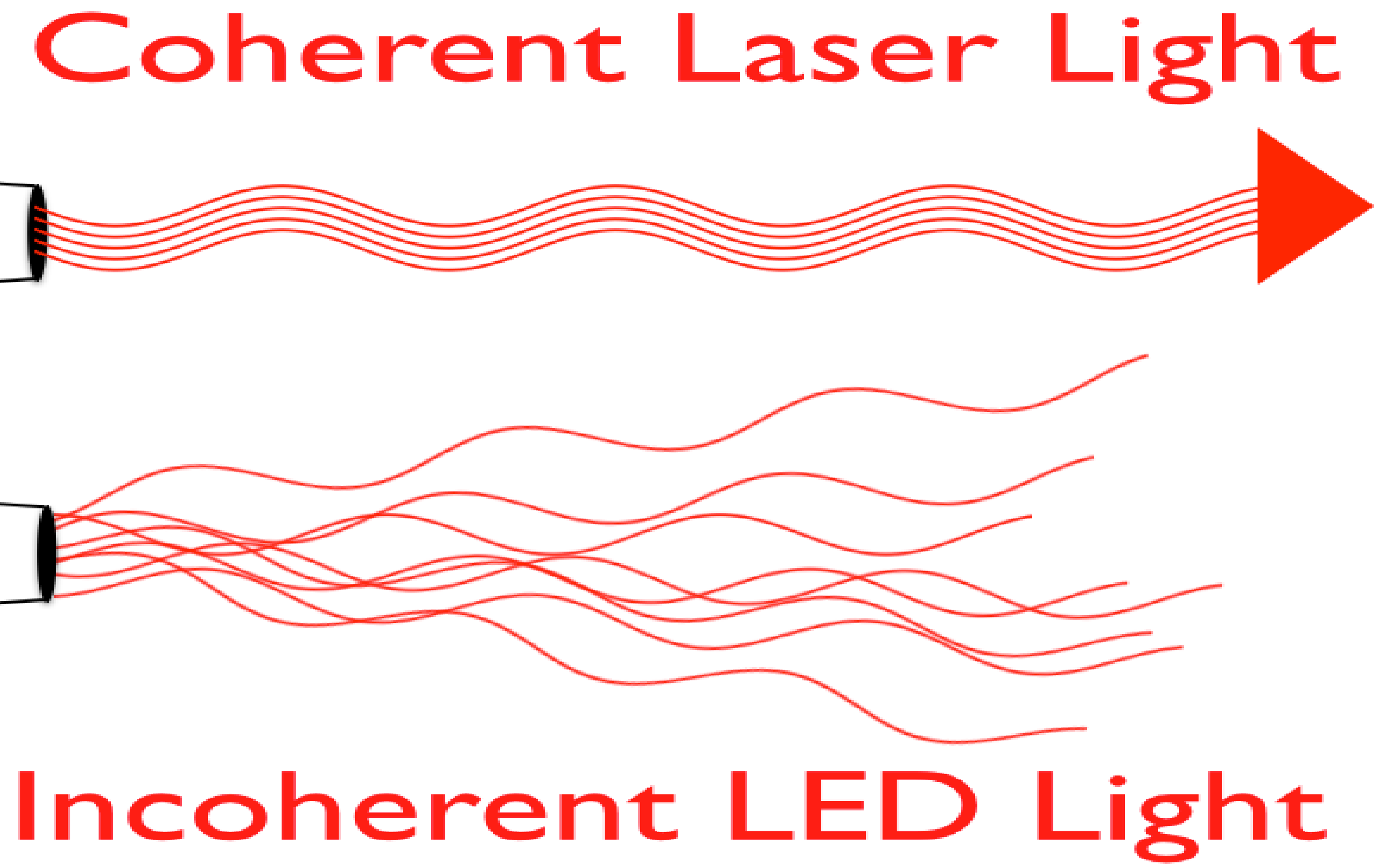


Module – 3
Optical Transmitters

LASER

Light

Amplification by

Stimulated

Emission of

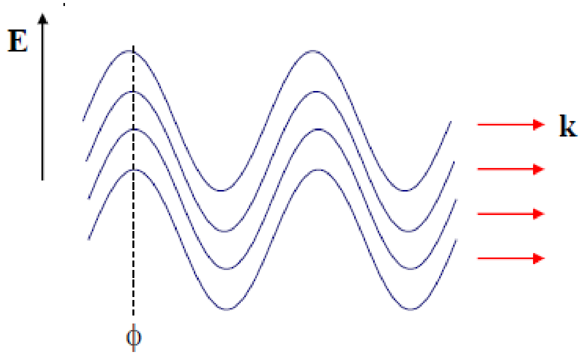
Radiation

Coherent radiation

- In a laser, however, the emission from individual atoms is synchronized, giving coherent radiation.

- The process of synchronization is stimulated emission
  - a concept introduced by Einstein in 1916.

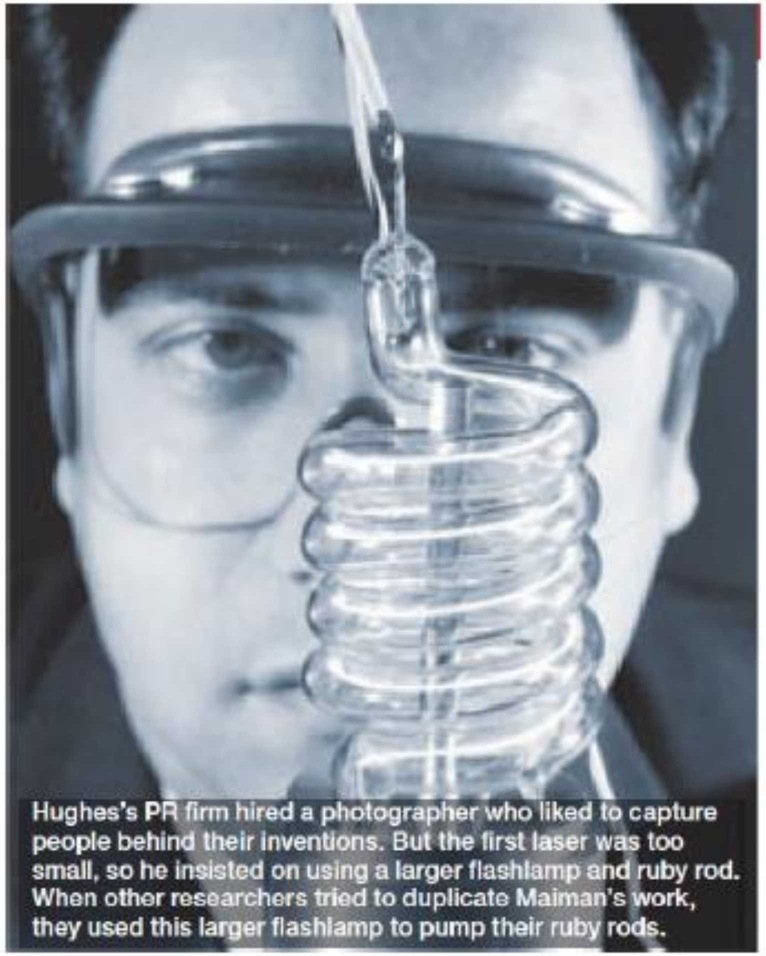
- The essential effect of stimulated emission is the coherent emission of radiation from excited atoms – adding precisely in phase and with the same direction and polarization



