Introduction to Non-Linear Optics and Its Applications
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Lecture – 14
Optical Rectification, Linear Electro-optic Effect

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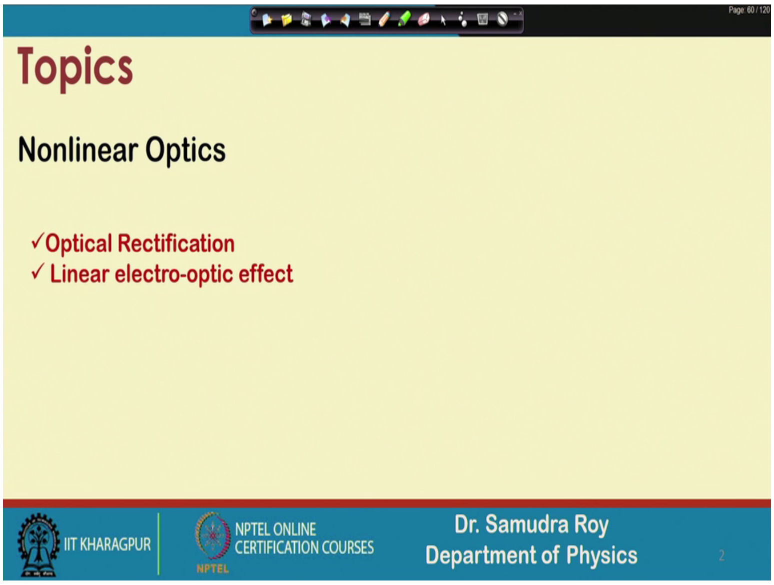

So, welcome backs student to the next class of Introduction to Non-linear Optics and its Application. So, in this lecture number 14, we will going to learn two very important concept. Last time we basically introduced that concept; so optical rectification and linear electro-optic effects. So, both the effects are very important in application wise, but before going to the applications we need to understand basically what is going on and the physics behind that.

So, in the previous class we understand in detail, how the second harmonic is generated. So, just using a very simple equation which is scalar in nature; so this scalar equation basically leads to a fact that when I launch an electric field of frequency omega into the into the system, then the non-linear polarisation can generate different terms so, non-linear polarisation has different frequency component. One frequency component is omega. Another frequency component was 2 omega and another term was there in the non-linear polarisation term which does not carry any kind of frequency term.

So, today we will going to understand what basically this term is and how it is effecting the system. So, this is called the optical rectification. We already mentioned.

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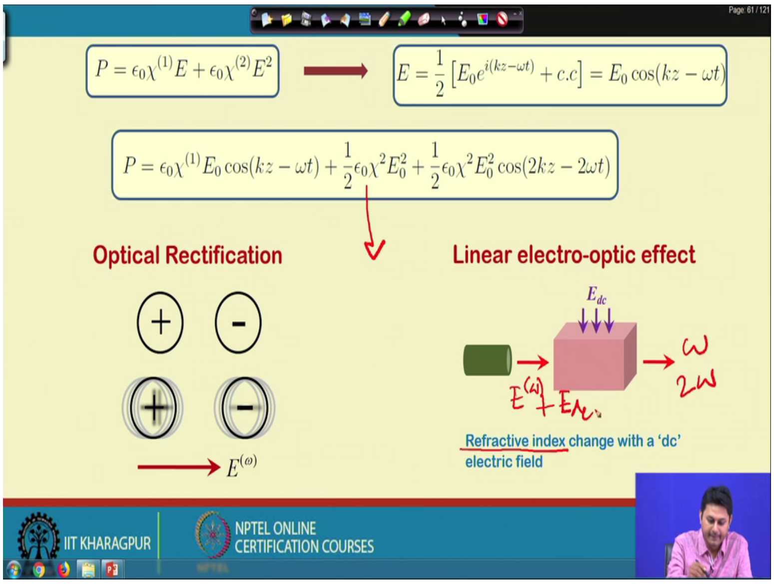

So, this is the total picture what we will going to learn today. So, let me give you some review that these was our total polarisation. P was equal to epsilon 0 chi 1 E plus epsilon 0 chi 2 E square. Now E was represented in terms of in terms of complex quantity which is E 0 to the power of i k z minus omega t, but we know that E is essentially a real quantity because electric field has to be real.

