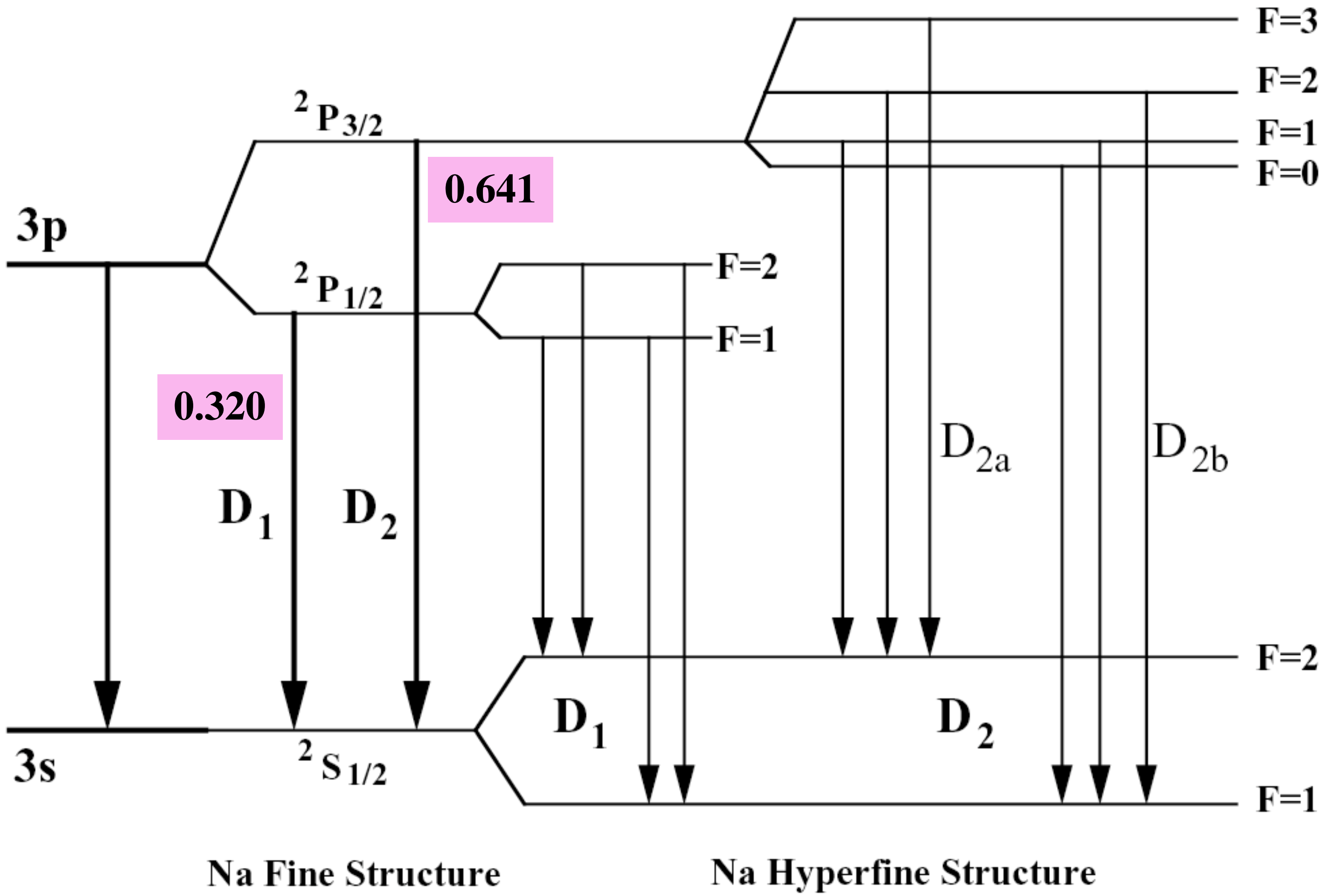
Lecture 14. Lidar Architecture (2) Laser and Optical-Electronics

- Introduction
- Na Doppler lidar: 3-frequency technique
- Laser principle in general
- Ring dye laser and frequency/bandwidth control
- Wavemeter (Michelson Interferometer)
- Na saturation-absorption spectroscopy
- Acousto-optical modulator
- Pulsed dye amplification
- Faraday filter
- Summary

Introduction

- In last lecture, we introduced the general architecture for lidar instrumentation.
- Na wind/temperature (Doppler) lidar represents a state-of-the-art lidar instrumentation because of its complexity and demanding requirements on laser frequency precision, linewidth and power etc.
- In this lecture, we discuss the Na Doppler lidar instrumentation in more details and give you more ideas about the laser and optical-electronics involved in the instrumentation.
- This is also a preparation for Sunday's visit to CSU Na wind/temperature lidar in real time.

Na Energy Levels: D_1 and D_2 Lines



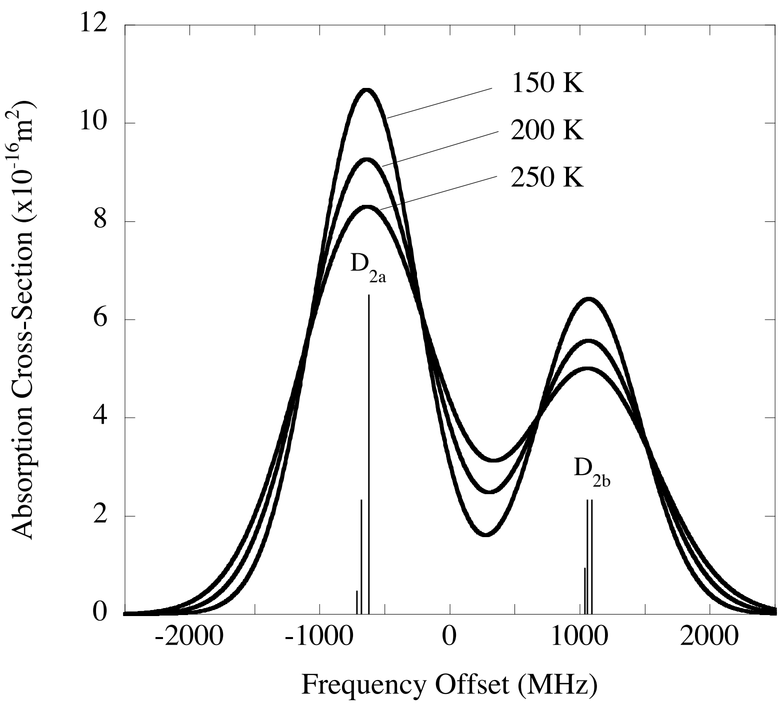
Energy Level Diagram of Atomic Na

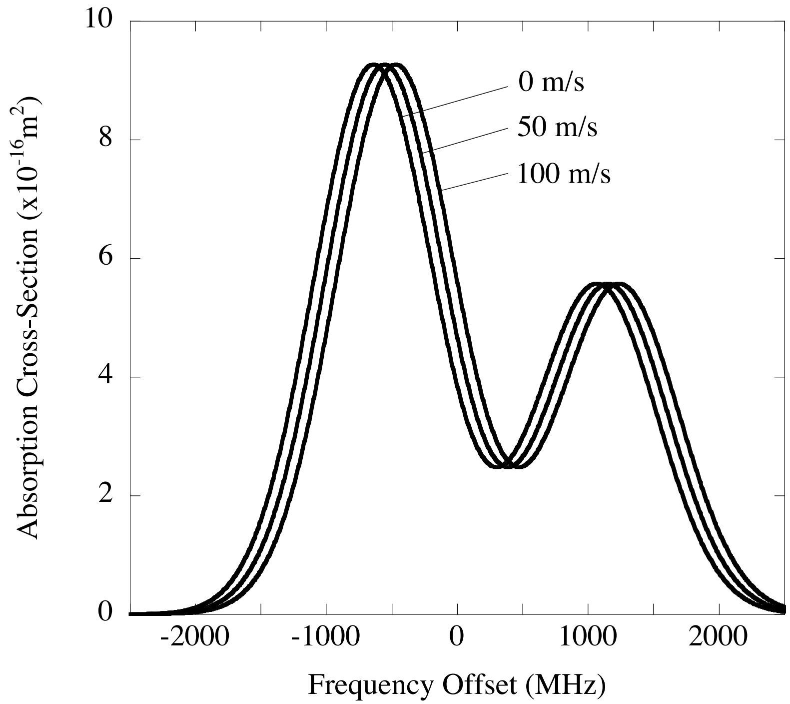
Na Doppler Lidar Principle

Na D_2 Line Effective Cross-section

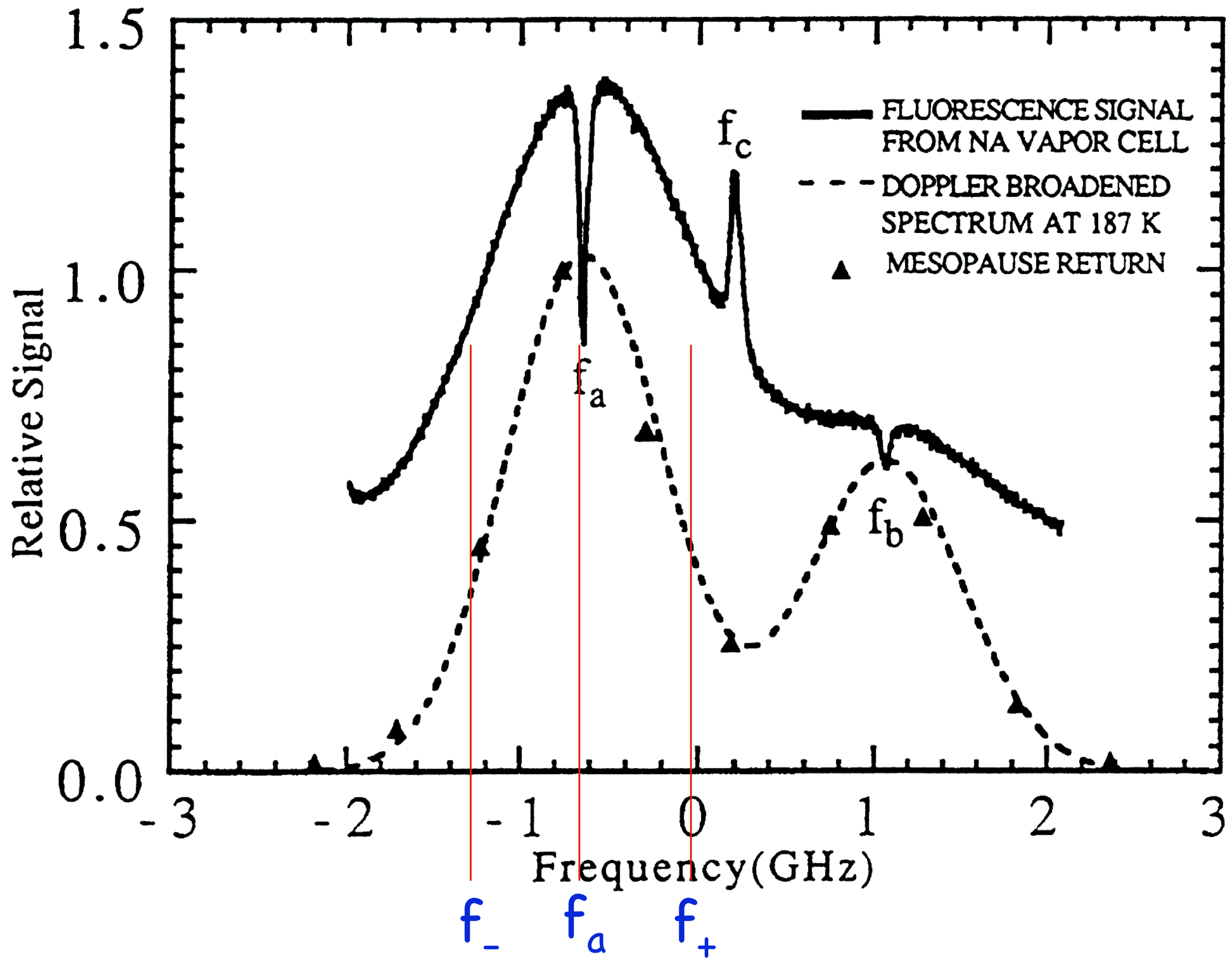
$$\sigma_{eff}(\nu) = \frac{1}{\sqrt{2\pi}\sigma_e}\frac{e^2 f_{ik}}{4\varepsilon_0 m_e c}\sum_{n=1}^{6} A_n \exp\left(-\frac{\left[\nu_n - \nu\left(1-\frac{\mathrm{v_R}}{c}\right)\right]^2}{2\sigma_e^{\ 2}}\right)$$

where $\sigma_e = \sqrt{\sigma_D^{\ 2} + \sigma_L^{\ 2}}$ $\quad \sigma_D = \sqrt{\frac{k_B T}{M\lambda_0^{\ 2}}}$ $\quad \nu' = \nu\left(1-\frac{\mathrm{v_R}}{c}\right)$





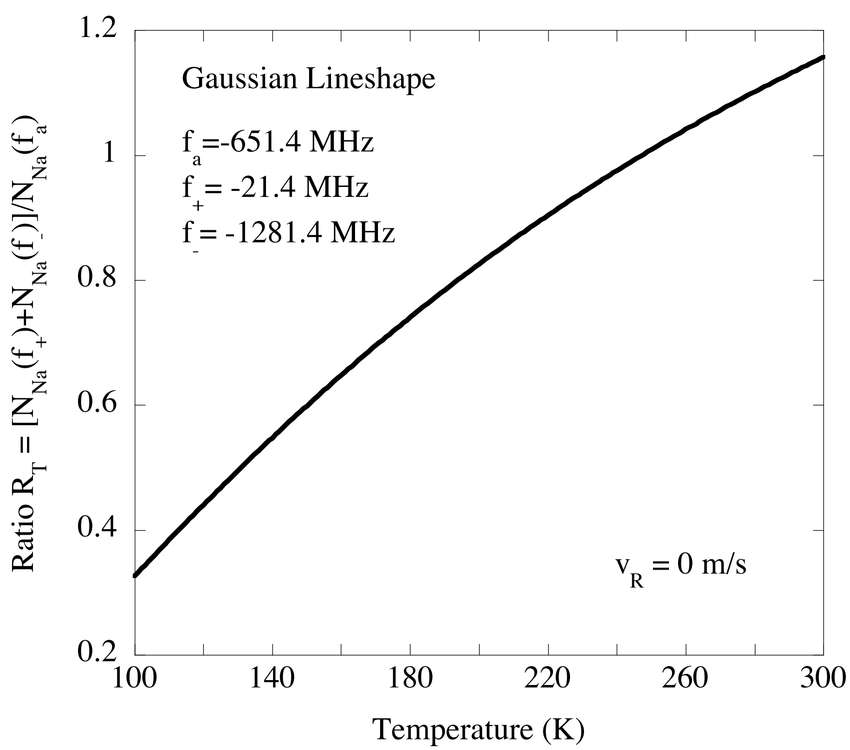
Doppler-Free Spectroscopy From Na Vapor Cell

