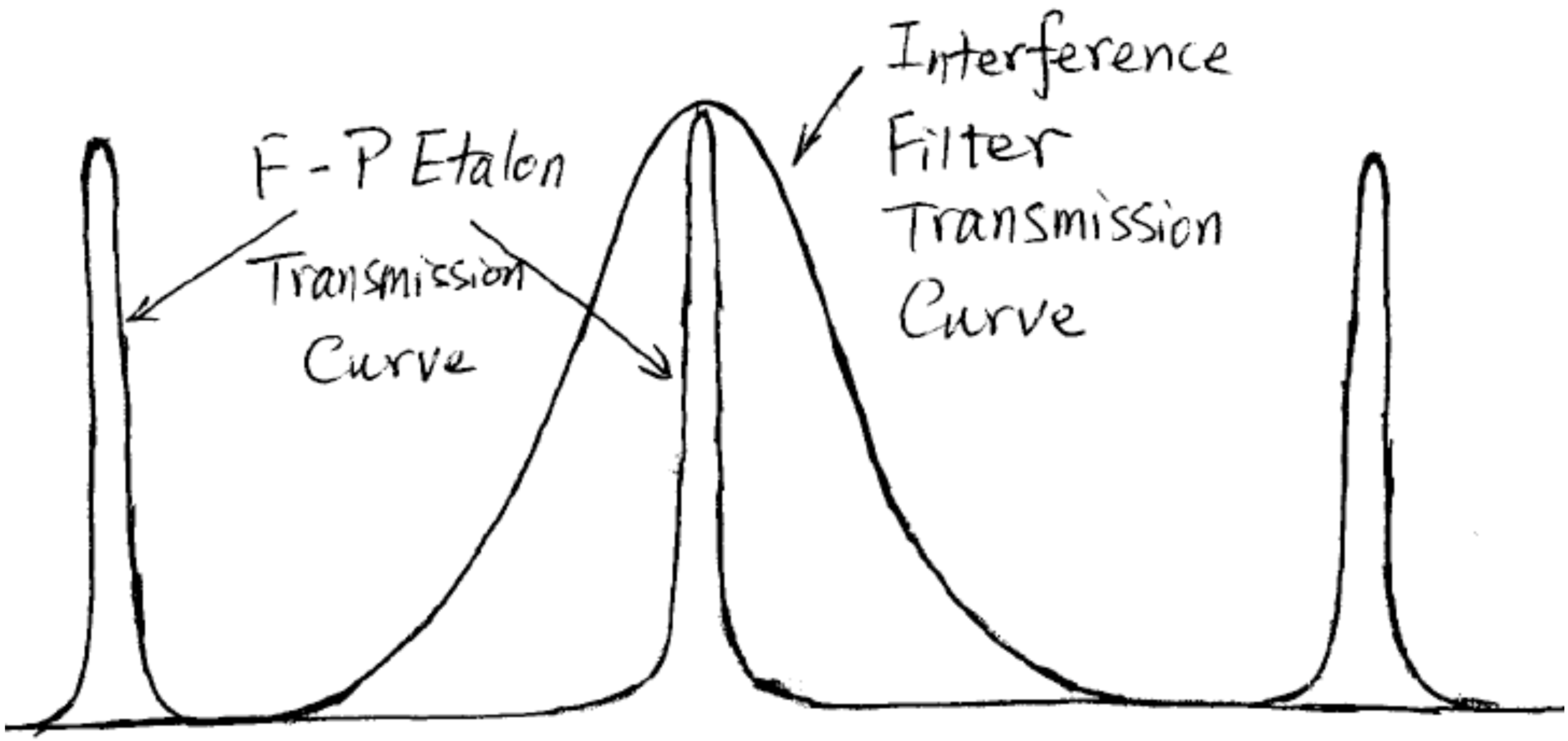
Effect of number of cavities on passband shape (normalized transmittance for ZnS/Na_3AlF_6 passband interference filters with 10-nm FWHM)

Interference Filter



- Colored glass etc is optional to further block wavelengths far away from desired wavelength, especially at shorter end.

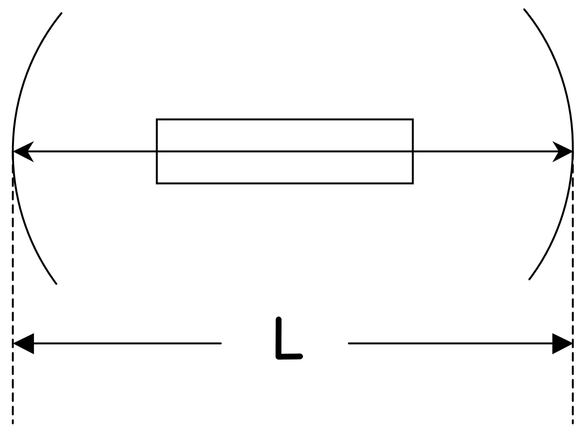
Combination of Interference Filter and Etalon in Lidar Receiver



- Typical bandwidth of F-P etalon in lidar receiver is about 10-30 GHz.

Laser Resonator: Positive Feedback

- Population inversion provides light amplification, however, a resonator is needed to maintain the laser oscillation.

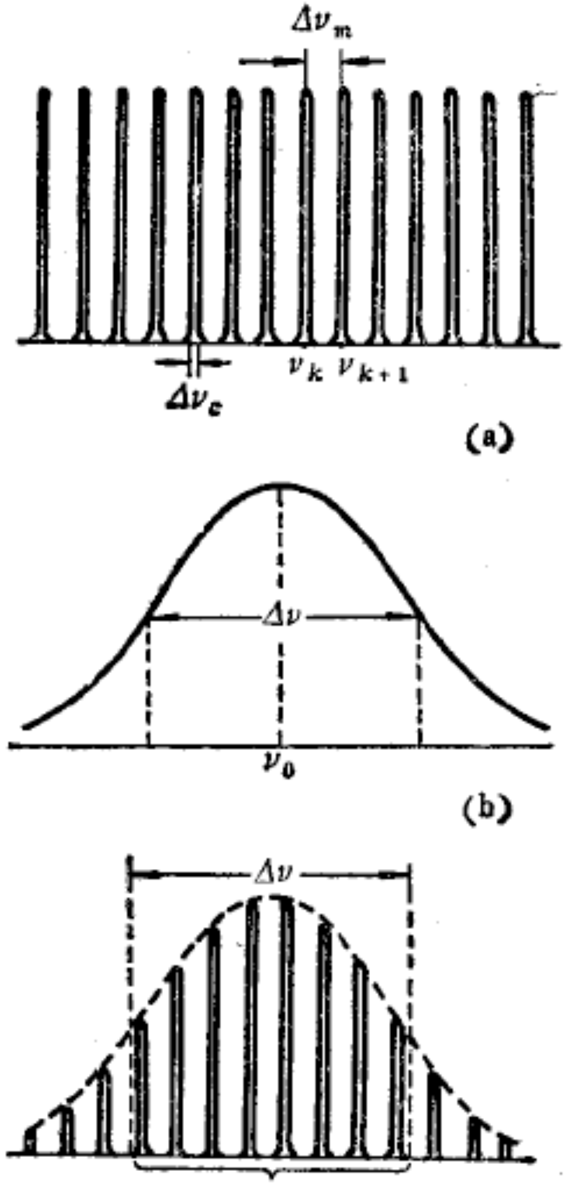


- For a round-trip inside the cavity, the optical length must satisfy the following relation

$$2nL = k\lambda$$

where n is refraction index, L is cavity length, λ is wavelength, and k is an integer number.

