Chapter-4

Stimulated emission devices LASERS

Semiconductor Laser Diodes

The Road Ahead

- Lasers
  - Basic Principles
  - Applications
- Gas Lasers
- Semiconductor Lasers
- Semiconductor Lasers in Optical Networks
- Improvement in Basic Design
- Recent Advances

Lasers: Basic Principle

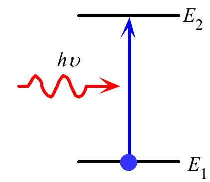
- **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation
- **Key Terms:**
  - Stimulated Emission
  - Metastable State
  - Population Inversion

Properties of Lasers

- **Monochromaticity**
- **Coherence**
- **Beam Divergence**
- **High Irradiance**
- **Properties vary with type of Lasers:**
  - **Gas, Solid, Semiconductor**

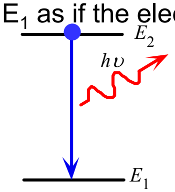
Spontaneous and Stimulated Emission

- An electron in an atom can be excited from an energy level E_1 to a higher energy level E_2 by absorption → photon absorption $h\nu = E_2 - E_1$.



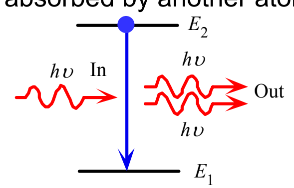
Spontaneous and Stimulated Emission

- Two possibilities of emission (an electron moves/transits down in energy to an unoccupied energy level → emits a photon).
  - Spontaneous
  - Induced
- Spontaneous emission: random direction → random photon.
- Transition for E_2 to E_1 as if the electron is oscillating with a frequency ν.



Spontaneous and Stimulated Emission

- Stimulated emission: incoming photon of energy $h\nu = E_2 - E_1$ stimulates the whole emission process by inducing the electron at E_2 to transit down to E_1.
- Emitted photon: in phase, same direction, same polarization, same energy with incoming photon → two outgoing photons.
- To obtain stimulated emission → the incoming photon should not be absorbed by another atom at E_1.

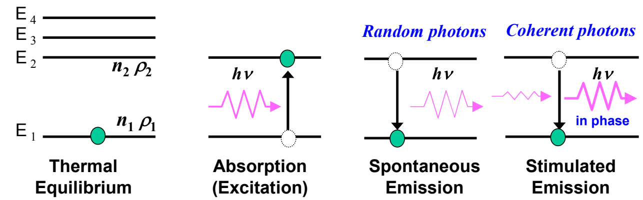


Spontaneous and Stimulated Emission

- Although we consider transitions of an electron in an atom, we could have just well described photon absorption, spontaneous and stimulated emission in term of energy transitions of the atom itself in which case E_1 and E_2 represent the energy levels of the atom.
- Consider the collection of atoms to amplify light → we must have the majority of atoms at the energy level E_2. Otherwise the incoming photon will be absorbed by the atom at E_1.
- **Population inversion**: more atoms at E_2 than at E_1.
- In steady state incoming photon will cause as many upward excitations as downward stimulated emissions → for only two energy levels → we never achieve atom population at E_2 greater than E_1.

Lasers: Basic Principle

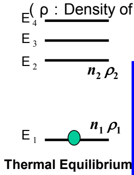
Absorption and Radiation Processes



Lasers: Basic Principle

Absorption and Radiation Processes

(ρ : Density of State)



Boltzmann Distribution

Number of electron at E_1 $\quad n_1 = \rho_1 f(E_1) = \rho_1 e^{[-(E_1-E_f)/kT]}$

Number of electron at E_2 $\quad n_2 = \rho_2 f(E_2) = \rho_2 e^{[-(E_2-E_f)/kT]}$

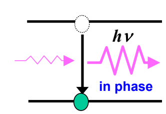
$$\frac{f(E_2)}{f(E_1)} = \frac{n_2\ \rho_1}{n_1\ \rho_2} = e^{[-(E_2-E_1)/kT]} \longrightarrow \left(\frac{n_2}{\rho_2}\right) = \left(\frac{n_1}{\rho_1}\right) e^{[-(E_2-E_1)/kT]}$$