So, that is why we just add complex quantity so, make it real and if I use this complex quantity a complex this cc; that means, complex conjugate term. So, this complex conjugate term basically add up with the main term. So, it gives rise to a real quantity and this real quantity is nothing, but E 0 cos k z minus omega t.

So, when we use this electric field the value of this electric field, my total electric field become this. This is a my total electric field; so last class we have already derived that. So, in this total electric field we find we have one frequency component omega. Another frequency component 2 omega and another term was sitting here without having any kind of frequency term. So, today we will going to understand what is the meaning of this term

So, here 2 figures are there. This is 1 figure and this is another figure; so, let us first try to understand this optical rectification and the schematic figure of optical rectification. So, in the first case we have the location of the dipole, the charges of the dipole. They are well separated and now if I apply some kind of electric field, so what happened that this charge will now going to vibrate. So, this is some sort of a case; the first one is a case where the launched electric field should not have any kind of frequency component.

So, now if we introduce some kind of frequency component, what happen? Both the charge will now start vibrating and there is a effective displacement from this position. If I now draw a line both the cases, you will find there is a effective displacement of both the charges. So, this effective displacement is basically due to this dc term so; that means, I am launching an electric field.

This electric field is now has a frequency component. When this electric field has a frequency component, my polarisation term; if I include the higher order effect E square having a frequency component 2 omega and also 1 term which we call maybe the dc term this dc term is there. So, on top of dc term we have a frequency component 2 omega so; that means, my dipoles are now going to vibrate. It will not going to vibrate, but also is not just vibrate, but also the average location of the plus and minus charge will may also separate. So, this separation of the average charge is basically a term as optical rectification

Well what happened if with this condition, we launch an additional electric field from the outside. So, this is the linear electro optic effect; that means, I am launching an electric field. This is the system and this system is non-linear in nature. So, in the output I should have a frequency omega, a frequency 2 omega optical rectification term is there, but on top of that we also launch an dc electric field on that.

So, what happen by launching this dc electric field? The refractive index of the material is going to change because of this electric field. Here in optical rectification, only for this term where no external dc term is there, what happen that it will just change the separation average separation of this things, but the refractive index will not going to change. But in linear electro optic effect what happen? There is a possibility that we can change the refractive index by launching the electric dc electric field outside. On top of that I mean I am launching electric field here which is a frequency component E omega on top of that I am launching a dc field. So, we will going to discuss in detail in the next slide ok

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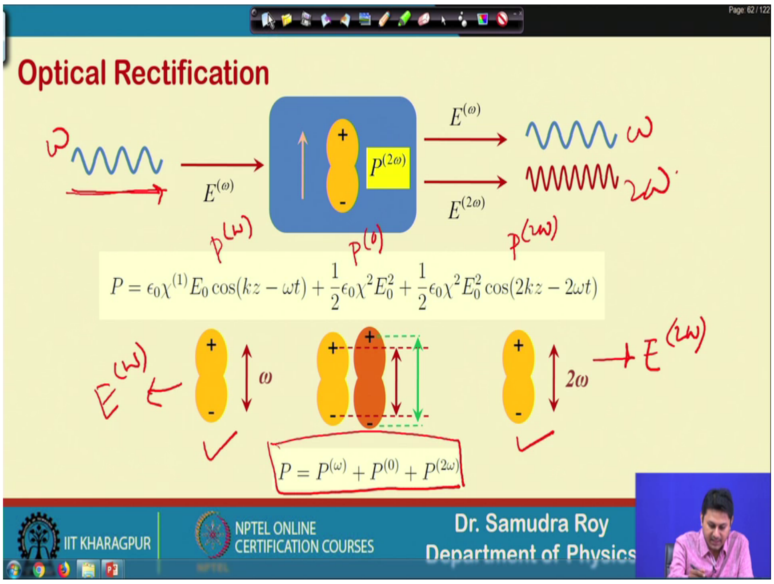

So, these two phenomena we will going to understand by using the simple equation that we have already used in our previous class. So, optical rectification as I mentioned this is the dc term. So, this figure is already used in earlier lectures that if I have a launching wave here with a frequency say omega, we should have a frequency omega and 2 omega and when we have a frequency omega and 2 omega; that means, the polarisation should have a frequency component omega, a frequency component 2 omega and also a frequency component or 0 frequency component or null frequency component we write it P 0. So, this is the equation essentially I am talking about. Here the total polarisation is represented at the three different parts.

