Introduction to Non-Linear Optics and its Applications
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Lecture – 10
Nonlinear Optics: An Introduction

So, welcome back student to the next class of non-linear optics. So, this is the tenth lecture. In the previous lecture, that means, in the ninth lecture, we just started the idea of non-linear optics. So, today we will start from that point once again. So, these are the over views of today's lecture. So, basic linear optics already we have done, but non-linear optics we have started. So, in this particular topic in this particular class we will going to cover the introduction of the non-linear optics and quick overview we just started this part in the last class.

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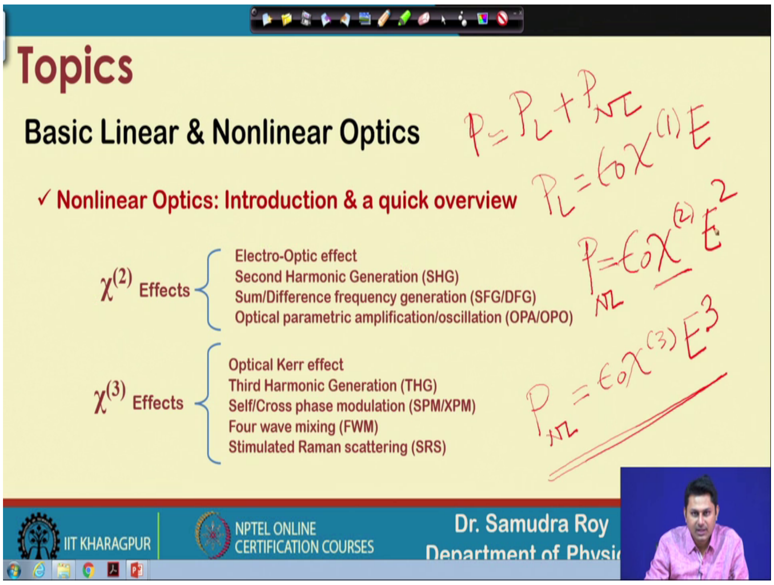

So, there are two major effects are there in the non-linear optics; one is called the chi 2 effect and another is called the chi 3 effect. The chi 2 effect it is containing with the term which is related to E square. So, polarization when the polarization is written. So, let me write here something. So, when my polarization P is represented in terms of electric field as this which should called is P non-linear polarization. So, only this E square term is there no other terms are there then the related effect is called chi 2.

Obviously, because this chi 2 term is here, when on the other hand if I write the non-linear polarization term as epsilon 0 chi 3 E cube then you have some different kind of phenomena and this phenomena is listed here we will discuss each and every phenomena in detail in this particular course, but the important thing you should know that in all cases the electric field and the polarization is related to this simple expression where E cube term is there. In general P is represented by P linear plus P non-linear, where P linear term is nothing, but the first order term which is epsilon 0 E.

Now, if I add up with this non-linear term P non-linear term in both the cases you will have two condition one is where the term is related to E square and in other case the term is related to E cube. When the polarization is related to E as well as E square then we will have the chi 2 effect. When the polarization is related to E and E cube and the chi 3 term is there so, the phenomena related to that is called the chi 3 effect.

So, now we have listed what is it chi 2 effect and what is chi 3 effect. In chi 2 effect we have four different phenomena. In fact, there are other phenomenas also, but we will going to discuss this four phenomena in detail one is Electro-Optic Effect, second is Second Harmonic Generation, then Sum and Different Frequency Generation and finally, we have Optical Parametric Amplification or OPA or Optical Parametric Oscillation or OPO. These are the topics that we will going to cover today we will just show you the overview that what is the meaning of these things in very simple way, but the detail calculation will be done in our future classes.

Now, chi 3 effects are also there in chi 3 effects we have also few terms like Optical Kerr Effect Third Harmonic Generation which is very important Self and Cross phase Modulation or in short SPM and XPM and then Four Wave Mixing and then finally, we will have Stimulated Raman Scattering. So, Stimulated Raman Scattering is also some kind of chi 3 effect we will going to discuss.

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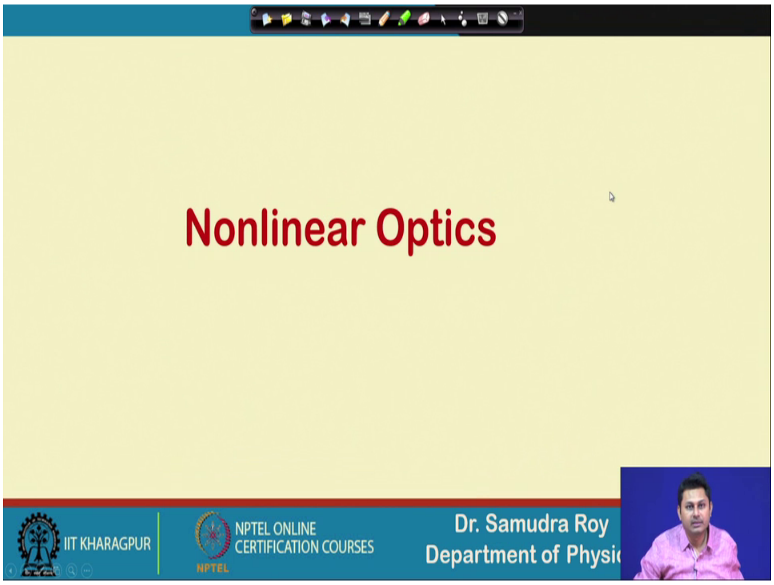

Now, let us go to the next slide and try to find out what is there in chi 3 effect. So, non-linear optics starts here. So, let us see what we have in this.

