Indian Institute of Technology Kanpur

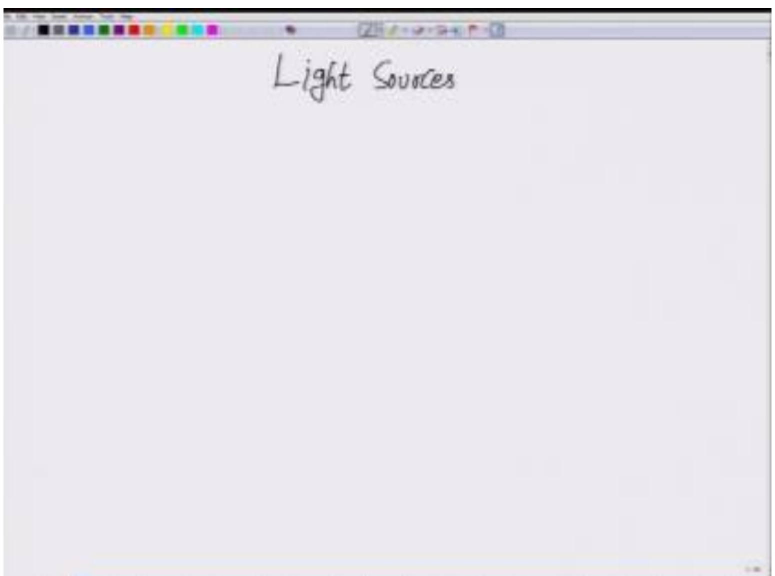
National Programme on Technology Enhanced Learning (NPTEL)

Course Title
Optical Communications

Week – VIII
Module-III
Light sources-I

by
Prof. Pradeep Kumar K
Dept. of Electrical Engineering
IIT Kanpur

(Refer Slide Time: 00:14)



Hello and welcome to the course on optical communications. In this module we will begin discussing light sources which are used for optical communications. In the first generation optical networks which worked around 800 nanometer not networks, first generation optical links which operated at 800 nanometer or 0.8 micrometer wavelength of light, the primary fiber type was the multimode fiber and the corresponding light source was a light emitting diode.

In second and third generation optical and so on after that, after that first generation months we moved away from LED as the optical source or the light source to a single mode optical or more or less a single mode semi-conductor laser diode as the optical source, and the fiber was also replaced from a multimode fiber into a single mode fiber. In fact, these two revolutions if you remember in the first class we talked about the revolutions that cause the optical network, you know optical network into just take off was the first one was the availability of a room temperature, laser diode, semi-conductor laser diodes.

And then with very, very narrow line widths that is very important to note and then you had a single mode fiber whose losses were brought down below the barrier of 20db per kilometer. So you could know couple light from a laser diode which is coming out of the laser diode into a single mode optical fiber and this was the reason why long distance optical communications was finally able to take off.

Earlier, first generation optical links were very limited in terms of the propagation distance because you were using multimode fibers as well as the light source was an LED which was very broad, the line width of a LED is quite large especially compared to that of the line width of a laser. In addition to this, lasers bring in additional aspects which enable them or which make them very attractive for long distance communications.

Chief among them is the coherence that the laser brings with it. Lasers as oppose to LEDs are as oppose to a tube light actually have a very high degree of coherence which means that one can, you know propagate this light over a long distance without it losing its coherence. This is not the module where we discuss coherence we will leave that discussion to some other module, but it is just important to note that lasers are so much superior compared to the light emitting diodes to enable the long distance communications that they have become the main choice or probably the only choice for light source in long distance optical communications.

So we are going to discuss semi-conductor laser diodes, but before that we will discuss laser in general okay. So remember this our optical fibers today all are single mode optical fibers except for some specialty applications where you are looking for multimode fibers. The sources almost always is a semi-conductor laser diode which can be operated in a room temperature and comes with a very small form factor.

The LEDs are almost never used as sources for long distance especially long distance high bit rate optical communications okay. With that kind of background we will begin with study of light sources, we will begin with study of lasers and we will first look at the concepts that are general to all type of lasers okay. Lasers, the idea was started around 1950s now mid 1950s and then the first laser was demonstrated in the year around 1960, 1962 I am not very sure what exactly is the year.

