Quantum Electronics
Prof. K Thyagarajan
Department of Physics
Indian Institute of Technology, Delhi

Module No. # 03
Second Order Effects
Lecture No. # 13
Non Linear Optics (Contd.)

Today, look into the three wave interaction process, where we have three frequencies simultaneously present inside the media. So, second harmonic generation and the degenerate parameter down conversation will be the special cases of this.

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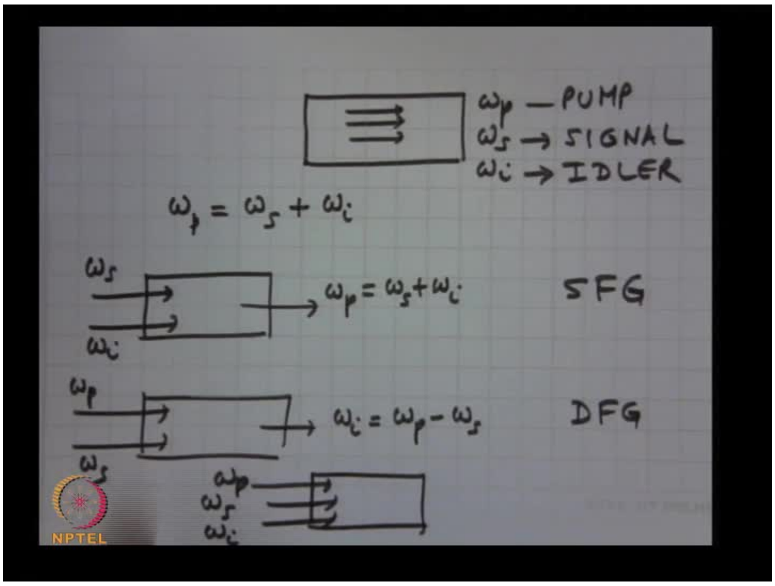

So, the problem we are looking at is - you have a crystal in which there are three frequencies present simultaneously - omega p, omega s, and omega i; they are satisfying the condition omega p is equal to omega s plus omega i.

So, depending on input conditions, I will have either of the various situations. So, for example, I can have an incidents of omega s and omega i to generate a new frequency omega p is equal to omega s plus omega I, this will correspond to some frequency generation, because the new frequency coming out is the some of these two frequencies.

If you have an omega p incident and an omega s incident, I will generate an omega i which is omega p minus omega s; this is difference frequency generation. p stands for pump, s stand for signal, and i stands for idler; these are names which have been borrowed from microwave technology.

So, here is, in the situation, photons at frequency omega, one photon at frequency omega s and one photon at frequency omega i, combine to form one photon at frequency omega p. In this process, photon and omega p frequency interacts with omega s frequency photon, and the omega p photon splits into an omega s photon and an omega i photon. So, in the process generating an omega i photon, and as you can see, the number of omega s photons will increase.

So, omega s will get amplified and in the process of generating the difference frequency. So, this is the, I will show you that this is a parametric amplifier, the signal will get amplified and in the process generate a new frequency omega i. So, the term comes from the fact that because this is the input signal, which is usually weak and you have a strong pump coming in, you can amplify the signal omega s and as a bonus you get a new frequency generated, which is omega i, the idler.

So, this is more for amplification or generation of a new frequency. If I use it as a generator of new frequency, I will amplify the signal, so, I will, but my interest is in omega i. But if my interest is in generating in amplifying omega s, I will amplify omega s, but in the process generating omega i, which will be, which I do not need to worry about that omega frequency will come out and I pick up the (( )) omega frequency.

Sir for connect frequency omega p will split into omega s and omega i that is why omega s will (( )) Yes, because I cannot generate omega i, I generate omega i by splitting omega p into omega s and omega i.

So, omega i will get generated and come out and every time an omega i photon appears, an omega s photon also has to appear, because of energy conservation. So, the number of omega s photons will increase as the interaction proceeds. So, omega s will get simply amplified. I can actually come to a situation which we will discuss later that I have all three incident.

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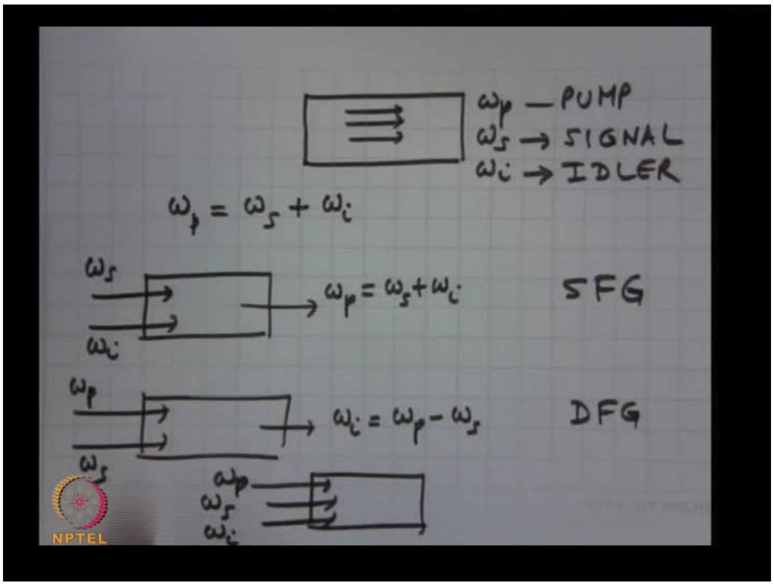

Here, the omega s will either can amplify or attenuated, depending on the phase at which these frequencies are being incident. In this case, omega s gets amplified irrespective of the phase of the signal; so, this is called phase insensitive amplifier. If I put all the three frequencies simultaneously, the omega s signal can get amplified or attenuated depending on the phase relationships between the wave omega p, omega s, and omega i.

So, I can use this process as a phase sensitive amplifier or a phase insensitive amplifier. The case we had considered earlier, where omega s was equal to omega i. This process with omega s equal to omega i is nothing but second harmony generation, and this process with omega s equal to omega i is nothing but the parametric down conversation process we had studied.

So, the case we had considered is a degenerate case, where omega s and omega i become equal, but in general, omega s need not be equal to omega i. So, this is the most general case of three wave interaction where I have three frequencies interacting simultaneously within the crystal - one at frequency omega p, one at omega s, and one at omega i, and the three frequencies satisfy this condition that omega p is equal to omega s plus omega i.