Resonator Characteristics



Cavity modes

$$2nL = k\lambda_1 = kc/\nu_1$$

$$2nL = k\lambda_2 = (k+1)c/\nu_2$$

Frequency spacing

$$\Delta\nu_m = \frac{c}{2nL}$$

Linewidth of each mode

$$\Delta\nu_k = \frac{1-R}{\pi\sqrt{R}} \cdot \frac{c}{2nL}$$

Longer cavity → smaller freq spacing

Longer cavity, high reflectivity

→ narrower linewidth

Laser: Gain vs. Loss

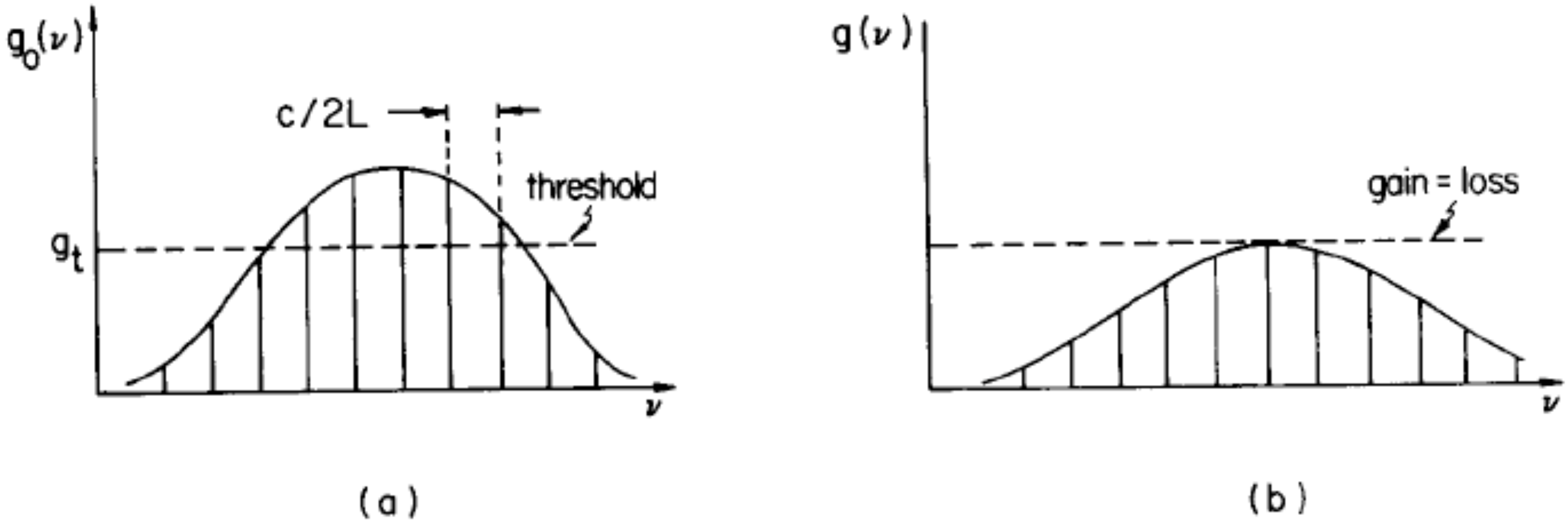
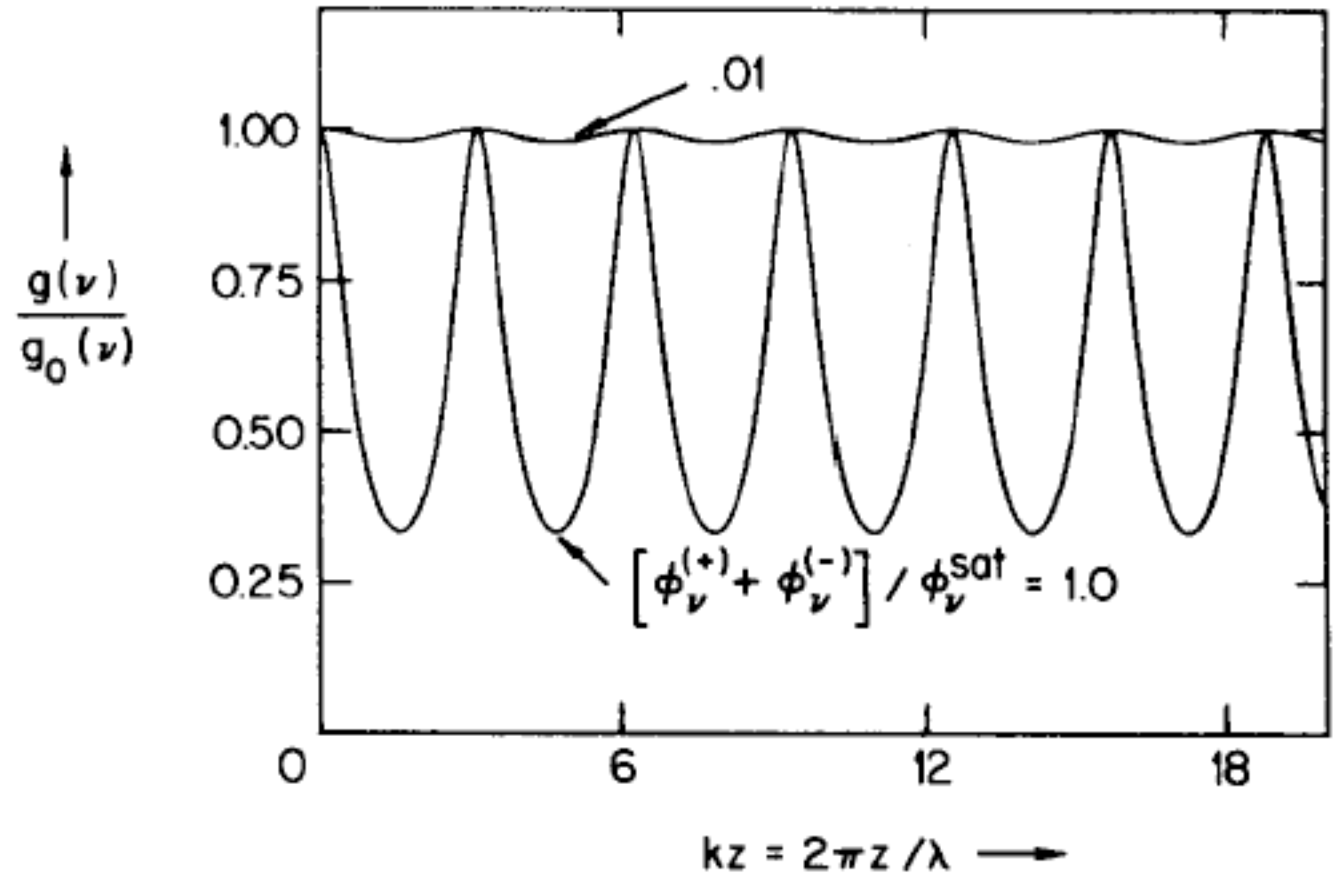


Figure 11.13 (*a*) A case in which five cavity modes have a small-signal gain g_0 larger than the threshold g_t for laser oscillation. (*b*) If the gain saturates homogeneously, only the mode with the largest small-signal gain is expected to lase. The others are saturated below the gain g_t necessary for laser oscillation.

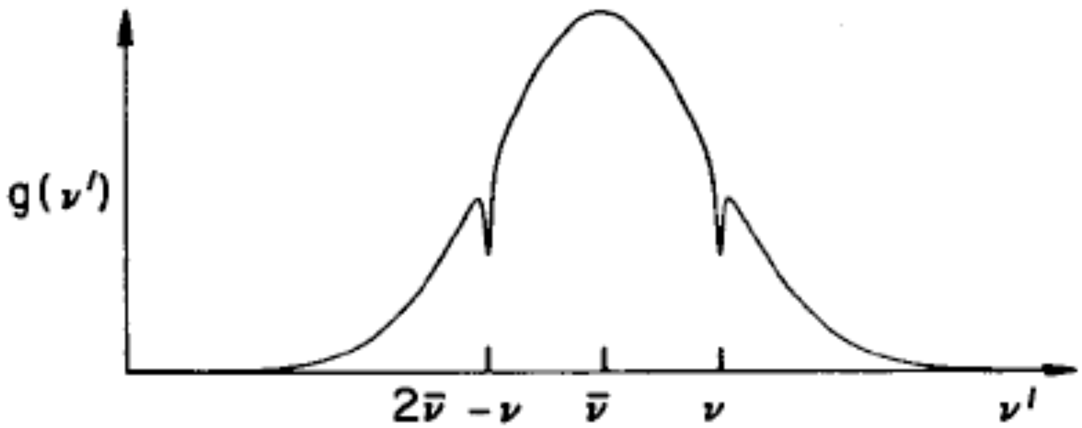
- In steady-state oscillation, "Gain = Loss". Therefore, without spatial and spectral hole burning, the laser is supposed to lase on only one mode at steady-state.

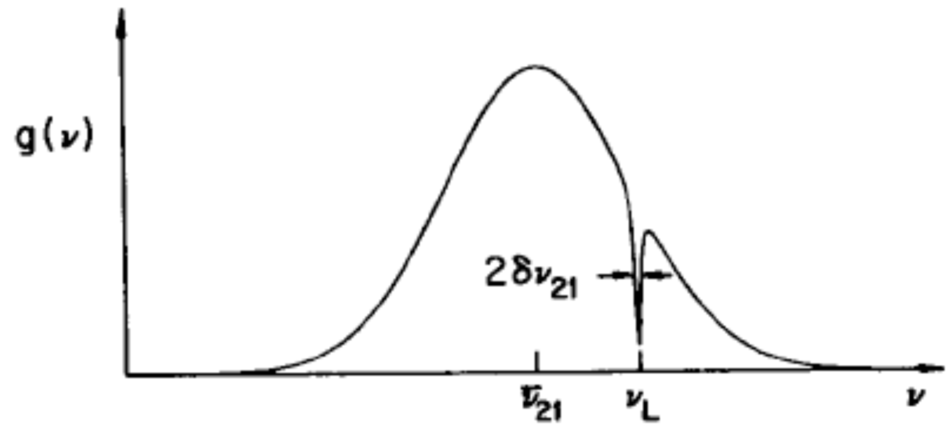
Spatial Hole Burning



- Standing wave causes spatial hole burning inside laser cavity, i.e., gain saturation is different at different spatial locations. It could be mitigated by atomic motion.