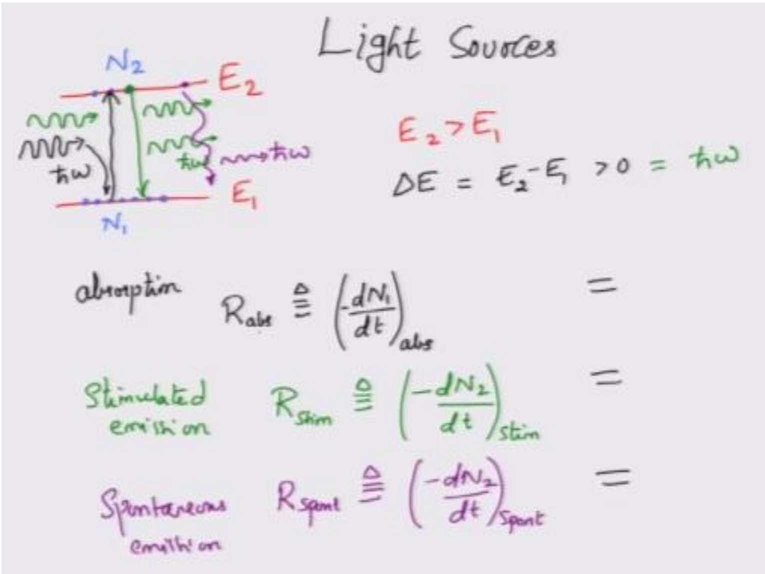
But that was the starting of the 60s and those early lasers were the huge lasers, you know the ruby laser or the neon, helium neon lasers they were all pretty large compared to the laser, carbon dioxide laser for example. So these were all pretty large compared to a semi-conductor laser which you can actually see that it would be of this size okay. And the advantage of semi-conductor laser diode is you can operate this at the room temperature, there is no specific heating or sorry, cooling requirement for this laser.

You can incorporate a simple cooling technique not like the running water that is required in some of the high power and different lasers that you would see in a lab. And also these semi-conductor lasers can operate with very high degree of coherence and they can also be part of long distance communication simply because it is very easy to modulate the laser by itself or use the laser light to module an external modulator.

So semi-conductor lasers have all these advantages and then we will look into semi-conductor lasers but before that we want to understand what a laser is you know what makes up a laser how is a carbon dioxide laser different from a semi conductor laser in principle they are essential the same the mechanisms by which the lass are may be are bumped especially are different but the general principles if you go to the quantum mechanical principles they are almost essentially the same.

So we are going to look at general concepts of laser first and then gradually move towards the semiconductor laser diodes in the upcoming modules, so having said that let me began by considering.

(Refer Slide Time: 05:41)



A basic concept that comes up in every laser discussion note that we have yet talked what a laser is we will talk about that one later you assume that we have material okay so this material has multiple energy levels okay these energy levels are quite spread in terms of the energy for simplicity consider this material to have exactly two levels okay these two levels have the energies E_1 and E_2 with E_2 being lager than E_1 so the way we have placed the one that is closer at the down words is the lower energy level the one that is there is the higher energy level.

Of course at these energy levels these material is not empty it is packed with some atoms okay so it is packed with some atoms the number of atoms or the atomic density here in energy level 1 can be written as N_1 this is would be the concentration or the density in the level one having an energy E_1 similarly you will also have some atoms populated okay in the level energy to how exactly did these atoms come to energy two we will talk about in a while but assume that there are some which are found here in the level two having an energy E_2 and the density of those can been written as N_2 okay.

Now there are three processes that we are going to discuss okay with the help of this simple picture we are going to discuss three process the first process happens when there is a photon incident do not ask me how the photon got here but just take by word that a photon as somehow been incident okay more over the photon as a frequency ω, ω radians per second such that it is energy is given by $\hbar$ x ω so let me write here because it just you cannot write it here so you have $\hbar$ ω as the energy of this particular photon okay.

The difference between the energy levels E_2 and E_1 let us designate it has δE, δE denotes the difference between the energy levels E_2 and E_1 and this quantity is obviously a positive quantity because E_2 I larger than E_1 what happens as this photon enters the material what happens is that one of these atoms in the ground level can actually absorb this photon and then make a transition to the other level so it can go from building on the ground floor to the building on the first floor if you assume that ground floor is level is 1 and first floor is level 2.

So if you make if you incident a photon you are kind of pushing the atom to go and make a transmission from level one to level two you are not just interested in having one atom go from level one top level two you are interested in knowing how many atoms at a time or what is rate of this transition from level 1 to level 2 that is happening okay this process can be called absorption process okay it is suppose to be stimulated absorption that is there as to be no photon in order to cause atoms to go from lower energy level to higher levels okay.

They go from lower energy level to higher energy level which means that they have to absorb some energy and this energy that is being absorbed must be supplied by the photons okay so you have absorption the rate of absorption let us denote this as R_{abs} and this is by definition the rate at which the atoms in population in level 1 are decreasing so there is a minus dN_1/dt and let us write this absorption okay so it is clearly obviously right if the atoms are leveling the energy level N_1 then the rate at which N_1 is changing will become negative so you have a minus dN_1/dt so this is the absorption thing.

Now a second process that happens is what is called as the stimulated emission in the stimulated emission what happens is that atoms that is there on the top okay at the energy level two will drop down to energy level one okay under the action of an photon but the surprising thing is that it will also emit a photon, okay. So you get two photons for 1 photon instead, so some sort of a small amplification is happening but will come to that one later but what is important is that when atoms go from energy level E2 to energy level E1 they do so by releasing an extra energy in the form of a photon.