- $(E_2 - E_1) > 0 \quad \rightarrow \quad \left(\frac{n_2}{\rho_2}\right) < \left(\frac{n_1}{\rho_1}\right)$
- If $\left(\frac{n_2}{\rho_2}\right) > \left(\frac{n_1}{\rho_1}\right)$ can be achieved by **pumping**,

→ $kT < 0$ (negative temperature: ***Population inversion***)

Lasers: Basic Principle

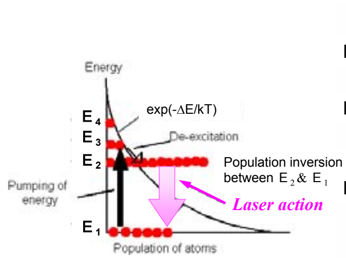
Absorption and Radiation Processes

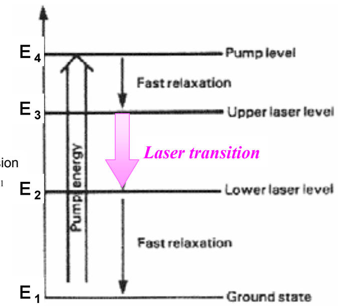


Stimulated Emission

Coherent photons
In phase
Same energy
Same direction
Same polarization

Laser: Basic Principle



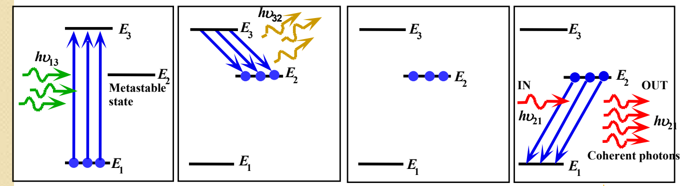


Basic requirement for Lasing action:

Metastable state, Population inversion, Optical resonant cavity

Lasers: Basic Principle

Lasing Action



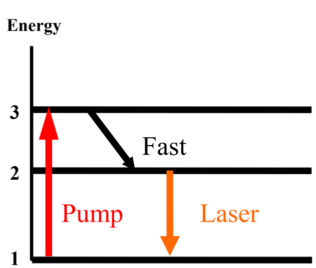
Atoms in the ground state are pumped up to the energy level E_3 by incoming photons of energy $h\nu_{13}=E_3-E_1$.

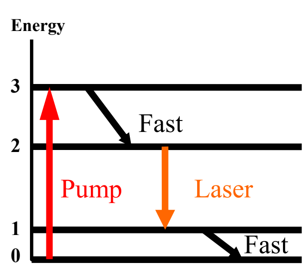
Atoms at E_3 rapidly decay to the metastable state at energy level E_2 by emitting photons or emitting lattice vibrations; $h\nu_{32}=E_3-E_2$.

As the states at E_2 are long-lived, they quickly become populated and there is a population inversion between E_2 and E_1.

A random photon (from a spontaneous decay) of energy $h\nu_{21}=E_2-E_1$ can initiate stimulated emission. Photons from this stimulated emission can themselves further stimulate emissions leading to an avalanche of stimulated emissions and coherent photons being emitted.

Lasers: Basic Principle



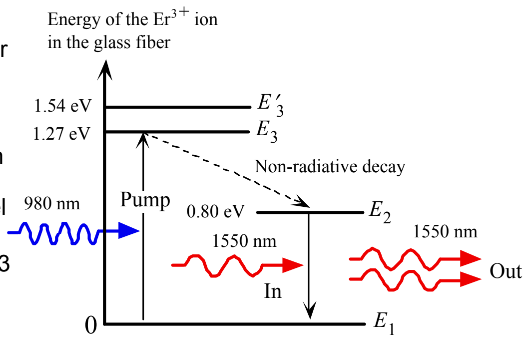


Optical Fiber Amplifier

- A light signal travels in long distance will suffer attenuation. → It is necessary to regenerate the light signal at certain intervals for long haul communications over several thousand miles.
- Practical optical amplifier is based on the **erbium ion (Er^{3+}) doped fiber amplifier** (EDFA).
- The core region of an optical fiber is doped with Er^{3+} or with neodymium ion (Nd^{3+}).
- The host fiber material is a glass based on SiO_3-GeO_2 or Al_2O_3. → Easily fused to a single mode long distance optical fiber by technique called splicing.