Spectral Hole Burning

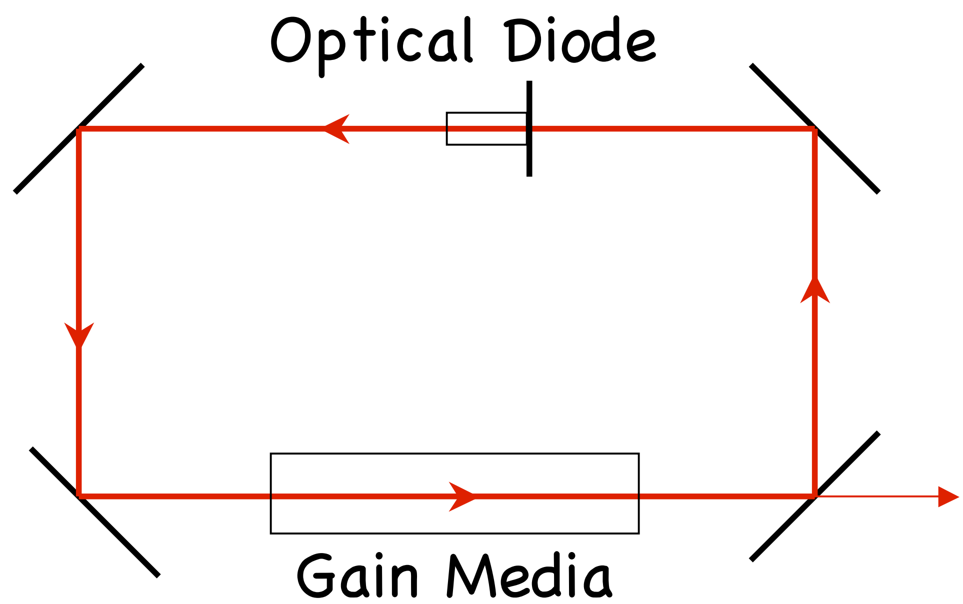




- ❑ Both standing wave and traveling wave can cause spectral hole burning in inhomogeneously broadened gain profile.
- ❑ Spatial and spectral hole burning allow multiple modes oscillations in laser cavity.

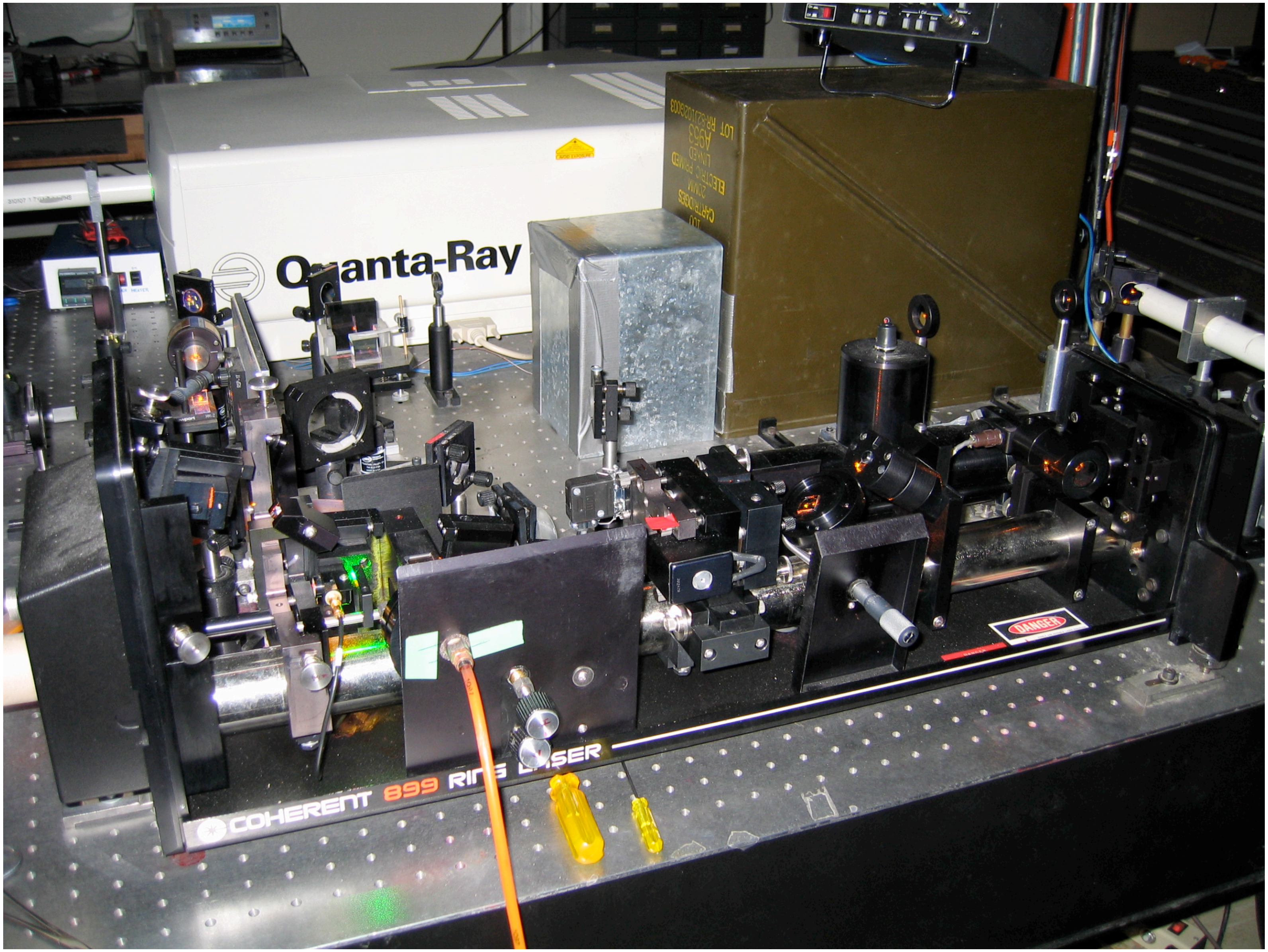
Solutions to Achieve Single-Mode

- To remove spatial hole burning, use traveling wave ring laser cavity.

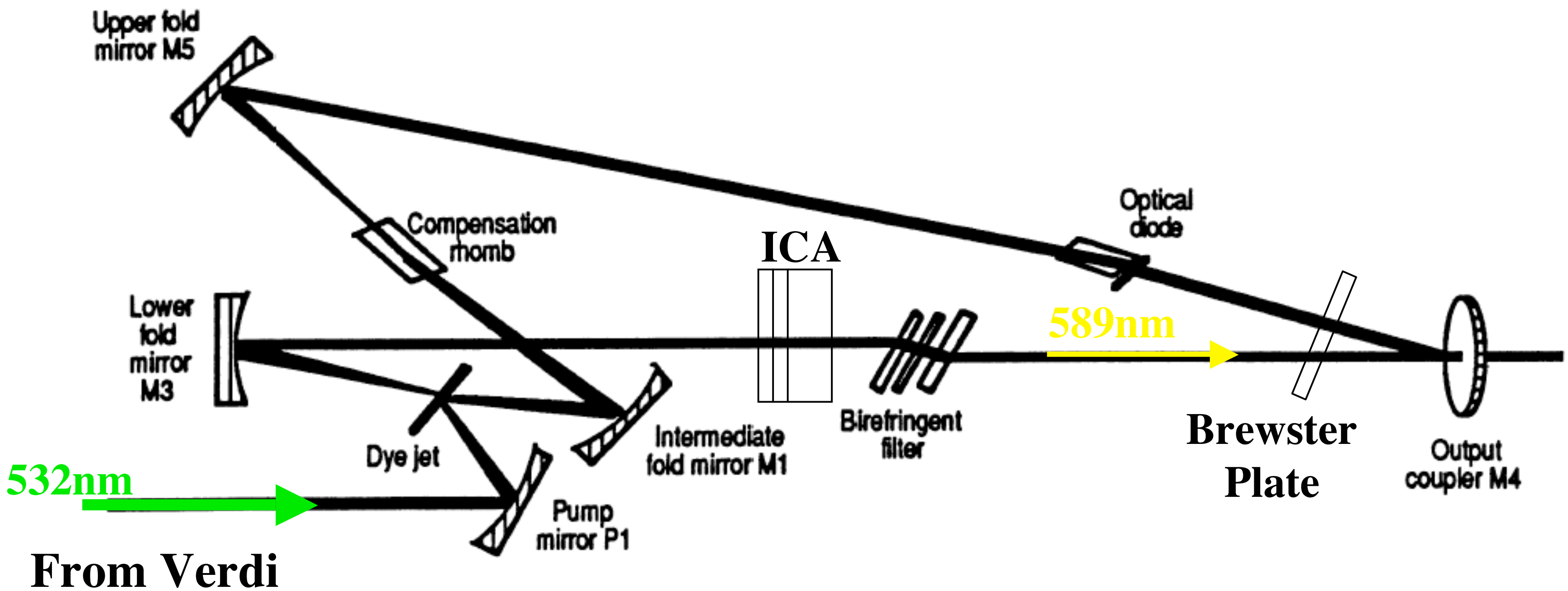


- To remove spectral hole burning, use homogeneously broadened gain medium, e.g., dye solvent has collision broadening - homogeneous broadening.
- To achieve reliable single-frequency operation, more passive optical filters and active stabilization techniques are needed to narrow down linewidth and ensure single-mode and single-frequency laser operation.

