Engineering Optics

R-1

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by

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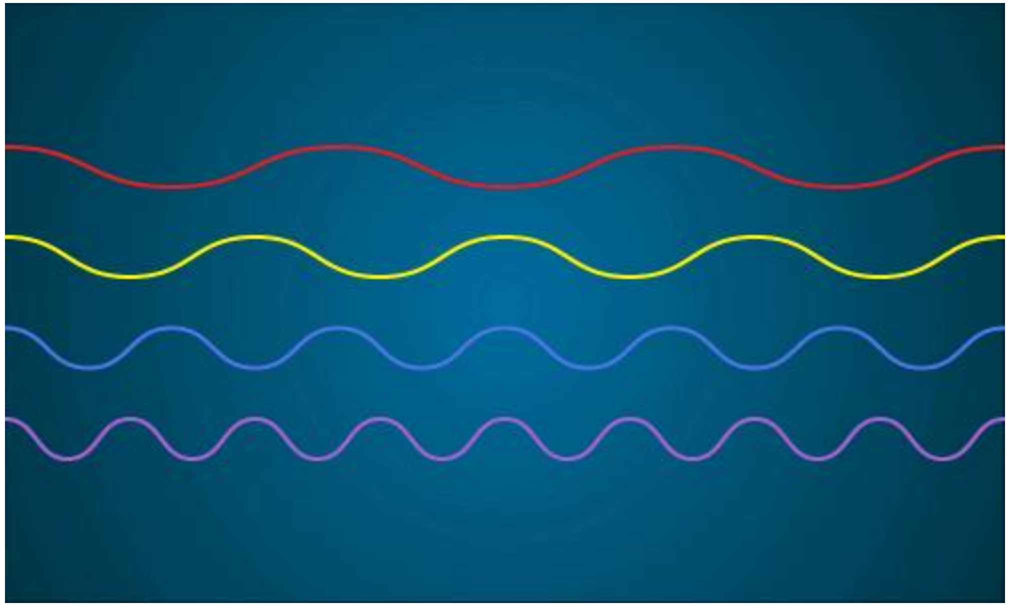
L A S E R

Light **A**mplification by **S**timulated **E**mission of **R**adiation

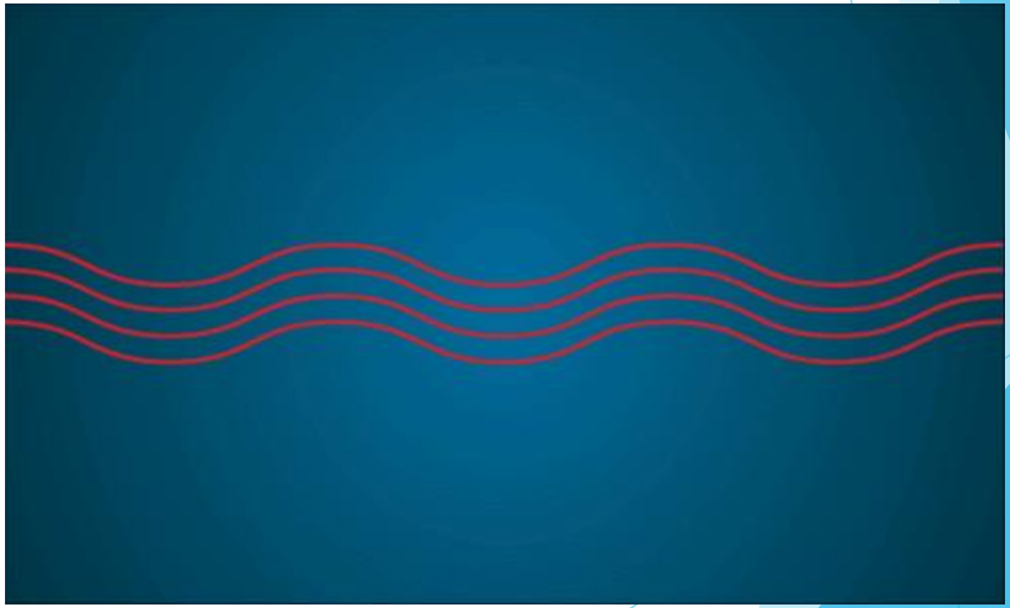
LASER is different!

LASER: Lasers produce a very narrow beam of light

Sunlight or a lightbulb—is made up of light with many different wavelengths. Each color of light has a different wavelength. $\lambda_V < \lambda_R$ Our eyes see this mixture of wavelengths as white light.



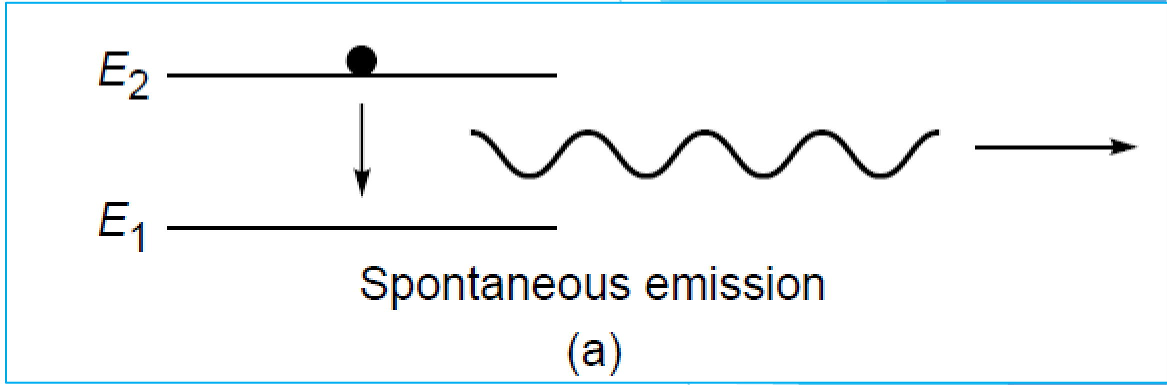
This Fig. shows a representation of the different wavelengths present in sunlight. When all of the different wavelengths (colors) come together, you get white light. Image credit: NASA



