Quantum Electronics

Prof. K. Thyagarajan

Department of Physics

Indian Institute of Technology, Delhi

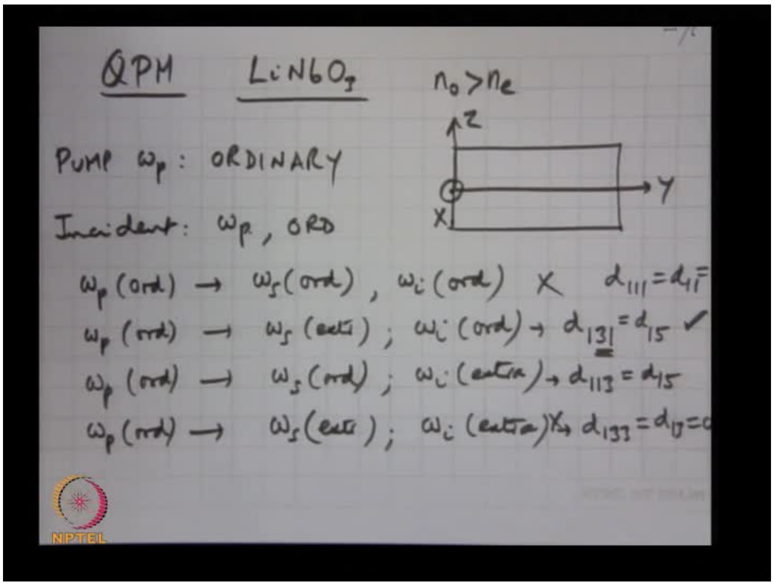
Module No. # 03

Second Order Effects

Lecture No. # 17

Non - Linear Optics (Contd.)

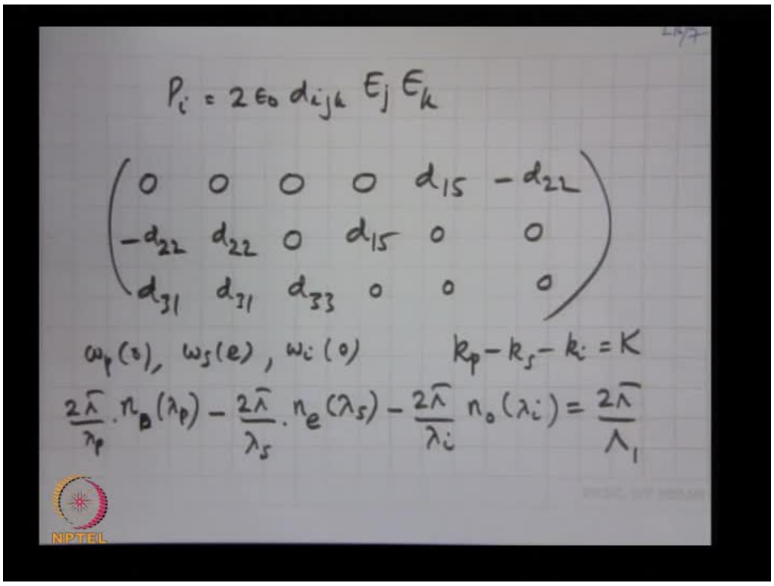
(Refer Slide Time: 00:38)



Let me recall what we were discussing last time. We started looking at the following situation, where the input pump is an ordinary wave, always along the x direction, and propagating along the y-axis in lithium niobate. Then, we found out the possibility of generating a signal and idler pair which are ordinary ordinary or extraordinary ordinary, ordinary extraordinary and extraordinary extraordinary; because of Quasi-phase-matching, I can always ensure that phase matching is possible through a Quasi-phase searching phenomenon; and hence, in principle, I should be able to generate any of these pairs.

So, for lithium niobate, we have found that to generate the ordinary ordinary from an ordinary pump, you need a d 11 element and that is 0 in lithium niobate; so, this process will not take place. The omega pump which is ordinary is getting converted to extraordinary ordinary pair or the ordinary extraordinary pair, can happen because of the d 15 which is non-zero; and then, to convert the ordinary pump into an extraordinary pair of signal and idler photons requires a d 13, which is also 0. So, the only possibility is, if I launch an omega pump which is ordinary wave, I can generate an orthogonal pair of signal idler photons or like, which is, that means, I can have either this signal as an extraordinary wave and an idler as an ordinary wave, or the signal as an ordinary wave and the idler as an extraordinary wave.

(Refer Slide Time: 02:26)

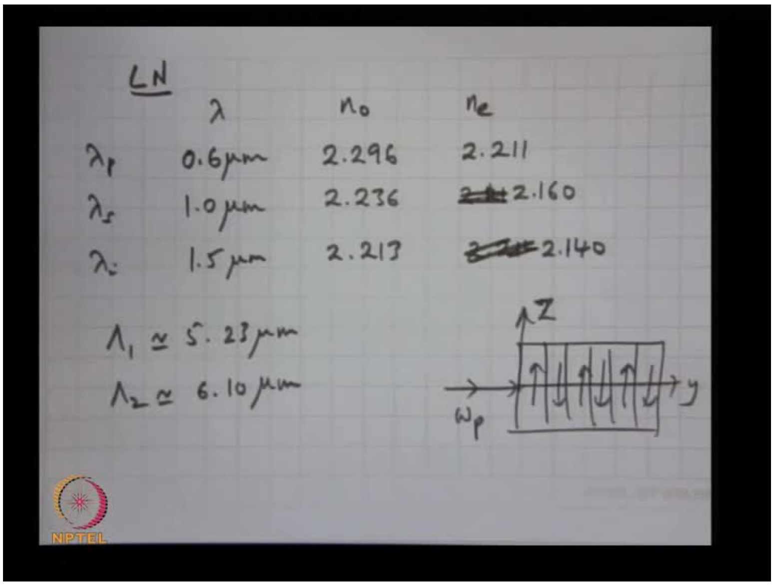


Because, these two processes are different, we need two different phase-matching conditions, and I have written down the phase-matching conditions corresponding to the two processes. The first 1, required this condition - the ordinary pump, extraordinary signal, ordinary idler and you need a capital lambda 1 periodicity for achieving Quasi-phase-matching.

So, if I generate a medium with this lambda 1 period, calculated from this equation, then an ordinary pump photon can down convert to an extraordinary signal photon and an ordinary idler photon; that is parametric fluorescence which we have not yet derived or obtained, that will come from quantum-mechanical analysis. But, at the same time, we have we can see, that if I launch an ordinary pump photon light and an extraordinary signal light, the extraordinary signal can be amplified by the same process.

Similarly, if I launch at lambda i wavelength, an ordinary wave and a lambda p wavelength, ordinary wave, the lambda i will get amplified and lambda s will get generated in the process. The polarization states of the output are automatically defined by the phase-matching condition and the non-zero element of the of the d tenser. It is also possible to generate a pair of ordinary signal photon and extraordinary idler photon, provided I have another period, capital lambda 2, because it depends now on the ordinary index at lambda s and the extraordinary index at lambda i; this lambda 1 depended on extraordinary index at lambda s and an ordinary index at lambda i.

(Refer Slide Time: 04:17)



So, as an example, let me take lithium niobate. Again, let me go back to lithium niobate and let me look at these following wavelengths, lambda n o n e; let me take a 0.6 micron wavelength, the ordinary index is 2.296 and extraordinary index is 2.211; at 1 micron wavelength, the ordinary index is 2.236 and the extraordinary index is 2.160, sorry 2.160 So, if this is the pump and this is signal, what will be the idler wavelength? Can you calculate? What will be the wavelength of the idler? How much?

0.67? No.

How much is it?

