Applied Optics
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Lecture 58
Introduction to Lasers - I

Hello everyone. Welcome to the class, today we will start the last topic of Module 12 which is introduction to lasers.

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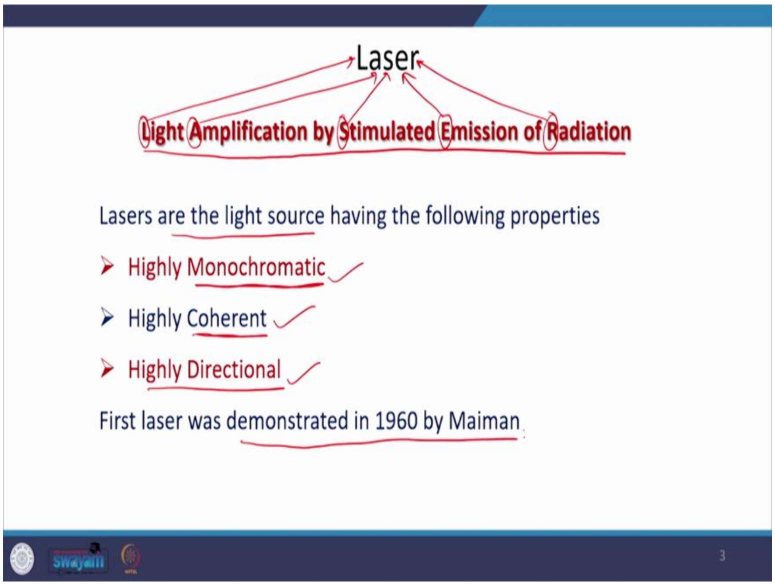

Now, the laser word is an acronyms for a big sentence which is Light Amplification by Stimulated Emission of Radiation. Now, if you pick the first character of each word, then it will form laser you see that L is coming from here, A is coming from here, S is coming from here, E is coming from here and R from here.

The light is being amplified through a process called stimulated emission of radiation. And in this process whatever output we receive we call it laser. Laser are the light source which have certain properties and these properties are that they are highly monochromatic, they are highly coherent and they are highly directional.

Monochromatic means, the bandwidth of a laser is very small, ideally it should be one wavelength or one frequency but this is not possible in reality and therefore, all the lasers has certain bandwidth. And therefore, the light which is emitted by a laser it has least bandwidth and therefore, we call it almost monochromatic light.

The second point is that laser light is highly coherent, which we have already studied the word we know what coherent is, the light emitted by laser, they maintain the constant phase relationship. And this is why we call them coherent light and they are highly directional they do not get diverge too early they propagate collimated through a long distance.

And the first laser which is called ruby laser was demonstrated in 1960 by Theodore Maiman. And this, demonstration revolutionize the field of optics. And then right after the invention of the laser, we saw that there appeared a huge application of this, but before that, we will go through the basics of laser.

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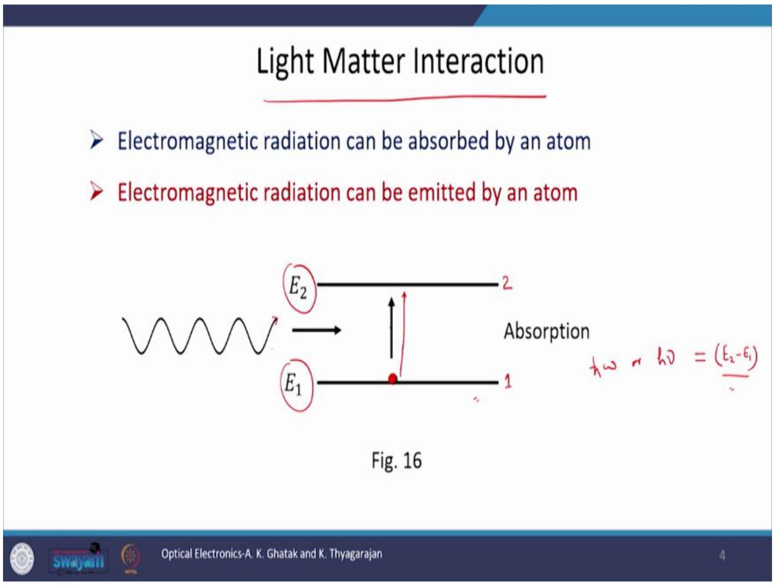

Now, here we will talk about Light Matter Interaction. At the route of light matter interaction, we have electromagnetic radiation absorption and electromagnetic radiation emission by an atom whenever we say atom, then the energy level diagram of an atom should appear in our mind which was initially proposed by Rutherford and then later corrected by Bohr. And then several other models appear.