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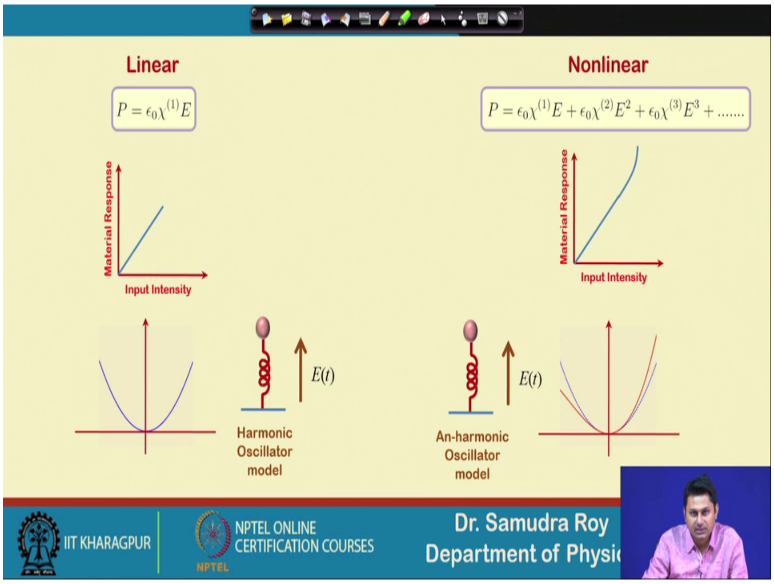

So, this is very old slide in the last class also we have used that the linear effect only contain t when t is proportional to E, but when t is related to E, E square, E cube then we have the non-linear terms. So, these non-linear terms give rise to the non-linear effect. In terms of electron vibration of the classical model the classical model supposed to change under non-linear effect because my polarization is not now function of E is the function of E square and E cube and because of that what happened when I launch the electric field which is very high the corresponding the corresponding potential under which the electron is vibrating is also not remain a harmonic oscillator, it should be a an-harmonic oscillator. So, we will change our model and when we change our model we will find a different kind of chi 2 and this calculation will be done in the future class in detail.

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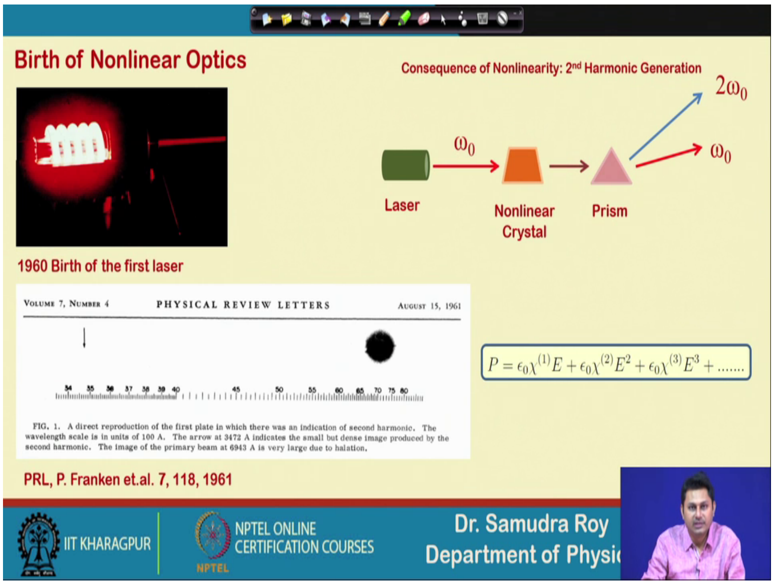

So, this notation and all this things is known this figure is also shown in the earlier class that how the non-linearity appear. So, non-linearity is basically related to very high field and we know that the laser is some kind of source through which if you if you excite a medium then what happened the medium behavior of the medium will become non-linear it is a very famous paper as I mentioned in the earlier class where first the second harmonic generation was introduced.

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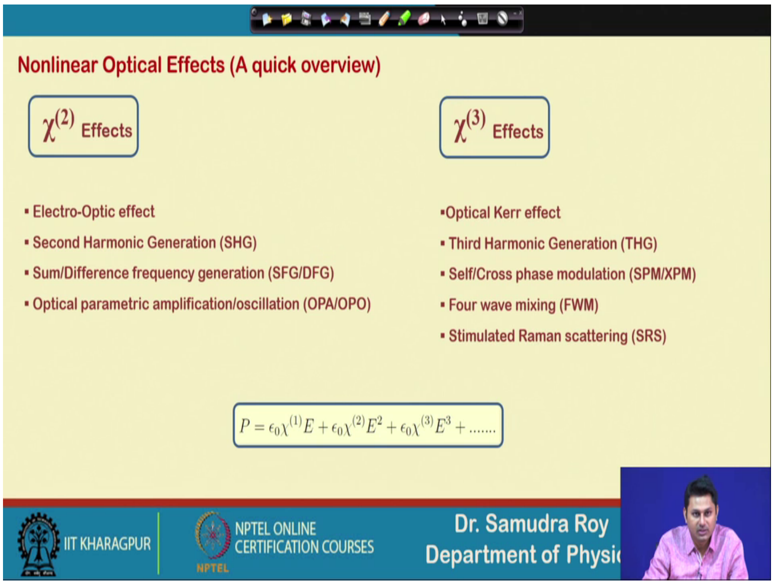

Now, let us understand what is the meaning of second harmonic generation. So, this is a list which will going to cover in chi 2 effect we have a electro-optic effect second harmonic generation sum and different frequency optical parametric amplification and in chi 3 effect these are the phenomena which will going to discuss today so, ok.

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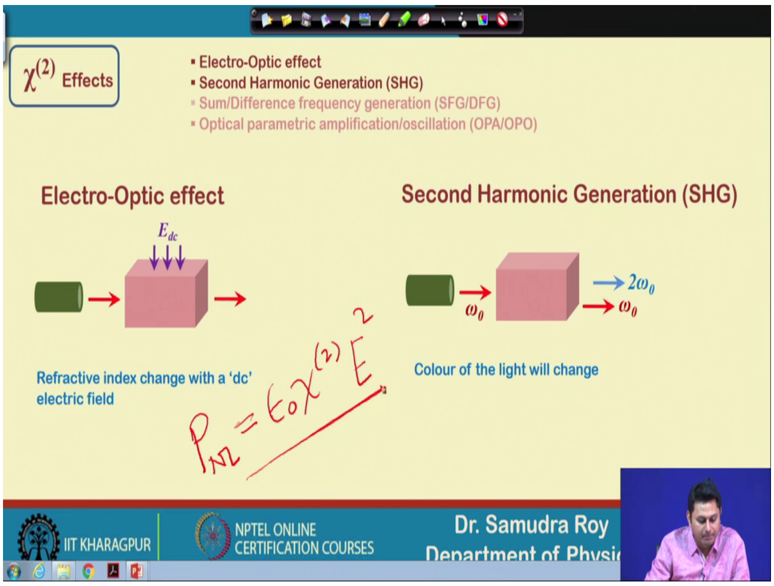

So, let us start with electro-optic effect and second harmonic generation the figure already we have shown for second harmonic generation, but we did not say anything about the electro-optic effect.

So, the outline of the electro-optic effect is nothing, but. So, let us concentrate here what is the meaning of electro-optic effect. So, this is my source, I am launching an electric field to a material shown here this is the material which is excited by the electric field and when I launch a electric field in the output I will have something since the material behavior is non-linear. So, I will have some different thing in the output.