So, what happened here, the dipole will vibrating with a frequency omega? Here dipole will vibrate the frequency 2 omega. Since it is vibrating with a frequency omega, it will generate in corresponding electric field of E omega which is nothing, but the fundamental electric field. It will start generating an electric field of 2 omega which is the second harmonic wave or second harmonic field, but what happened here. Let us understand which we have already explained in the previous slide that the this is the dipole and the average location of the dipole will going to change slightly because of this dc term

So, if this is my plus minus you can see that after applying, the field the location of the average location of the plus or average location of the minus charge is slightly changed and this is basically the effect that is happening because of this optical rectification well. So, after having this representation this nice representation, we will like to understand mathematically exactly what is going on.

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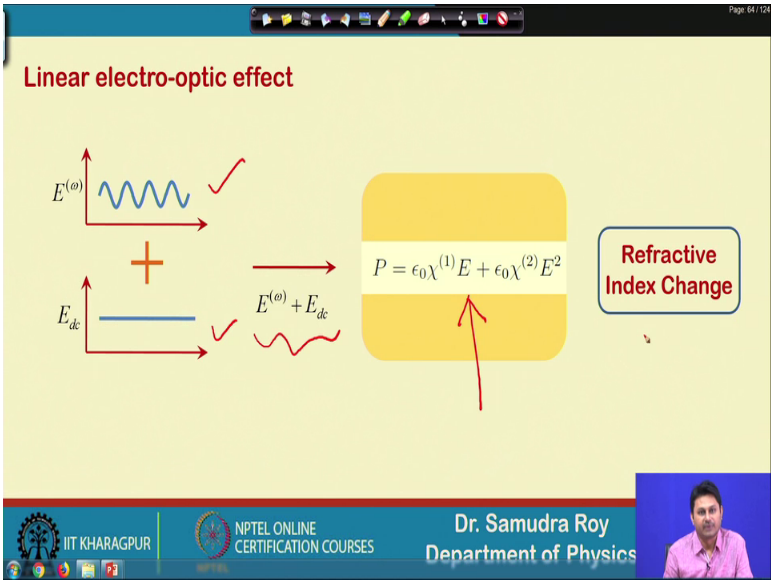

So, in linear electro-optic effect also we need to understand what is linear electro-optic effect. So, here basically in this slide, we can see that when I launch an electric field E omega; when I launch an electric field E omega which is this and a dc field which is basically since it is a dc it should not change with respect to time so; that means, it is nothing, but a straight line kind of things or dc part. So, this plus this basically the total electric field plus dc and if I go through the system where the polarisation is represented by this term, then what happen in the outcome is refractive index change. So, the refractive index is going to change this is a schematic representation of what is going on in electro-optic effect. So, that you can understand readily what is the process ok. So, as I mentioned, now we need to understand this mathematically.

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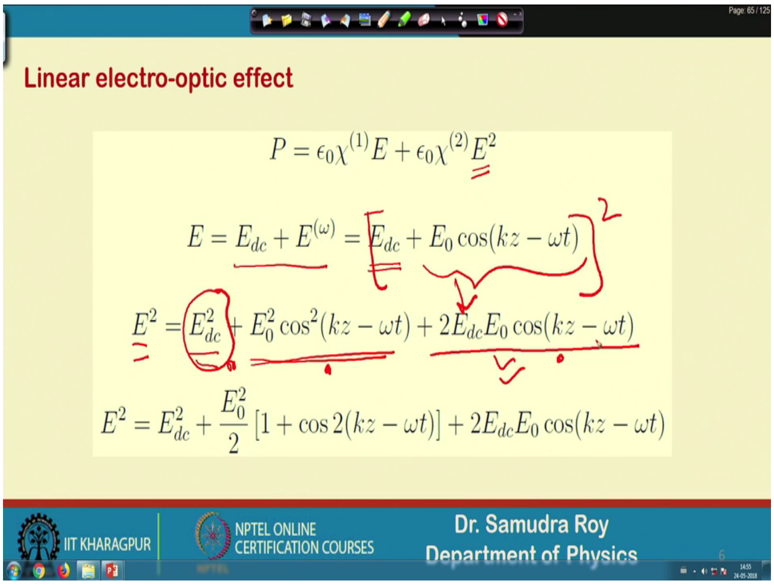

