كلية الهندســـــة بشبرا

FACULTY OF ENGINEERING- SHOUBRA

Optical Communications
ECE423/ELE424/CCE507/ELE480

LEC (07)
LASER Diodes - Part II

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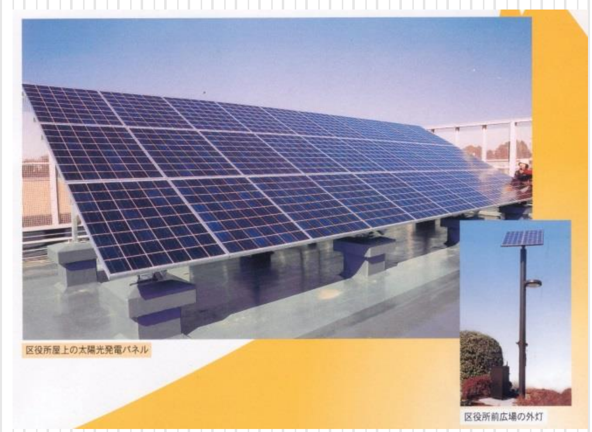


Laser types and classifications

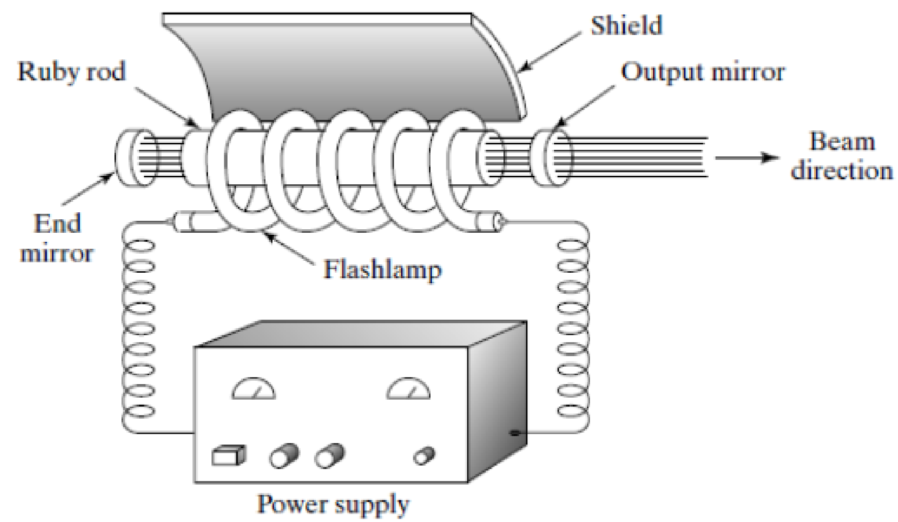
- Laser can be classified in several different ways:
  1. According to the physical state of the laser medium
  2. According to the mode of operation: Pulsed or continuous wave (CW) laser
  3. According to other properties:
     1. Applications.
     2. Wavelength of the emitted radiation.
     3. Power delivered by laser

- Lasers are classified into 4 main types based on the type of laser medium used:
  1. Solid-state laser
  2. Gas laser
  3. Liquid laser
  4. Semiconductor laser

Solid-state lasers

- The active medium is solid (crystal, glass, or ceramics) and using optical pumping for excitation.

- Examples:
    1. Ruby laser (694.3 nm)
    2. Nd:YAG laser (Neodymium-doped yttrium aluminum garnet matrix) emits in 1064 nm.



Ruby laser

Gas lasers

- The lasing medium is made of one or a mixture of gases or vapors. For examples, in He-Ne laser, the helium atoms is used to excite neon atoms. The atomic transition in the neon will produce the laser light.

- Examples:
  1. He-Ne (Helium Neon) laser (632.8 nm and others)
  2. CO_2 Carbon Dioxide laser (10.6 μm) – used in industry for welding and cutting.
  3. Nitrogen laser (337.1 nm)

Liquid lasers

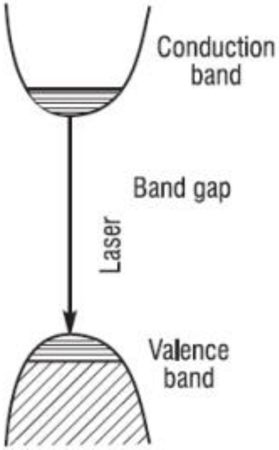
- A liquid laser is a laser that uses the liquid as laser medium. In liquid lasers, light supplies energy to the laser medium. A dye laser is a well-known example of these types which uses an organic dye (liquid solution) as the laser medium.
- They are widely wavelength-tunable such that dye laser can emit from UV to Near IR spectrum.