So, what different thing, we will discuss, we will discuss here we will get a different frequency and this frequency will be double of whatever the frequency we will have. So, we can calculate that and we can do rigorous calculation, but today we will not going to do that today we will just make a outline of this phenomena.

So, in electro-optic effect what happened if I launch the electric field into the material the material will behave in a non-linear fashion as I mentioned, but there will be no change of refractive index there will be no change of refractive index. So, I launch an electric field, but the material refractive index will not going to change if I consider this to be chi 2 effect; that means, that means if my non-linear polarization is represented by this term then this effect cannot leads to the change of refractive index, but we will find that the material refractive index of the material can be changed by launching very strong electric very strong electric field and this things is called Kerr effect which is not the chi 2 effect, but chi 3 affect.

However, we can still change the refractive index by launching some kind of dc electric field that is the phenomena here we will going to discuss. So, I am launching electric field here, only this electric field under chi 2 effect will not going to change the refractive index of the material, but with launching electric field if I launch some kind of additional dc field here then what happened, the total electric field is now the sum of the launch electric field, which is vibrating frequency omega and the dc electric field then what happened this dc electric field can in principle change the refractive index.

That means, I am launching electric field and by launching another dc electric field I can change or I can modulate the refractive index this effect is called electro-optic effect some kind of electric field dc electric field I am launching from outside and as a result I find that my refractive index of the material can be changed or modulated.

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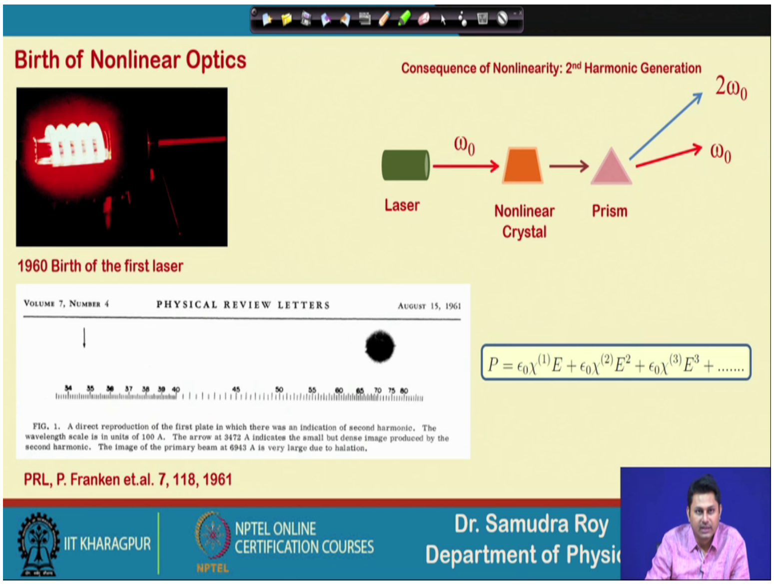

Well, next phenomena is second harmonic generation. Second harmonic generation phenomena is very very important in the last slide in the last slide this phenomena if already explained in this particular slide in the last class that if this is a laser light if the laser light is launched to a non-linear crystal then what happened this non-linear crystal will generate another waves the wave is nothing, but omega 0 multiplied by 2.

So, omega 0 wave is already there, but inside the material we will have another wave which is multiple of 2 of the fundamental frequency omega 0 and in the output we have 2 different frequencies. In this diagram we try to find out what is going on. So, non-linear crystal the electric field strong electric field is passing through the non-linear crystal, two different frequencies are generated here and from the prism what will do we just dispersed to different frequencies.

So, that you can see this 2 different frequencies side by side and this particular process can be initiated and one can do that by launching a very high electric field and this high electric field can be possible by just launching laser lights. So, laser is important.

Anyway, so, here we are doing the same thing I am launching if electric field omega.

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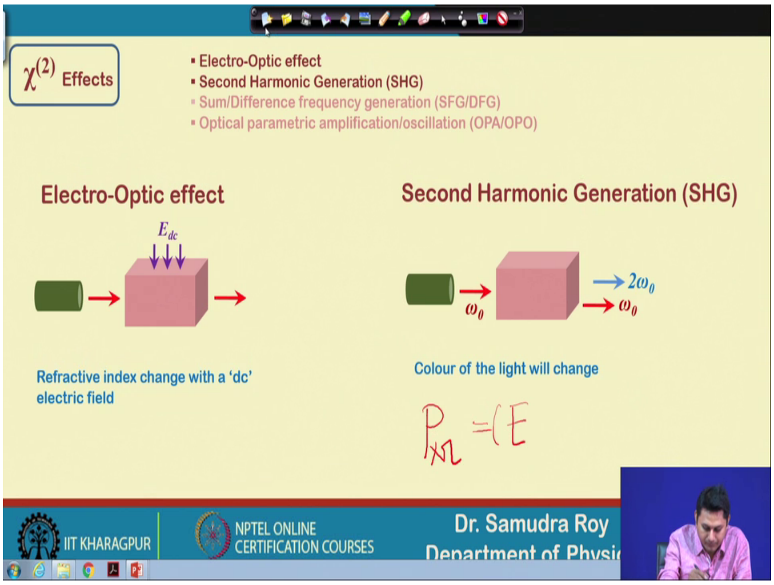

And, under chi 2 effect what happened that my if I now write so, let me briefly give you the ideas. So, P non-linear E is epsilon, ok.

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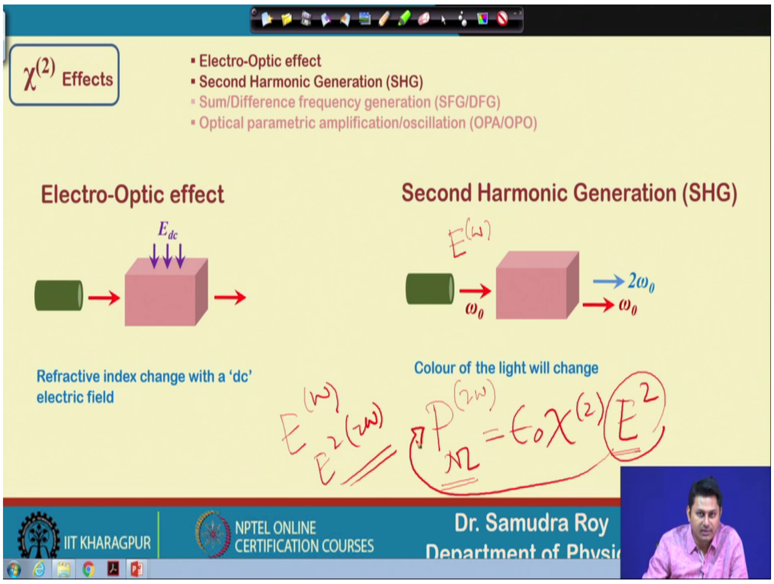

P non-linear is epsilon 0 chi 2 and E square this square term basically gives you so; that means, E if I write E is a frequency omega then E square will be some frequency 2 omega these square term gives rise to the frequency 2 mega. So, these 2 omega frequency basically generate some kind of electric field which is vibrating. So, because of this 2 omega what happened the non-linear polarization will also vibrate with the frequency 2 omega and this non-linear polarization basically give rise to another field which is vibrating in the frequency 2 omega.

