Laser and Fibre Optics (Module-V)

Light amplification by stimulated emission of radiation. (LASER)

Laser-
It is a device which amplifies electromagnetic radiation and generates extreme intense, coherent, monochromatic and directional radiation

Characteristics Of Laser Light-
→ They are highly directional.
→ They are monochromatic
→ Laser beam is spatially and temporarily coherent to one extra-ordinary degree. so, interference and diffraction effect can be observed by taking two independent laser
→ Laser beam are highly intense as compared to ordinary light.

Q. Write the diff. b/w Ordinary light and laser

Spontaneous emission & stimulated emission.
Meta stable state.
Population inversion.
Pumping.

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Atomic Transition.

There are 3 types of atomic transition

i) Spontaneous Emission
ii) Stimulated Absorption
iii) Stimulated Emission.

Diff. b/w Spontaneous Emission and Stimulated Emission

	Stimulated Emission
→ Atoms in the excited state at higher energy level may drop to lower energy level by emitting photon without any external provocation	→ The atoms in the excited state at higher energy level may force to drop to lower energy level by emitting photons with external provocation (by incident photon
Atoms emits Electromagnetic wave has no definite phase or directional relation with photons emitted by another atom.	The emitted photon is in phase with that of the incident photon and also in the same direction with incident photons.
No coherent sources can be produced by this method.	Coherent sources are produced by this method

Meta Stable State -

· It is an intermediate state in between excited state and ground state, and it is more close to the excited state.

The life time of atoms in this state is 10^{-5} sec to 10^{-3} sec.

In excited state the life time of atom is 10^{-8} sec. So it is insufficient for the interaction of incident photons with the atoms before stimulated emission.

So, for production of laser meta-stable state is require

Population Inversion-

In a normal condition or thermal equilibrium the density of atoms or population of atoms decreases if we go from lower to higher energy level.

But when the population of higher energy level is more than that of lower energy level then it is called as population inversion for the system or it is called as a active system.

Probability of spontaneous emission rate vs stimulated emission rate and Einstein's coeff. -

Let us consider a system or assembly of atoms in thermal equilibrium i.e. at temp. T (kelvin scale) with radiation frequency 'ν' and energy density '$f(\nu)$'

Under this condition let all the transition process occur.

(i) Stimulated absorption (Upward direction)

(ii) Spontaneous emission. (Downward direction).

Stimulated emission (Downward direction).

N_1 - no. of atoms per unit volume in lower energy level

E_1 - Energy of the atoms in lower energy level.

N_2 - no. of atoms per unit volume in higher energy level.

E_2 - Energy of atoms in higher energy level.

$E_2 - E_1 = h\nu$.

If $\rho(\nu)$ = Energy density of the interacting photons.
$= n h\nu$.

n - no. of interacting photons per unit volume.

Case I - Stimulated absorption.

Stimulated absorption rate $\propto N_1$
$\propto \rho(\nu)$
$= B_{12} N_1 \rho(\nu)$

B_{12} = Proportionality constant and known as Einstein's absorption coeff.

Case II - Spontaneous emission.

Spontaneous emission rate $\propto N_2$
$= A_{21} N_2$

A_{21} - Proportionality constant / known as Einstein's spontaneous emission coeff.

Case III - Stimulated emission

Stimulated emission rate $\propto N_2$
$\propto \rho(\nu)$
$= B_{21} N_2 \rho(\nu)$

B_{21} - proportionality constant / known as Einstein's Stimulated ~~rate~~ emission coeff.

Under thermal equilibrium total upward transition is equal to total downward transition

$$B_{12} N_1 \rho(\nu) = B_{21} N_2 \rho(\nu) + A_{21} N_2.$$

$$\boxed{\rho(\nu) = \frac{A_{21} N_2}{B_{12} N_1 - B_{21} N_2} = \frac{A_{21}/B_{21}}{\frac{B_{12}}{B_{21}}\left(\frac{N_1}{N_2}\right) - 1}} \quad \text{—(1)}.$$

By Boltzman distribution ~~level~~ law.
The population density at different energy level

$$N_i = N_0 e^{-E_i/KT} \quad \text{———} (2)$$

N_i – Population density in the i^{th} energy level.
N_0 – Population density at the ground state.