Stimulated emission

- One photon arrives at the excited atom, and two photons leave, with the same energy, traveling together and in phase
- The stimulated photon has the same momentum as the incident photon, and hence travels in the same direction
- Both photons can then repeat the stimulated emission process at other excited atoms, the resulting chain reaction causes the light wave to grow exponentially
- To make such an amplifier into a self-excited oscillator – the light must be fed back into the laser material. This is attained by enclosing the lasing material between mirrors, forming a resonant cavity.

The first laser

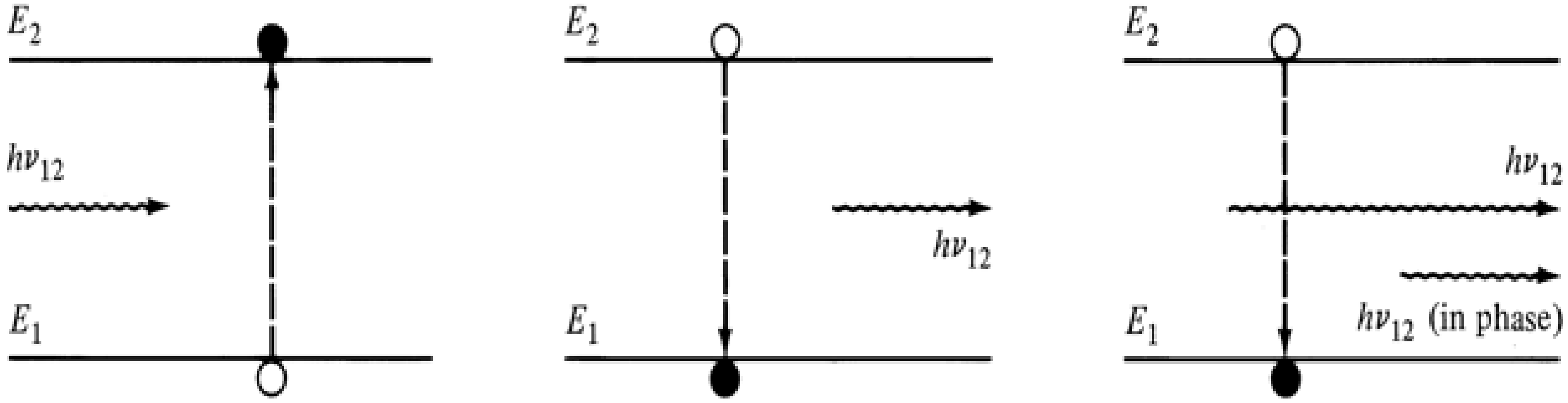


Laser light is

- Coherent
- Quasi-monochromatic (nearly single frequency), from soft x-ray (few nm) to mid-IR (e.g. 10.2 mm)
- Directional
- Polarized
- Can be high-power (e.g. kilo Watts)
- Can be continuously operated (continuous wave) or pulsed with narrow pulse widths (picosecond, femtosecond, attosecond)
- Can be generated from gas, liquid, solid medium (almost anything can become a laser if you pump it hard enough!)

Fundamental Transition Processes

Two level atomic System



(*a*) Absorption (*b*) Spontaneous emission (*c*) Stimulated emission

Population inversion

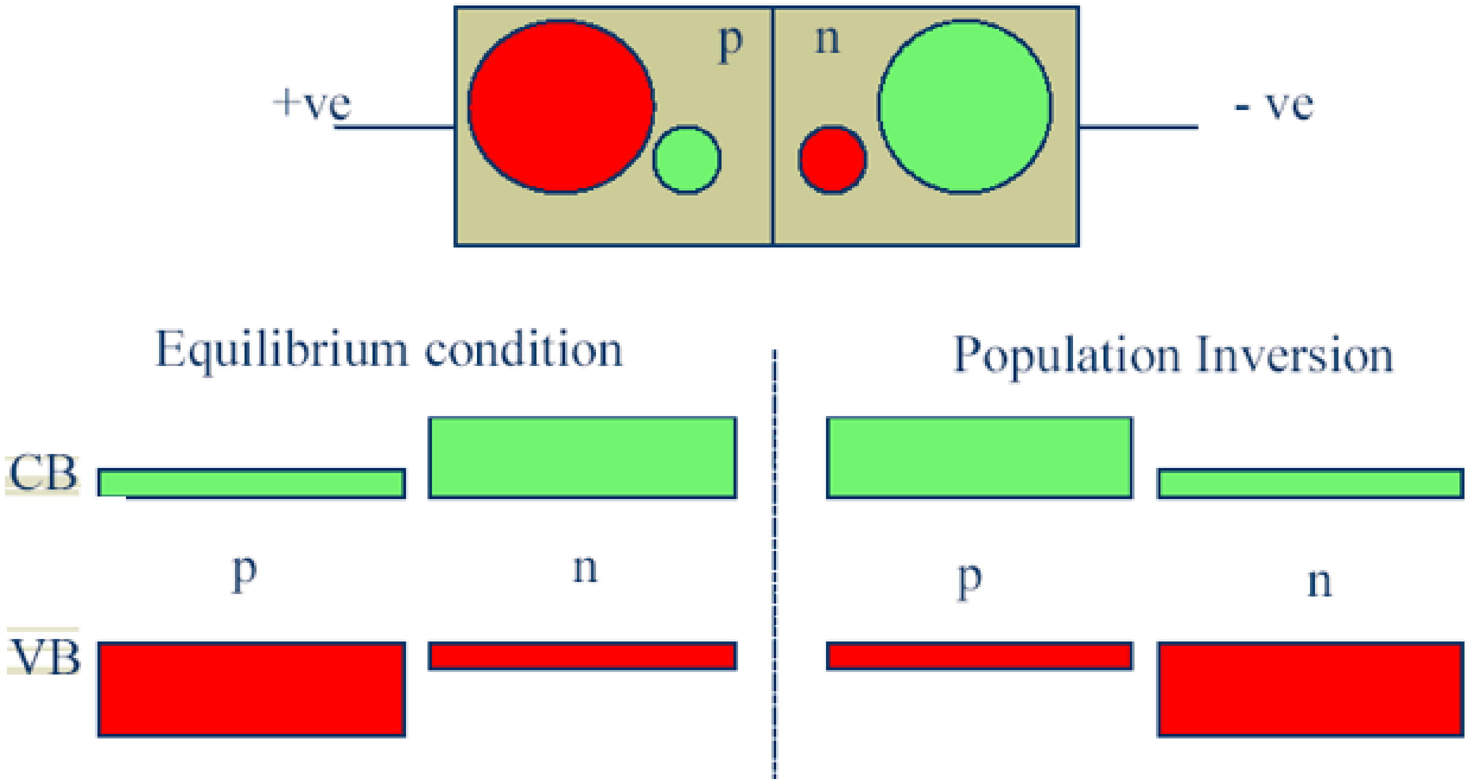
- Recall that the stimulated emission photon is an exact copy of the seed photon (identical frequency, phase, polarization and direction).