So, now linear electro-optic effect means we are launching electric field from outside. So, that is why the electric field, now not E omega E omega plus dc as I mentioned in the earlier slide. So, now, it is dc E dc plus E omega E omega is frequency component is electric field having the frequency component omega. So, it is nothing, but E cos k z minus omega t. So, since it is E 0 cos k z minus omega t, it is a real term and E d c is also a real term, but the important thing is that E d c is not having any kind of frequency component whereas, it has a frequency component term omega.

Now, the next thing is important we need to make a square of that. So, when I make a square term; so E square this E square is now here so; that means, I am making a square over this term. So, when I make a square over this term, what happen? We will have a square which is E d c plus b square which is this term the square of this term plus the coupling term; that means, 2 a b term. So, 2 a b means to dc plus E 0 cos k z minus omega t.

So, three term is appearing because of the additional term of dc mind it. When I make a square term when I make a square term because of the dc one term should be here that is for sure, but another term which is many more important is here this one. This term not only contain dc, but it coupled with the original electric field E 0 cos k 0 minus omega t so; that means, if dc is there the original field is coupled with that.

So, this is independent term, but this is independent term no d c is there, but there is a coupling term and this coupling term basically give rise the linear electro optic effect and you can understand you should realise that whenever you have a square kind of term; so this square kind of term basically if two terms are there a plus b and when i make a square of that a plus b whole square, then a square plus b square naturally it is coming. But these 2 term are not coupled, but 2 a b term is also there and this is coupled. When 2 a b term is there, things can happen I mean this coupling term basically give rise to a many important thing. So, here in non-linear optics we always find this kind of effects.

So, let us go back to our slides. So, now, what we will do we just recollect all the term. So E dc, I write E dc cos square k z minus omega t. I just want to reduce this square term in order to do that I just write 1 minus cos 2 theta with the half. So, this term also reduced and the final we have the last term and we just write the last term in simple way.

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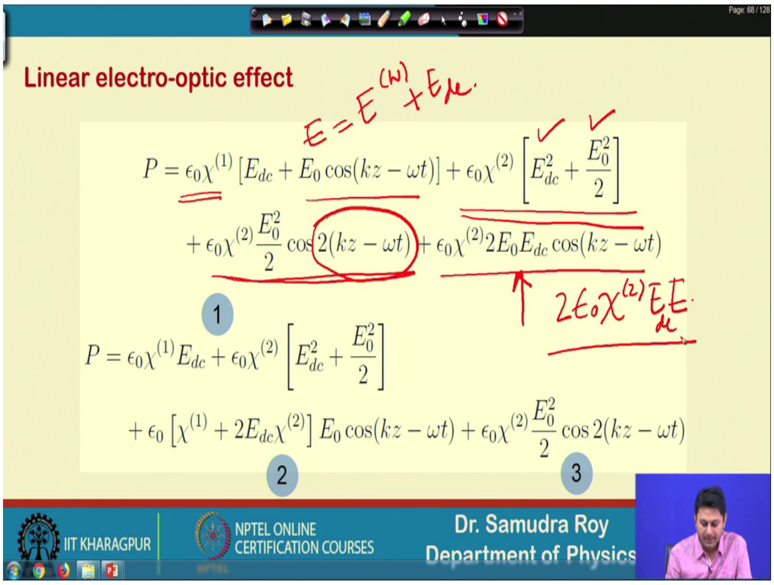

