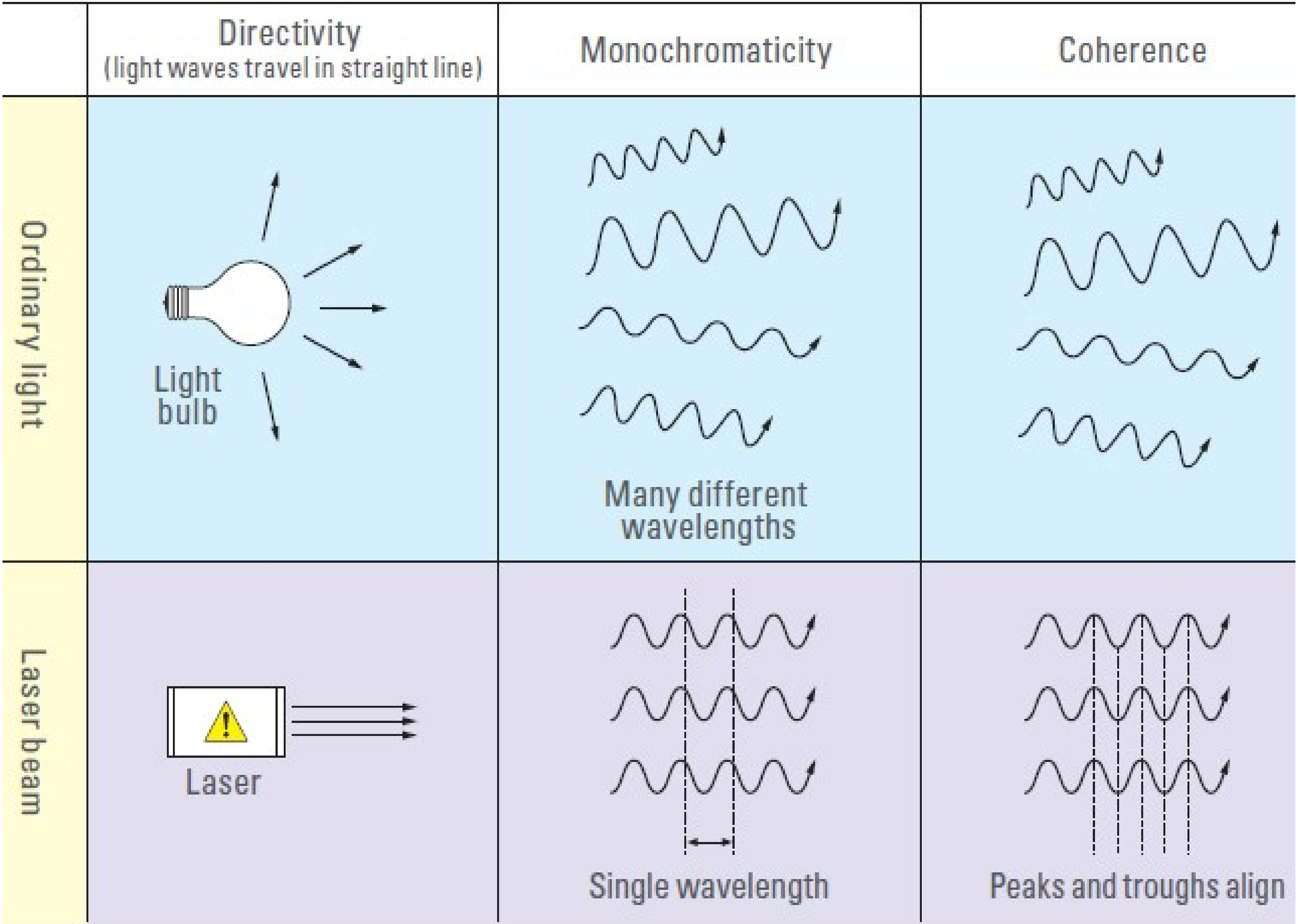
Laser

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

Laser Applications :

- Laser Cutting
- Laser Printers
- Barcode Scanners
- Laser Pointer
- Laser Surgery
- Fiber Optic
- Free-Space Communication
- Distance measurements
- so on...

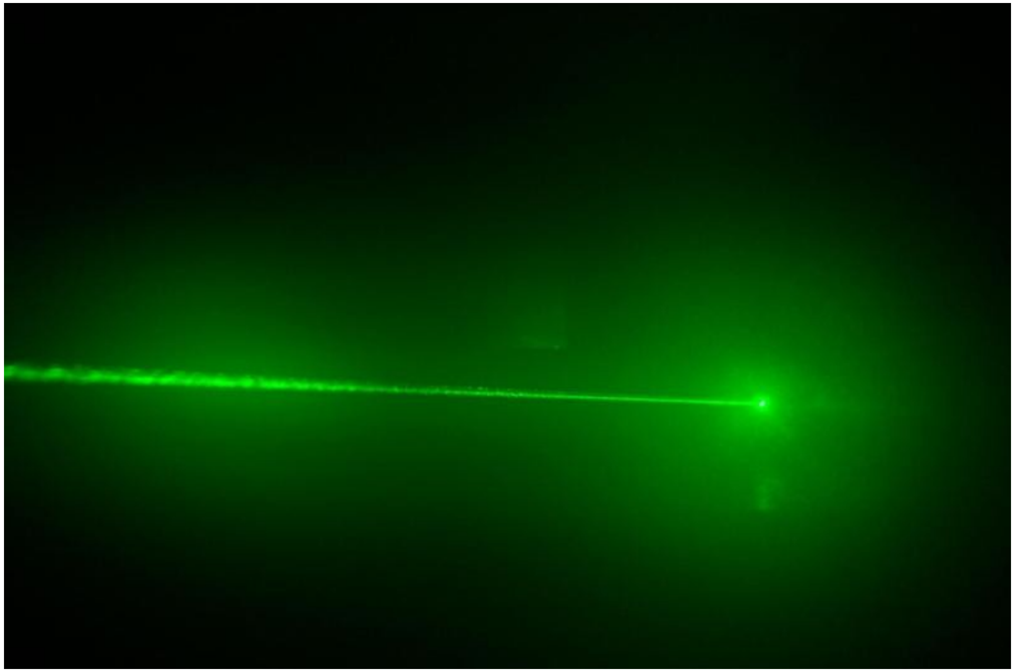

Directivity
(light waves travel in straight line)
Monochromaticity
Coherence
Ordinary light
Light bulb
Many different wavelengths
Laser beam
Laser
Single wavelength
Peaks and troughs align

Properties of Laser :

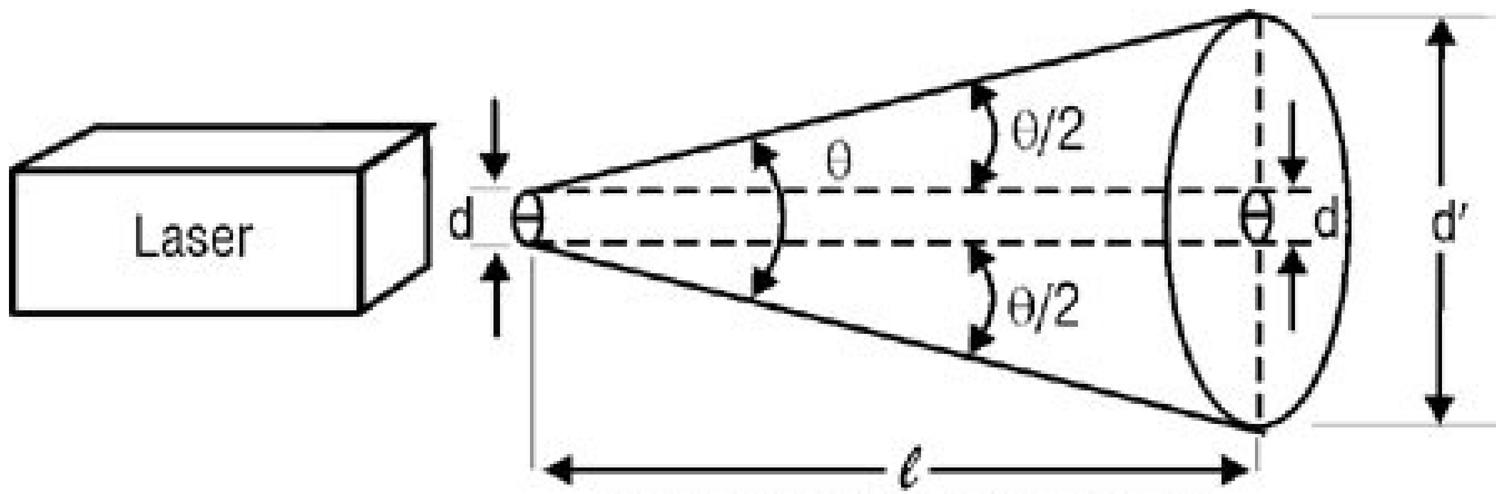
1. Directionality :

Laser beam is highly directional.