Now, since atom is a discrete quantity and if it is isolated then it will have a discrete number of energy levels. Let us pick two energy levels out of it, and let us name them as energy level 1 and energy level 2, the corresponding energies are represented by E_1 and E_2 respectively. Now say there is an electron in the lower energy state.

Now, if we launch a photon of appropriate energy by the word appropriate energy, I mean is following the energy which is $\hbar\omega$ or $h\upsilon$, it must be equal to the energy difference between the two levels. If a photon of this energy is launched into this atom, then there is a finite probability that this electron from energy level 1 may go to energy level 2, may transits to energy level 2. And in this process, the incident photon is absorbed by the transiting electron, the atom and this process is called absorption.

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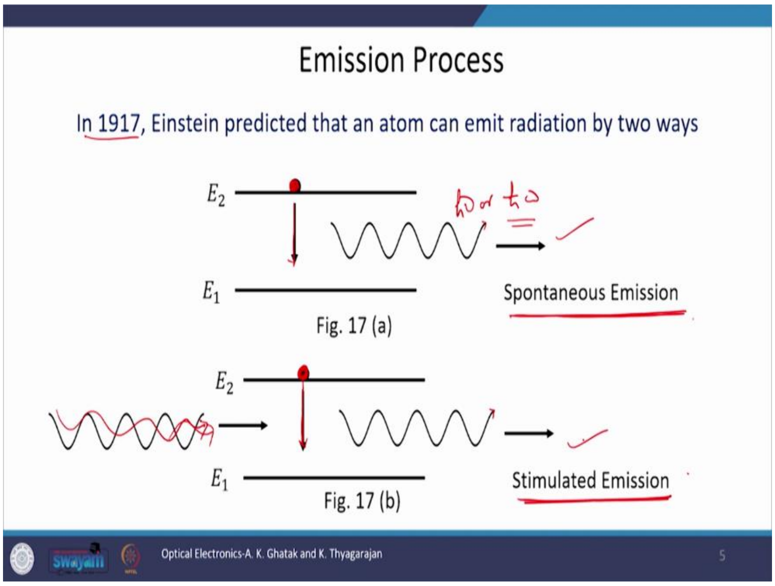

Similarly, if the electron is in the upper energy state, then after residing there for a while, it may go down to the ground state or the first state and during this process it emit a photon of energy $h\upsilon$ or $\hbar\omega$, this process is called emission. Now, in 1917, it was Einstein who predicted that an atom can emit radiation by two ways.

Although there was only one way of absorbing the photon or absorbing the radiation that we named as absorption, there are two ways of emission as proposed by Einstein and these two ways are called spontaneous emission and stimulated emission. In spontaneous emission the electron from the upper energy state make downward transition within emission of photon of appropriate energy.

Now, in this process, we see that as soon as the electron goes down, a photon get emitted and this happens spontaneously without the requirement of any external perturbation. And this is why the phenomena is called spontaneous emission. Second equivalent phenomena is stimulated emission here in the electron from the upper level it makes downward transition in presence of an external stimuli, which is photon here.

Now, in this case, suppose the electron is here in the higher energy state and if appropriate energy photon is launched, then the electron go to the lower energy state along with an emission of a photon of appropriate energy. Now, this emission happened in presence of an external stimuli or an external photon and therefore, this process is called stimulated emission. It requires an external field or external photon or external radiation. Now, this is the difference between the two here we do not require any external stimuli and here we require.