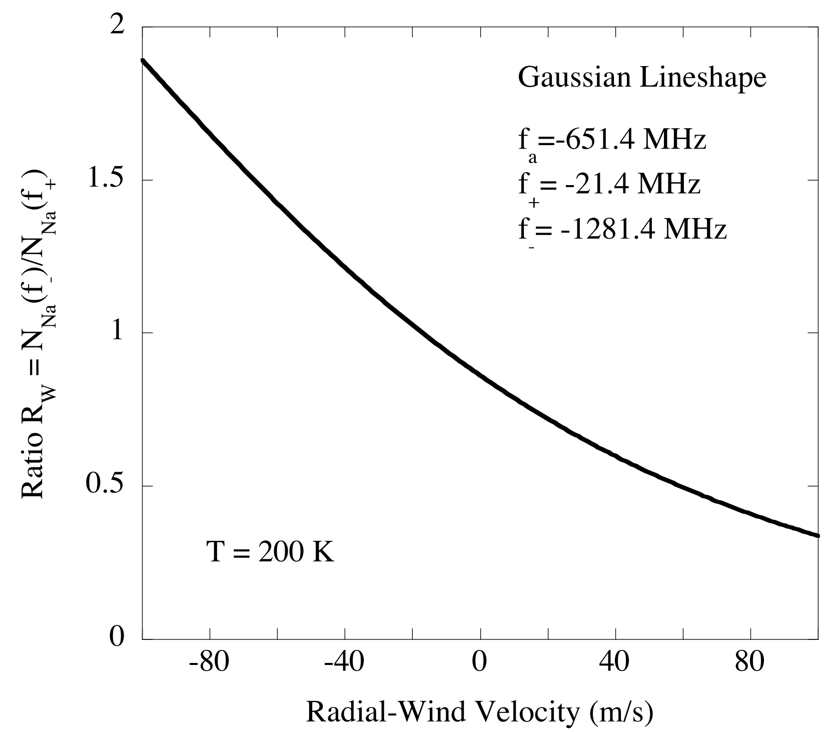


3-Frequency Technique

$$R_T(z) = \frac{N_{norm}(f_+, z, t_1) + N_{norm}(f_-, z, t_2)}{N_{norm}(f_a, z, t_3)} \approx \frac{\sigma_{eff}(f_+, z) + \sigma_{eff}(f_-, z)}{\sigma_{eff}(f_a, z)}$$

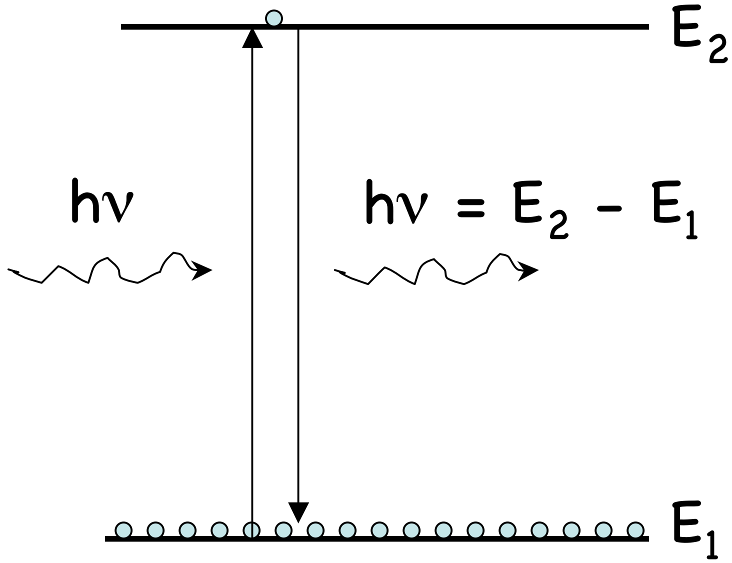
$$R_W(z) = \frac{N_{norm}(f_-, z, t_2)}{N_{norm}(f_+, z, t_1)} \approx \frac{\sigma_{eff}(f_-, z)}{\sigma_{eff}(f_+, z)}$$



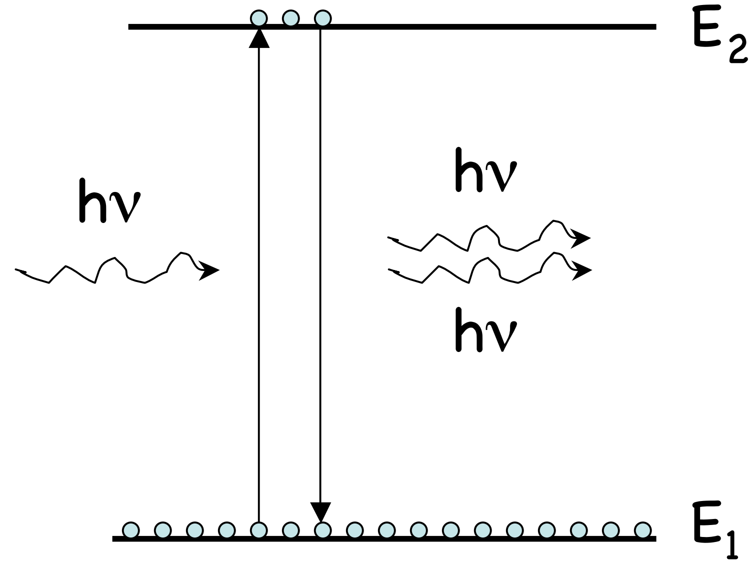


Laser Principle in General

Light Amplification by Stimulated Emission of Radiation



Absorption and spontaneous emission

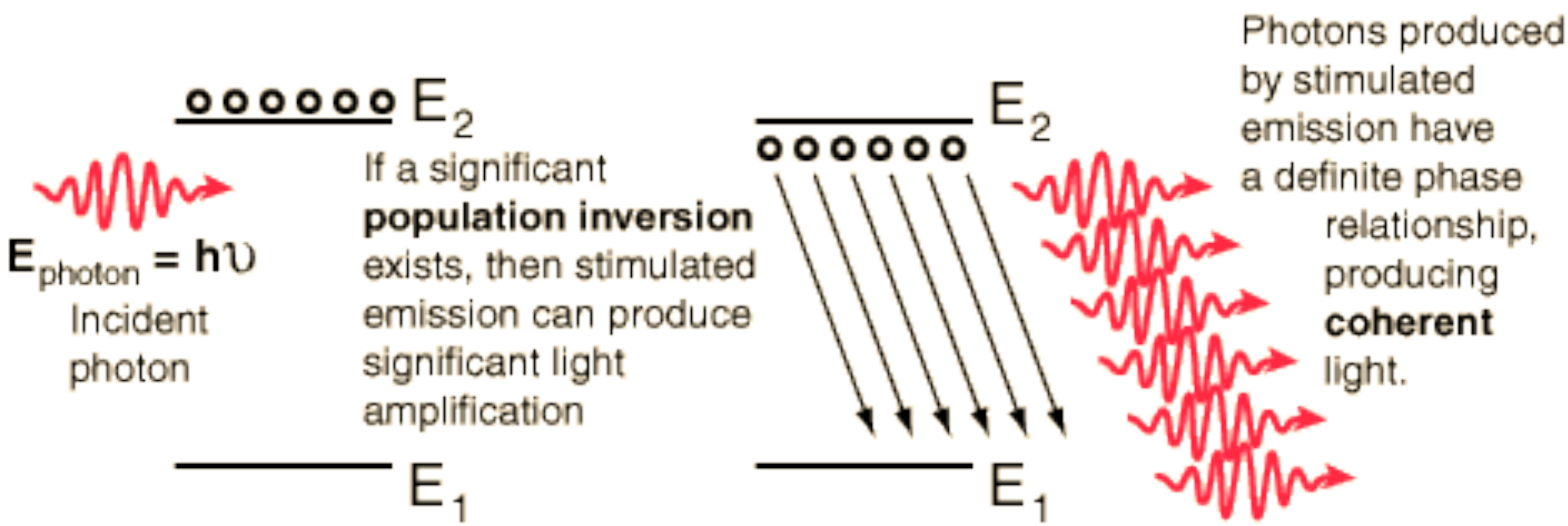


Absorption and stimulated emission

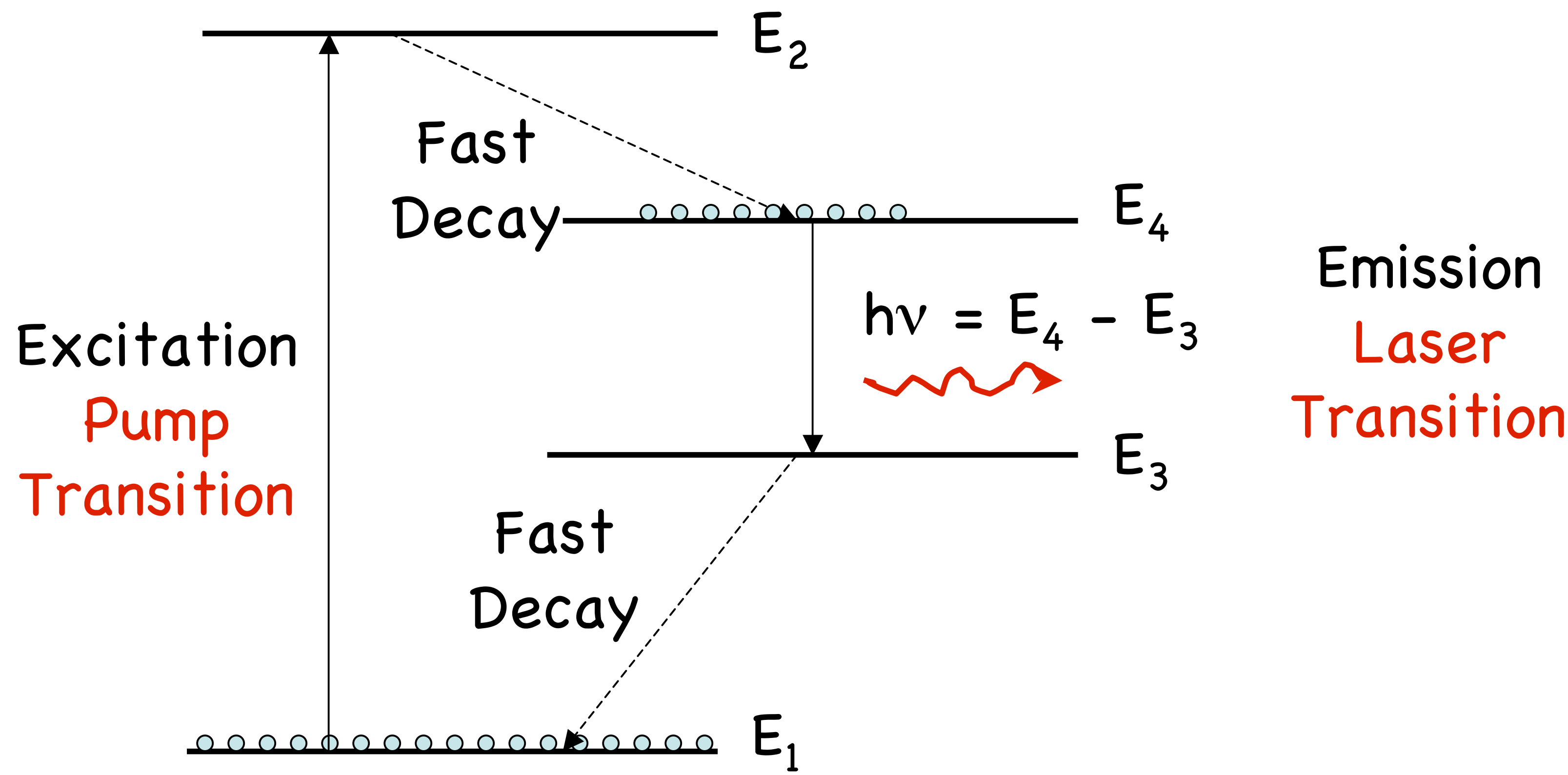
- Stimulated emission produces photons with the same frequency, same direction, and fixed phase as the incident photon, i.e., coherent light!