The divergence of the laser beam is usually limited by diffraction.



Beam divergence is defined as : $\theta \approx \frac{d' - d}{l}$



Divergence of a laser beam

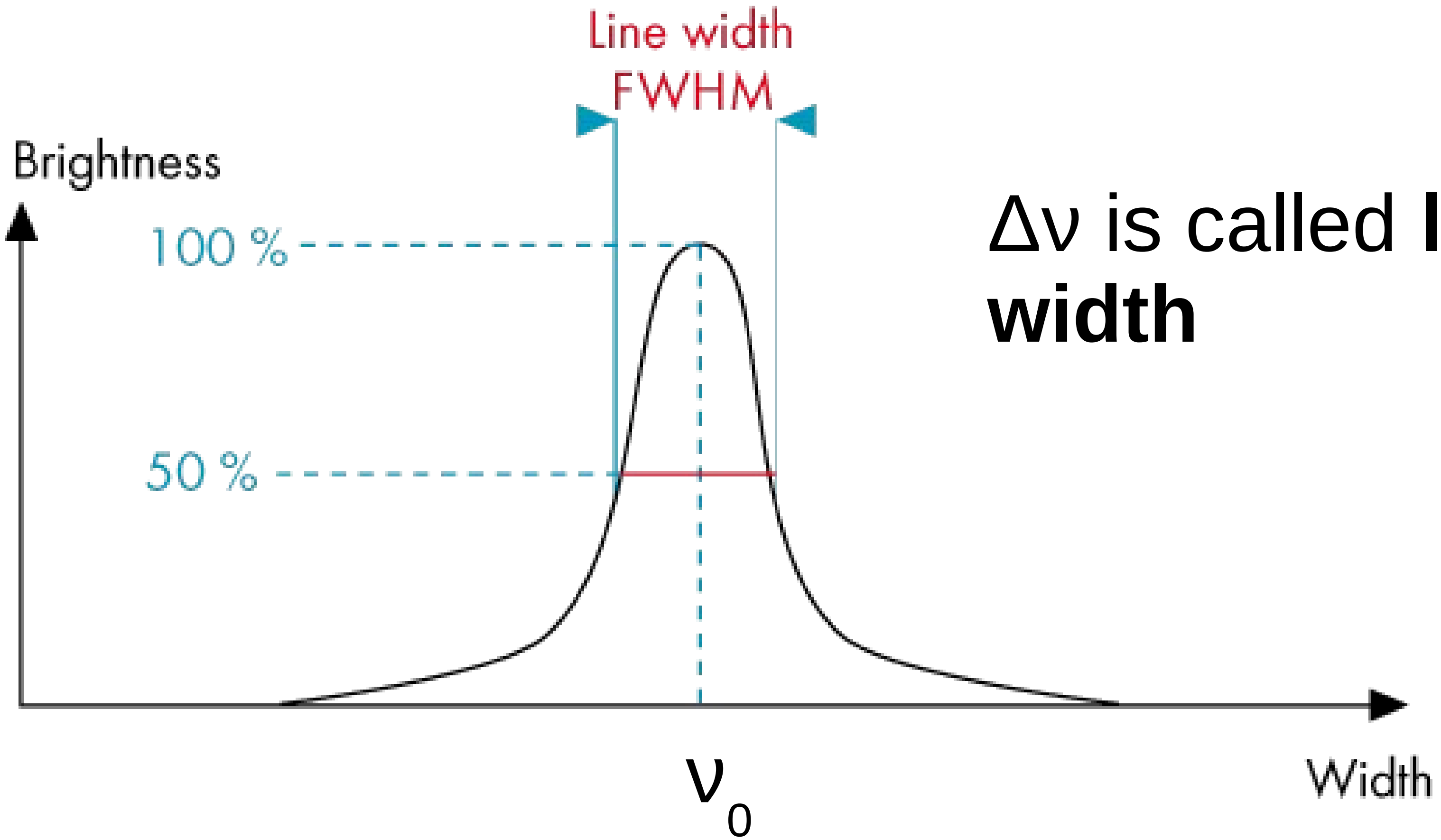
$$\tan\left(\frac{\theta}{2}\right) = \frac{\frac{1}{2}(d' - d)}{l}$$

Since divergence for laser is very small hence θ *is very small.*

$$\textit{Therefore} \tan\left(\frac{\theta}{2}\right) \approx \frac{\theta}{2}$$

$$\Rightarrow \frac{\theta}{2} \approx \frac{\frac{1}{2}(d' - d)}{l} \Rightarrow \theta \approx \frac{(d' - d)}{l}$$

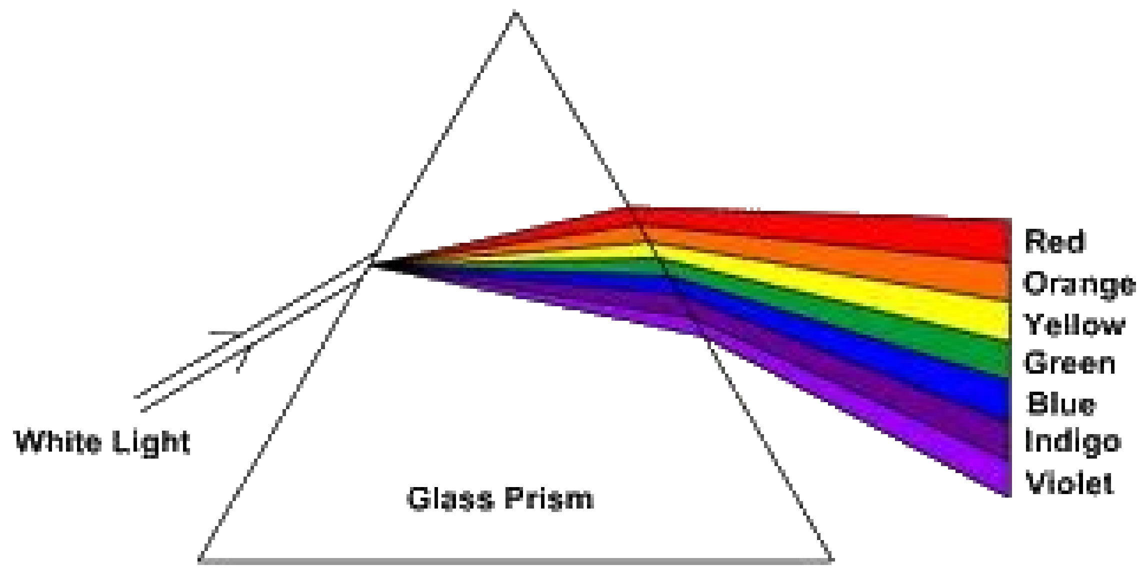
2. **Monochromaticity :** Nearly monochromatic light