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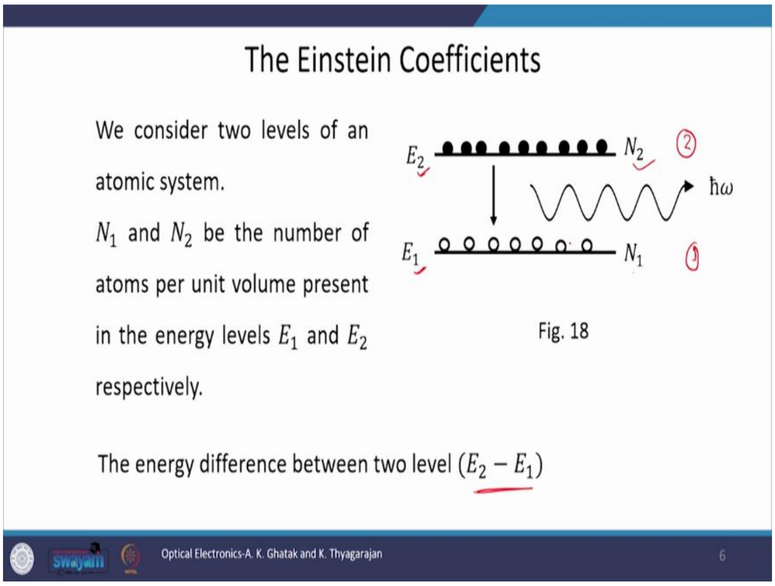

Now, consider two energy levels, that energy level 1 and energy level 2, the energies of these levels are designated by E_1 and E_2 respectively and the carrier densities that is number of electrons or number of atoms per unit volume present in energy levels E_1 and E_2 are respectively given by N_1 and N_2, as is clear from the figure the energy difference between the two level is $E_2 - E_1$, and there are certain distribution of charge carrier or electrons between these two energy levels.

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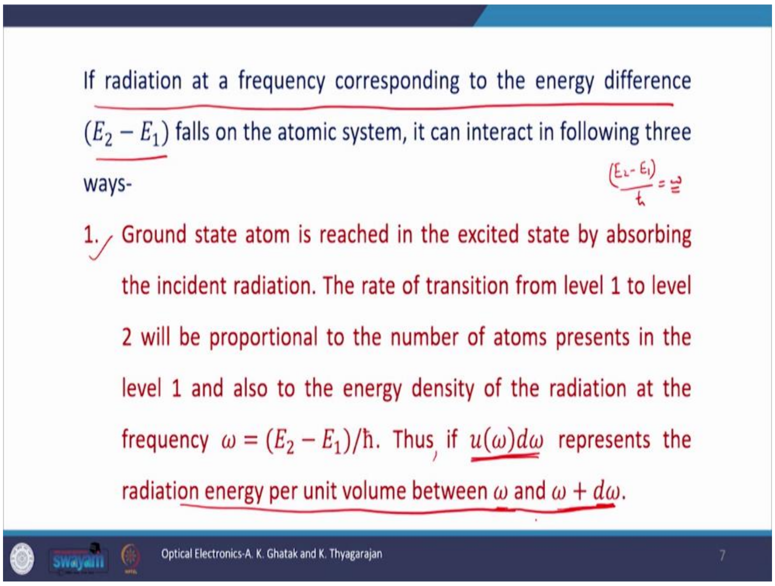

Now, if radiation at frequency corresponding to the energy difference $E_2 - E_1$ falls on the atomic system, then it can interact in the following three ways. In the first case, the ground state atom is reached in the excited state by absorbing the radiation and which we call absorption the rate of transition from level 1 to level 2.

It will depend upon the number of atoms present in the ground level or level 1 and it will also depend upon the energy density of the radiation at frequency ω and this ω is related to $E_2 - E_1$ through this relation, I repeat if we launched radiation on this two level system then the atoms from the ground state or the electrons from the ground state will absorb this radiation and move to the upper level.

Now, this upper level transition or this phenomena of absorption will depend upon the carrier density or the number of atoms present in the lower level and on the energy density of radiation at frequency ω. Thus, if $u(\omega)d\omega$ represents the energy density per unit volume between frequency ω and $\omega + d\omega$.

We are considering a width in the frequency because as I already said that the single frequency is not possible, there is always a width associated with each emission and absorption. Therefore, $u(\omega)d\omega$ represents the radiation per unit volume between frequencies ω and $\omega + d\omega$ in this bandwidth.