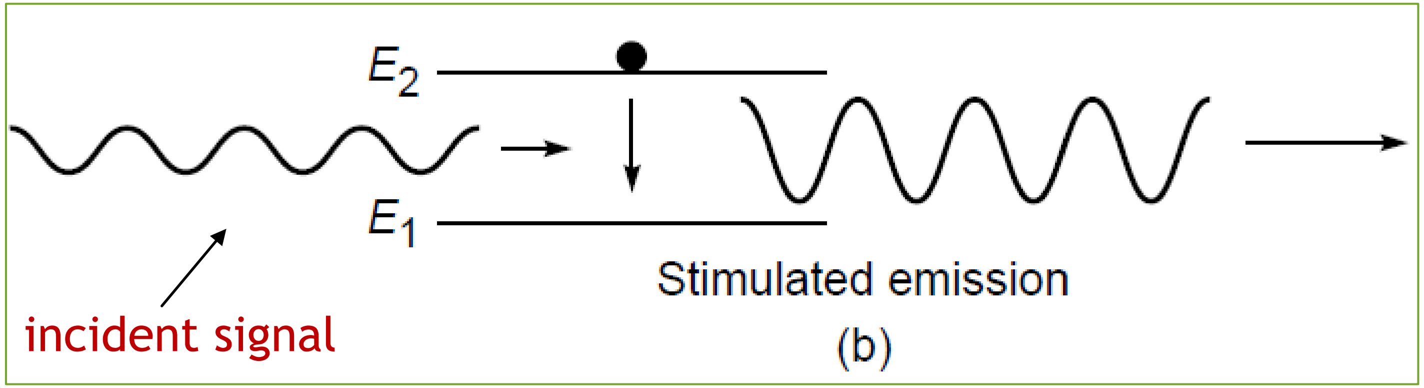
This Fig. is a representation of in phase laser light waves. Image credit: NASA

Spontaneous and Stimulated Emissions

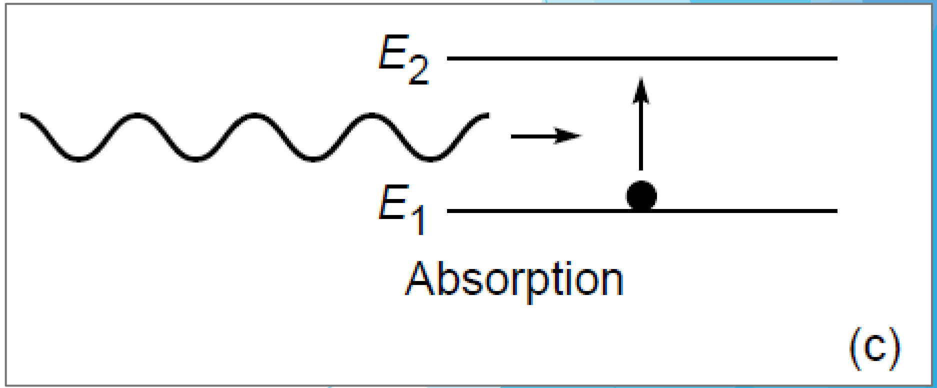
- Atoms → discrete energy states
- **Q: How does an atom interact with electromagnetic radiation??**
- Ans: according to Einstein → 3 different ways



The rate of spontaneous emission is proportional to the number of atoms in the excited state



The rate of stimulated emission depends on both the intensity of the external field and the number of atoms in the excited state



The rate of stimulated absorption depends both on the intensity of the external field and on the number of atoms in the lower energy state.

Optics, Ghatak

Population inversion

When the atoms are in thermodynamic equilibrium, there are larger number of atoms in the lower state → absorptions

For **Stimulated emission** → more and more atoms need to be in the excited state ← ***Problem***

Solution → create a state of **population inversion** in which there are larger number of atoms in the upper state

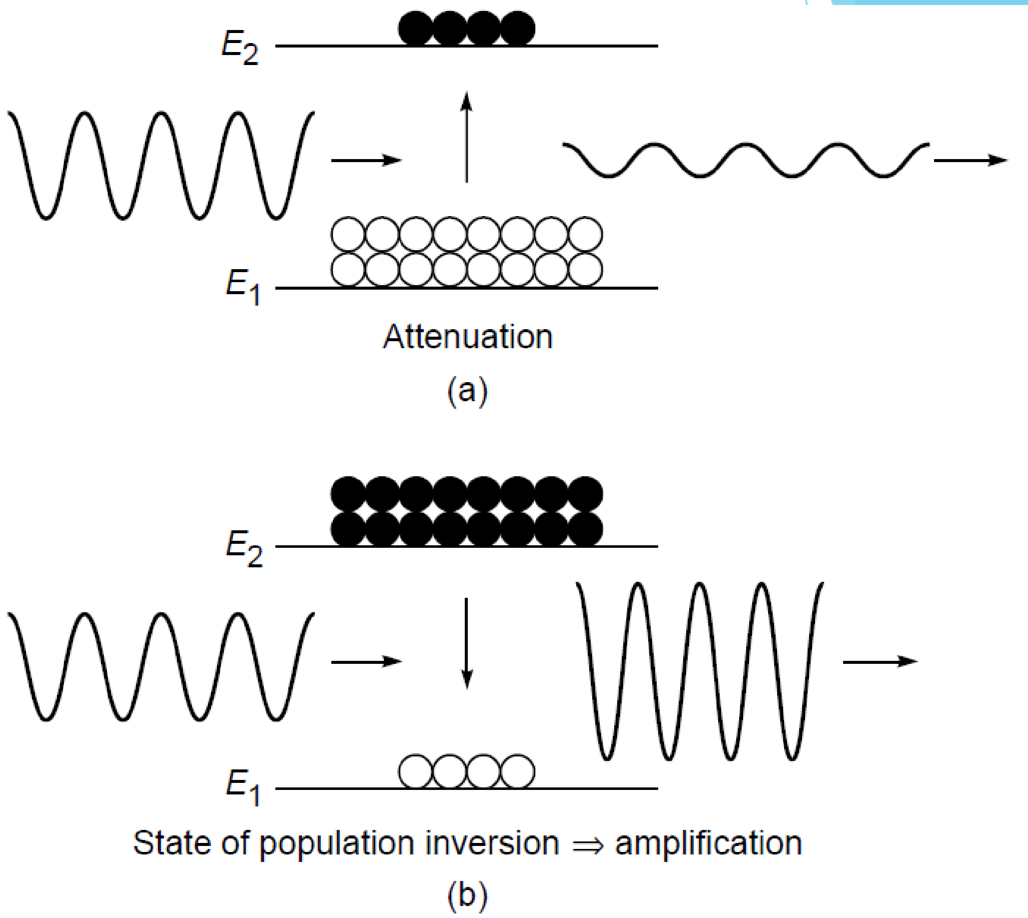


Fig. 26.2 (a) A larger number of atoms in the lower state result in the attenuation of the beam. (b) A larger number of atoms in the upper state (which is known as population inversion) result in the amplification of the beam.