CW Frequency-Stabilised Dye Laser

Semiconductor lasers

- The laser diode is a semiconductor laser.
- They are mode efficient, cost effective, and require less power than other types.
- The primary components of most semiconductor lasers are gallium (Ga), aluminum (Al), indium (In), Phosphorous (P), and Arsenide (As).
- Examples:
    1. GaAs (780–900 nm)
    2. GaAlAs (1064 nm)
    3. InGaAsP (1100–1600 nm)

       (for fiber optic communications)



Semiconductor Lasers

- The semiconductor lasers are also called **laser diodes (LDs)**, **diode lasers**, or **quantum well laser.**

- Semiconductor lasers operate:

  a) at wavelengths that stretch from the mid ultraviolet to the far-infrared.

  b) at output powers that range from nW (for nano-lasers) to W (for individual laser diodes) to kW (for banks of laser diodes).

Semiconductor Lasers

- The laser diode (LD) has a considerable similarity to the light emitting diode (LED).

- *The two important differences between the LD and LED are:*

1. Diode lasers use some direct semiconductor, like GaAs (Gallium arsenide), and have heavily doped p- and n-sides, while in LED the doping levels are not so high.

2. Laser diode operates at high forward current, larger than a threshold value, while LED operates at lower forward currents.

3. Emission of photons both in LD and LED is through the process of electron–hole recombination. The process of recombination is spontaneous in LED while it is simulated emission in case of laser diode.

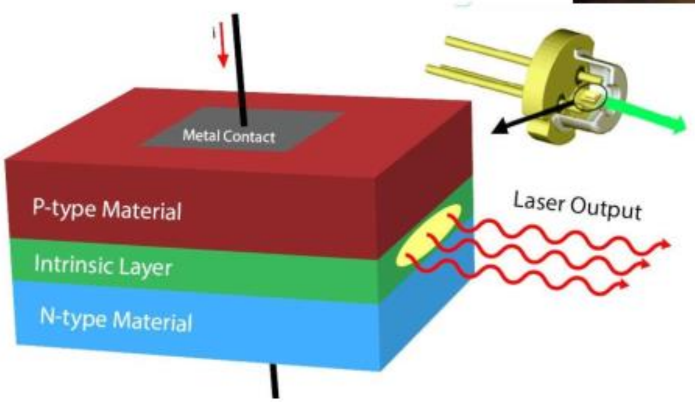
Semiconductor Lasers

➢ The laser diodes (LDs) have a number of advantages with respect to other types of laser:

1. Small size
2. Compatibility with electronic components.
3. High or low power.
4. High efficiency
5. Ease of pumping and modulation by electric-current injection.

➢ Simple construction of a Laser Diode:

1. Metal Contact
2. P-type Material
3. Active/Intrinsic material
4. N-type Material
5. Metal Contact



- In thermal equilibrium at temperature T (no external excitation), the ratio of the population densities of atoms, in two-level atomic system, satisfy a **Boltzmann relation**