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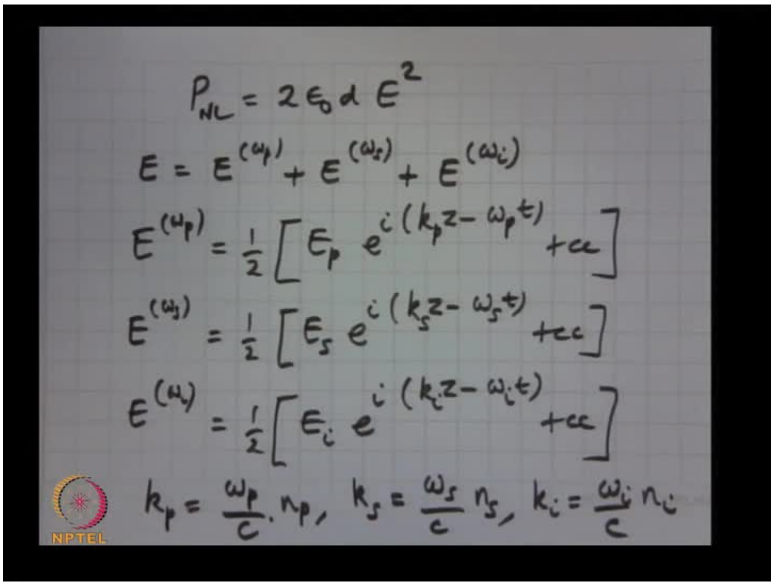

So, we use the same procedure as we did before. This interaction is completely non-linear; so, what we need to do is remember in second harmonic, what did we do? We started from this equation P non-linear is equal to 2 epsilon 0 d E square, where E is the total electric field within the crystal. A second harmonic case, we said E consists of waves at frequency omega, added to omega.

Now, in this case, the electric fields will consist of three parts: electrical field at omega p, electric field at omega s, and electrical field at omega I, all three frequencies will be present; so, E the total electrical field will actually consist of E at omega p plus E at omega s plus E at omega i.

So, for example, I will have E at omega p, I will write as half of E p exponential i k p z minus omega p t plus complex conjugate; k p is the propagation constant of the wave at frequency omega p, and E p is complex electric field of this omega p wave; this is assumed to plain wave propagating along the z direction, and as before, because of this non-linear interaction, E p will be a function of z.

Similarly, I will have for E at omega s half of E s exponential i k s z minus omega s t plus complex conjugate, and E at omega i will be equal to half of E i exponential i k i z minus omega i t plus complex conjugate. E p, E s, and E i are the electric field amplitudes of the fields of the waves at omega p, omega s, and omega i respectively.

So, k p dependents on the refractive index of the medium at frequency omega p. So, k p is omega p by c into the refractive index at tip top at the frequency omega p, which I call n p for example. So, k p will be something like omega p by c into n p; similarly, k s will be omega s by c into n s, and k i will be omega i by c into n i.

So, now, what do I do? How do I proceed? I have to calculate, I have to substitute in to the non-linear wave equation. Remember, we wrote the electric fields first, before that I need to calculate now, what is the non-linear polarization generated at these three frequencies? (Refer Slide Time: 10:03) So, I have to substitute the sum of this equation in to this equation and pick up terms, which will give me non-linear polarization at frequencies omega p, omega s and omega i.

Now, can you tell me from here, what will be P non-linear at omega p? So, I want to write P non-linear at frequency omega p, so, what I have to do is - to substitute the sum of these three and square it. So, what will be the term I will get at omega p frequency?

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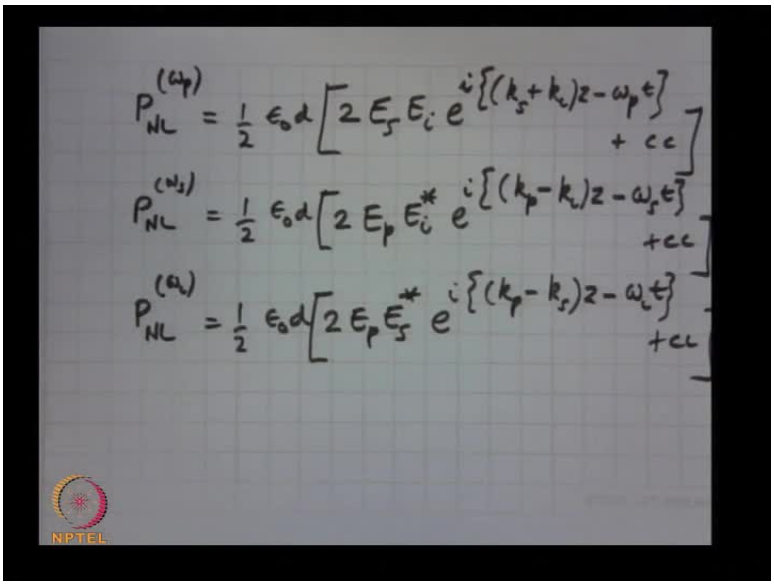

So, 2 epsilon 0 d into E square will be half epsilon 0 d, please note that this d is an effective non-linear coefficient, I am not writing d i j k. For a given orientation of the crystal, for a given propagation direction, for given polarization sates of these waves, I can, and for a given crystal, I can obtain this equation by substituting and calculating like we did for k d p and for lithium niobate, may be will two can example later, but d is an effective non-linear coefficient which depends on the state of polarization of the waves at omega p, omega s, omega i and also the non-linear tenser of the crystal.

Now, can you tell me, if I substitute this, what is the term I will get at omega p frequency? With any additional factor multiplying

(( ))

No, before that a multiplying factor I will have a plus b plus c plus d plus e plus f whole square; so, you are picking up a product of those two terms and there will be a factor of 2; so, you will have 2 E s E i exponential i, what will I get in the exponential?

(( ))

Not k p

K s plus k i into z minus omega p t plus complex conjugate, when you write all this and take a square, you will get twice E s E i, and actually, I would have got omega s plus omega i into t and omega s plus omega i is omega p and plus its complex conjugate and nothing else.

