Implementation Aspects of Quantum Computing
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Lecture – 15
Laser Basics

Every week we are looking at certain basics and the Implementation of the Aspects of Quantum Computing. So, last week we looked at the NMR Implementation of quantum computing and we introduced you to some of the basics of quantum mechanics in the beginning and then went ahead to look in to the basics of NMR and the implementation via NMR.

In this week we will look at the optical aspects of quantum computing and in that regard as we know very well lasers play a very vital role. So, we will introduce you to lasers in this week so that you are up to date with the concepts of laser that will be necessary for quantum computing purposes. So, we start off with the basics on lasers and then we will look to the various implementation aspects involving lasers in this week. It may spill over to the following week also, but this is how we start.

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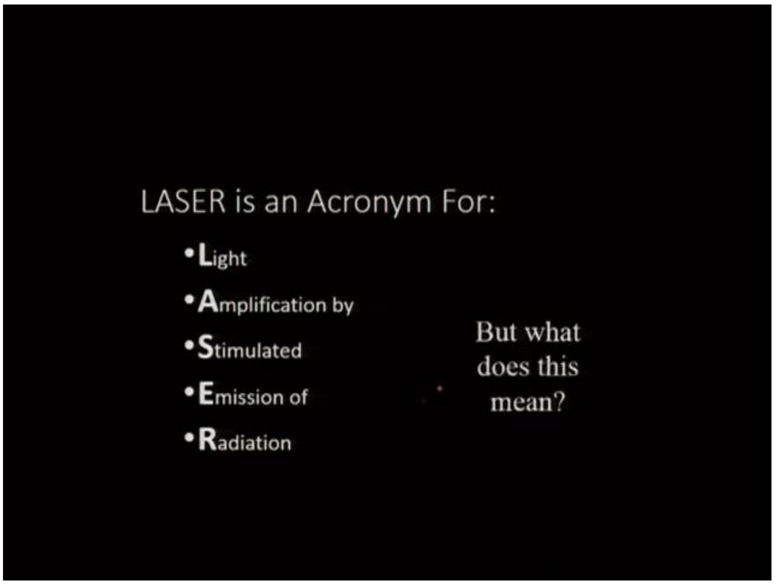

LASER as we know is in acronym Light Amplification by Stimulated Emission of Radiation, but it is much more than that.

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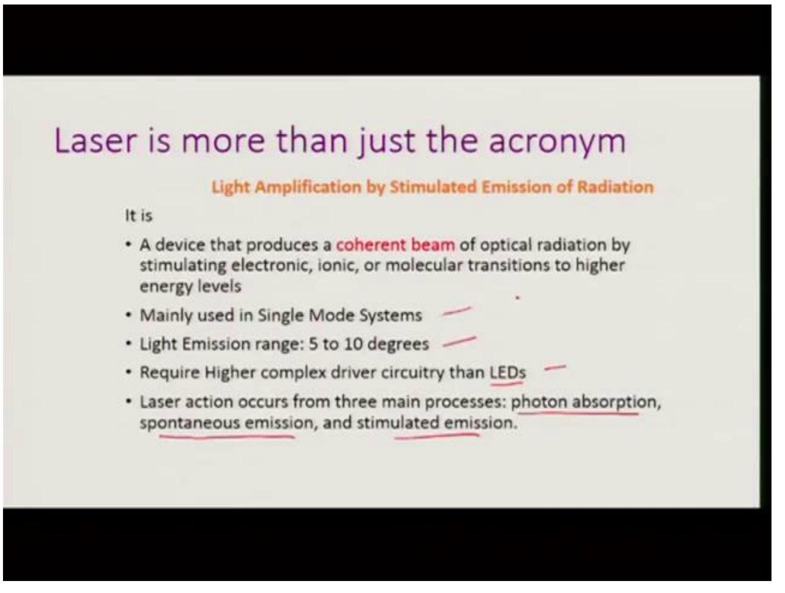

It is a device that produces coherent beam of optical radiation by stimulating electronic, ironic or molecular transition to higher energy levels. It is mainly used in Single Mode Systems. Light emission ranges from 5 to 10 degrees which means that it is highly directional and it does require a higher complex driving circuitry when we are looking at certain aspects compared to let us say Light Emitting Diodes these are action occurs from three main processes photon absorption, spontaneous emission and stimulated emission.

So, we look in to all these aspects in more detail just remember that whatever we say here none of them are to be avoided by in full detail as we go along and we will explain as how that happens.

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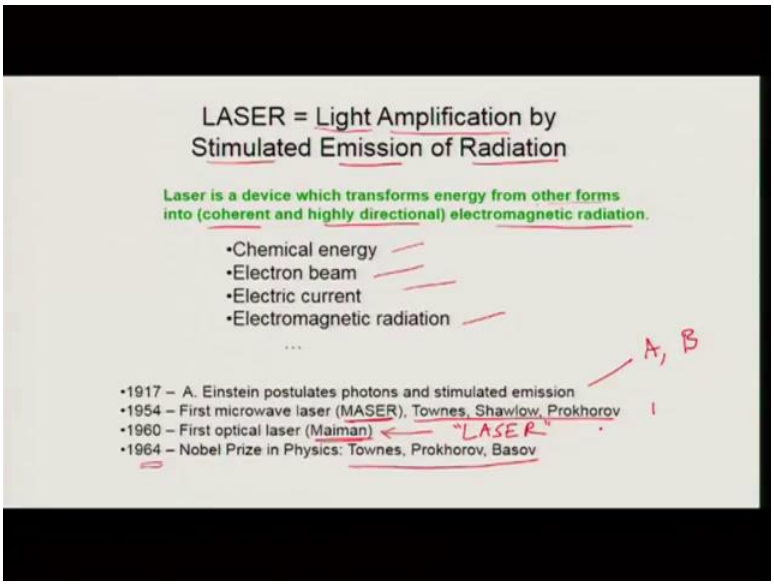

So, these principles of Light Amplification by stimulated emission of Radiation or laser can transform energy from other forms of energy into coherent and highly directional electromagnetic radiation and this other form of energy can be anything as diverse as Chemical Energy, Electron Beam, Electric Current, Electromagnetic Radiation and so on and so forth. And this is based mostly on the work of the postulates provided by Einstein who first gave the aspects of photons and stimulated emission by his famous A and B coefficients which we will go through here and the first microwave laser was demonstrated by Townes, Shawlow and Prokhorov in 1954 and it was called MASER.

And in 1960 the first optical maser as that time it was called Optical Maser it is which is eventually became laser was demonstrated though the Nobel Prize was given to Townes, Prokhorov, Basov for the demonstration of the principle of this entire process that is Maser in 1964 Maiman, eventually got the patent after a long battle on the laser and the laser patent is held by Maiman.

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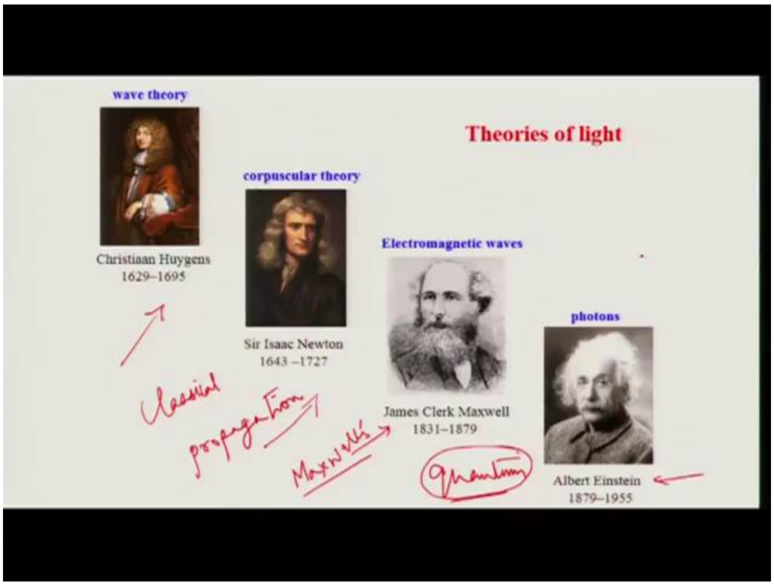

So, we know that there have been several Theories of Light starting from classical to quantum and we have already looked into the aspects in quantum mechanics in terms of the Planck's constant and Einstein whereas, the wave and the classical nature of light is better understood and propagation is better understood in terms of these either wave or particle later on this corpuscular was replace by particle and the propagation of electromagnetic radiation is understood in terms of Maxwell's equations.