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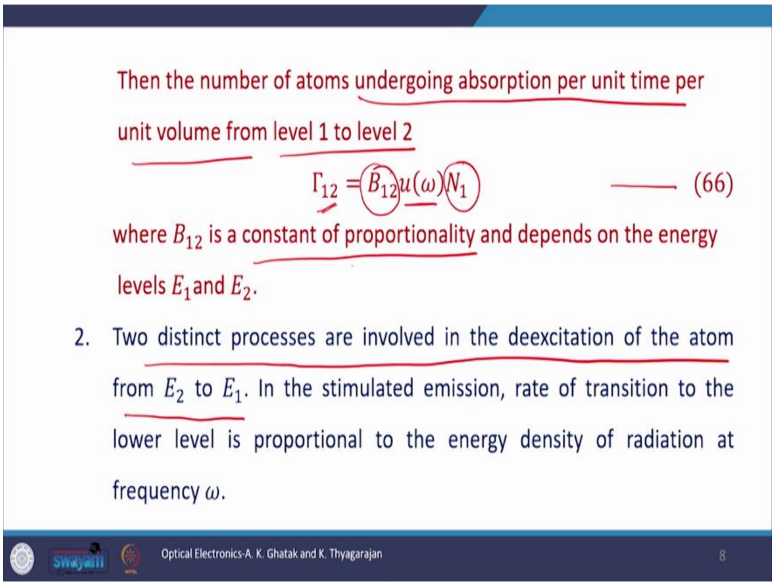

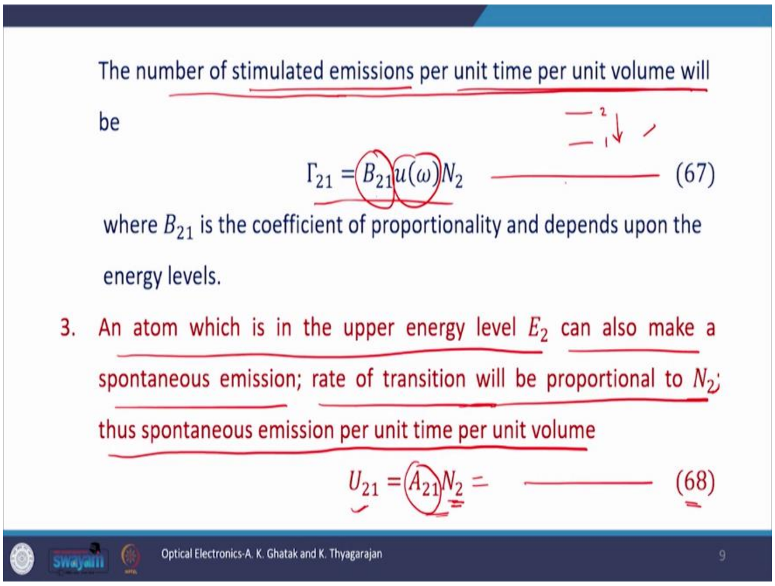

Now, with this the number of atoms undergoing absorption per unit time per unit volume from level 1 to level 2 is given by equation number 66 which says, Γ_{12} which is number of atoms undergoing absorptions per unit time per unit volume, it would be proportional to the energy density $u(\omega)$ and the carrier density in level 1, our density of atoms are a density of electrons in level 1.

And B_{12} is proportionality constant, it is constant of proportionality and it depends upon the energy levels E_1 and E_2. Now, the absorptions happens in presence of the external radiation now, what will happen to the atoms or electrons which are in the upper level in the level 2. They will make downward transition and which is called deexcitation. As we studied before, there are two process of deexcitation one is called the stimulated emission and the second is called spontaneous emission.

Now, two distinct processes are involved in the deexcitation of the atom from energy level E_2 to energy level E_1. In stimulated emission, the rate of transition to the lower level is proportional to the energy density of radiation at frequency ω and the number of atoms in energy level 2 or upper energy level. Therefore, the number of stimulated emission per unit time per unit volume would be given by equation number 67.

Now, I repeat, in the stimulated emission the rate of transition to the lower level is proportional to the energy density of radiation at frequency ω as well as it is proportional to the number of carriers or carrier density in energy level 2 or upper energy level. And therefore, the number of stimulated emissions per unit time per unit volume will be given by equation number 67 where B_{21} which is again a proportionality coefficient it depends upon the energy level.

Observe the difference between the two B coefficients which we show in equation 66. It is B_{12} this designating transition from level 1 to level 2. And in equation 67 we have B_{21} which is representing transition from level 2 to level 1. Here we are talking about the stimulated emission and in the earlier equation we were talking about absorption.

Now, let us talk about spontaneous emission, an atom which is in the upper energy level E_2 can also make a spontaneous emission, rate of transition here in a spontaneous emission will be proportional to N_2. And thus the spontaneous emission per unit time per unit volume it would be given by equation number 68 which says that the number of atoms or the number of spontaneous emission per unit time per unit volume would be proportional to N_2. Now, since spontaneous emission process does not require presence of external radiation.