Population Inversion

- To produce light amplification, we must have the gain larger than the loss when photons pass through the media – we call it gain media

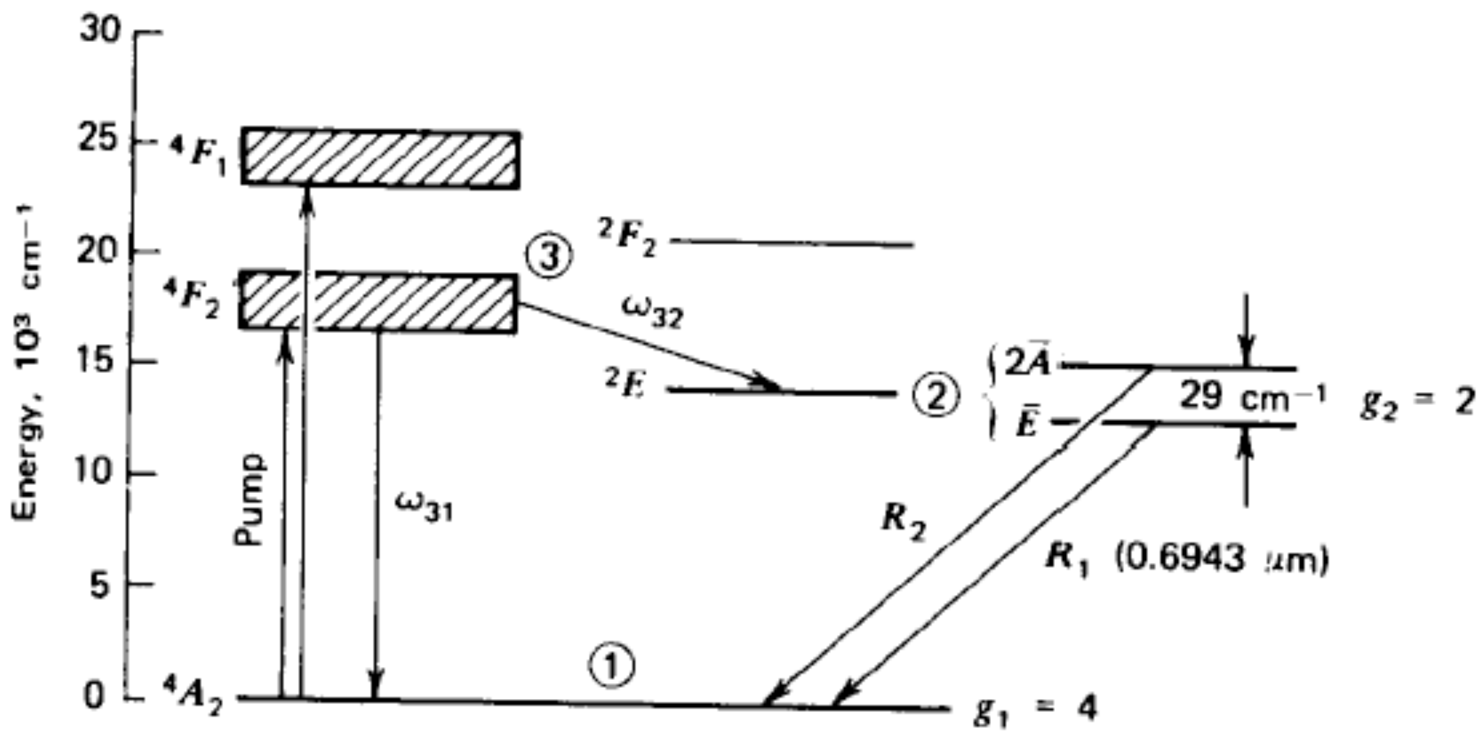


How to Achieve Population Inversion



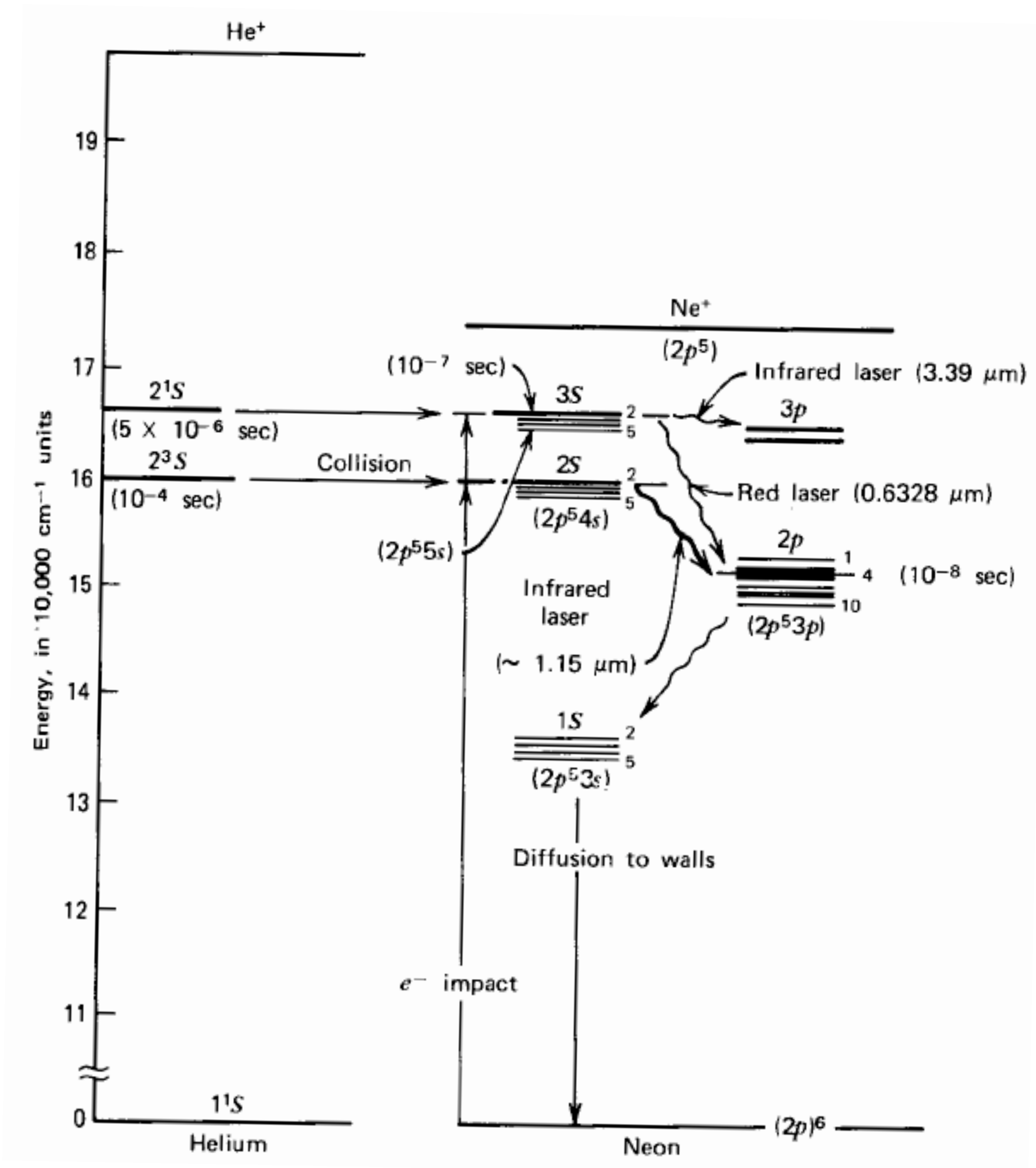
- Population inversion cannot be achieved with just two levels because of the same stimulated emission and absorption probability. At least 3 or 4 levels must be involved to generate population inversion.
- A common approach is the 4-level transition diagram.

Example: Ruby Laser

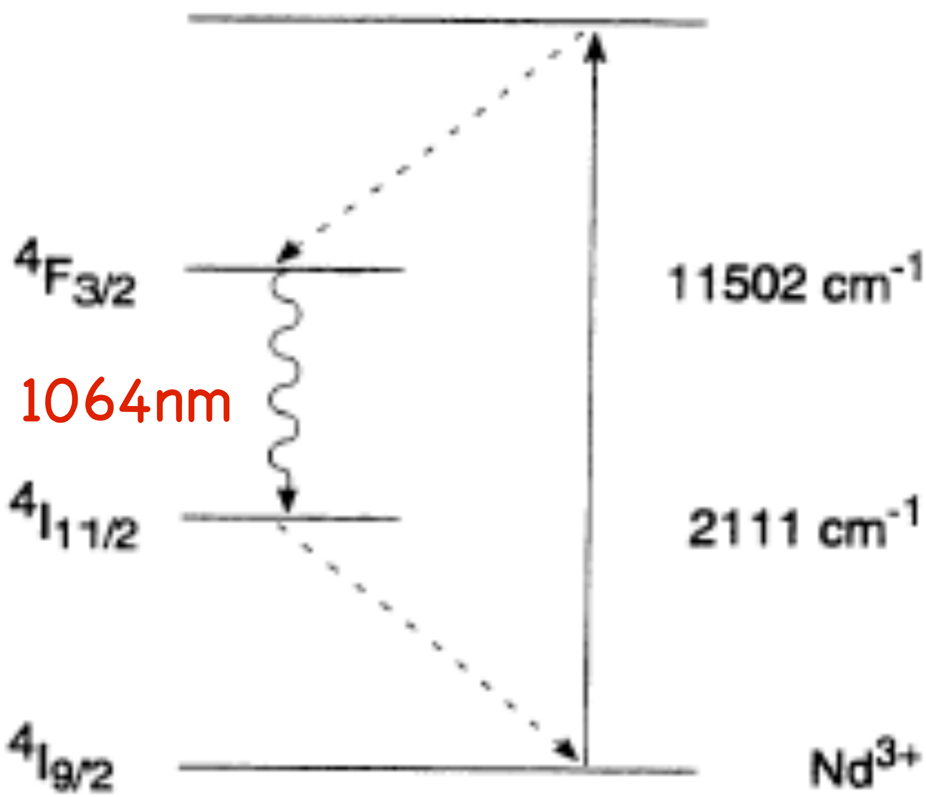


- Due to the 3-level approach used in the Ruby laser, it is difficult to achieve continuous wave operation.

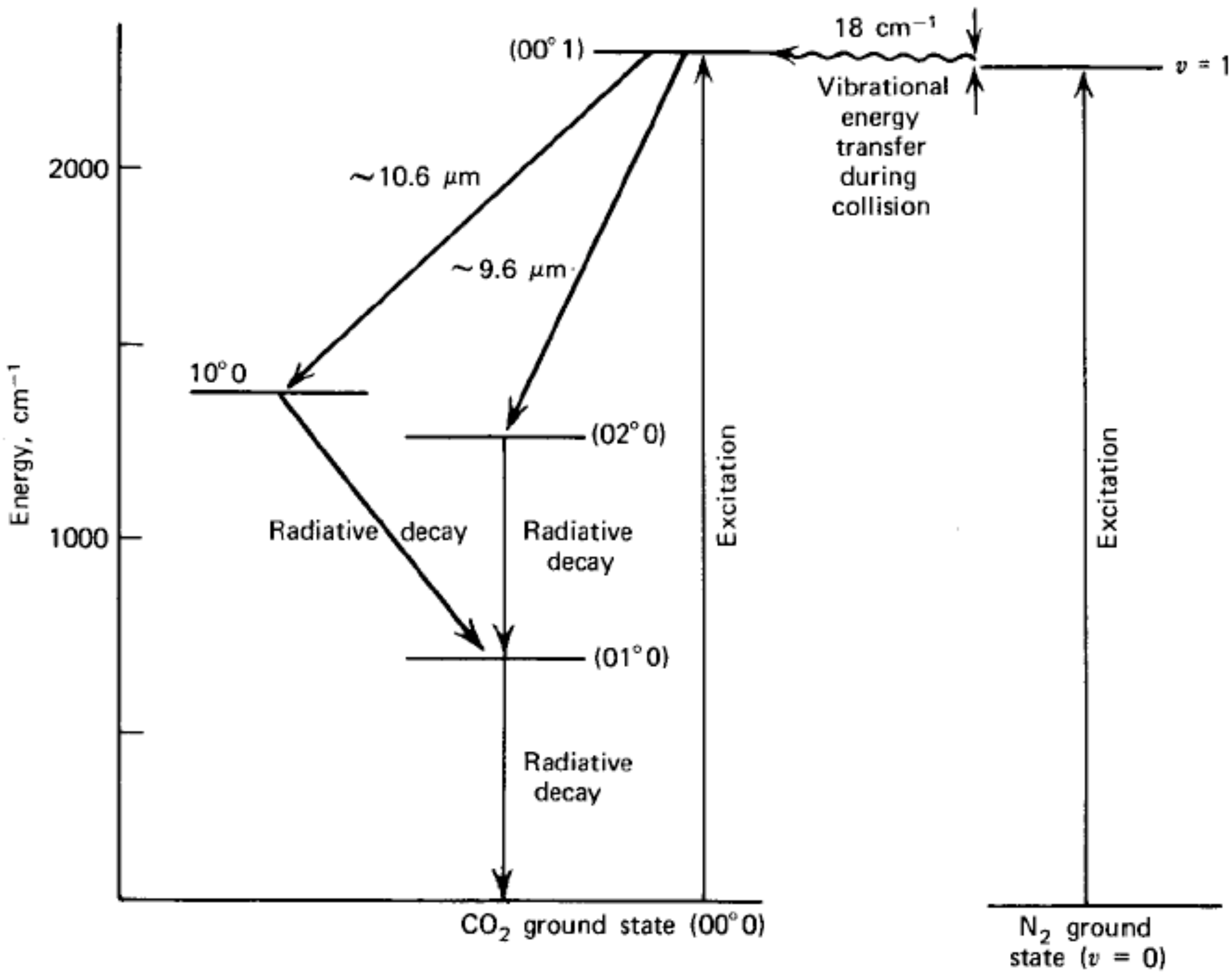
Example: He-Ne Laser



Example: Nd:YAG Laser



Example: CO_2 Laser



Example: 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.