Similarly, P non-linear at omega s will be half epsilon 0 d 2, what will I get? E p E i star exponential i k p minus k i z minus omega s t plus complex conjugate, please note, because omega s is omega p minus omega i, I will get E p E i star and I will get k p minus k i.

Similarly, P non-linear at omega i will be equal to half epsilon 0 d 2 E p E s star exponential i k p minus k s z minus omega i t plus complex conjugate.

We are using the same procedure as we did for second harmonic; this will contain more polarization terms, non-linear polarization terms and many other terms. We are not bothered about that because as we have seen already for efficient non-linear interactions, we need to consider only those terms which are close to phase matching.

So, we will assume that in this process, we somehow will manage, will find out what is the phase matching condition required for this process to take place and we are assuming that it has been almost matched; so that I am only worried about three frequencies - omega p, omega s and omega i.

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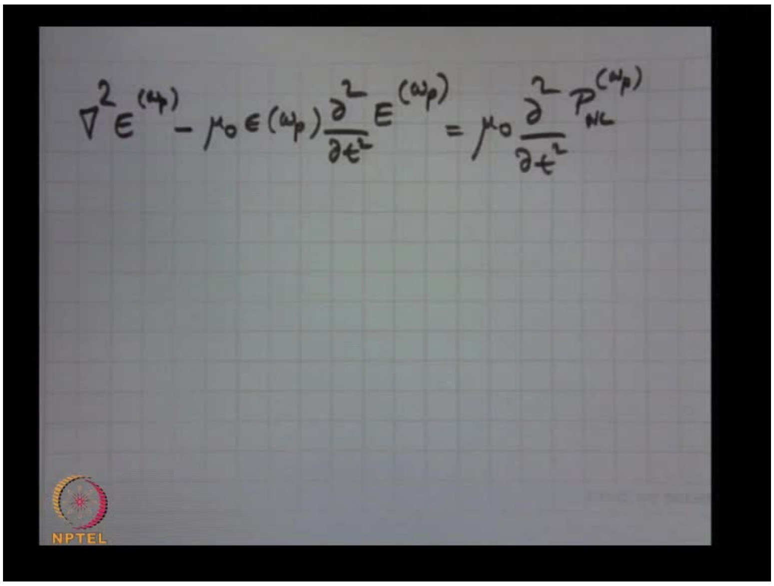

So, what did I do after this, for second harmonic? I substitute into the wave equation, remember, there was wave equation which we wrote down what was the wave equation? Suppose, I was looking at wave equation for omega p, I will have del square E of omega p minus mu 0 epsilon at omega p del square by del t square of E at omega p is equal to mu naught del square by del t square P non-linear at omega p.

For second harmonic, we had written del square E 2 omega minus mu 0 epsilon to omega del square by del t square E of 2 omega is equal to mu 0 naught del square by del t square P non-linear at 2 omega.

Each one of the frequencies must satisfy the wave equation. This is the source term, the non-linear polarization of the source term which is influencing the propagation of the corresponding frequency.

Similarly, I have an equation for omega s, where I just replace omega p by omega s, and another equation omega i, where I replace omega p by omega i.

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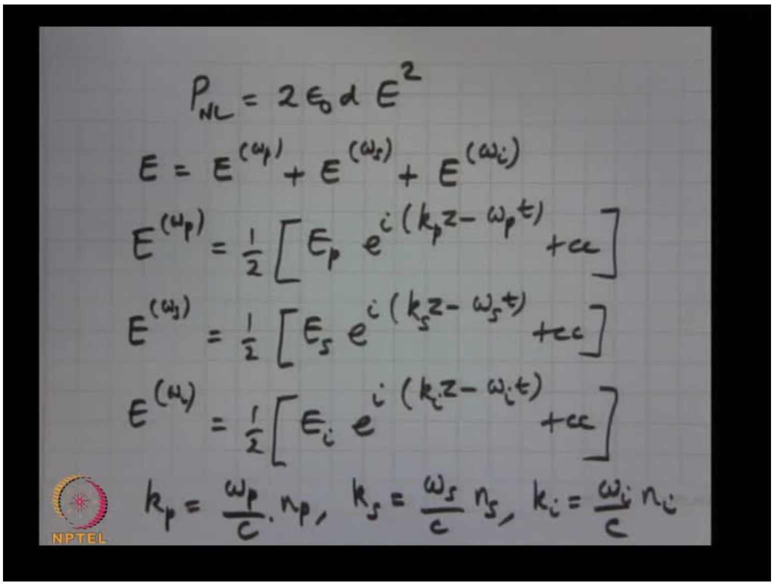

So, what I need to do is, now to substitute in this equation, substitute this expression for E of omega p and P non-linear at omega p on both sides and equate the terms coefficient of exponential minus i omega p t on both sides exactly the same procedure that I employed for second harmonic generation, and what did I neglect?

The second derivate of E p with respect to z, and I will use the condition that epsilon omega p and k p are related, k p square is equal to mu naught epsilon omega p into omega p square, the propagation constant and the permittivity are related through this equation.

So, if I use all this, this equation will simplify to the following equation. So, let me leave this substitution and simplification of this to you. Substitute the expression for E omega p from here, substitute the expression for P non-linear omega p from here, in to this wave equation and equate the terms the coefficient of exponential minus i omega p t on both sides.

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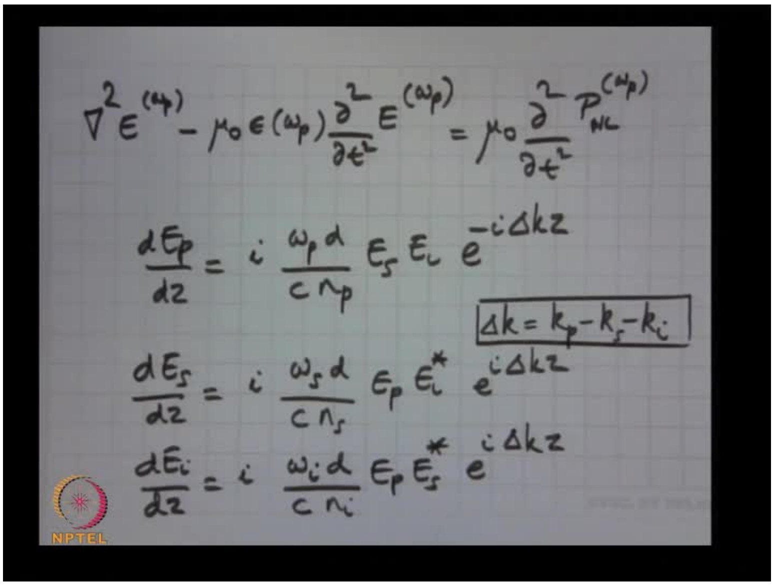

Neglect the secondary derivative E p with respect to z and use the relationship between E epsilon omega p and k p and you will land up with this equation - d E p by d z is equal to i omega p d by c n p E s E I, E s E I exponential minus i delta k z, where delta k is k p minus k s minus k i.