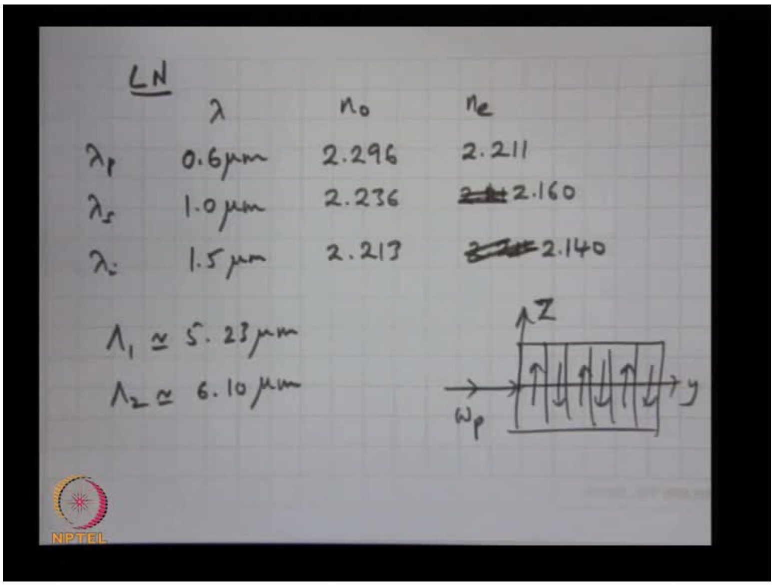
1.5 micrometer.

Please be careful with the calculations. 1.5 micrometer; so, that 1.5 micrometers, the ordinary index is 2.213 and extraordinary index is 2.140. So, I have actually calculated this from the Sellmeier equation for the ordinary and extraordinary indices of lithium niobate. So, these are estimated values so, I can use these equations to calculate lambda 1, because I know ordinary extraordinary indices at the three wavelengths; and similarly, I can also use the second equation to calculate capital lambda 2; and what I find is, lambda 1 comes out to be 5.23 micrometers and lambda 2 comes out to be 6.1 micrometer; not very close but... They are different, they are different periods. The periods are different, because the refractive index at the wavelength is different, and the polarization states are different.

So, if I make a grating of 5.23 micron and launch an ordinary polarized light at 0.6 micron, in the crystal; so, omega p I am launching, so, if the incident light at omega p is ordinary polarization, then, and of the grating here, this is a Quasi-phase-match grating here, corresponds to a period of 5.23 microns, then, I will convert the 0.6 micron to the two wavelengths 1 micron and 1.5 microns wavelengths; and their polarization states will be automatically determined by the fact, that the first one corresponds to a signal which is extraordinary; this one will give me an extraordinary signal and an ordinary idler; this one will give me an ordinary signal and an extraordinary idler pair.

So, as an amplifier, I can use this, this particular period, to amplify an extraordinary polarized signal, and in the process, generate an ordinary polarization idler; this one I can use, this period I can use to amplify an ordinary wave at 1.0 micron and generate an extraordinary wave at 1.5 microns. So, the crystal, the directional propagation and the polarization state of the pump, determines what is possible and what kind of periods I need to achieve this interaction process. Now, suppose I were to launch light at 0.6 micron, and imagine a situation where I have in this port crystal here, I could generate somehow both these periods.

(Refer Slide Time: 08:43)



Remember, I do not have to have a sinusoidal function, I can… I do not have to have one period; I can have a functional dependent which has more than one period - need not be periodic; if I have multiple periodicities in a function, I can have multiple spatial frequencies, I can have a function of time which has frequencies omega 1 and omega 2 simultaneously; cos omega 1 t plus cos omega 2 t, a function of this type has both frequencies.

Similarly, I can have a grating, a spatial variation in which both periods are present simultaneously; I will come to this problem later when I discuss the quantum-mechanical aspect. So, if I both getting simultaneously, what will happen if I launch a pump which is ordinary? So, in principle, both wavelengths will have both the pumps, will have both the polarization states.

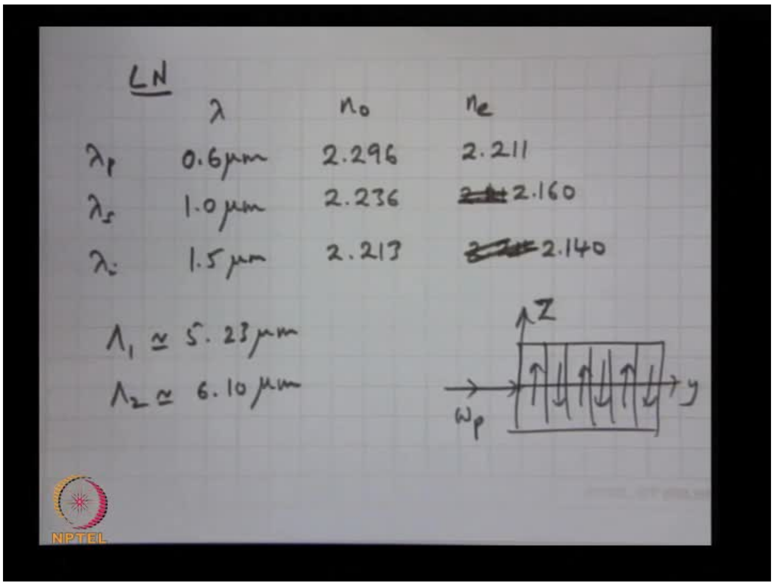
So, let me launch light pump light, so the pump photon which comes in, could interact with this grating and generate an extraordinary idler and an ordinary signal pair; it could, at the same time, have interacted with this grating and generated an ordinary signal and an extraordinary idler pair; both are possible. Classically, I will say that the output consists of either an extraordinary signal and an ordinary idler or an ordinary signal and an extraordinary idler. What I will show you is, when I look at the quantum-mechanical picture of this interaction process, this is incomplete. I will show you that the output polarization state of the signal and idler are undefined; they will get defined by the process of your measurement.

There is a complete difference in terms of pictures which I can generate from classical and quantum-mechanical analysis; and, the photons that will come out, the pair of photons that will come out here, have this property of what is called as an entanglement, polarization entanglement. And this, I will come to a little later when we discuss the quantum picture; but please note here, that I could have structures which has multiple Quasi-phase-matching periods; I showed you this is a part of domain engineering. I can have a domain reversal, which is, whose period is changing with position called chirped grating, I could have all kind of functional dependence; this functional dependence is my choice. And depending on the choice, I can generate, in the functional dependence, multiple periods and those multiple periods will then be responsible for interaction with this input pump photon to generate pairs of signal and idler or, idler photons.

So, that is a very interesting picture that will develop when we do the quantum-mechanical analysis, because the quantum-mechanical analysis is not just read trying to calculate a spontaneous efficiency and so on; the picture is completely different. The predictions from there have no classic counterparts; the properties of the generated photons here which are coming out cannot be explained classically. There are there are certain properties which have no classical explanation, and that needs a purely quantum-mechanical treatment; and, that is what we will do after we finish up the classical discussions on non-linear optics; and, one of them is the property of entanglement where the light coming out from here, now; the signal and idler photons which are coming out are said to be entangled in polarization states, that means, the state of polarization of the output here are undefined. The only thing I know for sure is that, signal and idler photons are orthogonally polarized.

Classically, I will say it is either the horizontal vertical pair of signal idler or the vertical horizontal pair of signal idler; if signal is like this, idler will be like this or, if idler is like this, signal is like this; this is the only conclusion I get from here. But what I will find out when I doing the quantum-mechanical analysis is, that, this is more than this; it has some properties or, I cannot even define the polarization state of the output light, or the signal or the idler; it is undefined.

