Photonic Integrated Circuit
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Lecture No. 38
Optical transition in semiconductors

Hello everyone, so let us look at light emission and light detection in this series of lectures. So, in particular we are going to look at semiconductor light emitters and detectors, because that is what we primarily use in integrated circuits. So, there are other forms of light emitters as well like gas lasers, diode lasers, but we are not going to look at those but though the principle is same, the medium is going to be now semiconductors.

So, why semiconductors because semiconductors possess the necessary condition or necessary properties for us to create photons and detect photons. So, in order to create and detect photons you need to have a band gap, so semiconductors offers this, this band gap. So, when we say bandgap it is the difference between the conduction band and our valence band.

So, in addition to having a band gap, there are again two main classifications there, it is not just bands, but whether those bands are direct or indirect, based on their momentum alignment between conduction and valence band. So, for materials, where you are conduction band and valence band are aligned that means, the value point of your conduction band and the peak of your valence band if they are aligned in the same k, we call those materials as direct bandgap material. So, the electrons can jump to the same k point. So, there is no need to add or give out any momentum there. So, that is the property of direct bandgap.

And we do have indirect bandgap materials and in this indirect bandgap materials the band is slightly misaligned. So, that means the valley point for your conduction band is not aligned with the peak of our valence band. So, that means, you need to give some momentum to your electron in order to move to the minimum point in your conduction band. So, this is what we characterize as indirect bandgap.

So, a good example of indirect bandgap material are silicon and germanium and direct bandgap material is all the III-V components, so indium phosphide, gallium arsenide and then all other material platforms. So, we have discussed this in our earlier lectures, when we talked about material and material properties, but in this lecture series, we are going to look at how we are going to exploit those materials for light generation and detection.

So, before going into the light generation and also looking at the structure, we need to understand the process of light generation itself. So, the light generation happens because of transition. So, there is optical transitions that happens in the material. So, when you give an external energy into the material, you can move the electron from the valence band to our conduction band. So, that energy helps us to move that electron from one band, the lower energy band to the higher energy band.

At this energy that you are applying, should be greater than the bandgap that we have. So, when you, when you have that energy, sufficient energy, you can do that. And this excited state of this particular electron is not a stable state. So, it is not going to stay there. That is why we call it as an excited state, it has to come down. So, then it will recombine with a hole in the valence band to create or generate whatever energy that it has absorbed.

So, that energy generation, in this case that energy emitted will be in the optical range or what we call a photon is emitted. So, it takes an incoming rate external stimulus, it could be optical, it could be electrical, it will take that energy. And then this transition happens and then, when there is a recombination, and this recombination will be radiative in nature. So, when it is radiative in nature, you get photons. There are possible recombination that are non-radiative.

So, when they are recombining it will be non-radiative, what is the meaning of non-radiative, means you are not giving out photons, that energy that was stored in the excited state will not be given out or emitted as an photon. So, in that case that energy will be spent as phonons, to heat. So, when it is coming back that is given as a heat into the lattice.

So, this is the simple process of optical transition, but we need to understand how this transition works, you might have done our 2 level system, 3 level system, 4 level system when you discussed lasers in your introductory courses in photonics, but in this case, we are not going to look at those in detail because I expect you to already seen it somewhere in the introductory courses, in this series we are going to add something new, so that you might have not really encountered.

We are going to look at this different transitions that we are going to have and what this transition results in. So, that is an absorption and there is an emission and the electrons are going to sit in the excited state and we are going to spend some time there and what is the implication of this transition on the emission properties. So, you expect photons coming out based on the bandgap.

But then what is the implication of having this lifetime of this excited particles in this material. So, let us look at those real details and relate those to the material properties as well. So, let us look at first optical transition in material.

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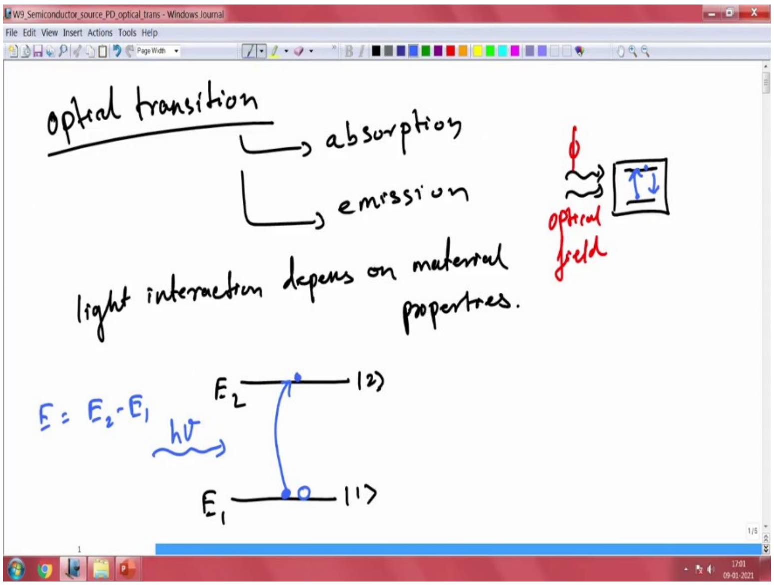
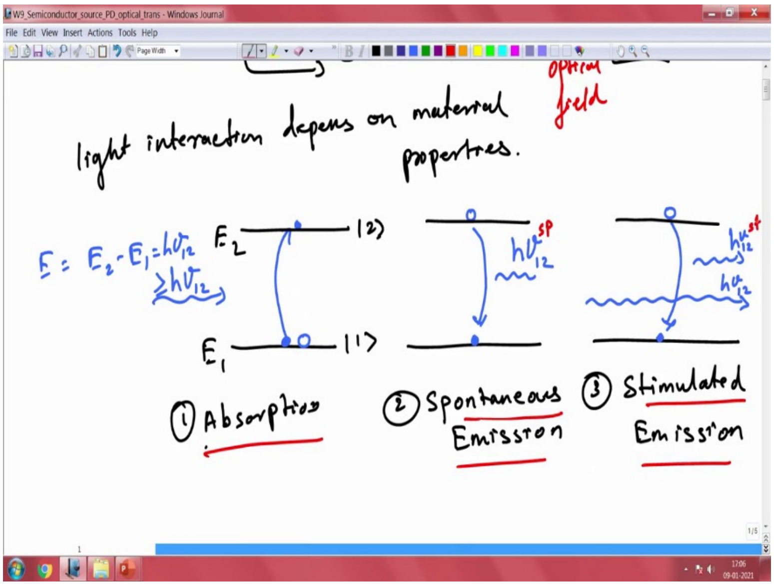


optical transition
- → absorption
- → emission

light interaction depens on material propertres.

$E = E_2 - E_1$



So, in order to create any photons, so you need to have absorption, so the optical transitions are primarily absorption and emission is what we are going to look at. So, optical transitions, you have absorption is one and then the next thing that happens is emission. So, how this absorption and emission happens? This happens because when you have an optical radiation that is interacting with the material, so I have a material system here which has ground state and excited state and then I have some incoming energy, in this case, let us say it is an optical field. So, that is an optical field that is coming in and it is interacting with the material.

So, this optical field is interacting with this material and what could happen here is you can move the electrons either from ground state to higher state or from higher state to ground state. So, this is something that you can do. So, this characteristics of interaction of optical field with the material and associated electronic transition is what we call the optical transition. So, this transition strongly depends on the optical properties or rather material properties. So, what are all the properties that dictates this is basically your band gap here.