It is very similar to the equation we had obtained earlier, d E 2 by d z i omega d by c n 2 E s E 1 square, etcetera, same equation, exactly a similar equation; except that, now, there is a particular frequency omega p and n p is the refractive index of the medium at the frequency omega p, and delta k is k p minus k s minus k i, there it was k 2 minus 2 k 1; so, if s is equal to i this simply becomes k 2 minus 2 k 1, exactly like the second harmonic.

So, this is the equation describing the change of E p, the amplitude of the electric field at omega p frequency as the wave propagates and this depends on the non-linear coefficient d and the electric fields at signal and idler frequencies.

Similarly, let me give you the other two equations - d E s by dz is equal to i omega s d by c n s E p E i star exponential i delta kz, and d E i by dz is equal to i omega i d by c n i E p E s star exponential i delta kz. So, that is a separate definition of delta k.

So, you have three equations coupled equations, three coupled non-linear equations connecting the electric field amplitudes of signal, idler and pump.

The d is the non-linear coefficient, effective non-linear coefficient that is responsible for this interaction. Please note that if I do not choose the polarization states appropriately, the d element, the t tenser element, which is responsible for this may become 0. So, I have to be careful, but I am assuming that I am using a situation where the polarization states of signal, idler and pump are such that d coefficient is finite; there is a non-linear tenser element, there is a coupling between these three waves.

Now, as before, we will see that maximum interaction will take place for maximum efficiency of this interaction delta k must be 0, which is again the phase matching condition.

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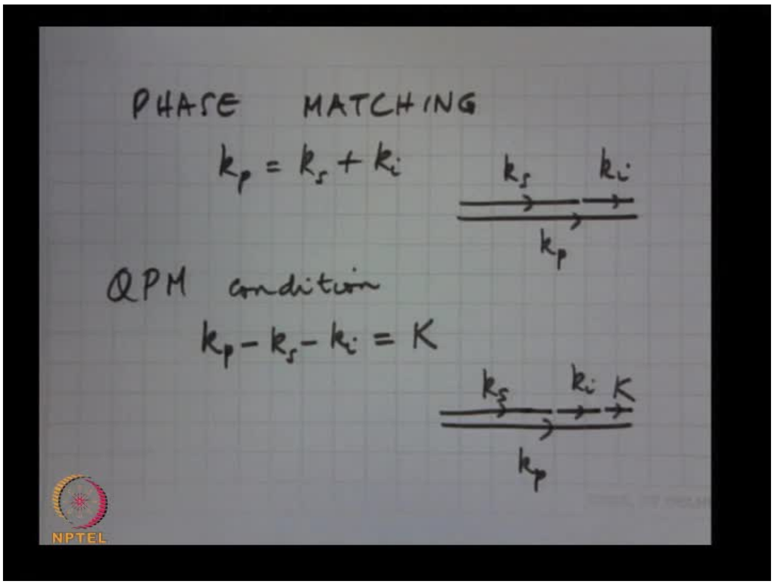

So, the phase matching condition, I will get here is k p is equal to k s plus k i, which means that I must have in terms of photon picture - the momentum of the pump photon is the sum of the memento of the signal and idler photons, that is generating or whatever it is.

In all the three process, whether it is sum frequency generation, difference frequency generation, parametric down conversation, whatever it is, I need to satisfy this condition for efficient interaction between these three waves.

Note that I can use the same quasi phase matching principle here, because in quasi phase matching, d becomes the function of z. So, what is the quasi phase matching condition? I need to satisfy. So, if I had a d varying with z, like sin capital k z, what should be the condition I will have to satisfy? k p minus k s minus k i must be equal to K, delta k must be equal to capital K. So, here, if I draw the vector diagram, I have a k p, k s, k i. By convention, the signal frequency is supposed to be higher than the idler frequency.

Pump frequency is the highest frequency, because omega p is omega s plus omega i, the highest frequency among these three is omega p, the pump frequency, then comes the signal frequency and then the idler frequency.

So, in the wave length space, idler is the longest wave length and pump is the shortest wave length. So, if I start with a wave length of 800 nanometers, so, 800 nanometer could be pump, 1300 nanometers could be signal, and I have something else which is around 1800 or 2 microns are something like as the idler. So, omega p is equal to omega s plus omega i, and conventionally, the signal frequency is higher than the idler frequency.

So, the signal wave length is shorter than the idler wave length. (Refer Slide Time: 23:49) This will be, in this quasi phase matching condition, this is k p. I have k s plus k i plus K; this is K, this is k i, this is k s, and it is for this reason that I am drawing the k s vector to be longer than the k i vector, because omega s is higher than omega i.

The refractive indices are not very different, they are different, but they are not very different. So, k s is omega s by c into n s; k i is omega i by c into n I, and because omega s is bigger than omega i, k s is usually bigger than k s.

So, the way I have drawn here, I have drawn the vector k s to be bigger than k i and k p is the biggest vector. Here, this is the quasi phase matching where I am not perfectly satisfying the phase matching condition, but I am having a periodic variation in the non-linear tenser coefficient d, such that it compensates for this delta k that is appearing here.

So, the discussion that we had for QPM for second harmonic is exactly valid here, provided I choose a capital K which satisfies this condition, which is the quasi phase matching condition.