Optics, Ghatak

Problem:1

A 10-mW laser is emitting at a mean wavelength of 500 nm. Determine the rate of occurrence of stimulated emission.

Answer:

We have that the laser puts out 10×10^{-3} J/s. We need to find out how much energy (E) each photon carries off. Since $E = h\nu$ and $c = \lambda\nu$

$$E = \frac{hc}{\lambda} = \frac{(6.626 \times 10^{-34})(2.998 \times 10^{8})}{500 \times 10^{-9}}$$

$$E = 3.973 \times 10^{-19}\ \text{J}$$

Rate of photon emission = rate occurrence of spontaneous emission

$$\frac{10 \times 10^{-3}\ \text{J/s}}{3.973 \times 10^{-19}\ \text{J}} = 2.52 \times 10^{16}\ \text{photons/s}$$

Problem- 2

$P_1 = 0.25, P_2 = 0.5, P_3 = 0.75$ are the probability of occurrence per second of three different atoms. Which wave will be having more life time at excited state.

Answer:

$$P \propto \frac{1}{\tau} \qquad\qquad \tau \propto \frac{1}{P}$$

$$P_1 = 0.25, P_2 = 0.5, P_3 = 0.75$$

$\Rightarrow$ 1ST atom will be having more life time

Problem: 3

Calculate the ratio of population densities of upper and lower laser levels. Assume that the material is in thermal equilibrium. It is given that the wave length separation between energy levels is $1\mu m$ at a temperature 295 K

Answer:

- Maxwell-Boltzmann distribution (N: number of atoms/volume)

$$N_i = N_0 \, exp^{-E_i/k_B T}$$

- higher E → fewer atoms there will be in that state

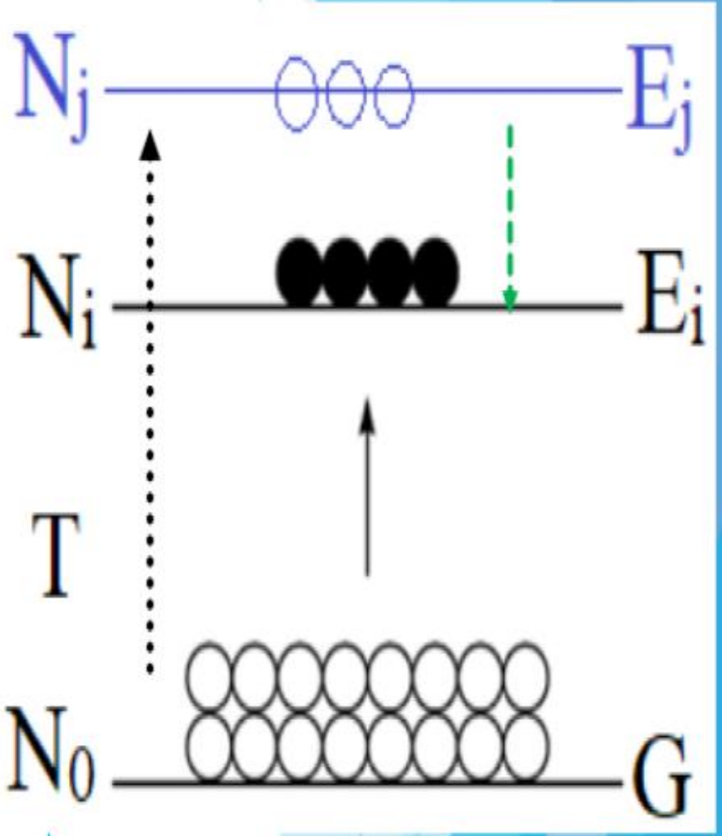
$$N_j = N_0 \, exp^{-E_j/k_B T}$$

- Where $E_j > E_i$

relative population,

$$\frac{N_j}{N_i} = \frac{exp^{-E_j/k_B T}}{exp^{-E_i/k_B T}}$$

$$= exp^{-(E_j - E_i)/k_B T} = exp^{-\Delta E/k_B T} = exp^{-h\nu_{ji}/k_B T}$$



constant for a given T

Here $\upsilon_{ji} = c/\lambda_{ji}$

Then
$$\frac{N_j}{N_i} = e^{-\frac{hc}{\lambda_{ji} k_B T}}$$

Where
$$hc = 1.98 \times 10^{-25} J\ m \qquad h = 6.626 \times 10^{-34} J\ s$$

$$\lambda_{ji} = 10^{-6}\ m, \text{ T=295 K}$$

$$k_B = 1.38 \times 10^{-23} J/K$$

$$\frac{N_j}{N_i} = e^{-\frac{1.98 \times 10^{-25}}{10^{-6} \times 1.38 \times 10^{-23} \times 295}} = 6.21 \times 10^{-22}$$

Problem: 4

A Nd:YAG laser rod is composed of Nd ions doped at a 1% concentration into an yttrium aluminum garnet host. That corresponds to a Nd^{+3} ion density in the laser rod of about $1.38 \times 10^{26}\ m^{-3}$. Suppose all of these ions are pumped to their upper $^4F_{3/2}$ levels.

From there they cascade downward, emitting radiation at 1060 nm. Determine the energy radiated per cubic meter of rod.

Solution-5

Let's first determine the energy of each photon. Then if we assume all the Nd ions radiate, we can find the total energy emitted. At 1060 nm the photon energy is

$$E = h\nu = \frac{hc}{\lambda} = \frac{(6.626 \times 10^{-34}\ \mathrm{J \cdot s})(2.998 \times 10^{8}\ \mathrm{m/s})}{1060 \times 10^{-9}\mathrm{m}}$$

$$= 1.874 \times 10^{-19}\ \mathrm{J}$$

Now if there are 1.38×10^{26} ions/m^3, each radiating a 1.874×10^{-19} J photon, the total amount of energy emitted per cubic meter is

$$E_T = (1.874 \times 10^{-19}\ \mathrm{J})(1.38 \times 10^{26}\ \mathrm{m^{-3}})$$