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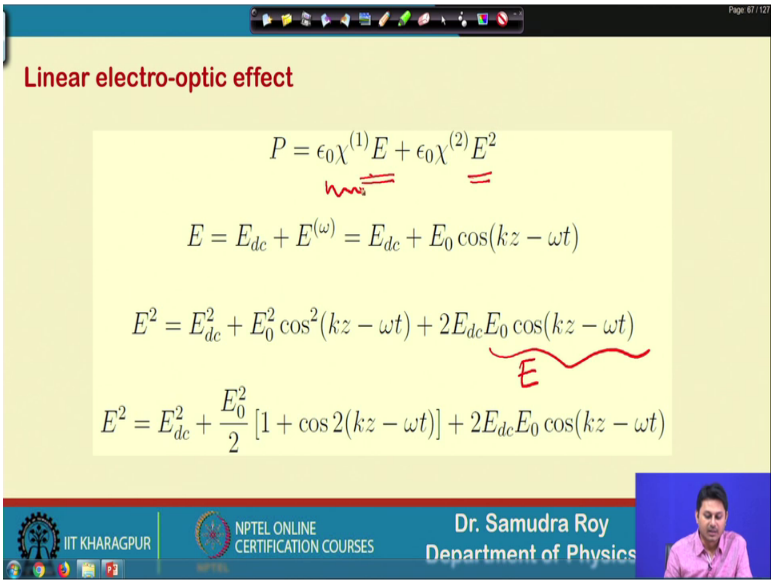

So, now after having all the terms, what we will do that we will again collect the term. So, when again collect the term means let us go back to this. So, in the first part, we have 1 electric field present here and when I make E square term here also 1 electric field term E will going to appear. In E square term 1 electric field term, E will going to appear. So, one can take common this E term both the cases. When you do that then readily find that this coefficient will going to change because of this because of this common fact

So, let us try to understand what exactly tried mean here. So, this E dc epsilon 0, we this term was there. In the previous case there is a coupling term and this coupling term basically this one and now this basically our total electric field E because my electric field was E omega plus E dc. So, I write this dc plus E omega means this term total electric field, I write here. Then I take common all the terms which are not depend on the frequency. So, this is the term where E d square term is there and E 0 divided by 2 term is also there because both the terms are not depends on frequency. So, this is the term where we have a no dependence no frequency dependence

And then we have one term where the frequency is 2 omega. If you see carefully, the frequency term is 2 omega which is naturally come because we are making square of that thing square of that thing. We are making E square. And finally, as I mentioned we have a coupling term E 0 cos kz minus omega t multiplied by E dc. So, if I write this term, you will find whether one can write it is a E 0 epsilon 0 by 2 E dc multiplied by E. So, this is a term which will going to have some effect ok. After having all this terms now again we start recollecting one by one.

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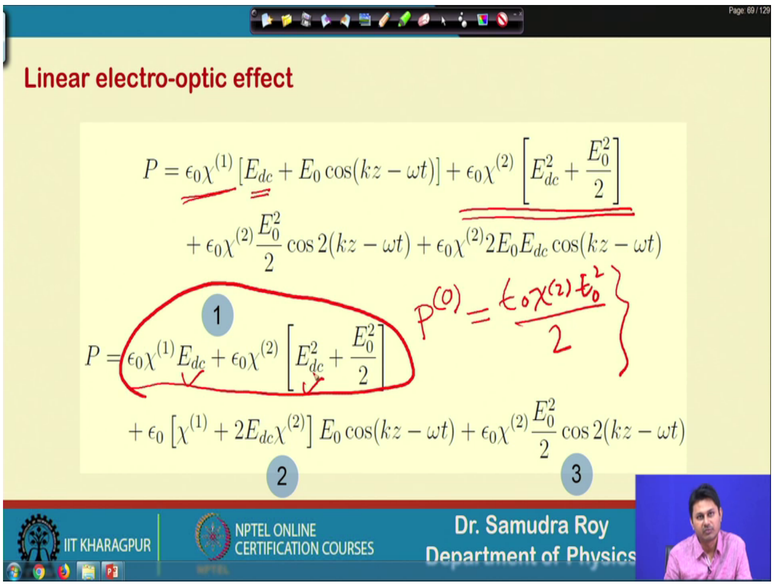

So, let us see what happen for the first term. The first term we have epsilon 0 chi 1 E dc. This term again should not have any kind of frequency component. Since this term has no frequency component, I can correlate this term with this one. Again this term is something which does not have any frequency component. So, we gather all this term and we call these things as term one as reading here this is my term one. So, the first term which does not have any frequency component, I can write P 0 mind it.