(Refer Slide Time: 13:47)



The polarization state will get defined, the moment I do a measurement of the polarization state; and what I will find is, whatever measurement I do on the signal photon, influences the result on the measurement of the idler photon, irrespective of the distance separating these two photons. So this, I will explain again later, but this is an interesting feature that will come out from purely quantum-mechanical argument; I cannot show this through a classical arrangement.

For a given period, let us say capital lambda 1, then also, quantum-mechanically, both the polarization states are possible; if you have a grating, first one into only period lambda 1.

Yes, I will only generate a signal which is extraordinary and an idler which is ordinary.

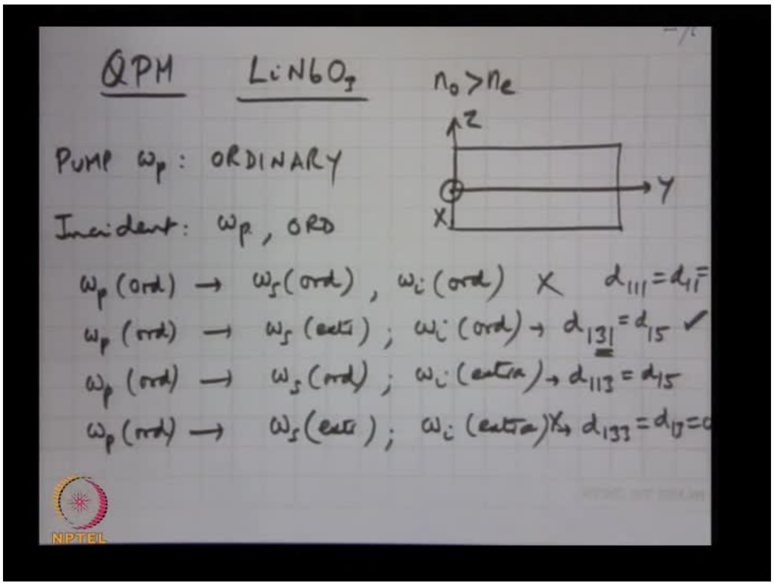
This is in agreement with quantum mechanics and but, if we have both the periods, then the entanglement property is there.

Yes, because, when I have both periods, both processes are possible; and the output is not simply either this or this; it is more than that; and that will come out when we do the quantum mechanical-analysis.

And classically, both kind of polarization of both the ladles are there, if you have double…

Yes, that is what I am trying to show you; classical explanation tells me that, with this grating, if… Because, when the photons comes in, if it interacts with this grating, it will generate an extraordinary signal ordinary idler pair; if it is this grating which affects it, it will generate the other pair. So, the output is much more than this classical interpretation of what is coming out. So, given a crystal, and given a crystal means, given the d tenser of the crystal, I can find out what are the possible orientations of the pump and signal and idler, which can interact through the non-zero elements of the d tenser; and knowing that, I can also calculate what are the grating periods required for this interaction to phase-match or Quasi-phase-match and so on. So, all this is contained in the energy conservation equation, the momentum conservation equation and the d tenser of the crystal.

(Refer Slide Time: 16:30)



So, what we have done in the class right now is, just discussed one example of incident line at omega p being an ordinary wave, and with the possibility of generating orthogonal polarization states of this signal and idler.

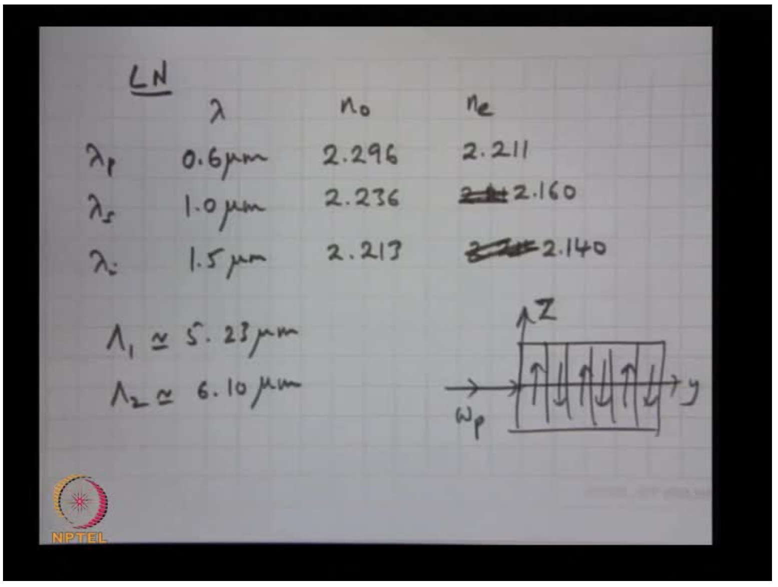
Sir, when we have two gratings and we will be having externally the polarization of both the signal and the idler, so there will be like interference of this; we have extraordinary signal and extraordinary idler, so they will…

No, they are two different frequencies anyway.

Which kind of signal?

Yeah, or the pitch are at such a high frequency, that you cannot normally observe them; unless the frequencies are very close, your detector will not, your detector will respond to your detector responds to e 1 plus e 2 mode square, which is e 1 square plus e 2 square plus 2 e 1 e 2 into cos phi, between the two electric fields; but, because the frequencies are different, the interference term is varying so fast like beats, exactly like beats, that normally you will not observe.

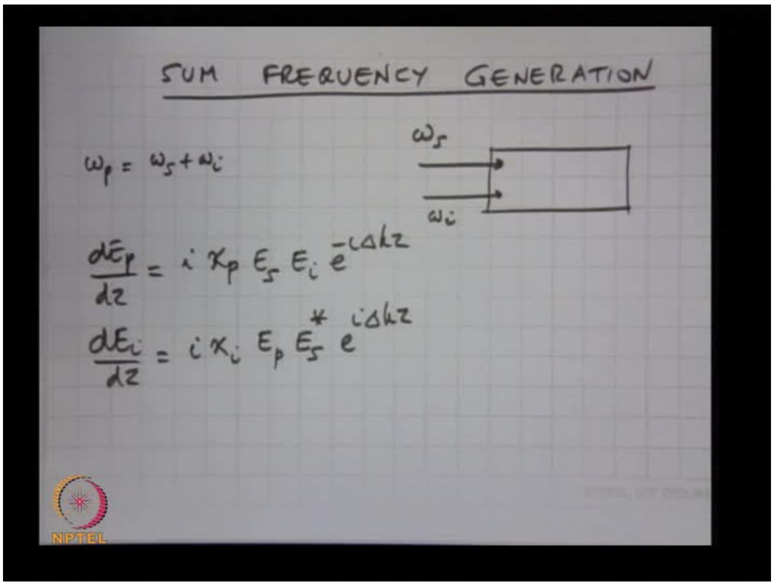
(Refer Slide Time: 04:17)



If the frequencies are close by a few kilohertz or few megahertz, then the detector can respond and tell you that there are beats coming in; that is possible, surely possible. So, these frequencies which were…; these wavelengths are very far apart. Frequency difference is so huge, that the detectors do not normally pick up theses beats, but otherwise, you are perfectly right. Anything else?

So, what I wanted to do before we move into an oscillator problem is to discuss the sum frequency generation. So, what we will do first is to look at the following problem, that now, I have, I want to look at sum frequency.

(Refer Slide Time: 18:12)



So, tell me what I should consider as input? omega s and omega i. Because, I want to generate an omega p, which is equal to the sum of the input frequencies; I could have called it omega 1 omega 2 and the output of omega 3; it is the same. But I want to use the same set of equations, so I will use the same equation for the frequencies, so, omega p is equal to omega s plus omega i. So, what pair of equations do I pick up to solve and what approximation should I make?