Ring Dye Laser

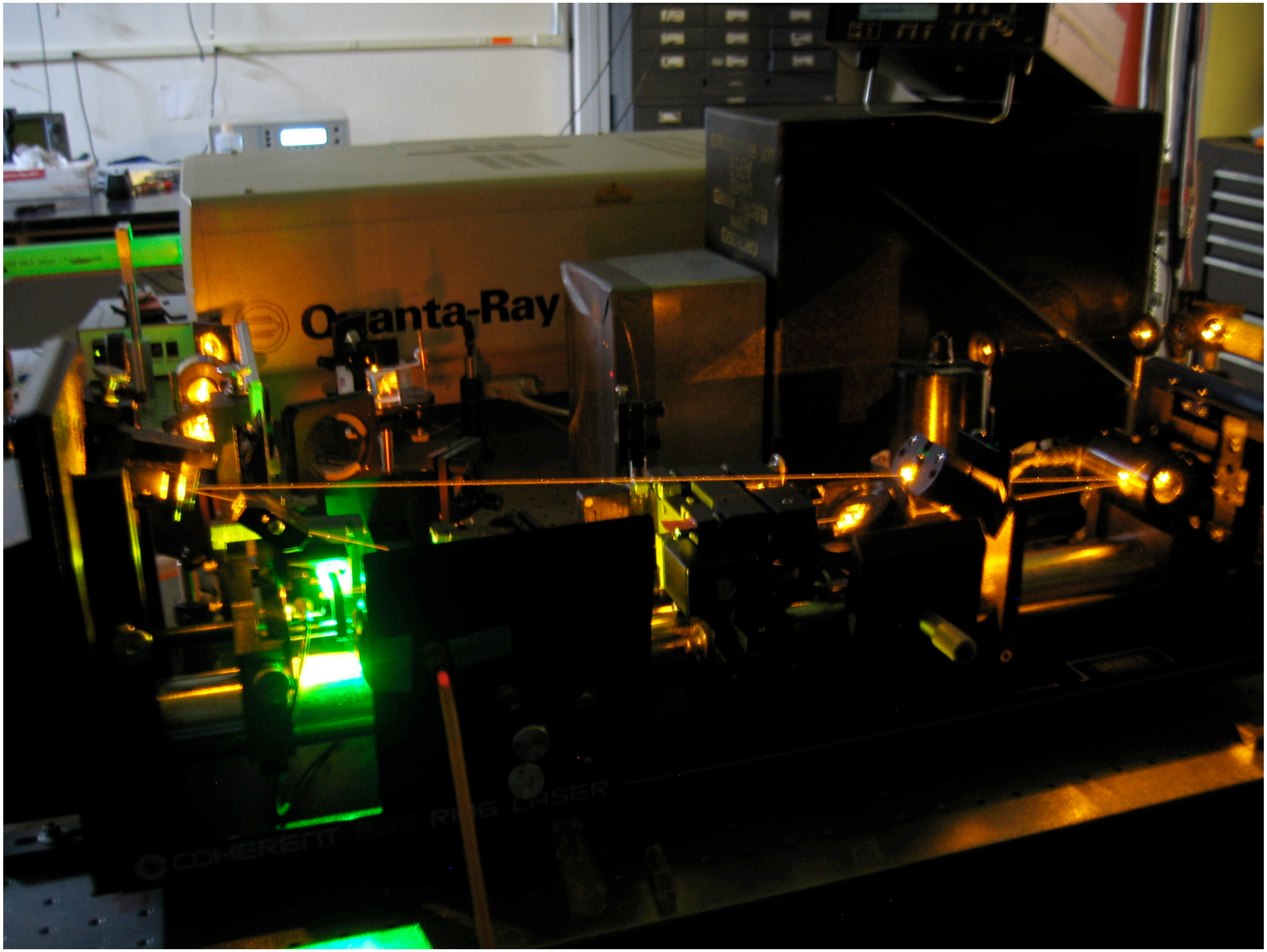


Ring Dye Laser

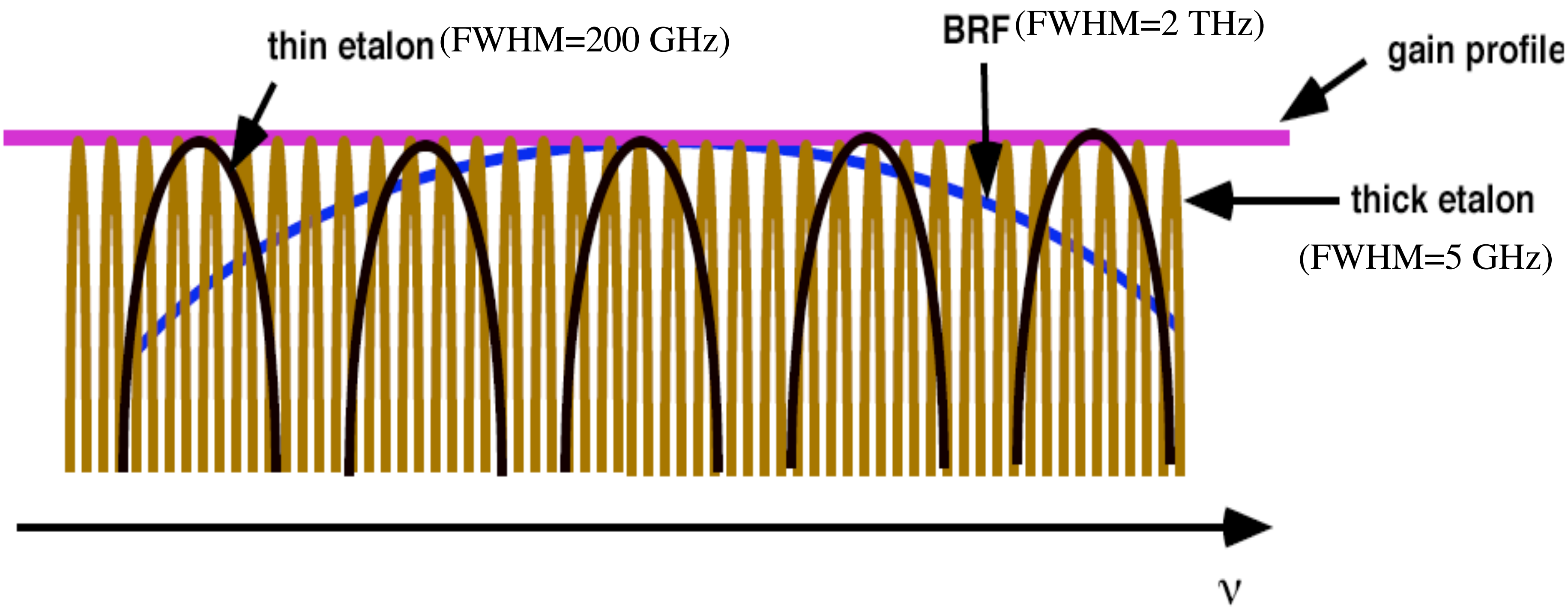


1. "Four mirror + Dye jet" form the laser resonance cavity.
2. Unidirectional lasing prevents spatial hole-burning.
3. Rhomb compensates the astigmatism effect.
4. Optical diode forces the unidirectional lasing.
5. BRF + ICA (etalons) select frequency and narrow bandwidth.
6. "Brewster plate + RCA + M3 PZT" actively control frequency.