$$N_1 = N_0 e^{-E_1/KT}, \quad N_2 = N_0 e^{-E_2/KT}.$$

$$\frac{N_1}{N_2} = e^{(E_2-E_1)/KT}.$$

$$\Rightarrow \frac{N_1}{N_2} = e^{h\nu/KT}.$$

$$\rho(\nu) = \frac{A_{21}/B_{21}}{\left(\frac{B_{12}}{B_{21}} e^{h\nu/KT} - 1\right)} \quad \text{———} (3)$$

From planck's law of black body radiation.
the energy density

$$\rho(\nu) = \frac{8\pi h\nu^3}{c^3} \times \frac{1}{e^{h\nu/KT} - 1} \quad \text{———} (4)$$

Comparing eqn (3) and (4).

$$\frac{B_{12}}{B_{21}} = 1 \quad \Rightarrow B_{12} = B_{21}.$$

$$\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{c^3}.$$

Let R be the ratio of spontaneous emission rate to stimulated emission rate.

$$R = \frac{N_2 A_{21}}{N_2 B_{21} \rho(\nu)} = \frac{A_{21}}{B_{21}} \frac{1}{\rho(\nu)}.$$

$$R = e^{h\nu/KT} - 1.$$

$$\Rightarrow R = e^{(E_2-E_1)/KT} - 1.$$

Explain why we cannot have transition b/w any two consecutive states.

Explain how population inversion is a negative temp. state

As $E_2 - E_1 = h\nu$ and that is positive the probability of spontaneous emission increases rapidly with the energy diff. of two states. So, under thermal eq. spontaneous emission is a dominant process.

$$\boxed{\frac{N_2}{N_1} = e^{-(E_2-E_1)/kT}}$$

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

$$N_2 - N_1 = N_1\left(e^{-(E_2-E_1)/kT} - 1\right)$$

$$\Rightarrow \boxed{\Delta N = N_1\left(e^{-(E_2-E_1)/kT} - 1\right)}$$

$> +ve$ for population inversion.

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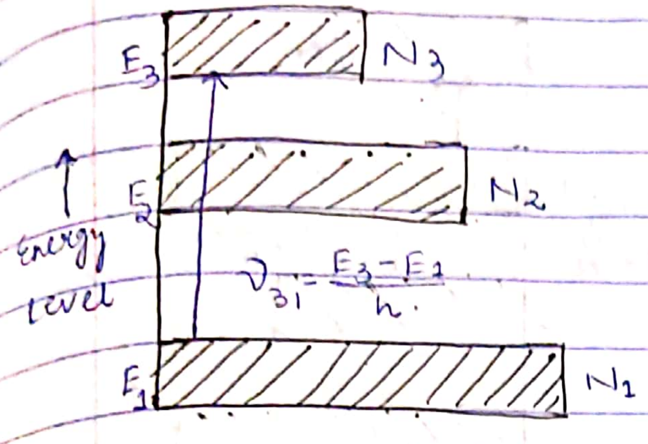
RHS can be +ve when T is -ve.
So, population inversion is refered as a negative temperature state

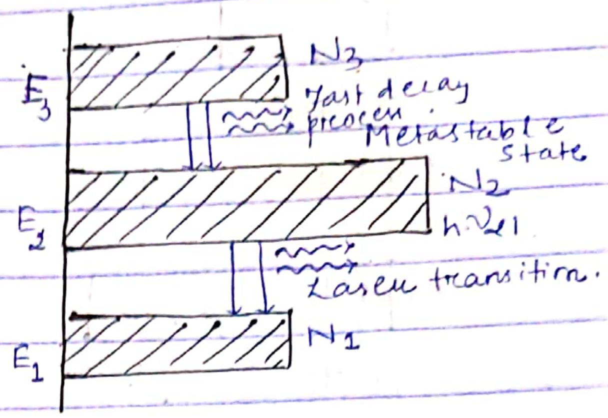
As $N_1 > N_2$ so, probability of stimulate absorption is more than that of stimulated emission.
[As $N_1 > N_2$ So, interaction of photons in the lower level is more than that of the higher level. So, stimulated absorption dominates]

So, the conclusion drawn the higher energy state can never be more populated than the lower energy state or ground state.
So, population inversion is not possible by direct excitation from a lower energy level to a higher energy level.