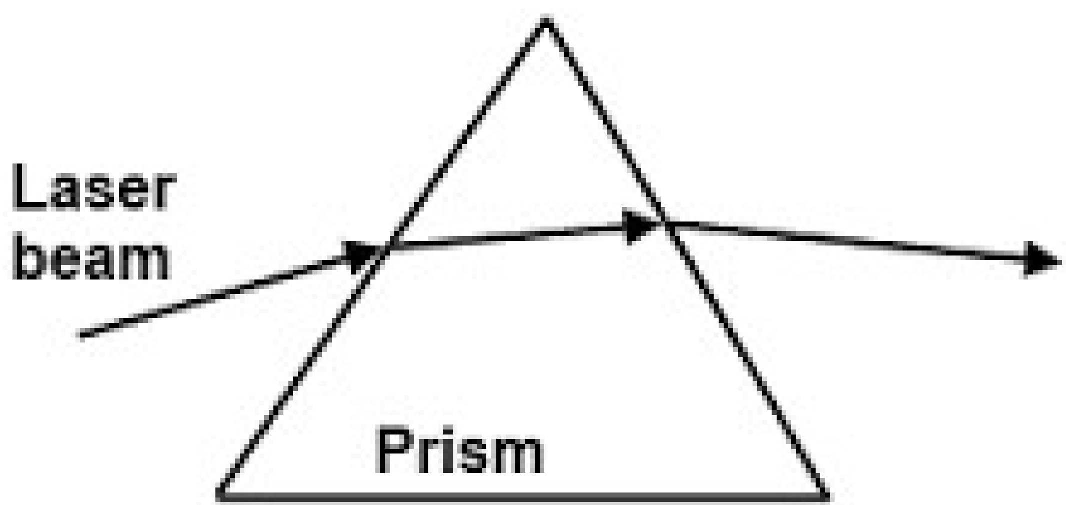


$\Delta\nu$ is called **line width**

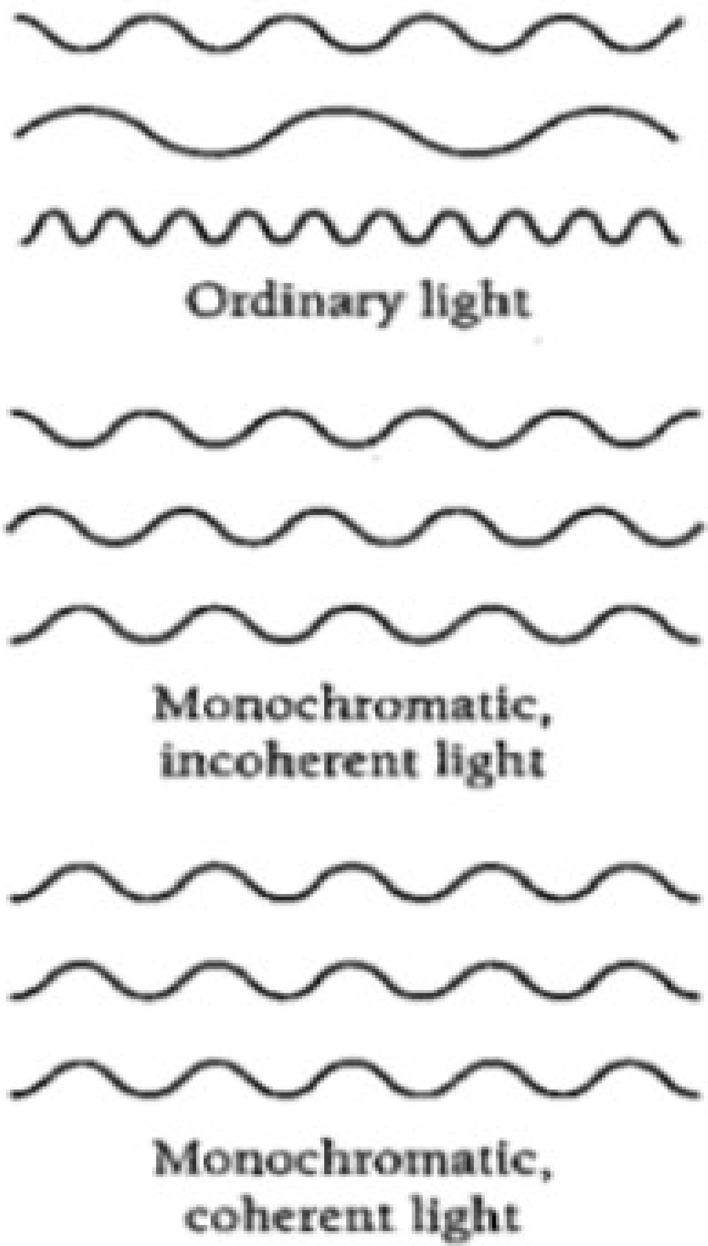
Range of frequency is $\nu \pm \Delta\nu$ or $\lambda + \Delta\lambda$

For He-Ne laser: $\lambda = 632.5$ nm; $\Delta\lambda = 0.2 \times 10^{-2}$ nm


Red
Orange
Yellow
Green
Blue
Indigo
Violet
White Light
Glass Prism


Laser beam
Prism

3. Coherence : Laser is both temporal and spatial coherent



Can see interference patterns with two independent laser lights.

The coherence length, $l_c = c \times \tau_c$

Where "c" is velocity of light and τ_c is called coherence time. Also,

$\tau_c = 1/\Delta\nu$ ($\Delta\nu$ is line width)

Therefore, $l_c = c \times \tau_c = c/\Delta\nu$

$$Now, c = \nu\lambda \Rightarrow \nu\Delta\lambda + \lambda\Delta\nu = 0$$
$$\Rightarrow \Delta\nu = -\nu\frac{\Delta\lambda}{\lambda} = -c\frac{\Delta\lambda}{\lambda^2}$$

Therefore, $l_c = c/\Delta\nu = \lambda^2/\Delta\lambda$

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The more monochromatic is a wave (less will be $\Delta\lambda$ and $\Delta\nu$), larger is coherent length and coherent time.

Source	$\Delta\nu$ (Hz)	$\tau_c = 1/\Delta\nu$	$l_c = c \times \tau_c$
Sunlight	3.75×10^{14}	2.67 fs	800 nm
Sodium lamp	5×10^{11}	2 ps	600 μm
He-Ne laser	1×10^{9}	0.67 ns	20 m

4. Intensity/Brightness : Highly intense that is why used for welding because heat is focussed on small spot.

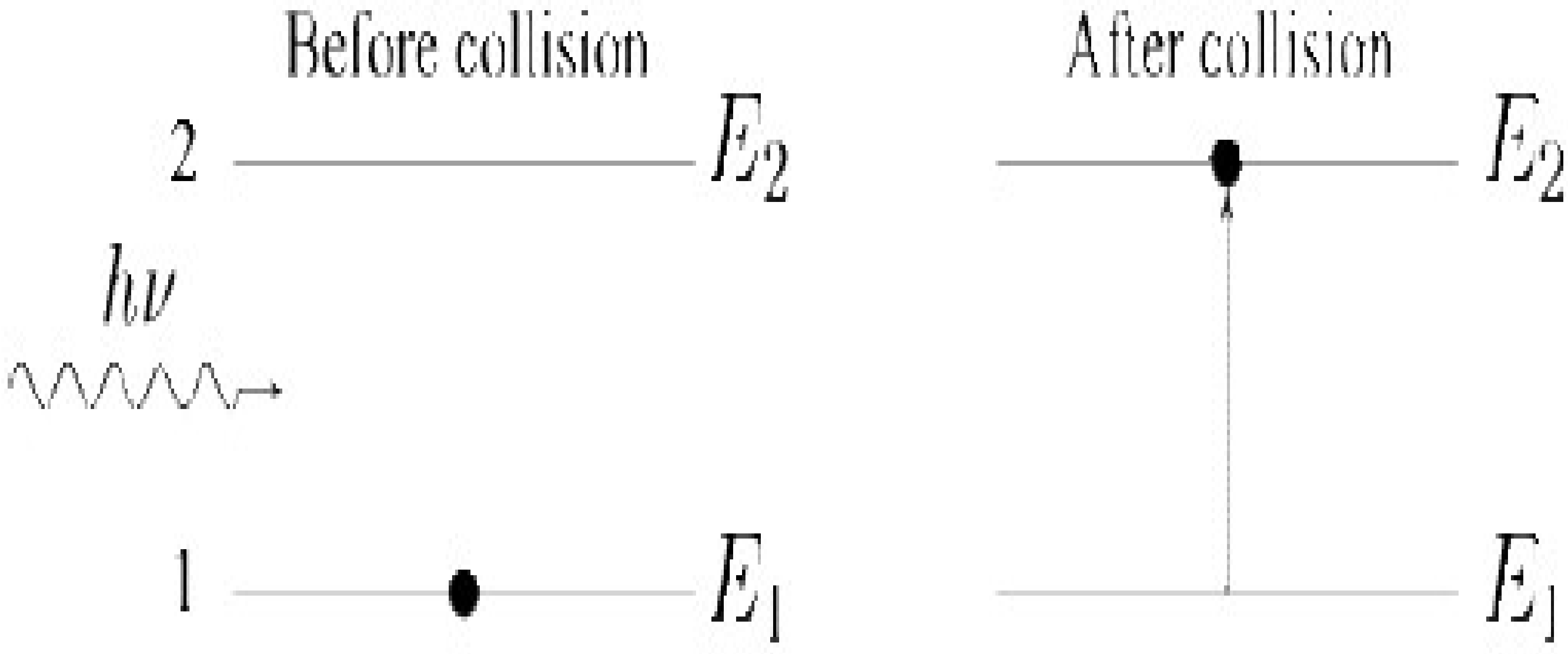
Intensity is high because laser is coherent.

Three transition processes can take place when a photon is incident on an atom:

1. Absorption
2. Spontaneous emission
3. Stimulated emission (Predicted by Einstein)

Absorption :

Consider a simple two level system with energy levels E_1 and E_2 , with $E_2 > E_1$.



Such an atom can emit or absorb a photon of frequency given by
$h\nu = E_2 - E_1$
At ordinary temperatures, most of the atoms are in the ground state E_1.

If a photon of frequency ν is incident on the system, it will be absorbed by an atom in the ground state E_1 and will, therefore, will be excited to the state E_2.