So, all these aspects are quite well preserved in the concept of laser the interesting part is the quantum aspects also which is utilize as we get into the principle of the laser.

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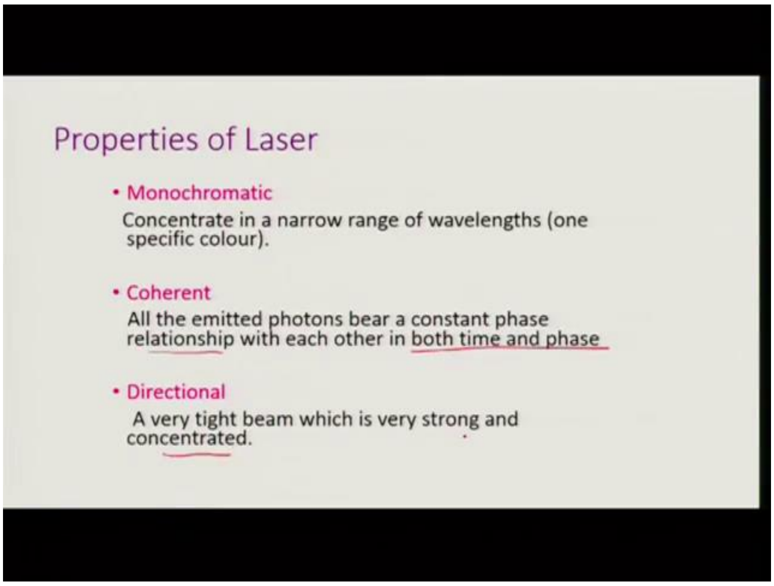

So, the properties of laser which are important are the concept of monochromaticity or Monochromatic which means that the lights is concentrated on a narrow range of wavelengths; ideally one specific color, but in real sense that is not exactly how it is, we will come to it. And the other important part is the coherence where all the emitted photons bear a constant phase relationship with each other in both time and phase. It is highly directional which means a very tight beam which is very strong and concentrated.

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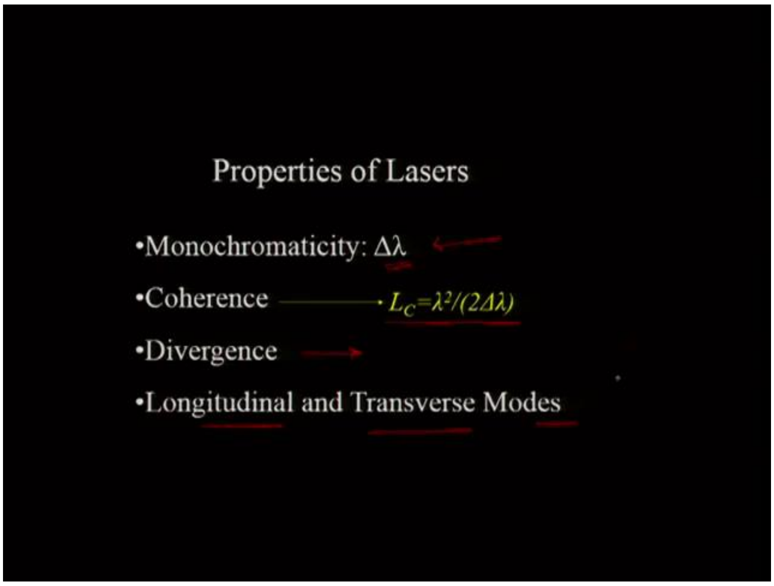

Let us look at it a little bit more technically; Monochromaticity is looked at in terms of the wavelength spread function which essentially tells how single wavelength or how much of a particular wavelength is been generated. Coherence is the range over which the phase has constant relationship it can be looked at the region of the length over which the coherence is maintained which means that the constant phase relationship will be maintained is given in terms of coherence Length Lc lambda squared over 2 delta lambda which is the monochromaticity.

Divergence is similarly another aspect which measures how much of the laser is spreading out with distance and there are both Longitudinal and Transverse Modes which are there in the laser which will discuss.

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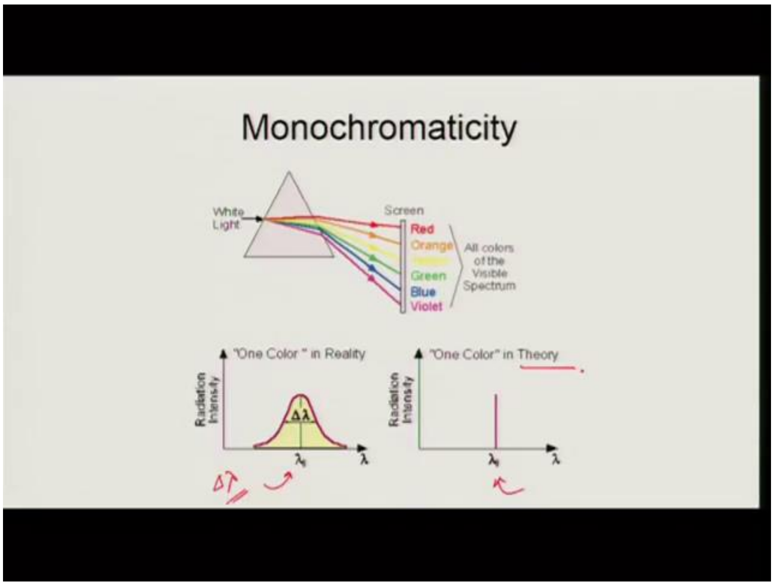

So, the monochromaticity as we mentioned is essentially the single possible wavelength that can be generated which in theory can be as simple as a stick or a single line; however, in reality it is always a spread which is delta lambda as we have discussed before. In fact, this has a Fourier relationship to time. In case you are going to have a laser which is going to measure events which are in time then we have to give up more and more on the single color feature or the monochromaticity of the laser in wavelength. Now we will discuss into that more as we get along this area.

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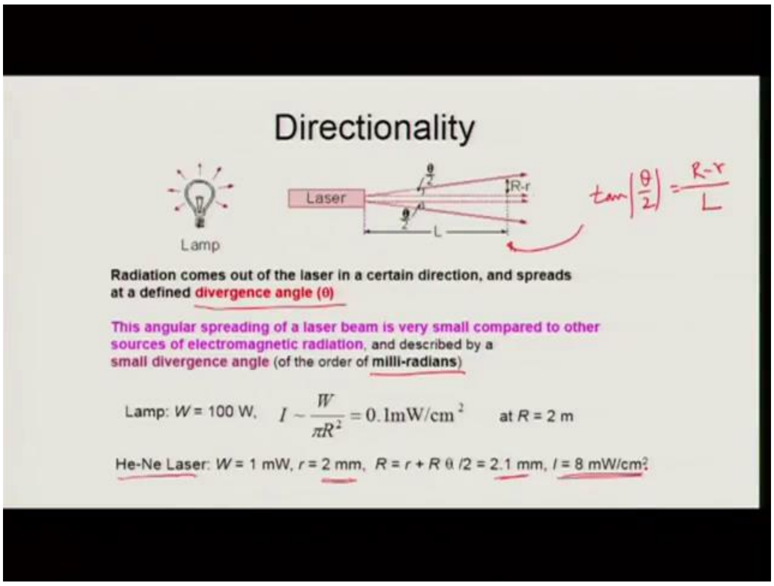

The other important part as we mentioned is the divergence or directionality which can be quantified in terms of let us say the angles spread as the distance keeps on increasing from the source point. So, roughly it can be looked at as if it is a function which is the spread function which can be somewhere of this dimension when you measure it somewhere at this point; radiation coming out of the laser has a directionality and spreads with a define divergence angle theta as we mentioned here and this angular spreading of a laser beam is very small compare to other sources of electromagnetic radiation and is describe by a small divergence angle of the order of milli-radians.