So, originally there was a electric field here which is omega inside the system what happened this system basically gives this electric field the square of this electric field basically give the non-linear polarization, which now will going to vibrate P, P of 2 omega. So, this non-linear polarization now vibrating is 2 omega; that means, the dipole will start vibrating the frequency 2 mega and because of the vibration of this dipole of 2 omega they will now start generating another field inside the material which will now vibrating in a frequency 2 omega.

So, directly it is related to the material properties or light material interaction is important, but the important thing the most important thing here is if I launch a frequency omega I can have a new frequency and this new frequency is 2 of omega; that means, we are getting some kind of if I launch the one colour of light say red I can able to generate a blue light from that out of that.

So, colour of light will change and we call technically is the second harmonic generation, but one can ask the question is it possible to generate third, fourth, fifth or sixth harmonic and the answer is yes. But, in all the cases what happened that we need to make some kind of phase matching condition to initiate this higher order frequencies that is important and thus it is not very easy here, ok. So, let us go back to our slides and see what other phenomena are there.

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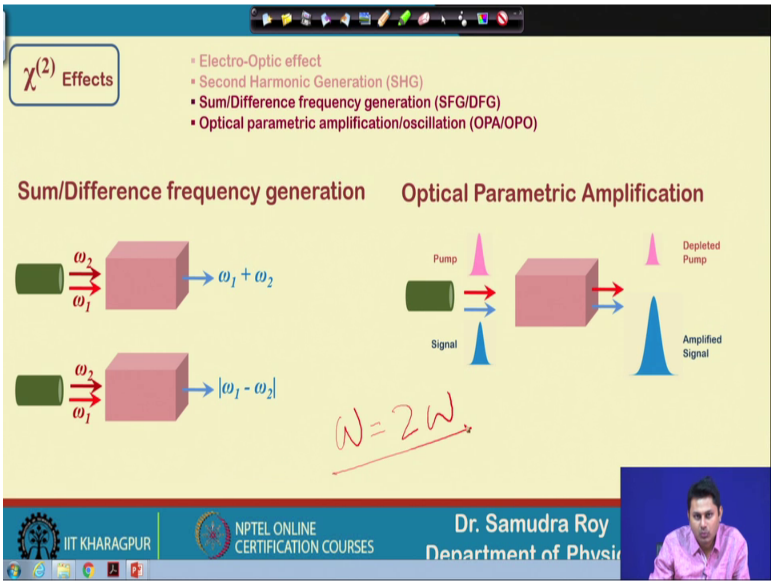

So, next two phenomena we will discuss under chi 2 effect is sum and difference frequency generation. So, sum and difference frequency generation it is important because in the previous case we find that if I launch an electric field omega if I launch an electric field omega I am getting a frequency say 2 omega that is a double of that frequency and in that case what happened I was launched just only one electric field, but here what we will going to do that I will going to launch two different electric field with two different frequencies.

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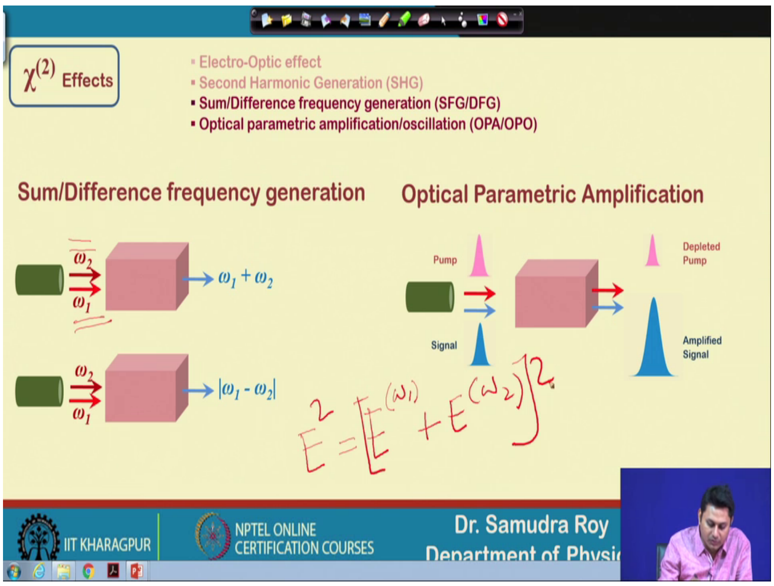

So, I am launching I am launching total this is my total electric field E this total electric field is the sum of two electric field having two different frequencies one is E omega 1 another is E omega 2. So, omega 1 correspond to one electric field omega 2 correspond to another electric field. So, when these two electric fields are together inside the material now what happened we have different kind of frequency mixing because of this E square term what will happen that we will have square of this term.

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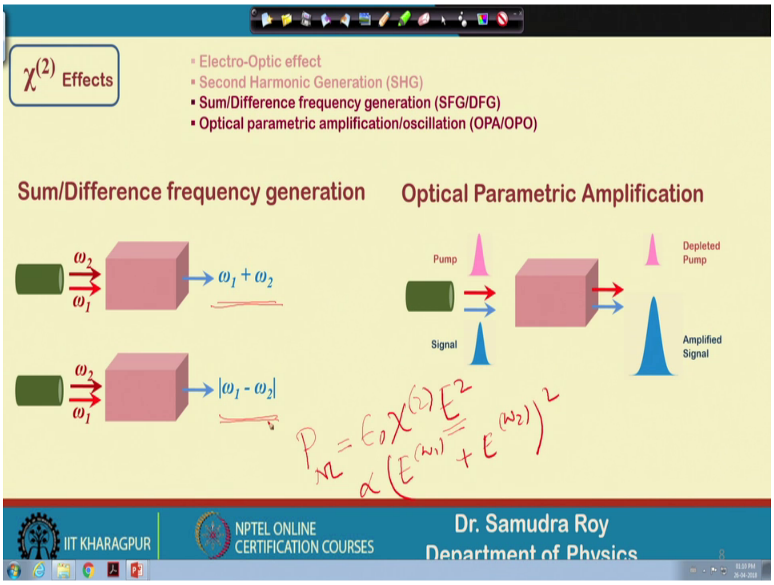

So, if you remember my P non-linear here the non-linear polarization term is epsilon 0 linear term is sitting there, but non-linear term is still there which is related to square. So, this E square is nothing, but E omega 1 plus E of omega 2 and square of that. So, there should be some kind of frequency mixing. This frequency mixing gives me either the sum of these two frequency or the difference of these two frequency very easily one can show that how the sum and difference of these two frequency can be generated under the second order effect.