So, light interaction depends on material property. So, when there is an interaction based on the material property, you could have a various things that is happening. So, let us see that the material has a band gap here. So, you have two energy levels, so there is energy level 1 and there is energy level 2, so the ground state is 1 and then the excited state is 2. So, there is E_1 and E_2.

So, when there is a absorption, when we say there is an absorption, we, what we mean by absorption is, there is the incoming photon $h\nu_{12}$ and this incoming photon as a certain energy, so what should be this energy, this energy should be difference of E_2 and E_1. So, this is the energy that you have with this photon. So, the photon has higher energy let us say. So, it should be greater than or equal to the energy difference that we have. So, when it is put into the material what you will have is a transition. So, the electron would go up creating there and then creating your hole. So, this is what we call absorption.

So, this is the process of absorption and we could, once we have this excited state electron, since you do not expect this to stay longer here it is going to come back at some point. So, you will see this transiting here it will come back again to the ground state and when it comes back, it has to give out that energy that was stored there. So, that energy will be given out and that energy that is given out will be the same energy level that you have as a bandgap here.

So, let us say it is the energy between 1 and 2 and the energy that you put in here $h\nu$, so this could be anywhere between 1 and 2 or greater. So, greater than or equal to $h\nu_{12}$ and this is basically $h\nu_{12}$.

So, this is the second process that I just mentioned is what we call emission, but we are qualifying that emission by using another term what we call spontaneous emission. So, this is emission, but precisely spontaneous emission. Why we call this spontaneous emission because the transition from higher level to lower level is not induced, we are not forcing it to come back, it is happening spontaneously. The third process, as you might already guessed, it is going to be a emission process there is two types of emission process that could happen this will again generated 1 2, but in this case, we are going to put in another photon of same energy level.

So, when I am putting an external photon inside the system while your electron is sitting in the excited state. So, this emission is called stimulated emission, it is called stimulated emission. So, these are all the three fundamental processes that electron can make between the two energy levels and this is primarily how the photon is going to interact with the material we have.

So, this is a fairly basic understanding of how this transition is going to happen. So, as I mentioned, these are all the three important processes, one is absorption, spontaneous emission and then stimulated emission. So, there is an absorption and emission the emission is primarily based on whether you are inducing it, stimulating it with an external photon or it is naturally radiating and then coming back to the ground state which is spontaneous process.

So, this whole process of stimulated emission, I think Einstein had done extensive work on this one and he points out that the stimulated emission is essential in the overall balance between emission and absorption, about to reaching the thermal equilibrium for a system of atoms. So, that is what Einstein proposed and this is the Einstein relation is all about. So, we need to have this stimulated process, to balance out whatever is happening here, when it comes to lasing, primarily light generation of coherent light generation. So, what is this stimulated process and spontaneous process, the emission we understand this by the process.

So, in terms of process the [spontaneous] emission is instantaneous while the stimulated process is induced. So, let us look at the property of the photon that is generated due to this spontaneous and stimulated. So, we can, we can see this as a ‘sp’ and then you can call this as ‘sd’. So, these are all two different photons. So, let us look at what is the properties of this photons because of stimulated and spontaneous process.

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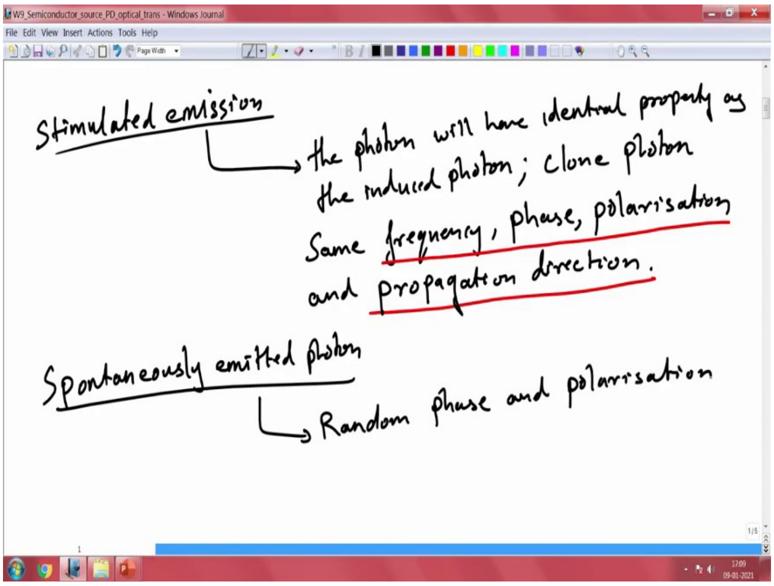

Stimulated emission

→ the photon will have identical property as the induced photon; clone photon

Same frequency, phase, polarisation and propagation direction.

Spontaneously emitted photon

→ Random phase and polarisation

So, simulated photon, alias, stimulated emission. So, the nature of stimulated emission is that the photons will have identical property as the induced photon. So, we had incoming photon, let me go to this. So, we had this incoming photon here and it has certain property, and we had a photon that is generated based on this radiative recombination. So, this radiative recombination generates $h\nu_{12}^{st}$ that is stimulated and then $h\nu_{12}$ is our inducing photon.

So, the photon that we generate, this will be a clone photon of what we sent in that is the reason why we call it as identical property or in other terms you could call clone photon. So, that means, we should have same frequency or wavelength, phase, polarization and propagation direction as well. So, you have all these important characteristic properties being identical between the generated photon and inducing photon. So, this is the characteristic of a stimulated emission.

So, you can create clone photons, it is very important, so later on we need such clone photons when we are doing lasers or lasing process will generate these kind of things. So, let us look at spontaneous, spontaneously emitted photon. So, what is the nature of spontaneously emitted photon? So, this photon that is getting spontaneous will not have such properly defined property. So, here we are going to have a random phase and polarization. So, they are going to be random in phase and random in polarization as well.