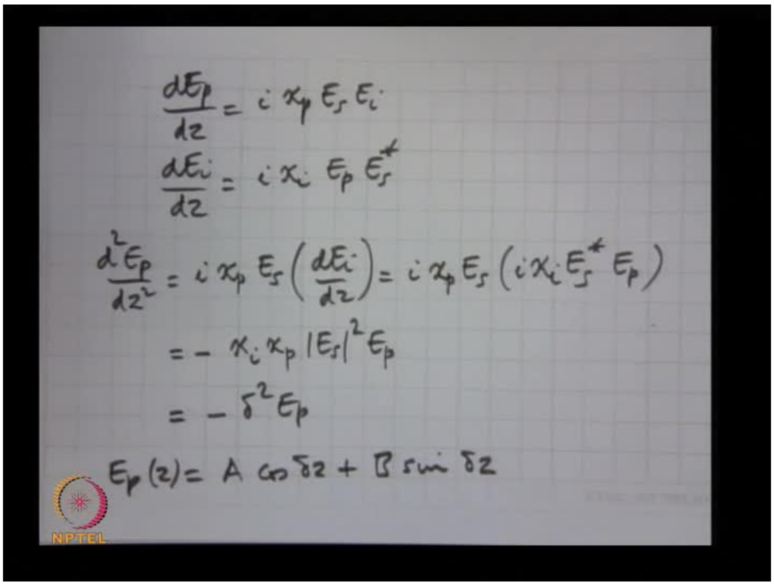
I have 3 equations; one for omega p, one for omega s and one for omega i. So, out of this, for example, remember, in difference frequency generation, we had omega p and omega s coming in; and I assumed omega p is a strong light beam, intense light beam, and omega s is weak, so, I amplify omega s and I generate omega i. Here, I want to do some frequency generation, so one of these beams has to be high power; so, let me assume that to be omega s, and omega i is a weak beam. So, let me give you a typical example; remember, omega i is smaller than omega s, so, lambda i is larger than lambda s. So, suppose I have light coming at 1.8 microns wavelength, there are no efficient detector there for this light; and secondly, the detectors which are available are quite noisy.

So, what I would like to do is to convert the light signal at 1.8 micron into less than 1 micron, where I can use silicon detectors to detect light and process signal; it is a very efficient method. So, I have 1.8 micron, I put a light at a lower frequency, say, 1 micron;

the sum of these two, you can calculate; it comes to below 1 micron. So, I can actually convert light at higher wavelengths to light at smaller wavelengths by using the sum frequency generation process; it is very similar to second harmonics. Second harmonic is omega s is equal to omega i, here they are different. So, now tell me which equations should I take? omega i and omega p equation. And assume E s is almost a constant, so let me write down the equation; so, d E p by d z is equal to i kappa p. What are the two terms I will get here? E s E i exponential minus i delta k z, and then, d E i by d z is equal to i kappa i E p E s star exponential i delta k z.

So, I have a strong signal coming in; omega s is a strong light wave, omega i is a weak light wave and it can be weak or strong; it does not matter. But omega is assumed to be strong, so that, I neglect the depletion of the omega s wave. Obviously, I cannot generate omega p, unless I deplete the omega s, so, as an approximation. So, now, first let me look at… again I know that when delta k is equal to 0, I will have maximum efficiency of this process.

(Refer Slide Time: 22:25)



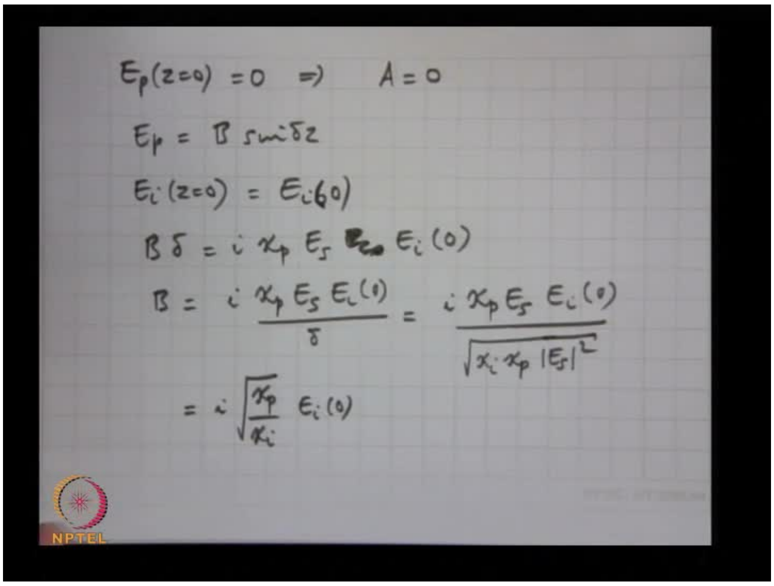
So, let me look at these equations for delta k is equal to 0, that is, phase matched case; so, I will get d E p by d z is equal to i kappa p E s E i; and d E i by d z is equal to i kappa i E p E s star. So, let me differentiate the first equation, so I get d square E p by d z square is equal to i kappa p - E s is assumed to be constant - into d E i by d z which is equal to i kappa p E s into i kappa i E s star E p, which is equal to minus kappa i kappa p mod E s square E p.

What is the difference between this equation and the equation we had got for different frequency generation?

(())

Yes, it is a negative sign here, so its solutions will be oscillatory; so, let me call this minus of delta square or something - E p, so, what are the solutions? E p of z is equal to A cos delta z plus B sin oscillatory solutions.

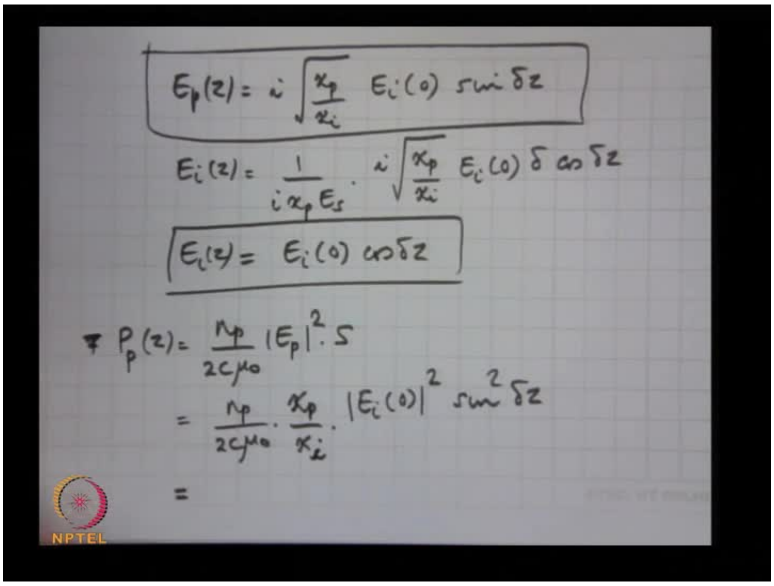
(Refer Slide Time: 24:36)



So, how do I find out the constants A and B? I have the initial conditions E p of z is equal to 0, because I am only coming in with the signal and the idler. So, E p is equal to 0 at z is equal to 0, and so, E p at z is equal to 0, is equal to 0, implies A is equal to 0. So, the solution is E p is equal to b sine delta z. So, also, let me assume that E i at z is equal to 0, is equal to E i 0; that is the other condition that I am coming in with the signal and idler; so, there is no pump, so I use this equation and I write, d E p by d z is B delta d E p by d z at z is equal to 0, is equal to i kappa p E s E i at z is equal to 0, so, this gives me B delta is equal to i kappa p E s E i 0.