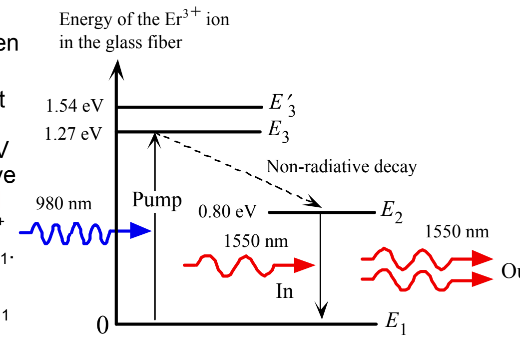
Optical Fiber Amplifier

- Er^{3+} has energy level as indicated in the figure.
- Er^{3+} is optically pumped from laser diode to excite them to E_3.
- The Er^{3+} ions decay rapidly from E_3 to E_2 (**long-lived**) energy level ~ 10 ms.
- The decay from E3 to E2 involves energy losses by radiationless transition (phonon emission).



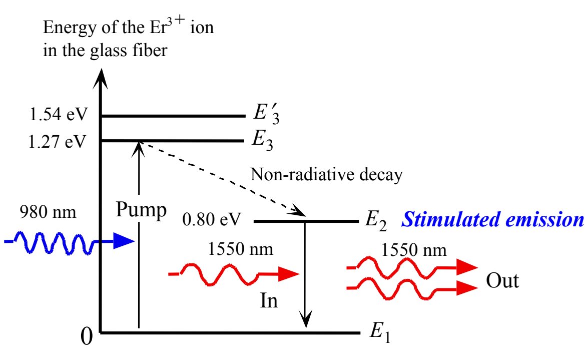
Optical Fiber Amplifier

- The accumulated Er^{3+} ions at E_2 leads to a population inversion between E_2 and E_1.
- Signal photons at 1550 nm have energy of 0.80 eV ($E_2 – E_1$), and give rise to stimulated transitions of Er^{3+} ions from E_2 to E_1.
- Meanwhile, any Er^{3+} ions left at E_1 will absorb in incoming 1550 nm photons to reach E_2.



Optical Fiber Amplifier

EDFA: Er-doped Optical Amplifier

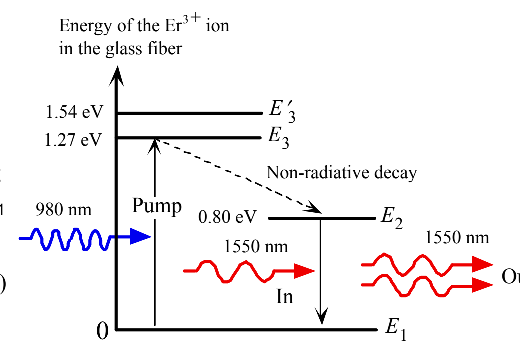


Energy diagram for the Er^{3+} ion in the glass fiber medium and light amplification by stimulated emission from E_2 to E_1. Dashed arrows indicate radiationless transitions (energy emission by lattice vibrations)