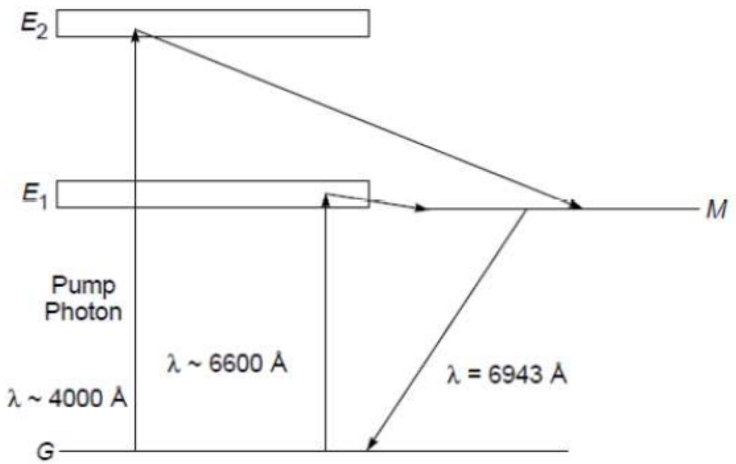
$$E_T = 25.9 \times 10^{6}\ \mathrm{J/m^3}$$

Problem: 5

In Ruby laser an output of wavelength 694.3nm is obtained. Calculate the relative population at a temperature 300K between E_1 and ground state

We know that

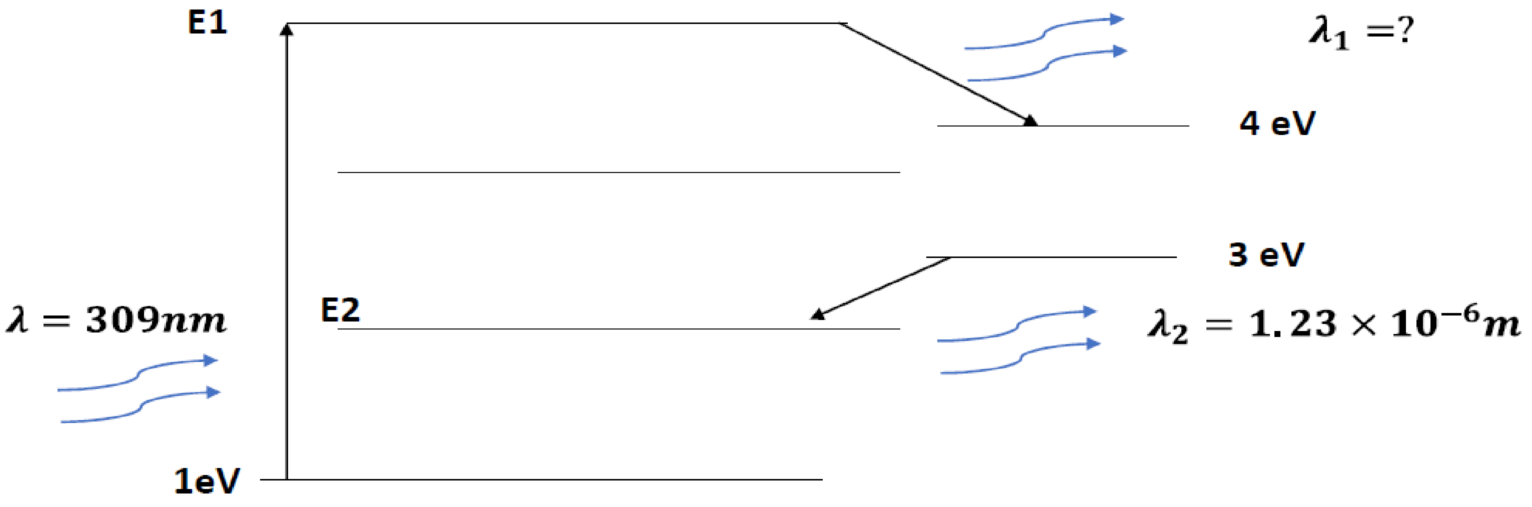
$$\frac{N_j}{N_i} = e^{-\frac{hc}{\lambda_{ji} k_B T}}$$



$$\frac{N_j}{N_i} = e^{-\frac{1.98\times10^{-25}}{694.3\times10^{-9}\times1.38\times10^{-23}\times300}} = 1.21 \times 10^{-30}$$

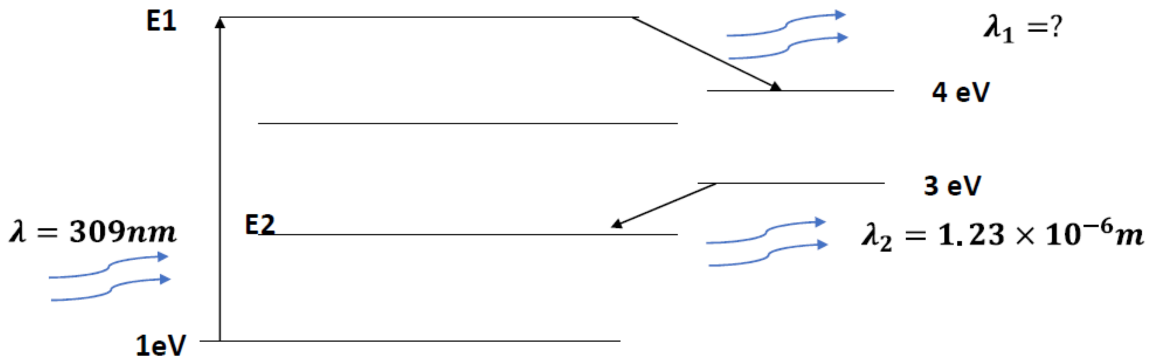
Problem 6

From the given energy spectra of the 4 level laser find out the unknown energy levels E_1, E_2 and λ_1.



Solution 4

Answer:



E_1 calculation

$$E_1 - 1eV = \mathrm{hc}/\boldsymbol{\lambda}(\boldsymbol{eV})$$

$$\frac{\mathrm{hc}}{\boldsymbol{\lambda}}(\boldsymbol{eV}) = \frac{1.98644582 \times 10^{-25}}{309 \times 10^{-9} \times 1.62 \times 10^{-19}} = 4eV$$