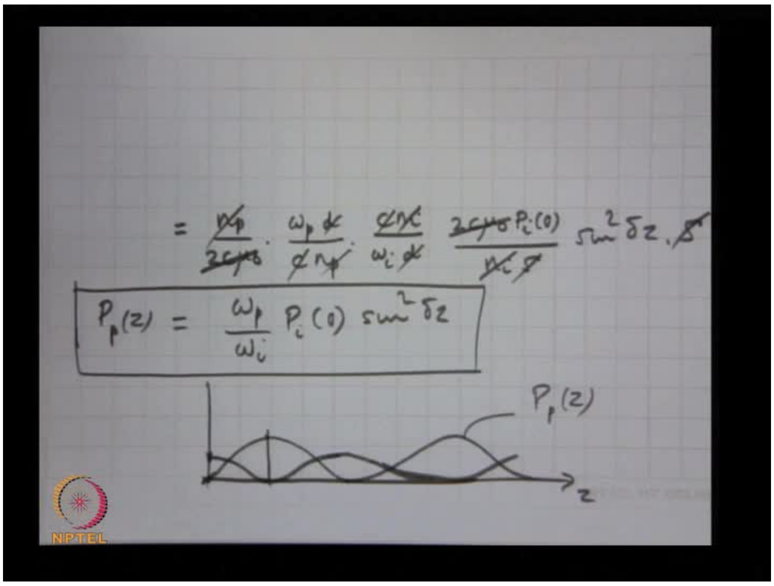
Let me write this as E i of 0, let me just keep the same notation E i of 0; so, b is equal to i kappa p E s E i of 0 divided by delta. And delta is, from here, so this is i kappa p E s E i of 0 - divided by delta - is square root of kappa i kappa p mod E s square; so, this is equal to i times square root of kappa p by kappa i. Let me assume E s is real, let me assume the phase of the signal to be 0, so E s, mod E s square is equal to E s, and I get into E i of 0.

(Refer Slide Time: 26:52)



So, the solution I get for E p… Let me write the two solutions for E p of z, E p of z becomes i times square root of kappa p by kappa i E i of 0 sin delta z; and, how will E i of z vary? E i of z, I get from this equation, so E i of z will be 1 by i kappa p E s into d E p by d z, which is, square root of kappa p by kappa i E i of 0 delta cos delta z. E i of z is 1 by i kappa p E s times d E p by d z, so, d E by p by d z I substitute from here; and all these factors you can show will cancel off, and I get E i of 0 cos delta z. They have to cancel, because, if z is equal to 0, E i of 0 is equal to E i of 0, so, these factors you can substitute back for E s and delta and kappa; all these factors will this just cancel off and I will finally get this, so E i of z. So, I am going to calculate - what is the power in the signal in the pump, or in the converted frequency. n p by 2 c mu 0 mod E p square into area, which is equal to n p by 2 c mu 0 kappa p by kappa s kappa i mod E i 0 square sin square delta z, which is equal to…, let me substitute all the quantities.

(Refer Slide Time: 29:19)



Let me substitute all the quantities here, is equal to n p by 2 c mu 0 kappa p is omega p d by c n p kappa i is omega i d by c n i; and I want to replace E i 0 square by the power at the omega i frequency. So, how is the power related to this? p i of 0 is equal to n i by 2 c mu 0 mod E i 0 square into area; so, this is 2 c mu 0 p i of 0 by n i into area into sin square delta z; this is n p by 2 c mu 0 kappa p by kappa i into E i 0 mod square into sine square delta z, 2 c mu 0 goes off from here, n i, n i there is...There has to be an s here, area, please write this s here; there is an area here which cuts off, d c n p omega p by omega i p i of 0. Why is this factor omega p by omega i coming?

It is a photon number problem. The maximum power I can generate at the pump is omega p by omega i times p i of 0; p i of 0 h cross omega i is the number of photons entering per unit time into the crystal at omega i frequency, this implies, I have completely converted all those photons. If I convert all the photons at omega i frequency to omega p frequency, how many photons will I generate? p i of 0 by h cross omega i, because, p i of 0 is the input power at omega i frequency, p i of 0 by h cross omega i is the number of photons at omega i entering per unit time at omega i; If I can convert all that into the omega p frequency, the number of photons which will be coming out per unit time at omega p is p i of 0 by h cross omega i; and so, the power at the pump omega p will be this multiplied by omega p, which is simply omega p by omega i into p i of 0 sin square delta z. So, this now, is completely different solution compared to what we got for some frequency; so here what happens is, p p of z will go like this.

So, this is a function of z, this is p p; and p i where its amplitude would be as much as this, or it will be smaller or larger? Smaller. Smaller, because omega i is smaller than omega p; the number of photons finally are equal, so this idler will have to go like this. When the it starts with full power in idler and no pump, no omega p, it converts everything to omega p and then, back to omega i, back to omega p; it is oscillatory. This solution is very different from the solution for difference frequency generation; this is sum frequency generation. So, you can actually convert all the power from the idler, the omega i frequency to omega p frequency, provided you have phase matching condition.

So, if you launch a certain number of idler photons, in principle, if you choose a length which is… How much is the length I must choose? delta z must be equal to pi by 2. I must choose a length, such that, the sin function becomes 1; and, if I choose that length of the of the crystal, then at the end of the crystal, I would convert all the idler photons at omega i frequency to omega p frequency at the output. Of course, if the omega i frequency signal is weak, I will still have a less number of photons coming at the pump, but they are at a different wavelength.

Where is this extra energy coming from? omega s. This here, the number of photons are equal, but you have also taken out exactly the same number of photons from omega s light and converted to omega p. Every time you generate an omega p photon, you have consumed an omega i photon and an omega s photon; you cannot generate omega p from only omega i, you need omega s also.

So, the omega s is absolutely required, and the, you can actually calculate what is the decrease in power of the omega i at this point. Here, at this point, what will be the content of the crystal? omega p and omega s. After this, omega p down converts to omega s and omega i.

From here, there was incident and omega i and omega s; omega i got converted to omega p, so, at this point, you had omega p and omega s. Beyond this point, the power flows from omega p to omega s, and omega p becomes 0, generating omega i and omega s and it is just an oscillatory function of distance.

We have assumed that E s is not depleting, so E s is constant.

In this calculation?

Should also reflect this, or there is some inconsistency in the equations. Because, if you are saying that the energy you get taking some photons from s to have (()) then, we are assuming that there is some depletions, there is some depletion going on, that is,…

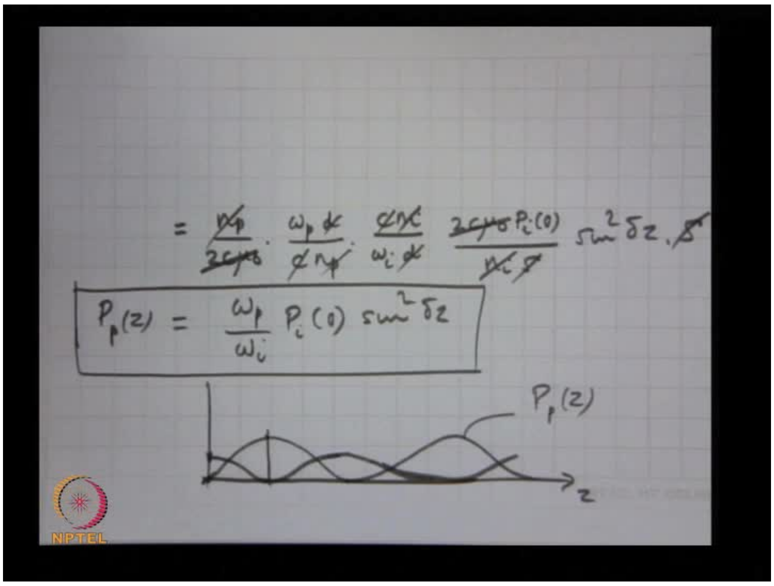
No, that depletion is not apparent in my simulation; here, I am assuming p s is constant. So, there is an inconsistency, because, the some of the power conservation is not being maintained in my simulation, because I cannot have p p, p i and p s, the way I have done. But the interpretation that p s must have decreased is by my logical argument; that is all. This analysis, I have assumed p s is constant and that is not correct.