Ring Dye Laser



Overall Frequency Selection



- Mode competition and Gain vs. Loss

Freq Selection by BRF & Thin Etalon

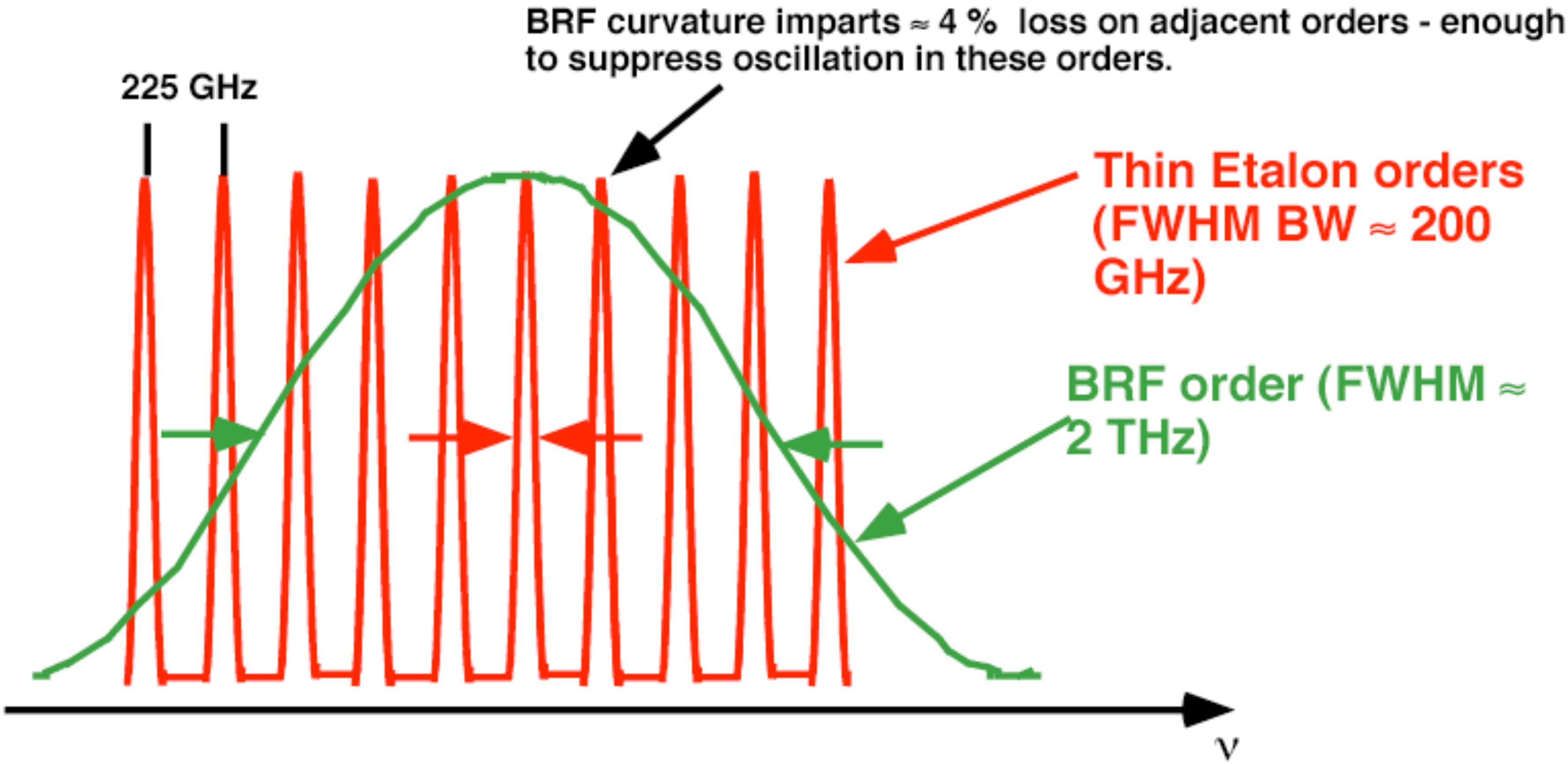


Figure 1.1-17. Thin Etalon Frequency Selection.

Freq Selection by Thick Etalon

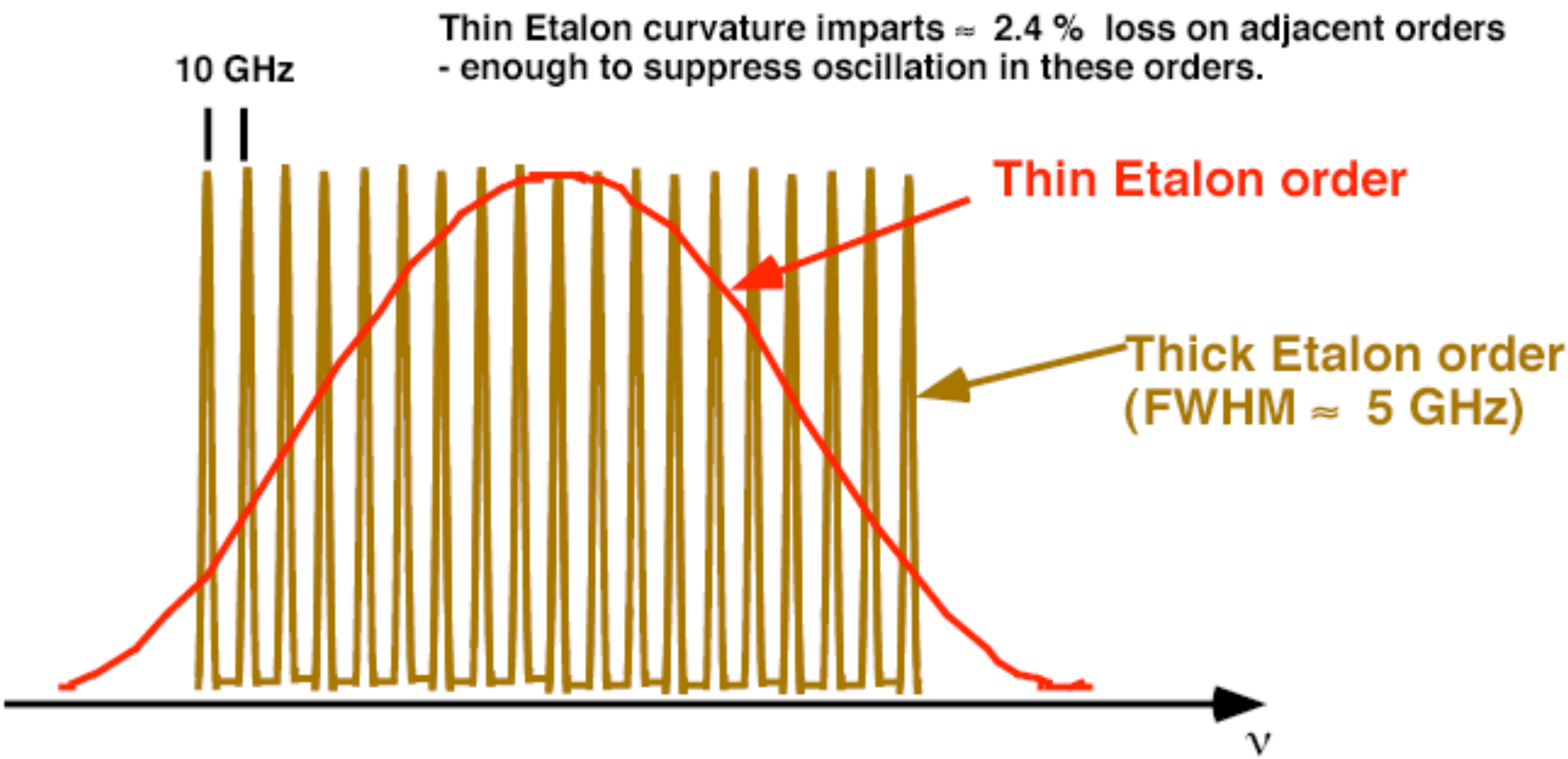
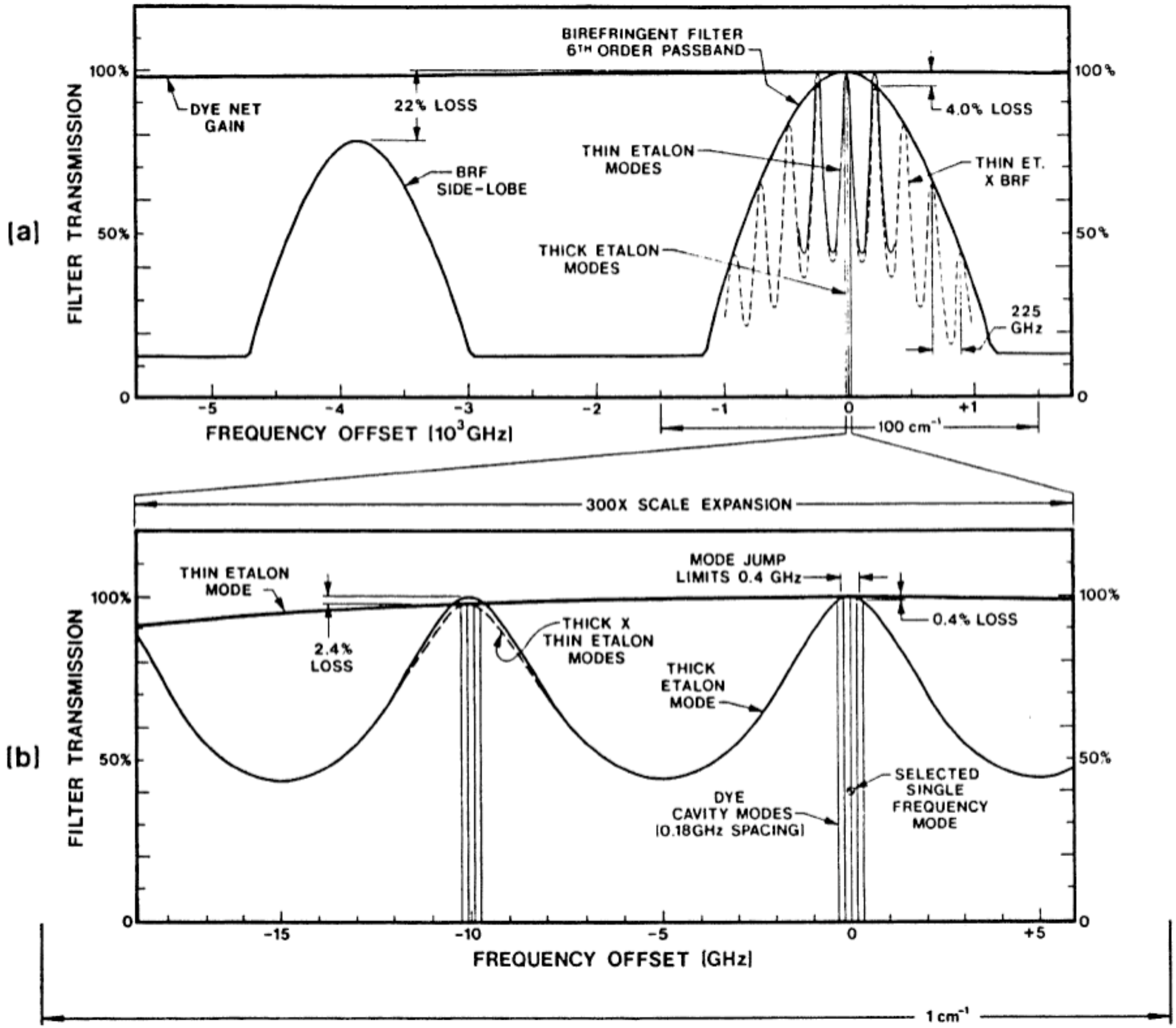