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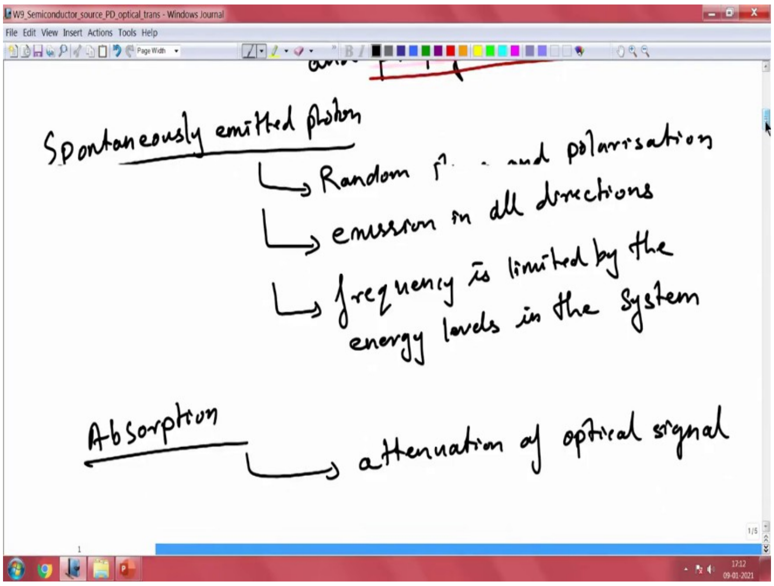
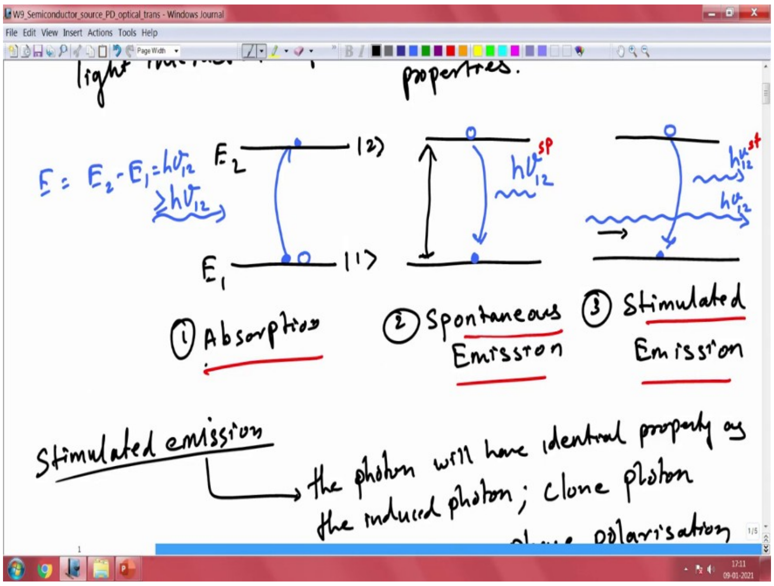


Spontaneously emitted photon

- Random ... and polarisation
- emission in all directions
- frequency is limited by the energy levels in the system

Absorption

- attenuation of optical signal

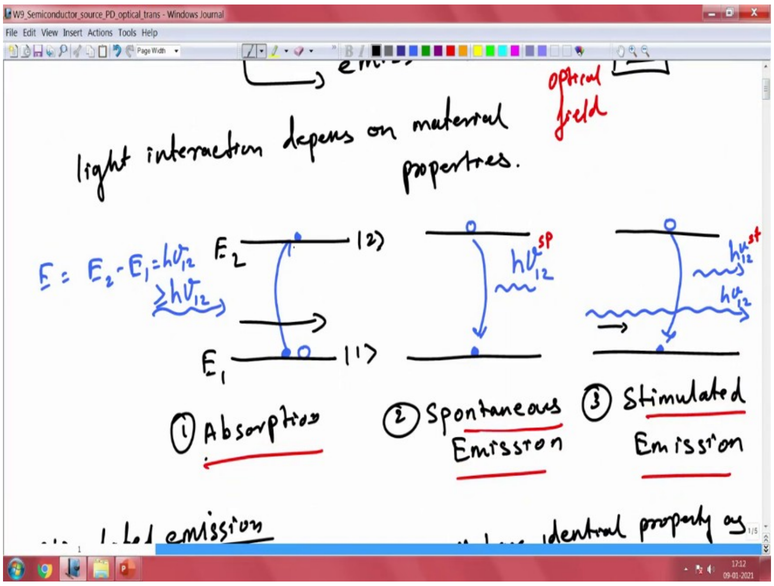


① Absorption ② Spontaneous Emission ③ Stimulated Emission

Stimulated emission

- the photon will have identical property as the induced photon; clone photon

... polarisation



optical field

light interaction depends on material properties.

① Absorption ② Spontaneous Emission ③ Stimulated Emission

... lated emission ... identical property as

The next thing is this is isotropic. So, the emission will be in all direction, emission in all direction. However, the frequency is limited by the energy level. So, you cannot have any frequency. So, frequency is limited by the energy levels in the system. So, the phase and polarization and direction are all very different from the stimulated emission. So, it can have random phase random polarization and it can be in any direction but the frequency of emission depends on the energy level.

So, that is fine. So, that is an important property here, you cannot have any energy that you want. So, that, your energy is defined between the E, E_2 and E_1. So, that frequency or energy is fixed. However, the other properties like phase, polarization and direction is going to be random in nature. So, that is on the emission side.

What is absorption? Absorption, what would lead to absorption? Absorption is nothing but attenuation of the optical signal, attenuation of optical signal. So, when the light starts to propagate through this system here, you are absorbing it. So, that the energy is absorbed and then you are doing work on the electron here. So, this is what absorption would do. So, it will reduce the signal that is going through. So, as I mentioned the frequency of the emission depends on the energy level.

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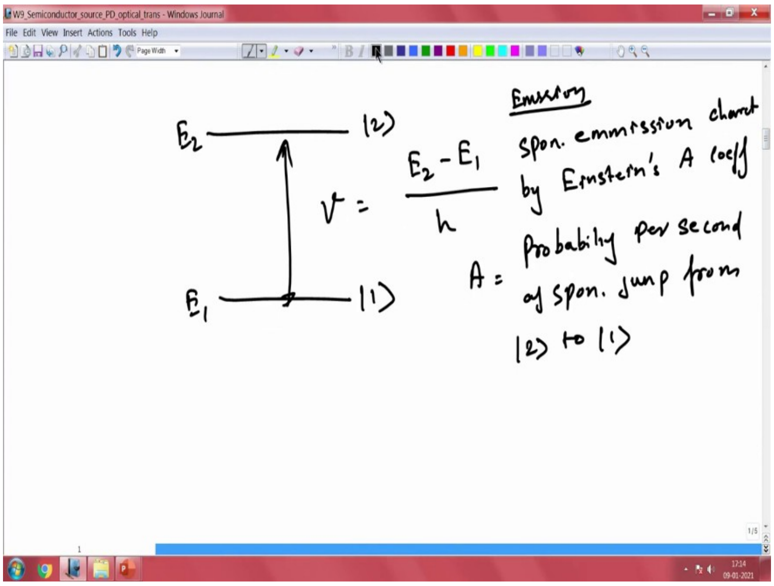
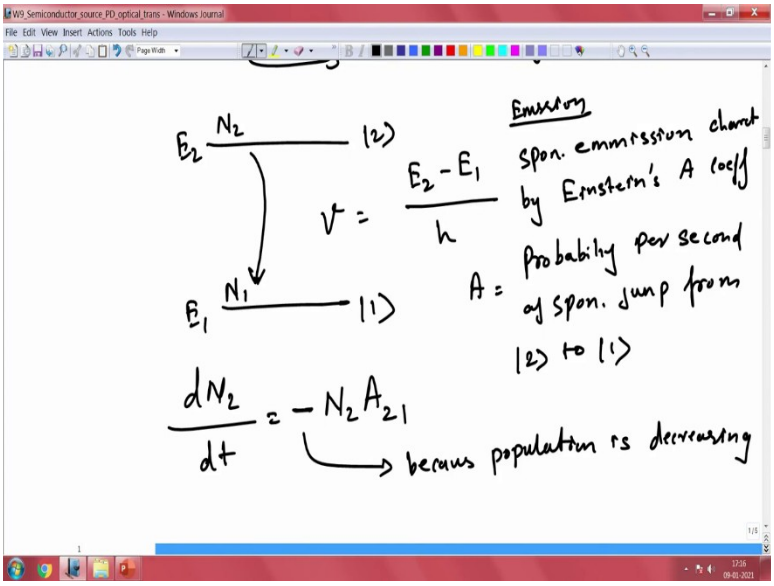


Emission

$\nu = \frac{E_2 - E_1}{h}$

Spon. emmission charct by Einstein's A coeff

A = Probabily per second of spon. jump from $|2\rangle$ to $|1\rangle$



Emission

spon. emmission charct by Einstein's A coeff

$$\nu = \frac{E_2 - E_1}{h}$$

$A =$ Probabily per second of spon. jump from $|2\rangle$ to $|1\rangle$

$$\frac{dN_2}{dt} = -N_2 A_{21}$$

because population is decreasing

So, let us say we have the two energy levels here, is the level 1 and 2 and then we have E_1 and E_2. So, what is the frequency of emission here, to be nothing but $\frac{E_1 - E_2}{h}$. So, this is the frequency we have when it comes to emission. And what is the associated probability of generating these photons, this is given by the spontaneous probability coefficient defined by Einstein. So, that is the Einstein coefficient for spontaneous emission the A coefficient. So, if we are going to look at the emission here so, this spontaneous emission is characterized by Einstein's A efficient.