Well in second order effect also we have something called parametric optical parametric amplification this is a very important process. So, like launching two different frequencies now I will do the same thing, but I am just change my name. So, I change name as signal and pump frequencies. So, if I launch one signal frequency and one pump frequency so, this is say my signal frequency and this is my pump frequency. So, what happened that because of this frequency mixing some of the energy from the pump frequency will be now transferred to the signal frequency. So, eventually what happened the signal frequency will get amplified. So, this process is called optical parametric amplification.

So, there is a relation between the pump and signal. The pump and signal can transfer the energy in between them. So, we can do some kind of proper parametric condition under which what happened that the pump can be used is energy to amplify the signal. So, what happened the pump will be depleted. So, the energy of the pump will be going down and the energy of the signal will be increased. So, this process is called optical parametric amplification. So, some kind of amplification is possible. So, we can amplify some signal through the second order effect, well.

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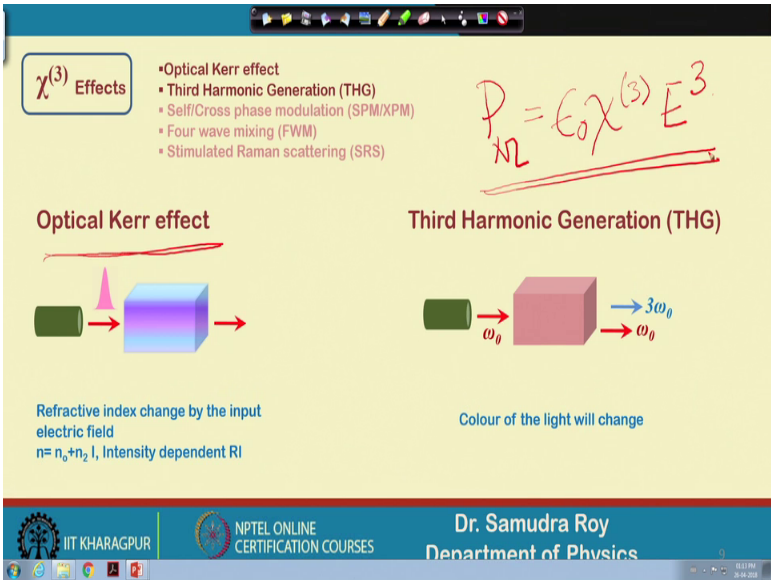

So, the next thing is chi 3 effect. So, in chi 2 effect we find that we can generate one frequency and other frequency the combination of these two frequencies if I launch two different frequencies together in chi 3 effect we have very important effect called optical Kerr effect. This is one of the most important effect we have in non-linear optics and this effect has a very profound implications. So, let us try to understand what is the meaning of that, what is the meaning of that.

So, here in optical Kerr effect what happened that if I launch an electric field now you should note that P non-linear is not related to chi 2 rather chi 3. So, I should write it as chi 3 E cube this is the non-linear time right now we are having inside the system. So, P non-linear is epsilon 0 chi 3 E cube once we have the non-linear term related to E cube then what happened that if I launch an electric field here as shown it will going to change the refractive index of the system which is a very very important phenomena.

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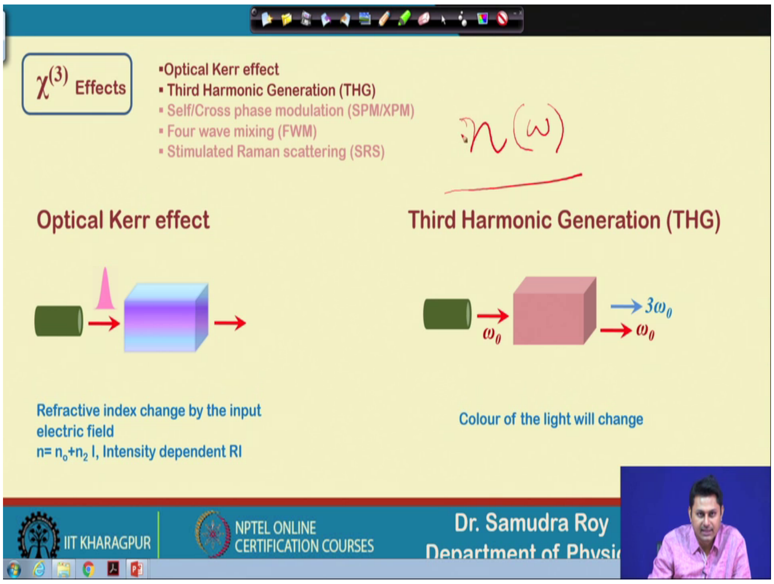

Normally, what happened the refractive index the refractive index n is a function of omega only. So, we know that is a linear optics n is a function of omega; that means, if I launch an electric field with a fixed frequency then what happened the material will behave and the behaviour in terms of refractive index will not going to change because my omega is fixed. If I now change my omega the refractive index of the material will going to change and we will have different refractive index for different frequencies that is a well known phenomena and the change of refractive index with respect to omega is called the dispersion.

However, in this case what we are trying to say that even if I am launching one single frequency omega, but if my launched light has a very high intensity then we will have a new expression in my hand in terms of refractive index.