So, this is an approximate equation which I have got assuming the omega s; omega p s is constant, but I know, that when I solve all the equations exactly, I will be able to convert from omega i to omega p, and I would have also taken up some energy from omega s, in this process. Because, I know this process interpretation as a merging of photons at omega s and omega i to generate omega p. So, every time I lose a pump photon at omega I, I should have lost a photon at omega s also, simultaneously. So, that is an important thing, but, so, this equation right now is inconsistent, because I have only assumed p p is a function of z, and p i is a function of z, and p s is independent of z; this is not correct. We have not satisfied this set of equations; they will approximately satisfy this set of equation, not correct.

(())

You will not be, because, you will see the p p of z plus p i of z plus p s of z is not a constant. Because p is constant, and you will not find p p plus p i; it is not constant. You see, p i is p i 0 sin square cos square delta z, and this plus this not constant, I need the other one to make it a consistent. So, the sum frequency has applications in converting light from a longer wavelength to shorter wavelengths; and essentially, you can achieve this by using non-linear effects, which means, effectively, you can convert light at a infrared wavelengths to into the visible regional spectrum.

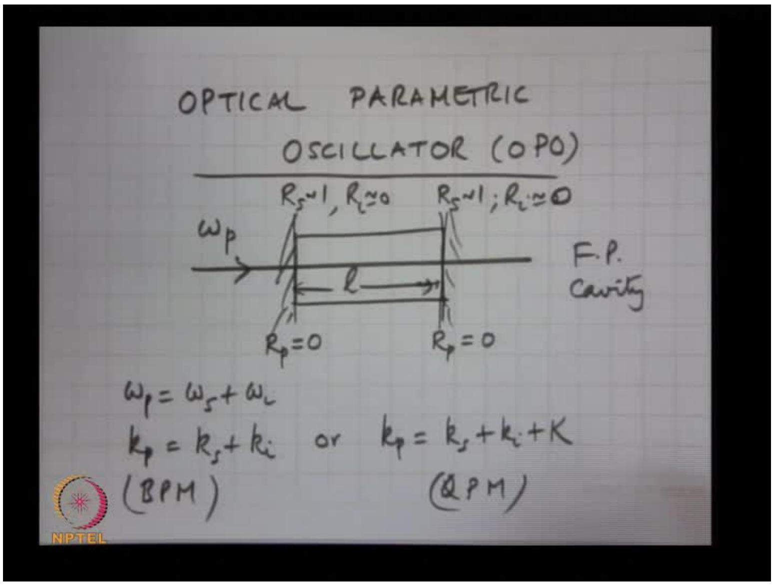
(Refer Slide Time: 38:18)



The efficiency, etcetera, depends, of course, on the non-linear coefficient which is contained here and the kind of lengths required; I mean, delta depends on the non-linearity; you see here, delta depends on kappa i kappa p; and, kappa i and kappa p, both are functions of non-linearity, so, delta square is kappa i kappa p mod E s square. So, it depends on the signal power and also the non-linearity, which is contained in the de-coefficients inside the kappa. So, how much is the length required to do this, etcetera, is a function of the crystal.

Of course, in all these analysis, we have assumed that there is no other last mechanism of this light waves; we are assuming the crystals are completely transparent. So, in principle, I need to take that into account, if the lens becomes longer and longer; I cannot neglect the fact that light could be lost by scattering processes or absorption by other mechanisms and so on. So, that finishes sum frequency generation from two input low frequency signals to generate a higher frequency signal at the output. And, as I was mentioning, the second harmonic generation is one special case of the sum frequency, where 2 frequencies are equal; omega s is equal to omega i, and I can generate a 2 omega light at the output. Now, I want to discuss optical parametric oscillators, also called OPO.

(Refer Slide Time: 39:38)



So, I have shown, that if you launch light at omega p and omega s and satisfy the phase matching condition, you can amplify omega s light; the power at omega s frequency goes up as cos hyperbolic square gamma, gamma s or something. So, that is an optical amplifier; this amplification is very similar to what you can amplify light by using population inversion. In lasers, you have population inversion, which means, you put more atoms in the excited state compared to the ground state, and then, because of most emissions, the input light gets amplified, and you make an optical amplifier.

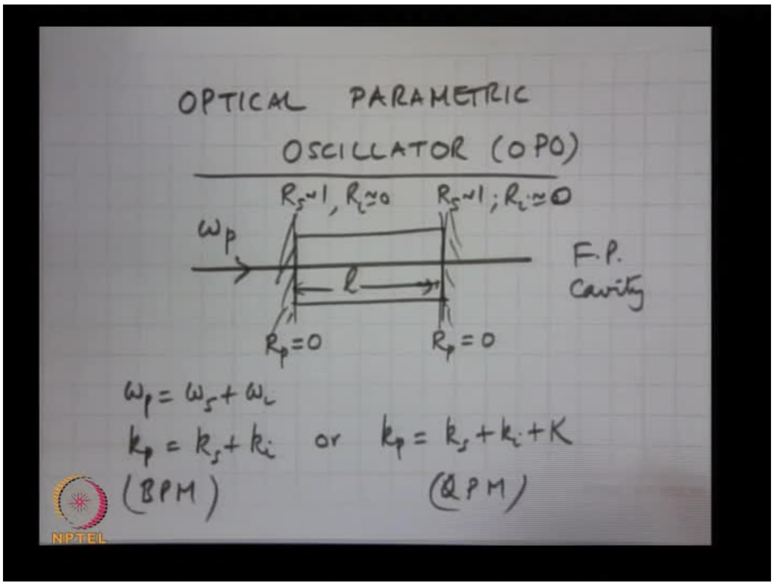
So, this is another kind of amplifier; the great advantage here, is this amplifier does not depend on the existence of certain energy levels at certain frequencies. Because, as long as the crystal has non-linearity and it is transparent, I can generate any pairs of omega s, omega i, omega p; I can have any combination as long as I can satisfy the phase matching condition. And, d-tenser is finite; there is a de-tenser element which gives you a coupling.

So, these are optical amplifiers; and I can convert an amplifier to an oscillator, that means, a source of radiation; an oscillatory is a source. An amplifier is only amplifying for an amplifier; you input the signal, it gets amplified as it comes out. A source, you just give it energy, and it generates radiation at a certain frequency.

So, just, I can convert an amplifier into an oscillator by putting this amplifier within a pair of mirrors. So, let me take a pair of mirrors, let me assume that I have… This is omega p coming in; now, usually, I will choose the reflectivity of this mirror at the pump frequency to be 0. I can make mirrors having reflectivity at certain wavelengths and complete transmitting in other wavelengths; this is possible by using… What do I do? Thin film dielectric coatings; I can have a coating, and by interference effects, I can have very strong reflectivity at certain wavelengths and very weak reflectivity at other wavelengths.

So, theoretically I am assuming that these two mirrors have 0 reflectivity, the pump just goes through. So, now let me assume, that I have bi-mechanism, either by Birefringence-phase-matching, and or by Quasi-phase-matching, I have I am satisfying the phase matching condition for one pair of frequencies, omega s and omega i.