So, A coefficient is a spontaneous emission coefficient which is nothing but probability per second of spontaneous jump from level 2 to level 1. So, this is how you can understand what is the rate at which your spontaneous emission happens. So, let us look at it a little bit more carefully. So, the probability per second of spontaneous emission, how can we understand this. So, you have two levels. So, then we need to define the number density here. So, how many particles are there, the ground state and that the excited state, so that is given by N_1 and that is N_2. So, that is the number density there.

So, now you are going to deplete in 2. So, that means for a given point of time you are going to emit the photons from this system. So, that means what is the rate at which your N_2 is depleting. So, that is given by N_2 times A here. So, A is the probability of emission. So, the depletion of the population in the excited state is given by whatever we have the excited state times A, in this case let us say A_{21}. So, we are going from 2 to 1 and there is a negative sign that you have to do, so this negative sign is because population is decreasing.

So, this is a very simple expression of total rate at which the transition is happening between the two levels. So, this is just considering that there are, there is one level you have the ground state or the lower level, but you could have more states, you could have N_1', N_2'' and so on. So, there could be a lowest, lower levels as well. So, here you are primarily looking at electrons jumping to one of the lowest level. So, that is a good enough understanding that you can have so far. So, it can jump back, but then the population in the excited state here at N_2, it is going to fall at what rate? It is going to exponentially fall with respect to time.

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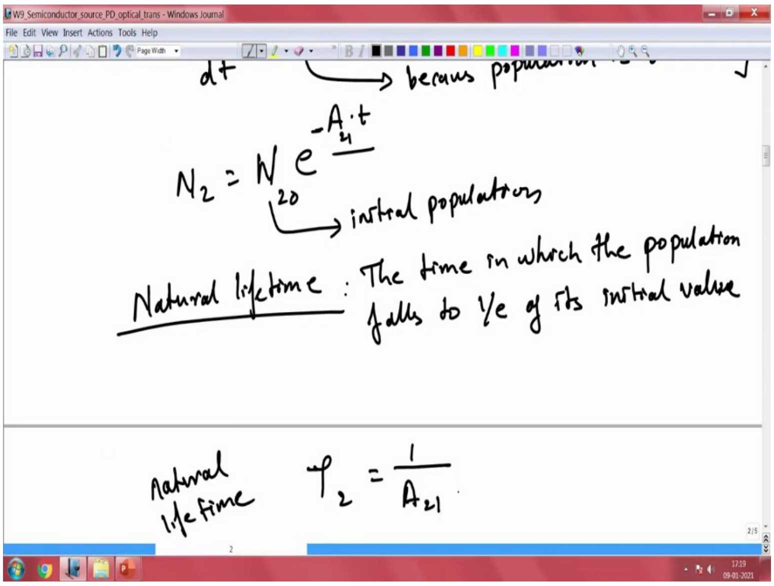

dt → becaus popula

$$N_2 = N_{20}\, e^{-A_{21} \cdot t}$$

$\xrightarrow{}$ initial population

Natural lifetime : The time in which the population falls to 1/e of its initial value

natural lifetime $\tau_2 = \frac{1}{A_{21}}$

So, your N_2 the population that you have, N_2 will have exponential decay here because you are reducing the population at the rate of A_{21}, that is what is going to happen, that is your rate of decrease in the population that you have, as a function of time. And you start from initial state. So, let us say N_{20}, so this is our initial population to start with, it starts reducing as a function of the spontaneous decay A_{21} times t. So, let me do this, A_{21} [it look like I]. So, now, you are decaying at a certain rate.

So, now we can define some time constants here, the time in which the population falls to 1/e is what we call natural lifetime. So, there is a lifetime associated with this and that lifetime is called natural lifetime. And what is this natural lifetime? The time in which the population falls to 1/e of its initial value. So, this is what we call a natural lifetime and this natural lifetime, you can look at the equation that we have here. So A_{21} is the decay rate. So, if A_{21} is our decay rate your lifetime is inverse of that. So, your lifetime here. So, this is your natural lifetime, and your natural lifetime is nothing but 1 divided by A_{21}.

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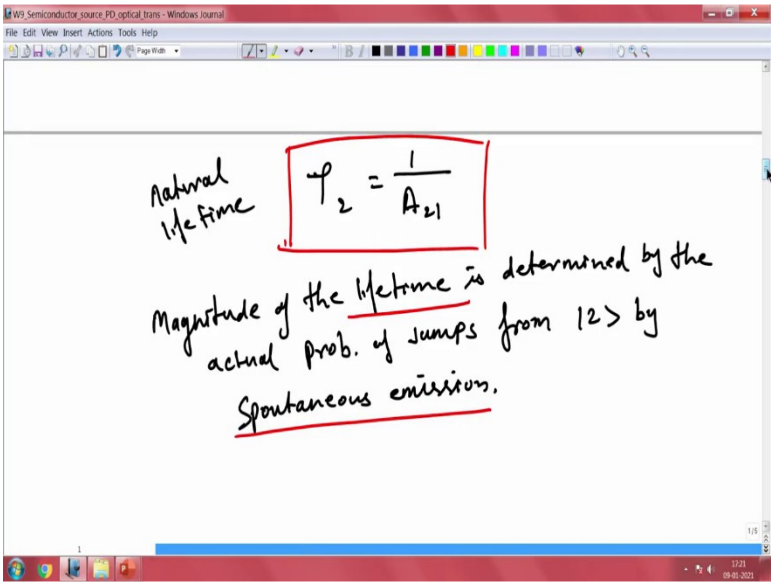
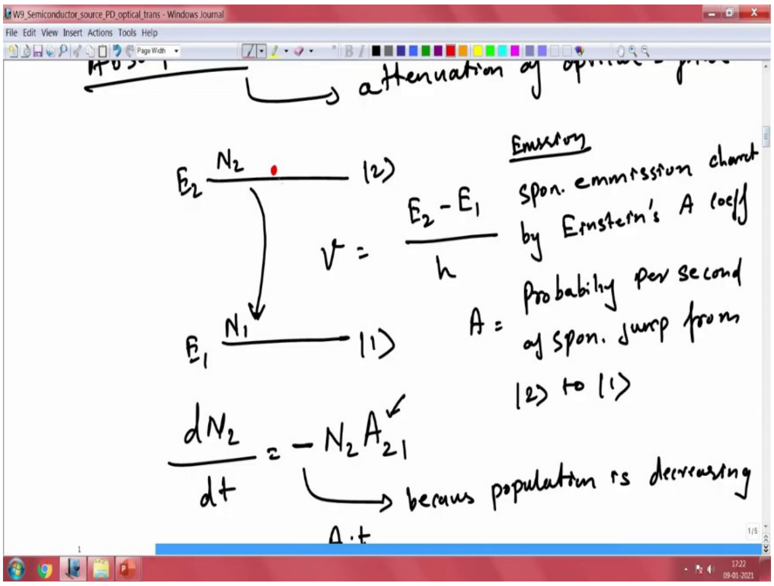


natural lifetime $\boxed{\tau_2 = \frac{1}{A_{21}}}$

Magnitude of the lifetime is determined by the actual prob. of jumps from $|2\rangle$ by spontaneous emission.