$$\frac{N_2}{N_1} = e^{-\frac{(E_2 - E_1)}{K_B T}} = e^{-h\nu_o / K_B T}$$

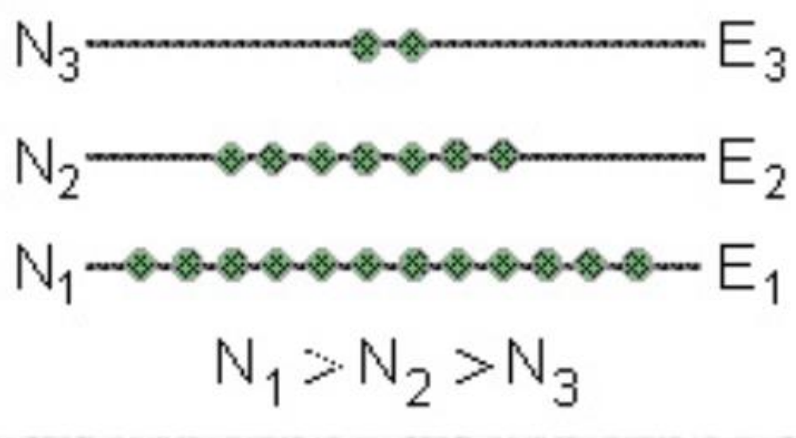
ν_o is the center frequency

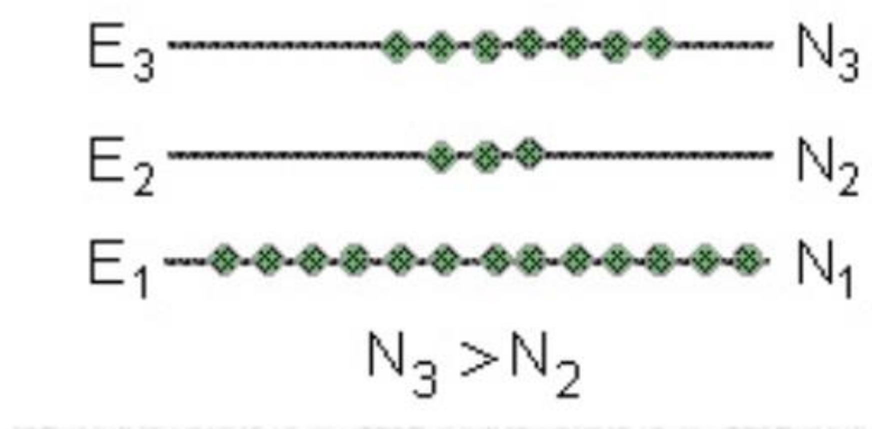
K_B is the Boltzmann constant = 1.38 × 10^{-23} m^2 kg s^{-2} K^{-1}

T is the absolute temperature in Kelvin

- In this case, N_2 is always less than N_1. Thus, it is required to add energy via a process known as "pumping" in order to raise enough atoms to the upper level.

Three-level System





Normal Population

(Thermal equilibrium)

