Quantum Electronics
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Module No. # 05
Lecture No. # 42
Questions

Anyways, so what we can do is, as I was mentioning, I will try to present you some experimental configurations, which people have analyzed, and the results of which depend on essentially the quantum properties of light. Remember, I was mentioning that in interference experiments, if you have knowledge of the path of the photon - single photon interference - if there is knowledge of the paths taken by the light in an interference experiment, you lose the interference pattern.

And in fact, you do not need to observe the path of the photon, you do not need to do an experiment to observe the path of the photon, the existence of information and about the path in the experiment destroy the interference. Now, I will show you a very interesting experiment which was performed in 1991, and which shows some deserved results, here is the experiment.

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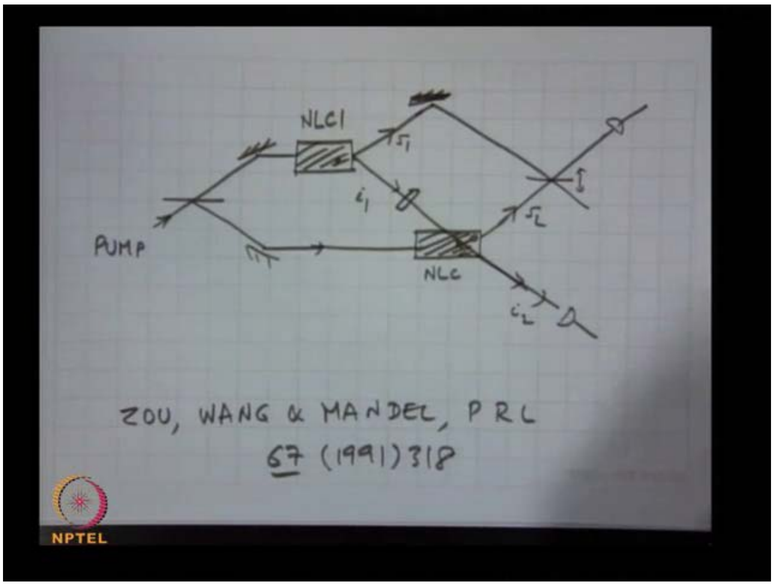

So, I have a beam splitter, this is pump lights, so then I have two mirrors here which make the beam go horizontal, here I have a non-linear crystal which generates parametric down conversion, 2 photons signal and idler, idle goes here ok. This part goes to another non-linear crystal and generates another pair of signal idler, let me draw this, this is signal 1, idler 1 signal 2 idler 2, and there is a detector here, and there is a detector here, this is 1 crystal here, this is another crystal here.

So, the experiment is as follows, here is a pump laser, yeah.

Sir, when we have done the analysis was it not that the signal and idler would propagate along the same direction as the input.

We were looking at a configuration where the phase matching was like that, but it is also possible that the phase matching takes place with non collinear propagation of signal and idler, then the phase matching condition will become vector equation, k p vector is equal to k s vector plus k I vector rather than all the vectors being parallel to each other.

So, in many geometries the pump comes and then generates a signal idler pair which are not propagating in the same direction ok. So, what happens is, the pump comes from here and the pump is weak enough, so that is the let me assume a single photon of pump comes here, it goes into superposition state of being in this arm and in this arm, then this arm goes through a non-linear crystal generating a signal idler pair.

This arm goes through same identical non-linear crystal generating signal idler pair, and this mirror is movable, there is a beam splitter again here which combines this signal path and this signal path and goes into the detector. Now, here is the experiment I make sure that this idler path and this idler path are exactly overlapping, remember this crystal is transparent to signal and idler, so this idler photon generated here will pass through a crystal without any effect.

This idler generated by this crystal also propagates in the same direction, so I ensure in my experimental setup that this idler photon and this idler photon are exactly overlapping, so that when I receive an idler photon here I do not know whether it got generated here, or it got generated here ok. So, now, I measure the intensity here as a fraction of position of this mirror, I c interference, what is happening is that the signal arriving here can arrive in 2 different paths, it could have got generated here and along this path or it would have got generated here, and goes along this path.

There is only one pump photon coming in, it goes into superposition state that superposition state leads to a superposition of signal idler pair generated here and a signal idler pair generated here. This signal pair are made to overlap on a detector, the two idler photons are exactly overlapping and there is no information as to whether this idler came from this crystal or this crystal.

So, what happens is, because the signal arriving here could have arrived from this crystal along this path or from this crystal along this path, the probability of arriving of the signal here is the sum of the amplitudes of this path and this path, and then if you vary this mirrors position you find interference effect here. Please note there is only 1 signal idler pair, because there is only one pump photon entering, there is one signal idler pair being generated, but it is in a state in which this signal idler pair could have come from here or from here and this interference patter fringes here.