→ attenuation of

Emission

$\nu = \frac{E_2 - E_1}{h}$

spon. emission charact by Einstein's A coeff

A = Probability per second of spon. jump from $|2\rangle$ to $|1\rangle$

$$\frac{dN_2}{dt} = -N_2 A_{21}$$

→ becaus population is decreasing

So, this is the natural lifetime that you may want to remember, and the magnitude of this lifetime is [this] determined by the actual probability of this jump, from level 2 by spontaneous emission. So, this is the spontaneous emission process that defines the natural lifetime. So, the natural lifetime is determined by this spontaneous emission. This is something that you should, you should also carefully look at. So, the magnitude of the lifetime is determined by the actual probability of jumps from level 2 by spontaneous emission.

So, this is very important to understand, the lifetime is determined by the spontaneous emission process only. So, that is what we call the natural lifetime. So, when we look at this emission process here let me go to that, yeah, so here we had this admission process coming from spontaneous or you could have stimulated. So, in the spontaneous process, it happens on its own which is called a natural lifetime, but then in the stimulated emission, this is induced. So, that is something on top of the lifetime that we have. So, the natural lifetime is determined by your spontaneous emission rate.

So, since we have a lifetime associated with the excited electron here, so it is going to sit here and then it will sit there for some time. So, that is the time that we just found out that is τ_2. So, when it is coming down it is going to generate some photons of certain frequency. So, when it is emitting it gives a certain frequency. So, that is where the spectral line width comes. So, when the photons are generated, it creates a spectrum.

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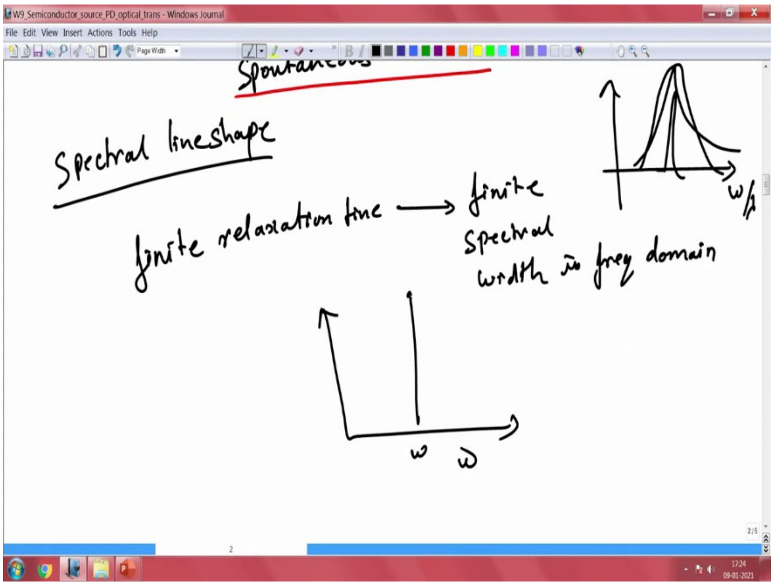
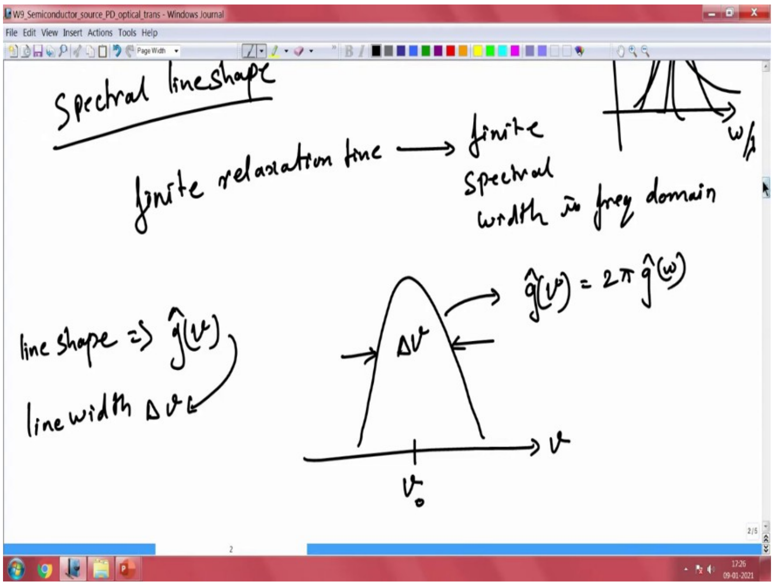


Spontaneous

Spectral lineshape

finite relaxation time → finite spectral width in freq domain



Spectral lineshape

finite relaxation time → finite spectral width in freq domain

line shape ⇒ $\hat{g}(\nu)$

linewidth $\Delta\nu$

$\hat{g}(\nu) = 2\pi\,\hat{g}(\omega)$

So, that the spectral line shape, so what is the shape of the spectrum. So, the spectral line shape is nothing but as a function of frequency or a function of lambda how my emission is going to look like. So, is what we call the spectral line shape it could be like this, it could be Gaussian, it could be just delta function. So, it can be of many shapes and size. So, this characteristic is called spectral line shape.

So, any allowed resonance transition between two energy levels has a finite relaxation time. So, there is a, that is what we just saw, any transition that happens will have a relaxation time constant between the higher level and the lower level, because of this spontaneous emission. And we all know that when there is a finite time involved, the spectral width is also finite. So, that is very, very important to make this two relations, any response that has finite relaxation time will have a finite spectral width.

So, let us do that relation here, a finite relaxation time would result in finite spectral width, finite spectral width in, let us say frequency domain. So, the time to frequency relation is something that you can easily bring out here, because of the spontaneous emission linewidth you are going to have this effect of finite linewidth. So, ideally what you would expect this, is a single frequency so when you are emitting, you just, you think that you will have, as a function of frequency, just one single frequency at Omega, but this is not going to happen because of the quantum mechanical limits.

Because once you have a finite time in the excited state, then the uncertainty principle comes in, because of the probability of this spontaneous emission process you will have a certain line shape. And this line shape or the line function is given by, let us say, g(ν), $\hat{g}(\nu)$, is your line shape and the line width, this is your, let us say, line shape function, is given by $\hat{g}(\nu)$ and then we have linewidth that is Δν.

So, this would result in a certain line width. So, let us look at the normalized line shape function. So, how would the line shape is going to look like. So, if this is your frequency spectrum, so you will have the base frequency and you will have a spread across it. So, you will have some spread around this and this spread, this line width is given by Δν and this line shape is $\hat{g}(\nu)$ which is nothing but $2\pi\hat{g}(\omega)$.