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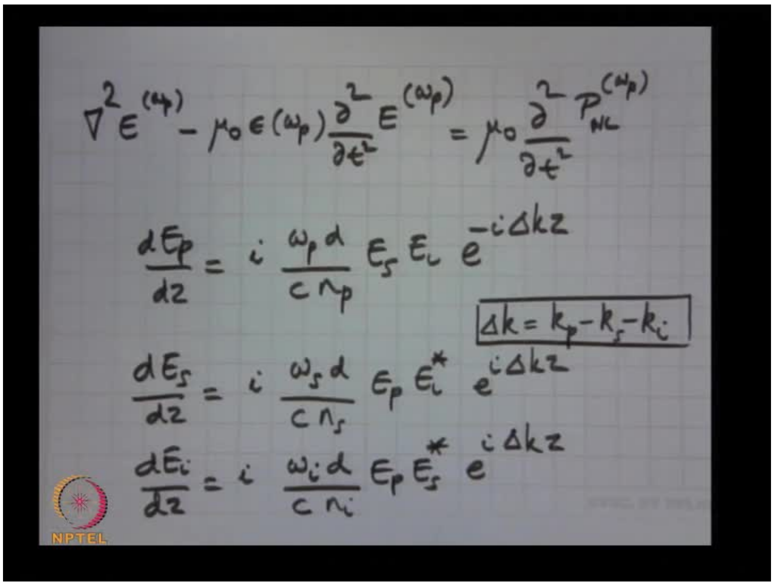

So, now, these three equations are the most general equations describing these three wave interaction process and we can use these three equations to study any one of the processes. Some frequency generation is difference frequency generation, and as before, I can show that if you have only the pump incident, you will not be able to generate signal and angular; this requires a spontaneous down conversation. So, if I take a crystal and shine only omega p, classically, just, omega p just propagates.

Quantum mechanically, I can show that an omega p incident can spontaneously generate an omega s and an omega i satisfying omega p is equal to omega s plus omega i.

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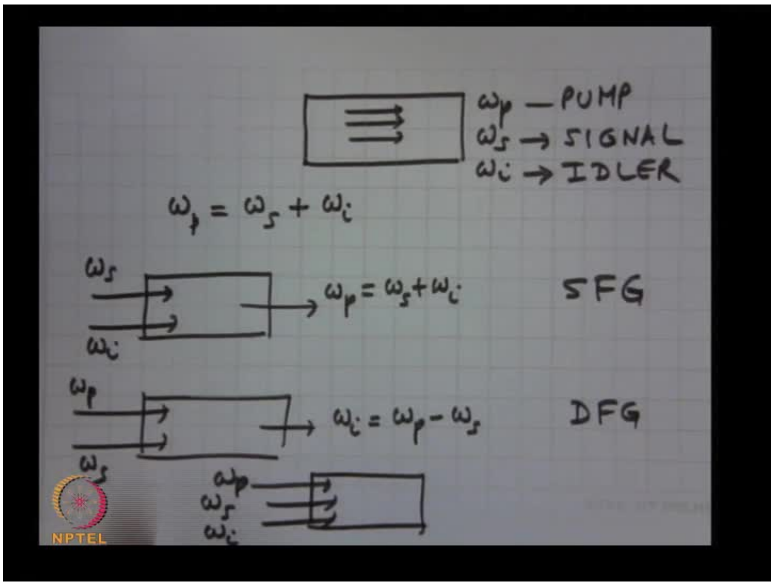

Now, because this equation has infinite number of solutions; for a given omega p, there are infinite combinations of omega s, omega i, which can sum to omega p.

So, which pair will come out, that pair satisfying the phase matching condition. (Refer Slide Time: 26:10) Because I need to satisfy this condition, as well as the phase matching condition if I need to satisfy, if I need to generate efficiently which means, I need to satisfy omega p is equal to omega s plus omega i and this condition or this condition.

There will be one pair of frequencies which will satisfy both these conditions; for given omega p, k p is fixed. For example, if I look at these two equations for a given omega p, k p is fixed and there is one omega s, omega i combination, which will satisfy both these equations that will be the one, which will be most sufficiently generated in this process.

Omega s omega i the first equation (( )) we are getting omega p is equal to omega I, that equation is different

You have to be careful, because there is, what happens is - for second harmonic, we have only one wave incident. So, when omega s becomes equal to omega i, we did not consider there were two waves at omega which were incident; so, there is a factor of two which will be coming because of this problem. So, I have to, that is why I did second harmonic from the first principle, so, I got an equation; I do the same thing here, but I cannot substitute omega p is equal two omega and go there.

Because, then remember here, there are two waves incident; I did not consider two omega incident and one or two omega have been generated; so, there is no direct transfer for here to there.

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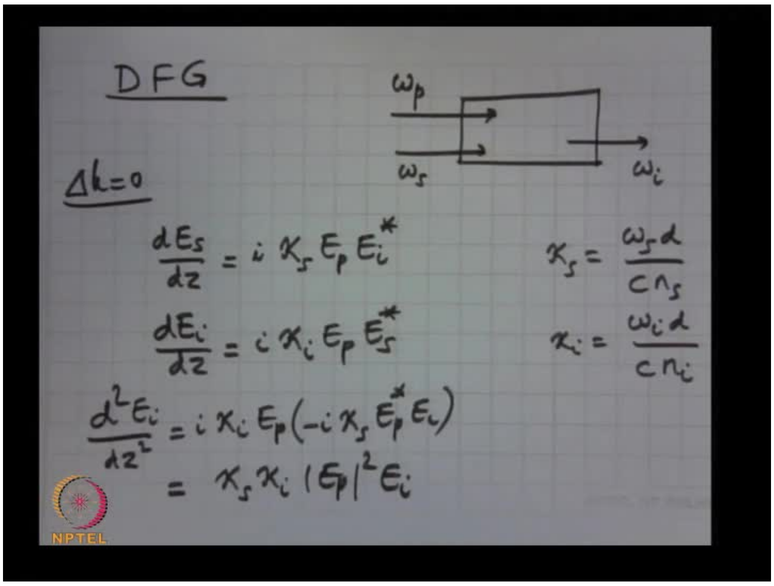

So, now, the first example let us look at difference frequency generation. So, we just look at this today and understand what is happening in the difference frequency generation.

So, what is difference frequency generation? I have the non-linear crystal, I launch an omega p wave and an omega s wave, and my objective is to generate a wave at the difference frequency omega i, which is omega p minus omega s and I will show in this process, omega s will get automatically amplified.