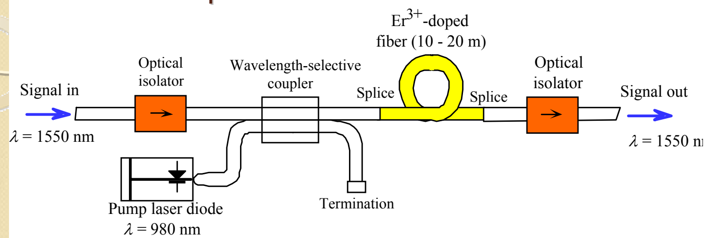
Optical Fiber Amplifier

- Thus, to achieve light amplification we must have stimulated emission exceeding absorption. → Only possible if more Er^{3+} ions at E_2 (N_2) than at E_1 (N_1).
- The net optical gain G_{op}: $G_{op} = K(N_2 - N_1)$

where K is constant which depends on



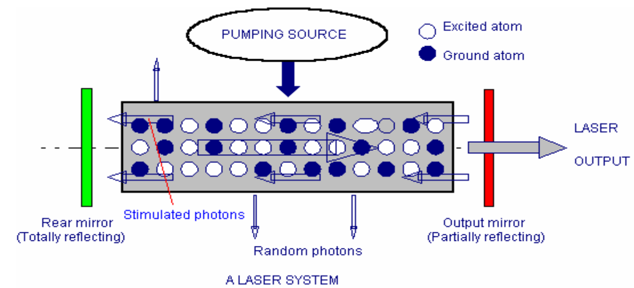
Optical Fiber Amplifier



A simplified schematic illustration of an EDFA (optical amplifier). The erbium-ion doped fiber is pumped by feeding the light from a laser pump diode, through a coupler, into the erbium ion doped fiber.

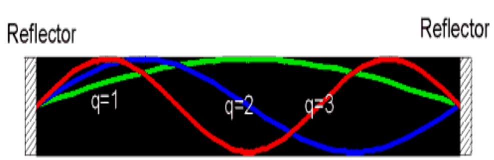
- Optical oscillators are inserted at the entry and exit to allow ONLY the optical signals at 1550 nm to pass in one direction and prevent the 980 pump light from propagating back or forward into the communication system.
- Energy level E_1, E_2, and E_3 are not single unit levels, but rather consists of closely spaced collection of several levels → range of stimulated transitions from E_2 to E_1 (1525 – 1565 nm) with 40 nm optical bandwidth → wavelength division multiplexed system (WDM) systems.

Laser: Basic Principle



Laser: Basic Principle

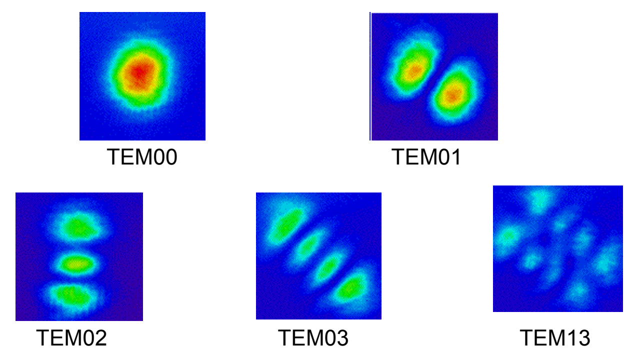
Longitudinal Modes



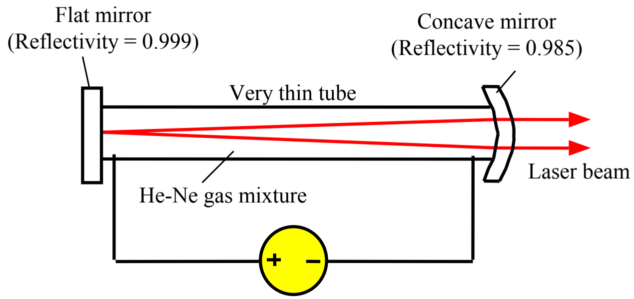
A lot of wavelengths are produced, but only some are amplified.