- Each stimulated emission photon could stimulate more photon emissions, leading to the build-up of a coherent wave of very large intensity.

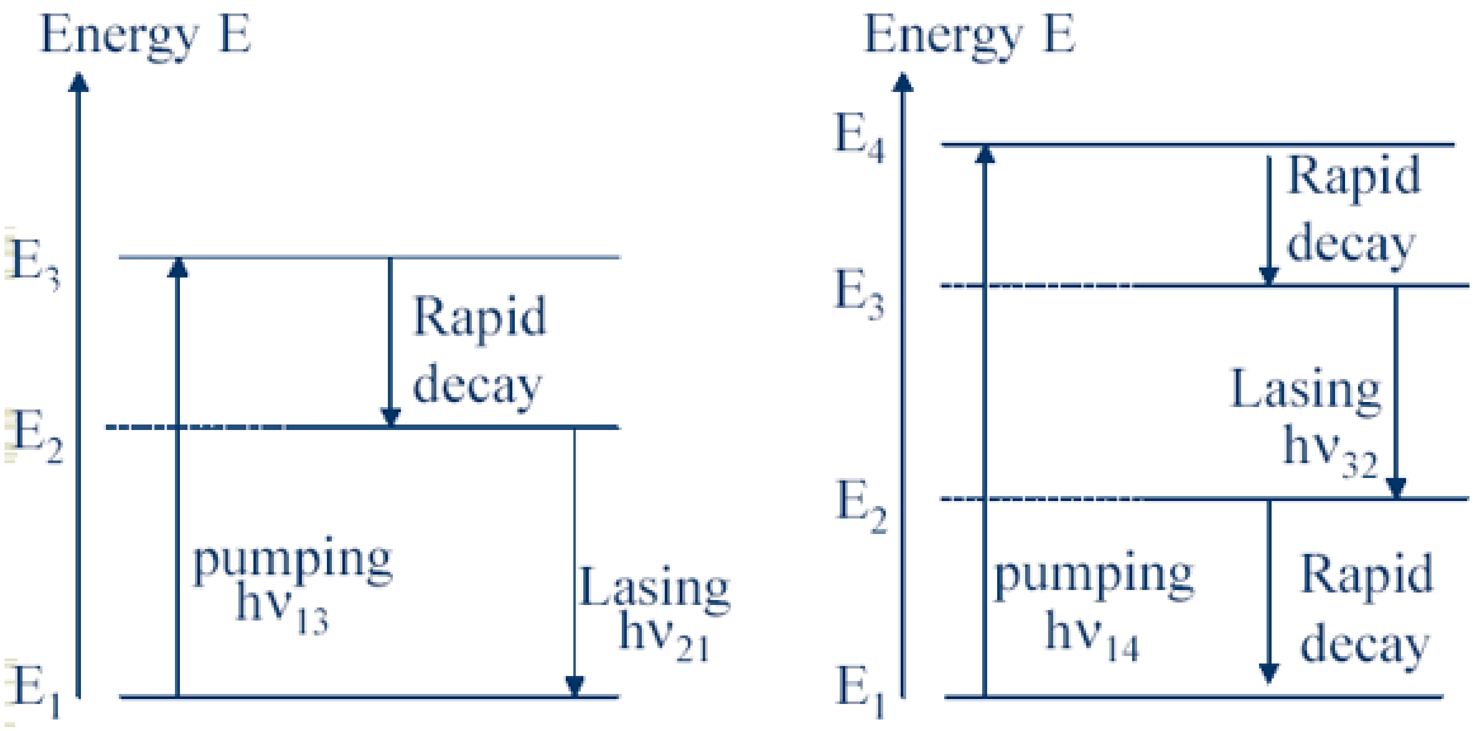
- This requires the number of atoms in the higher energy level N2 to exceed the number in the lower level N1, a condition known as population inversion.

- The rate of stimulated emission exceeds the rate of absorption.