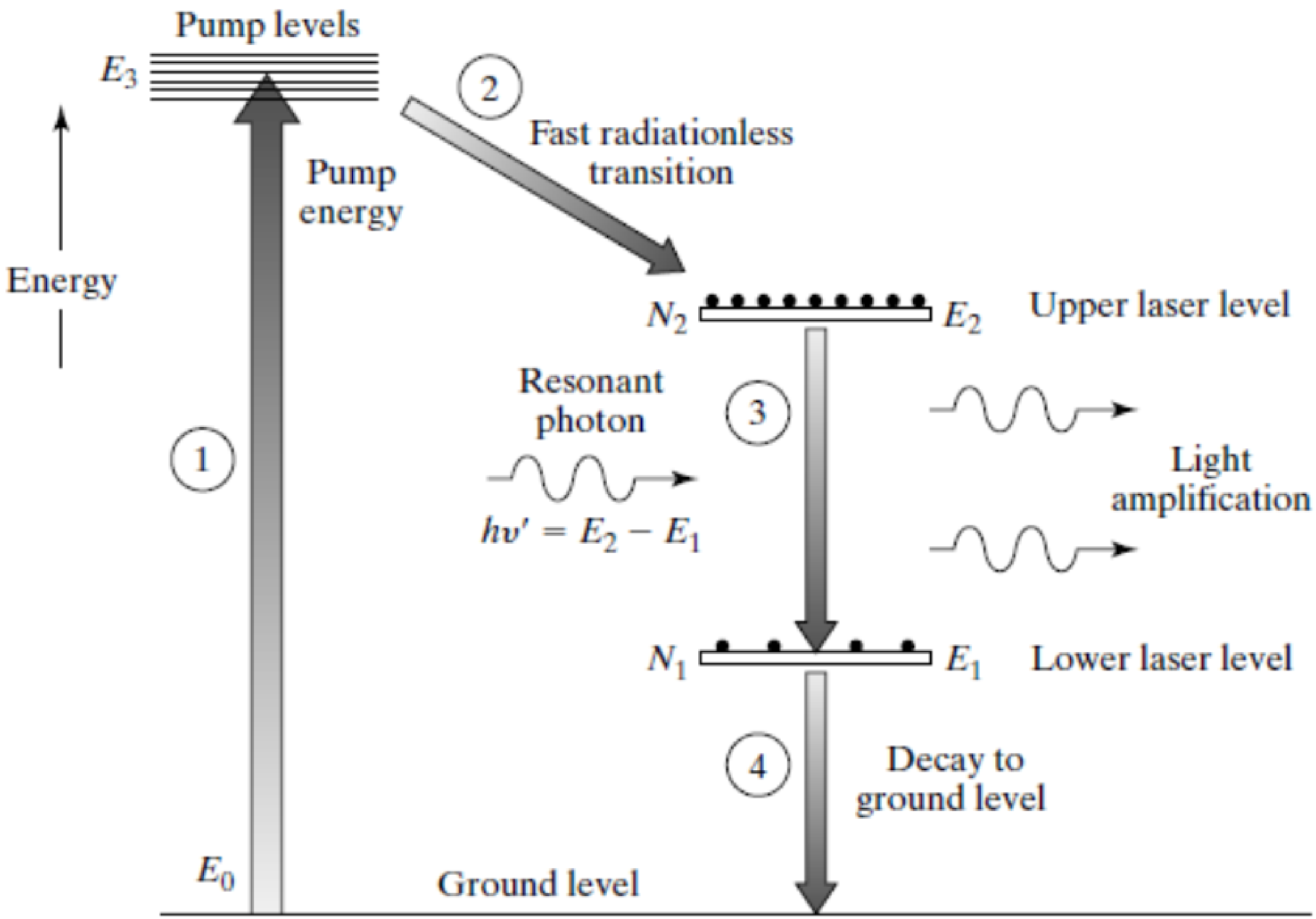
Population Inversion

In this situation there are more atoms (N_3) in an higher energy level (E_3), than the number of atoms (N_2) in a lower energy level (E_2).

Scheme for Four-level laser

1. The energy from an appropriate pump is coupled into the laser medium. The pump energy and rate is sufficiently high to excite a large number of atoms from the ground state E_o to (several excited states) E_3.
2. The atoms starts decay E_3 to a special level E_2 (upper laser level).
3. Level E_2 is a special in the sense that it has a long lifetime. Whereas most excited levels in an atom might decay in times of the order of 10^{-8} s, E_2 is a metastable level with a longer lifetime of the order of 10^{-3} s.
4. Therefore, as atoms pipe rapidly from pump levels to they begin to pile up at the metastable level (functioning as a bottleneck).
5. In this process, N_2 grows to a large value. The atoms in the level E_2 does decay, say by spontaneous emission, to the lower laser level E_1.
6. E_1 Level is an ordinary level that decays to the ground state quite rapidly. The net effect is the production of a population inversion required for light amplification via stimulated emission.

Scheme for Four-level laser



Optical resonator (Fabry-Perot resonator)

- The resonator (or optical cavity) is considered as an optical "feedback device" that directs photons back and forth through the laser (amplifying) medium.

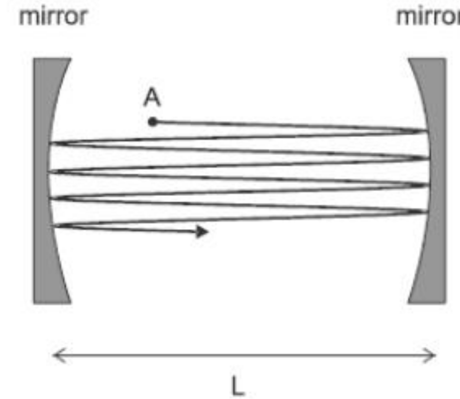
- If laser cavity is considered with no optical gain (without laser medium), it is referred as a passive optical resonator or Fabry-Perot resonator.

- The resonator consists of a pair of carefully aligned plane or curved mirrors centered along the optical axis of the laser system .

- One of the mirrors is chosen with a reflectivity as close to 100% as possible. The other is selected with a reflectivity somewhat less than 100% to allow part of the internally reflecting beam to escape and become the useful laser output beam.

Optical resonator

- The resonator acts also as a frequency filter.



- If the laser cavity consisting of two flat mirrors separated by an distance L will only support standing wave modes of wavelengths λ_m and frequencies ν_m that satisfy the constructive interference condition (*m* is a positiveve integer number or *mode number*):