I block this beam, what is the effect of blocking this beam, if I receive an idler here; I know that the signal that is coming here is from this crystal, if I receive a signal here and no idler here, I know the signal has come from this crystal.

As I move this mirror there is no interference.

Please note, I have not touched the arms of the signal, all I have done is that there is information in my experiment of the path of the signal and which distracts interference. If I do not block it fully, but if I block it, say, I put a filter which passes 10 percent of the idler there is 10 percent uncertainty interference fringes come back with lower contrast. So, what is actually happening is, so this person who is receiving this light here, in fact he does not have to put even detector you are doing the experiment, and suddenly I put, I block this beam, your interference is lost, that is because in this experiment there is information about the path of the signal that arrives on this detector. This is a very interesting paper, those who are interested should refer to this paper zou wang and mandel, physical review letters 67 volume 1991.

Please note here, I am not disturbing the signal at all, and in no way I am touching the signal anywhere, all that I am doing by putting this block here is to create information in my experiment which will help me to identify which signal has come on this path detector. What is the path taken by the signal, and that destroys interference, and these are experiment, and so this is very, very, interesting experiment which shows the importance of information of the path, of the signal photon in this experiment which destroys interference. So, interference effects I can regain interference effects if I remove the block, and introduce in my system - I mean - no knowledge about which signal whether the signal was generated here or here.

In fact, if I misalign this crystal, and if I misalign the crystal, so that this beam comes out separately compared to this beam I will lose the interference, because then I know again which crystal has generated the signal. So, that is a very, very, interesting experiment is discussed in this paper here which you can entertain you by reading this, and see how quantum effects are playing at this stage here. The other experiment which I wanted to mention is based on our analysis of the following problem.

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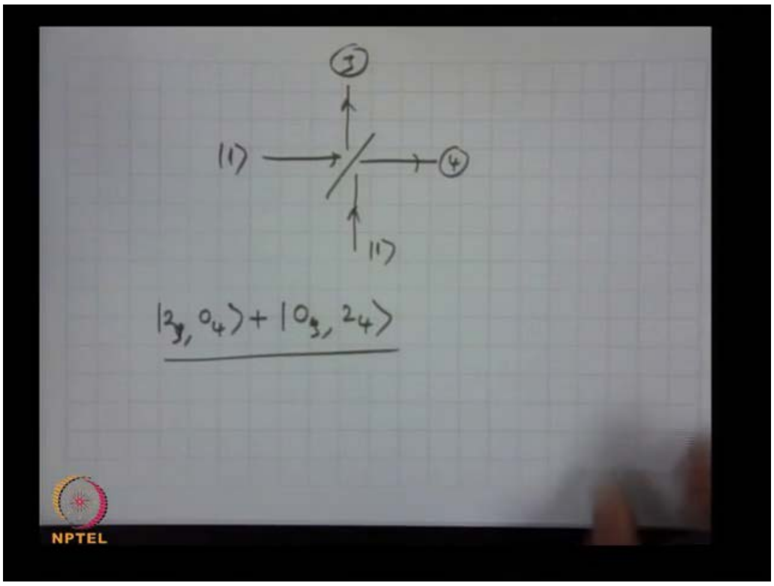

We had looked at a stage I had one photon coming in from here another photon coming from here, so what was the output we had calculated? Remember, we found an output which was 2304 plus 0324; that means, either both photons arrive in path 3 or both photons arrive in path 4, the probability of 1 photon in 3 and one photon is 4 is 0. Now, experiment based on this was conducted by again a group from rochester and here is experiment.

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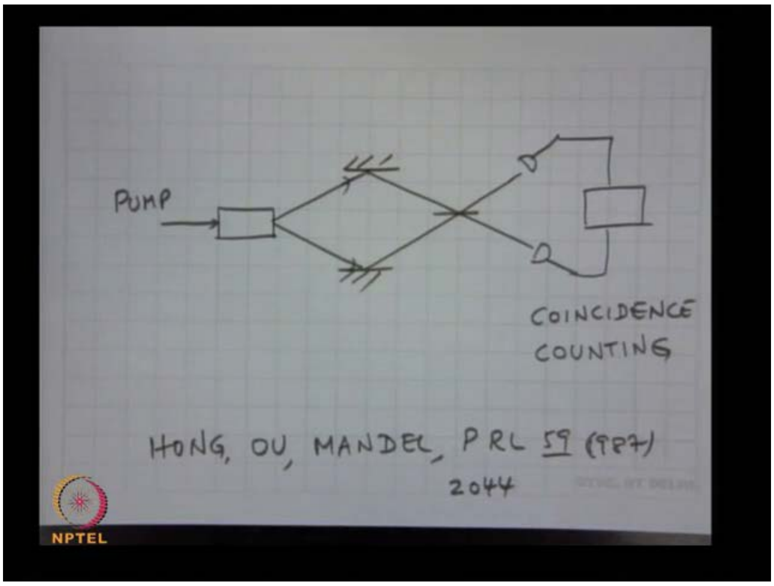