Population inversion

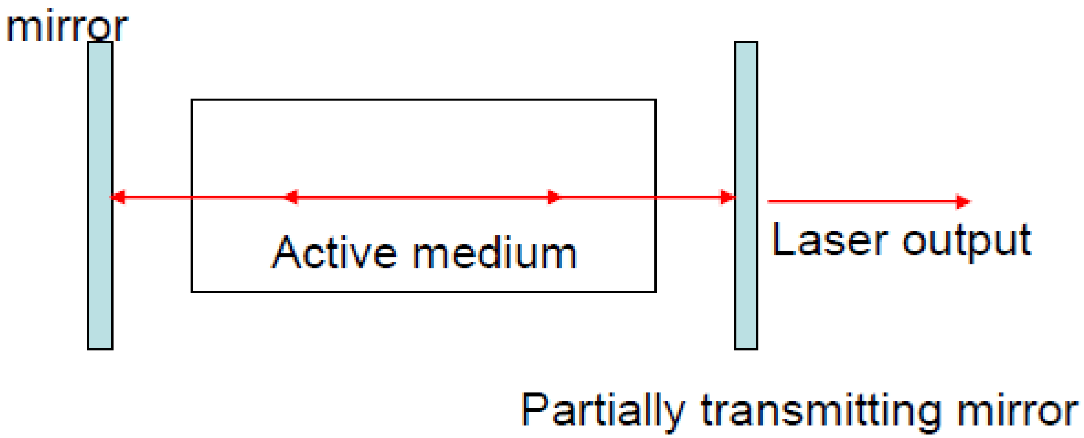


Three/Four level system



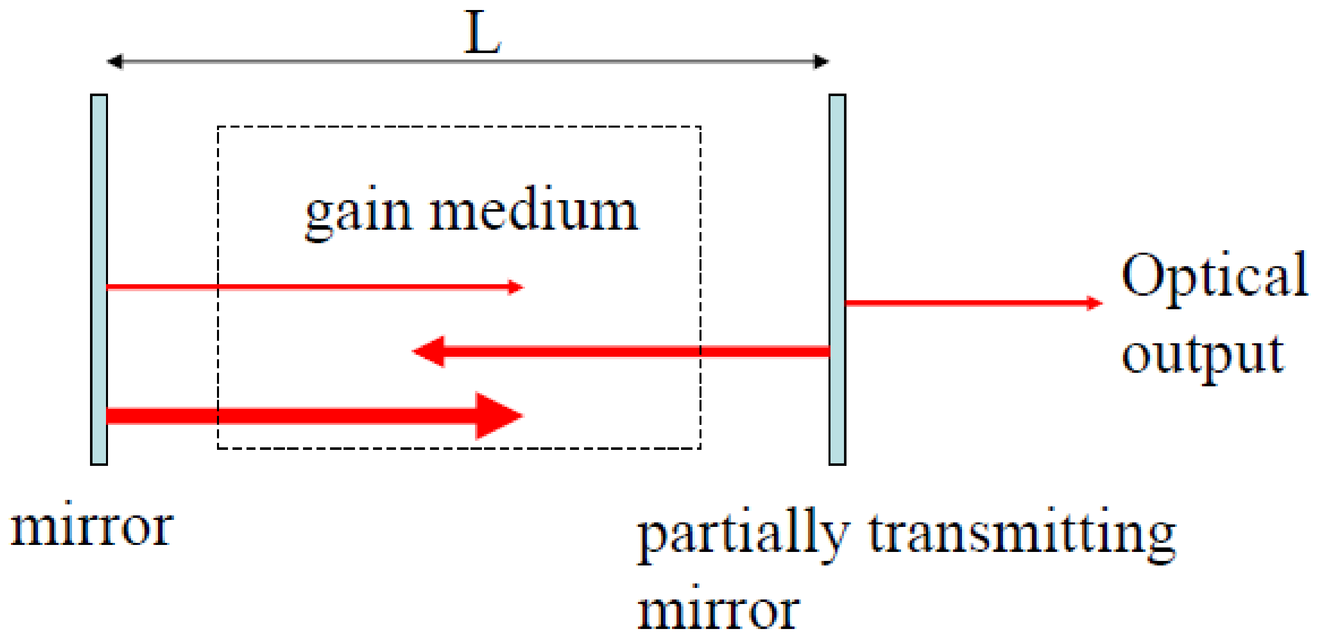
Laser is an optical-frequency oscillator

- A laser is an optical-frequency oscillator constructed from an optical-frequency amplifier with positive feedback.
- Light waves which become amplified on traversing the amplifier are returned through the amplifier by the reflectors and grow in intensity, but this intensity growth does not continue indefinitely because the amplifier saturates.
- Spontaneous emission photons serve as "noise" to start the optical oscillator.



To make a laser

- Population inversion – a criterion to provide gain
- Stimulated emission
- Optical feedback

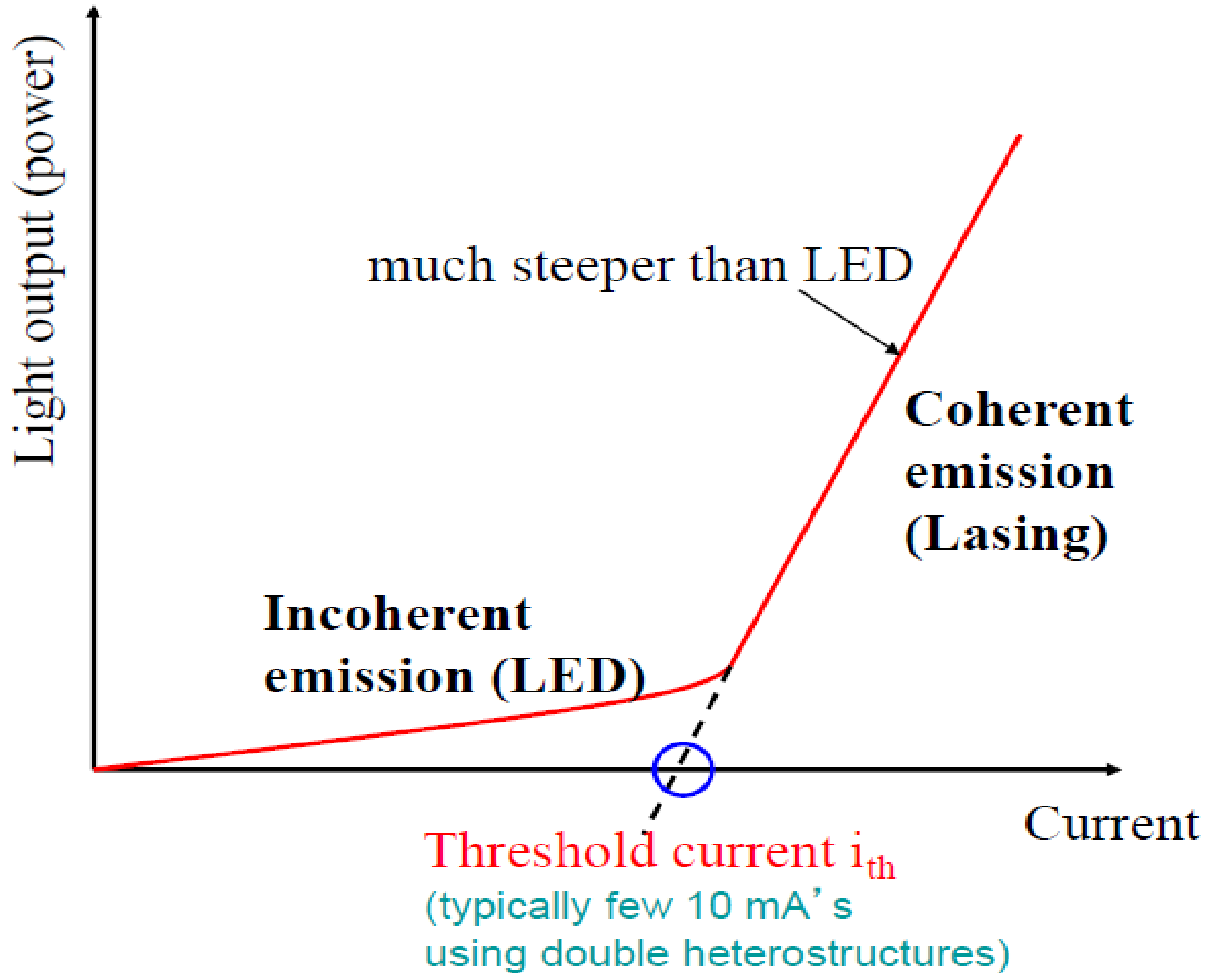


Conditions for laser oscillation

- The gain condition determines the minimum population difference, and thus the pumping threshold required for lasing