$$2L = m\,\lambda \quad \Rightarrow \quad \lambda = \frac{2L}{m}$$

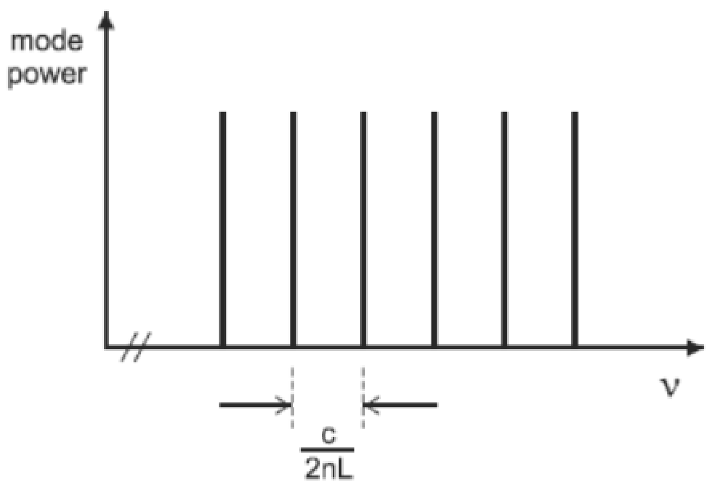
- If n is the refractive index of the medium inside the cavity, the optical resonance frequencies that give constructive interference are then

$$\nu_m = \frac{c/n}{\lambda_m} \quad \Rightarrow \quad \boxed{\nu_m = m\,\frac{c}{2nL}}$$

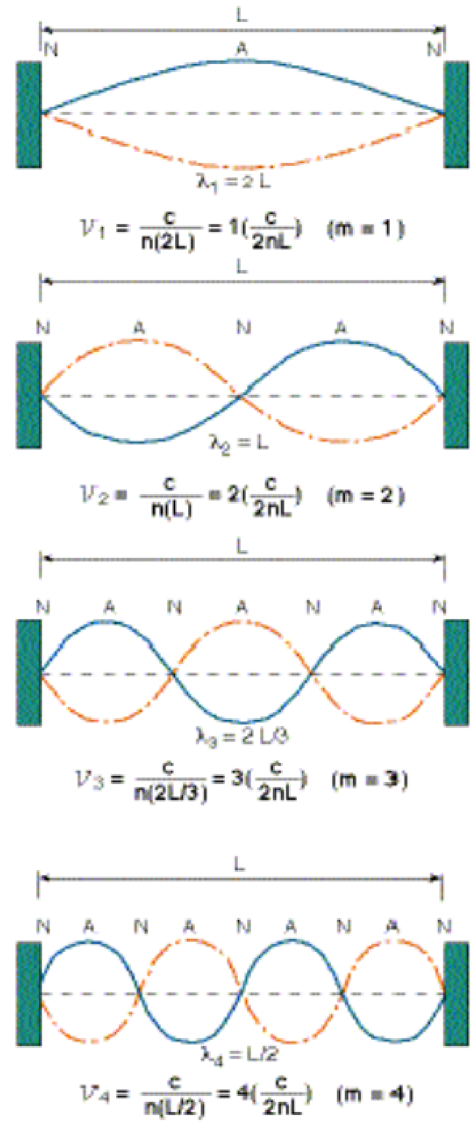
Mode frequency

Optical resonator

- The physical significance of the mode (or resonant) frequencies is that optical power can be stored in the laser cavity only at these particular frequencies.
- The mode frequencies are all multiples, or harmonics, of a base frequency c/(2nL). The frequency distribution of optical power stored in the resonator cavity is then a "comb spectrum".



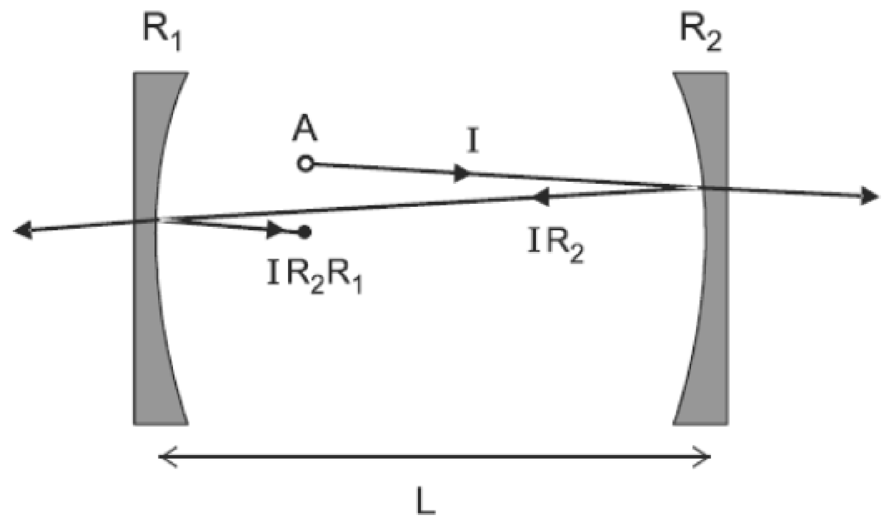
Standing waves



Optical resonator

Mode Width and cavity lifetime

- Consider a passive optical resonator in this analysis.
- Assume that the light has initial intensity *I* at point A in the cavity, after one round trip 2L, the change in the intensity :