This photon will also carry an energy of h-bar ω okay, now the difference in the energy is ΔE so this must actually be equal to the energy of the photon either being absorbed or being created okay, now you might ask a question what happens if my input photon actually has a higher energy than the difference ΔE, what happens is that this photon will be absorbed the atom will move from level 1 to level 2, okay.

But while moving from level 1 to level 2 it will consume an energy of ΔE but this is the consumed energy ΔE there is a small energy that is still left unused this energy will be converted into a kinetic energy, so the atoms will just move a slightly to the other distance and then basically settle down after losing all the energy there okay, what happens if the energy is actually below the required energy?

Then the very hardly a transition happening okay, so you require the energy to be greater than or you know equal to or greater than for transition to happen it does not actually mean that there would not be transition but that transition is not exactly covered by this particular process which we are talking about we have to go to the quantum mechanics to look at what is the probability of such a transition happening when the energy is less, okay.

For our discussion in this module and in the next module we will assume that the energies are exactly matching so that the incoming photon energy is exactly equal to the energy level difference and once the photon comes or for once the atom comes from level 2 to level 1 the energy will be exactly equal to the energy of the photon h-bar ω, okay. This is absorption process, now we have also talked about the stimulated emission process.

So let us call this as stimulated emission okay because someone else has stimulated it right, in this stimulated emission which we can write this as R_{stim} and define it as the rate at which the atoms in second level are decreasing the density is decreasing in second level and subscript that with STIM, okay. Finally you have another phenomenon which is called as spontaneous emission okay.

With spontaneous emission what happens is that an atom in N2 can spontaneously D and no can spontaneously got to the level 1 it will also release a photon because any time when an atom move from higher energy to the lower energy it has to do so by emitting the photon in this case, okay. It does release a photon which will have the sesame energy h-bar ω but only thing is that this process of you know going from E2 to E1 without any external input.

Without any photon being stimulating this process okay will result in a photon whose direction will be completely different random with the and has no relationship with the previously emitted photon or with any other photons that are present there it will have a random polarization it will also have a random direction, okay. So it is kind of completely random photon that you are going to get and over if in a material if these type of transitions dominate the stimulated emissions.

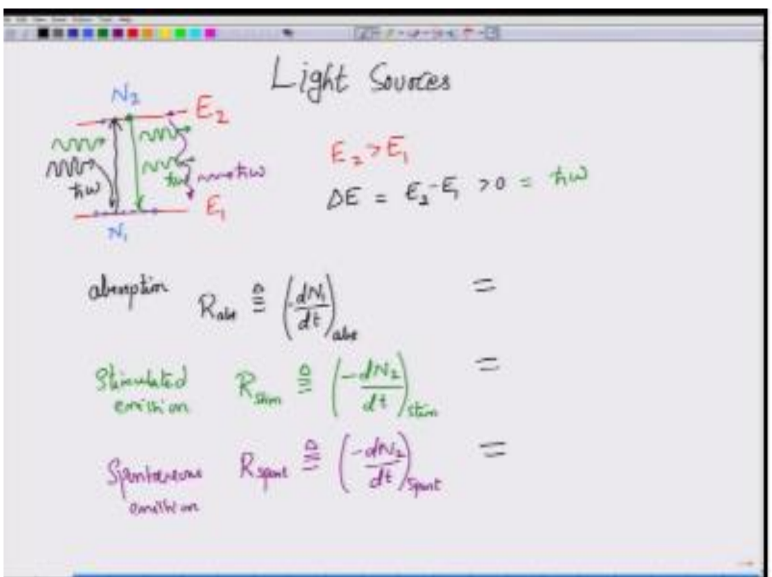
Then you see that on an average there would not be any optical power on optical oscillation or you would not get any laser action at all okay so this process which happens without regard of any external input is called as spontaneous emission so we can write down what happens with the spontaneous emission denote it as R_{spont} which is again by definition the rate of change of density in level 2.

But this density is different I mean this rate of change is different from the stimulated emission so this is spontaneous, okay. Now Einstein actually showed that or actually not showed that actually he postulated that these processes can be described by a couple of constants is like those constants are known as Einstein A and B constants and these where I mean this theory was proposed by Einstein before quantum mechanics was properly understood, okay.

Atleast the quantum mechanics of light was not yet understood we had a fairly good understanding of quantum mechanical properties of matter but we did not have a quantum mechanical theory for radiation that is light, okay. So this is that is why this sometimes called as phenomenal logical theory because it is a kind of it is a, there is a phenomenon and you are trying to fit a theory into that, okay expect that this theory was very nice you know it gave a very nice match with all the experiments and this is what we are going to discuss.