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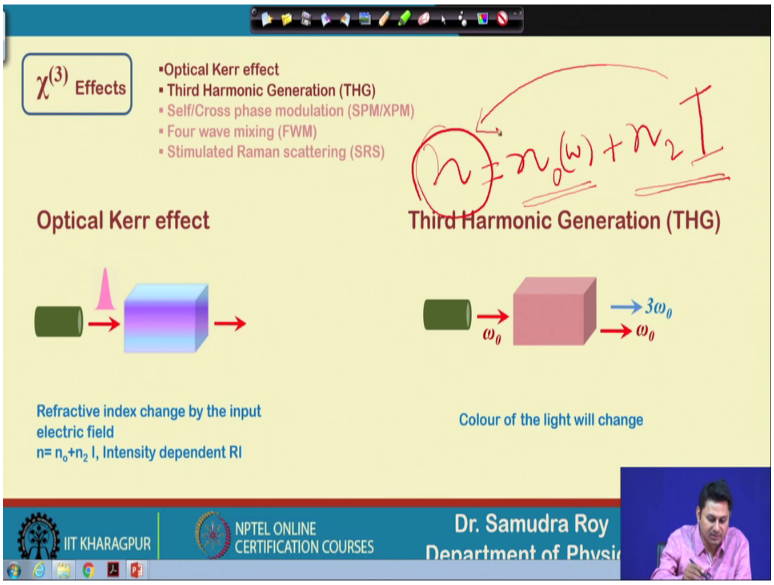

So, what is the new expression of the refractive index? My refractive index n can be represented in terms of the intensity of the launched light. This is the expression of Kerr non-linearity we will prove this expression in our future classes, but you should one thing you should appreciate that here this refractive index is a total refractive index. This total refractive index is now related to some sort of refractive index, which is frequency dependent this is the classical refractive index we have or the linear refractive index we have on top of that we have some additive term which is n 2 multiplied by I.

That means, if I increase my intensity I there is a possibility from this equation we can see that my refractive index is going to increase. So, refractive index will going to increase by external electric field frequency is not going to change I just changed the intensity and because of that the refractive index is changing this phenomenon is called Optical Kerr effect.

So, in optical Kerr effect we have a very interesting thing that from outside just changing the intensity of the light you can change the refractive index of the material, which is in my opinion one of the fascinating thing one can think of in non-linear optics like second harmonic generation here also we have some kind of frequency mixing and in the previous case we find in the second harmonic generation if I launch an electric field of frequency omega 0, then we have some new wave in the output which is having some kind of frequency like 2 mega 0, that is why you called it is a second harmonic.

Here, we will do the similar kind of things we will have a similar kind of things. In this figure we just try to find out if omega 0 is launched then omega 0 will be there in the output frequency output field, but another field will going to evolve there, which is of the frequency 3 omega 0. It is just the extension of the second harmonic generation and this extension is called the third harmonic generation and the obvious reason is that the frequency that is generating is the multiplication of 3 of the fundamental frequency because of this 3 we called this is a third harmonic generation.

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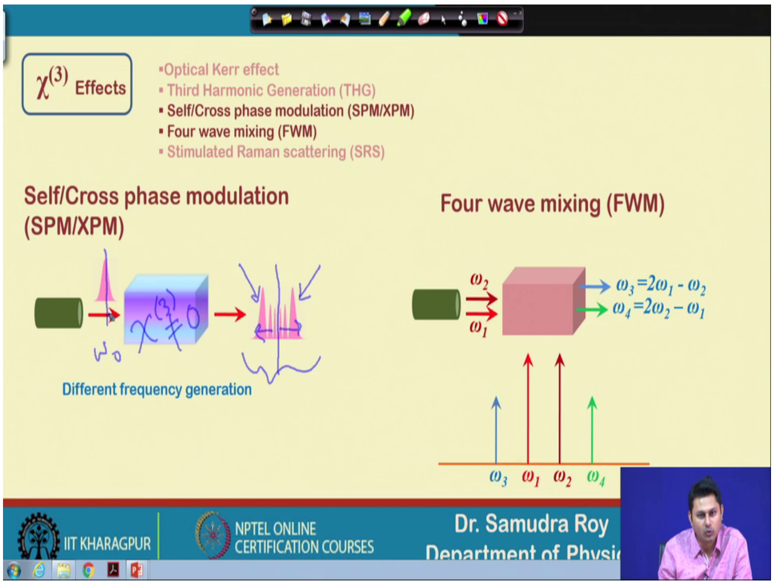

Well, next thing we will learn is self and cross phase modulation. In chi 3 effect there is a thing called self phase modulation on cross phase modulation which is also very important. So, what is the meaning of self phase or cross phase modulation let us try to find out. In this figure we try to show something that I am launching one light say with frequency omega 0. In the third harmonic generation or the second harmonic generation in the output we are getting some sort of frequency which is either multiplication of 2 of the frequency omega 0 or 3 of the frequency of omega 0. So, 2 omega 0, 3 omega 0 this kind of discrete frequency we are getting and the output under second and third harmonic generation.

However, self phase modulation and cross phase modulation is a phenomena let us try to find out what is the meaning of self phase modulation first because this diagram is shown only for self phase modulation. I am launching an electric field here in a medium where chi 3 is there. So, this medium where chi 3 is high chi 3 is not equal to 0 and high chi 3 is a material property. So, it is a very high chi 3 over there. So, let me use another colour, so that you can understand. So, chi 3 is not equal to 0 here, well. So, if chi 3 is not equal to 0 here then we will have the third order effect and on the third order effect the self phase modulation is there and self phase modulation basically suggest that, if I launch an electric field with some frequency say omega 0 this is the central frequency omega 0 then in the output we will have a distribution of the frequency.

You can see that the frequency is distributed. So, self phase modulation basically gives me some additional frequency like this one like this one. So, there is a broadening of the frequency. So, I will launch I am launching one particular frequency and apart from that particular frequency we have some other frequency in his left and right side.

So, these particular process is very important and this is happening because of the fact that refractive index is now function of intensity and because of that the phase is going to change. So, when the light is propagating inside the material we will show that the phase of the light will going to change. So, instantaneous frequency inside the pulse is going to change because of that and as a result we will have different kind of frequencies of the pulse while I have launched omega 0, but that the output we will find omega 0 plus minus some kind of frequencies in this particular figure we try to show that.

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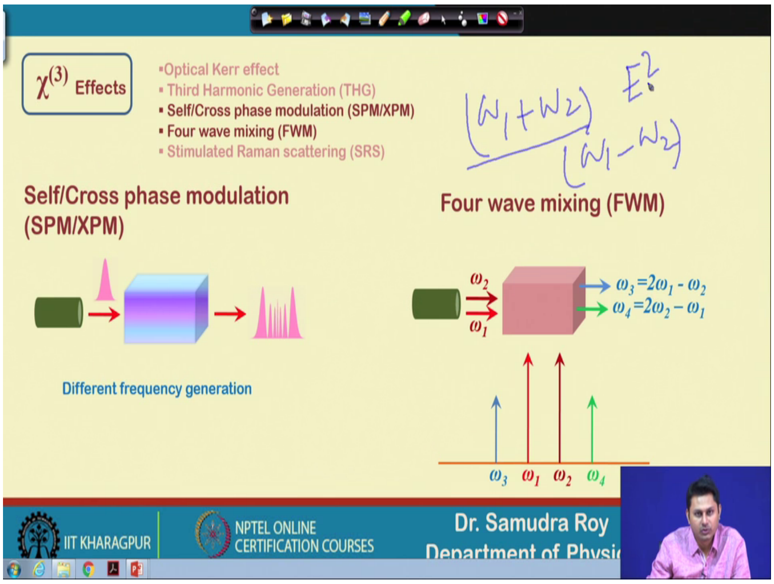

Here, we have one particular frequency at sitting here. So, omega 0, but here we have different frequency components. So, different frequency components will be generated under self phase modulation. Cross phase modulation in similar kind of phenomenon, but in cross phase modulation what we will do we will not launch one light, but we will launch another strong light like this. This is another light will going to launch.