And therefore, in equation 68 we see that we do not have any expression of u here as we saw this in equation number 67 and 66, contrary to these two expressions, we do not have u in equation number 68. We have only N_2 and proportionality constant which is A_{21} which is a constant of spontaneous emission.

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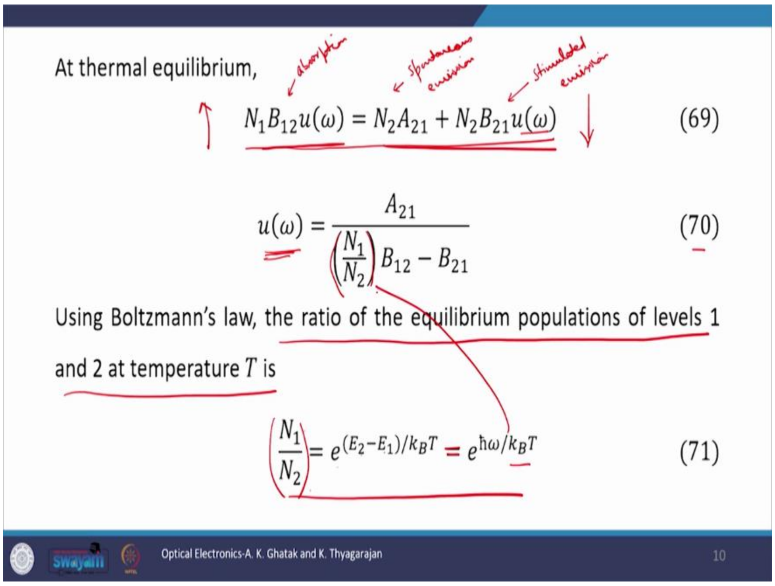

Now, at thermal equilibrium when the number of upward transition is equal to number of downward transition, the 1 to 2 transition means this upward transition would be equal to 2 to 1 transition, this is the downward transition. This is absorption and here we are having this is spontaneous emission and this is for stimulated emission.

Now, let us solve this equation 69 for u and after bit of algebra, we get an expression of $u$which is energy density. And we see here that in the denominator we have N_1/N_2 term, but, we know from the Boltzmann law, the ratio of the equilibrium populations of levels 1 and 2 at temperature T is given by this expression, which says $N_1/N_2 = e^{(E_2-E_1)/k_BT}$.

And since $E_2 - E_1 = \hbar\omega$, this expression would be equal to $e^{\hbar\omega/k_BT}$. Therefore, N_1/N_2 in equation 70 can be replaced by $e^{\hbar\omega/k_BT}$.

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where k_B ($1.38 \times 10^{-23}\ J/K$) is the Boltzmann's constant. Hence

$$u(\omega) = \frac{A_{21}}{B_{12}e^{\hbar\omega/k_BT} - B_{21}} \qquad (72)$$

Now according to Planck's law, the radiation energy density per unit frequency interval is given by

$$u(\omega) = \frac{\hbar\omega^3 n_0^3}{\pi^2 c^3}\frac{1}{e^{\hbar\omega/k_BT} - 1} \qquad (73)$$

where c is the velocity of light in free space and n_0 is the refractive index of the medium.

Comparing eqn. (72) and (73)

$$B_{12} = B_{21} = B \qquad (74)$$

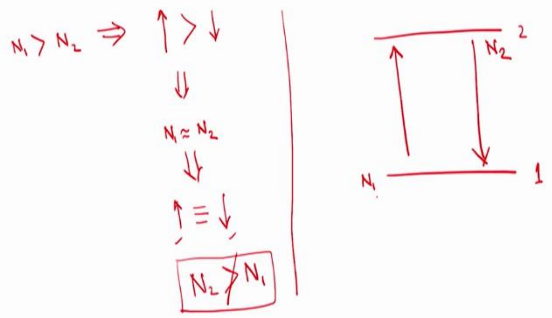
$$\frac{A_{21}}{B_{21}} = \frac{\hbar\omega^3 n_0^3}{\pi^2 c^3} \qquad (75)$$

The coefficients A and B are known as Einstein A and B coefficients.

At thermal equilibrium, the ratio of the number of spontaneous to stimulated emissions is given by

$$R = \frac{A_{21}N_2}{B_{21}N_2 u(\omega)} = e^{\hbar\omega/k_BT} - 1 \gg 1 \qquad (76)$$

At thermal equilibrium T, for large frequencies $\omega \gg k_BT/\hbar$, spontaneous emission dominates. Hence, at optical frequencies, the light from usual light source is incoherent (say $T = 1000\ K$).