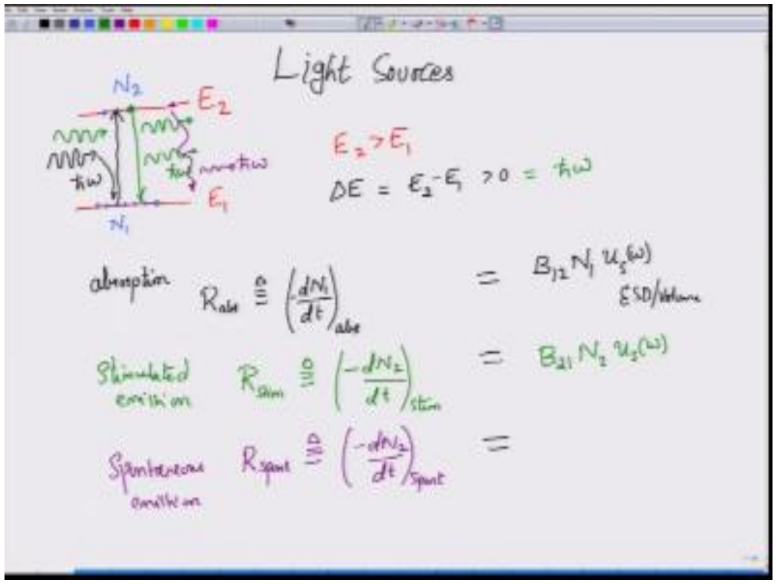
For our purposes we do not need quantum mechanics this is all that we are going to do. What Einstein said was that.

(Refer Slide Time: 15:39)



The way or the rate at which photons are being absorbed from level atoms in order to go to level 2 must really first of all depend on the number of atoms you have in the lower level, right. If you do not have any atom there is no one who is actually absorbing this light and moving up the ladder, so only when you have the number of atoms then you can talk about those atoms absorbing the photons.

(Refer Slide Time: 16:05)

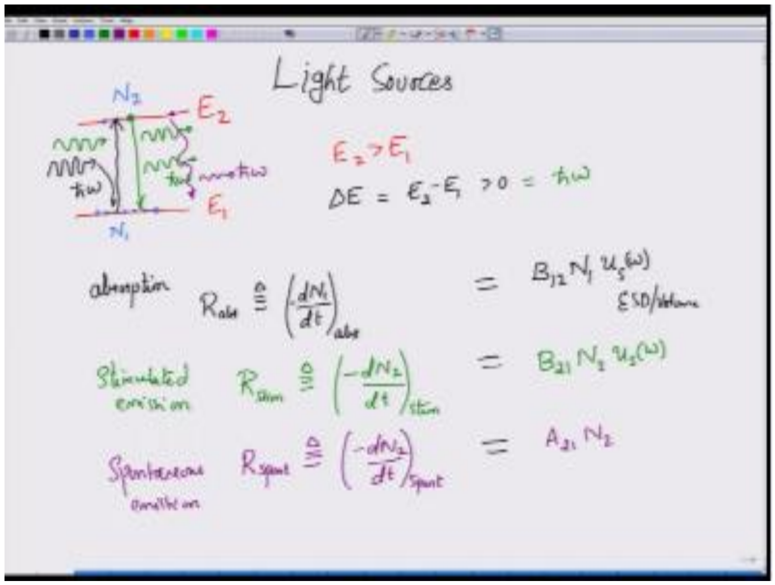


So first of all this must be a function of atoms that are there in that particular level, then because this requires an external energy in the form of photon or in the form of an external energy spectral density it must also be proportional to the external photon coming in, right so the photon flex or equivalently the energy spectral density which we will called it as Us(ω), Us(ω) is the energy spectral density per unit volume N1 is course the volumetric density so this one is the volumetric energy spectral density, energy spectral density per unit volume this one is centered at a frequency ω, okay.

Then he said that it is the product of these two times there is a constant which he called as the constant B and he put a subscript of B12 to indicate that this transition is going from level 1 to level to 2, okay. So this is what the absorption should look like that is what he said, he also said that stimulated emission should similarly be described by another constant B21 it of course depends on how many atoms you have in the level 2 which is N2 and finally what is your photon the energy spectral density of the radiation that is present.

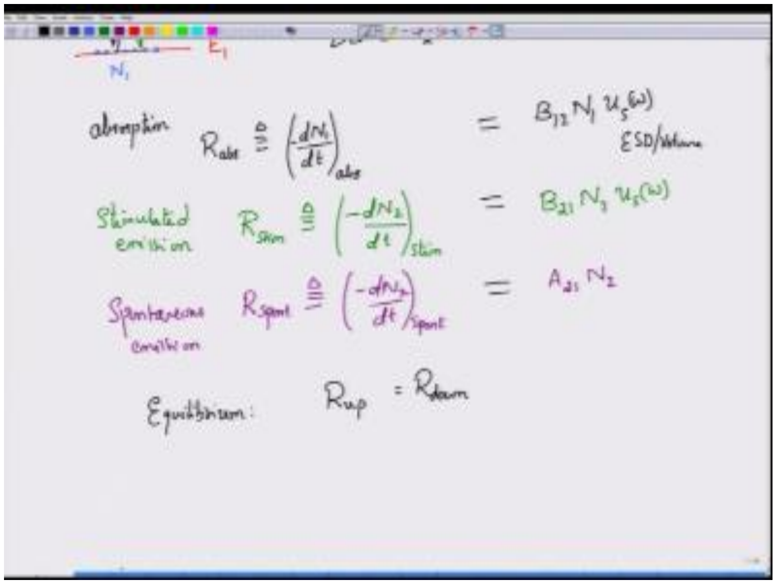
So this is the stimulated emission, for spontaneous emission there was no need to have any external photon agency it happens spontaneously.