So, these two light will going to interfere and similar kind of phenomena one can generate and this process is called the cross phase modulation, ok. Four wave mixing in the previous case when chi 2 effects was there we find out that there is a frequencies sum and different frequency generation can be possible. So, if I launch omega 1 and omega 2 then omega 1 omega plus omega 2 can be generated omega 1 minus omega 2 can be generated these are the two possibilities we have there.

We will show that, mind it; in that case it was just proportional to E square. So, if E has omega 1 and omega 2 this square term suggest that there will be not much frequencies omega 2 omega 1 frequency 2 omega 2 frequency will be there apart from that the combination of omega 1 omega 2 is there. So, omega 1 plus omega 2 will be there or omega 1 minus omega 2 will be there.

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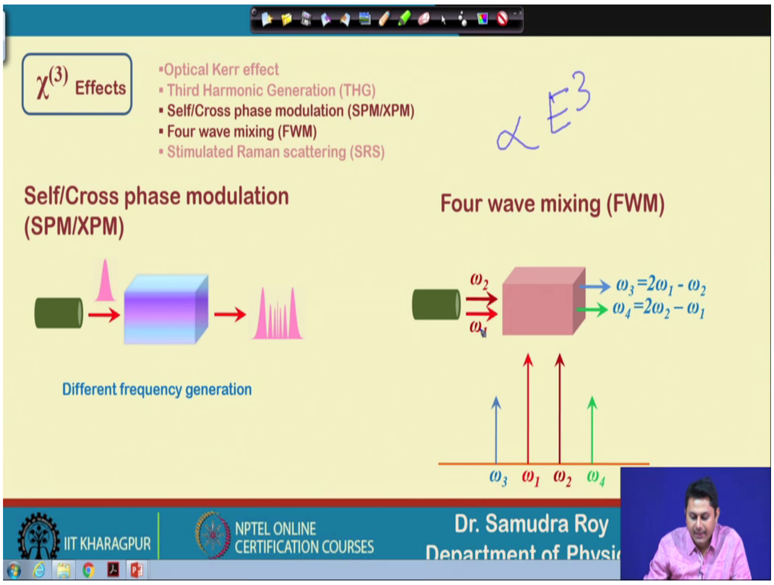

But, here since the proportionality condition is E cube. So, what happened, we will have more frequencies in our hand? So, one particular frequency is we have here is called four wave mixing. So, four wave mixing is basically two frequencies are there and I will going to generate a very specific frequency which is say we will have one frequency omega 1 here another frequency omega 2 here.

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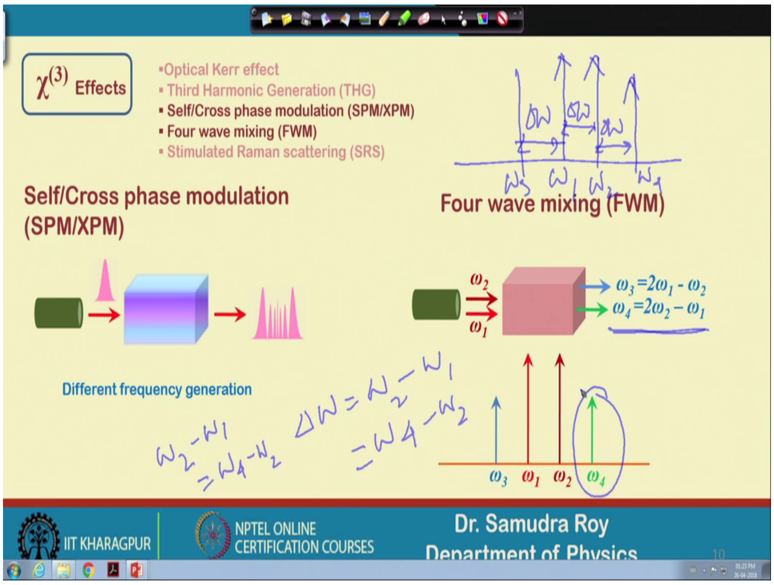

This is the figure which is there, but I am doing once again the same thing. So, we will have a frequency separation here like delta omega. So, now, if I want to find out some frequency here which is also delta omega or some frequency here which is also delta omega then I will have two different frequency if I write this is omega 3 and if I write this is a omega 4, then my equation is something like that omega 1 and omega 2 is related to delta omega.

So, delta omega will be omega 1 omega 2 minus omega 1 and delta omega can also be represented by omega 4 minus omega 2. If I equate these two if I equate these two then I will eventually have omega 2 minus omega 1 is equal to omega 4 minus omega 2. So, from here I can write omega 4 is a frequency like this.

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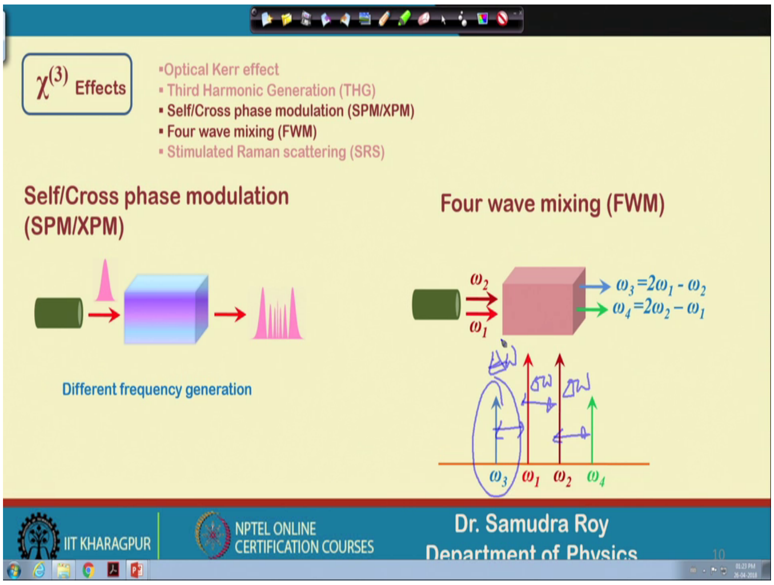

So, this frequency is basically one frequency that will be sitting here in this location in the similar way we can also generate also generate another frequency which is sitting in the left hand side with the same spacing this spacing, this spacing and this spacing are the same spacing, all cases it is delta omega delta omega and delta omega.