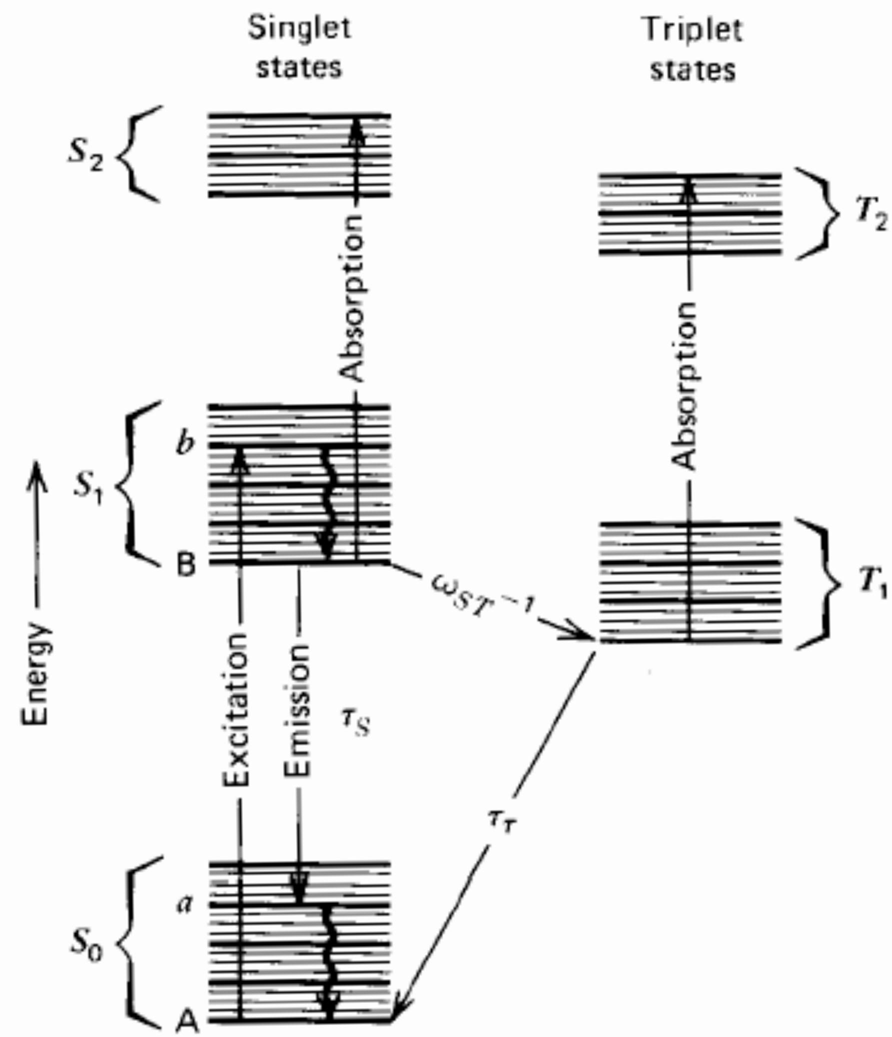
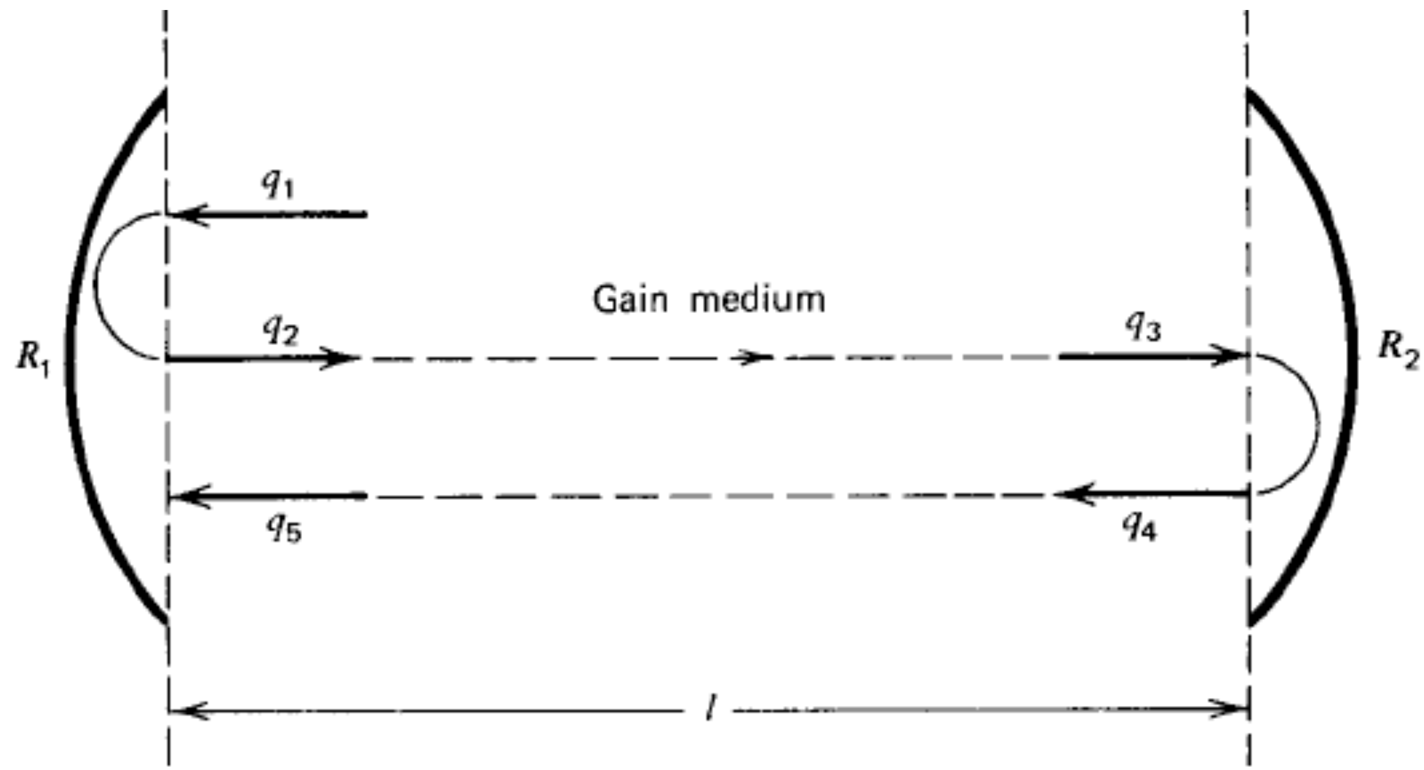
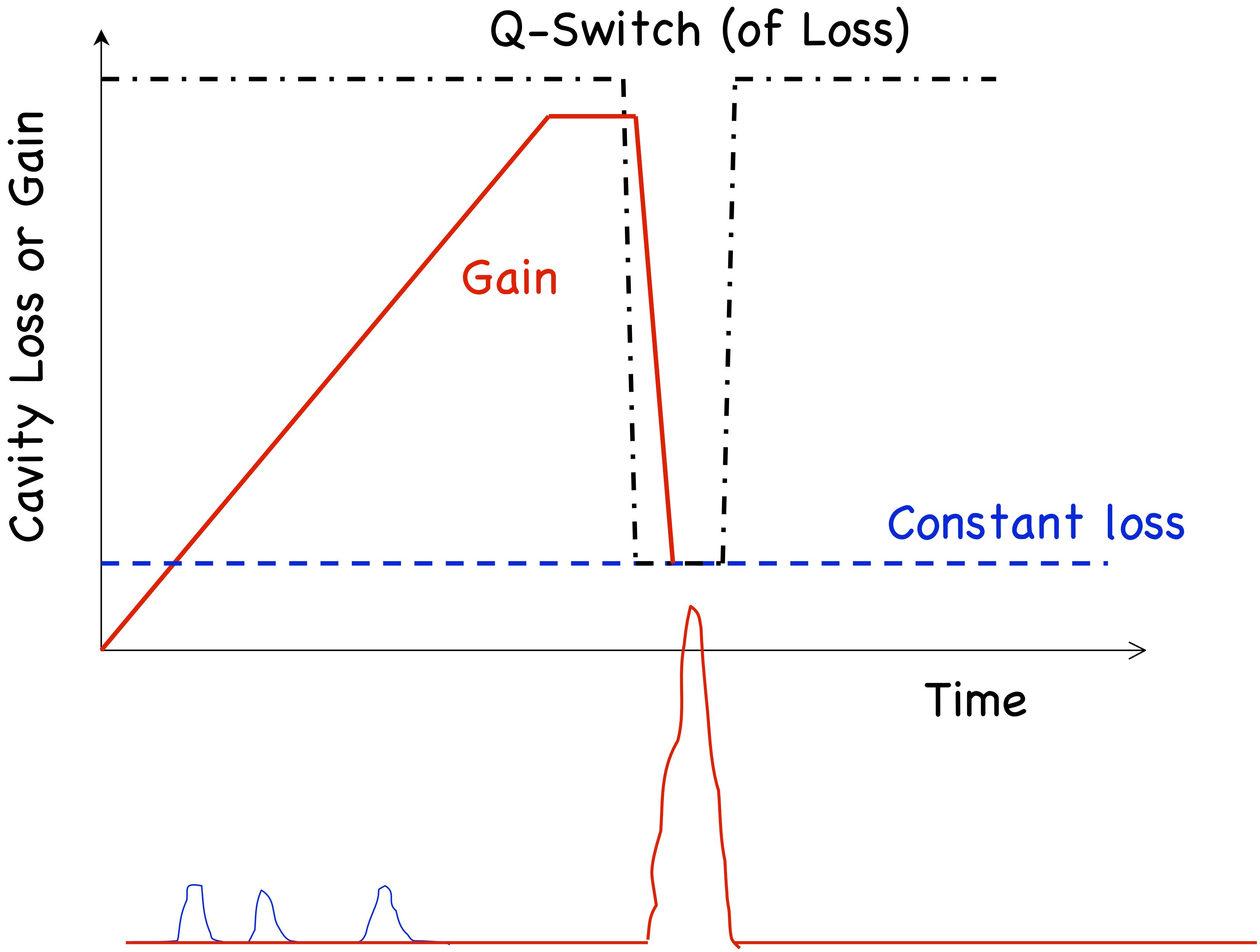


FIGURE 10.23 Schematic representation of the energy levels of an organic dye molecule. The heavy horizontal lines represent vibrational states, and the lighter lines represent the rotational fine structure. Excitation and laser emission are represented by the transitions $A \rightarrow b$ and $B \rightarrow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