Figure 1.1-18. Thick Etalon Frequency Selection.



[a]
FILTER TRANSMISSION
100%
50%
0
BIREFRINGENT FILTER
6TH ORDER PASSBAND
DYE NET
GAIN
22% LOSS
4.0% LOSS
BRF
SIDE-LOBE
THIN ETALON
MODES
THIN ET.
X BRF
THICK ETALON
MODES
225
GHz
-5
-4
-3
-2
-1
0
+1
FREQUENCY OFFSET [10^3 GHz]
100 cm^-1
300X SCALE EXPANSION
[b]
THIN ETALON
MODE
MODE JUMP
LIMITS 0.4 GHz
0.4% LOSS
2.4%
LOSS
THICK X
THIN ETALON
MODES
THICK
ETALON
MODE
DYE
CAVITY MODES
(0.18GHz SPACING)
SELECTED
SINGLE
FREQUENCY
MODE
-15
-10
-5
0
+5
FREQUENCY OFFSET (GHz)
1 cm^-1

Frequency Locking in Ring Laser

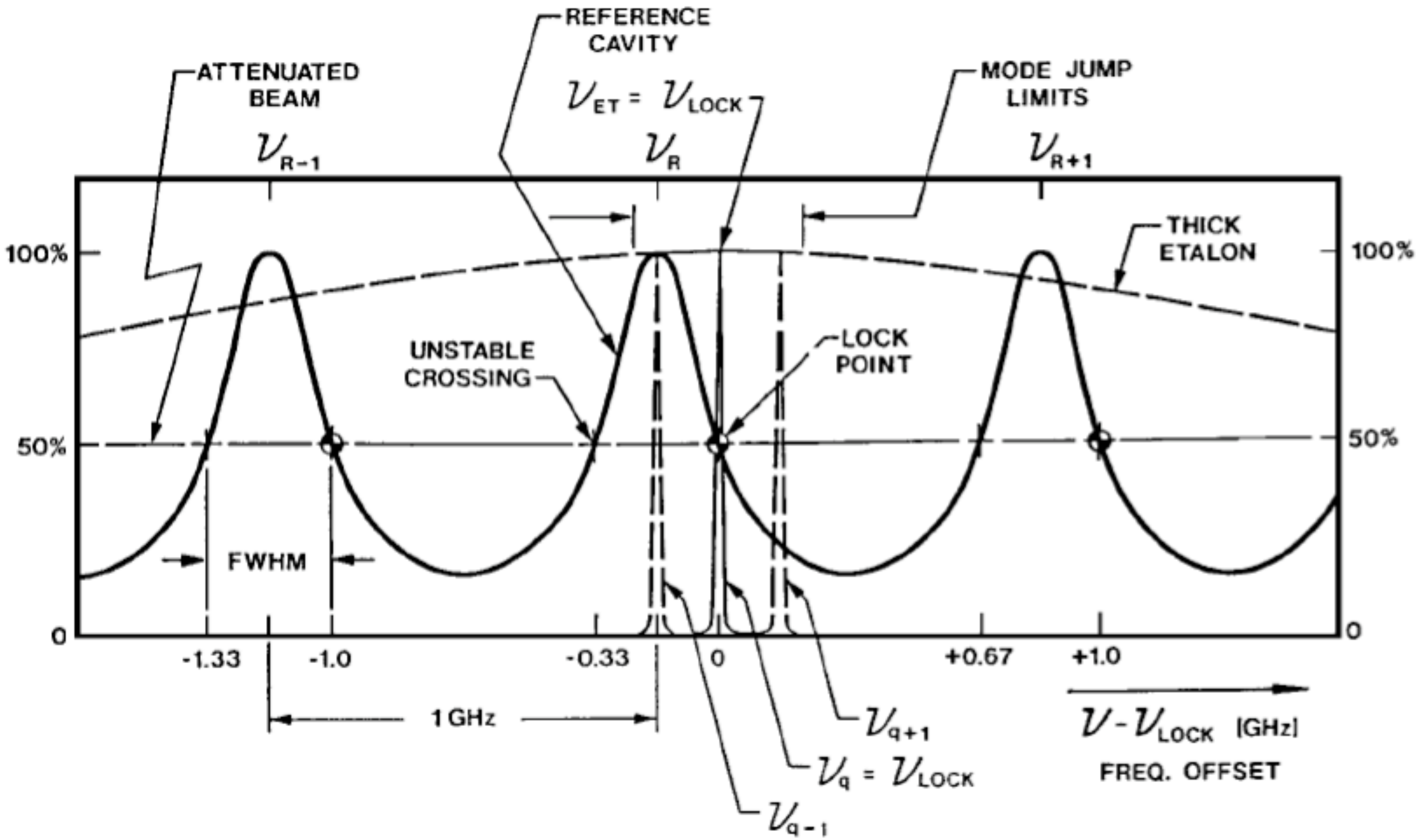
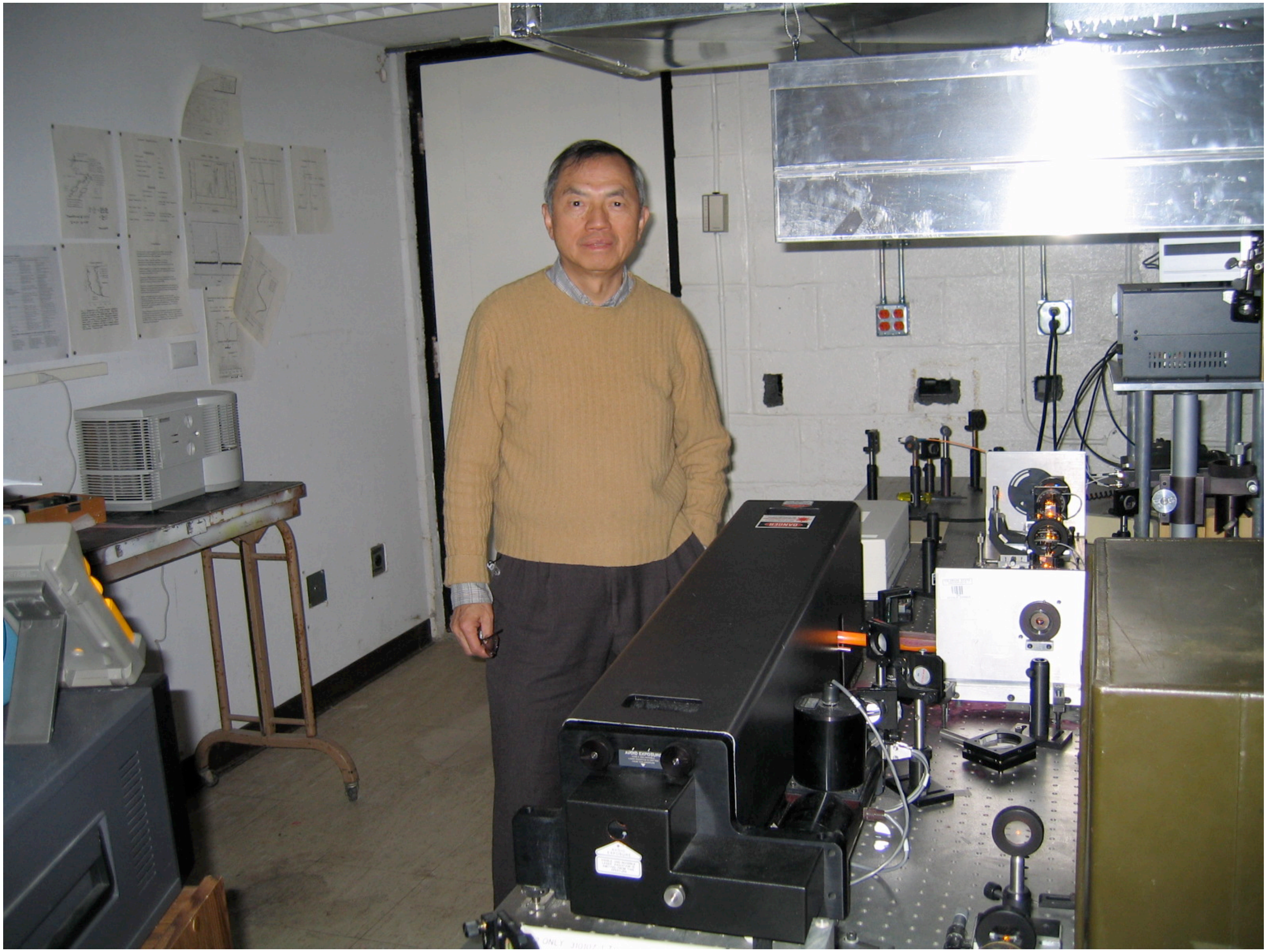