- The phase condition determines the frequency (or frequencies) at which oscillation takes place

Laser threshold: a key signature of oscillation



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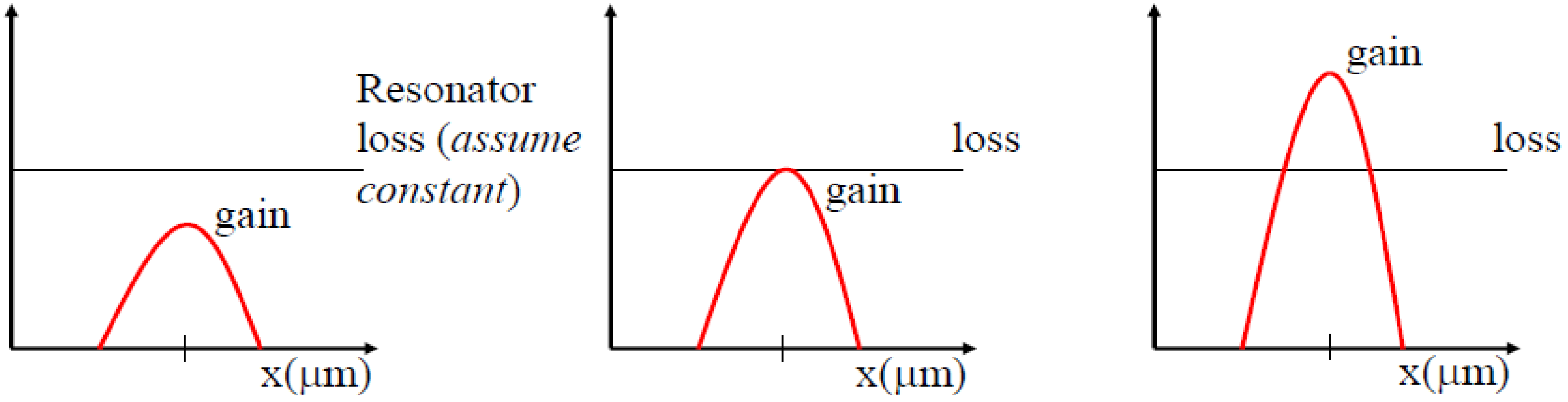
Laser threshold

- A certain fraction of photons generated by stimulated emission is lost because of the resonator loss (absorption, scattering, extraction of laser light).
- The unsaturated optical gain needs to exceed the resonator loss such that the photon population can build up. The resonator loss thus sets the threshold gain.
- The laser oscillation condition:

$$g_0(\upsilon) > \alpha_r$$

- where α_r is the resonator loss coefficient (cm^{-1}).
- For laser diodes, the injection current that is needed to reach the threshold is called the threshold current.

The unsaturated gain must exceed the resonator loss



gain < loss

gain = loss

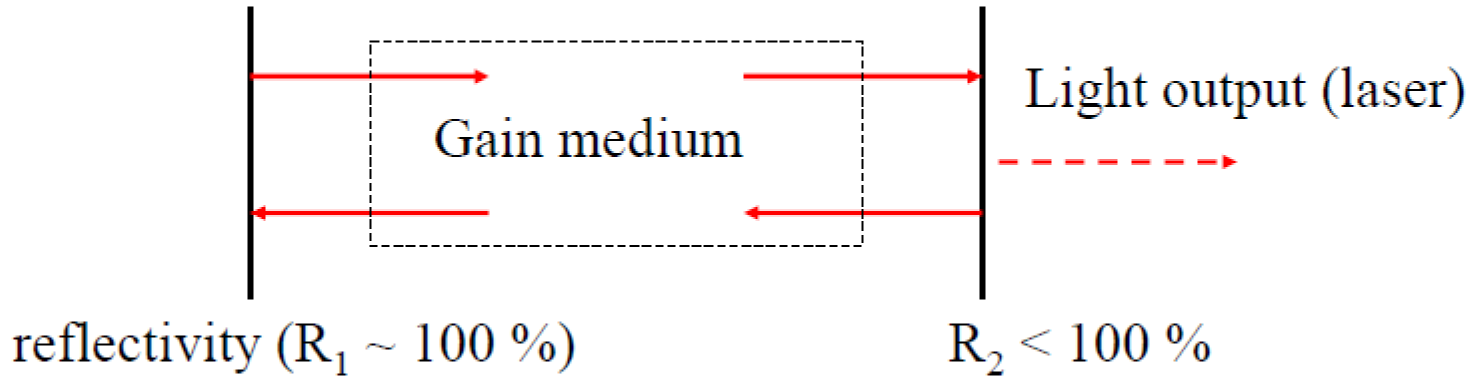
gain > loss

- **sub-threshold (incoherent emission)**
- **Threshold (oscillation begins, start to emit coherent light)**
- **above-threshold (increase in coherent output power)**

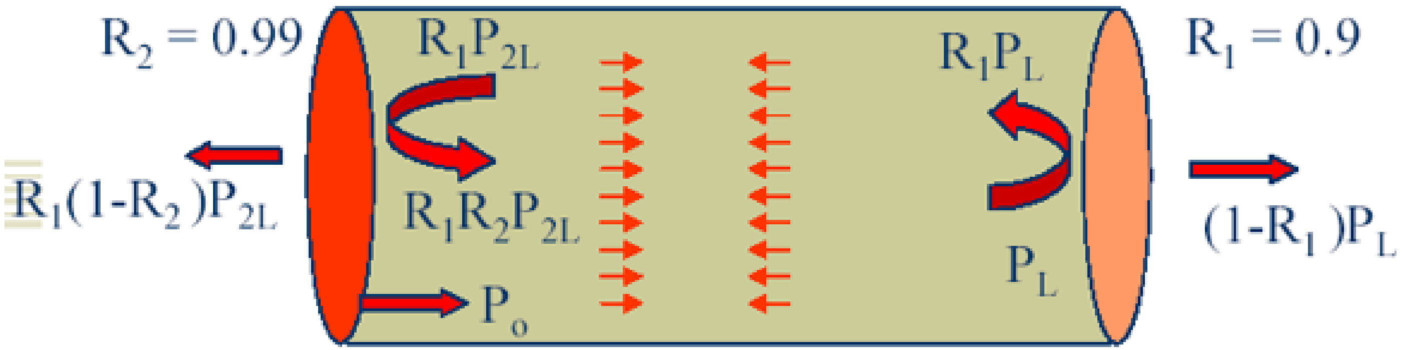
x: dimension along an active layer

Optical resonators

- In practical laser devices, it is generally necessary to have certain positive optical feedback in addition to optical amplification provided by a gain medium.
- This requirement can be met by placing the gain medium in an optical resonator.
- The optical resonator provides wavelength selective feedback to the amplified optical field.
- In many lasers the optical feedback is provided by placing the gain medium inside a "Fabry-Perot" cavity, formed by using two mirrors or highly reflecting surfaces