$$\Delta I = I(t+\Delta t) - I(t) \quad \Rightarrow \quad \Delta I = I(t)R_1R_2 - I(t) \quad \Rightarrow \quad \Delta I = I(t)[R_1R_2 - 1]$$

but $\Delta t = \dfrac{2L}{c}$

- The time rate of change in intensity $\dfrac{\Delta I(t)}{\Delta t} = \dfrac{R_1R_2-1}{2L/c} I(t) = -\dfrac{1-R_1R_2}{2L/c} I(t)$

Optical resonator

- In laser cavities, the mirror reflectivities are usually high, so the fractional loss per roundtrip is << 1. In this case, *I(t)* can be approximated as a continuous function:

$$\frac{dI}{dt} = -\frac{1-R_1R_2}{2L/c}\, I(t) \longrightarrow \frac{dI}{dt} = -\frac{1}{\tau_c}\, I(t) \qquad (1)$$

where the photon lifetime or cavity lifetime τ_c (or τ_{ph}) is defined as the time for the light intensity to decay to 1/e of its initial value.

$$\tau_c = \frac{2L}{c(1-R_1R_2)}$$

- The solution of equation 1 is $I(t) = I_o\, e^{-t/\tau_c}$
- The light intensity in the cavity decays exponentially in time, with a decay time equal to the photon lifetime τ_c.

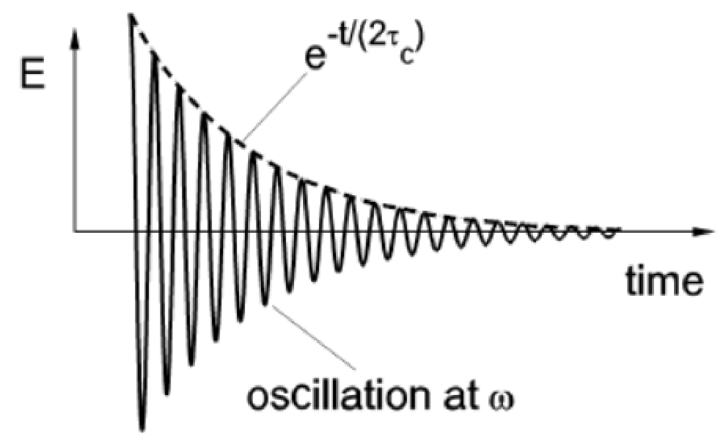
Optical resonator

$$I(t) = I_o\, e^{-t/\tau_c}$$

- Since $E \propto \sqrt{I(t)}$ ⇒ The electric field inside the cavity is

$$E(t) = E_o\, e^{-t/2\tau_c} \cos \omega t$$

- Note: The time decay of the *E* field in an optical resonator is similar to that of a damped harmonic oscillator.



$$I = \frac{1}{2}\varepsilon_o c n E_o^2$$

- This type of time decay is characterized by the *uncertainty relation*

$$\Delta\omega_{1/2}\,\tau_c \approx 1$$

where $\Delta\omega_{1/2}$ is the angular frequency *full width at half maximum* (FWHM) of the optical mode.

but $\Delta\omega_{1/2} = 2\pi\,\Delta\nu_{1/2}$ ⇨ $\Delta\nu_{1/2} = \dfrac{\Delta\omega_{1/2}}{2\pi}$

⇨ $$\boxed{\Delta\nu_{1/2} = \frac{1}{2\pi}(1 - R_1R_2)\frac{c}{2L}}$$

Frequency width (or resolution) of mode

$$\tau_c = \frac{2L}{c(1 - R_1R_2)}$$

Quality Factor Q

- The Q-factor is a measure of the frequency selectiveness of a resonator (measure of the "goodness" or quality of a resonant cavity).
- ***The quality factor Q of a resonance*** is defined as the resonant frequency divided by its frequency width (FWHM):

$$Q \equiv \frac{\nu}{\Delta\nu_{1/2}}$$

$$Q = \frac{\nu \;\, 2\pi \;\, 2L}{c(1 - R_1 R_2)} = \frac{4\pi L}{\lambda(1 - R_1 R_2)} \quad \Rightarrow \quad Q = \frac{4\pi L}{\lambda(1 - R_1 R_2)}$$

- The higher the Q-factor, the more selective the resonator, or narrower the spectral width.

$$\Delta\nu_{1/2} = \frac{1}{2\pi}(1 - R_1 R_2)\frac{c}{2L}$$

Cavity Finesse

- As the laser cavity length *L* increases, the modes become narrower, but the spacing between modes also decreases.