In the previous case, when we were try to find out what is going on and try to find out what was P 0; in that case in the previous case our P 0 was simply epsilon 0 chi 2 E square divided by 2 that was my P 0 in the previous case. But here as soon as I add another term E dc to my total electric field from the outside, I have 2 E dc term here which also does not have any kind of any kind of frequency component.

So, the important thing one should remember that for this linear electro-optic effect, the optical rectification term is also modified. So, here the optical rectification term in the previous case was this, but here by applying the additional dc electric field, it is now increased and this increase thing is coming; the increased value of optical rectification term is coming because we are launching the dc electric field from the outside which is quite natural ok; that was the first term.

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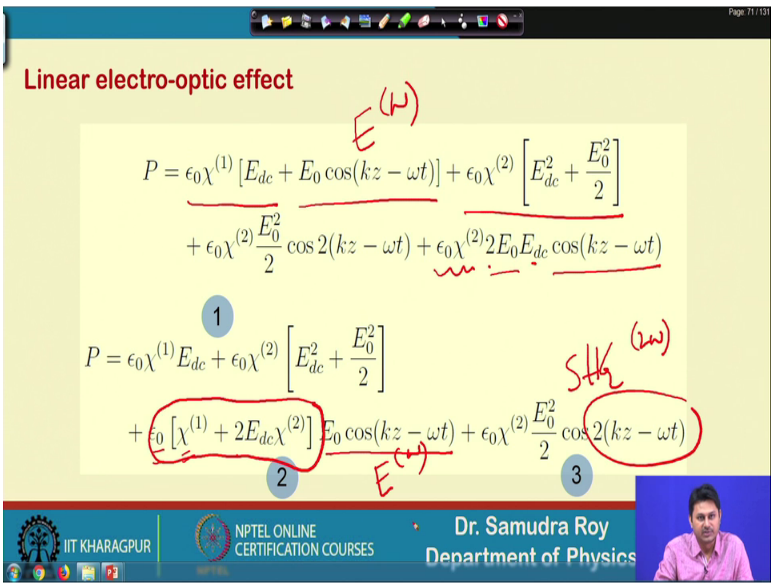

What about second term? The second term we will we collect all the term having the value E 0 cos kz omega t. That means having the value E omega. So, E dc this term, I take common; this term I take out this term I take out. So, next term is epsilon 0 chi 1 E 0 cos k z omega t. So, and another term is here E 0 cos k z omega t, but the coefficient is different here; epsilon 0 chi 2 E 0 dc. So, epsilon 0 is common both the cases. So, I write epsilon 0 here. In this case it is chi 1 and in this case it is chi 2 E dc and there is a 2; so, I do that.

And next term, E 0 cos k z omega t and E 0 cos k k z omega t both are same; so, I take it common. E 0 cos k omega t is a common and then we will have one important term here as a coefficient, in second in set of this 2 equation; I mean this if I write this is a 2 number 2 term in P. So, we have a different kind of coefficient in front of this and finally, we have a term which was already there in the previous case which is basically the second harmonic generation term having the frequency component 2 omega. So, that term is already there, in the previous case and for linear electro-optic effect, when we launch the electric field dc electric field outside this term is also there

So, when we have these three terms; the first term is basically the optical rectification modified optical rectification, term two is also modified because of the electric field and it is related to the fundamental field E omega and the next term is second harmonic generation ok. After having all these three terms, now we can understand that my coefficient is changed.