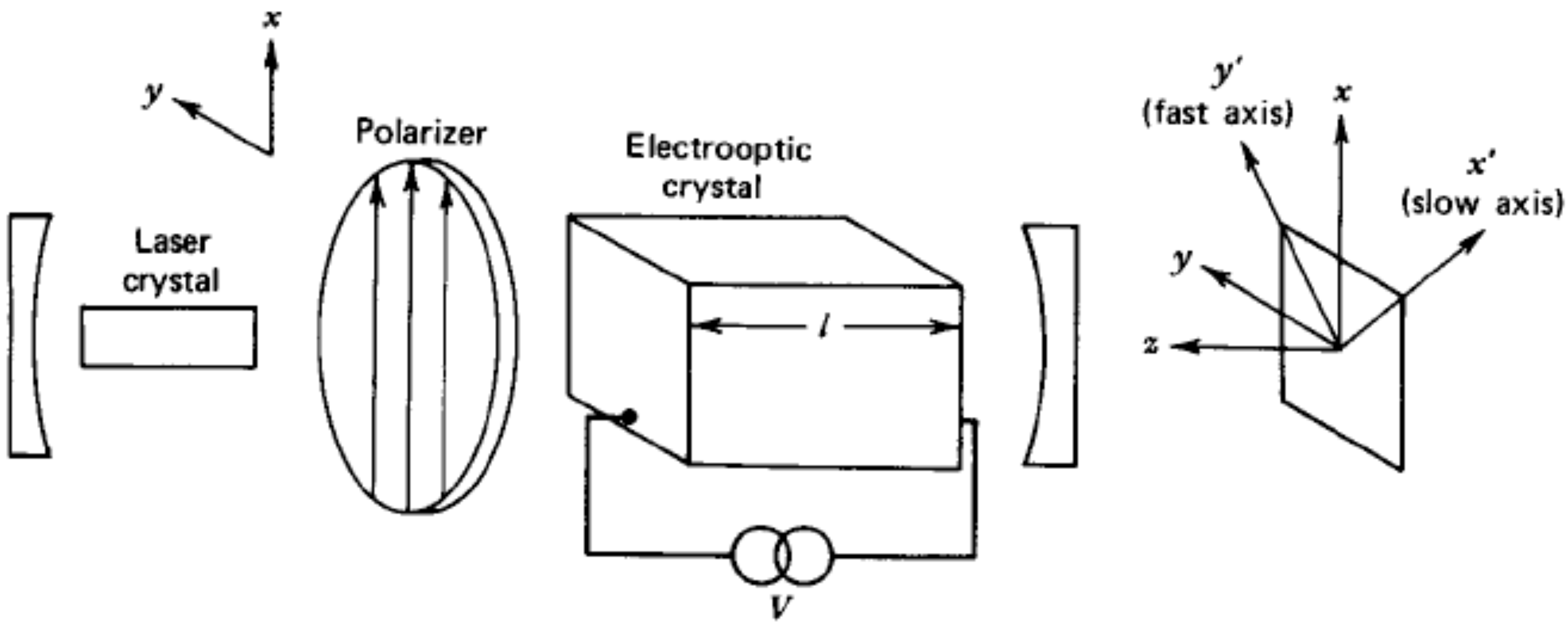
Resonator Cavity: Positive Feedback



Q-Switch to Produce Giant Pulse

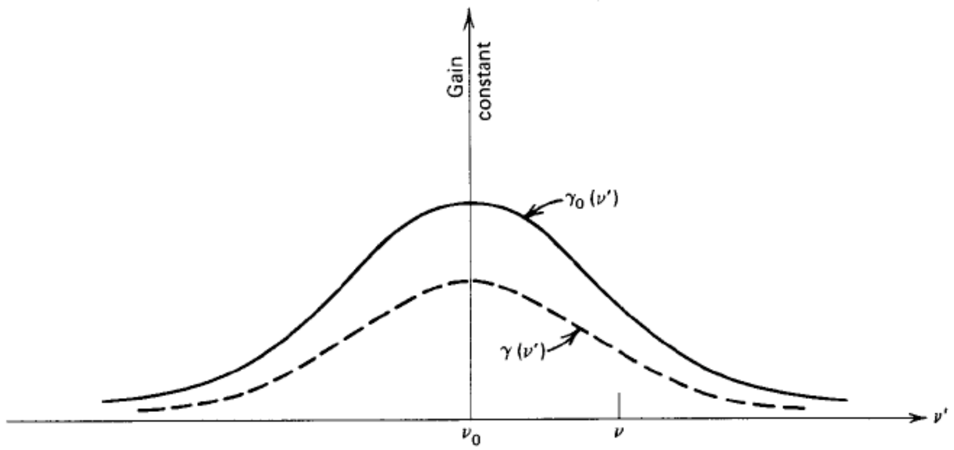


Q-Switch to Produce Giant Pulse

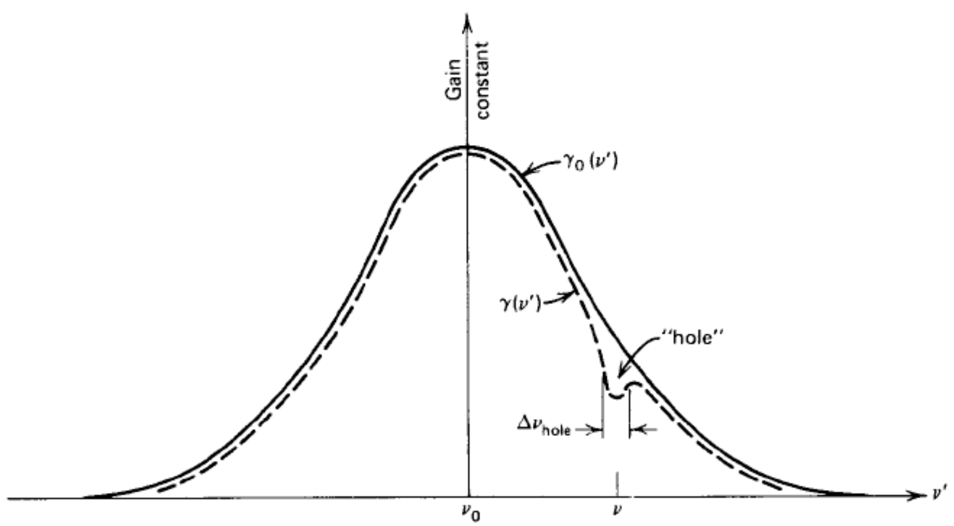


- Pöckels cell: electro-optic crystal to rotate light polarization

Standing Wave Cavity versus "Spatial Hole Burning"

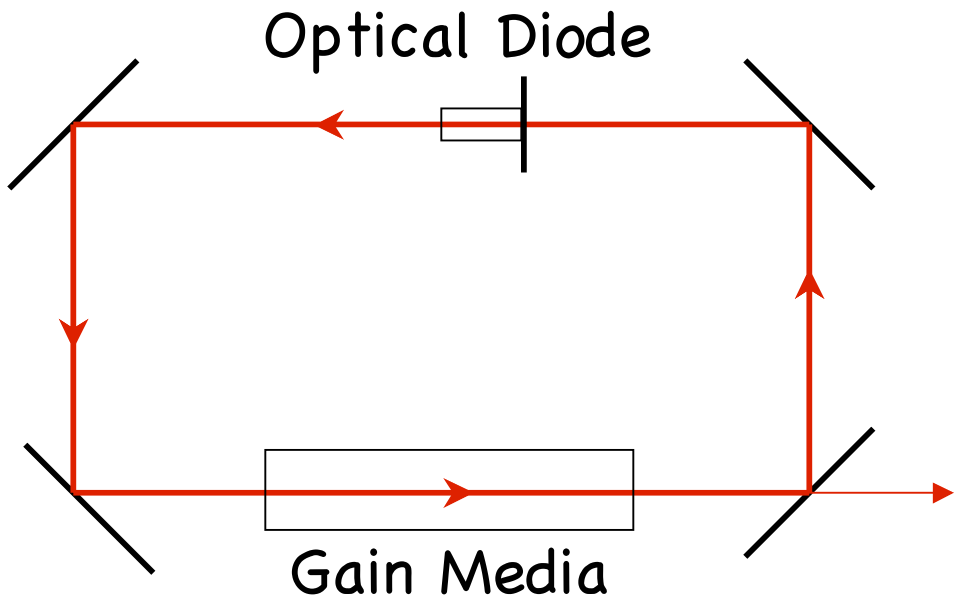


(a)

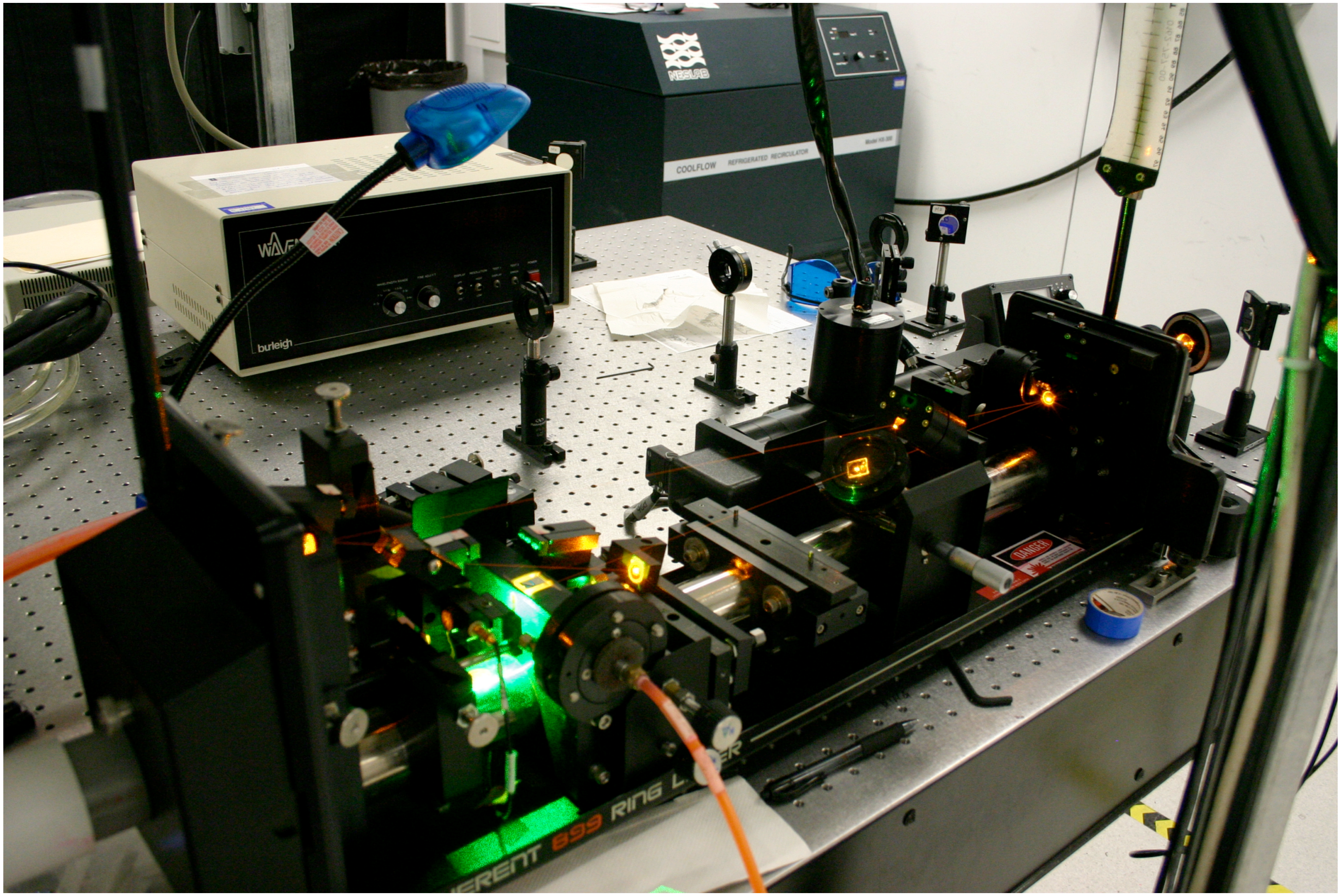


Traveling Wave Ring Laser

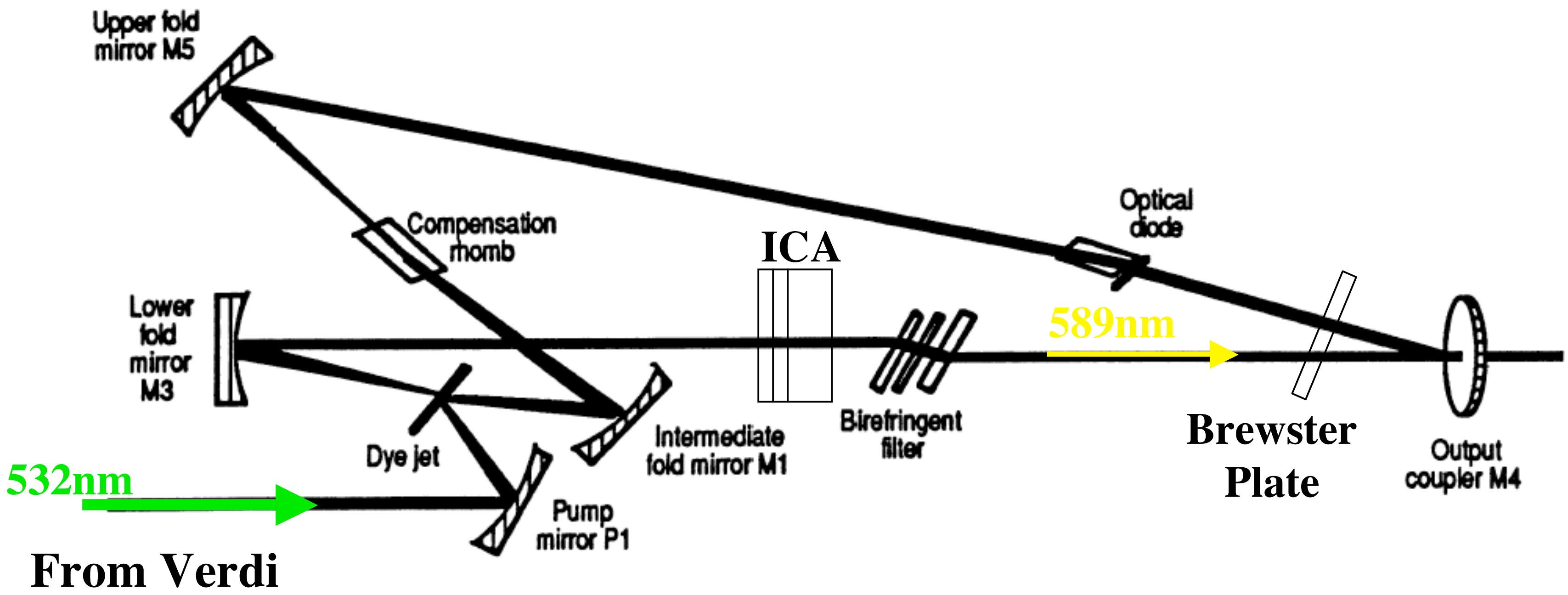
- Ring cavity with traveling wave to avoid spatial hole burning --> for single frequency operation



Ring Dye Laser

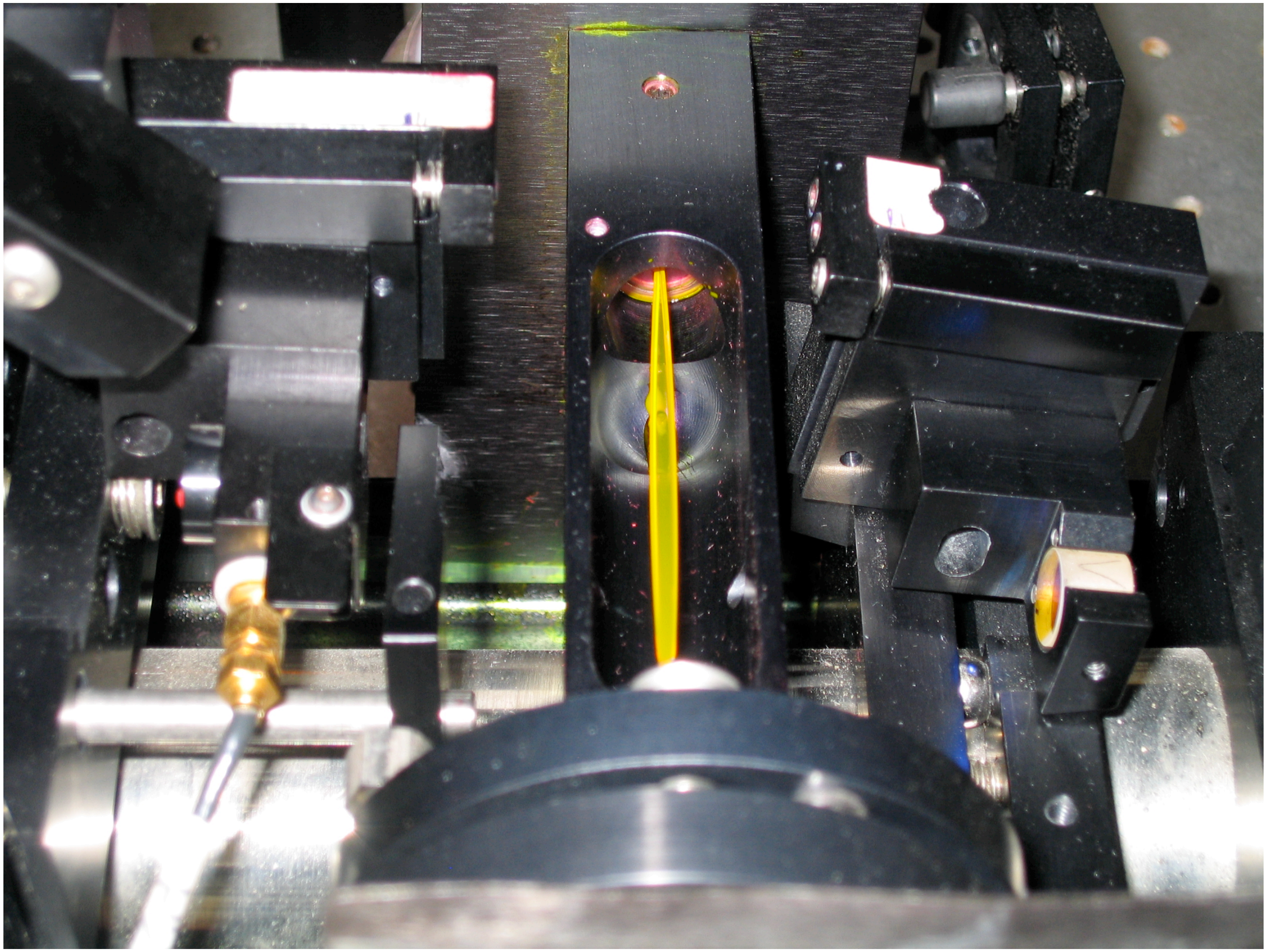


Ring Dye Laser



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.

