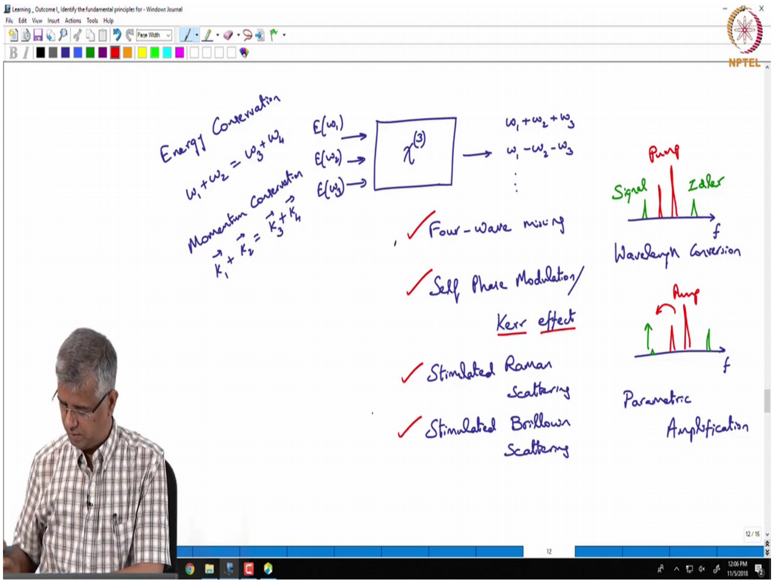
Introduction to Photonics
Professor Balaji Srinivasan
Department of Electrical Engineering
Indian Institute of Technology, Madras
Non-linear optics simulated Raman scattering

(Refer Slide Time: 0:16)

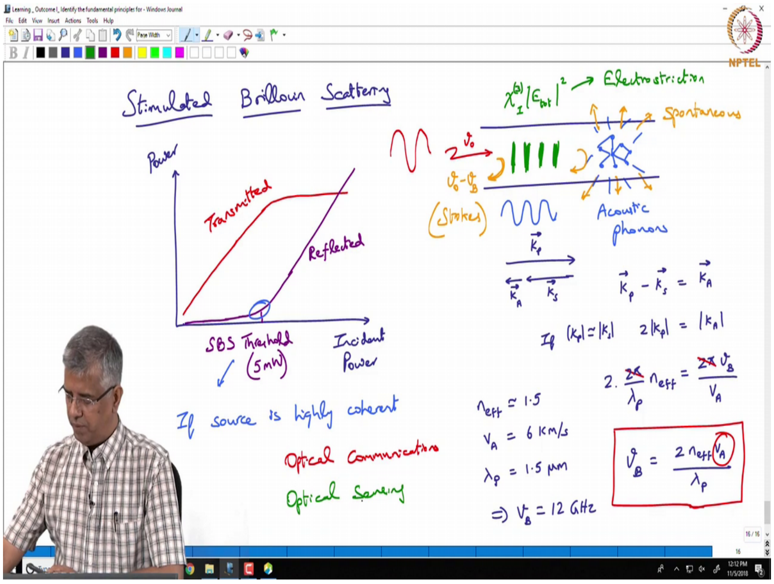


Now hopefully this will be the last lecture that we have and I think we want to have one more session at least to discuss tutorial problems which have not been uploaded on nodal because I am sort of reviewing that but hopefully it will be up later today. So what we are thinking is we will meet once for discussing those tutorial problems and if you think it is necessary we can meet once more to just review everything that has gone on in the course so far or if you would like to go on a lab tour that is another option available so we can take you guys around show some things that are happening in some of the other big optics things that are happening in the lab.

So we can discuss that off-line but thinking after today's lecture we will not have anything on Wednesday and Thursday we can probably schedule the tutorial session, is it okay? Yes so Wednesday post Diwali recovery whatever so we will just let that go and any further sessions will let you know. So hoping we will not have to meet again next week and then I think we are…so everybody is saying November 28 they do not have a problem for the lab viva is that decided November 28 is the date for the lab viva? It could be 27th and 28 I think, we will have to announce that separately, we may have to have 2 different sessions to accommodate everyone and…well we do not want to crowd the place with all of you there together so we will have to do this in probably 2 batches but we will see if it can all be done in on 28th or we need to do that on the 27th also we will let you know separately.