This is my non-linear crystal, this pump generates 2 identical photons, I have detector here, I have detector here and I do coincidence counting. So, this is the paper again physical review letters 59, what the experiment is essentially, you have pump coming from here, generates a pair of photons degenerate down conversion, then these 2 photons are actually remixed on a beam splitter. Now, you see when we discussed parametric down conversion process, we assume perfect phase matching, but suppose, I do not have perfect phase matching, what will happen? I will still generate pairs of photons, but with a slightly lower efficiency, which means if I take a single frequency pump omega P - omega P is equal to omega s plus omega i, I need to satisfy remember two conditions, omega p is equal to omega s plus omega i and k p is equal to k s plus k I phase matching condition, this is nothing but omega p n p is equal to omega s n s plus omega i n i.

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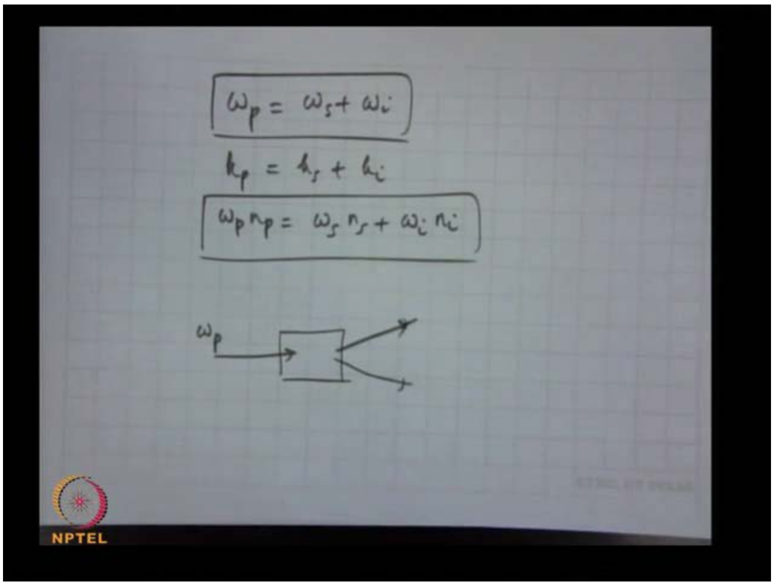

So, I need to solve these two equations, but remember, actually, this has infinite number of pairs of omega s omega i, one pair which all will also satisfy this equation, satisfies both these conditions will have maximum down conversion efficiency. There will be other pairs of omega s omega i which satisfies this condition, but which satisfies this approximately, so their efficiency will be slightly less.

So, even if I take a crystal and if I launch a single frequency pump, I will not generate one mono chromatic omega s and omega i only, I will generate a range of frequencies; which means, there will be, the probability of one particular pair is much higher which it satisfies the phase matching condition, than other pairs of photon frequencies which will still be satisfying this equation but approximately satisfying this equation.

So, what I get out is a multi mode single photon state, it is a wave packet coming out, it is a photon wave packet, because there is a spectrum of frequencies of the signal which is coming out, there is a spectrum of frequencies of the idler which is coming out, and a spectrum of frequency, but there is only one photon of the signal and one photon of the idler.

So, this will be a single photon multimode signal state and this will be a single photon multimode idler state. The width of those duration will depend on the spectral width of the emission process, if the spectrum is broader the wave packet will be narrower, if this spectrum is narrower the wave packet will be broader, it is a Fourier transform relationship between the time space and the frequency space. So, if you have a broader spectrum of generation of down conversion you will have a narrower pulse, a narrower width single photon wave packet, otherwise if you have a narrower spectrum of down conversion then you have broader wave packet.

So, what is actually happening in this experiment is, there is a one wave packet coming from here, another wave packet coming from here. Now, you see that when we do this, to interpret this experiment actually both the photons should arrive at the beam splitter at the same time, otherwise there is no interference.

If I make sure that this path is shorter than this path, then this photon will arrive because they are both generated simultaneously in a crystal, this photon will arrive slightly earlier compared to this, and when this photon wave packet arrives there is no interference it splits into two halves or it goes into a state of being here or here, and similarly, when the next one arrive, it also goes into a state of being here and here.

If I move this mirror or if I move this set up, so that I change or I make the path differences exactly equal, when the path length becomes exactly equal, then both the down converted photons will arrive at the same time and both of them will go into one of the arms according to this picture. So, what people do is, I get a signal from here, I get a signal from here, and find out over a small window of time, whether I see any coincidence; that means, whether both detectors click at the same time. If both detectors click, one of them has come here the other one has gone here, but if this state is generated, I should have note this coincidence, because both photons will either go here or both photons will either go here and so there will be no coincidence, so if I plot the coincidence rate verses the position of this beam splitter, I see a dip, this position is the position of this beam splitter where both wave packets arrive are simultaneously on the beam splitter.