Figure 1.1-24. Reference Cavity: Transmission.

Prof. Chiao-Yao She @ CSU Lidar



Ring Laser Frequency Tuning & Locking

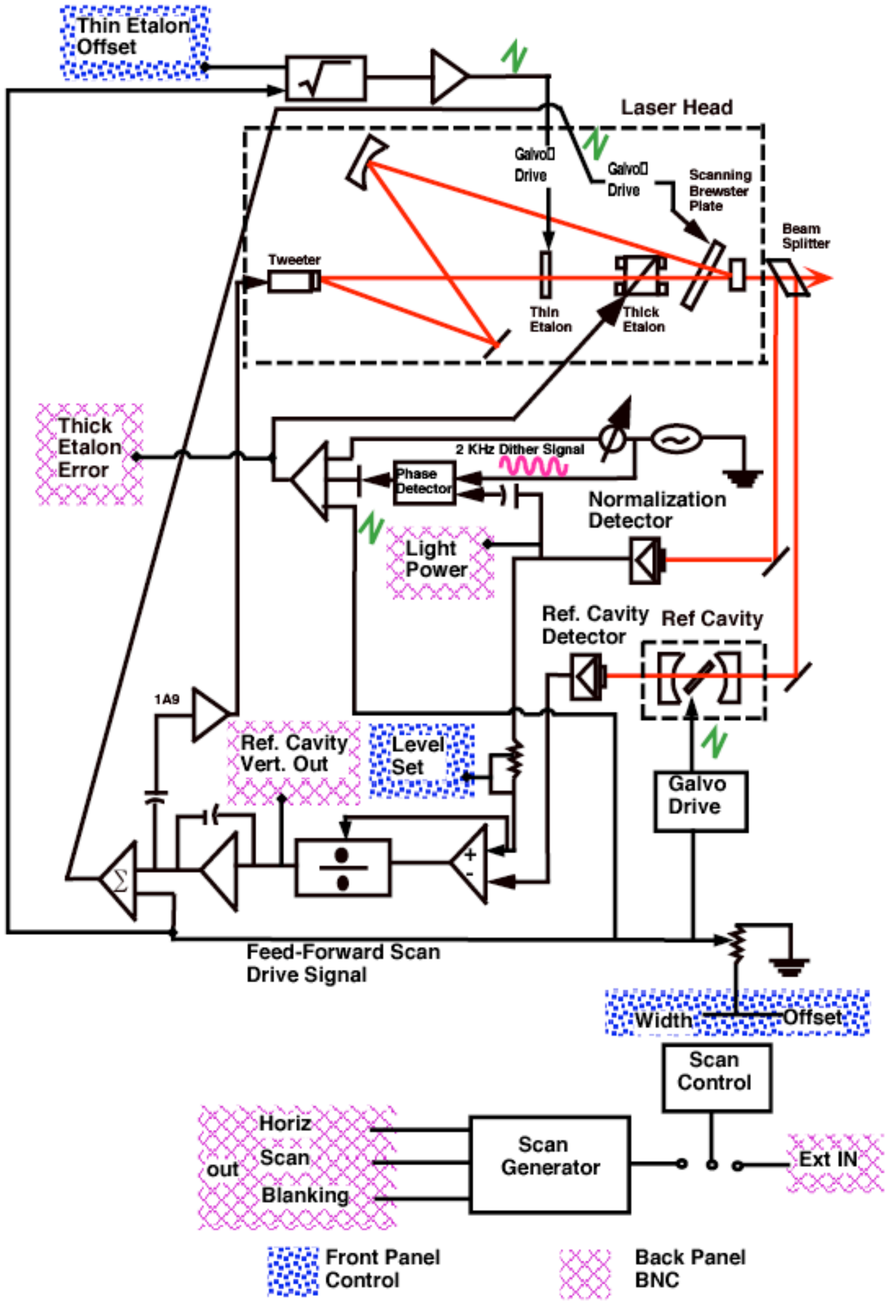
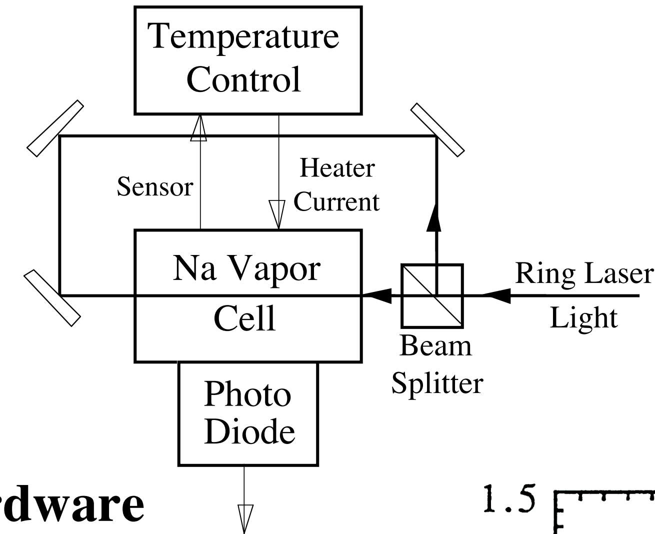
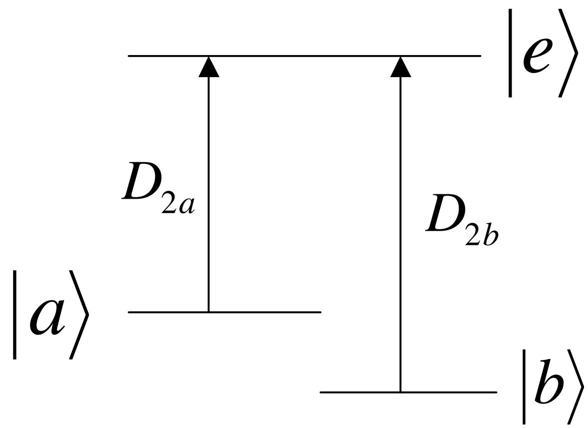


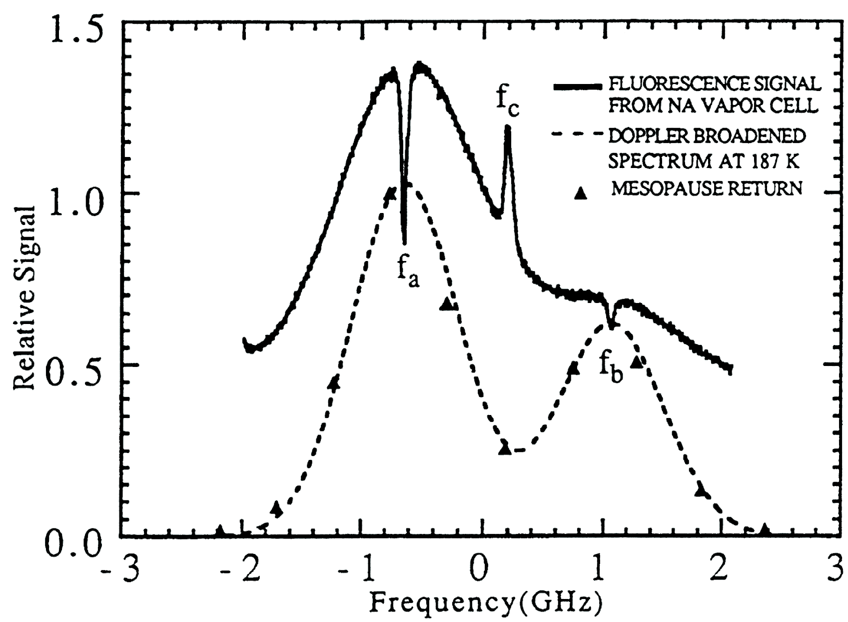
Figure 1.1-26. Ring Laser Optical and Electronic Layout.