Okay welcome to introduction to Photonics, in the last few lectures we have been talking about non-linear response of material to electromagnetic waves, so we looked at chi 2 process that is processes that are relying on the 2nd order susceptibility and lately we have been looking at processes that are on chi 3 which is the 3rd order susceptibility, so far we have been looking at processes that are enabled through the 3rd order susceptibility chi 3, so we looked at 4 way mixing, we looked at self-phase modulation, we looked at its simulated Raman scattering and today we will look at simulated Raman scattering.

(Refer Slide Time: 4:05)



So when we discuss stimulated brillouin scattering we talked about interaction of light wave ideal case it is monochromatic light wave that is scattering of what are called these acoustic phonon which are nothing but acoustic vibrational modes that are present in the medium at room temperature and because of part of that scattering is going towards the source we looked at the specific case of how this is happening in an optical fibre and we said that light is beating with the light that is incident and that beating provides change in the refractive index and this changed actually corresponds to chi 3 multiplied by the magnitude of the total field the whole square, this is through a process what we call as electrostrictive.

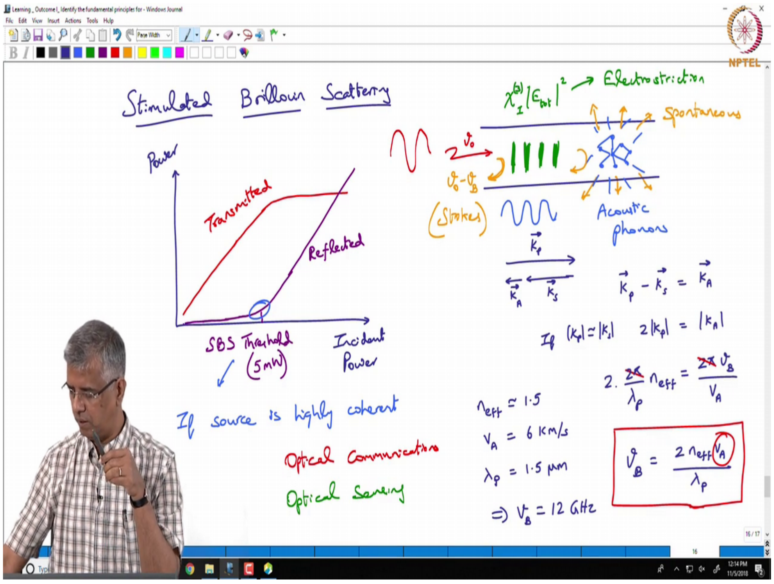
So electrostrictive basically says that whenever you apply an electric field across a material, the material response by changing its density is so lightly and that density change can actually be causing a change in the refractive index of the medium and through that you could actually have scattering of light and of course we say normally you have scattering which is… this sort of scattering is spontaneous in nature but if that spontaneous scattering is generating this index grating and it is allowing for more intense scattering that is essentially…the spontaneous scattering is stimulating the (())(6:28) further then you have stimulated brillouin scattering and essential when we are talking about this threshold here, the threshold that we are defining for stimulated brillouin scattering okay.