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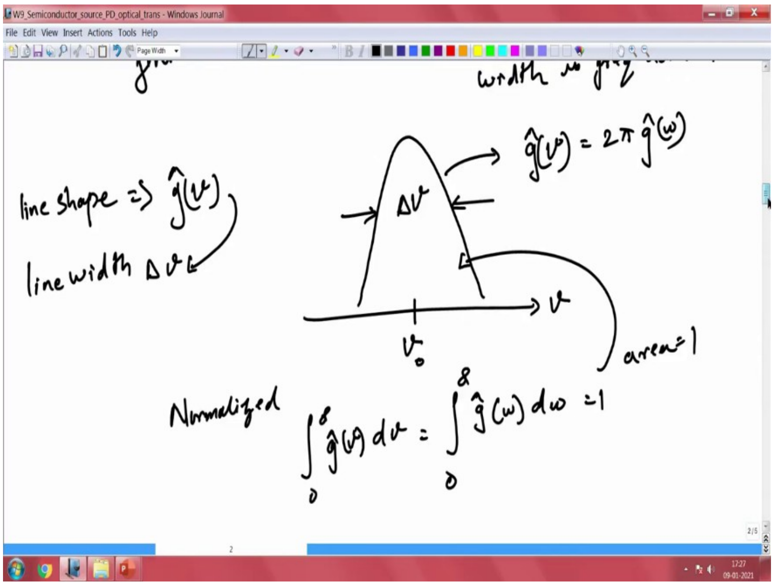

line shape => $\hat{g}(\nu)$

line width Δν

Normalized $\int_0^\infty \hat{g}(\nu)\,d\nu = \int_0^\infty \hat{g}(\omega)\,d\omega = 1$

So, you can look at the normalized relation, line shape in a normalized form, it is nothing but integrating over the frequency range, which is equal to 1, so that means, in this case area under this curve is equal to 1. So, this is the effect of having a finite lifetime or natural lifetime that you have in the system, coming from the relaxation time, where you cannot, you cannot really beat this, because this is a fundamental limit of having some relaxation time that you have and we have also seen this in dispersion where this relaxation time is imminent.

So, now this this line shape that we have it is really the fundamental limit. So, when you have a line shape, which is fundamental limit let us say, but then only you can make it worse? You cannot make it any better because of the relaxation time that we have, there are ways to try to, engineer this, but this line shape is going to be there, we can make it really narrow by reducing this relaxation time, this spontaneous emission time could be reduced by working with the system. So, you can really engineer the emitters in order to have this really narrow, but it is going to be there.

But then in any practical system, when you are, there are a number of atoms. So, that is why we go for really quantum dots, single quantum dots and so on, so there is a single emitter. So, there is a single emitter, then the effect of associated relaxations could be really taken away, but then when you are working with a group of atoms, a group of molecules, then what you are going to see is the emission properties of individual atoms and individual molecules are going to play a role.

So, here the line shape cannot get any better, but it will broaden, and this broadening can be classified into two ways, so one is homogeneous broadening and the other one is inhomogeneous broadening. So, these are all the two ways of looking at this broadening process. There are two ways that this broadening could take place. But we should know how this two process could result in broadening.

So, let us look at first homogeneous broadening. So, homogeneous broadening, as the name suggests, it is a uniform broadening. So, let us say these different atoms are there and they are a emitting and they will have their own line width. So, when you have an external disturbance, and when you have some sort of perturbation in the system, that equally influences all the atoms. So, then we call this as homogeneous broadening.

So, this broadening process affects all the emitters the same level. So, there is a equal disturbance on all the emitters. So, that means, your broadening that you see in the line shape is homogeneous, that means, all are facing the same kind of disturbance and in this case we do not have to do much the shape remains the same, but then it just broadens. So, there is a delta nu that we saw, the delta nu is going to increase, but the shape would remain reasonably identical.

However, in [in]homogeneous broadening the shape can be, can change. The reason for that is each atom is going to experience this disturbance in a different way and that could result in shift in the peak frequency here. So, we looked at this ν_0. So, you are centred around ν_0 and then you had a bandwidth. But now, this ν_0 that the frequency itself can shift, the shape will remain same for individual emitters, but then they will start moving. So, let us look at how this process happens and how we can mathematically write this shapes.

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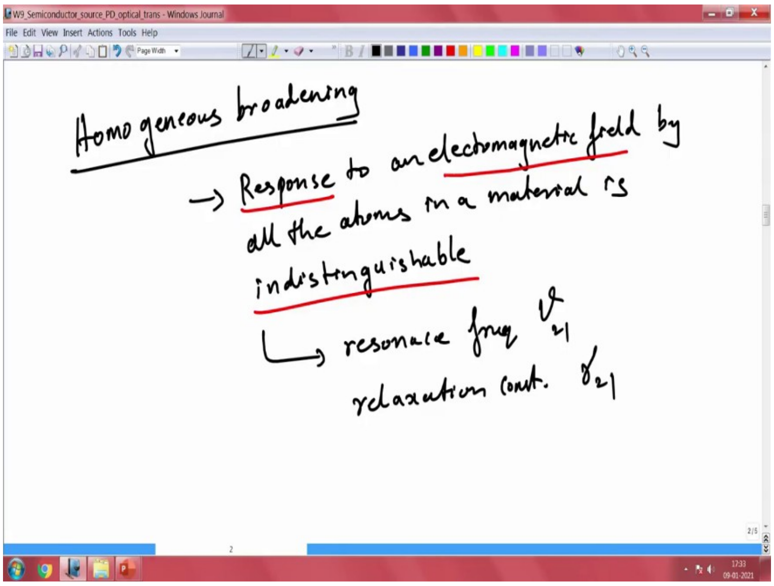

Homogeneous broadening

→ Response to an electromagnetic field by all the atoms in a material is indistinguishable

↳ resonance freq ν_{21}

relaxation const. γ_{21}

So, let us look at first homogeneous broadening. So, as I mentioned this homogeneous broadening is that, all the atoms in the material there response is indistinguishable to any external electromagnetic field. So, we can say that response to an electromagnetic field by all the atoms in a material is indistinguishable. So, when you have this the response of this electromagnetic field is indistinguishable, then you can easily write the response will be at the same frequency or all are moving or responding in the same way, so that means the resonance.

So, the resonance frequency would still be the same and your relaxation. So, the relaxation constant, so relaxation constant will also be same. So, you will not have any change in the line shape, but only the width, the line width will be affected. So, this process is called homogeneous broadening, the spectral broadening due to this particular mechanism is called homogeneous broadening.

And the another way to look at this broadening is looking at this as a damped response of any resonating system and the way that we could write this, you can you can relate this particular damping to our dispersion relation that we have. So, this damping, one can understand this through damping.