So, for example, a he-ne laser which we will discuss here with the moderate is laser power of 1 milli watts has a very low divergence. So, which is about 2 mm in diameter will grow to may be about 2.1 mm after quite a long distance and which means that you r intensity of the laser remains quite high irrespective of the space at which you are intercepting the laser.

So, the photon flux availability of a laser is extremely high.

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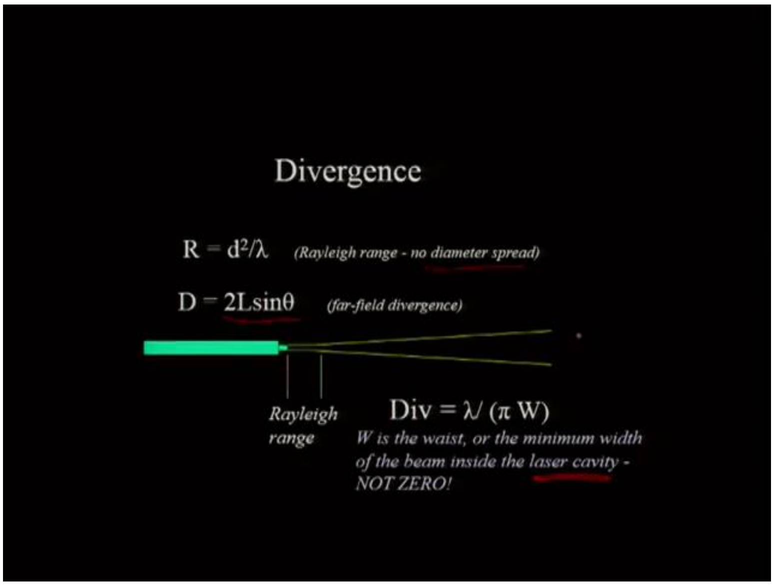

So, in a little bit more technical term divergence is the measure of this directionality and it has certain important terms associated with it the Rayleigh range over which no diameter spread happens about that laser beam coming out. Here for example, it is shown that the range is the region over which the laser just comes out of the output point and remains steady over the region and it is technically defined in terms of the diameter squared over the wavelength. So, it is depending on the wavelength and so and. so of the laser.

The far field divergence can be defined into 2 L sine of theta in similar to the way I had defined the divergence in the earlier slide where I had talked about the time tan theta as a ratio of two numbers of length versus the spread.

Similarly, divergence at the far field is going to be defined in terms of wavelength over the waste or the minimum width of the beam inside the laser cavity which is never going to be 0 and that is roughly the divergence which is stated for a laser which is very low essentially showing that this directionalities preserved very high and the intensity availability is very high over a large distance.

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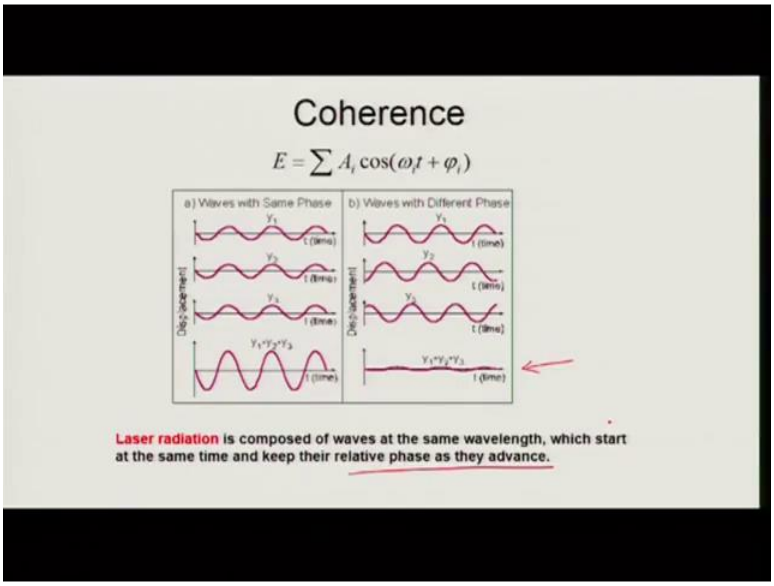

Coherence on the other hand is the fact that the phase relationships within the electromagnetic waves emitted are going to be very high. So, for a laser for example, another waves with same phase start almost at the point in time and therefore, as it goes along it is always bearing a constant relationship with the other waves. As a result you get and the phase to remain steady over distance; however, if you have waves with different phases they interfere and they eventually die out in terms of the amplitude.

So, there laser radiation is composed of waves of the same wavelength which start at the same time and keep the relative phase as the advance giving its uniqueness in terms of its capability of retaining its photon flux as well as these properties over a very long distance.

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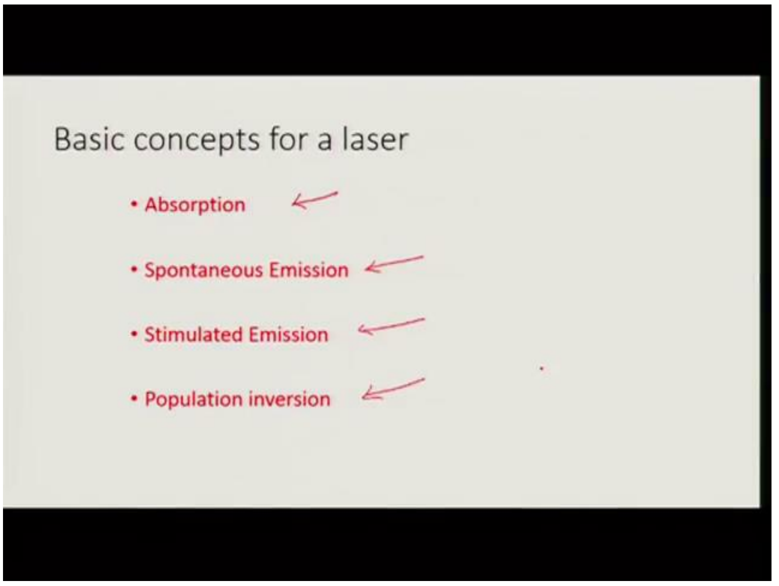

So, the basic concepts of a laser in terms of its operation depends on certain principles which are the principle of absorption, spontaneous emission, stimulated emission and a concept known as population inversion. We will go through them now.