Fabry Perot Resonator



- The resonator contributes to losses. Absorption and scattering of light in the gain medium introduces a power loss per unit length (effective loss coefficient α_{eff} in cm^{-1})
- The effective gain coefficient reduces to (g_{21}- α_{eff})

$$P_L = P_0 \exp\{(g_{21} - \alpha_{eff})L\}$$

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Fabry Perot Resonator

- After one complete round trip

$$R_1R_2P_{2L} = R_1R_2P_0 \exp\{(g_{21} - \alpha_{eff})2L\}$$

- Gain in one round trip is

$$G = R_1R_2 \exp\{(g_{21} - \alpha_{eff})2L\}$$

- Threshold condition

$$G = R_1R_2 \exp\{(g_{21} - \alpha_{eff})2L\} = 1$$

- Threshold gain coefficient

$$g_{th} = \alpha_r = \alpha_{eff} + \left(\frac{1}{2L}\right)\ln\left(\frac{1}{R_1R_2}\right)$$

- For lasing, the gain $g \geq g_{th}$

Summary: Conditions for laser oscillation

- The amplifier unsaturated gain must exceed the loss in the feedback system so that net gain is incurred in a round trip through the feedback.

- The total phase shift in a single round trip must be a multiple of 2π so that the feedback input phase matches the phase of the original input.

- A stable condition is reached when the reduced gain is equal to the resonator loss. Steady-state oscillation then prevails.

Numerical problem

- Find the optical gain at threshold of a laser diode having following parametric values:

  $R1=R2=0.32$, $\alpha eff=10/cm$ and $L = 500\ \mu m$

Numerical problem

- Find the optical gain at threshold of a laser diode having following parametric values:

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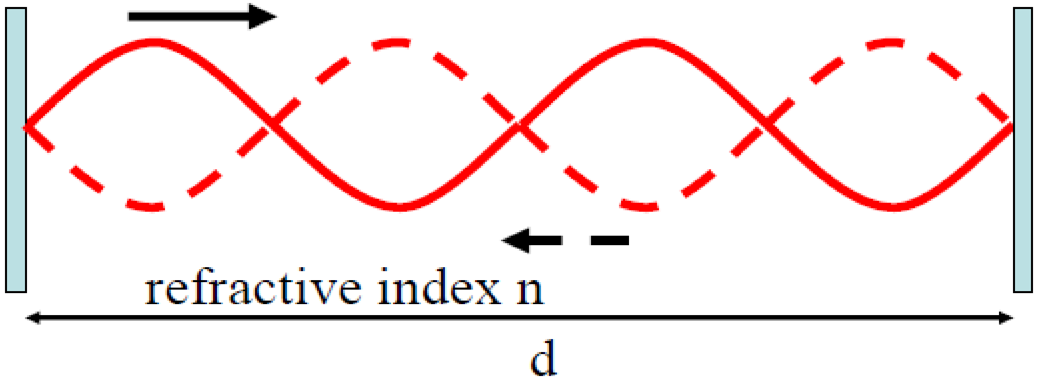
$$g_{th} = \alpha_r = \alpha_{eff} + \left(\frac{1}{2L}\right)\ln\left(\frac{1}{R_1 R_2}\right)$$

$$g_{th} = 32.7/\text{cm}$$

Fabry-Perot cavity resonances



- Only standing waves at discrete wavelengths exist in the cavity
- The laser wavelengths must match the cavity resonance wavelengths
- The resonance condition:

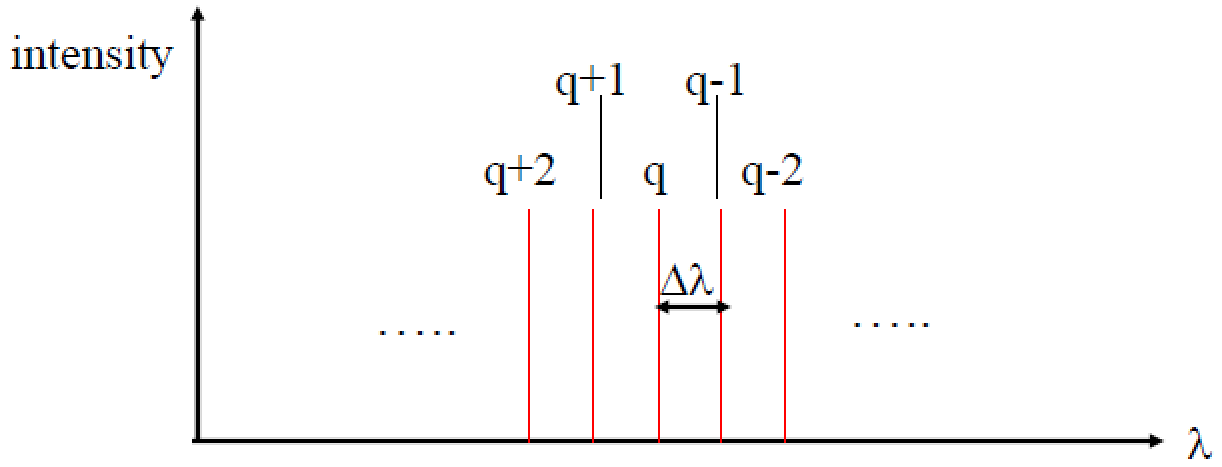
$$2kd = 2\pi m$$

- where m is an integer, known as the longitudinal mode order

$$k = 2\pi n / \lambda \qquad m = \frac{2dn\nu}{c}$$

Fabry-Perot cavity resonances

- The modes along the cavity axis is referred to as longitudinal modes
- Many λ's may satisfy the resonance condition => multimode cavity



- The longitudinal mode spacing (free-spectral range):

$$\Delta\lambda = \frac{\lambda^2}{2nd}$$

Fabry-Perot cavity resonances

- The longitudinal mode frequency:

$$\nu = \frac{mc}{2nd}$$

- The mode spacing (free-spectral range) in frequency unit

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

Numerical problem

- A GaAs laser diode operating at the wavelength of 850 nm and has length of 500 μm, refractive index n = 3.7. Calculate frequency and wavelength spacings.