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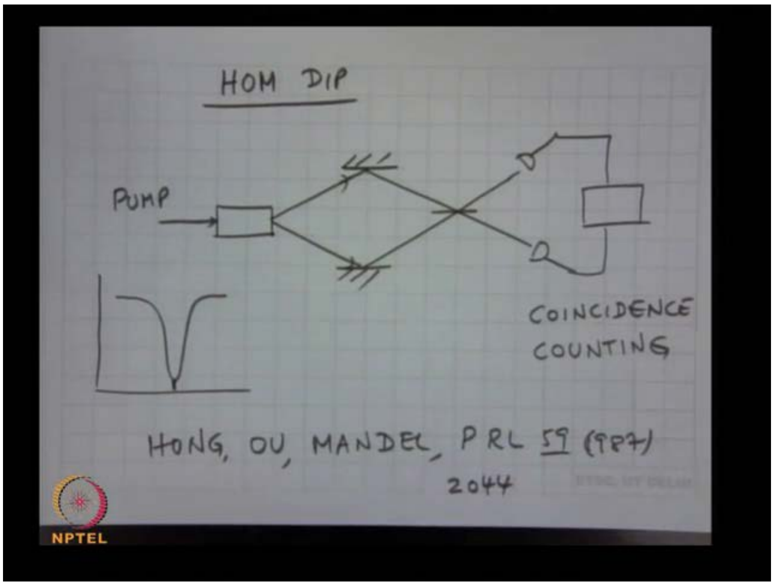

And as you move away from this position, one of them arrives earlier than the other and so within the open window of this detector one of them goes here and the other one goes here for example. So, there is a finite probability of coincidences between the two detectors but if you come into a state where both of them arrive simultaneously on the beam splitter you will either have both the photons here or both photons here and the coincidence becomes minimum.

Sir, this time window detector we have turn over time is equal to the relaxation time of detector or the time for which I keep the detector open, I open the detector and close it, simultaneously both of them and that has to be a finite duration, may be nanosecond, may be some time, within which any photon that arrives is detected by this detector, it cannot be instantaneous detection. So, within the time window, if the photon arrives, here and here it detects as a coincidence counting.

Now, the interesting feature about this is if the wave packet coming from here is very narrow, the width of this peak the width of this dip is very narrow, because, suppose, this width is 20 femto seconds, if you delay if you change the path length between these 2 by 20 femto second time delay you will have coincidences. So, you have to position this as accurately as possible, so that within the path length or the time taken difference between these two is less than the wave packet width.

So, if it is 20 femto seconds, I can actually measure this to an accuracy of 20 femto seconds, these detectors are not at that speed at all operating at that speed, but I can actually measure time delays, extremely small time delays, by using the quantum interference effects, this is called the hong ou mandel dip, they were the first ones to do this experiment, this dip is called the hong ou mandel dip, and he actually tells me how closely identical this two photons are.

If this was signal and idler which was different frequencies, this is not the right way, because this photon is different from this photon the frequencies are different, so I cannot add them like this, I have to define more number of modes, this is one frequency mode, this is another frequency mode, this does not hold, so this is one way to make. So, this is a degenerate count process in which an omega p comes in here and splits into an omega p by 2, and omega p by 2 and then, I make them interfere and this is very interesting because, then I can actually measure very, very, small time delays. And this is another way of checking whether the photons that are generated are identical etcetera, etcetera.

Now, because I can measure such small time delays, people have used this effect to measure what is the velocity of a single photon inside glass. So, all I need to do is have an experiment in which in one of the arm, so I set up an experiment in which there is a position in the beam splitter, which gives me a dip - minimum position - then I insert my glass in one of the arms, now I have to readjust the position of the beam splitter to come back to the same minimum position and the distance by which I move will tell me an indication - give me an indication - of the velocity of the photon, single photon, and if the wave packet is sufficiently broad, it has been found that the velocity of singe photon is the group velocity that you calculate classically.

This is single photon is propagating through glass as a wave packet and the velocity of that single photon is actually the group velocity of light, because now it is its not it is a group because, it is not a single frequency wave, it is a wave packet and that packet travels at the group velocity inside the medium.

Now, what is interesting is that people did this experiment to measure how much time light takes to tunnel through a barrier.