$$E_1 = 5eV$$

$\boldsymbol{\lambda_1}$ calculation

$$\boldsymbol{5eV - 4eV = \mathrm{hc}/\lambda_1\ (eV)}$$

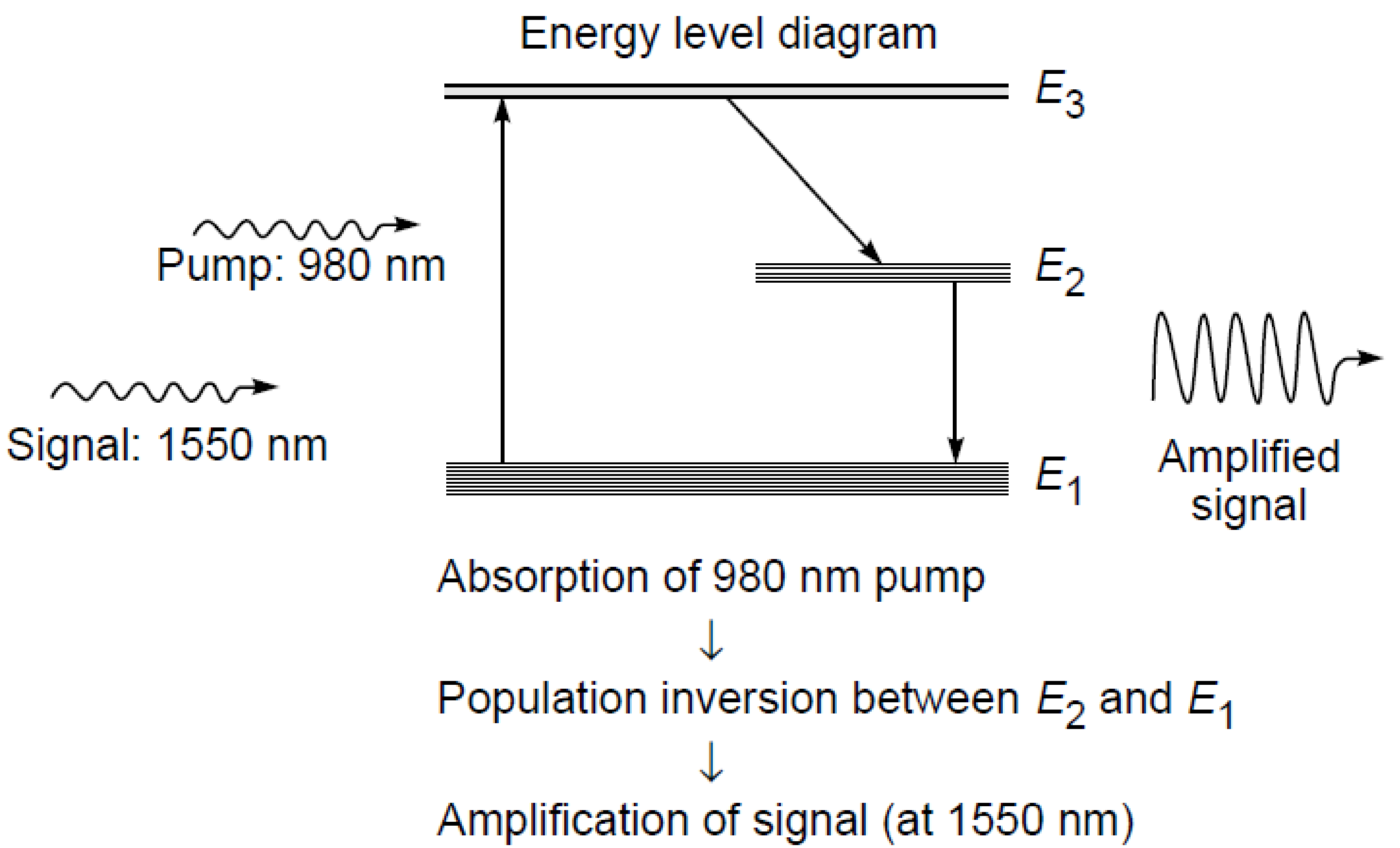
$$\boldsymbol{1.62 \times 10^{-19} = \mathrm{hc}/\lambda_1}$$

$$\boldsymbol{\lambda_1 = 1.98644582 \times 10^{-25}/1.62 \times 10^{-19}}$$

$$\boldsymbol{\lambda_1 = 1.23 \times 10^{-6} m}$$

$$\boldsymbol{\Rightarrow E_2 = 2eV}$$

EDFA



Er^{3+} concentration $\approx 7 \times 10^{24}$ ions m^{-3} pump power ≈ 5 mW

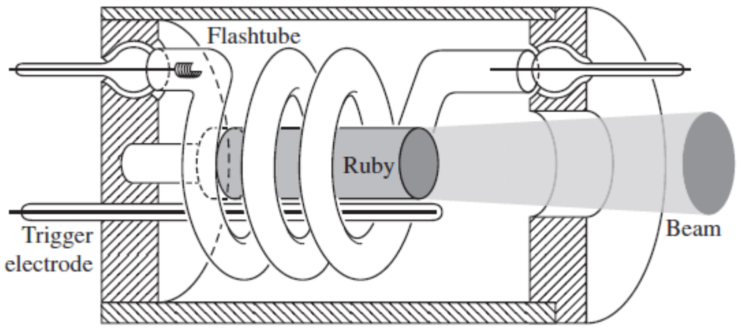
and, the optimum length of the erbium doped fiber $\approx$ 7m.

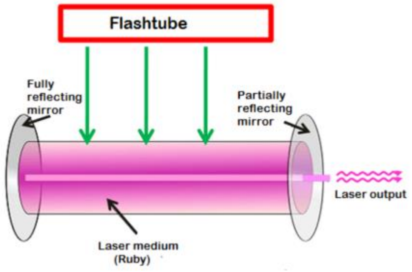
- $E_3 - E_1$ = 1.3 eV → 980 nm
- $E_2 - E_1$ = 0.81 eV → 1550 nm
- When a trigger of 980 nm is fed → Er atoms jump to E_3 → *pump*
- Atoms in E_3 jumps to E_2 → *heating*
- State E_2 is ***metastable*** → long lifetime (few milliseconds).
- large lifetime of state E_2 than E_3 → the population of the erbium atoms in state E_2 grows with time
- Population inversion can be achieved
- $N_2 > N_1$
- Send a signal beam (1550 nm) → it gets amplified
- Why? → stimulated emission of radiation