Laser: Basic Principle

Transverse Modes

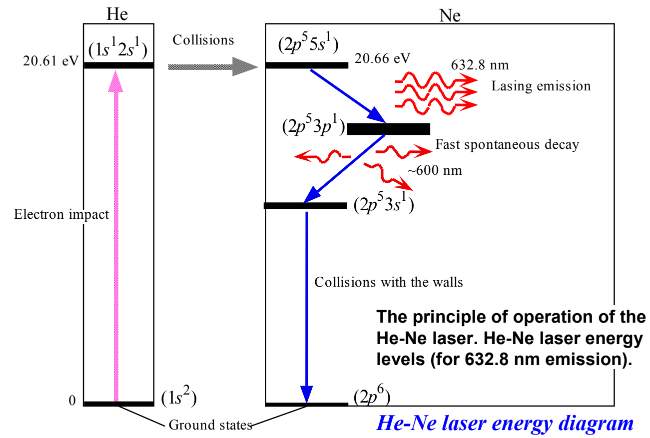


Lasers: Gas Lasers
He-Ne Lasers



Current regulated HV DC/RF power supply
He atom to become excited by collision with drifting electrons

Lasers: Gas Lasers
He-Ne Lasers

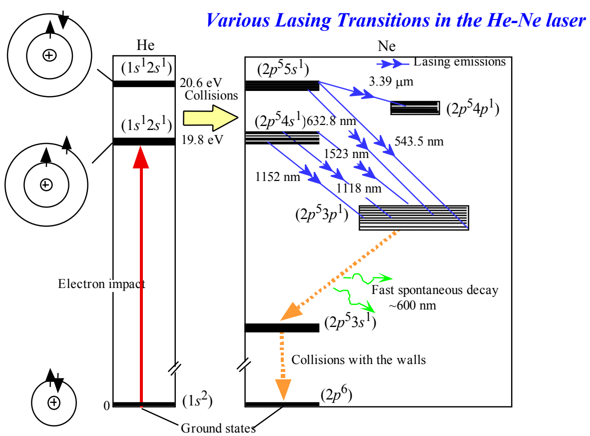


The principle of operation of the He-Ne laser. He-Ne laser energy levels (for 632.8 nm emission).

He-Ne laser energy diagram

Lasers: Gas Lasers
He-Ne Lasers

Various Lasing Transitions in the He-Ne laser



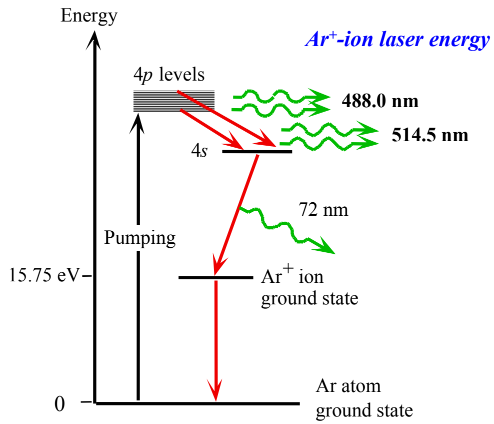
$$\text{Overall efficiency} = \frac{\text{Optical Power Output}}{\text{Electrical Power Input}} \times 100\%$$

Typical commercial He-Ne laser characteristics

Wavelength (nm)	543.5	594.1	612	632.8	1523
	Green	Yellow		Red	Infrared
Optical output power (mW)	1.5	2	4	5	1
Typical current (mA)	6.5	6.5	6.5	6.5	6
Typical voltage	2750	2070	2070	1910	3380
Overall efficiency = P_{out}/IV	0.0084 %	0.015 %	0.030 %	0.040 %	0.005 %

Lasers: Gas Lasers

Ar^+-ion Lasers



Ar^+-ion laser energy diagram

Gas Lasers: The He-Ne LASER

- By using dc or RF high voltage, electrical discharge is obtained within the tube which causes the He atoms to become excited by collisions with the drifting electrons,

$$He + e^- \rightarrow He^* + e^-$$

- The excited He atom, He^*, cannot spontaneously emit a photon → large number of He^* atoms build up during the electrical discharge.
- When He^* collides with a Ne atom, it transfers its energy to the Ne atom by resonance energy exchange.

$$He^* + Ne \rightarrow He + Ne^*$$

- A spontaneous emission of a photon from one Ne^* atom gives rise to an avalanche of stimulated emission process → lasing emission with a wavelength 632.8 nm in the red.