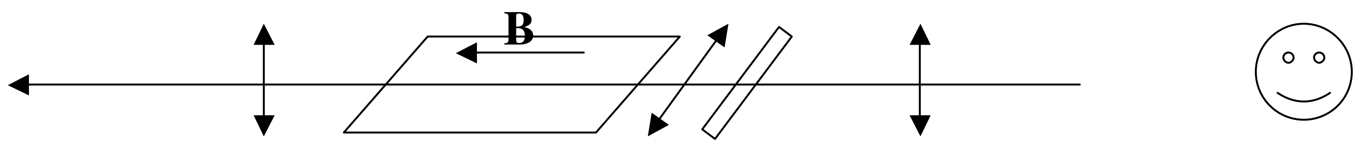
Ring Laser: Dye Jet



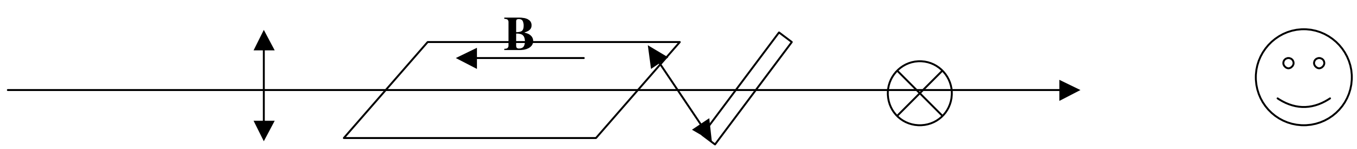
Optical Diode

Optical Diode: “Faraday Rotator + Optical Activity Crystal”

Passing



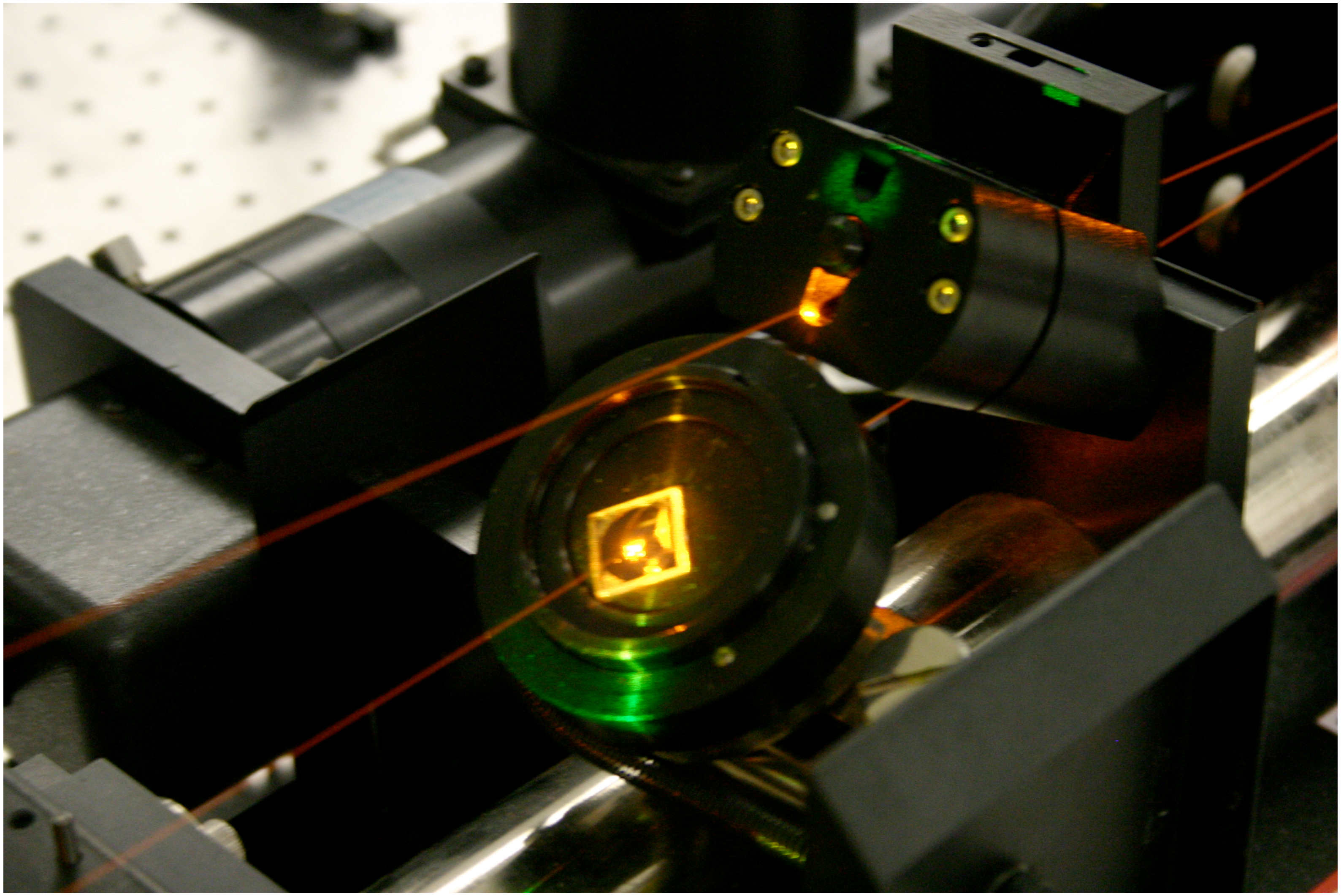
Blocked



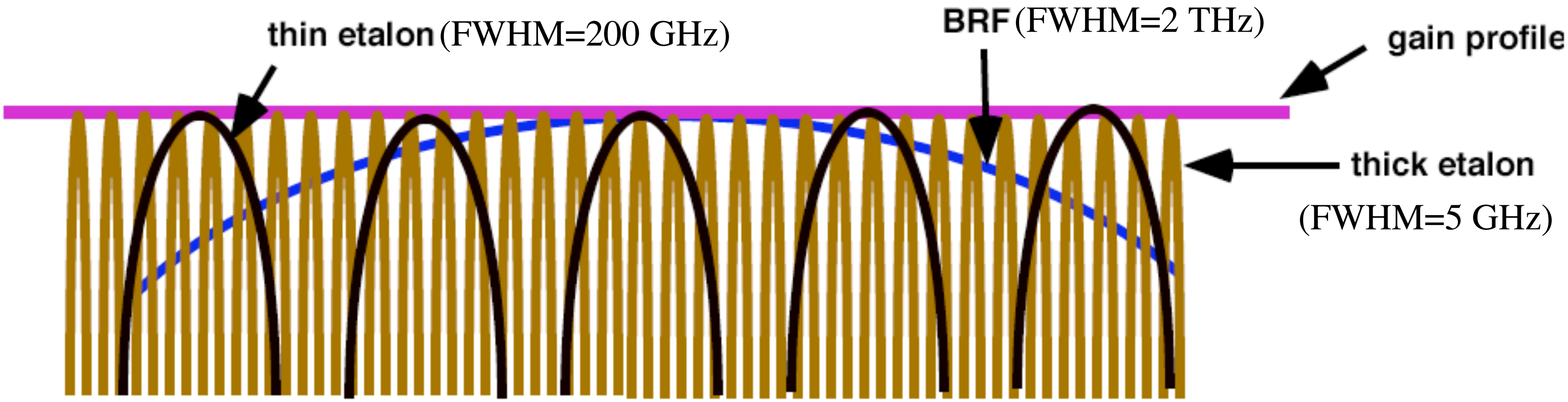
When looking from a fixed direction,

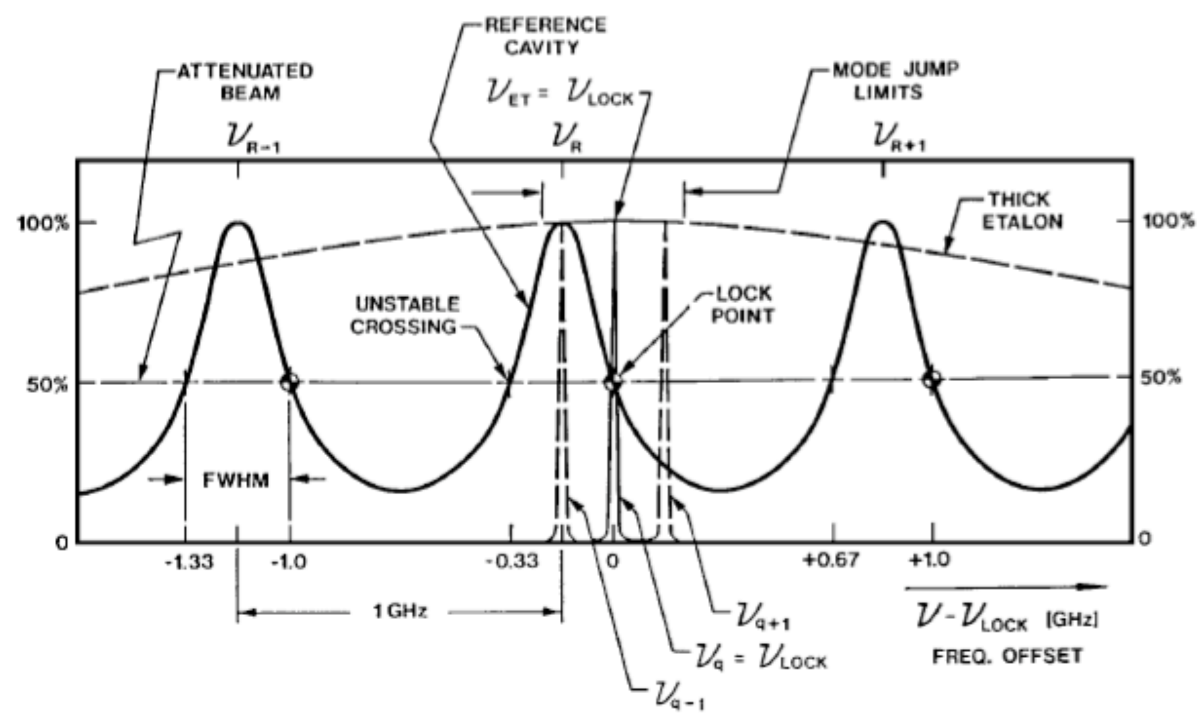
1. Faraday rotator: rotate linear polarization in the same direction regardless the light propagation direction
2. Optical activity crystal: rotate linear polarization depending on the light propagation direction