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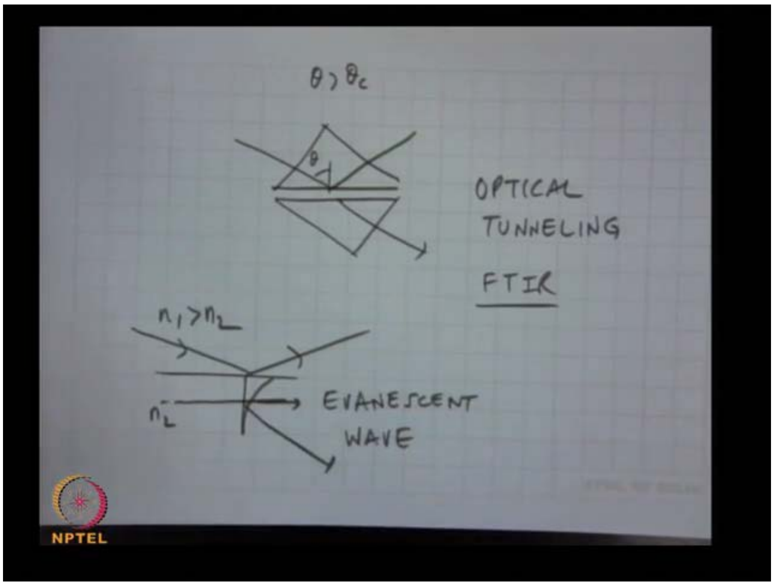

Remember, if I have for example, if I have a prism and if my angle of incidence is more than critical angle, this theta is greater than theta c, this total internal reflection, but if I bring another prism here, what are the lights get transmitted, this is optical tunneling, it is also called frustrated total internal reflection. This happens because there is a evanescent field on total reflection, when you have a wave totally reflected, there is an evanescent decaying field which is propagating like this; this is n 1, this is n 2, n 1 greater than n 2 and it is called the evanescent wave. If you bring another medium close by which interacts with this evanescent field then light and actually go to the other medium, this is optical tunneling, in quantum mechanics particles can also tunnel ok. So, an alpha decay is a process in which they are tunneling out of the nucleus from the nucleus.

The question is how much time does the light take to tunnel across the barrier? And please remember these barriers have to be very close because, if they are far away there is no tunneling, because you will be too far away between the two interfaces, so that you do not pick up the evanescent field at all, so you have to come very close, but if you come very close the distance is very little, so you need to measure very small time.

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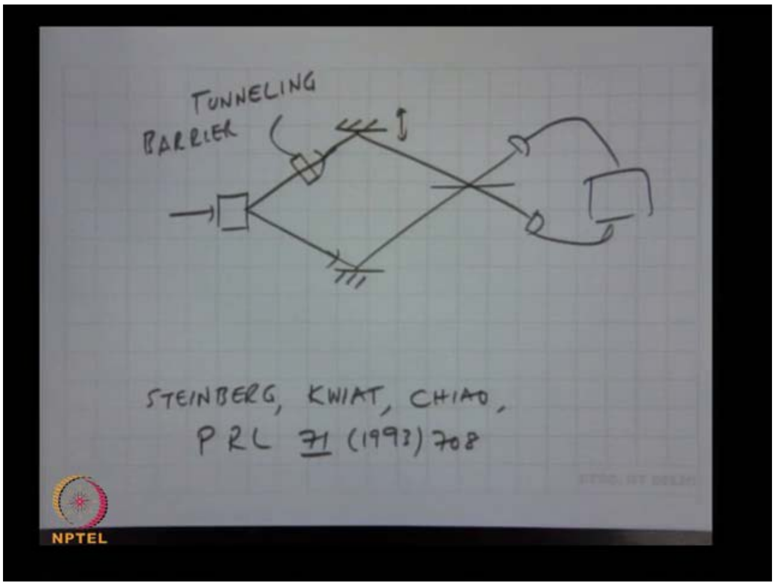

This is an ideal experiment to measure this tunneling time, and so what was done by this group, here is a papers, Steinberg, Kwiat, Chiao again physical review letters 71, 1993 708 ok.

So, parametric down conversion is very useful, so here is my tunneling barrier, so I can move this mirror to adjust the time, now normally I would have expected that suppose, there is a position without this barrier, suppose I could adjust that the medium is still there, but it is not tunneling it is propagating through, I will have a certain position of this mirror where I get this dip, which means both the photon wave packets arrive simultaneously at the beam splitter, which tunneling I would have expected this to be move away or closer. If it travels slower if it takes some time to tunnel through, so I would have to move closer right, when they did the experiment, they found it has to be moved away.

It looks like light is tunneling at more than velocity of light in free space, super luminal tunneling, this experiment is possible because of extremely small time scale that is measurable using this Hong ou mandel dip, of course, there are arguments and discussions on what is the meaning of tunneling time, and what is it, see it may happen, it may so happen because, it is a wave going through if you have a wave packet going through a medium.

The velocity of the wave packet depends on how the velocity of individual frequencies in the wave packet travels, what is the velocity of individual wave packet? Individual wave change or wave packet and it may so happen, because of the dispersive effects that, even before the peak of a wave packet enters the medium, the peak has already come out, it looks as if the time taken is negative, but what is actually happening is, there are distortion effects on the wave packet or other effects that are taking place which are making you to measure at velocity which is faster than velocity of light, but there is no information transfer at greater than velocity of light.