(Refer Slide Time: 17:37)



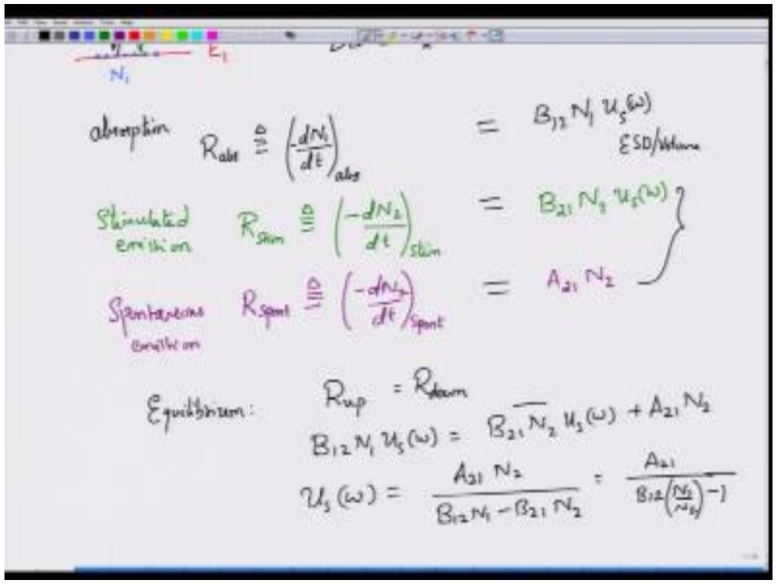
So for spontaneous emission he said that this can be another constant which he called as A21 because the transition is actually from 2 to 1 you have N2 there is no photon energy or energy spectral density of the radiation, okay. So these are the three process that are happening in laser continuously, okay.

(Refer Slide Time: 17:54)



Or in any material which is active, for equilibrium of course you want all the process to be balanced out, right so under thermal equilibrium, right the rate of upward transitions must be equal to rate of downward transmission. What are the transition that are there for upward transition only the stimulated absorption for the downward transitions you have a spontaneous emission as well as a stimulated emission. So you combine both and put them left hand and the right hand side.

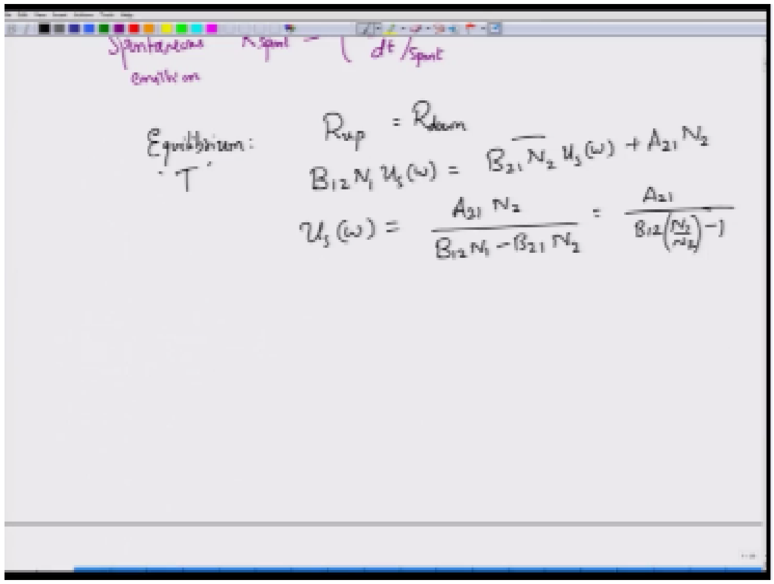
(Refer Slide Time: 18:32)



So you get upward transition as B12 N1Us(ω) that must equal to the downward transition which then becomes a sum of these twp, right. So you have B21 N2 Us(ω)+A21N2 from which we can actually rearrange the equation to obtain the energy spectral density of the radiation which is Us(ω) given by A21 N2 divided by, so you can pull this term to the left hand side and then divide by whole thing so you get B12N1-B21N2 this can be rewritten as A21/N2 I am taking it as constant so I get B12(N1/N2)-1, okay.