Birefringent Filter and Optical Diode

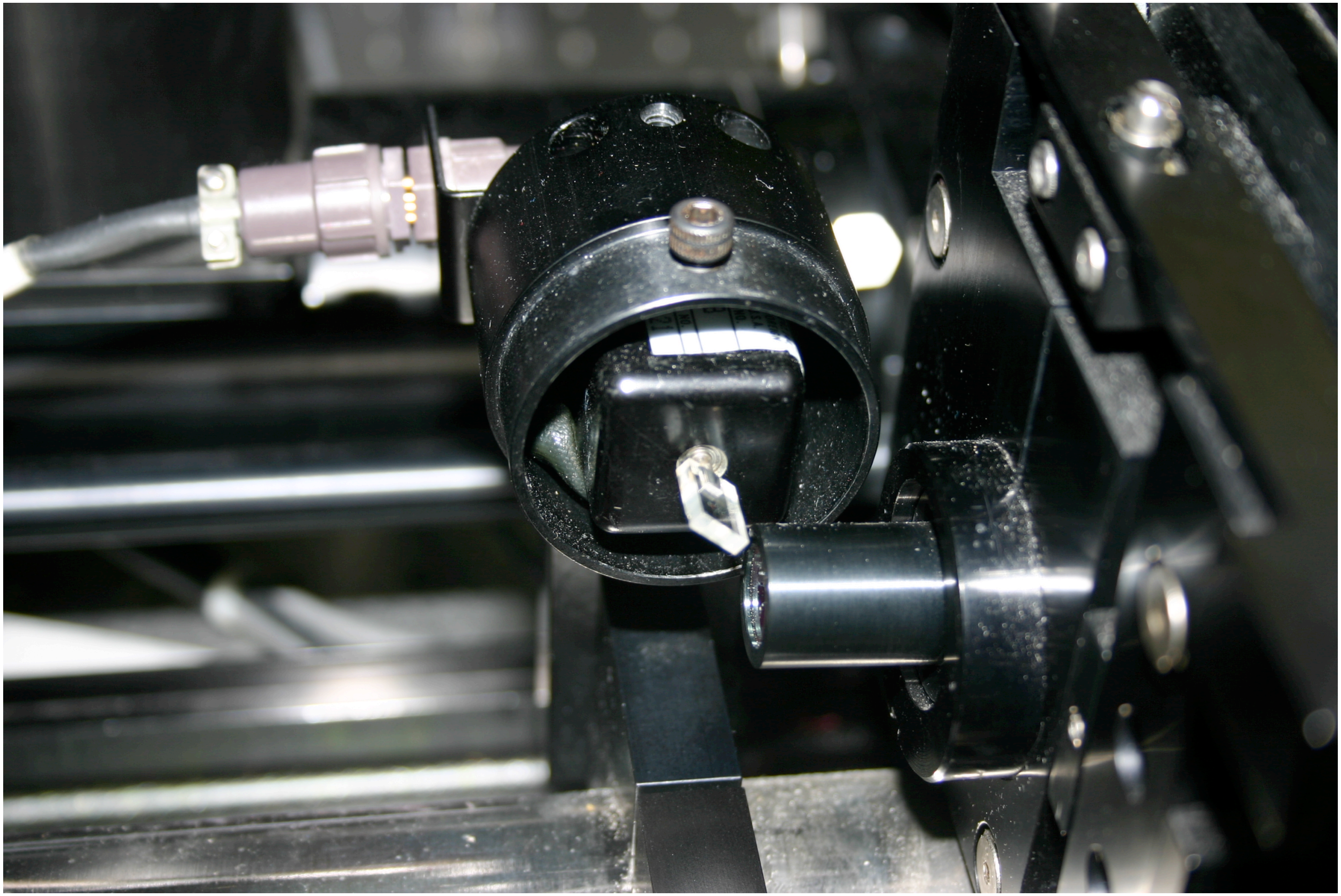


Frequency Selection in Ring Laser

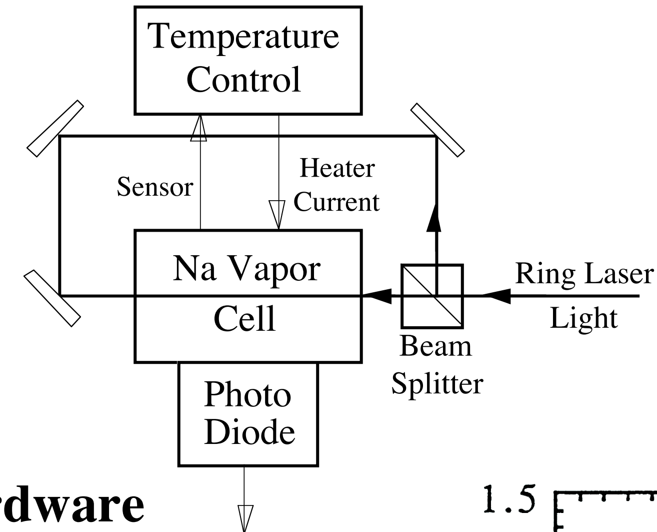




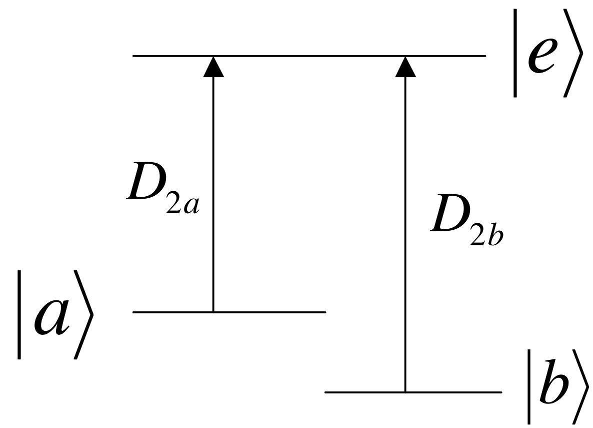
Rotating Galvanometer-Driven Brewster Plate



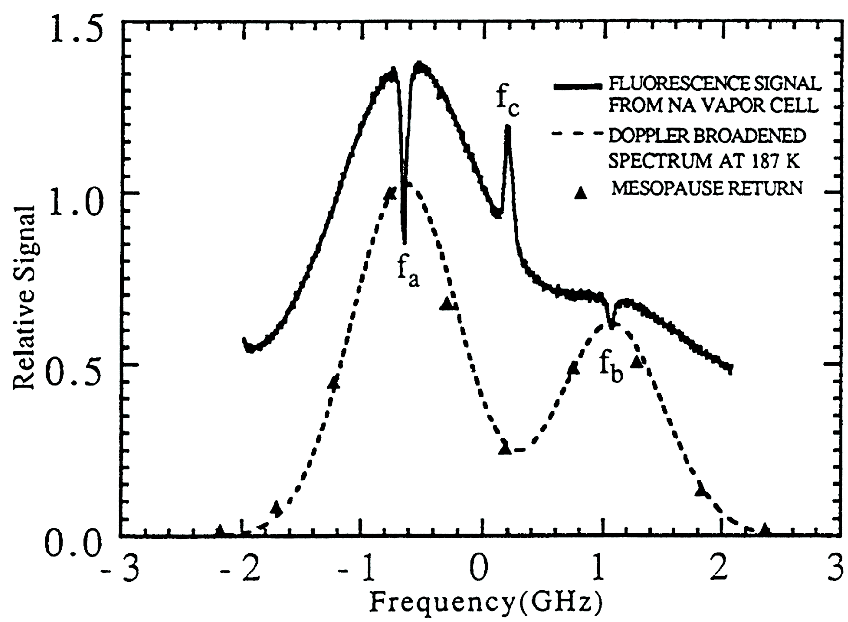
Na Saturation-Absorption Spectroscopy & Laser Freq Lock



Hardware



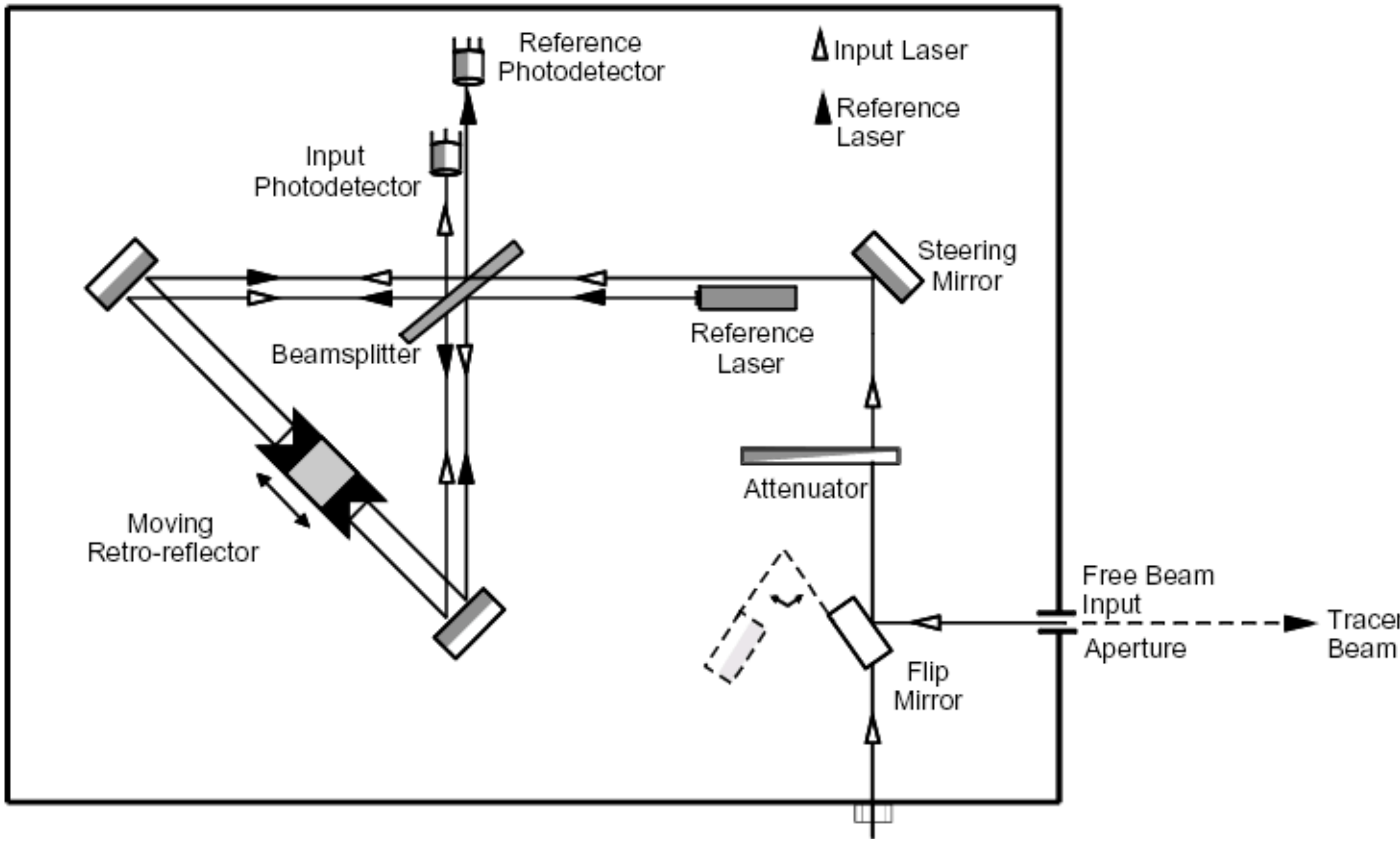
3-Level Explanation



Laser Frequency Scan and Lock

- Use computer to scan laser frequency and lock it to the D_{2a} dip of the Na saturation-absorption spectroscopy.

Wavemeter: Michelson Interference



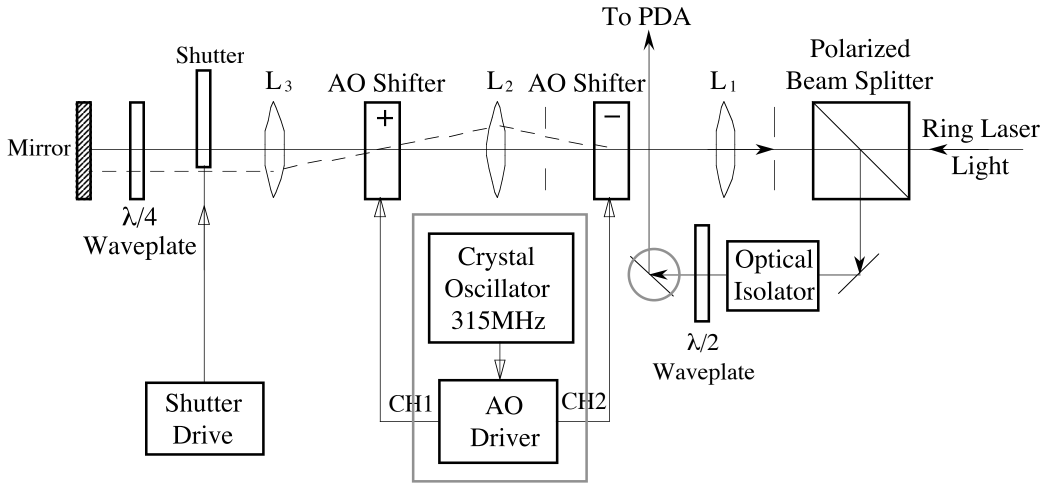
Unknown laser $m\lambda = 4n_\lambda d$

Reference laser $m_0\lambda_0 = 4n_0 d$

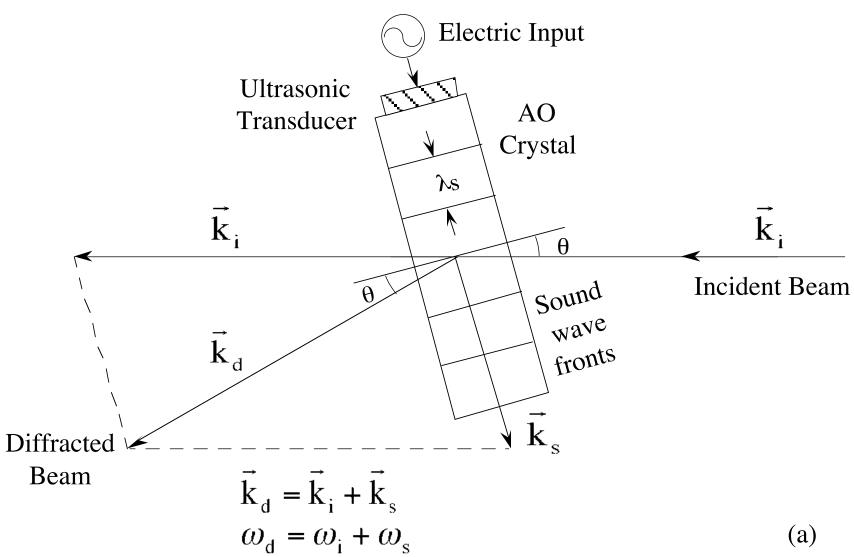
$$\Rightarrow \quad \lambda = \frac{m_0}{m} \cdot \frac{n_\lambda}{n_0} \cdot \lambda_0$$