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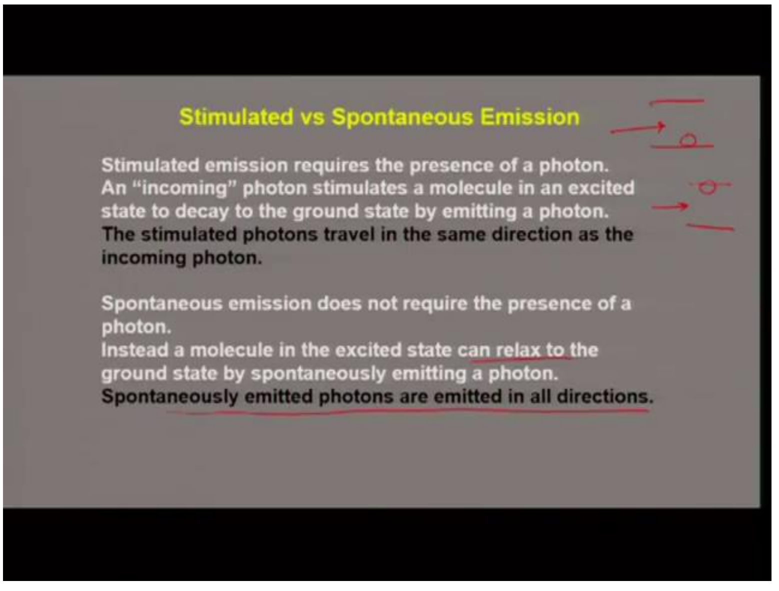

So, let us look at the different principles one after the other and the Stimulated versus the spontaneous emission. So, stimulated emission requires the presence of a photon and incoming photon stimulates a molecule in an excited state to decay to the ground state by emitting a photon. Now this is under the principles that when we have light coming in the process of taking the system from the ground state to the excited state is absorption as we will discuss, but in this particular case the photon is essentially not going to do that part, but it is looking for case the state already exist in the excited state and the photon is going to bring it down. So, that is the stimulated emission case.

The stimulated photons travel in the same direction as the incoming photon. Spontaneous emission does not require the presence of a photon on the other hand. So, instead of a molecule in excited state being hit by a photon so that it come down; in this case the molecule can just come down on it is own which is a relaxation process to the ground state by spontaneous emitting a photon. So, that is the reason why spontaneously emitting photons are emitted in all directions whereas, in the other case it follows a directions of the photons coming in.

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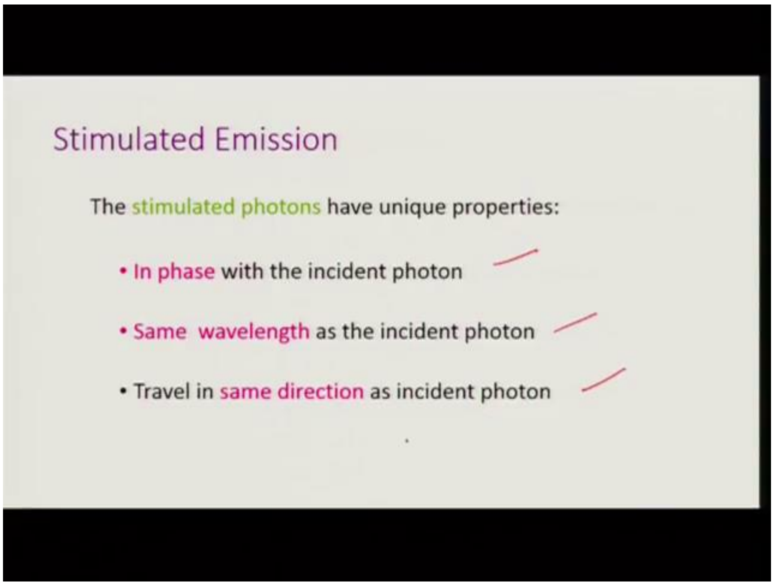

So, the stimulated photons have unique properties which are in phase with the incident photon, same wavelength as the incident photon and travel in the same direction as the incident photon; essentially giving rise to the principle of the laser.

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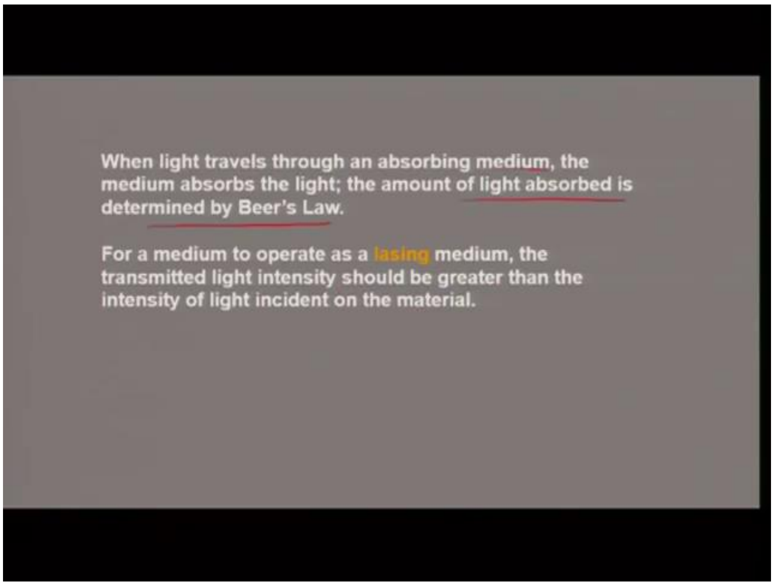

When light travels through an absorbing medium the medium absorbs the light; the amount of light absorbed is determined by Beer's Law which we know; which means that the moment we have photon being absorbs the light availability as it goes through the system keeps on going down. So, for a medium to operate as lasing medium the transmitted light intensity should be greater than the intensity of the light incident on the material.

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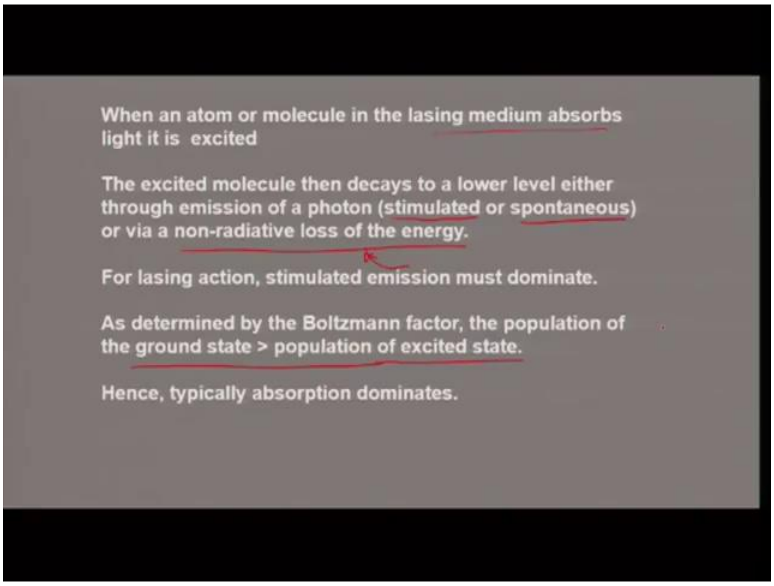

When an atom or molecule in the lasing medium absorbs light it is excited. So, that is the absorbing process. The excited molecule then decays to a lower level either through emission of a photon which can be either stimulated or spontaneous or via a non radiative loss of the energy. Now in this particular case of non radiative loss of energy this is not doing anything to us is just a loss factor.

For lasing action stimulated emission must dominate. As determined by the Boltzmann factor; the population of the ground state is always greater than the population of the excited state. So, typically absorption would dominate that is what is the natural way of thinking of things. For stimulated emission to be the dominant process the excited state population must be larger than the lower state population.