See, tunneling means, you have a certain fraction of the incident light that is going through, remaining is all reflected back, in this case if I keep a distance so that the tunneling is one percent 99 percent of the incident light is reflected and there is only one percent transmitted. So, what you are measuring here is that one percent of the transmitted light which is forming this dip, and there are lot of analysis and sort of estimations and calculations of what is the meaning of this super luminal tunneling etcetera.

But what is interesting is that this kinds of experiments helps one to experimentally see effects which are otherwise not possible, otherwise measure time scales of less than less than few femto seconds or 10 femto seconds, especially when the in problem like this, where I need to measure the time taken by the light to propagate to a very, very, small distance, yeah.

Sir, in general if there is no frustrated question then is it true that the all the energy is reflected.

Yes.

Hundred percent energy is reflected

Yes.

Now, then also there is an evanescent wave.

Yes.

So, some energy should be - I mean - does it how is it possible that once the wave has been converted to evanescent wave, and then it has we say that it has no energy it is evanescent. No, it has energy it has energy propagating parallel to the interface.

Reconverts into propagating wave.

It is a propagating wave.

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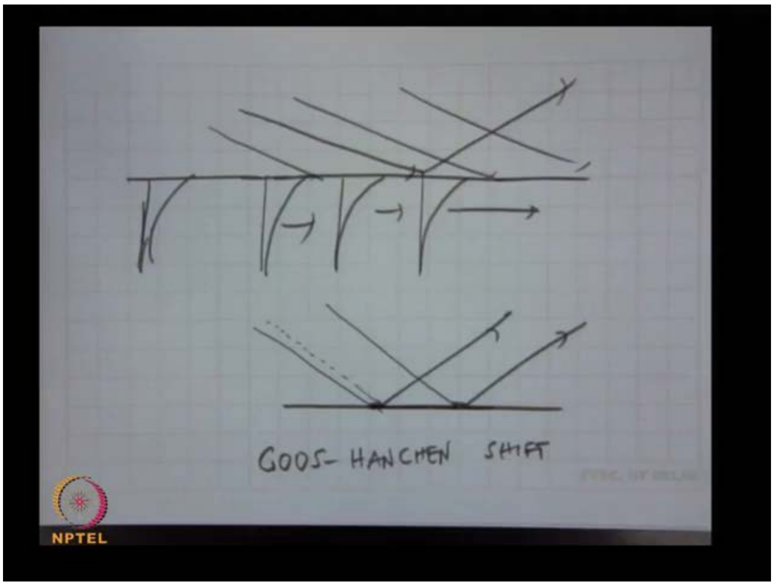

I have interface, I have wave coming from here, have a reflected wave

Vertical direction propagating on the other

Yeah, but it has energy know, I can actually measure the energy, if I put a detector here I will detect energy, only thing is its not leaving its attached to the surface, now your question is how can there be total reflection when there is energy here.

Does the reflected beam has all the incident energy.

Yes.

Then.

Yes, the problem arises because normally we are dealing with infinitely extended plane waves, for the infinitely extended plane waves there is no beginning, so I will say this evanescent wave has come from here, where has this has come from? This has come from here, this energy is continuously propagating, this energy is continuously getting reflected. If you ask me where this has come? This has come from here, this has come you go back ok.

Now, how do I solve the problem, so I say I take a beam of finite width, see the problem is, as this wave hits this boundary, it needs a set of boundary conditions, satisfy boundary conditions, so it needs to have an electric field in this other media, otherwise I cannot satisfy boundary condition, so the field enters, sets up the boundary condition. So, in the initial portion of the beam there is less reflection than total, once this field has set up in the rarer medium, no more energy is entering to set it out because already set up.

From this point onwards everything is reflected, at this point when the beam ends, there is still evanescent field which will have to set up a boundary condition on the other medium, so it comes out, and the beam comes out like this, have you heard of this? Yes, this is a goos hanchen shift.

Now, there is another way of looking at this problem, and this is a beam which is a a beam is not a plane wave, it consists of large number of plane waves in all directions ok. So, in fact, in a beam I cannot have total reflection because, sum of the components of this beam are incident at less than critical angle, they will lead to transmission ok.

So, the problem is because of infinite extent of the plane waves that you have an evanescent field which is carrying energy, but the reflection is still total, I think that is all I would like to present some interesting experiments.

If you have any questions, queries, we can address them right way.

Sir, in the tutorial that.

Um

It has given there is a question regarding calculation of the property of iodine chloro ionization the last 1.

Um um.

So, that was.

for a two frequencies.

For two frequencies.

Yeah.

So, I have did it and I was not able to get the beats per.

Why?