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

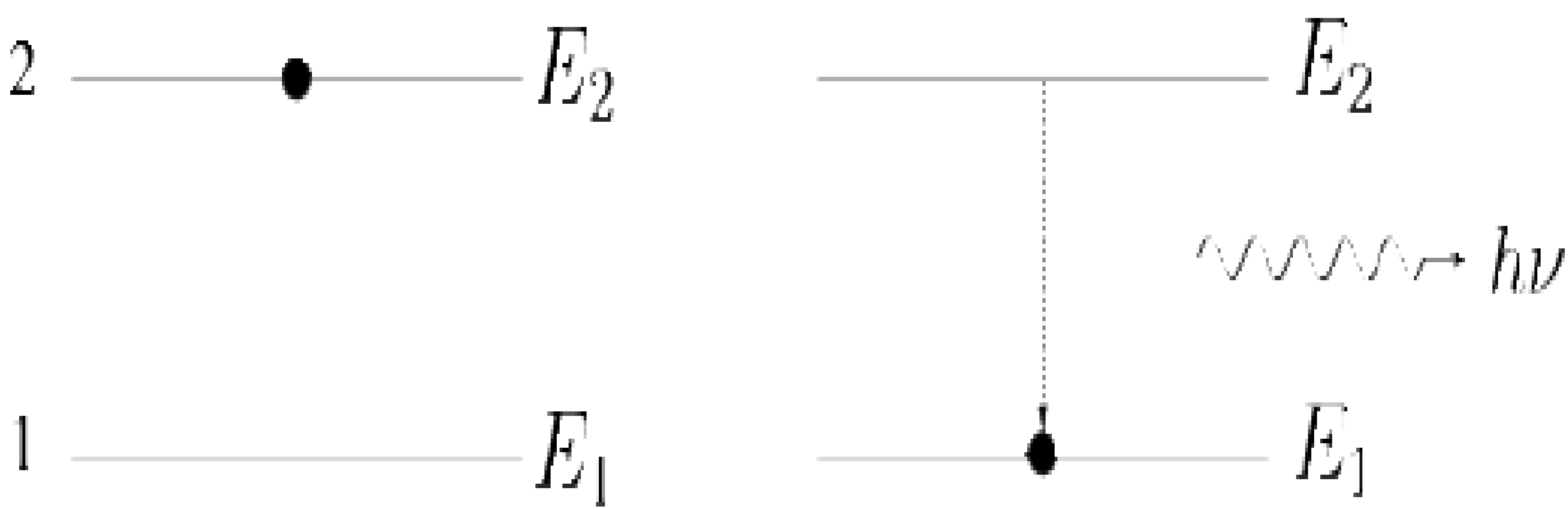
Once the atom is in the excited state, it can decay (or drop back to a lower energy state) after a short time, typically from 10^{-9} to 10^{-3} seconds, by two different processes:
spontaneous emission and **stimulated emission**.

Spontaneous Emission :

In an excited state E_2 the atom stays for a finite time before it falls into ground state by **spontaneously** emitting a photon of frequency :

$$\nu = (E_2 - E_1)/h$$

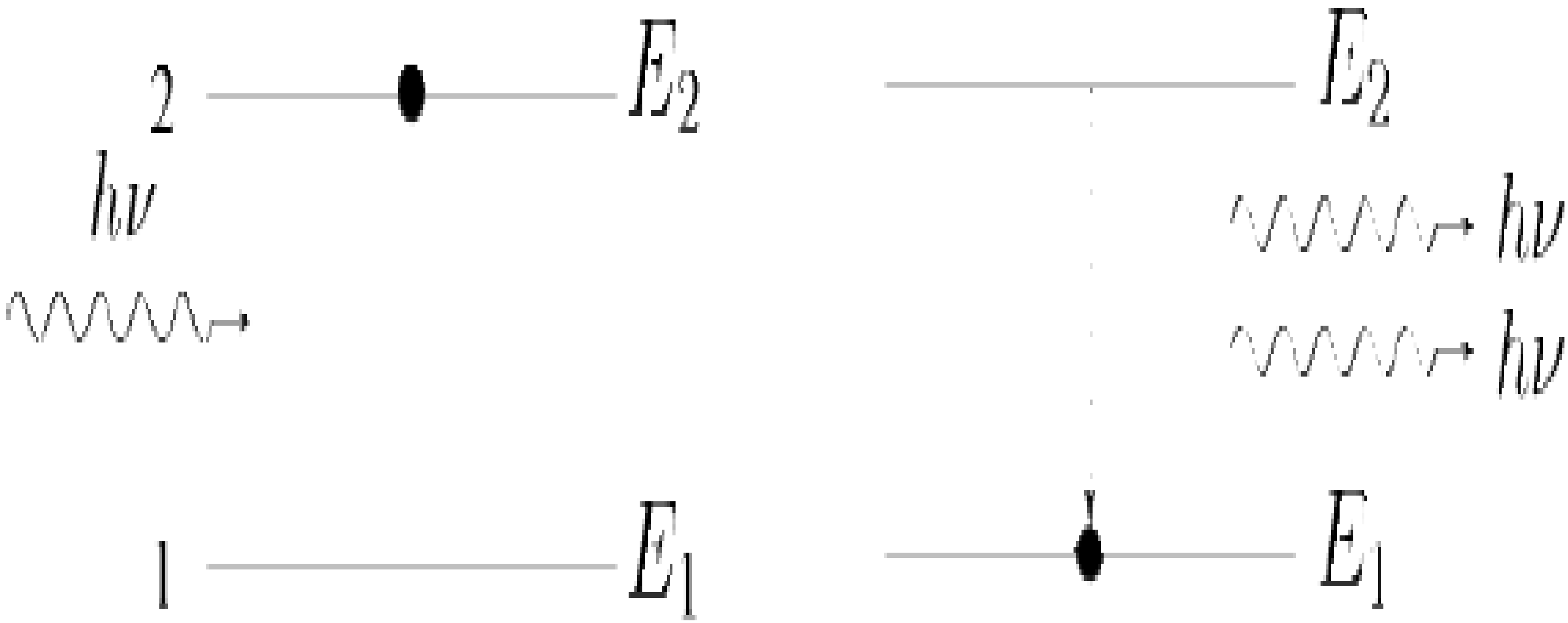
This is called *radiative transition*.



- The duration of stay in level E_2 is called **lifetime** of the level.
- ***The photon emitted by atom is in random direction.*** In an ensemble of atoms, photons are emitted in random directions and have no phase relationship between them.
- The rate at which electrons fall from excited level E_2 to lower level E_1 is at every instant proportional to the number of electrons remaining in E_2.
- The transition probability depends only on the two energy levels.
- Since this process can occur even in the absence of any radiation, this is called **spontaneous emission.**

Stimulated Emission :

Photon of energy $h\nu = (E_2 - E_1)$ can interact with an atom in excited state E_2 and **induce(stimulate)** transition to E_1.



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

Energy difference (E_2- E_1) is emitted in the form of photon of frequency "ν" and *this photon has same direction as incident photon.*

Moreover, this photon is in phase with incident photon and has same polarisation as incident photon.

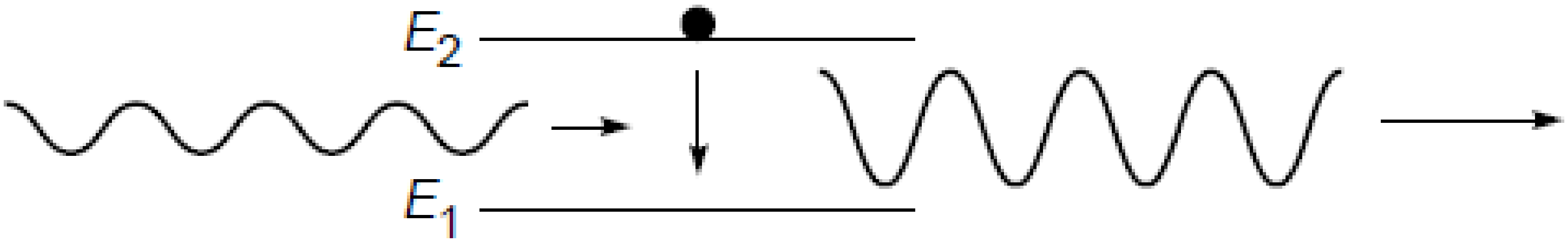
For every photon, there are two outgoing photons going in the same direction. This leads to **amplification of incident photon**.

*In summary, emitted photons have the same frequency and are in phase with the incident photon. This way we can achieve an **amplified and unidirectional coherent beam**.*

Quantum mechanically, there is finite probability associated with each transition.

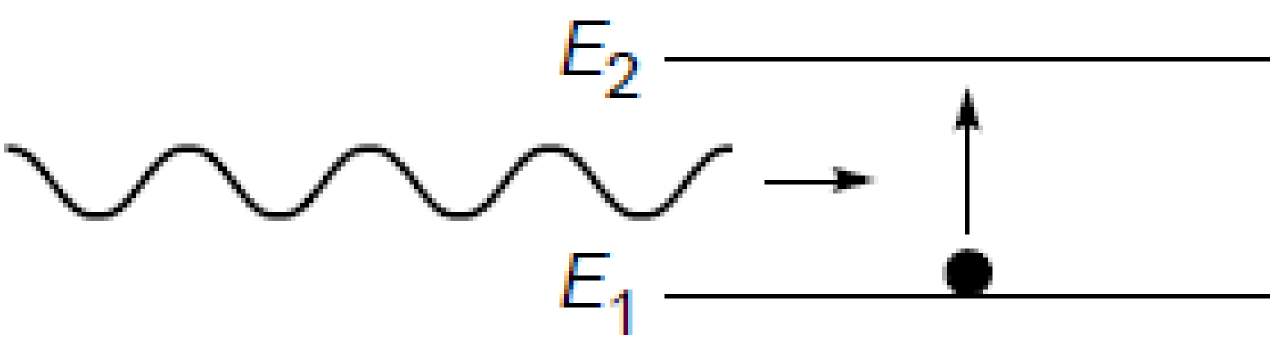
The total probability of emission transition from E_2 to E_1 ($E_2 \rightarrow E_1$) is the sum of **spontaneous and stimulated emission probabilities**.