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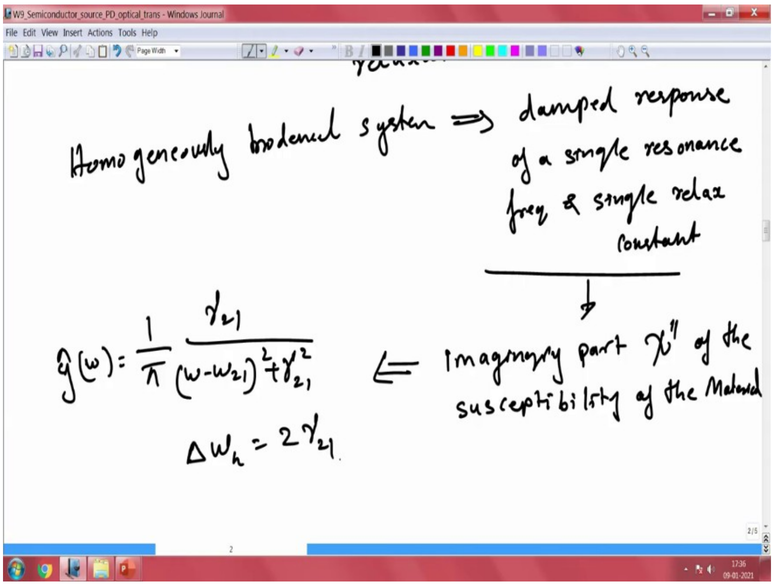

Homogeneously brodened system ⇒ damped response of a single resonance freq & single relax constant

↓

Imaginary part χ'' of the susceptibility of the Material

$$\hat{g}(\omega) = \frac{1}{\pi}\frac{\gamma_{21}}{(\omega-\omega_{21})^2+\gamma_{21}^2} \Leftarrow$$

$$\Delta\omega_h = 2\gamma_{21}$$

So, homogeneous broadening, homogeneously broadened system is nothing but damped response. So, this is nothing but a damped response of a single resonance frequency and single relaxation constant. So, if you read this one, this should ring a bell, we have already seen this kind of system in the earlier part of the lecture.

So, when we introduced about dispersion, so dispersion is nothing but very simple oscillator, the electron oscillator model. So, you could have an oscillation and then you find the solution to that oscillation, that is basically your damp, they are coming into picture. So, this is your susceptibility of the material basically. So, this is nothing but the imaginary part, χ’’ of the susceptibility of the material.

So, here we already know, how to write this particular function and that is given by $\hat{g}(\omega)$, which is given by $\frac{1}{\pi}\frac{\gamma_{21}}{(\omega-\omega_{21})^2+\gamma_{21}^2}$. So, this is exactly the imaginary part of your susceptibility. So, you can go back and then have a look at it, it will exactly look the same and this would have a full width half max, the frequency is $2\gamma_{21}$.

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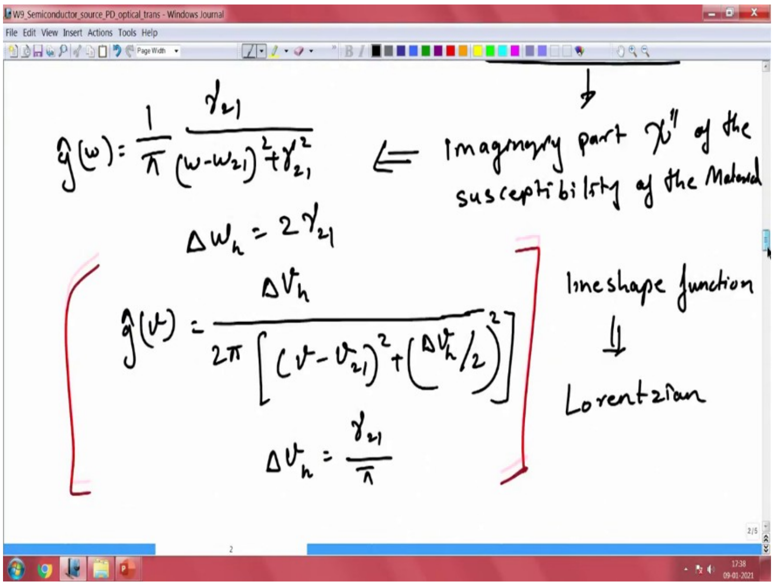

$$g(\omega) = \frac{1}{\pi}\frac{\gamma_{21}}{(\omega-\omega_{21})^2+\gamma_{21}^2} \Leftarrow$$

Imaginary part χ'' of the susceptibility of the Material

$$\Delta\omega_h = 2\gamma_{21}$$

$$g(\nu) = \frac{\Delta\nu_h}{2\pi\left[(\nu-\nu_{21})^2+\left(\Delta\nu_h/2\right)^2\right]}$$

lineshape function ⇓ Lorentzian

$$\Delta\nu_h = \frac{\gamma_{21}}{\pi}$$

And we could write this as the frequency function, $\Delta\nu_h$, h is for homogeneous broadening. So, $2\pi\left[(\nu-\nu_{21})^2+\left(\frac{\Delta\nu_h}{2}\right)^2\right]$. So, this is basically our line shape. So, this is nothing but our line shape, this is our line shape function. So, you are going to have this for any emitter and when you look at this, this would look like a Lorentzian shaped. So, when you plot this one, this will be a Lorentzian in nature. So, this is a line shape is, this is Lorentzian in nature.

And here this $\Delta\nu_h$ is nothing $\frac{\gamma_{21}}{\pi}$. So, this is our line shape, that, keep that as a quantity here, because we are going to use this in multiple places as you go through, we are not going to write the whole relation, but we will be using this line shape to understand the emission properties and how it is going to affect the emission. So, this is about homogeneous broadening. So, we talked about homogeneous broadening.

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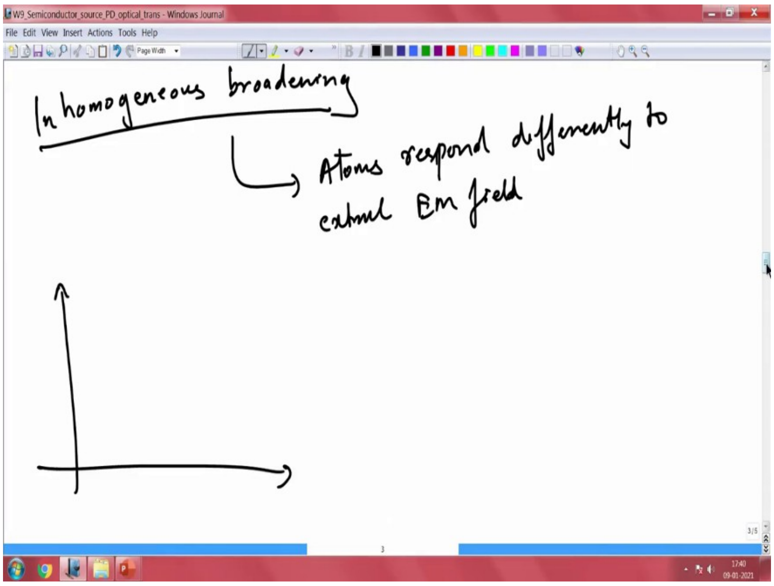
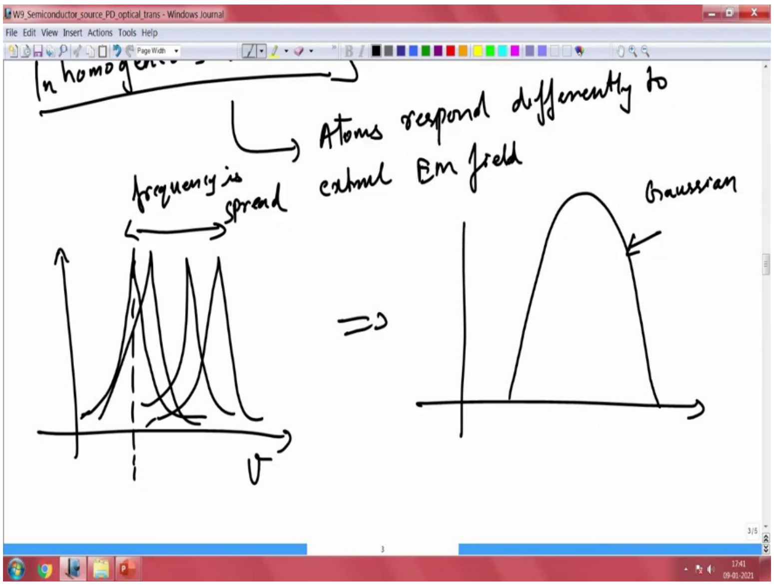


Inhomogeneous broadening

↳ Atoms respond differently to external EM field



So, the other type of broadening is inhomogeneous broadening, that is the opposite of homogeneous, inhomogeneous broadening. So, in this case, there are the atoms that we have here, well, respond differently to this external or electromagnetic field here. So, atoms respond differently to this external EM field.