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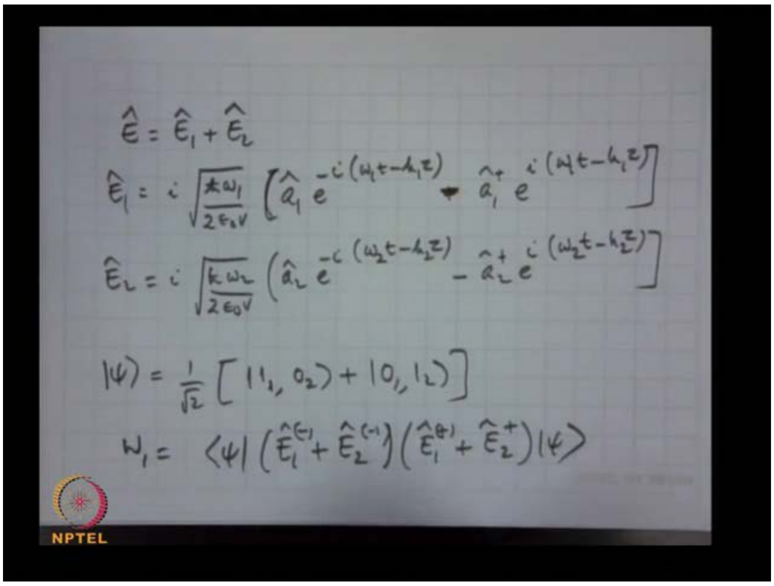

Your electric field will be the first electric field plus second electric field operator right.

So, the electric field operators would be i square root of h cross omega 1 by 2 epsilon 0 v a 1 minus i omega 1 t minus k 1 z plus, sorry, minus a 1 dagger exponential i omega 1 t minus k 1 z, similarly, for e 2. And then you have to calculate the expectation value, what did I say, I have a super position of single photon states, so what is the state you will take, so what is the state you will take? 0112 and point.

Yes, 1 is this frequency, 2 is this frequency, and then, you calculate w 1 which is psi e 1 minus plus e 2 minus into e 1 plus plus e 2 plus. So, these all will contain the dagger operators, so this part is e 1 plus this part is e 1 minus, this part is e 2 plus this part is e 2 minus, so all the minuses are here pluses are here. So, you will have a 1 a 1 dagger, sorry, a 1 a 1 dagger a 1 a 1 dagger a 1 a 2 dagger a 2 a 1 dagger a 2 a 2 dagger a 1 etcetera.

You should get, and this psi, this type, this state.

Sir, there will be 2 number operators a 1 dagger a 1 a 2 dagger a 1

Yes.

And there will be 1 term containing a 1 dagger a 2 and a 2 dagger a 1

Yes.

Yeah these are the 4 terms that will be there.

Yeah.

Now, in these 4 terms, the term containing a 1 dagger a 2 and a 2 dagger a 1

Will give intensities, No, sorry, a 1 dagger a 1 a 1 and a 2 dagger a 2 will give you intensities.

That is fine, the term containing a 1 dagger a 2 and a 2 dagger a 1 when they operate on this sign, they will give me exponentials, basically.

Yes, two exponentials you will get, yeah.

And when I sum them up I guess.

Cosine.

Cosine 2.

Yeah.

So, that is not the essentially the beats, beat pattern means basically product of two cosine terms and that would be.

No, what is the cosine term you get.

Omega 1 minus omega 2 t.

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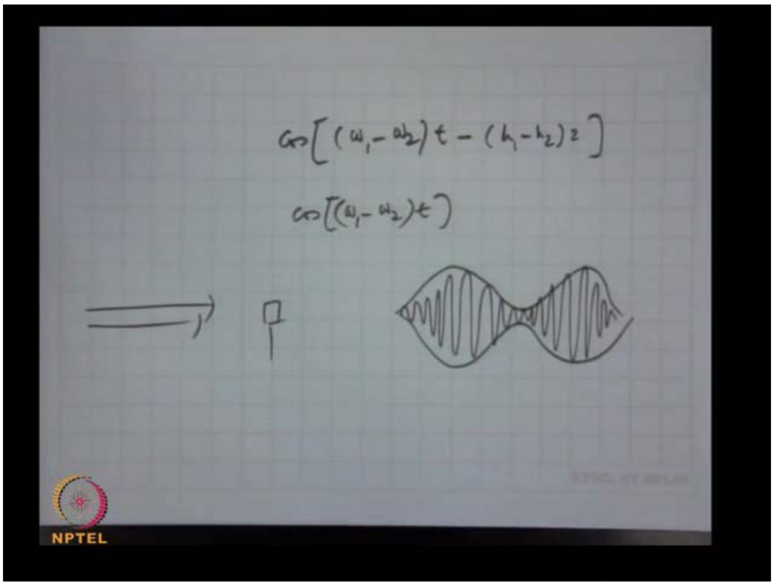

So, cosine you will get omega 1 minus omega 2 t minus k 1 minus k 2 z.