So, I can look at this problem as if I want to amplify omega s or to generate omega s, it is a same problem. So, how will I solve these three equations? So, what is the approximation I will make (( )) depletion which means, I will assume E p is almost a constant, so, I do not have to worry about this equation. I have to only solve these two equations simultaneously, assuming E p is a constant.

So, and, so, let me first assume delta k is equal to 0 to get some easy solutions. So, I will have two equations d E s by dz is equal to i. Now, let me write this as kappa s into E p E i star and d E i by dz is equal to i kappa i E p E s star. So, I am solving the equations for the case delta k is equal to 0, because I know already that the maximum generation of difference frequency will take place, if I satisfy the phase matching condition.

So, in these two equations, I am going to assume E p is a constant. So, let me, for example, because I am looking at generation of E i or the electric field at frequency omega i, let me differentiate the second equation. So, I will get d square E i by dz square is equal to i kappa i; so, kappa s is omega s d by c n s, and similarly, kappa i is omega i d by c times n i.

So, i kappa i E p into d s star by dz, which is the complex conjugate of this one, which is minus i kappa s E p star E i; (Refer Slide Time: 30:56) so, this is equal to kappa s kappa i mod E p square into E i.

I am assuming E p is a constant - is a high power pump coming in, so, I am assuming E p is a constant. (Refer Slide Time: 31:30)So, let me call this as, g square is this coefficient kappa s kappa i mod E p square, this is g square.

What is the solution of this equation?

So, E i of z sin hyperbolic (( )) hyperbolic

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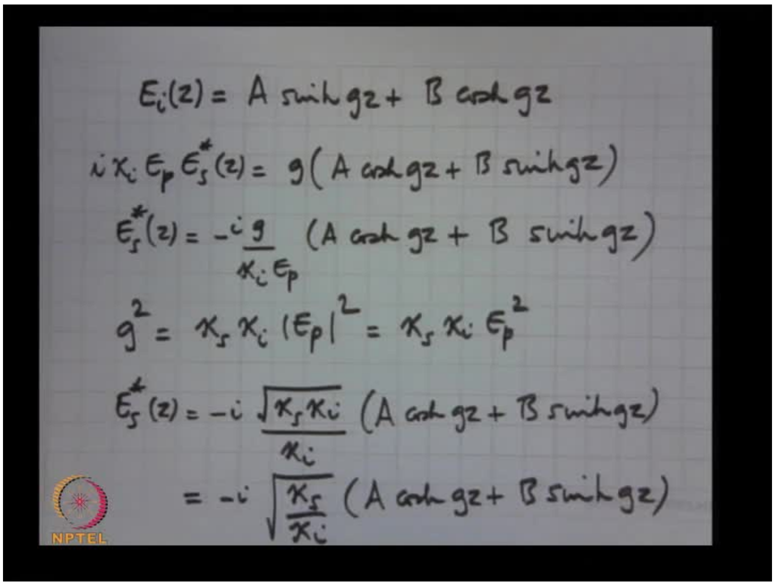

So, E i of z is equal to A sin hyperbolic gz plus B cos hyperbolic gz, how do I get the solution? For E s, I have another equation, but they are not independent remember.

We can subtract the power

No, I want, not in terms of power, in electric fields. So, what do I do? I have a solution for E i.

(( )) the linear energy will be proportional in both of them

But, you see, I want electric fields, not powers. Powers will be (( )) square, I want the electric fields.

I can again differentiate the first equation, substitute from the second equation, but I left two more constants c and d; I do not have to do that, I can substitute my solution here and get equation for E s star. Actually, I can do c and d, and then I have to substitute back in to this equation and make sure that they are satisfying this. So, instead of that, I just substitute E i of z in the second equation and get the following equation. So, i kappa i E p E s star of z is equal to d E i by dz, which is g times A cos hyperbolic gz plus B times sin hyperbolic gz.

So, E s star of z is equal to minus i g by kappa i E p A cos hyperbolic gz plus B sin hyperbolic gz. I remember, we had written g square is equal to kappa s kappa i mod E p square.

Now, let me assume that I defined the phase of the pump as 0, that is E p is the real quantity; E p remains constant and I take the phase of the pump as the reference phase, I relate all phases to that pump phase.

So, I assume E p is real quantity, so, this simply becomes kappa s kappa i into E p square. So, E s star of z is minus i, so, this g is now square root of kappa s kappa I, E p cancels off and I get kappa i into A cos hyperbolic gz plus B sin hyperbolic gz, which is minus i square root of kappa s by kappa i A cos hyperbolic gz plus B sin hyperbolic gz plus B sin hyperbolic gz.

(( ))

No, phase is also assumed to be 0 real, not decaying means, amplitude of E p remains constant, but I am also assuming the phase, I am relating all phases to that I could have substituted, but then I will get an extra phase sitting here that is all. (Refer Slide Time: 36:03) If I had written E p as E p times exponential i by p, I will get here, there will be an exponential minus i by p because of this E p here and there is mod E p square in g, but E p in here, so, I will have an exponential. Some phase factor will be sitting, it does not matter, but we will come to it a little later when we have all three waves incident and I look at a phase sensitive amplification process.

Now, what is kappa s by kappa i? Actually, I can substitute kappa s kappa i and I get this equation, so, this is E s star of z minus i. Now, kappa s by kappa i is how much?

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There is also omega.

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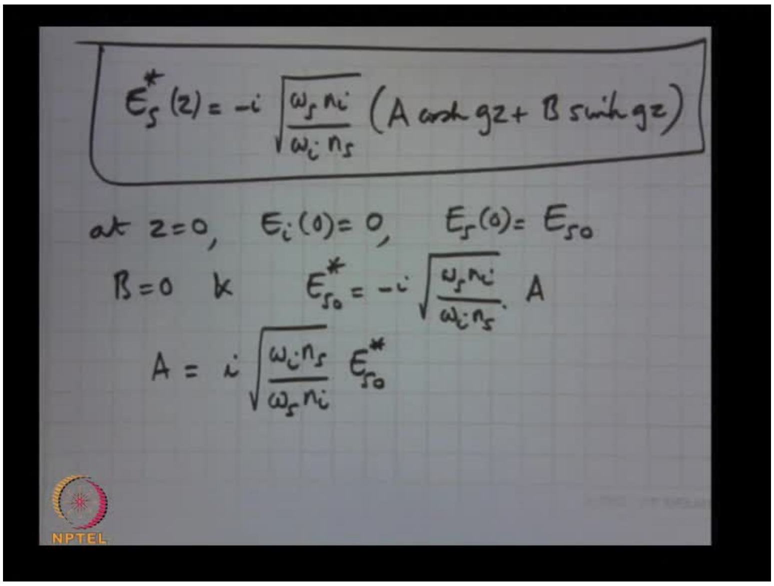

So, I will have square root of omega s and i by omega i n s into A cos hyperbolic gz plus B sin hyberbolic gz; so, these are the two solutions, E i of z and E s star of z. Now, how do I find out the values of A and B? Apply boundary conditions.