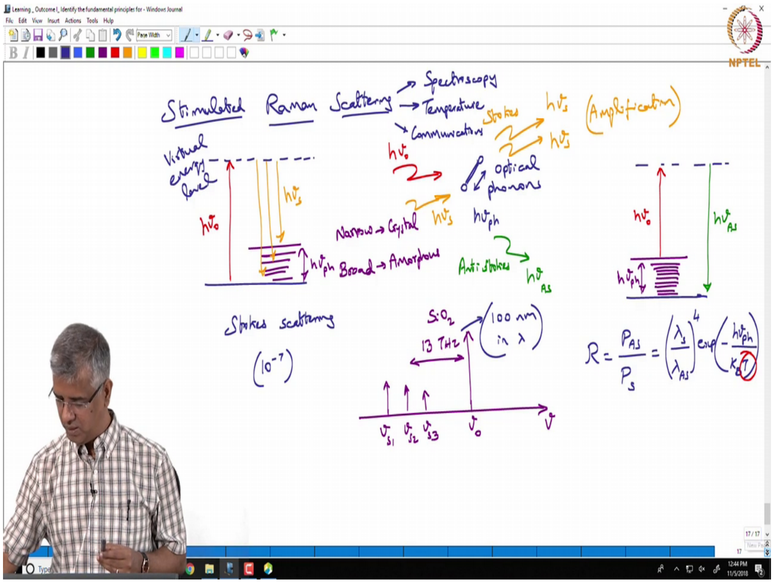
So spontaneous scattering is happening at any power level at stimulated brillouin scattering happens only beyond a certain power level at which the grating that we are generating is strong enough that you have large reflection of a large (())(7:09) of the incident power into this mu naught minus mu b which incidentally is actually called the stokes scattering, so whenever it is a process where the part of the energy is given to the medium and you are scattering of with lower energy right that sort of process is called stokes process and then of course when we talk about Raman scattering we will also talk about anti stokes process in which case it is gaining, the photon is actually gaining energy.

So that is what the question is whether the spontaneous scattering can stimulate this brillouin scattering. We are saying is the spontaneous scattering has to be strong enough especially in the backward direction, so that you can see this simulated scattering okay, so at lower power level spontaneous scattering happening but there are not enough spontaneously scattered photons that can create that modulation of the electric field which gives you that modulation or the refractive index of the material.

So you do not have stimulated scattering at lower power levels okay, so we looked at this being problem for you know so it is not so good for optical communications, it is a problem for optical communications but we said it is actually a very nice way of picking up strain or temperature of the material, so it is very good or optical sensing applications Okay, so you are fighting against optical communication but you are exploiting it in optical sensing.

(Refer Slide Time: 9:45)





So now we will move on to other topic which is…we will look at stimulated Raman scattering, so what is Raman scattering in the 1st place? So when light actually is incident on molecule right which is basically 2 atoms sharing a bond between them, we said it could be looked upon as 2 masses connected by a spring and once again at room temperature this is not in at rest you will have basically the atoms are bouncing around their mean position and the process stretching the spring and these sort of modes, the vibrational modes corresponding to this are essentially the phonon modes of the structure okay and in this case to differentiate it from what we were seeing previously acoustic phonons these are called optical phonons okay.

So to give you a feel in the previous case we were looking these vibrational modes of collection of molecules networked in this class matrix, the entire collection, entire network vibrating… all of them are moving around and if the entire thing is going around then we call it as acoustic vibrations whereas if it is just corresponding to the vibration modes of molecule you have much higher frequency at which this vibration happens, so they are called optical phonons.

So nevertheless if you have a light wave incident on this optical phonons you have scattering of light happening. In one case let us say that molecules is at rest okay and this electromagnetic wave comes around, it can actually give energy to… Because electromagnetic wave can influence a charge body as of a molecule because the molecule is sharing an electron that is what constitutes a bond of that molecule, so it is charged body so the electromagnetic wave can influence that charge body and in this case it is actually… It can give energy to this optical phonon and then it can essentially scatter of with lower energy, so you are coming in with h nu naught but you are scattering off with h nu s, so h nu s is less energy compared to h nu naught, so where did the rest of the energy go?

It went into exciting this phonon vibration modes or this optical phonons, right. So that is one scenario so we can represent this in terms of an energy level diagram, so you say okay your phonons this particular molecule is at rest but upon excitation of your optical radiation h nu naught it is going to a higher energy state and at that higher energy state it is essentially given off part of this energy to what is called this h nu phonon right, it is giving some energy to the vibration mode and then it is essentially scattering of with lower energy okay.

So this process is the Raman stokes scattering process okay and of course this is not something that happens for every photons that comes around okay, so this is the phenomena that happens in let us say with the probability of 10 power minus 7, 1 in 10 power 7 photons is undergoing something like this, so it is a very unlikely event but nevertheless if you look very enough you should be able to pick up this stokes photon, so that is one process. The other processes is if the molecule is already in a vibrational state that means it possesses this energy h nu phonon then an incoming photon has an opportunity to suck that energy out of the system and you can scatter of with even higher energy photon.