Gas LASER Output Spectrum

- **Doppler effect** → resulting the broadening of the emitted spectrum → output radiation from gas laser covers a spectrum of wavelengths with a central peak.
- Given the average K.E. of (3/2)kT, radiation freq. υ_o (as source frequency), due to Doppler effect, when gas atom is moving away from the observer, the latter detects a lower frequency υ_1 $$\upsilon_1 = \upsilon_o\left(1 - \frac{v_x}{c}\right)$$

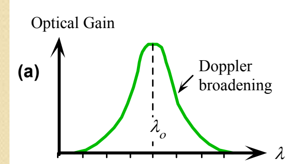
  where v_x is the relative velocity of the atom along the laser tube (x-axis) with respect to observer.
- When atom moving towards the observer, the detected freq υ_2 is higher:

$$\upsilon_2 = \upsilon_o\left(1 + \frac{v_x}{c}\right)$$

Gas LASER Output Spectrum

- Since the atoms are in random motion the observer will detect a range of frequencies due to Doppler effect.
- Resulting the frequency or wavelength of the output radiation from a gas laser will have a "linewidth" $\Delta\upsilon = \upsilon_2 - \upsilon_1$. It is called **Doppler broadened linewidth**.
- → Stimulated emission wavelength of lasing medium or **optical gain** has distribution around $\lambda_o = c/\upsilon_o$.
- The full width at half maximum FWHM in the output intensity vs. frequency spectrum is:

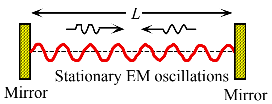
$$\Delta\upsilon_{1/2} = 2\upsilon_o\sqrt{\frac{2kT\ln(2)}{Mc^2}}$$



where M is mass of lasing atom or molecule

Gas LASER Output Spectrum

- Let consider an optical cavity of length L with parallel end mirrors (etalon – Fabry-Perot optical resonator).



- Any standing wave in the cavity must have an integer number of half-wavelengths $\lambda/2$ that fit into the cavity length L,

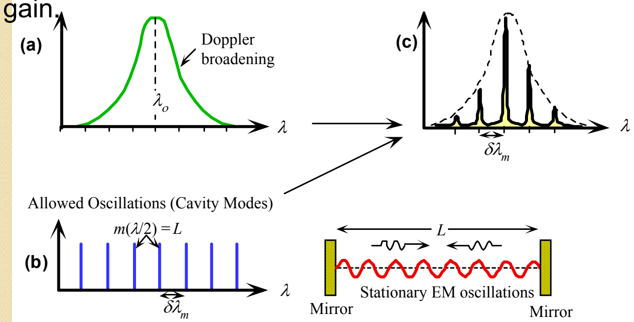
$$m\left(\frac{\lambda}{2}\right) = L$$

where m is mode number of the standing wave.

- **Cavity mode**: each possible standing wave within the cavity (laser tube) which satisfy the above equation.
- **Axial (longitudinal) modes**: existing modes along the cavity axis.

Gas LASER Output Spectrum

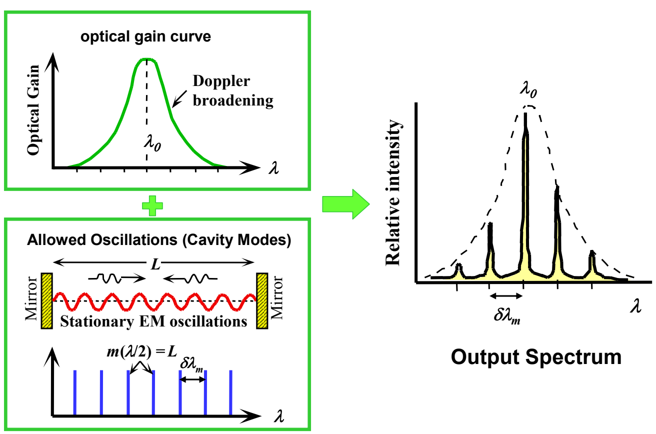
- The laser output thus has broad spectrum with peaks at certain wavelengths corresponding to various cavity modes existing within the Doppler broadened optical gain.



The output spectrum is determined by satisfying (a) and (b) simultaneously.