Na Saturation-Absorption Spectroscopy



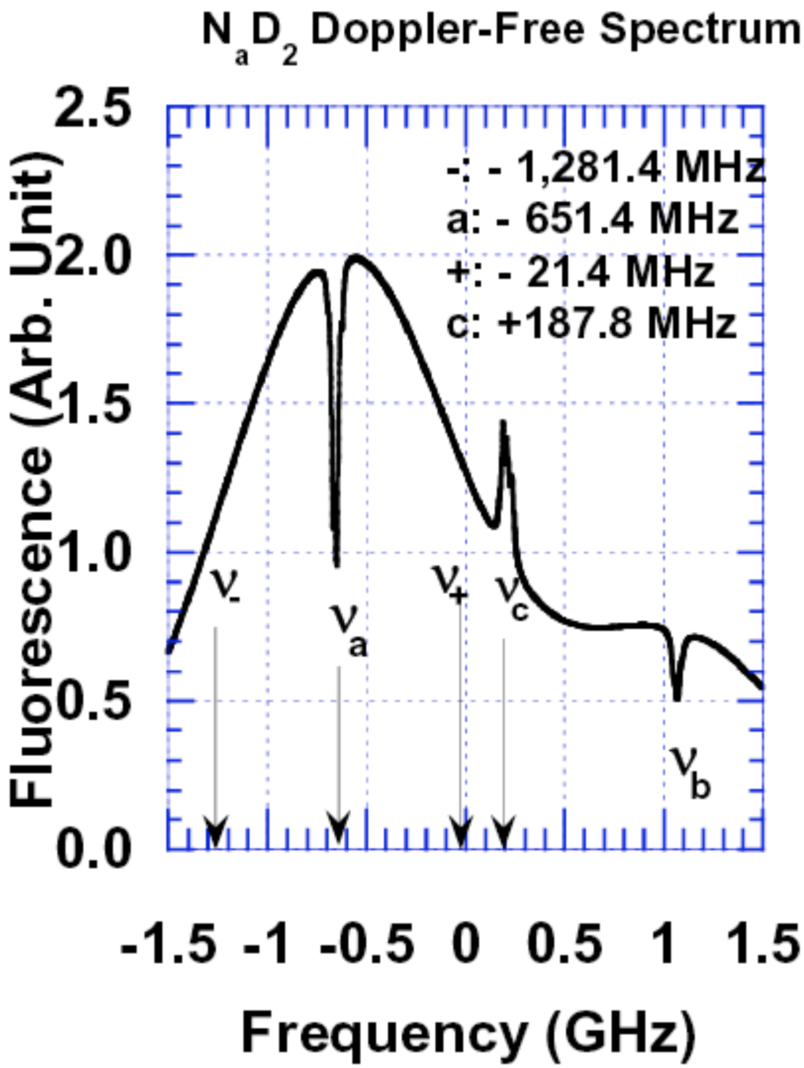
Hardware

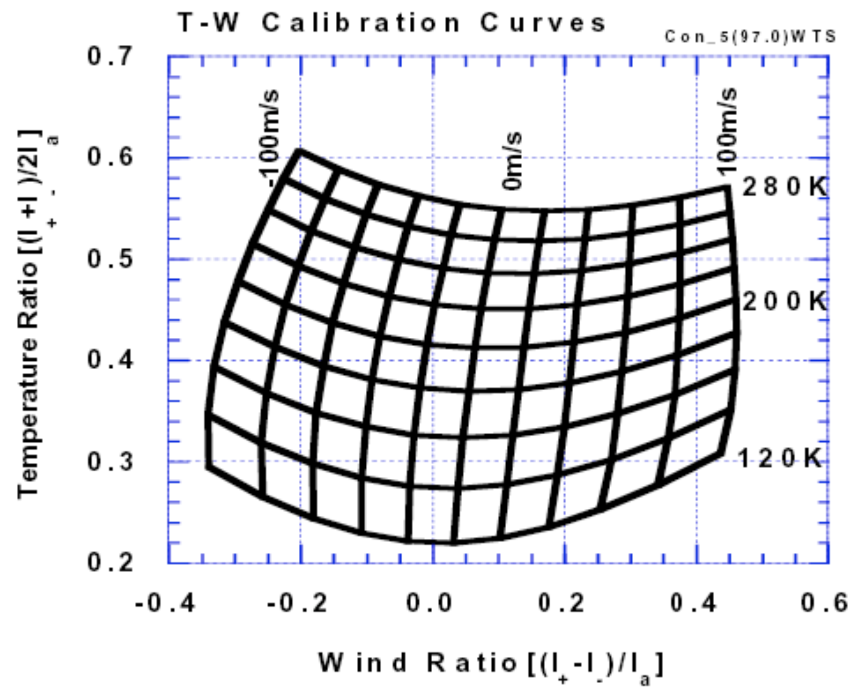




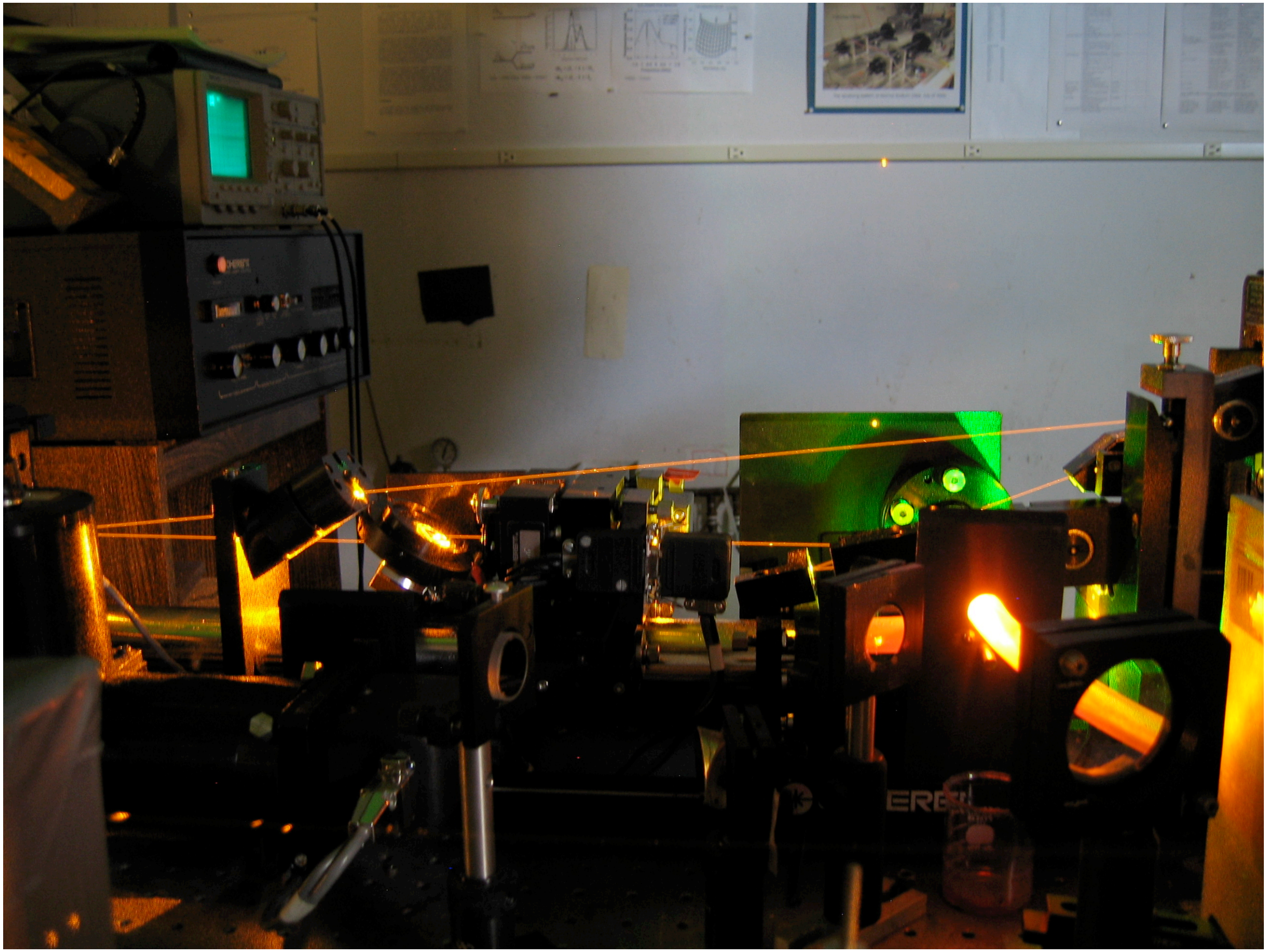
3-Level Explanation

Na Spectroscopy in Na Lidar





Another Look at Ring Dye Laser



Summary

- By now we have completed the discussions of lidar principle, architecture, and data retrieval in general.
- Any questions ?
- Let's talk about them in the next lecture, as many as you want.
- Comments and suggestions to the class are more than welcome.