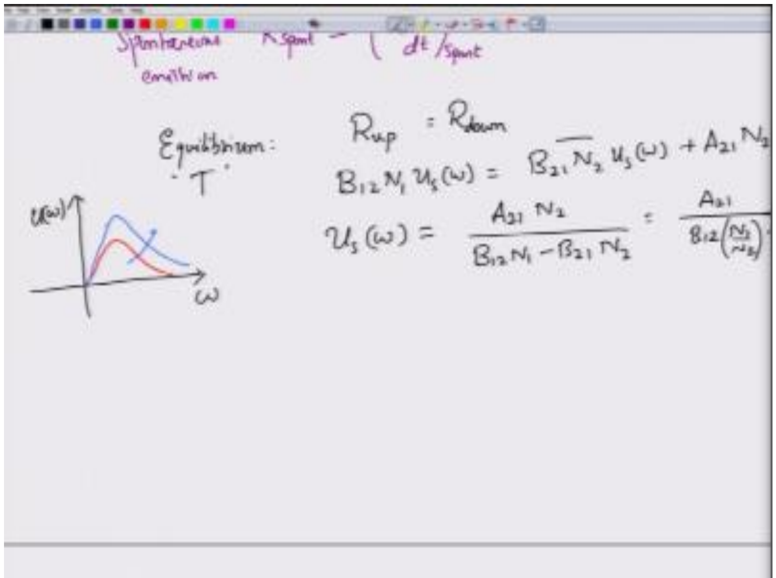
We of course do not know what is A and B relation and here is where Einstein masses stoke was h said that, this is process is actually happening in thermal equilibrium, right which means that the temperature is essentially constant.

(Refer Slide Time: 19:40)



And it is happening inside a material, okay we know the radiation coming of a material or emitted by a material you know under equilibrium has to follow Planks law, okay so Plank couple of years ago had developed the quantum mechanical theory and he said that, if you look the radiation confine the black body radiation that is confined in a lack body know which is under the thermo equally pram at t temperature t this radiation has a particular pattern okay.

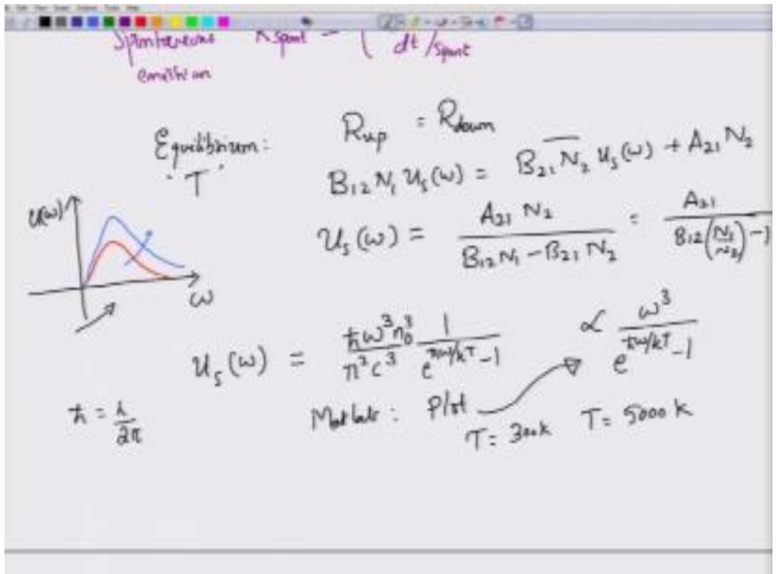
(Refer Slide Time: 20:15)



So you must have probably see this cures right so as a function of frequency and the radiation intensity normally you would say the radiation intensity for different temperature you would have see this type of curves right, so you would have seen this curve for red and then you would seen a blue cure blue is at a higher temperature than the red that something like you would have seen as the temperature would increased this is what I would have happen.

So you must have seen this ands you must have also seen something like you know on one hand you have riley gens limit and then you have another limit all those things might probably come to you, but we not concern with that what we are concern with is them.

(Refer Slide Time: 20:56)