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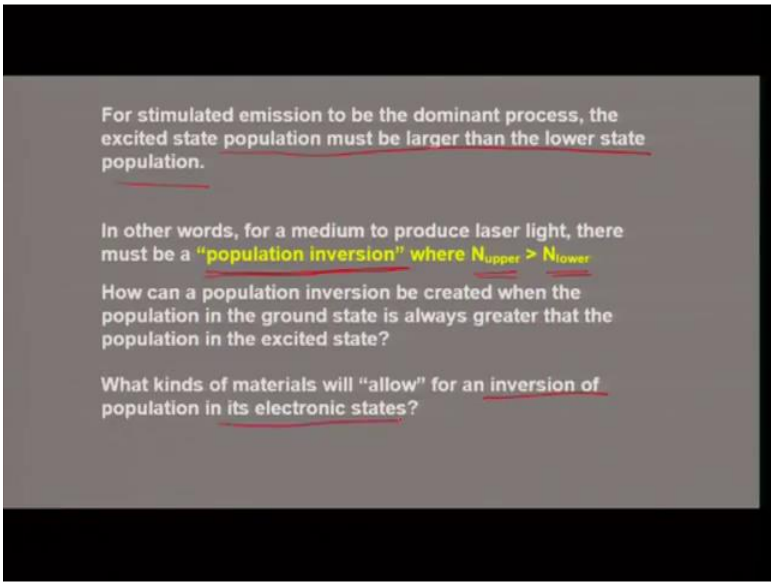

Now, this is one of the places where it is important. In other words for a medium to produce laser light there must be population inversion, so that was the fourth term that was there when I mentioned what are the essential requirements for a laser. So, this population inversion essentially ensures that the upper state population is greater than the lower state population.

So, how can a population inversion be created when the population in the ground state is always greater than the population in the excited state; this is what we know from our Boltzmann Distribution. So, what kind of materials will allow for an inversion of population in it is electronic state.

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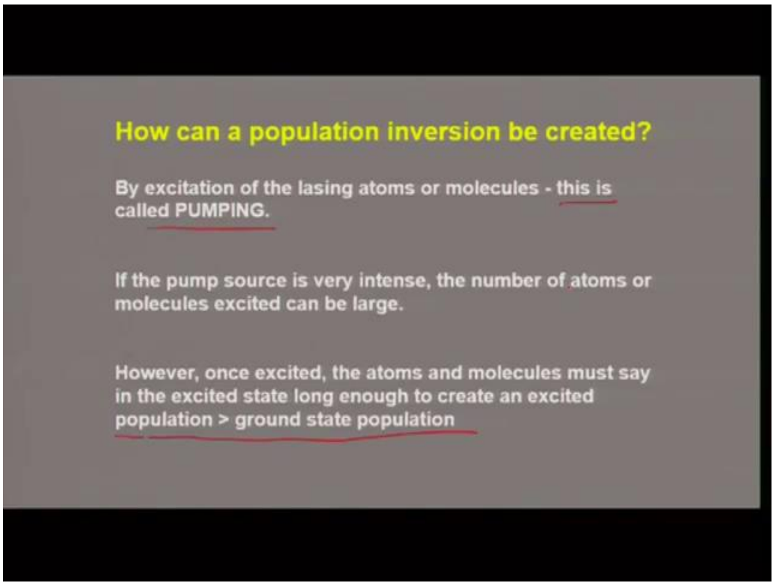

So, we can ask the question how a population inversion can be created. One way of looking at it is by exciting the laser atoms or molecules and this process is called Pumping. If the pumps source is very intense; the number of atoms or molecules excited can be large. However, once excited the atoms and molecules must stay in the excited state long enough to create an excited population which is greater than the ground state population.

So, essentially we are looking at an equation of motion here in some sense you are creating some population in the excited state and that has to stay therefore, certain time so that an inversion process can happen that is what we are asking.

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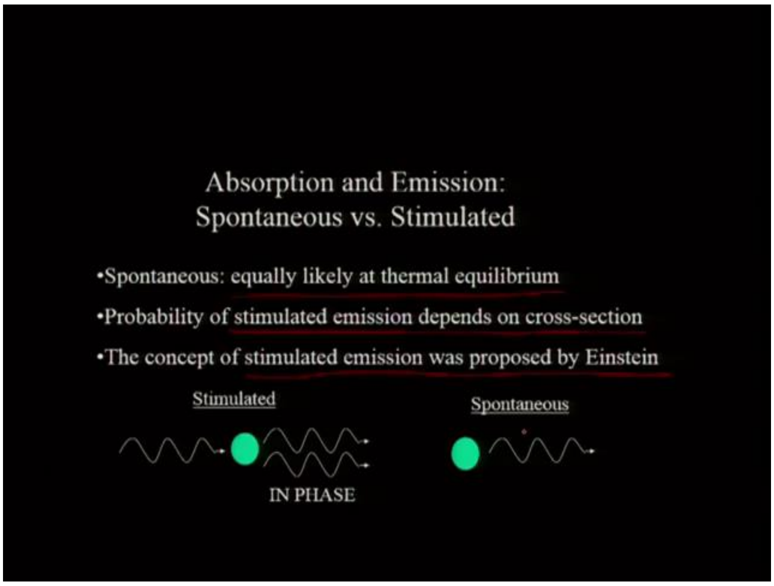

So, the absorption and emission process and the Spontaneous and Stimulated process as we have looked at essentially means that they are equally likely at thermal equilibrium. Probability of stimulated emission; however, depends on the cross section because you need another photon to be present or absorbed during this process. The concept of stimulated emission was first proposed by Einstein as I mentioned. So, stimulated emission therefore, has this curious property of being in phase in contrast to that of spontaneous which can be in any direction.

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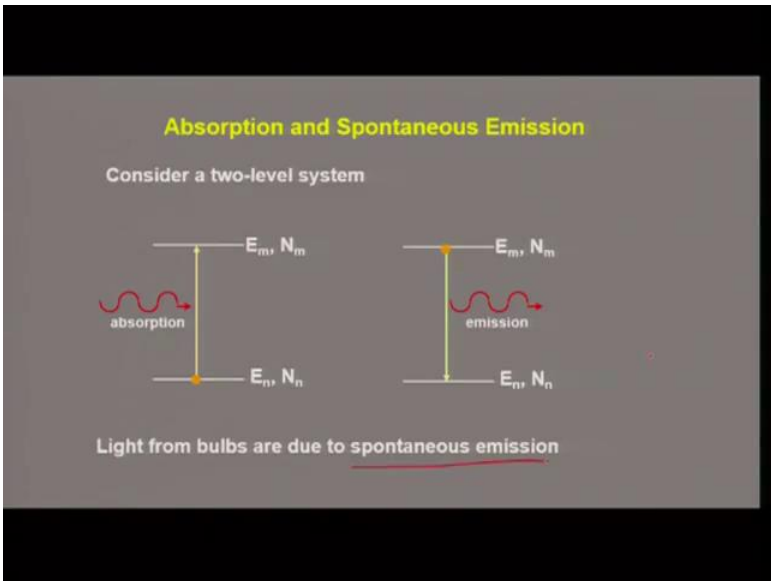

So, the absorption and spontaneous emission can now be looked at in many different ways. Let us consider the simplest of them which is a two-level system. So, in a two-level system we have said the exact energy in necessary to the system so that it gets excited. So, it is absorption process which would be followed by an emission process which is spontaneous.

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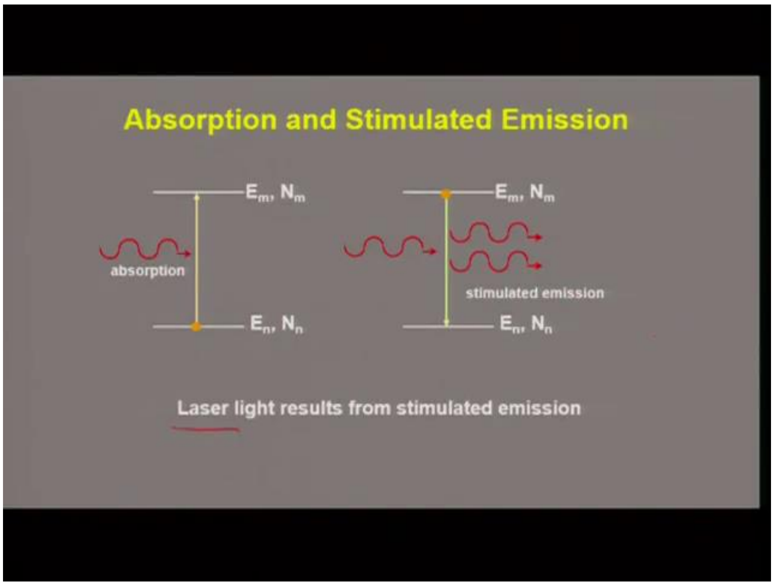

So, light bulb works in this process. So, light that I am standing in front you the scatter that you see from regular light is based on this process of spontaneous emission; on the other hand if after absorption the photons are available in plenty so that it can still push the population from the excited state.