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$$\Delta\lambda = \frac{\lambda^2}{2nd} = 0.19nm$$

$$\Delta\nu = \frac{c}{2nd} = 81GHz$$

Numerical problem

- A semiconductor laser diode has a cavity length 400 mm with a refractive index of 3.5. The peak emission wavelength from the device is 0.8 mm. Determine the longitudinal mode order and the frequency spacing of the neighboring modes.

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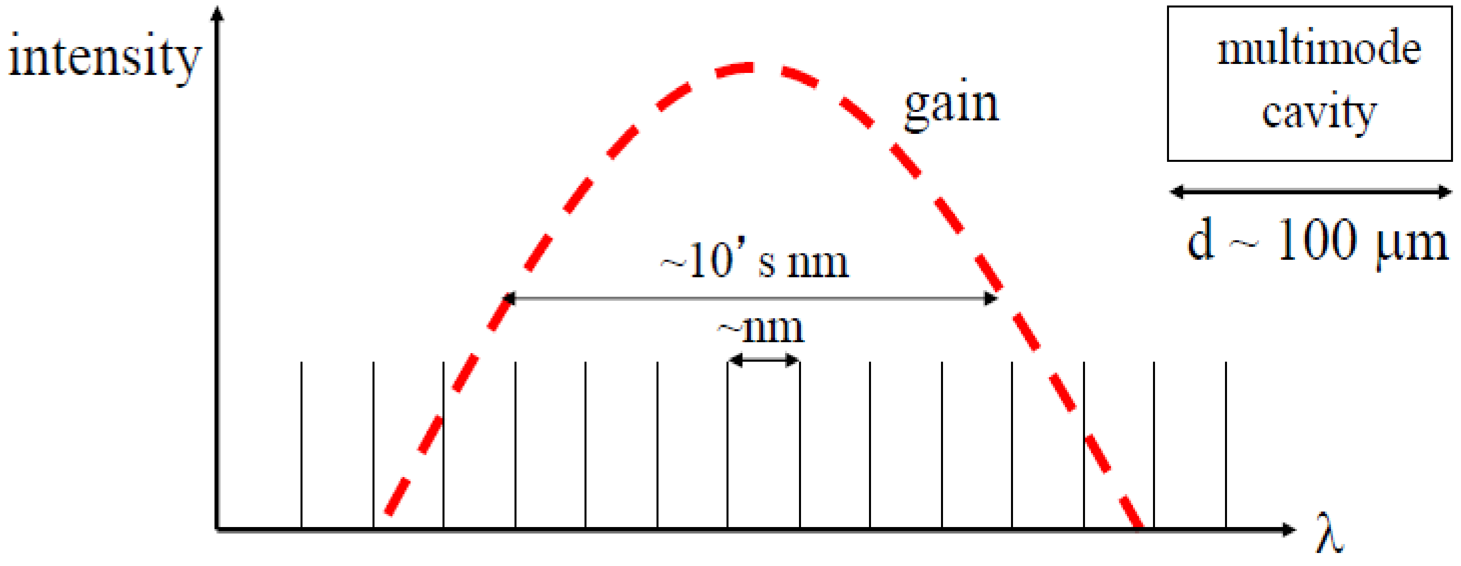
$$m = \frac{2dn}{\lambda} = 3500$$

$$\Delta \nu = \frac{c}{2nd} = 107 MHz$$

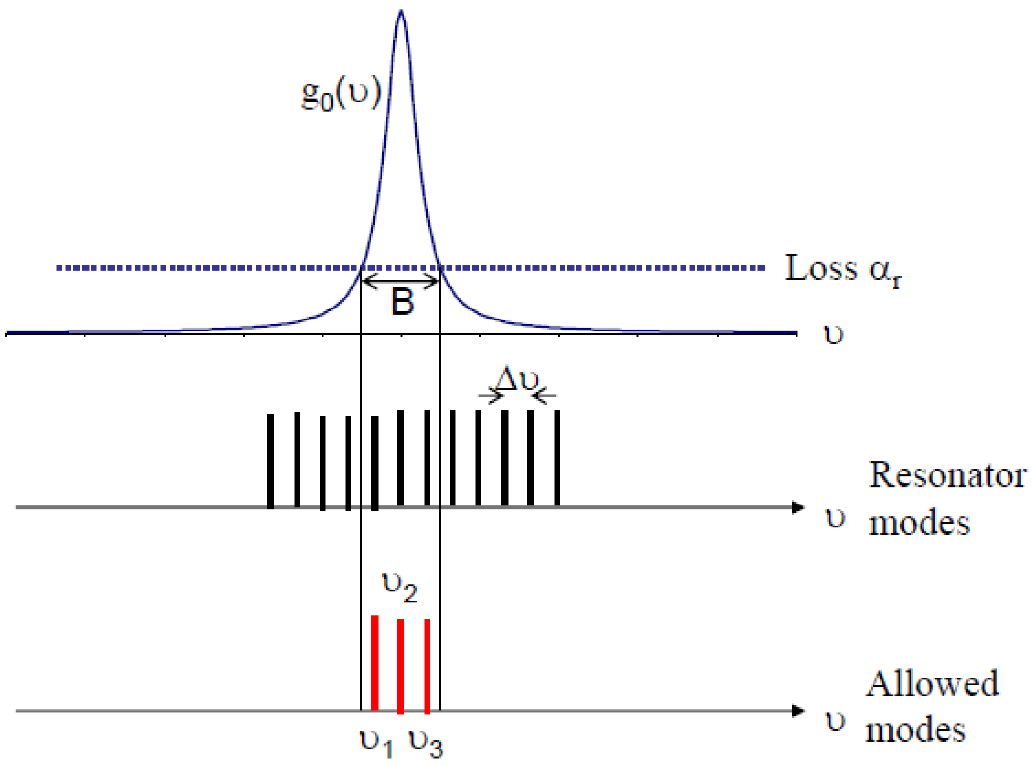
Laser Modes

- An active medium provides optical gain (stimulated emission) only within the gain bandwidth.
- In the case of semiconductors, the gain bandwidth is about 10 - 20 THz.
- Only cavity resonant wavelengths that lie within the gain curve may oscillate.



Laser Modes

- Laser oscillation can occur only at frequencies for which the unsaturated gain coefficient exceeds the resonator loss coefficient.
- Only a finite number of oscillation frequencies are possible.