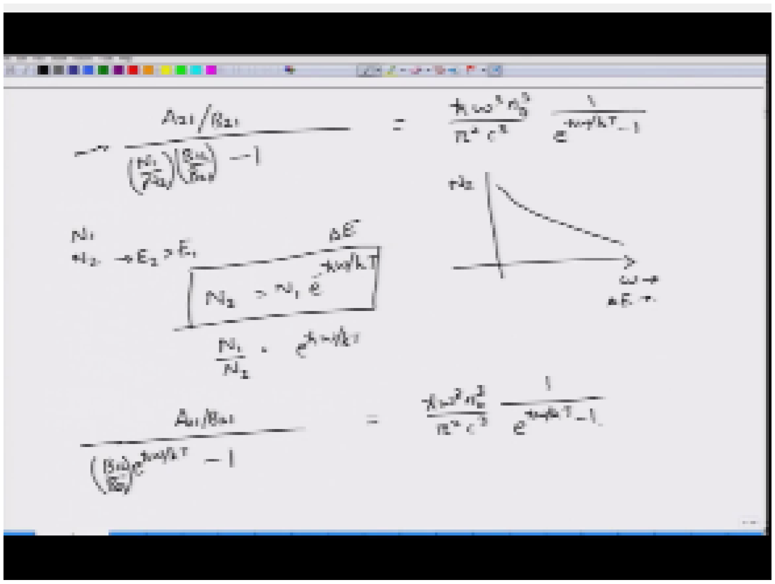
Way in which this particular radiation pattern looks like and what plank at shown was that this radiation can be written has h/ Ω^3/ π^2 c^3 and importantly you have 1/$e^{h/\Omega/kT}$ – 1 just a note here h/ is actually planks constant h/ 2π okay so this is h / and this should be equal to h/Ω there is also the refractive index that we need to consider which is n_0^3 okay if it is here of course n_0 will be = 1 and you can simply through it out.

So you have Us (Ω) the important point is apart from all this s key constant like h/π^2 c^3 n_0^3 the important thing is in terms of the frequency it is really Ω^3/ $e^{h/\Omega/kT}$ – 1 you know you can actually use mat lab to simply plot this particular curve okay you can plot this particular curve which is Ω^3/ $e^{h/\Omega/kT}$ for different temperature so you try it T = 300k you try T – 5000 k which is very close to the surface temperature of the sun right.

So you can try all this different temperatures and see for yourself as you change Ω that you will be able to reproduce this graphs okay so you would be able to reproduce this graphs okay now we have Us (Ω) here which we have written down we have a Us (Ω) from this equation so obliviously I can relate her two right so I will equate them so if I do that and I do that after here it should be b12 and I forgot to put b21 her so I can take b21 as a common factor so I get a21/B21 /

N1/N2 x B21/ B21 -1 this would be the radiation pattern in terms of a and b co efferent, this should then be equal to h/ Ω^3 n_0^3 / π^2 C^3 1/ $e^{h/\Omega/kt}$ -1.

(Refer Slide Time: 23:17)



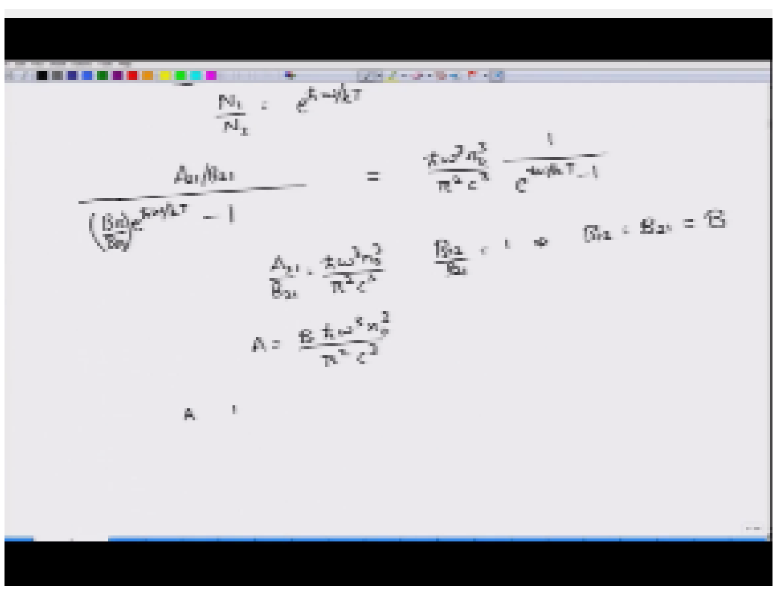
To proceed further I do not know a and b but I do know what is N1and N2 from thermal equal erbium okay, since N2 is occurring with an energy level E2 or N2 items have an energy level E2 which is greater than E1 it is natural if you do not actually do anything to the system it is natural and it is your intuition must tell you that much of the atoms must reside in the lower level right the density of atoms in the higher level which is at a level N2 must dk exponentially.

So it would dk exponentially and it does so in this particular passion okay it does so in this particular passion where h/π is basically λ e so for any energy level difference λE it could actually be the air molecules in the beach and the air molecules on the mountain if the mountain is adjacent to the beach the number of air molecules on the mountain would be smaller compare to the number of molecules in the on the beach and the difference is actually the potential energy difference which is required to rise the atoms from beach to the mountain okay.

That mg x h where is h is the height of the mountain and that would be λ a in that particular case so any the point here is that if you work to sketch N2 population density right as a function of frequency Ω you would see that at higher and higher frequency the energy basically drops off exponentially okay so has Ω increases equivalently λ E also increases correct so art higher and higher energy level difference if you start making the density becomes less and less okay exponentially going down and this relationship can now be used okay to write down the ratio of N1/N2.