Acousto-Optical Modulator

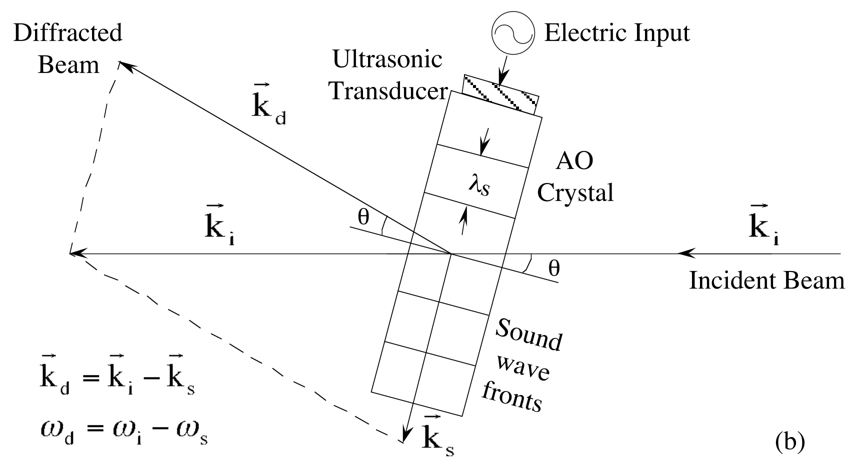
Hardware



Explanation: Doppler shift or Photon/Phonon Annihilation

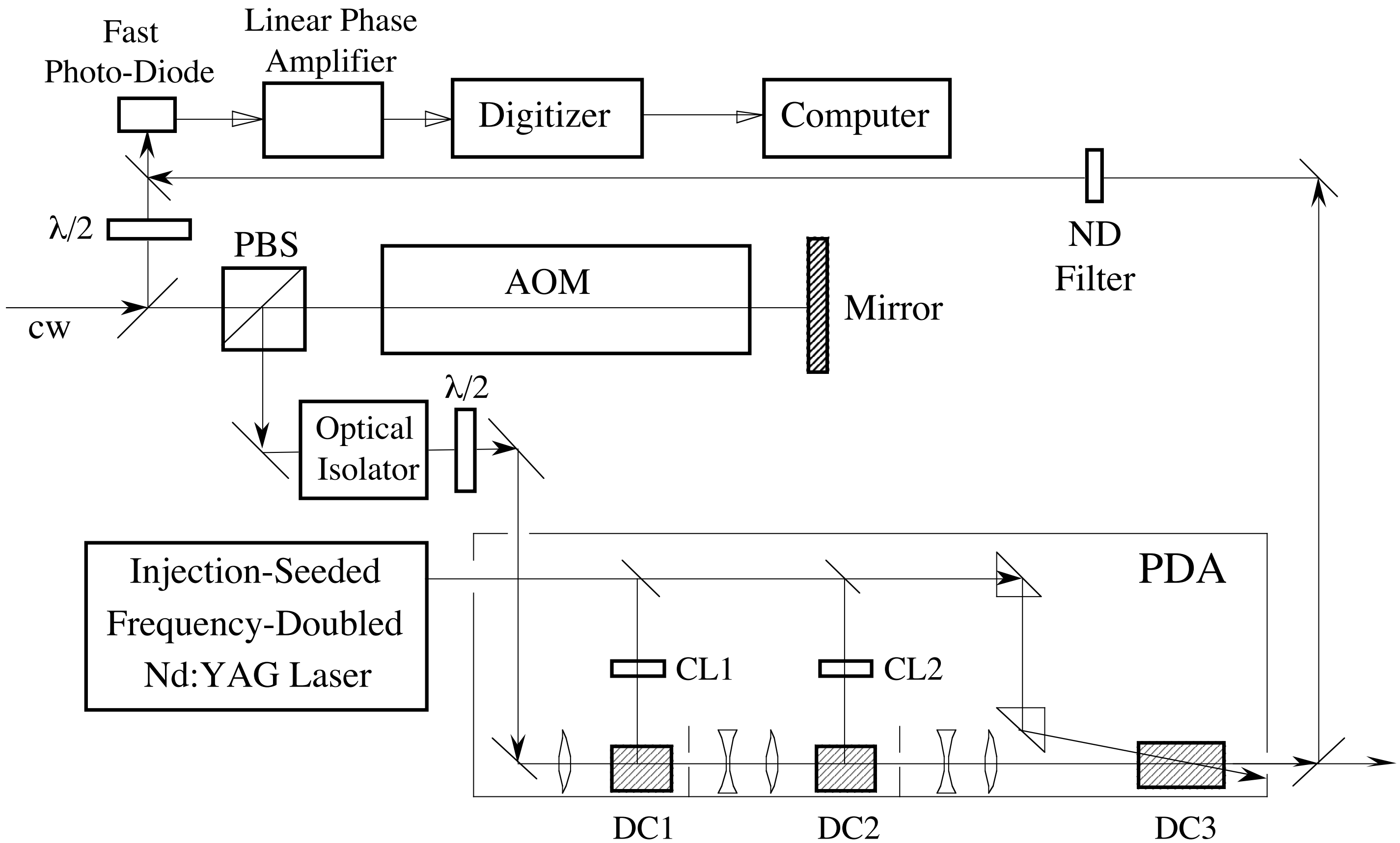


(a)



(b)

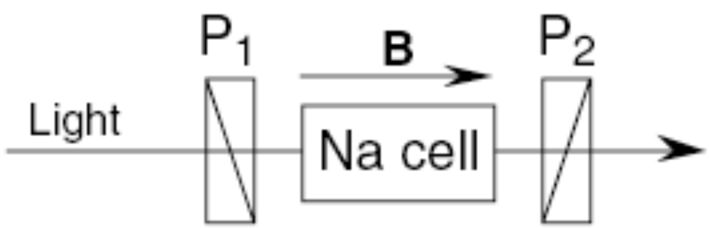
Pulsed Amplification

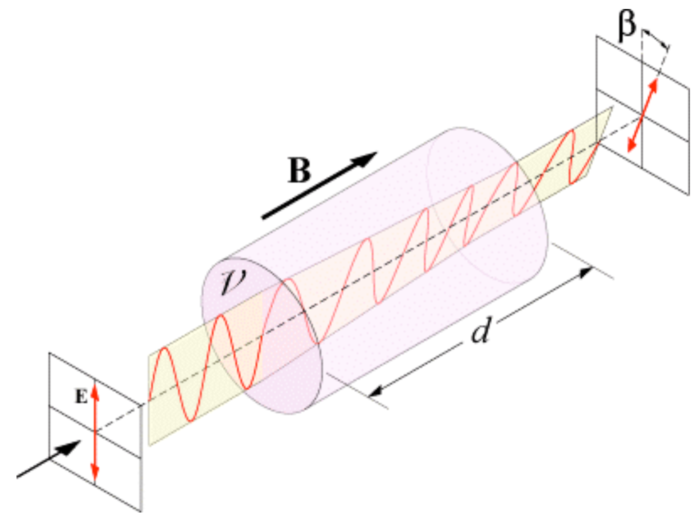


1. **Amplified Spontaneous Emission (ASE)**
2. **Injection-seeded Nd:YAG laser**
3. **PDA chirp caused by pulsed amplification**

Faraday Filter

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





❑ Refraction index n of dilute Na vapor

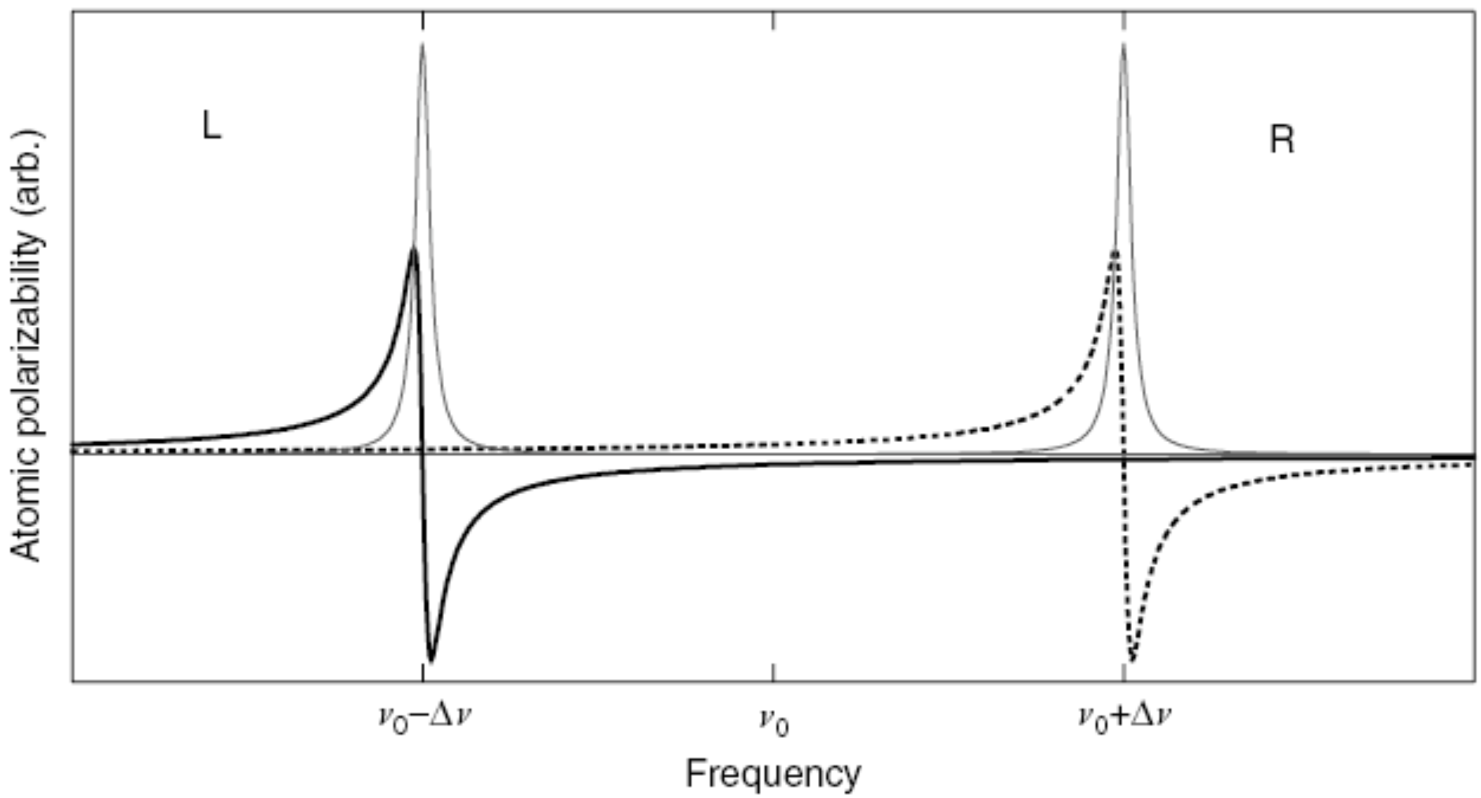
$$n = \sqrt{1+\chi} \cong 1 + \frac{1}{2}\chi = 1 + \frac{1}{2}\chi' - \mathrm{i}\frac{1}{2}\chi'' \qquad (5.74)$$

χ is the electric susceptibility of Na vapor

Faraday Filter

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

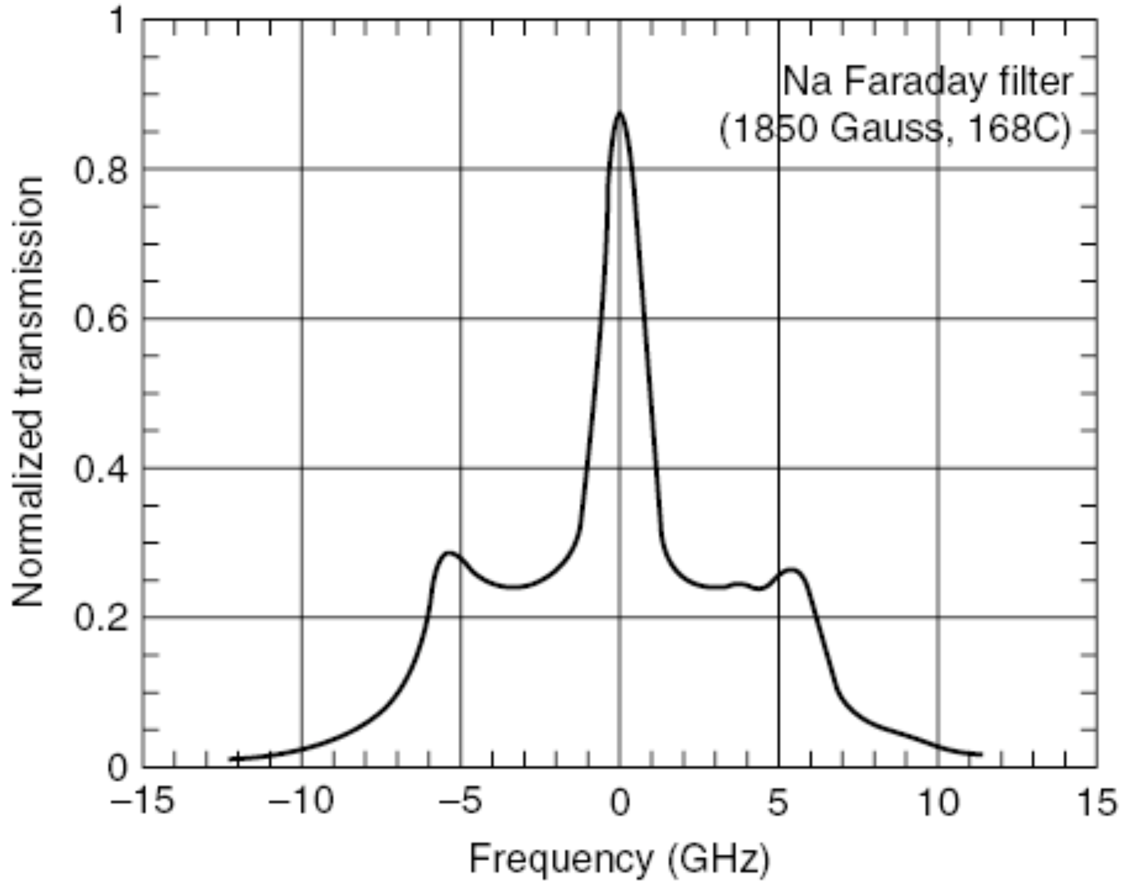
$$\chi'' = \frac{Ne^2 f}{2m\omega\epsilon_0} \frac{\gamma/2}{(\omega_0 - \omega)^2 + (\gamma/2)^2}$$ Resonance absorption



Faraday Filter

- Phase shift between two circular polarizations

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



Summary

- The architecture of Na wind/temperature lidar is analyzed to considerable details.
- The special techniques used in the Na lidar include

(1) ring dye laser (how the ring cavity avoid spatial hole burning and what components are used to narrow down laser linewidth)

(2) Na saturation-absorption spectroscopy (how it is used to lock ring laser frequency)

(3) Acousto-optical modulator (how it works and how it is used to produce two wing frequencies)

(4) Pulse dye amplification (how it works, how chirp is produced and how chirp affects measurements)

(5) Faraday filter (how it works)

Summary

- In addition, considerable optical-electronic techniques are used in the Na Doppler lidar, such as

(1) Michelson interferometer - wavemeter

(2) Optical fiber

(3) Interference filter

(4) F-P spectrum analyzer

(5) Nd:YAG laser technique

(6) Injection seeding to the Nd:YAG laser

- Students are expected to find extra books to study these materials.