This only can be possible when we consider atleast a 3 energy level state.

Three energy level-





→ Stimulated absorption excites the atoms from ground state E_1 to the highest level E_3 by incident radiation of frequency, $\nu_{31} = \frac{E_3 - E_1}{h}$

→ But as the life time of the excited atoms in the level E_3 is very short so they decay quickly to E_2.

→ It will remain for a longer period in E_2 than E_3. So, E_2 is called as a metastable state.

→ We intense pumping from E_1 to E_3 and rapid decay from E_3 to E_2, the population of E_2 exceeds E_1 and at this condition the system refered as a active system. So, suitable for emitting laser radiation of frequency ν_{21}/ν_{12}

i.e. $\nu_{21} = \frac{E_2 - E_1}{h}$

demerit of 3 energy state is merit of 4 energy state.

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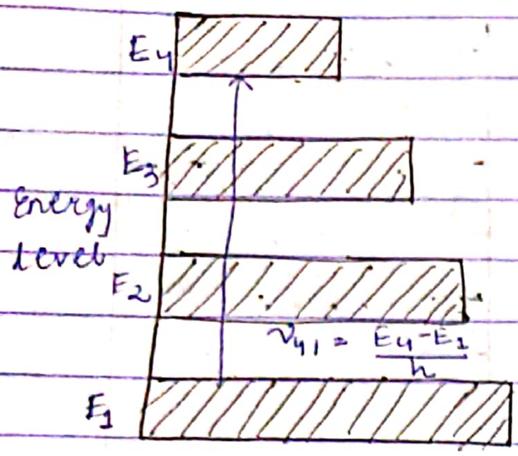
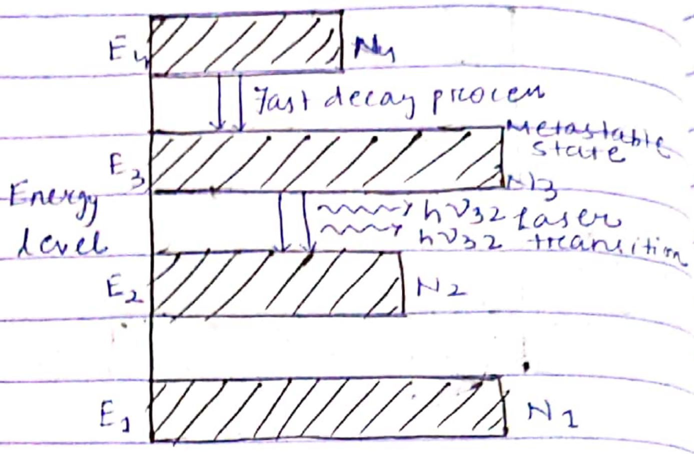
Four energy level state -





Population inversion achieved in b/w N_3 & N_2

~~Merits~~/.

→ Here stimulated absorption excite atoms from ground state E_1 to the highest E_4 level by incident radiation of frequency $\nu_{41} = \frac{E_4 - E_1}{h}$.

→ As the life time of the excited atom in the energy level is very short, they decay quickly to E_3 level which is the upper level of meta-stable state.

→ So population inversion achieved in b/w E_3 and E_2 level. (the atoms present for the time $\sim 10^{-3}$ sec

→ If the light radiation of frequency ν_{32} is incident on the active system it stimulates the radiation of same frequency.

→ Both the original incident radiation and and stimulated radiation are coherent.

Merits/Advantages of 4 energy level with respect to 3 energy level. (de-merit of 3 energy level)-

→ As the ground level is not the lower level for laser transition so there is no need to pump more than one half of the population from the ground level, so less energy is required for pumping

→ As E_2 is the lower ~~laser~~ laser level so it is easy to maintain the population inversion in b/w E_3 and E_2.

→ So, the laser transition is continuous emission in this case.

Pumping-

It is a method of achieving population inversion externally.