Sir, since they are propagating in the same direction.

So, you assume z is equal to 0

Yeah.

So this, so what is the meaning of this statement? So, if I have a detector here, at this place, and the waves this state is coming from here, at certain intervals of time I will have more intensity - more probability, at certain intervals of time I have less probability, that is beats, light beats in time domain, beating of light waves not sound.

It is like classically if I have two different frequencies, I will get like this, this is beats, this would exactly I am getting, at certain intervals of time whenever the cosine is 0, whenever the cosine is plus 1, I have more probability whenever the cosine is minus 1, I have less probability. And the probability of detection, if I have a large number of detectors simultaneous and measuring an ensemble of states.

Give me just the envelop functions

Yeah, I know I am not measuring the high frequency electrons, yeah.

Anything else?

When we have the third order non-linearity.

Yeah.

You said that depending on the n 2.

Um

There is an expansion or the frequency will increase.

Sure.

Yeah.

So that means, that the photons are going to come out will have a higher or lower frequency.

Now, first thing is we did not discuss that in photon picture.

You need not.

Yeah, so if you send, yeah, there will be spread of with this.

You have new frequencies generated in the medium right, because of the non-linearity and if you try to measure the frequency, you will be able to measure photons and also at different frequencies arriving at.

That is the number of photons increased.

No.

Then, if the frequencies are changing and.

No, not changing, what it implies is, I send, I have a large number of ensemble of fibers same medium for example, I send one photon here at certain frequency, I measure a certain frequency coming out, I do the same experiment again or do another experiment, I send the same frequency photon, I measure the different frequency coming out. And if I now plot, what is the number of photons at different frequencies, I will get a spectrum and that spectrum is broader than the input spectrum, I cannot predict whether in my first experiment what is the frequency of the photon that I will measure.

It will follow probability distribution which is the classical wave packet that I will generate in my classical analysis.

But the energy has to be conserved.

Yeah.

So, how is it conserved?

No, it is a 4 way mixing process.

It would not be there is.

Sorry.

If there is just 1 photon.

No, but it is does not one wave incident, there is a wave which is incident with multiple photons, so what you are generating is, what you are doing in that process is a general.

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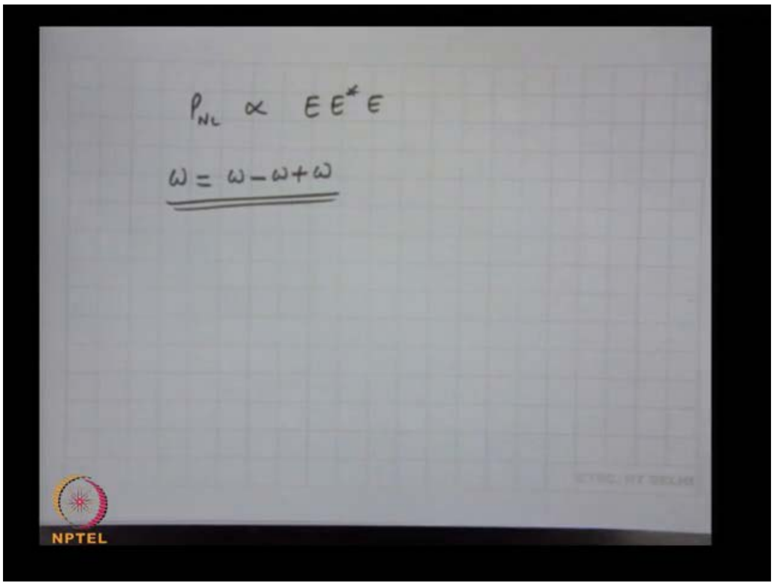

So, you see what is the chi three term gives me a non-linear polarization proportional to e e star e, so this is three waves at three different at the same frequency and mixing, so what you are generating is the frequency omega by this process, e, this e corresponds to omega, this e star corresponds to minus omega, this e corresponds to omega.

These three photons are mixing to generate a new wave at a frequency omega, so it is a mixing process. So, if you are generating new frequency, obviously, you are losing energy at the other frequency that we will put.

Just like in the second harmonic case or in the parametric down conversion case, or some frequency generation, you are generating photons at different frequencies that higher frequencies, obviously, you are losing some photon into a lower frequency or some other frequency to generate a new frequency.

If we have only one photon and you do not observe this or there is no

No, I do not know whether it is, no, not with 1 photon may be I have to put 1 photon as my pump, and 1 photon as my signal, that signal photon will it get affected by the single photon of the pump, which means at that power levels single photon non-linear effects, and there are people working on this kind of problems, but I do not I wouldn't I wouldn't be able to say what will happen energy has to be always conserved. So, I think that is the end, thank you very much.