Where k_B is nothing but Boltzmann constant, the famous Boltzmann constant and the modified expression for energy density u hence given by equation number 72, but, we also have a Plancks formulation for the energy density and according to Planck's law, the radiation energy density per unit frequency interval is given by equation number 73.

Now, we will compare equation number 72 and 73 because, on the left hand side we have the same term $u(\omega)$, in this expression c is speed of light and in vacuum or in free space and n_0 is the refractive index of the medium. Now, if you compare equation number 72 and 73, then we see that $B_{12} = B_{21}$, and let us say that this is equal to B only.

Now, if you assume that $B_{12} = B_{21}$ and we can take this out of this bracket and then we will have this term which would be equal to $\hbar\omega^3 n_0^3/\pi^2 c^3$ which is term which appears in equation number 73 here. Now, the coefficients A and B are known as Einstein's A and B coefficients here. I have removed the subscripts 21 and 12 from A and B, there is A and B are known as Eisenstein A and B coefficients.

Now, at thermal equilibrium the ratio of the number of spontaneous to stimulated emission is given by this expression and here what you see is that $A_{21}N_2$ is the spontaneous emission and $B_{21}N_2u(\omega)$ is a stimulated emission. The spontaneous to stimulated emission numbers is equal to $e^{\hbar\omega/k_BT} - 1$. Because A_{21}/B_{21} is equal to this number and N_2 from this expression will go away and we will be left with $e^{\hbar\omega/k_BT} - 1$.

Now, if in this expression in equation 68. Now, if you add thermal equilibrium T for large frequencies, large frequencies means when ω is much-much larger than $k_BT/\hbar$, then you see that when ω is much much larger than $k_BT/\hbar$ at thermal equilibrium, the spontaneous emission dominates because this term you see that this is exponential and if ω is much-much larger than $k_BT/\hbar$, then this term would be much much larger than 1.

Therefore, the numerator would be much-much larger than the denominator and numerator here represents the number of spontaneous transition while the denominator represents the number of stimulated transitions. At thermal equilibrium, for visible light where ω is much-much larger than $k_BT/\hbar$ spontaneous emission dominates and hence at optical frequency light from usual light source is therefore, incoherent.

Because spontaneous emission is dominant therefore, at ambient temperature or at thermal equilibrium said at T is equal to 1000 Kelvin, we always see spontaneous emission, we always see an incoherent light source. Now, we know that in two level system, the rate of upward transition, it depends upon the carrier density in lower energy state while the rate of downward transition it depends upon the carrier density in upper energy state.

Now, if $N_1 > N_2$ then the upward transition rate would be larger than the downward transition rate or upward transition rate it would be larger than the downward transition rate, but with this a situation will arrive because upward transition rate is larger. Therefore, the number of electrons which are getting transited to the upper energy state, it would be more, the number of electron which is getting transited to the energy level 2 per unit time would be larger therefore.

And therefore, a situation will come where this will lead to a situation where N_1 would be almost equal N_2, in this situation, there would be 50-50 distributions of electrons in the two energy levels. Now, in this case, since N_1 is almost equal to N_2, the rate of upward transition would also be equal to the rate of downward transition, and therefore, this will lead to rate of upward transition equal to rate of downward transition.

Now, since the upward transition rate is equal to downward transition, system is now in equilibrium, by anyhow we cannot invert it or by anyhow we cannot make the upward transition rate smaller than the downward transition. And therefore, if initially N_1 is larger than N_2, we can never have N_2 larger than N_1, this will never happen.

Now, the situation where N_2 is larger than N_1 is called a population inversion, or inverted state. When N_2 is larger than N_1, then the number of downward transitions would be larger than number of upward transition and in this case, we will have some gain from the system, the number of absorbs photon would be smaller than the number of emitted photon, then effectively we will have some output from the 2 level system, but, we can see from the Einstein relation that in 2 level system the population inversion cannot happen.

Population inversion means the state in which N_2 is larger than N_1 or population density or carrier density in upper energy state is larger than the lower energy state. This can never be achieved in two level system. And therefore, we cannot realize laser in two level system. We will talk more about lasers. But let us stop here in this class. We will continue in the next class. And thank you for joining me.