Which one of these will happen if photon of energy (E_2-E_1) is incident?

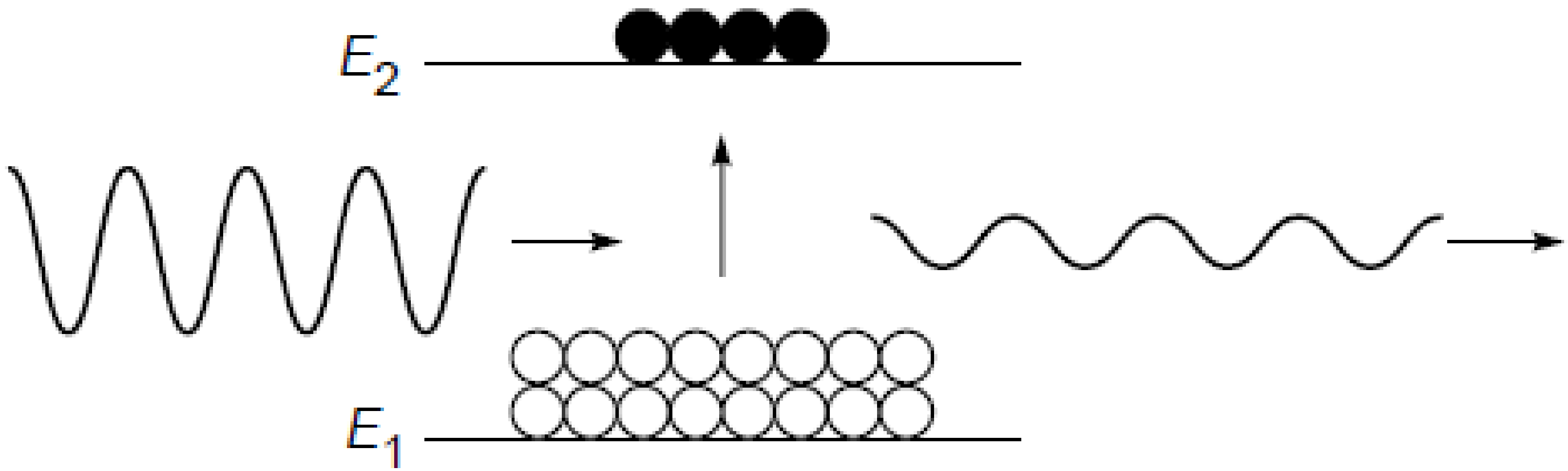


Stimulated emission

Notice the larger amplitude of outgoing wave here (equivalent to 2 photons in previous slides)

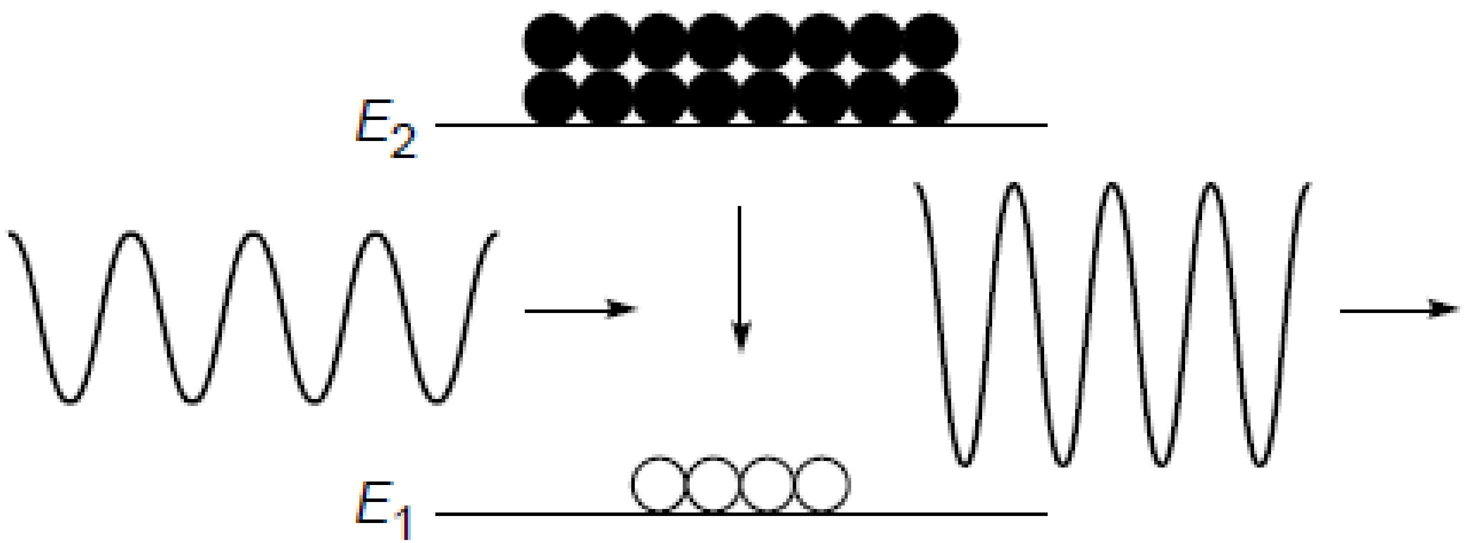


Absorption



Attenuation

(a)



State of population inversion ⇒ amplification

(b)

When the atoms are in thermodynamic equilibrium, there are larger number of atoms in the lower state, implying that the number of absorptions exceeds the number of stimulated emissions; this results in the attenuation of the beam (shown in (a) in previous slide).

On the other hand, if we are able to create a state of **population inversion** in which there are larger number of atoms in the upper state, then the number of stimulated emissions exceeds the number of absorptions, resulting in the (optical) amplification of the beam (shown in (b) in previous slide).

Population Inversion :

The term population inversion describes an assembly of atoms in which the majority are in energy levels above the ground state.

When in termal equlibrium at temperature T, number of atoms in various levels are given by Maxwell-Boltzmann's distrrirbution :

$$N_i = N_0 e^{-E_i/kT}$$

Where N_i is number of atoms having energy E_i, N_0 is number of atoms in ground state, ***k*** is Boltzmann's constant, T is tempertaure in Kelvin.

At equlibrium Population is maximum in ground state and decreases exponentially as one goes to higher energy states.

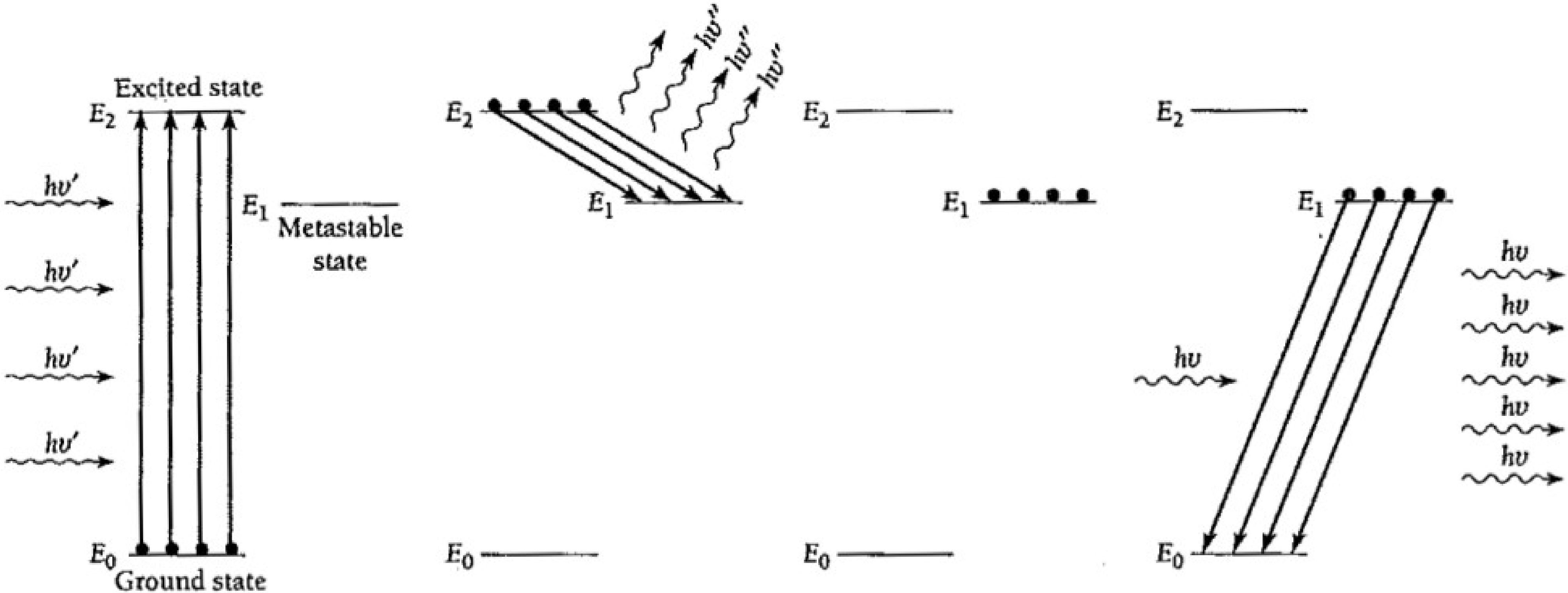
If N_1 and N_2 are population of atoms in level E_1 and E_2 respectively,