So N1/N2= $e^{h\,\omega/kt}$ okay so I can substitute that relationship on to the top here in this equation, and write here as A_{21}/B_{21} / $e^{h\,\omega/\,kt}$ then you have B_{12}/B_{21}-1= $\hbar\omega^3$ N_0^3/ π^2 c^3, 1/$e^{\hbar\omega/kt}$-1, now all you have to do is to, pair by term by term, So when you pair them term by term.

(Refer Slide Time: 25:52)

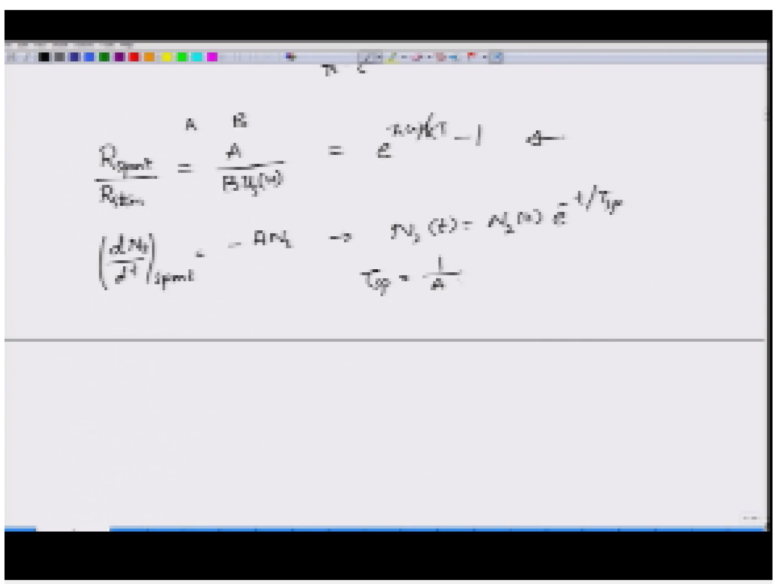


You will see that $A_{21,}$ first of all you will see that $B_{12}/B_{21=}$1, which implies that the upward transition co efficient $B_{12=}$ B_{21}(downward co efficient transition), and we will might as well call this as a constant B, okay so this would be the constant or the co efficient B, the ratio $A_{21/}B_{21}$=$\hbar$ ω $^3n_0^3$/ π^2 c^3 and there is no reason to keep saying A_{21} there is only one “A” here, because the transitions spontaneous emission is happening from level 2 to level 1.

So you can drop the subscript to 1, you can also drop the subscript 2 one for “B” and simply write that $A=B \hbar \omega^{3} n_0^3/\pi^2c^3$, is that okay? So what we have done is to obtain to coefficients, these are called as Einstein’s A and B co efficient, Einstein’s A coefficients refers to the spontaneous emission, Einstein’s B co efficient refers to the stimulated absorption and stimulated emission. Okay.

So this phenomenal logical theory is quite sufficient to understand how laser actually operates? But let us actually verify this statement that in laser without an external agency doing something there is no laser output, right? So what we mean is that if spontaneous emission is the major contribution to the radiation then obviously that because spontaneous emission is kind of random on an average you won’t get any net radiation at all. So it basically kind of tends to average out okay. For that to happen you have to calculate,

(Refer Slide Time: 27:41)



What is the ratio of spontaneous to stimulated emissions? What is the ratio of this spontaneous to stimulated emission? Well I know that spontaneous emission is proportional to a, right? stimulated emission is proportional to $B*u(\omega)$, the radiation density, of course there is an N_2, N_2

here which has been cancelled out on both sides, so you can substitute for Us(ω), and you know from the earlier equation and then you can substitute for the ratio A/B, from the earlier equation we have obtained.

And show that this is simply given by $e^{\hbar\omega/kt}$-1, okay. And before we do anything about this one lets also just this point solve the spontaneous emission equation to introduce one more variable, so I know that spontaneous emission dn_2/d_t spontaneous is given by $-AN_2$, I have put the minus sign from left hand side to the right hand side, and if you solve this you are going to get N_2 (t) $=N_2$ (0) $e^{-t/\tau}$ spontaneous where τ spontaneous is equal to 1/A. In the next module we will look at what happens to the remainder of this equations thank you.

<u>Acknowledgement</u>

Ministry of Human Resources & Development

Prof. Satyaki Roy

Co-ordinator, NPTEL, IIT Kanpur

NPTEL Team

Sanjay Pal

Ashish Singh

Badal Pradhan

Tapobrata Das

Ram Chandra

Dilip Tripathi

Manoj Shrivastava

Padam Shukla

Sanjay Mishra

Shubham Rawat

Shikha Gupta

K. K. Mishra

Aradhana Singh

Sweta

Ashutosh Gairola

Dilip Katiyar

Sharwan

Hari Ram

Bhadra Rao

Puneet Kumar Bajpai

Lalty Dutta

Ajay Kanaujia

Shivendra Kumar Tiwari

an IIT Kanpur Production