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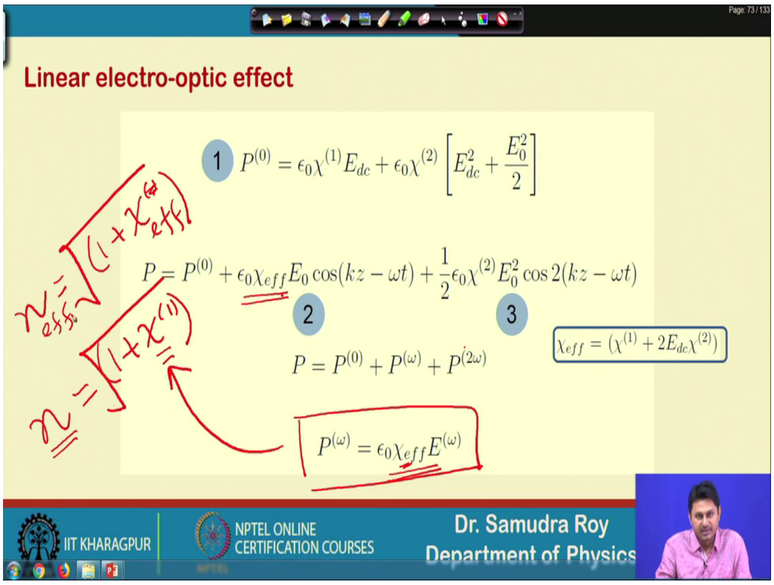

So, now if I write as I mention in the previous case that my P 0 term is now modified which is the rectification term. And now I write here, if I go back to the previous slide my two, my two term second term I have a coefficient here; in a second term, I have a coefficient here. This coefficient now I write chi effective.

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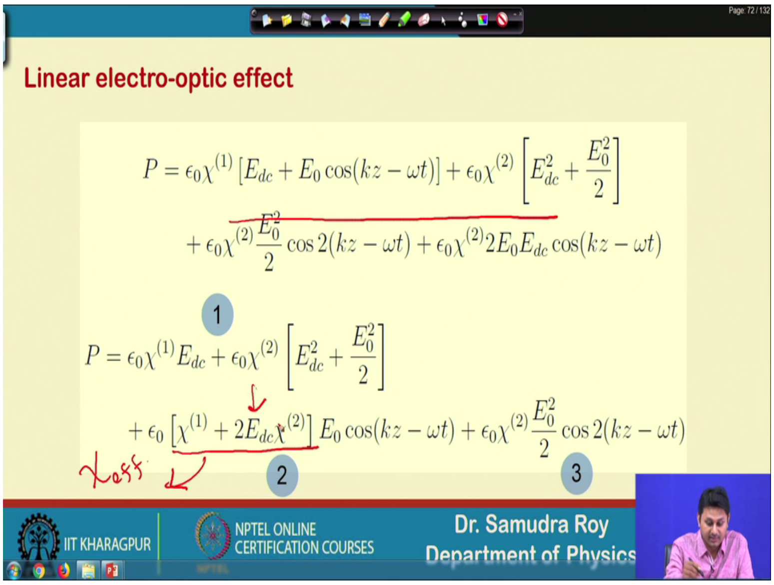

So, effective means now instead of having susceptibility chi 1, I have chi 1 plus chi 2 with the additional E dc term with multiplication of that thing. So, this combination we call chi effective. So, this chi effective is basically now a new susceptibility, linear susceptibility term. So, this new linear susceptibility term is basically a term which change the refractive index.

So, now we write here chi effect. Now we write here chi effective. All the 2, 3 terms; this is the second harmonic term as it is the P 0 term is as I mentioned the modified optical rectification term. But here the most important term is a second one. Second one term is now modified with chi effective. So, chi effective now this is P omega is E omega; that means, it is a linear relationship. So, linear part of the polarisation basically give rise to the refractive index, linear part of the refractive index.

Now inside the refractive index, we know that susceptibility is related to the refractive index because n is 1 plus chi 1 whole to the power root over of that so; that means, refractive index is directly related to the susceptibility. After applying the dc electric field, what happened here; that my susceptibility term is now modified by this effective susceptibility.