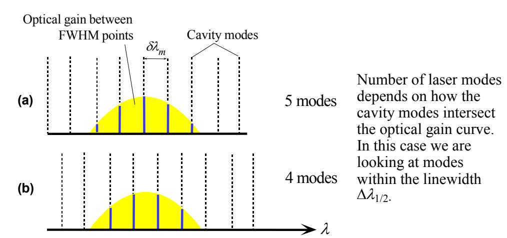
Lasers: Basic Principle

Output Spectrum of Laser

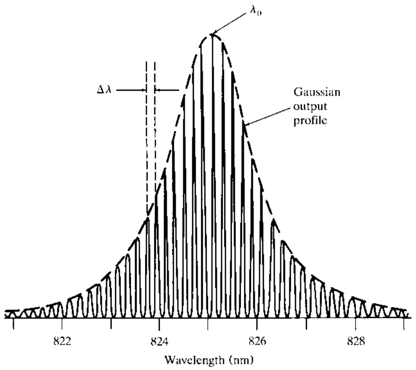


Lasers: Basic Principle

Optical Gain



Lasers: Basic Principle
Fabry-Perot laser spectrum



Example:

A typical low power 5mW He-Ne laser tube operate at a DC voltage of 2000V and carrier a current of 7mA . What is the efficiency of the laser?

Solution:

Efficiency=output light power/Input Electric power
$=5 \times 10^{-3}W/(7 \times 101^{-3}A)(2000V)$
=0.036%
Note that 5mW over a beam diameter of 1mm is $6.4kW/m^{-2}$

4.2 The He-Ne Laser A particular He-Ne laser operating at 632.8 nm has a tube that is 50 cm long. The operating temperature is 130 °C

a Estimate the Doppler broadened linewidth ($\Delta\lambda$ in the output spectrum.

b What are the mode number *m* values that satisfy the resonant cavity condition? How many modes are therefore allowed?

c What is the separation $\Delta\nu_m$ in the frequencies of the modes? What is the mode separation $\Delta\lambda_m$ in wavelength.

Solution

a The central emission frequency is

$$\upsilon_o = c/\lambda_o = (3\times10^8 \text{ m s}^{-1}) / (632.8\times10^{-9} \text{ m}) = 4.74\times10^{14} \text{ s}^{-1}.$$

The FWHM width of the frequencies $\Delta\upsilon_{1/2}$ observed will be given by Eq. (3)

$$\Delta\upsilon_{1/2} = 2\upsilon_o\sqrt{\frac{2k_BT\ln(2)}{Mc^2}} = 2(4.748\times10^{14})\sqrt{\frac{2(1.38\times10^{-23})(130+273)\ln(2)}{(3.35\times10^{-26})(3\times10^8)^2}}$$

$$= 1.515 \text{ GHz}$$

To get FWHM wavelength width $\Delta\lambda_{1/2}$, differentiate $\lambda = c/\nu$

$$\frac{d\lambda}{d\upsilon} = \frac{c}{\upsilon^2} = \frac{\lambda}{\upsilon}$$

so that $\Delta\lambda_{1/2} \approx \Delta\upsilon_{1/2}|-\lambda/\upsilon| = (1.515\times10^9 \text{ Hz})(632.8\times10^{-9} \text{ m}) / (4.74\times10^{14} \text{ s}^{-1})$

or $\Delta\lambda_{1/2} \approx 2.02\times10^{-12}$ m or 0.00202 nm.