So, basically you make an absorption with the photon and then you have more of that available so that you can now stimulate the excited state to come down then there will be a phase relationship as we mentioned with the input photon which will result in stimulated emission and that is the process through which the laser happens. So, it has to be made to happen.

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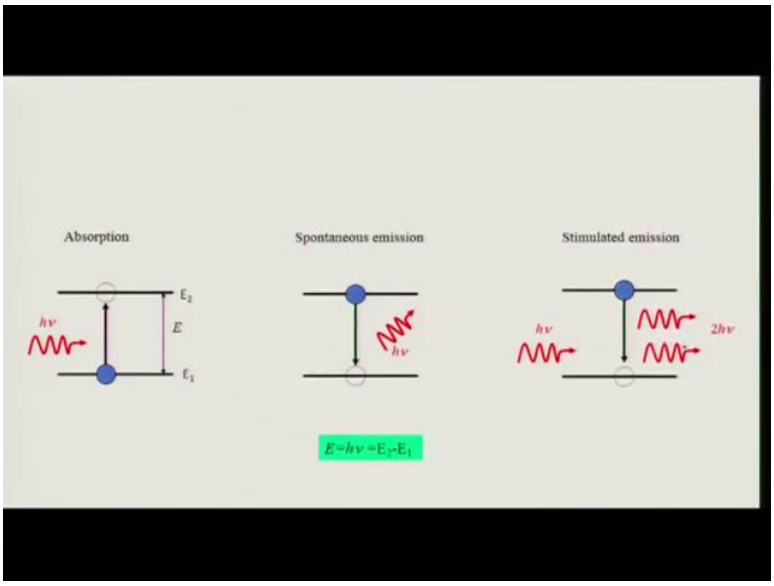

So, in summary we have this overall process that we been looking at that it is absorption process simply taking a two-level picture. We have the exact energy gap which is been provided by the applied field; then it can either undergo in spontaneous emission the excite state can just come down emitting the same energy photon or if the same energy photon is available it can also stimulate the excited state to come down and then two photons of energy having the same phase as the incident photon would be coming out. So, this is the unique case of stimulated emission.

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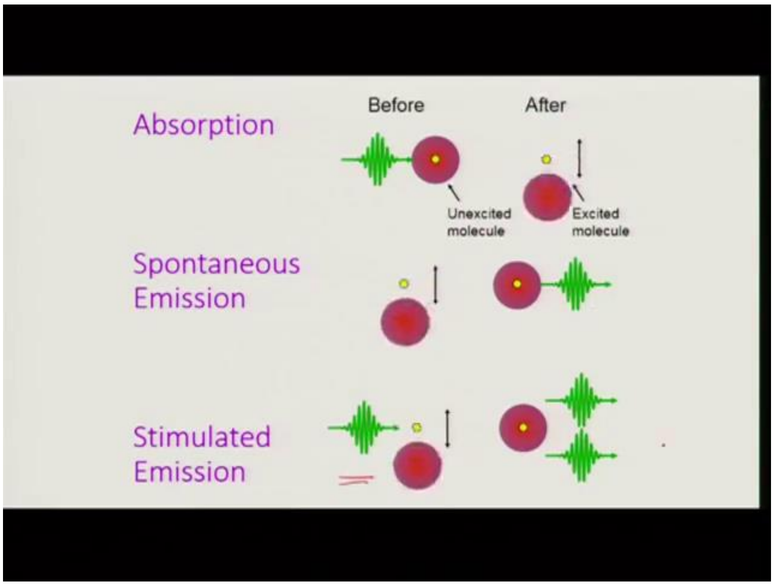

Pictorially this is what we are looking at; we have unexcited molecule which is being excited by the radiation; we get the excited molecule if it under goes just simple emission of photon then it is spontaneous emission; however, if you another photon available for it to bring it down to the ground state then we get stimulated emission which is the one with the phase.

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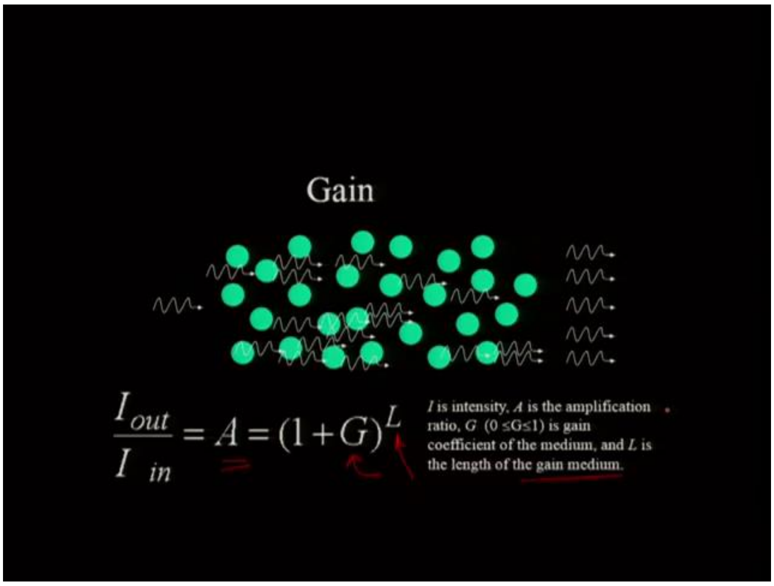

Now, the other very important thing in this process is to have this process go on and have a gain in the process as we continue (Refer Time: 20:51) So, here is the principle here we have the incident and the output intensity going in and the output going out as long as there is an amplification factor A; then we can say that there is a gain associate with this process and the length of the absorber that we are looking at or the length of the gain medium is our L. So, as long as there is an amplification process we will have this expression valid and so we can have a gain in the system.

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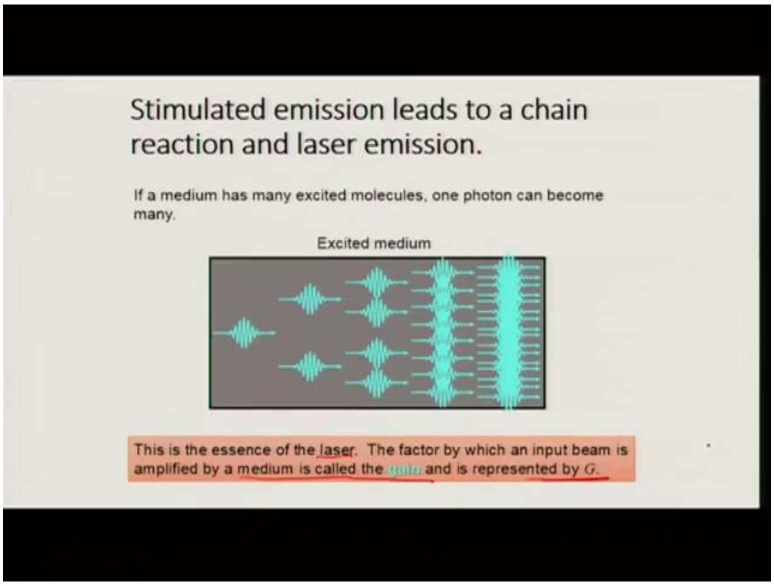

So, it can look something like that. The stimulated emission leads to a chain reaction and laser emission. So, this is the cartoon of such a situation; if a medium has many excited molecules one photon can become many and here is a cartoon showing that in availability of inverted system would allow for multiple photons to be generated from itself so much so that you finally get an output and this is the essence of the laser.