$$\frac{N_2}{N_1} = e^{(E_1 - E_2)/kT} = e^{-h\nu/kT} < 1$$

Hence $N_2 < N_1$. Therefore, at thermal equilibrium *number of atoms undergoing spontaneous emission is greater than the number of atoms undergoing stimulated emission*.

It is absolutely necessary for laser action that number of atoms undergoing stimulated emission is greater than the number of atoms undergoing spontaneous emission i.e. $N_2 > N_1$. This condition is called population inversion.

Laser Principle:



Atoms in ground state are pumped to state E_2 by photons of $h\upsilon' = E_2 - E_0$ (or by collisions).

Rapid transition to metastable state E_1 by spontaneous emission of photons of $h\upsilon'' = E_2 - E_1$ (or in some other way).

Metastable states occupied in many atoms.

Stimulated emission occurs when photons of $h\upsilon = E_1 - E_0$ are incident, with the secondary photons themselves inducing further transitions to produce an avalanche of coherent photons.

Population inversion is not possible with 2 levels.

Laser Principle:

A number of ways exist to produce a population inversion and the process is known as **pumping.**

A steady state population inversion cannot be created between two levels just by using pumping between these levels. Thus, in order to produce a steady state population inversion, one makes use of either a **three level or a four level system.**

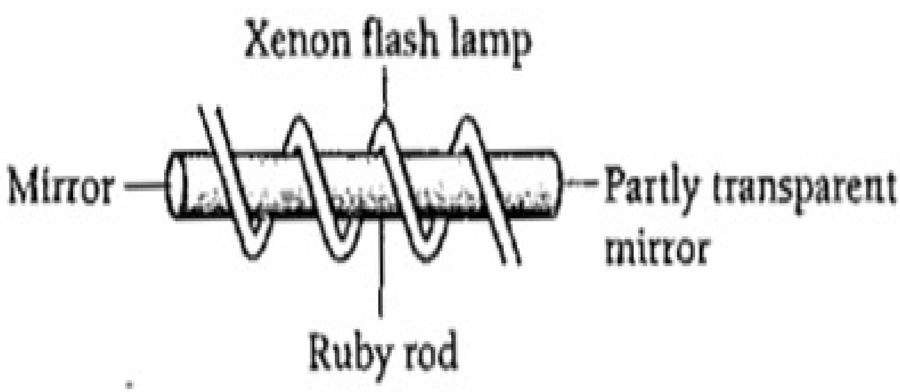
A three-level laser, the simplest kind, uses an assembly of atoms (or molecules) that have a metastable state hν in energy above the ground state and a still higher excited state that decays to the metastable state.

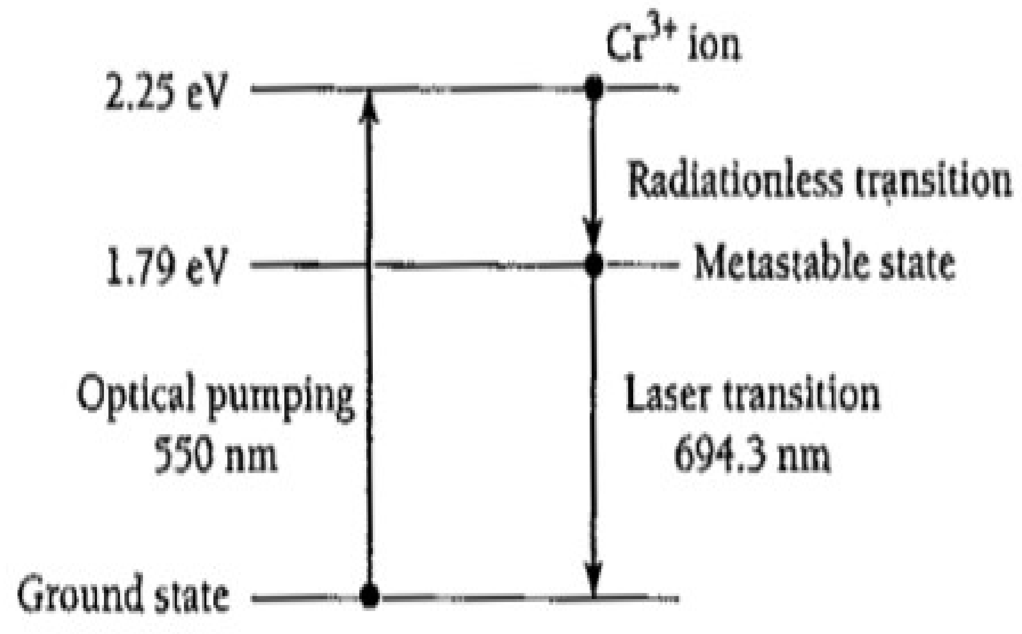
More atoms are required in the metastable state than in the ground state so that stimulated emission can be achieved by shining with light of frequency ν. A metastable states have lifetimes of 10^{-3} s or more instead of the usual 10^{-8} s and are hence relatively long-lived states.

In a three-level laser, more than half the atoms must be in the metastable state for stimulated induced emission to predominate.

Ruby Laser :

A ruby is a crystal of aluminum-oxide, Al_2O_3, in which some of the Al^{3+} ions are replaced by Cr^{3+} ions (~ 0.05% by weight), which are responsible for the red color. Ruby laser was the first successful laser and is based on the three energy levels in the chromium ion Cr^{3+}.





The ruby laser is an example of a three-level laser.

In the ruby laser, a xenon flash lamp excites the Cr^{3+} ions to a level of higher energy (2.25 eV) from which they fall to the metastable level (1.79 eV) by losing energy to the lattice. Thus, there is also a cooling system provided (circulating water or liquid nitrogen) to cool the crystal.

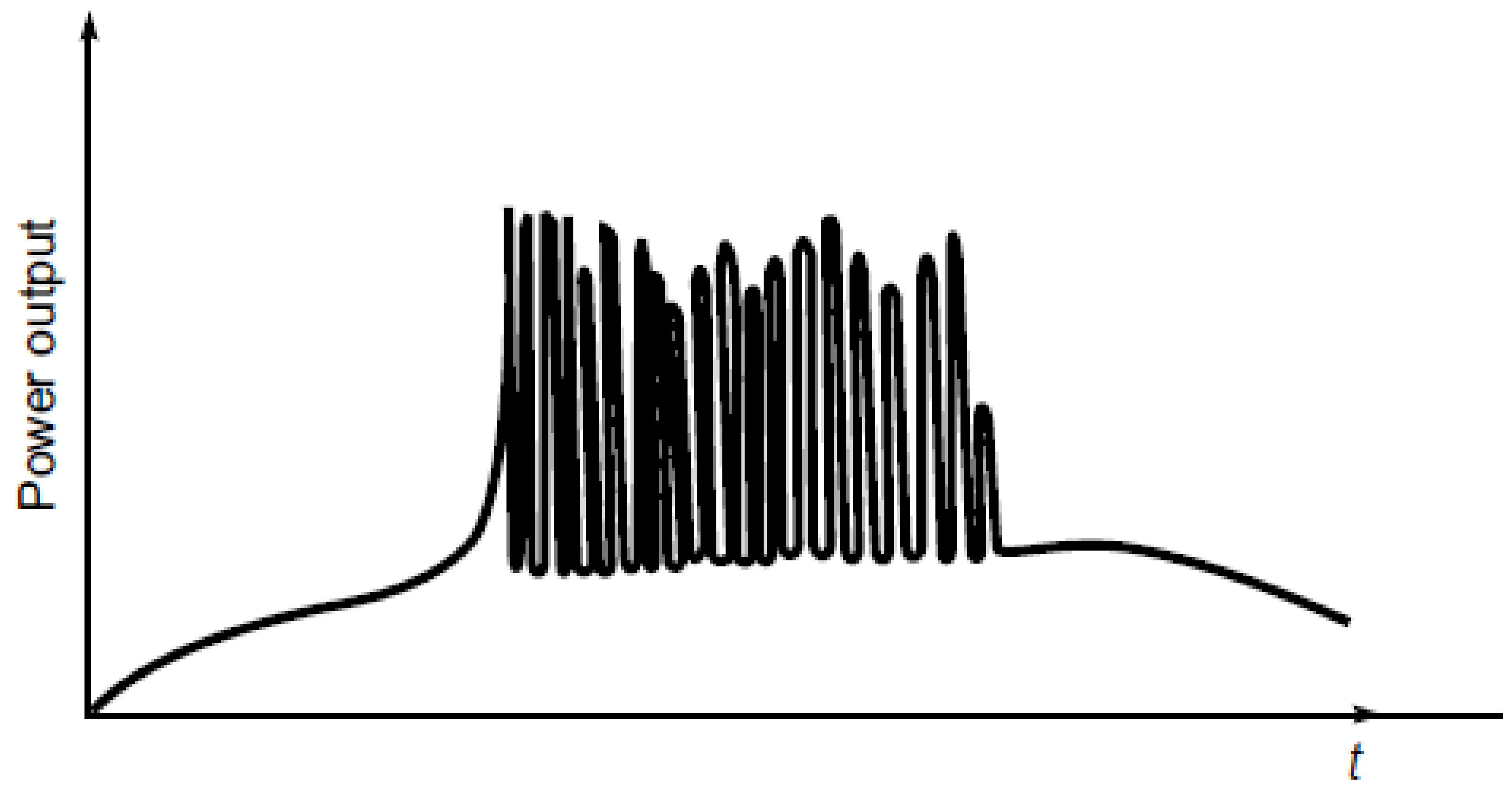
The metastable level in Cr^{3+} ion has lifetime approx. 0.003 s. Level at 2.25 eV has lifetime of $\sim 10^{-8}$ s, number of atoms keep increasing in the metastable state.