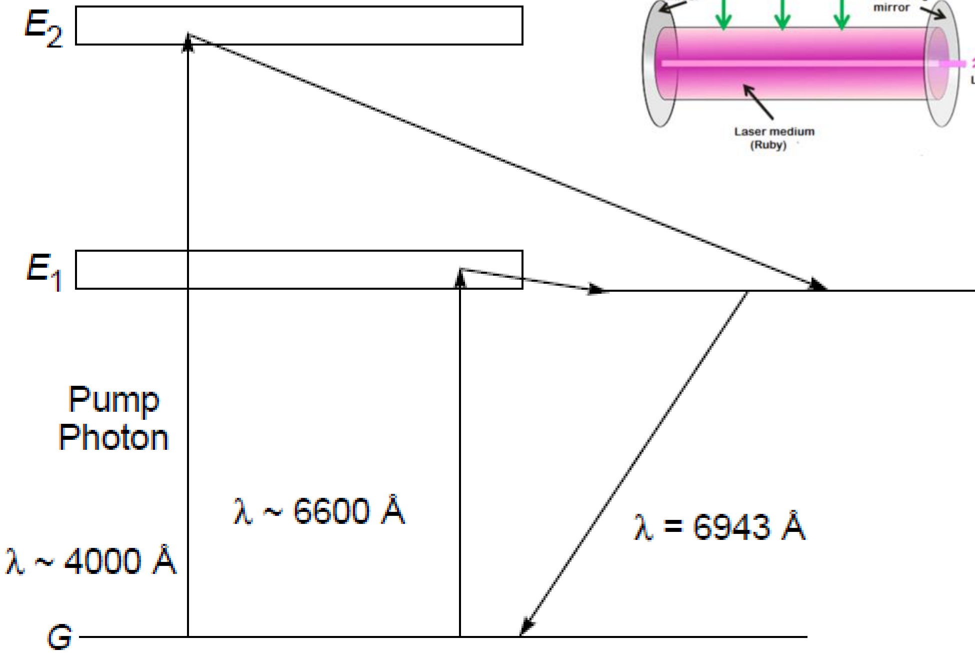
$$\text{Gain (dB)} = 10 \log \frac{P_{output}}{P_{input}}$$

Optics, Ghatak

Ruby LASER







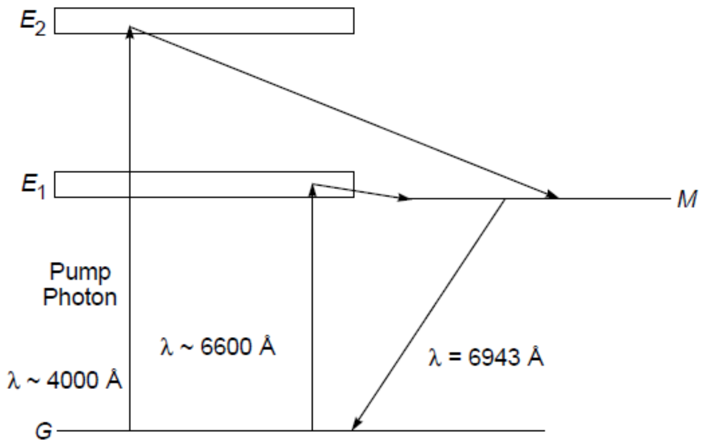
The energy levels of the chromium ion; G and M represent the ground and metastable states, respectively.

Optics, Ghatak; Hecht

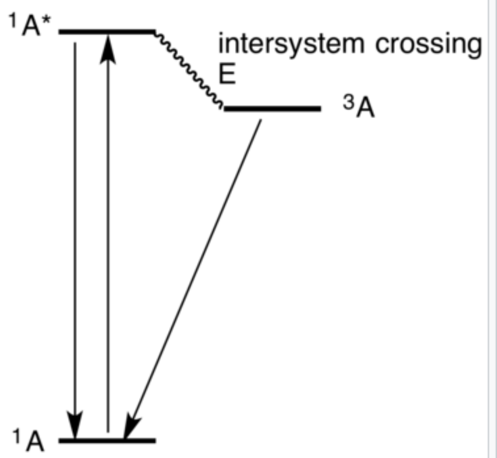
1. photons are produced by the flash lamp
2. The chromium ion in its ground state can absorb a photon (~ 4000 Å) and make a transition to E_2 → by optical pumping OR to E_1 (6600 Å)
3. Once in E_2 or E_1 → it immediately makes a **nonradiative transition** (in a time ~ 10^{-8} s) **to the metastable state *M*** *(3 ms lifetime)*
4. the excess energy (transition from E_2/E_1 to M) is absorbed by the lattice and does not appear as EM radiation.
5. *M* has a very long life, the number of atoms in this state keeps increasing and one may achieve population inversion between states *M* and *G*.
6. Once population inversion is achieved, light amplification can take place, with two reflecting ends of the ruby rod forming a cavity.

- The ruby laser is an example of a three-level laser.
- Applications: medical and cosmetic procedures, holography

Working principle



The energy levels of the chromium ion; G and M represent the ground and metastable states, respectively.



A Jablonski diagram showing the excitation of molecule A to its singlet excited state (^{1}A*) followed by intersystem crossing to the triplet state (^{3}A) that relaxes to the ground state by phosphorescence.

Wikipedia

The chromium ion in its ground state can absorb a photon (whose wavelength is around 6600 Å) and make a transition to one of the states in the band E_1. It could also absorb a photon of $\lambda \sim 4000$ Å and make a transition to one of the states in the band E_2—this is known as optical pumping, and the photons which are absorbed by the chromium ions are

produced by the flash lamp (see Fig. 26.16). In either case, it immediately makes a nonradiative transition (in a time ~ 10^{-8} s) to the metastable state M—in a nonradiative transition, the excess energy is absorbed by the lattice and does not appear in the form of electromagnetic radiation.

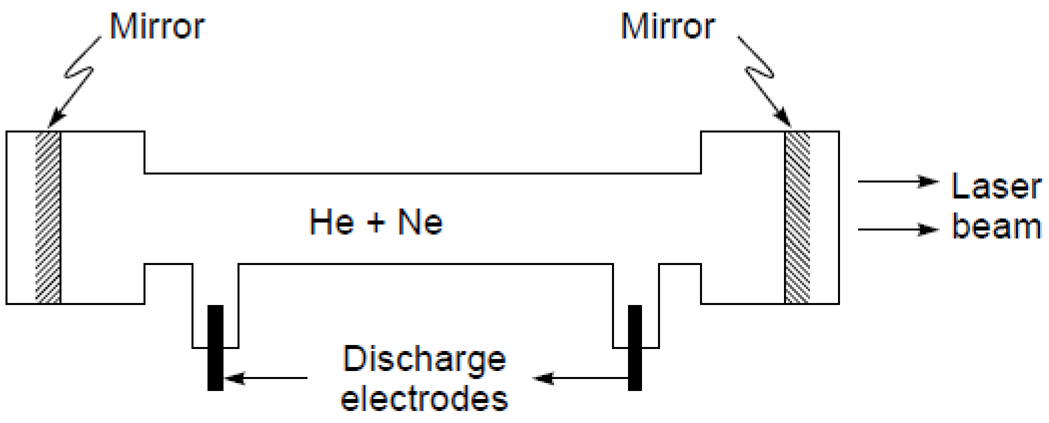
Also since state M has a very long life, the number of atoms in this state keeps increasing and one may achieve population inversion between states M and G.