(Refer Slide Time: 43:25)



k p is equal to k s plus k i or k p is equal to k s plus k i plus k; this is birefringence phase-matching; this is Quasi-phase-matching. By some arrangement, I can achieve phase matching. So, now, I launch a pump light into the crystal. Can you can you tell me an electronic oscillator, how does it start?

I have an electronic oscillator, which means, a function generator - instrument which generates electric waves at a certain frequency. How do they generate? How do they start? And what frequency will they emit? So, I am just feeding power into the system; they may emit a resonant frequency. But, why does it generate at all? Why does it start to generate? How does it start from… Where does it start to generate?

It is only an amplifier, remember.

I have a circuit in which I keep on feeding energy, and that circuit has a resonant mode, which is…

No, but, your energy is fed into different frequency. So, how does it generate a new frequency?

(())

Noise. If there was no noise, there is no oscillation; there must be some noise.

In a laser, what is the noise? Spontaneous emission. The moment you take atoms in the excited state, they will start to jump down, and without any stimulation, and, that light which generates, generated by the spontaneous emission process, is the noise that starts the laser. If the spontaneous emission did not take place, there is no laser; so, spontaneous emission, like noise, is absolutely required for the start of the oscillator. What is the noise here?

Modes are only frequencies which can exist in a system; it does not mean they will exist.

What noise? From where do I get omega s that first?

All the frequencies are present at all times.

Now, here, what is the process which will start this laser, like spontaneous emission incident?

We have omega p incident and omega s will be there by the surrounding noise, that is

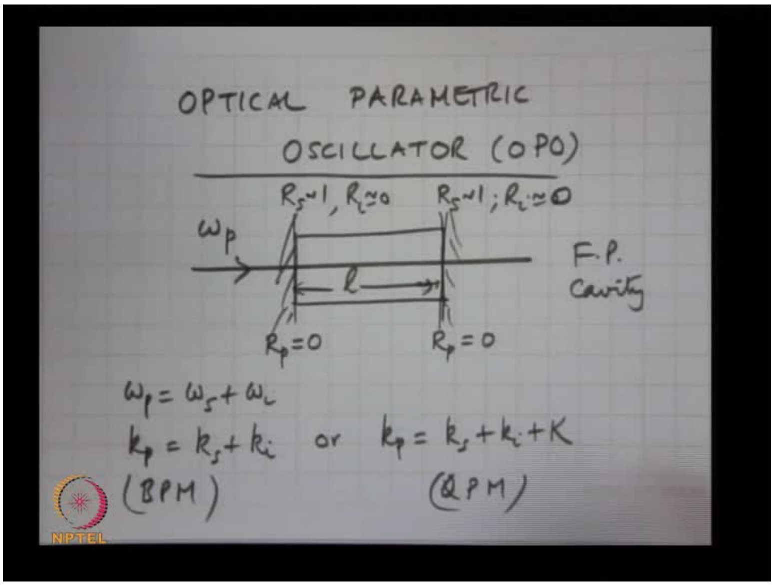
Quantum fluctuating noise? which results in what first?

Generation of omega i and omega s. From what process?

Spontaneous parametric fluorescence or down conversions. omega p photon comes in, it interacts with the crystal and spontaneously down-converts to a pair of omega s and omega i photons; that down conversion is brought about by the vacuum fluctuation just like spontaneous emission is brought about by the vacuum fluctuation. So, this omega p photon comes in or light comes in and spontaneously split into omega s omega i photons, some of them.

Now, I can have, for example, this is the reflectivity of the signal wavelength is close to 1 and reflectivity at the signal wavelength is also close to 1, for example., I make the mirrors which are transmitting at pump, but very high reflectivity at signal wavelengths, so, what is going to happen is… And, let me assume that R i is also 0 and R i is also 0; the reflectivity at the idler wavelengths are 0.

(Refer Slide Time: 47:12)



So, the spontaneously generated i signal photons, which direction will they be generated? In the forward direction. So, when they come here, part of them will get reflected back, some of them will transmit; suppose 99 percent, 1 percent gets reflected back; and as it propagates to the crystal, does it get amplified?

No.

Why?

Because, the k vector is going in the opposite direction, so, it will not be phase matched.

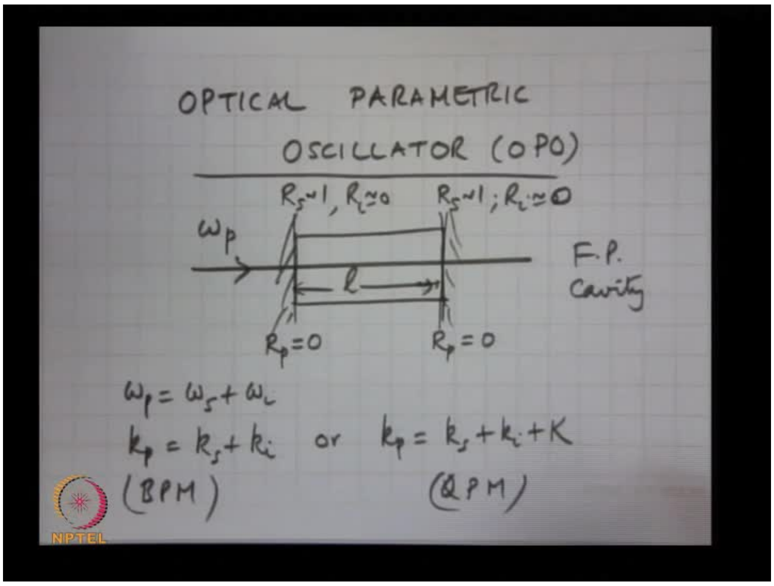
K p is like this and k s is like this, you will not satisfy the phase matching, that is, you will require a negative k s here; this will not satisfy either of these conditions. So, the signal light comes back without amplification; in a laser, it gets in a normal population inversion laser, it gets amplified in the reverse direction also. It uses the same population inversion that gets amplified in the reverse direction; it comes here, then again, partly transparent, partly reflected; and once it starts again, now it uses the pump and gets amplified; because, I have shown you that the signal at this point, now, there is a signal and pump; and the signal will now draw energy from the pump and get amplified as it propagates; and, this will go back and forth and will increase this signal inside. And of course, the level of idler will have to idler is not increasing inside; it is escaping from the cavity. Because, you are not holding it on inside the cavity; this is a Fabry-Perot cavity. You studied Fabry-Perot in a course; this is a Fabry-Perot cavity. So, the signal light is trapped inside the cavity with little bit of escaping from both sides; and as the signal increases in intensity, what should happen? It cannot go on increasing infinitely.

No, but amplification is always there.

Gain saturation. Any amplifier has to have a gain saturation; because, start you start with a loop gain more than 1. So, the amount of loss is less, then gain, so it increases in amplitude; if you have all the time gain, more than loss; this will keep on increasing to infinity. But what is going to happen is, as the signal becomes larger and larger, it will bring down the gain; and it will bring down the gain to a value, such that, gain is equal to loss; that is gain saturation.

So, what is going to happen is, as the signal power increases, the pump power will start to drop; our assumption that the pump is non-depleted will fail, at that point. I cannot keep assuming pump is un-depleted when the signal becomes so strong, and so much of energy being drawn out from the pump. So, the pump power will drop down; and once the pump power drops, the gain will drop, because, the gain depends on the pump power.

(Refer Slide Time: 50:02)



And I will reach a gain saturation where the signal will be, such that, the round trip gain is equal to round trip loss, and the light will come out at both omega s and omega i. Omega i omega s are very strong wave because, it is a fraction of what is contained inside, but there is a lot of power at omega i also coming out of the cavity.