The factor by which an input beam is amplified in a medium is called a Gain as we just discussed and it is represent by G and this will follow the expression that we will discuss that the they will be a gain which will be giving rise to the amplification factor for A given length of the gain medium.

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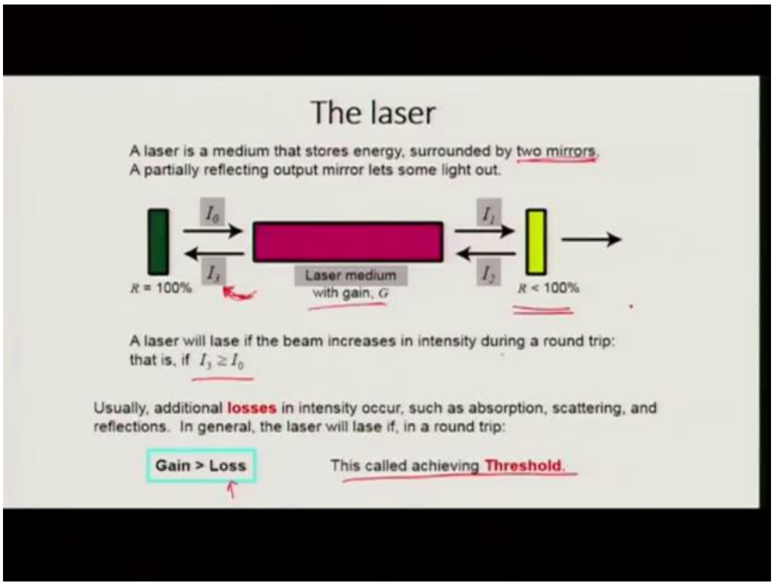

So, the laser therefore, is a medium that stores energy surrounded by two mirrors. Now why do you need this two mirrors; that is because we want have a situation where we want to keep on having the process over and over again. So, it is the repeatability of the principle which is what we are looking at in the simplest possible case; the laser medium with gain G is placed within a cavity which is essentially these two mirrors in which the system can continuously keep going back and forth. And the laser will laze if the beam increases in intensity during a round trip that is if my (Refer Time: 23:12) is going to be increasing with respect to my input.

Usually there are additional losses in intensity such as absorption, Scattering and Reflections; however, those are taken in terms of loss parameter. In general the laser will laze if in a round trip the gain is greater than the loss and this is known as Threshold because you need a certain amount of gain process to occur so that the increase of the entire process happens and you can look at it. Only a very small amount of this entire process of the gain circulating in the system is taken out through a partially reflecting mirror that what is the simplest design of the laser.

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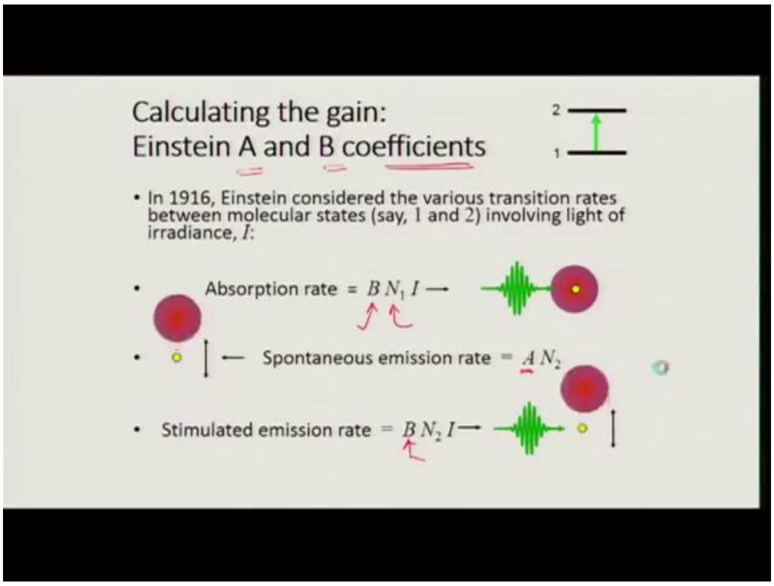

Now, how can you calculate the gain? So, in this case it is going back to what Einstein had done in 1916 where he considered two parameters A and B and these where his Einstein's A and B coefficient they are called. So, he gave this as the various transition rates between the molecular states say 1 and 2 involving the light of irradiance I. The absorption rate will be equal to the B coefficient times the number of absorbers or in case of a molecules; the electron which are there in state 1 which is going to be excited. So, that is the absorption rate.

A spontaneous emission rate would them be simply proportional to coefficient A times the number of electrons or whatever is been excited into the excite state which is being pulled down. Stimulated emission process would; however, depend on availability of photons. So, that will be B coefficient again which will be then the number of excited electrons present times the intensity of the available photon. So, that is how it will be equated.

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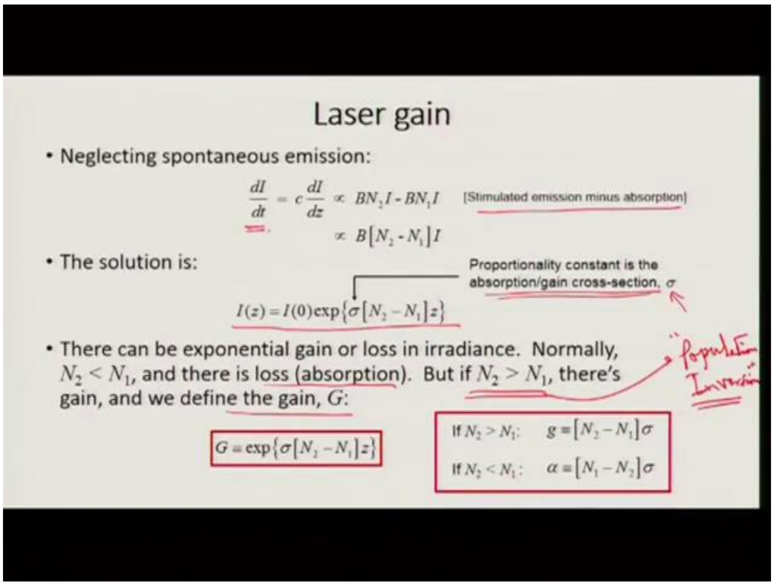

And the laser gain can be then be written in terms of the rate equation neglecting spontaneous emission. It is a simple equation where the stimulated emission minus the absorption gives rise to the gain or the change in the flux or the applied intensity gain in the process. The solution therefore, is can be written for this differential equation in terms of an exponential form where the proportionality constant is the absorption or the gain cross section sigma. There can be exponentially gain or loss in irradiance normally since the excited population going to be less than the ground state population; there is loss due to absorption, but if the excited population is greater than the ground state population there is gain and we define that gain as G. So, this is again the reason of where you need population inversion.