This width is between the half-points of the spectrum.

b For $\lambda = \lambda_o = 632.8$ nm, the corresponding mode number m_o is,

$$m_o = 2L / \lambda_o = (2\times 0.5 \text{ m}) / (632.8\times 10^{-9} \text{ m}) = 1580278.1$$

and actual m_o has to be the closest integer value to 1580278.1, that is 1580278

Consider the minimum and maximum wavelengths corresponding to the extremes of the spectrum at the half-power points:

$$\lambda_{\min} = \lambda_o - \tfrac{1}{2}\Delta\lambda = 632.798987$$

and

$$\lambda_{\max} = \lambda_o + \tfrac{1}{2}\Delta\lambda = 632.801012$$

c The frequency separation $\Delta\upsilon_m$ of two consecutive modes is

$$\Delta\upsilon_m = \upsilon_{m+1} - \upsilon_m = \frac{c}{\lambda_{m+1}} - \frac{c}{\lambda_m} = \frac{c}{\left(\frac{2L}{(m+1)}\right)} - \frac{c}{\left(\frac{2L}{m}\right)} = \frac{c}{2L}$$

or

$$\Delta\upsilon_m = \frac{c}{2L} = \frac{3\times 10^8}{2(0.5)} = \mathbf{3\times 10^8\ Hz}.$$

The wavelength separation of two consecutive modes is

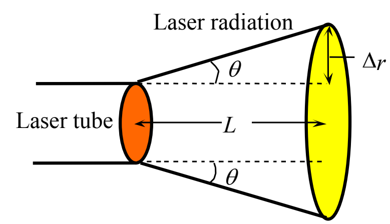
$$\Delta\lambda_m = \frac{\lambda_m^2}{2L} = \frac{(632.8\times 10^{-9})^2}{2(0.5)} = 4.004\times 10^{-13} \text{ m or } \mathbf{0.4004\ pm}.$$

Note:

$$\text{Modes} = \frac{\text{Linewidth of spectrum}}{\text{Separation of two modes}} \approx \frac{\Delta\lambda_{1/2}}{\Delta\lambda_m} = \frac{2.02 \text{ pm}}{0.4004 \text{ pm}} = 5.04.$$

Lasers: Laser beam Divergence

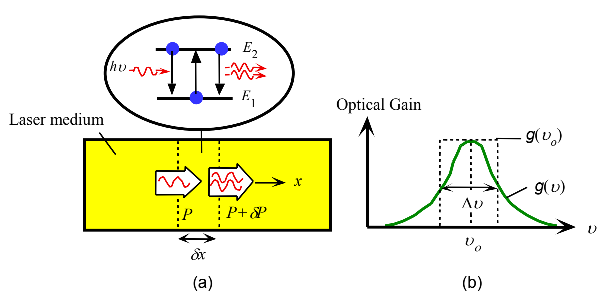
Output Spectrum of a Gas Laser



The output laser beam has a divergence characterized by the angle 2θ (highly exaggerated in the figure)
Δr=Ltanθ. What is the diameter of the beam at a distance of 10m, if divergence is 1mrad?

Lasers: Basic Principle

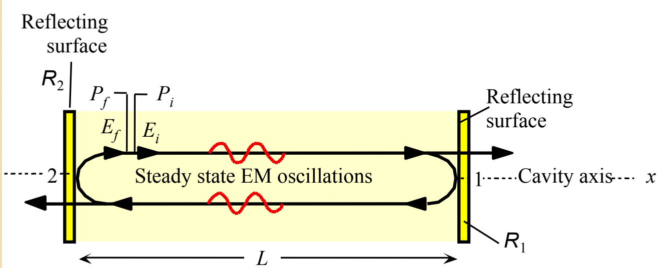
Optical Gain

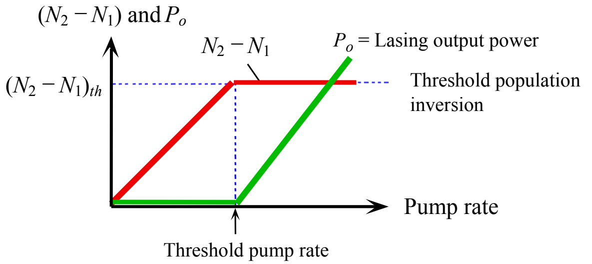


(a) A laser medium with an optical gain (b) The optical gain curve of the medium. The dashed line is the approximate derivation in the text.

Lasers: Basic Principle

Optical cavity resonator





Simplified description of a laser oscillator. $(N_2 - N_1)$ and coherent output power (P_o) vs. pump rate under continuous wave steady state operation.