What would contribute to the loss?

The loss is the finite reflectivity; suppose 99 percent- suppose 99 percent, every time I go through one round trip, I lose 2 percent of that light; so, I must gain the 2 percent. So, the pump power will adjust itself to give me a gain of 2 percent for every loss of 2 percent in one round trip.

(())

Gain. For any oscillator, that is the place where the oscillation will become steady, and you will get a continuous signal coming out.

But the amount the power of the signal that comes out, it is only like 1 or 2 percent of the omega p; maximum if we say that all the power omega p is converted to omega s, let us say, I mean…

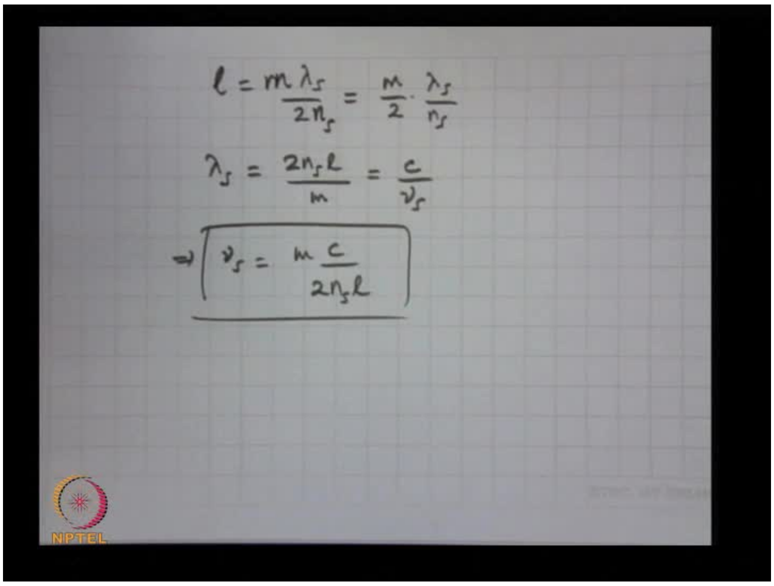
It is only a fraction of what is contained inside the cavity at omega s, omega p is still coming out; I am not converting all omega p to omega s. If this is 99 percent, and 99 percent, what I am getting is, 1 percent of one either side of what is contained inside the cavity.

Whatever is contained inside of the cavity, so, it has to be of the order of power of omega p; and the output we are getting very less power of omega s, because it is only 1 percent of the maximum that is achieved inside the cavity.

Yes.

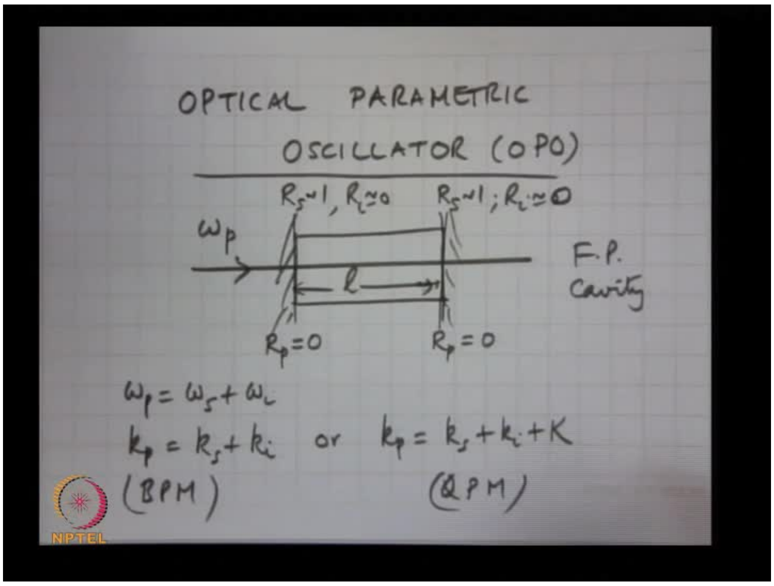
That could be in watts; I can put 10 watts of power at omega p and I can get a watt of power at omega s. We will put some numbers and calculate. When we actually calculate with these, the oscillation condition. So, what we need to do is, we need to have an oscillation condition. What is the pump power required by the laser, for the oscillator to start and what will be the frequency? The frequency is given by this, is, there any other condition on omega s. It has to be a resonant mode inside the cavity; so, what is the frequency which will be resonant inside this cavity?

(Refer Slide Time: 53:03)



Yes. So, if the length, if I call the length as l, l is equal to n lambda s by 2 and let me call it m; and this is m by 2, please remember, this is, I must write refractive index. Because, this is usually the wavelength which I am using, are free space wavelengths, so, the wavelengths inside the cavity is lambda s minus. So, the wavelength which will come out, which will oscillate, is in terms… in fact, I can write in terms of frequency. So, this is c by nu s, so, this implies nu s is equal to… The frequency has to satisfy this condition as well as this condition of omega p is equal to omega s plus omega i and this condition of k p is equal to k s plus k i.

(Refer Slide Time: 54:08)



So, this omega s will actually adjust itself to satisfy these conditions and what will come out is, suppose to be light at this frequency omega s; and, of course, omega i light is also coming out of the cavity. This is what is called as a singly resonant oscillator, SRO, which means, only the signal is resonating inside the cavity; the idler is not resonating, because the mirrors have 0 reflectivity at the idler. I can also have a situation where R i is also close to 1, then it is called a doubly resonant oscillator because then, the signal and idler will both resonate inside the cavity.

I can also have a situation where pump also resonates inside the cavity, and I will have a triply resonant oscillator. We will discuss the doubly resonant and the singly resonant oscillator in the class, and I will show you that the powers required for operation of the doubly resonant are much lower than required for the singly resonant oscillator, but at some price, and the price is in terms of instability of the laser system itself.

So, we will stop here now, so, what we will do is discuss and calculate what is the threshold pump power required for the laser for the oscillator to start, for the singly resonant case, for the doubly resonant case, and how does it depend on the reflectivity of the mirrors, the length of the cavity etcetera. Do you have any questions?

Sir, omega s is trapping, so, how will you…

No, not fully trapped, close to 1, I am writing; 99 percent may be, reflectivity, like a laser; the laser has mirrors. If you have mirrors of 100 percent reflectivity, nothing comes out its oscillating, but nothing comes out, but I want something output. So, I need to have a something, at least one of the mirrors to be having reflectivity less than 1, and that will be transmitting that fraction. So, this mirror has a finite reflectivity at the resonant omega s frequency, and so, a little light at omega s will be coming out, and that is quite strong already. The mirrors are not perfectly reflecting at all wavelengths, then you cannot see what is inside; nothing comes out from inside; this is completely opaque for you.

In general, in the lasers, when we do second harmonic generation, so, in that also, do we have oscillators, such that, the power coming out at the second harmonic…

No, you can have a laser and the second harmonic generator outside, or you can put the second harmonic generator crystal inside the cavity.

Intra-cavity second harmonic generation.

Light in pulse lasers, usually, when they are used for the laser emission processes, there is a second harmonic which is coming out, so inside, there is some oscillator of some kind….

There is a crystal. So, the mirrors are 100 percent reflecting at the omega frequency and partially transmitting at 2 omega frequency.

So, we have such a system inside.

Not such a system, just a crystal; it is exactly the same as a laser, where the population inversion…

For any laser, there are mirrors; there are mirrors, there is a laser cavity and there is a crystal. Inside that crystal, actually, helps to convert the oscillating omega to 2 omega, and what comes out is 2 omega and not omega. Anything else?

Thank you.