So, there are each atoms that you have, they are going to respond in a completely different way, that means, your line shape is going to also change because of this and also the centre frequency at which they are going to oscillate that resonant frequency will also going to be different. So, that means, let us look at a simple case we talked about, each atom having a Lorentzian, so Lorentzian response is what we have, so that means, you have a Lorentzian type response.

So, this is for one atom. So, now you are going to have many such atoms. So, they are going to be placed at a certain ν_0, let us say. So, this is your frequency, but now because of non-uniform response, you will have response that are spread, the frequency is spread. So, this spread in the frequency that you have for individual atoms would result in something of a Gaussian type response, so the line shape here is Gaussian as a result of individual spread in the frequency here. So, the individual Lorentzian emission lines that you have here, of different atoms put together is going to create a Gaussian.

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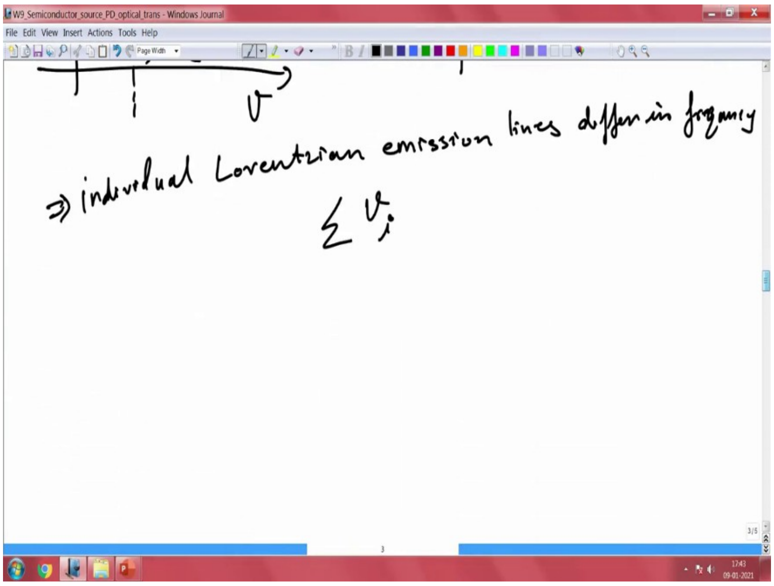

ν

⇒ individual Lorentzian emission lines differ in frequency

$\sum \nu_i$

So, the whole idea of the whole reason why this is Gaussian is that the individual Lorentzian emission lines differ in frequency. So, then the total field is going to be a summation of this individual frequencies and that is going to look like a Gaussian and this difference in this emission is primarily, because of the atomic dipoles of this atoms. So, that is the reason why we see this the Lorentzian emission being spread and this is characteristics of inhomogeneous broadening.

So, let us look at how it is going to affect other forms, but before looking at that, we need to understand how this broadening would look like. So, we characterised our broadening through this equation that we saw here.

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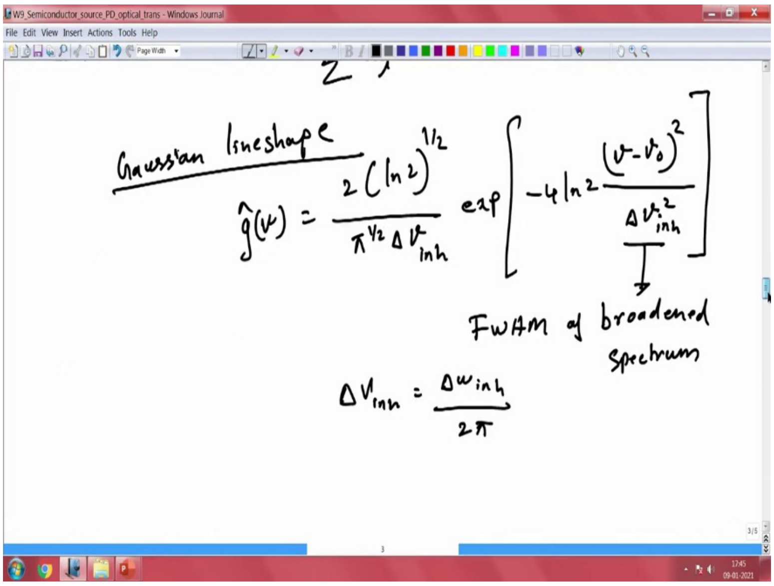

Gaussian lineshape

$$\hat{g}(\nu) = \frac{2(\ln 2)^{1/2}}{\pi^{1/2}\Delta\nu_{inh}} \exp\left[-4\ln 2 \frac{(\nu-\nu_0)^2}{\Delta\nu_{inh}^2}\right]$$

FWHM of broadened spectrum

$$\Delta\nu_{inh} = \frac{\Delta\omega_{inh}}{2\pi}$$

Similarly, for an inhomogeneous broadened spectrum the Gaussian shape, Gaussian line shape because of this, of this inhomogeneous broadening is given by this particular relation, $4\ln 2\frac{(\nu-\nu_0)^2}{\Delta\nu_{inh}^2}$. So, here $\Delta\nu_{inh}$ is the full width half max of the inhomogeneously broadened spectrum. So, this is our full width half max of let us say of broadened spectrum and that is given by, from the frequency, angular frequency going to this.

So, this is how your Gaussian line shape could look like that could result in inhomogeneous broadening. So, based on the nature of the disturbance and how the atoms are going to respond, you could either have homogeneous broadening or inhomogeneous broadening. So, with that understanding, so far, we discussed about optical transitions between the excited state and the ground state and when this transition is happening, you are going to generate a photon of a certain frequency and that frequency spread depends on the line shape and that line shape is coming from our natural lifetime or spontaneous emission rate that we have.

So, the reason why we have a certain line width from any emitter is because of this fundamental reason and then shape could broaden. So, it can only broaden and when it is broadening there are two associated factors to it. One is, it could be [a] homogeneous broadening where all the atoms are uniformly getting shifted or you could have inhomogeneous broadening because of the individual dipoles that are emitting or all resonating at different frequencies, though the emission is Lorentzian in nature your individual emission is going to be spread across a frequency. So, the Lorentzian spectrum would become a Gaussian.

So far, we understood how the emission line shapes are going to be. So, in the, in the following lectures we will understand how the transitions are happening and how do we understand the conditions required for light emission in a semiconductor. Thank you very much for listening.