So, we will have instead of having two frequencies we will have four different kind of frequency and they will going to mix it up and when they are mixing up we will have four different frequency that is why it is called the four, four way mixing. So, they will going to mix and they will have four wave mixing.

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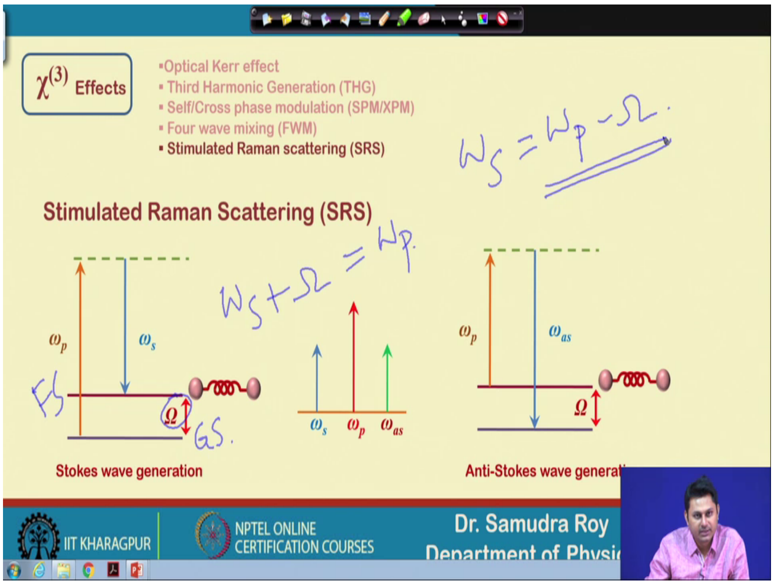

Finally, we will have one phenomena and that is stimulated Raman scattering this is a very very important phenomena and the Raman effect we know that when I launch the electric field some frequency omega p. So, what happened that the molecule will go from one energy state to higher energy state and then it return back to say this is this state is say ground state. So, this state is a ground state let me use this one. This is the ground state and this is the first excited state say Fs. So, in the ground state and frocks excited state there is a frequency difference and this frequency difference is say omega.

So, what happened that if I launch the electric field into the material the material from goes from ground state. So, the molecules can go from ground state to higher energy state some virtual level and return back to first excited state. So, that means, the molecular now start vibrating in a different frequencies since it is a first excited state when it return back.

It will now launch now radiate some kind of frequency omega s this frequency omega s plus omega will be equal to omega p, the pump wave length. So, omega it is a frequency that we will have here will be omega P minus omega. So, this is the new frequency that will be generated by the system the Raman Effect is well known. So, this new frequency will be generated and when this new frequency will be generated this frequency will be lower that whatever the frequency we will launch here. So, this is called the stokes wave generation.

So, in our in our course we will learn this Raman effect in detail also with the same thing can happen in the opposite kind of thing can happen. So, what the originally the molecules are in higher energy state and I launch in electric field with the frequency omega P, this molecules can go to higher energy level and then return back to ground state.

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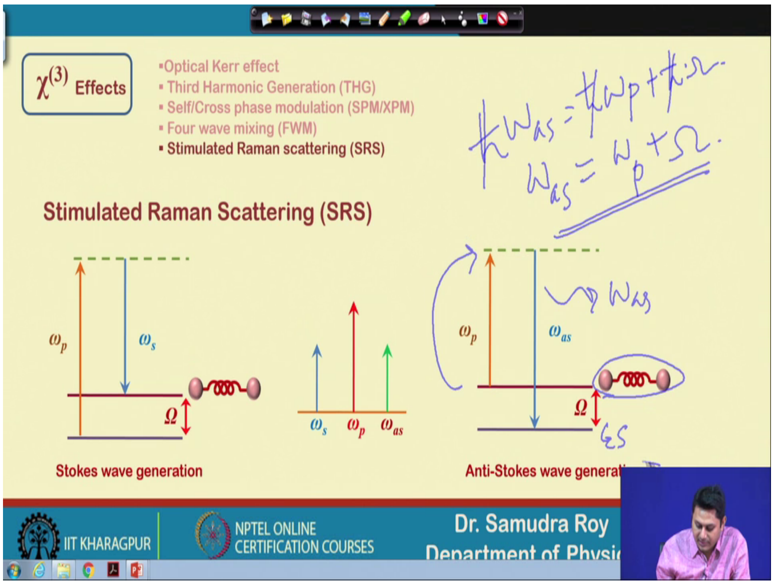

Since so, if I now write the energy conservation equation so, it will be a omega say this frequency this radiation is of the frequency omega a s. So, omega a s is nothing, but omega p plus omega this is the energy conservation. If I multiply h cross so, h cross a s is equal h cross omega p plus h cross this is the energy conservation. So, if I cut this h cross in all the cases. So, this energy conservation think and we write in terms of frequency only. So, this frequency omega s is basically omega p plus big omega. So, this basically gives you a frequency which is higher than omega p. So, this kind of process is called the anti stokes generation.

So, here if I now write these two things together I am launching in electric field here I can generate some kind of wave here in the right hand side in the higher frequency side and also in the lower frequency side. If I generate in the higher frequency side which is normally not the case this is called the anti stoke wave and if it is generated in the lower frequency side it is called the stoke wave. So, some kind of energy is going from material to that thing. So, that is a second third order effect, third order non-linear effect. So, we will going to study how this things happening say energy is going from pump to the signals and they will going to amplified it is called the Raman amplification. So, we will also going to study the Raman amplification.

So, these are roughly the overviews of whatever the topics we will have in our hand. So, in the next few classes we will going to study chi there and then after we will start chi 2 and then after we will start chi 3. So, this chi 2 and chi 3 all the effect today's class we have discussed roughly the overviews of process and from the next class we will studying detail for chi 2 effect and chi 3 effect how the non-linear process is there the detail calculation and all these things will be there in the next class.

So, with that note let me conclude here. So, see you in the next class. So, thank you for your kind attention and best of luck.