There are various types of pumping-

(i) Optical pumping (External source is a lamp, ~~sou~~ or led)

(ii) Electric field pumping (~~Ruby~~ He-Ne laser is an Ex).

(iii) Electron beam pumping

(iv) Chemical pumping.

Components of Laser-

(i) Energy source-

(ii) Optical feedback.

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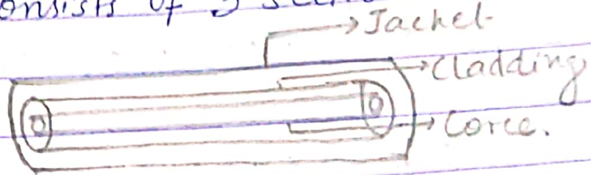
Advantages of Optical Fibre Lines over conventional line (wire) -

- Long distance signal transmission.
- Large band width, light weight and small diam.
- Easy installation and easy transportation
- Non conductivity.
- Dielectric in nature.
- Used for security concern.
- Cheap.

Structure -

Optical fibre mainly consists of 3 sections. -



(i) Core
(ii) Cladding
(iii) Outer Core / Jacket

(i)

It is the inner most section and is made up of glass or plastic. Its diam. is about 5μm to 100μm. Remarkable property of conducting an optical beam.

(ii)

Core is surrounded by cladding which is made up of plastic or glass and its diam. is about 125 μm. It has the diff. optical property than that of the core. Such that the refractive index of core is greater than the refractive index of the cladding

(iii)

It is the outer most section made up of plastic, polymer or some suitable material and mainly used.

for the protection against moisture, crushing or any type of environmental hazards and its diamr is about 250 μm.

Classification Of Optical Fibre-

There are 2 methods of classification of optical fibres-

(i) One method is based on the variation of refractive index of the core.

(a) Step index fibre.

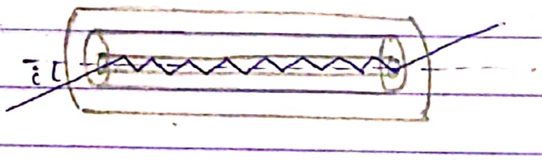
(b) Graded index fibre.

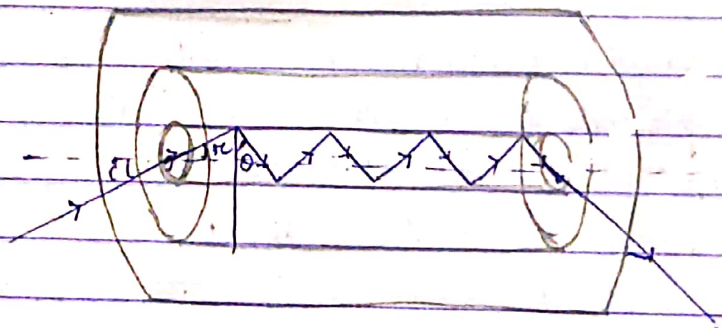
(ii) Other method is based on the core diam. or mode of transmission of light. Those are-

(a) Single mode fibre.

(b) Multi mode fibre.

Principle Of Optical Fibre-





i - Angle of incidence at the core.

r - Angle of refraction with axis

θ - Angle of incidence at core and cladding interface.

The total internal reflection is the main principle of optical fibre communication. The light signal entering at one end of fibre has to travel through the entire length and emerge with other end without much loss.

Derivation for Numerical apperature and acceptance angle -

Condition for propagation of light signal through optical fibre -

(i) Core must have higher refractive index than that of cladding.

$$\mu_1 > \mu_2$$

μ_1 - R.I of core
μ_2 - R.I of cladding

(ii) Angle of incidence at cladding should be more than that of the critical angle.

$$\theta > \theta_c$$

$$\text{or } \theta \geq \theta_c$$

$$\sin\theta \geq \sin\theta_c \quad \text{--- (1)}$$

$$\sin\theta_c = \frac{\mu_2}{\mu_1} \quad \text{--- (2)}$$

From fig., $\theta = 90 - r$.

$$\sin\theta = \sin(90 - r) = \cos r \quad \text{--- (3)}$$

from eqn (1), (2) and (3).