So, since it is modified the effective susceptibility, I should write my n from this equation like root over of 1 minus susceptible sorry root over of effective. So, these E effective is now become a new term as I mentioned which change the refractive name. If I write n, then I should write here n effective. So, effective refractive index is going to change here because of the application of the dc electric field.

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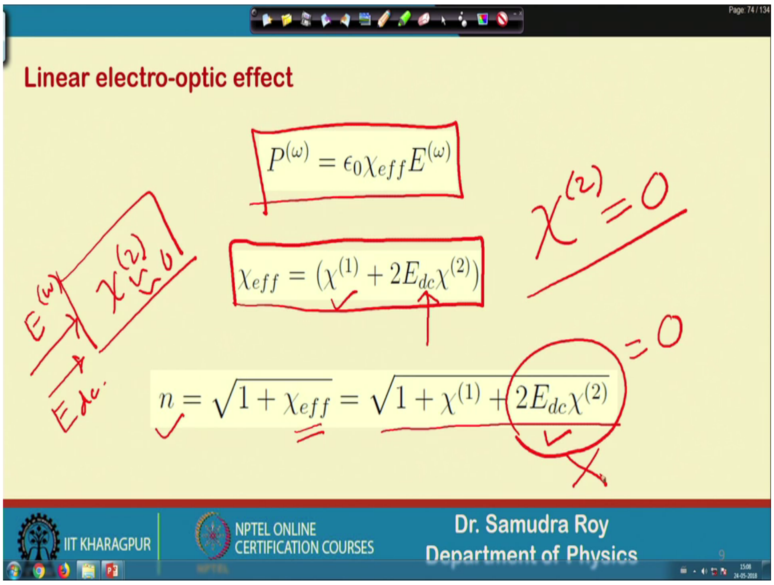

So, if I now write the whatever I mention; if I write carefully, then we will find that P omega as I mentioned P omega which is epsilon 0 chi effective E omega which is a new term that is appearing because of this dc effect. So, effective susceptibility can be represented by this; chi 1 is a fundamental susceptibility of the first order susceptibility. On top of that we have one addition term E dc in the susceptibility multiplied by chi 2. So, these 2 term basically, this combine these 2 term; if I combine together we have an effective susceptibility.

Now, after having this effective susceptibility, if I try to find try to understand what is my refractive index? So, my refractive index is nothing, but 1 plus susceptibility effective. So, this susceptibility effective if I write, I should write in this way. So, this additional term is basically is responsible for the change of the electric change of the refractive index so; that means, I can change the refractive index.

The beauty of this term is that I can change my refractive index, but in order to change the refractive index either E dc or chi 2 both has to be non-zero. If E dc is not be there; that means, if I if I not launch any kind of dc field, then this term is not there; that means, we will not going to change my refractive index. So that means, E dc is important thing, but it is not always that E dc is there. You can see that the susceptibility, second order susceptibility is also is sitting here.

So, if chi 2 is 0 in one case. So, some cases chi 2 is 0 or very close to 0 or the material is not non-linear at all, then also this term will going to vanish; that means, if I have a material where we have chi 2 nearly equal to 0. If I launch the electric field, I will with the dc electric field then; obviously, the second harmonic will not going to generate that is for sure that the second harmonic will not going to generate. But the same time the linear electro-optic effect is not also going to generate, as per the equation suggests that chi 2 is 0. So, this term again will going to vanish and if this term is not there will not going to have any kind of effect susceptible, any kind of effect here

So, today we will we have find, we have learned very important concept; two very important concept one is optical rectification and optical rectification is nothing, but if I launch an electric field in a non-linear medium having second order susceptibility, then one dc term will appear automatically that basically change the average displacement of the dipole which is already vibrating and this basically rectify this thing optically rectify the thing, but does not change the refractive index.

On the other hand, if I launch an electric field from the outside with my fundamental field, then what happen that because of this non-linear interaction due to the application of this external dc field the refractive index will going to change which is called the linear electro-optic effect. So, with that note let me conclude here. So, thank you for your attention. So, in the next class we will discuss more on the frequency mixing. So, with that note, let me finish here.

Thank you for your attention. So, see you in the next class.