Once population inversion is achieved, light amplification can take place, with two reflecting ends of the ruby rod forming a cavity. The ruby laser is an example of a three-level laser.

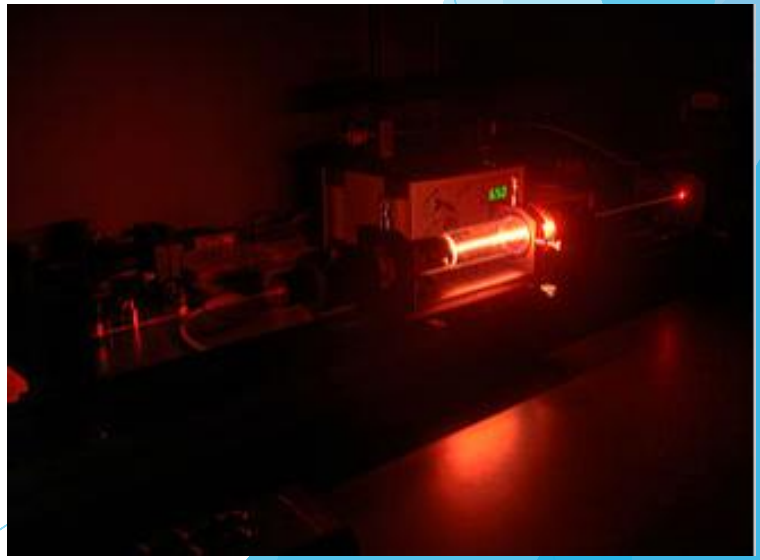
Optics, Ghatak

He-Ne LASER

- He-Ne laser which was first fabricated by *Ali Javan* and coworkers at Bell Telephone Laboratory in the United States. → 1st gas laser to be operated successfully.
- The He-Ne laser consists of a mixture of He and Ne (ratio ~10 : 1), placed inside a long, narrow discharge tube
- Fixed pressure inside the rube (1 torr).
- system → enclosed between a pair of plane mirrors → resonator



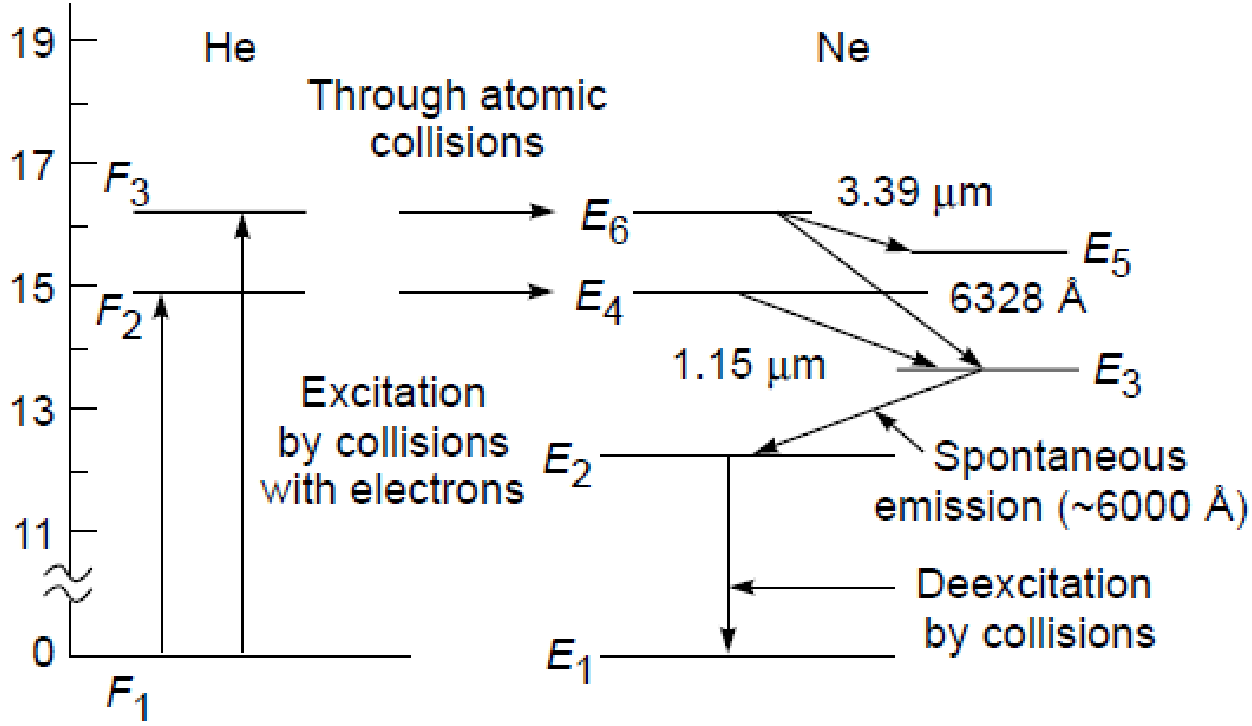
The helium-neon laser.