Once population inversion is achieved, light amplification can take place, with two reflecting ends of the ruby rod forming a cavity.

Photons from the spontaneous decay of some Cr^{3+}ions are reflected back and forth between the mirrored ends of the ruby rod, stimulating other excited Cr^{3+} ions to radiate. After a few microseconds the result is a large pulse of monochromatic, coherent red light from the partly transparent end of the rod.

The rod’s length is made precisely an integral number of half-wavelengths long, so the radiation trapped in it forms an optical standing wave.

Spiking in Ruby Laser :



Characteristic spiking of ruby laser.

Spiking in Ruby Laser :

The flash operation of the lamp leads to a pulsed output of the laser. As soon as the flashlamp stops operating the population of the upper level is depleted very rapidly and lasing action stops till the arrival of the next flash.

Even in the short period of a few tens of microseconds in which the ruby is lasing, one finds that the emission is made up of spikes of high-intensity emissions having random amplitude fluctuations of varying duration. This phenomenon is known as **spiking.**

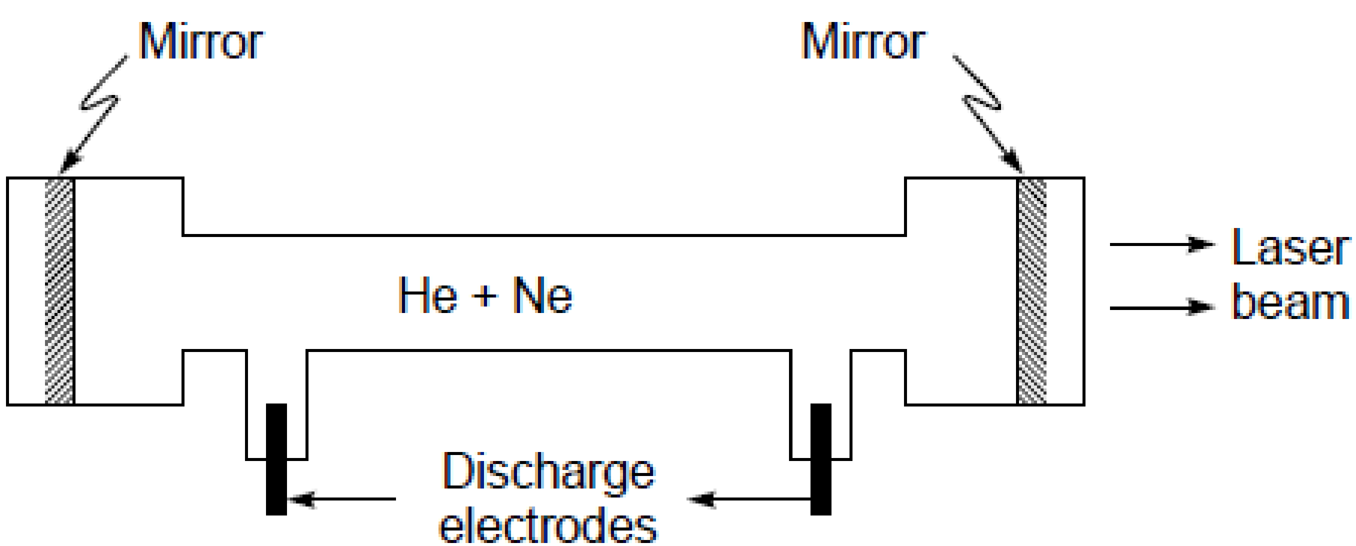
When the pump is turned on, the intensity of light at the laser transition is small and hence the pump builds up the inversion rapidly. Although under steady-state conditions the inversion cannot exceed the threshold inversion, on a transient basis it can go beyond the threshold value due to the absence of sufficient laser radiation in the cavity which causes stimulated emission. Thus the inversion goes beyond threshold when the radiation density in the cavity builds up rapidly. Since the inversion is greater than threshold, the radiation density goes beyond the steady-state value which in turn depletes the upper level population and reduces the inversion below threshold. This leads to an interruption of laser oscillation till the pump can again create an inversion beyond threshold. This cycle repeats itself to produce the characteristic spiking.

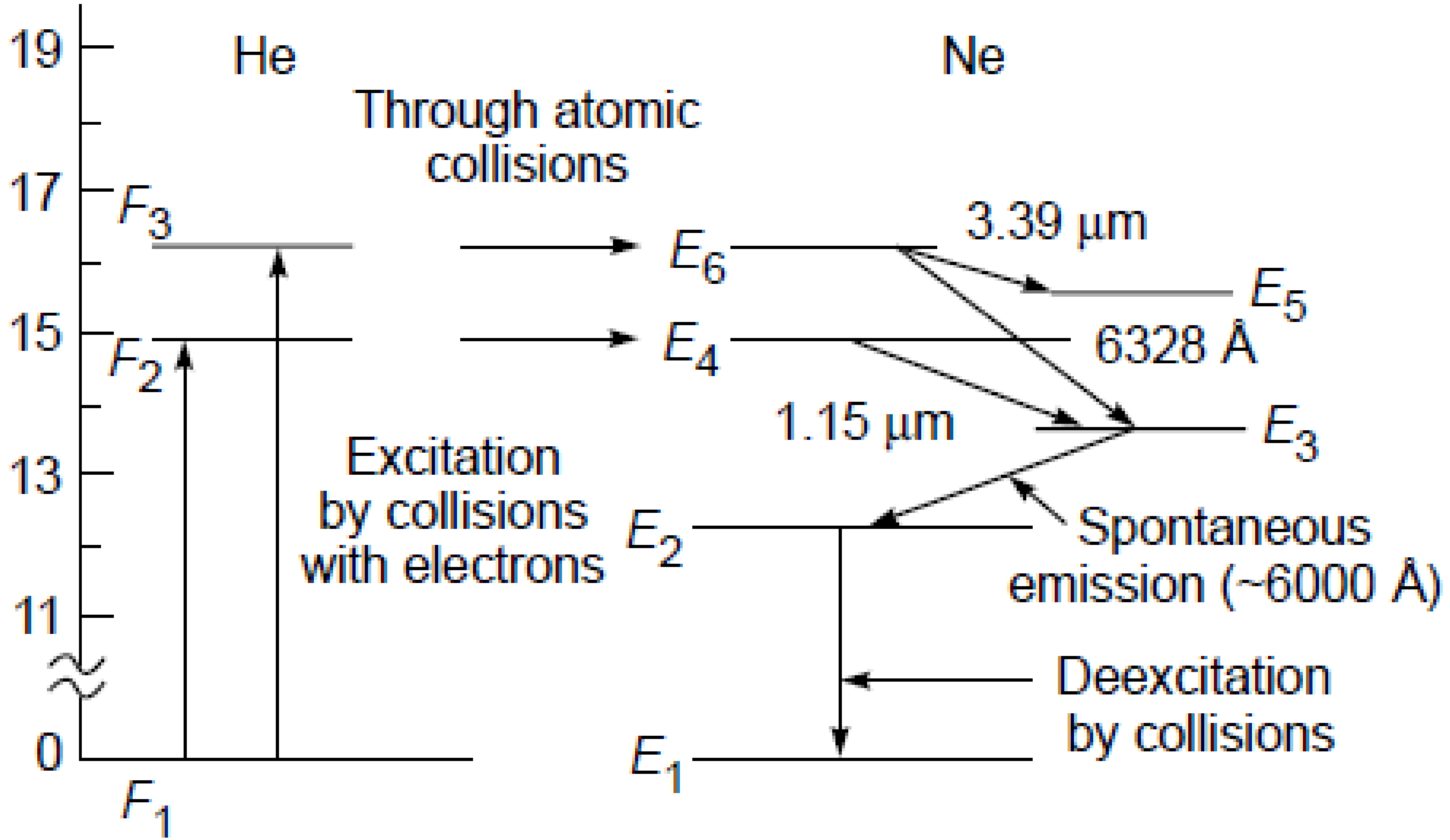
He-Ne laser:

The He-Ne laser consists of a mixture of He and Ne in a ratio of about 10:1, placed inside a long, narrow discharge tube. The pressure inside the rube is about 1 torr.