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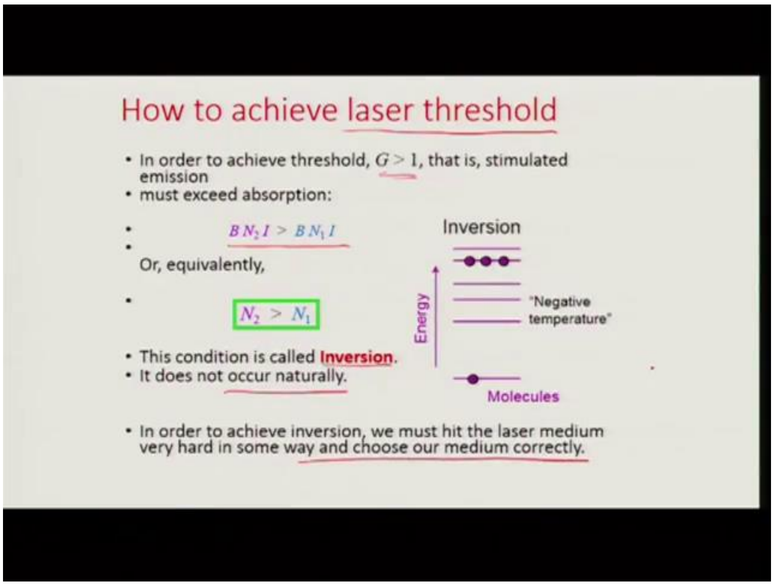

So, in terms of laser the idea of population inversion is critical. So, how to achieve this laser threshold which means that we would like to have inversion, in order to achieve the threshold where my gain is greater than one that is stimulated emission must exceed absorption; we have to have this satisfied. So, this is the simplest case ignoring spontaneous emission which means that I will have to have an inversion in terms of my population profile which does not occur naturally. In order achieve inversion we must hit the laser medium very hard in some way and choose our medium correctly. So, that is the basic criteria for having the laser to work.

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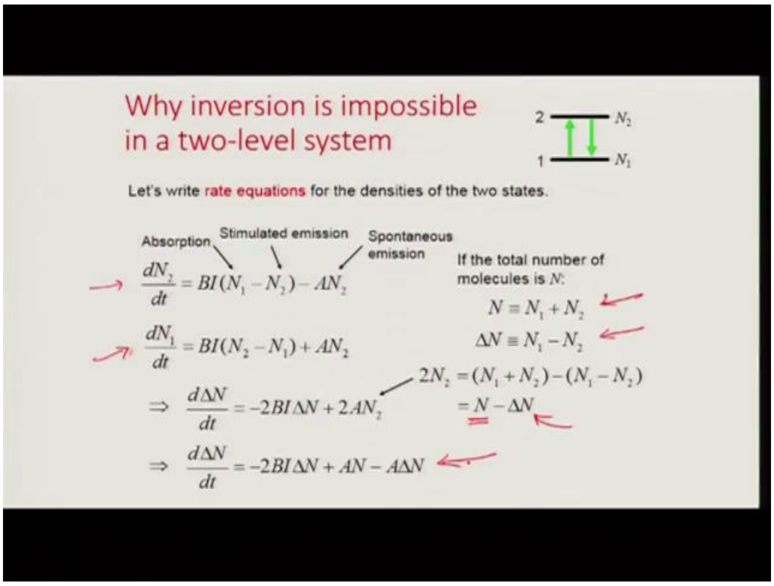

So, the first question to ask them is that what happens when we consider the simple case that we have been treating right now; the two-level system. It turns out that inversion is actually impossible in a two-level system. So, how do you look at it? So, here is the going back to the rate equations; we can write how the population would change with respect to time based on these expressions that we have just devised.

So, these coefficients in terms of these intensity of the available photons and the number of ground state versus the excited state situation. So, we will have absorption, stimulated emission and spontaneous emission. If the total number of molecules is N; this is what we get number of molecules is equal to N 1 of absorbing and N 2 of the excited state.

So, we can write the two different equations which will relate to the ground and the excited versus the ground state dynamics and by looking at with respect to the change of the total number which is the difference between these two; we can write an expression in terms of the total number of molecules versus the change that we are looking at. If we rewrite this expression in this form we are able to finally, get to an expression where we have this form.

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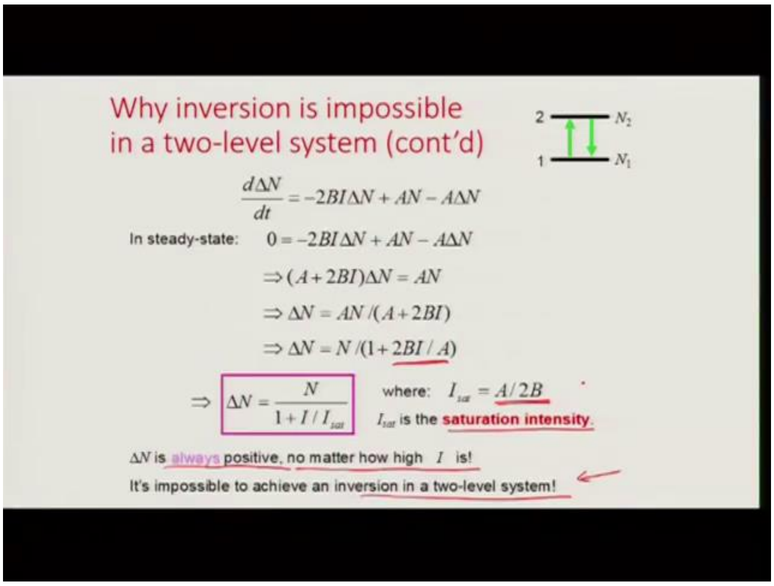

And at study state what will happen is the rate of change would be equal to 0; because whatever goes to the excited and ground ability becoming 0. So, in that case we get a situation where the we have the change that we are looking for delta N; it is going to be total numbers over 1 plus I over I of saturation.

Now, I saturation is defined as the I saturation which we have replaced it here which means that I saturation is equal to the ratio of A is to 2 half of the ratio of A into B. Now in this case what we notice; is delta N is always going to be positive no matter how high the value of I is going to be. So, it is therefore, impossible to achieve an inversion of a two-level system. So, that is the basic reason as to why we cannot actually create an inverted system for Two-Level by looking at it in this simple possible manner because no matter how hard we try; the best we can achieve is an equilibrium between the ground and excited state.

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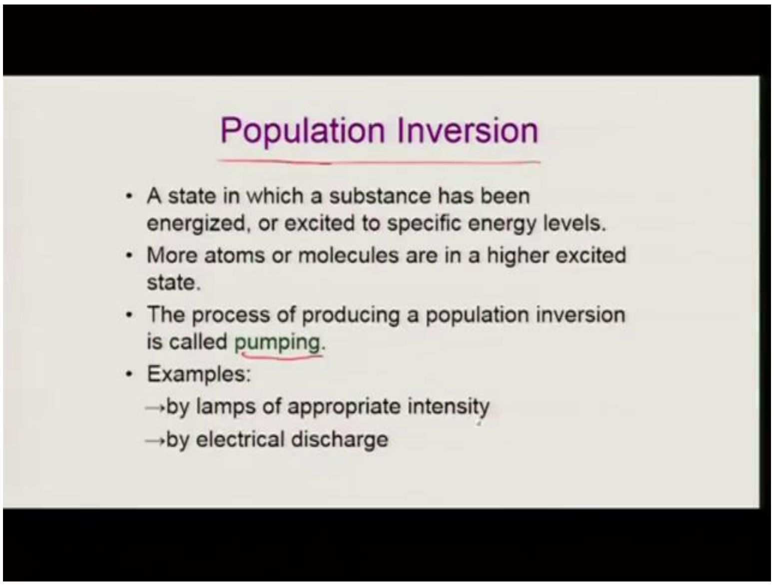

So, in order to look at into something known as this very important term of population inversion; a state in which a substance has been energized or excited to a specific energy levels. More atoms or molecules are in a higher excited state than in the ground state. The process of producing a population inversion is called Pumping; these are all the details that we have done. The examples of such process can be by the use of lamps of appropriate intensity or by using electrical discharge.

Now this forms one of the very critical forms of principles that we are looking at for lasing action. In this particular first lecture I think it is important that I conclude it at this point where we are giving you the basic principles on what we are going to look for in terms of a lasing action and the critical parameters of all the things that we have looked at are stimulated emission. And finally in order for a laser to happen is the population inversion.

So, since we reached at this point let me stop here. In the next class we will be going in to the more details of laser process, how are these different lasers defined and also I will try to see if I get to your time resolved or lasers with possibility of measuring times which we will also look into. See you next time.