wikipedia

Optics, Ghatak

He-Ne LASER

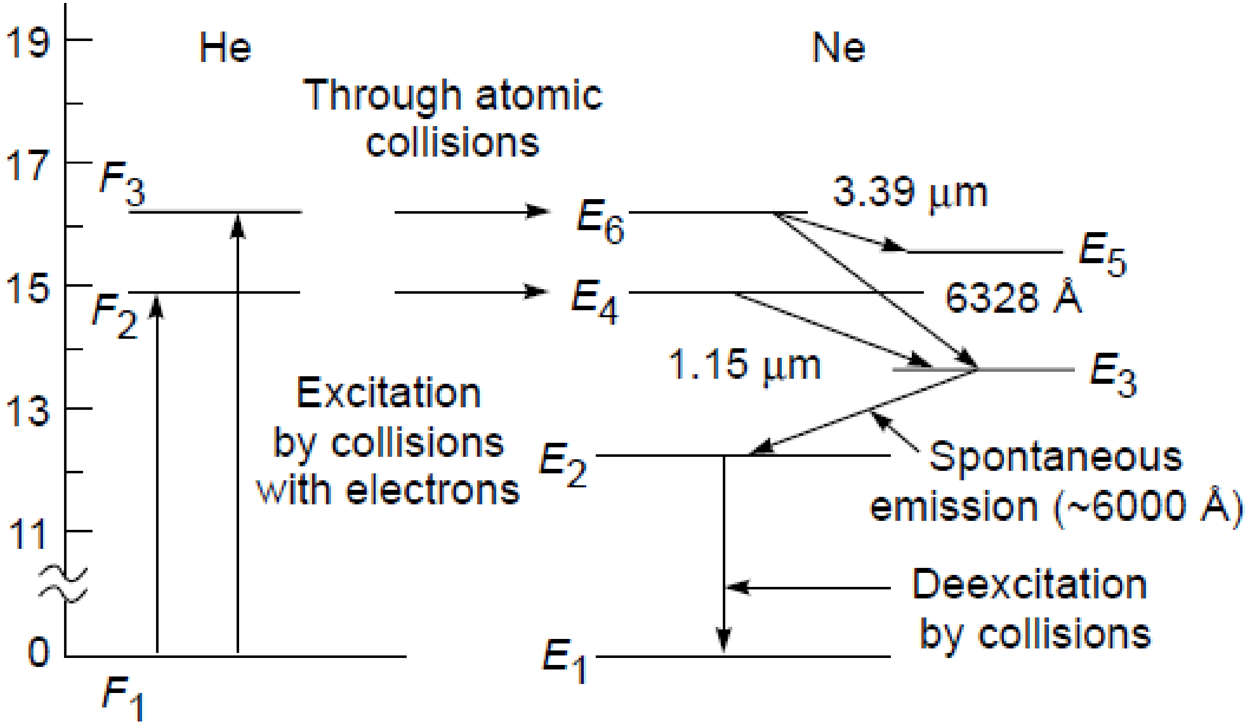


Relevant energy levels of helium and neon.

- When an electric discharge is passed through the gas, the electrons → collide with the ***He atoms***
- ***He atoms excited*** *from the ground state F_1 to F_2 and F_3.*
- He atoms excited to these states stay in these levels before losing energy through collisions.
- Collisions with whom?? → Ne atoms present in the same tube
- Due to collision → these collisions, the Ne atoms are excited to E_4 and E_6
- Thus when the atoms in levels F_2 and F_3 collide with unexcited Ne atoms, they raise them to the levels E_4 and E_6, respectively.

Optics, Ghatak

He-Ne LASER

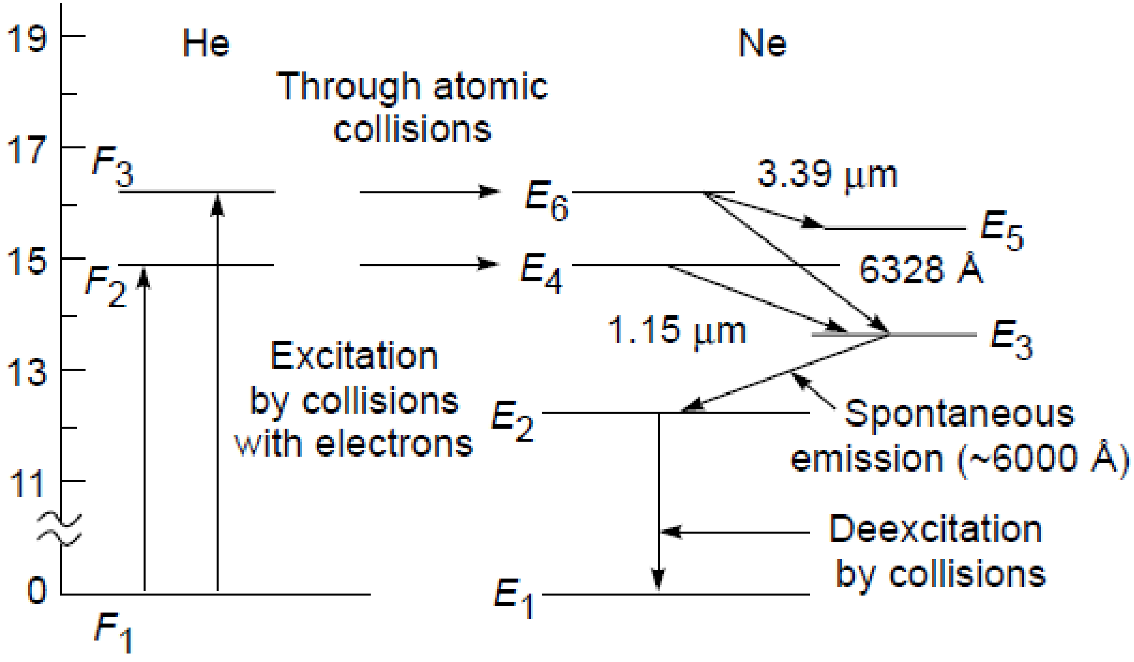


Relevant energy levels of helium and neon.

- ***What happens next?***
- He atom in excited state F_3 + Ne atom in ground state → He atom in ground state + Ne atom in excited state E6
- Similarly, He atom in excited state F_2 + Ne atom in ground state → He atom in ground state + Ne atom in excited state E_4
- **Consequence?** population of E_4 and E_6 >> E_3 and E5. → population inversion is achieved
- Light amplification can be achieved

Optics, Ghatak

He-Ne LASER



Relevant energy levels of helium and neon.

- **Possible transitions:**
- The transitions from $\mathbf{E_6}$ to E_5, $\mathbf{E_4}$ to E_3, and E_6 to E_3 result in the emission of radiation having wavelengths of 3.39 μm, 1.15 μm, and 6328 Å, respectively.
- Note that the laser transitions corresponding to 3.39 and 1.15 mm are not in the visible region→ infrared
- The 6328 Å transition corresponds to the well-known red light of the He-Ne laser.

https://www.sciencedirect.com/topics/physics-and-astronomy/laser-cavities

Wikipedia/ Optics, Ghatak

Few points to note

- Ne and not He is related to the lasing action. He → buffer
- Not optical but electrical pumping method is used
- The tube containing the gaseous mixture is made ***narrow*** so that Ne atoms in level E_2 can get de-excited by collision with the walls of the tube.
- There are a large number of levels grouped around E_2, E_3, E_4, E_5, and E_6. Only those levels are shown in the figure which correspond to the important laser transitions.
- **Advantages:** more directional and more monochromatic than solid-state lasers→ ***Why?*** This is so because of the absence of such effects as crystalline imperfection, thermal distortion, and scattering, which are present in solid-state lasers.
- A large group of gas lasers operate across the spectrum from the far IR to the UV (1 mm to 150 nm).
- Primary among these are helium-neon, argon, and krypton, as well as several ***molecular gas systems***, such as carbon dioxide, hydrogen fluoride, and molecular nitrogen (N_2).

Thank You