Laser Modes

- The number of possible laser modes

$$M = \frac{B}{\Delta \nu} \qquad M = \frac{B}{\Delta \lambda}$$

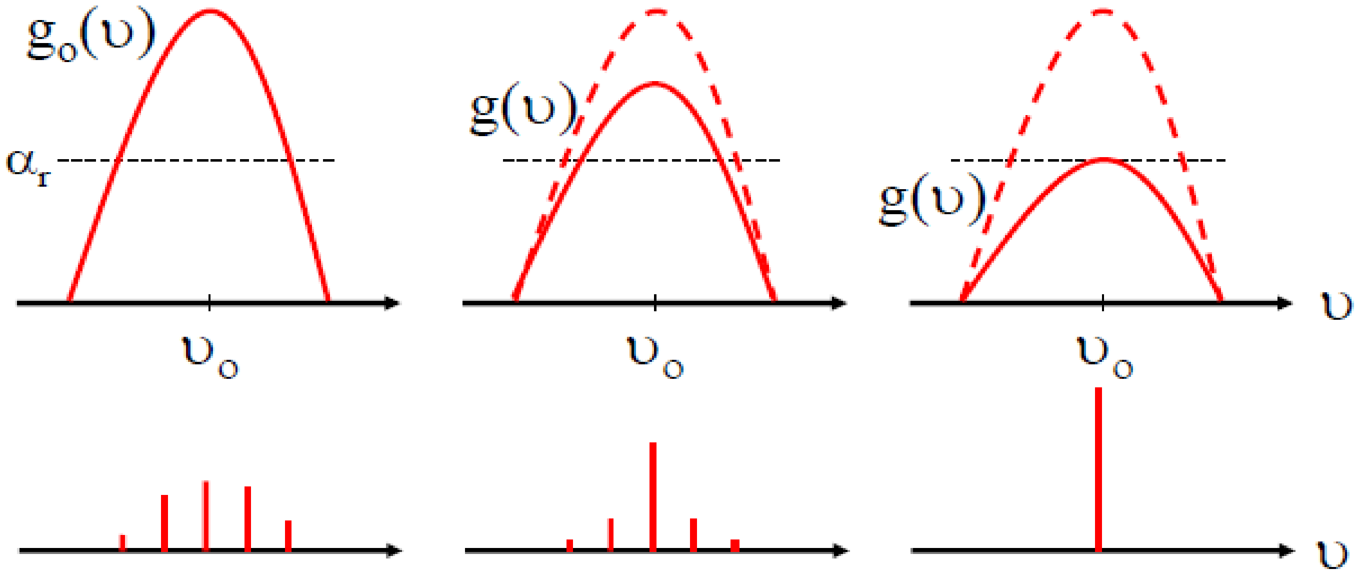
- However, of these M possible modes, the number of modes that actually carry optical power depends on the nature of the spectral lineshape broadening mechanism.

- For a homogeneously broadened medium (e.g. semiconductor) these modes compete, rendering fewer modes (ideally single mode) to oscillate.

- For an inhomogeneously broadened medium (e.g. HeNe gas, Er3+-doped glass) all M modes may oscillate (albeit at different powers).

Growth of oscillation in an ideal homogeneously broadened medium

- Immediately following laser turn-on, all modal frequencies for which the gain coefficient exceeds the loss coefficient begin to grow, with the central modes growing at the highest rate. After a transient the gain saturates so that the central modes continue to grow while the peripheral modes, for which the loss has become greater than the gain, are attenuated and eventually vanish. Only a single mode survives.



External Quantum Efficiency

- The external quantum efficiency is defined as the number of photons emitted per radiative electron hole pair recombination above the lasing threshold.

$$\eta_{ext} = \frac{\eta_{\text{int}}(g_{th} - \alpha_{eff})}{g_{th}}$$

- η_{int} = 0.6 – 0.7 at room temperature

- Experimentally,

$$\eta_{ext} = \frac{q}{E_g}\frac{dP}{dI} = 0.8065\lambda(\mu m)\frac{dP(mW)}{dI(mA)}$$

- For standard lasers, the external quantum efficiency is 15 – 20% and for high quality lasers it is 30 – 40%.

Numerical problem

- A GaAlAS laser diode has a 500 um cavity length which has an effective absorption coefficient of 10/cm. For uncoated facets the reflectivties are 0.32 at each end. What is the optical gain at the lasing threshold?
- (a). If one end of the laser is coated with dielectric reflector so the reflectivity is now 90 percentage, What is the optical gain at the lasing threshold?
- (b). If the internal quantum efficiency is 0.65, then calculate the external quantum efficiency.

Numerical problem

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$$g_{th} = \alpha_r = \alpha_{eff} + \left(\frac{1}{2L}\right)\ln\left(\frac{1}{R_1R_2}\right)$$

g_{th}=32.7/cm

g_{th}=22.44/cm

$$\eta_{ext} = \frac{\eta_{\text{int}}(g_{th} - \alpha_{eff})}{g_{th}} = 36\%$$

Numerical problem

- A GaAS laser diode emitting at 800 nm has a 400 um cavity length with a refractive index n =3.6. If the gain exceeds the total loss throughout the range 750 nm$<\lambda<$850 nm, how many modes will exit in the laser?

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$$\Delta\lambda = \frac{\lambda^2}{2nd} = 0.22nm$$

$$M = \frac{B}{\Delta\lambda} = 455\,\mathrm{mod}\,es$$

Numerical problem

- Consider a GaAs laser with an optical cavity length of 250 μm and width 100 μm. At the normal operating temperature, the gain factor β = 21 x 10-3 A/cm3 and the effective absorption coefficient α_{eff} = 10 cm-^{1}.
- If the refractive index is 3.6, find the threshold current density and the threshold current. Assume the laser end faces are uncoated and the current is restricted to the optical cavity.
- What is the threshold current if the laser cavity width is reduced to 10 μm.

Numerical problem

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$$g_{th} = \alpha_r = \alpha_{eff} + \left(\frac{1}{2L}\right)\ln\left(\frac{1}{R_1 R_2}\right)$$

$$g_{th} = \beta J_{th}$$

$$J_{th} = \frac{1}{\beta}\left[\alpha_{eff} + \left(\frac{1}{2L}\right)\ln\left(\frac{1}{R_1 R_2}\right)\right] = 2.65 X 10^3 A/cm^2$$

$$R_1 = R_2 = \left(\frac{n-1}{n+1}\right)^2 = 0.32$$

$$I_{th} = J_{th} LW = 663 mA$$

$$I_{th} = J_{th} LW = 66.3 mA$$