$$\cos r \geq \frac{\mu_2}{\mu_1} \quad \text{--- (4)}$$

From Snell's law.

$$\frac{\sin i}{\sin r} = \mu_1.$$

$$\sin r = \frac{\sin i}{\mu_1}$$

$$\cos r = \sqrt{1 - \sin^2 r}$$

$$\Rightarrow \cos r = \sqrt{1 - \frac{\sin^2 i}{\mu_1^2}} \quad \text{--- (5)}$$

Equating eq^n (4) and (5)

$$\sqrt{1 - \frac{\sin^2 i}{\mu_1^2}} \geq \frac{\mu_2}{\mu_1}$$

$$1 - \frac{\sin^2 i}{\mu_1^2} \geq \frac{\mu_2^2}{\mu_1^2}$$

$$\Rightarrow \mu_1^2 - \sin^2 i \geq \mu_2^2$$

$$\Rightarrow \mu_1^2 - \mu_2^2 \geq \sin^2 i$$

$$\Rightarrow \sin i \leq \sqrt{\mu_1^2 - \mu_2^2}$$

Take the maximum value of i and let it be i_m.

$$\boxed{\sin i_m = \sqrt{\mu_1^2 - \mu_2^2}}$$

This is the numerical apperature

$$\sin i_m = \sqrt{(\mu_1 - \mu_2)(\mu_1 + \mu_2)}$$

$$\sin i_m = \sqrt{2\mu_1 \Delta\mu}$$

Limiting case.

Upper limit $i_m = 90°$

$$1 = \sqrt{\mu_1^2 - \mu_2^2}$$

$$\mu_1^2 = 1 + \mu_2^2$$

This is not a practically physible optical fibre through which the communication can take place.

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In all the practical cases,

$$\mu_1^2 < (1+\mu_2^2)$$

Lower limit: $i_m = 0$.

$\Rightarrow \mu_1 = \mu_2$.

Acceptance Angle -

It is the twice of the critical angle ($\neq \theta_c$) and the critical angle is the max. value of the incidence angle (i)

$i_c = 2 i_m$ → Acceptance angle.

Q1: The refractive index of the core and cladding for a step index fibre are 1.52 and 1.41 resp. Calculate the numerical apperature of fibre.

Q2. Advantages of Optical Fibre Communication System -

FOCS - Fibre Optics Communication System

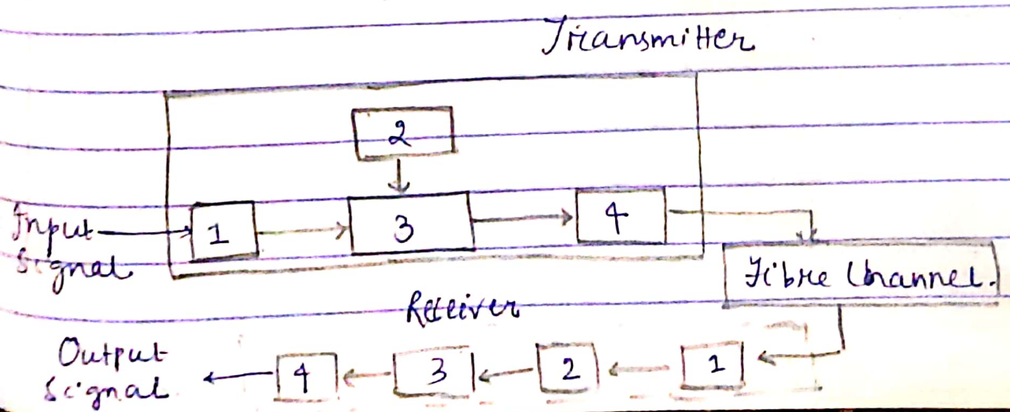
FOCL - Fibre Optics Communication Link.

↳ This mainly consists of three section.

(i) Transmitter.

(ii) Optical fibre channel

(iii) Receiver.



Transmitter -

1 - Coder

2 - Carrier Source

3 - Intensity modulator

4 - Input Channel Coupler

Receiver -

1 - Output Channel Coupler

2 - Detector

3 - Signal Processor.

4 - Decoder.