So, at z is equal to 0; so, normally, what I will have is – here, this is my problem. So, z is equal to 0, which I call this plane E i is 0. So, at z is equal to 0, E i of 0 is equal to 0, and E s of 0 is sum E s 0, there is some signal incident at the input and no idler, just a signal.

So, what are the values of the constants I get? (Refer Slide Time: 38:12)

The first one tells me B is 0, because this is 0 at z is equal to 0 that means, B is equal to 0, and E s 0 must be equal to minus i square root of omega s n i by omega i n s into A.

(Refer Slide Time: 38:37) Because if I substitute here, B is anyway 0; so I get A is into this is equal to E s star, so, E s star of 0. So, A will be equal to i times square root of omega i n s by omega s n i into E s 0 star.

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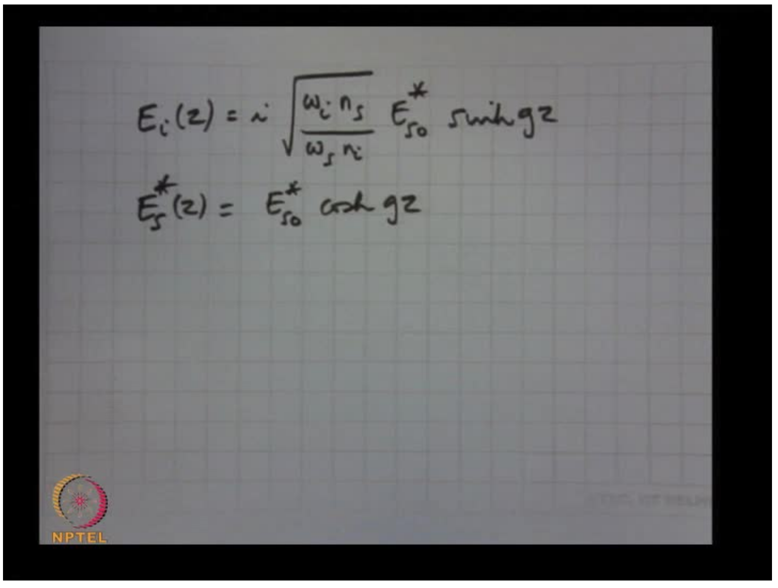

So, here, at solutions, finally solutions which I get from these two equations are So, if I substitute the values of A and B in this E i of z, so, E i of z is equal to B 0 s A sin hyperbolic gz, so, i times square root of omega i n s by omega s n i E s 0 star sin hyperbolic gz, and E s star of z is equal to E s 0 star minus i into this will be E s 0, so, E s0 star cos hyperbolic. (Refer Slide Time: 40:00) A times this minus is actually E s 0 star; so, I get A E s star of z is E s0 star cos hyperbolic gz. So, at z is equal to 0, this is 0, and this is E s 0 star.

So, first thing you notice is that, at z is equal to 0, there is no idler, but as z increases, the idler amplitude keeps on increasing. Sin hyperbolic function, how does it behave? As extent as the argument times infinity, it keeps on increasing; it is monotonically increasing function.

So (( )) idler will keep on increasing. Of course, as before, I cannot use these equations when the efficiencies become very large. So, there is an increasing of the idler power, but the signal power is also increasing; cos hyperbolic gz is also an increasing function of z. (Refer Slide Time: 40:55)

So, this process generates an idler, but also amplifies the signal and the amplification here is independent of the phase of the E s 0 the stage appearing here, but mod E s is square is always cos hyperbolic square gz.

So, this signal will get amplified irrespective of the phase of the signal with respect to pump or idler whatever it is, independent of this input condition this signal will always get amplified provided, I satisfy the phase matching condition.

So, this is an example of phase insensitive amplifier, where the amplification takes place irrespective of the phase of the signal. (Refer Slide Time: 41:42) Why is this coming factor? Please remember that every time there is a signal generated, there will be an idler generated.

So, the number of photons that are coming out at the idler frequency must be equal to the increase in the number of signal photons coming out of the crystal, because I cannot generate a million idler photons without having also generated a million signal photons.

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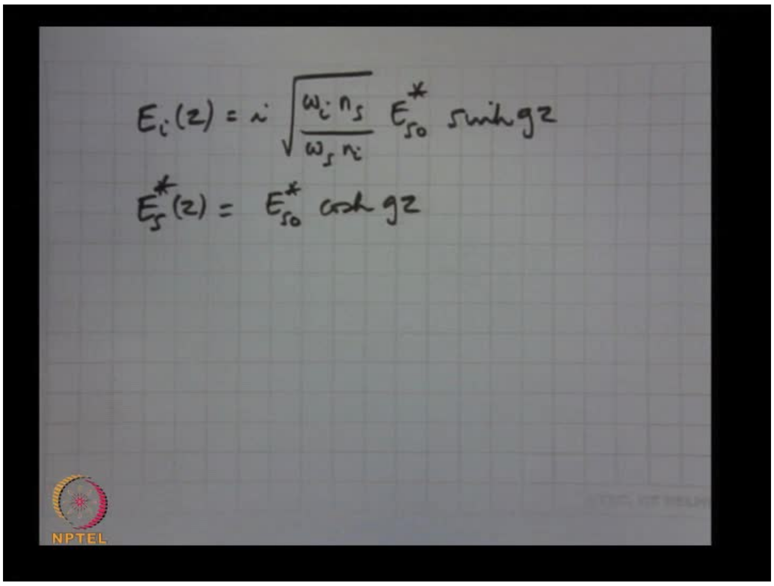

So, the increase in the number of signal photons must be equal to the generated idler photons, because at the input there was no idler, because every time an idler gets generated, a signal will generated. So, we will discuss this, we will discuss these solutions a little more detail in the next class. (Refer Slide Time: 42:43)

So, what I will show you is that this is simply the process that the pump photon is splitting into an idler and signal photon, which is generating an idler photon, and a signal photon.