- A useful parameter that gives the mode width compared with the mode spacing is the ***finesse of the cavity***, defined by

$$\mathrm{F} \equiv \frac{\text{mode spaing}}{\text{mode width}} = \frac{c/(2nL)}{\Delta\nu_{1/2}}$$

or

$$\mathrm{F} = \frac{2\pi}{1 - R_1 R_2}$$

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

$$\Delta\nu_{1/2} = \frac{1}{2\pi}(1 - R_1 R_2)\frac{c}{2nL}$$

- Note that the finesse is independent of the cavity length, depending only on the mirror reflectivities.

- The finesse and cavity Q can be related (for n=1)

$$Q = F\frac{2L}{\lambda} = F\frac{2L\nu}{c} = F\frac{\nu}{c/2L} = m\,F$$

$$Q = F\frac{\nu}{c/2L} = m\,F$$

$$\mathrm{F} = \frac{2\pi}{1 - R_1 R_2}$$

$$Q = \frac{4\pi L}{\lambda(1 - R_1 R_2)}$$

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

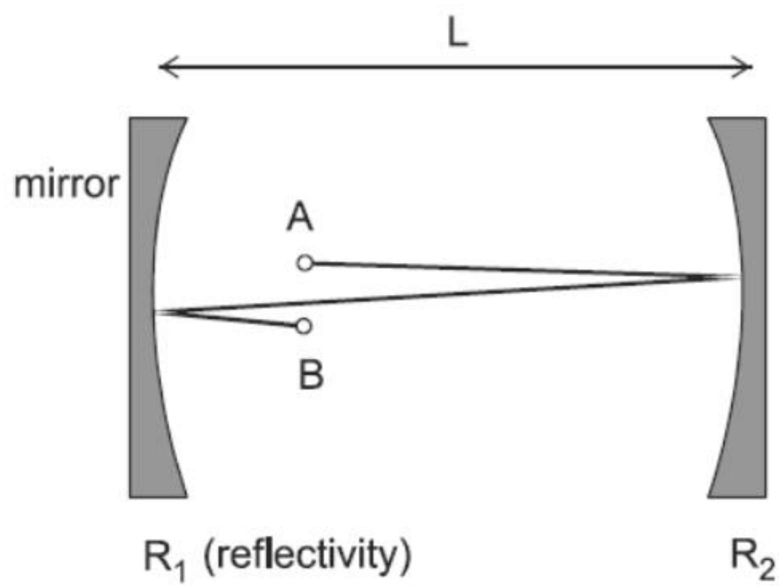
- The three quantities *Q*, *F*, and $\Delta\nu_{1/2}$ are thus equivalent ways of describing the spectral width of the cavity modes.

Laser Oscillation

- In the following analysis, we will consider the conditions under which the feedback provided by the mirrors be sufficient to achieve laser oscillation. It will be seen that there is a minimum pumping power required to achieve lasing, termed the *threshold pump power.*

Threshold Condition

- As the light makes a round-trip through the cavity from point A to point B, it is amplified with a gain coefficient γ, while at the same time being attenuated (due to absorption or scattering) by the loss coefficient α.



Laser Oscillation

- If I_A is the intensity of light originating at point A, then, the intensity of the light arriving at point B (I_B) can then be written as

$$I_B = I_A R_1 R_2 e^{(\gamma-\alpha)2L}$$

- For lasing to occur, it is necessary that $I_B > I_A$, so that the light intensity will grow exponentially in time. The threshold condition for laser oscillation then becomes:

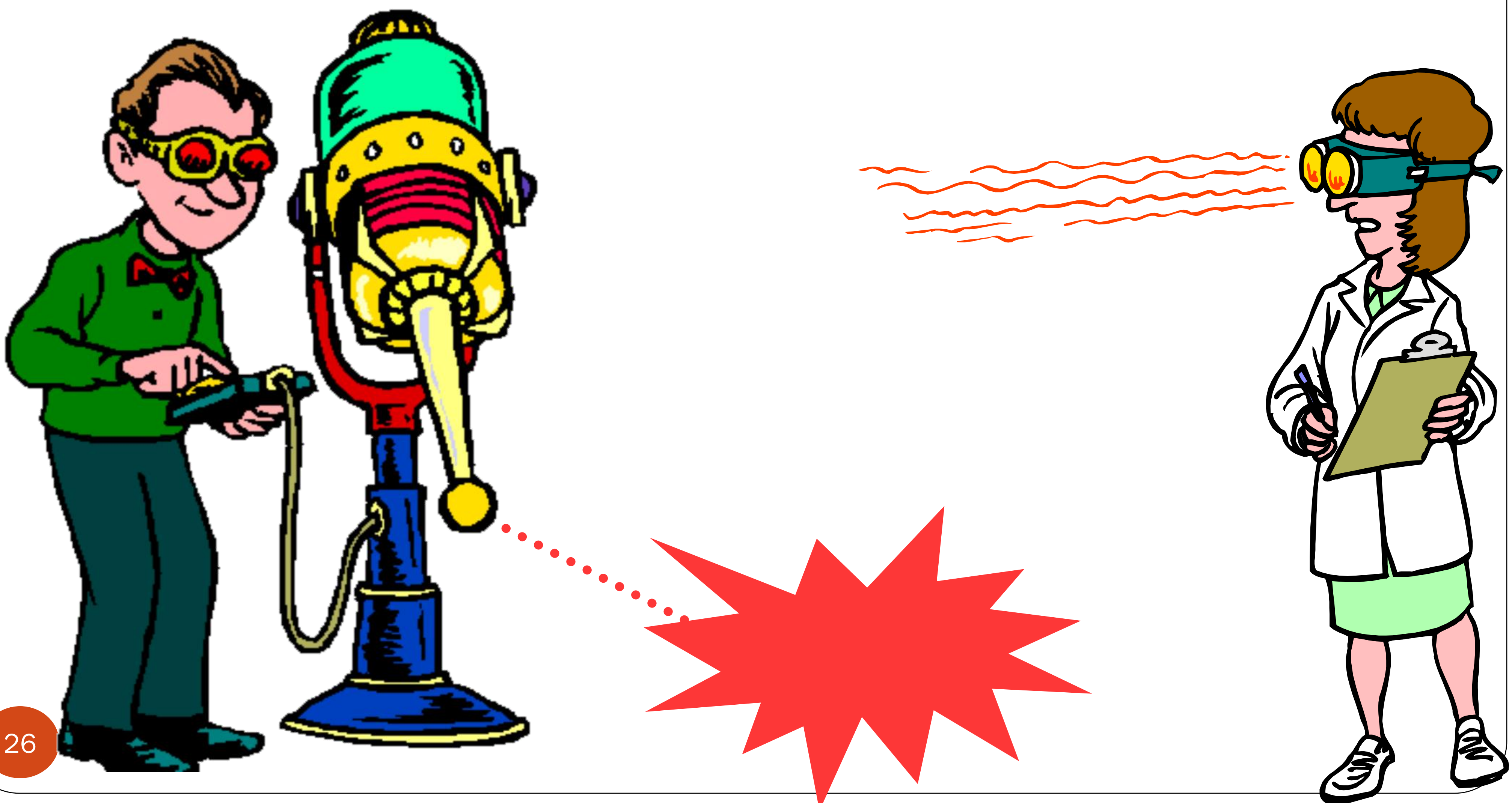
$$R_1 R_2 e^{(\gamma-\alpha)2L} \geq 1$$

- The smallest value of γ that satisfies this inequality is termed the *threshold gain coefficient (γ_{th})*

gain=

$$\gamma_{th} = \alpha + \frac{1}{2L}\ln\left(\frac{1}{R_1 R_2}\right)$$

Laser Hazards



Types of Laser Hazards

1. **Eye** : Acute exposure of the eye to lasers of certain wavelengths and power can cause corneal or retinal burns (or both). Chronic exposure to excessive levels may cause corneal or lenticular opacities (cataracts) or retinal injury.
2. **Skin** : Acute exposure to high levels of optical radiation may cause skin burns; while carcinogenesis may occur for ultraviolet wavelengths (290-320 nm).
3. **Chemical** : Some lasers require hazardous or toxic substances to operate (i.e., chemical dye, Excimer lasers).
4. **Electrical** : Most lasers utilize high voltages that can be lethal.
5. **Fire** : The solvents used in dye lasers are flammable. High voltage pulse or flash lamps may cause ignition. Flammable materials may be ignited by direct beams or specular reflections from high power continuous wave (CW) infrared lasers.

Thank you for your attention