The gas system is enclosed between a pair of plane mirrors or a pair of concave mirrors so that a resonator system is formed. One of the mirrors is of very high reflectivity while the other is partially transparent.

The actual lasing atoms are the neon atoms and helium is used for a selective pumping of the upper laser level of neon.





Relevant energy levels of He and Ne.

When an electrical discharge is passed through the gas, the electrons which are accelerated down the tube collide with helium and neon atoms and excite them to higher energy levels.

The He atoms are excited from the ground state to the levels marked F_2 and F_3(lifetime $\sim 10^{-4}$ and 5×10^{-6} s respectvely). These levels are metastable; i.e., He atoms excited to these states stay in these levels for a sufficiently long time before losing energy through collisions.

Since the levels E_4 and E_6 of neon atoms have almost the same energy as F_2 and F_3 , excited helium atoms colliding with neon atoms in the ground state can excite the neon atoms to E_4 and E_6 . Since the pressure of helium is ten times that of neon, the levels E_4 and E_6 of neon are selectively populated as compared to other levels of neon.

This results in a sizeable population of the levels E_4 and E_6. The population in these levels happens to be much more than those in the lower levels E_3 and E_5. Thus a state of population inversion is achieved, and any spontaneously emitted photon can trigger laser action in any of the three transitions

The transitions from E_6 to E_5, 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. The laser transitions corresponding to 3.39 μm and 1.15 μm, are not in the visible region. **The 6328 Å transition corresponds to the well-known red light of the He-Ne laser.**

The Ne atoms then drop down from the lower laser levels to the level E_2 through spontaneous emission. From the level E_2 the Ne atoms are brought back to the ground state through collision with the walls.

Conditions:

The pressures of the two gases must be chosen so that the condition of population inversion is not quenched. Thus the conditions must be such that there is an efficient transfer of energy from He to Ne atoms.

The level marked E_2 is metastable, electrons colliding with atoms in level E_2 may excite them to level E_3 , thus decreasing the population inversion. The tube containing the gaseous mixture is also made narrow so that Ne atoms in level E_2 can get de-excited by collision with the walls of the tube.

Comparison of Ruby and He-Ne laser:

Gas lasers are, in general, found to emit light, which is more directional and more monochromatic. This is so because of the absence of such effects as crystalline imperfection, thermal distortion, and scattering, which are present in solid-state lasers. Gas lasers are capable of operating continuously without need for cooling.

Ruby laser is a pulsed laser while gas laser, like He-Ne laser is a continuous laser. In Ruby lasers, the pumping is usually done using a flashlamp. Such a technique is efficient if the lasing system has broad absorption bands. In He-Ne lasers since the atoms are characterized by sharp energy levels as compared to those in Ruby, electrical discharge is used to pump the atoms.

Laser Application : Optical Communications

Optical communication is any form of telecommunication that uses light as the transmission medium.

An optical communication system consists of a transmitter, which encodes a message into an optical signal, a channel, which carries the signal to its destination, and a receiver, which reproduces the message from the received optical signal.

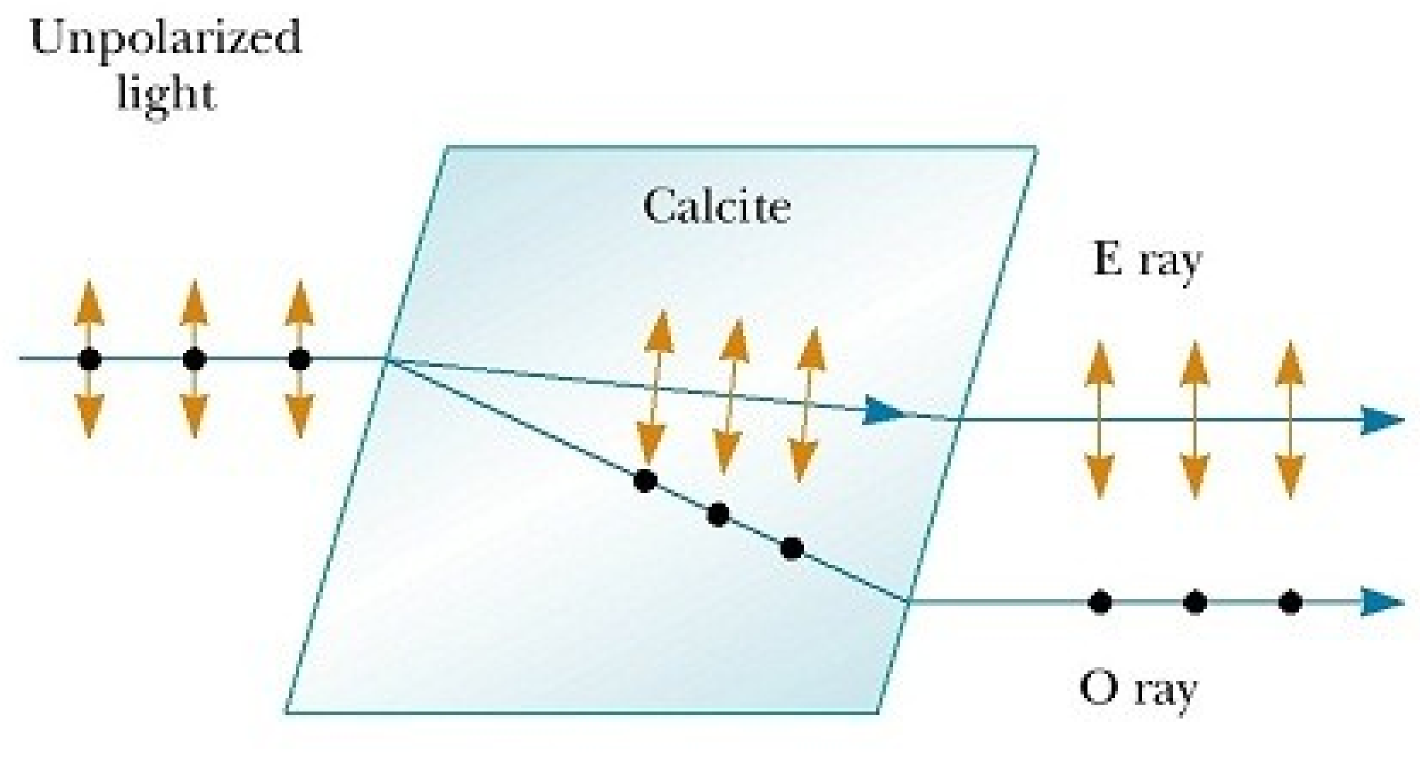
For modulation of the signal without the addition of any noise, the carrier wave should be of a very narrow spectral width ($\Delta\nu$). For communication purposes, the laser beam is modulated by the signal. At the receiving station, the modulated beam is demodulated (detected) to separate the required signal from the laser beam (carrier). The output current, which varies with the intensity of the signal, is amplified and then fed to the speaker.

Laser Application : Optical Alignment

The negligible divergence of the laser beam stimulated a number of ideas for providing hitherto impossible accuracy and sensitivity in the alignment of tools. Serving as an optical axis, the beam guides the machines used for levelling the concrete facing of the airfields, checking the verticality of the framework of tall buildings, sinking mines, and cutting tunnels from two ends and joining them without tilt.

Laser ends here

For numerical no. 4 in tutorial sheet in Polarisation :



The path difference between E and O ray will be given by
$= (\mu_o - \mu_e)\, t$ (where $\mu_o > \mu_e$)
where t is thickness of crystal, μ_e and μ_o are the refractive indices experienced by the E and O rays, respectively.

The phase difference between E and O ray will be given

By = $\frac{2\pi t(\mu_o - \mu_e)}{\lambda}$ (where $\mu_o > \mu_e$)

where t is thickness of crystal, μ_e and μ_o are the refractive indices experienced by the E and O rays, respectively.