But please remember, here - these are Maxwell’s equation, we have not quantized the radiation at all and these conclusions are arising just from the classical equations. I will show you that the number of idler photons coming out is exactly equal to the increase in the number of signal photons, and we will derive an equation called the (( )) relation which tells you this relationship between the number of photons coming out at the signal idler. Also remember that if I have generated a million idler photons, how many pump photons should I have lost? (( )) Same in one million.

So, if I had generated million idler photons, I should have lost a million pump photons and I would have also generated a million signal photons; I am not conserving the number of photons, because I am splitting the photons.

So, I have a million photons coming in, I convert all of them idler and I also generate a million signal photons; there will be two million photons coming out, but each photons has a lower frequency there, a lower energy; so, energy conservation is always maintained. Do you have any question? Otherwise, you will have a quiz.

(( )) does it come because of the boundary condition Right now, we have assumed that the input at only the signal and the pump. Later on, I will look at case where the input contains signal, idler and the pump. Because in the last case also when (( )) In the 2 omega case

You see, in that case, I cannot have 1 omega coming in and 1 2 omega coming in and not the other omega coming in, because here I can, because I have three frequencies, I can have omega p and omega s and no omega at the input.

There if I put omega, then I have both the inputs, it is as if putting all three waves simultaneously. So, there was no situation of phase insensitive case in the 2 omega omega case. Here I can have either omega p, omega s input or omega p, omega s and omega i input.

(( )) phase sensitive All of them will have to be phase sensitive And for theta equal to (( )) This is always phase sensitive; so, the amplification not depends on the phase of the signal of omega with respect two omega. Here, because there is only omega s and omega i incident, the phases of the various waves automatically get fixed up to amplify the signal and to generate the idler.

What we require (( )) ultimately they are still having a phase matching No, that is phase matching; phase match - that means, delta k is equal to 0, what I will show you later on is that if I input this signal, idler, and pump simultaneously, the signal will get amplified only under certain condition of phase relationship between the signal and idler and pump. If I change the phases of the signal, I will get de amplification, that means, I can either have omega p generating omega s omega i and amplifying omega s or omega s and omega i mix together to generate omega p, which will attenuate the signal.

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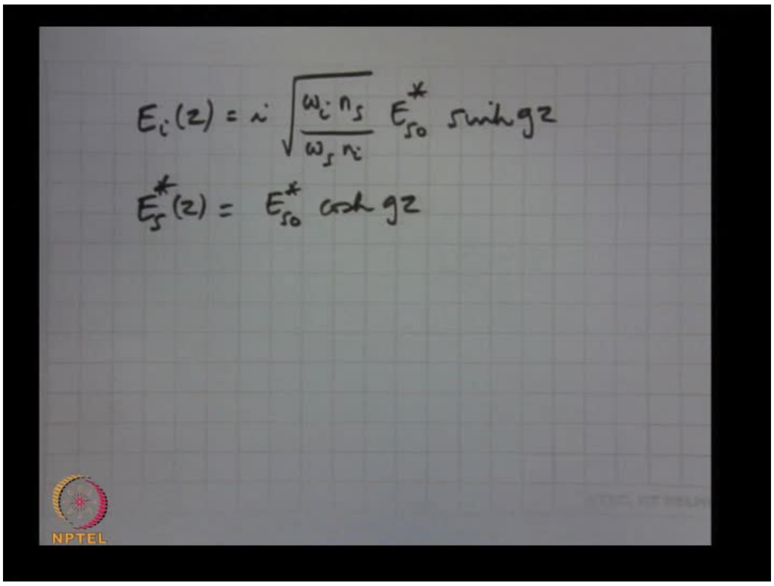

So, depending on the phase relationships, I will either amplify the signal or attenuate the signal. So, the energy is getting converted some omega p to omega s or omega s to omega p, and that will be phase sensitive.

So, that will be phase sensitive nature of an amplifier; here, there is no phase sensitivity, because the idler automatically picks up its phase, so that the signal always gets amplified and that is the difference between phase insensitive and phase sensitive.

Phase sensitive we will look at little later, but right now, we will discuss a little bit more on these solutions and get some important conclusions from these solutions. Anything else.?

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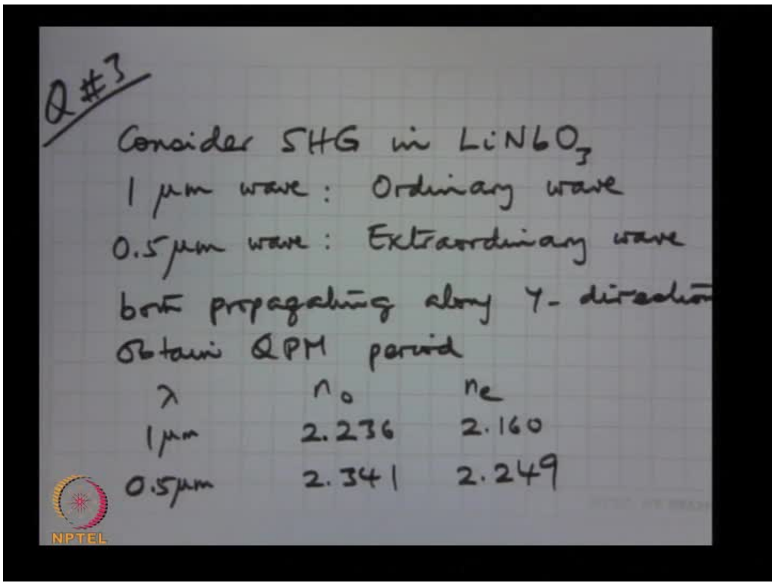

So, we have a quiz now. Fine, the last quiz before the (( )) This is quiz number 3. So, the problem is - we are considering second harmonic generation in lithium niobate, the 1 micro meter wave is an ordinary wave and the 0.5 micro meter wave is extraordinary wave and both of them are propagating along the y direction; this y is the principle axis, y direction. What is the quasi phase matching period required for this process - first order quasi matching period?