So that process is called anti stokes scattering, so this is anti-stokes scattering and in this case what are we saying we basically have this molecule at a lower level here but because of phonons it is actually going on to higher energy level and from there whenever this optical radiation comes along energy h nu naught then you have scattering happening, so you have a transition like this so you take that energy of the phonon which is denoted here and scattered off with higher energy photon and that is actually called the anti-stokes process so top one is the stokes process and this is the anti-stokes process okay.

So this anti-stokes component is actually very good for sensing applications because one of the major reasons why molecule will be in an excited state, in the vibrational state would be temperature, so if you heat up the material all these atoms are bouncing around their mean position, so it is all in a vibrational state okay. So if you have a hot body, the material with higher temperature if you come around with a photon with energy h nu not it can actually take that energy that phonon energy and scatter off with higher energy which is what we are calling as the anti-stokes, so by looking at the anti-stokes radiation you can actually tell what is the temperature of that particular material.

So specifically if you are counting the number of photons in the stokes and number of photons in the anti-stokes for a given power incident in that material then you can actually look at the ratio of the 2, so when you are looking at the ratio of the anti-stokes scattered power over the stokes scattered power that ratio since this scattering is inversely proportional to the lambda power of 4 that ratio can be written as lambda s over lambda As to the power of 4 and then exponential minus of h nu phonon divided by KBT right actually I am not writing down the individual scattering probability but if you do that and call them together you get a final ratio like this.

So that ratio of the anti-stokes scattered power versus the stokes scattered power is highly dependent on temperature, so it actually gives you an opportunity to measure the temperature of that material by observing this okay. So that way this Raman scattering is actually very nice tool for temperature sensing applications okay so that is one aspect. The other aspect is that this phonon energy is actually different, it is a characteristic of the medium right if the medium is actually a crystal what do you expect?

If it is a crystal then it is actually periodic arrangement of all these atoms and so all the molecules are exhibiting similar properties, so the phonon energy spectrum is going to be very narrow meaning that the phonon energy will be a very specific energy okay but if it is an amorphous material that phonon energy will have multiple sort of energy level, so it will be that phonon energy will be relatively broad in nature right, so what I am saying is this phonon energy spectrum is narrow for crystals it is a rather broad for amorphous material.

So by observing this Raman scattered radiation right if it is broad then that h nu s can go into any one of those levels and it can end up in anyone of those energy levels so that h nu s is actually a broad spectrum right by observing the stokes scattered light spectrum you can actually get some insight on the phonon energy spectrum and by observing the phonon energy sector you can tell what sort of material it is right so this is actually very good for material studies.

So the question is are there any additional components due to spin of the phonon very much right so the vibrational modes could be just translation modes or rotational modes so there could be a lot of modes so that is what you are referring to as spin of the phonon right all those will have their own signatures in terms of the phonon energy that it possesses all these different vibrational modes, so by picking of the corresponding scattered photons you can tell whether what is the vibrational mode also, whether it is actually corresponding to this sort of vibration or this sort of vibration and so on.

So there is lot more to this than what I am explaining you but this is just the basic principle it is extremely powerful tool to understand some medium. You give an unknown medium and let us say it is a transparent medium because if it is not transparent light is not propagating very far okay so let us say it is transparent medium then you are asked to tell what are the constituents of the medium? What are the different things that are happening in the medium?

Main thing you do is Raman's spectroscopy this is what is called Raman's spectroscopy you illuminate with one frequency of light and then you look at the scattered light spectrum and from the scattered light spectrum you can tell things like these you know the phonon energy spectrum and from the phonon energy spectrum you can actually classify all these different types of phonons that are present in the medium and you can also imagine that…I am showing one particular molecule for which the phonon energy will have one particular structure. In reality that material may have multiple molecules, different types of molecules like even in germanosilicate fiber you have germanium oxygen bonds you have silicon oxygen bonds right?

Each of those bonds exhibits at different phonon energy spectrum, they have a characteristic vibrational mode with each of them, so when you look at that scattered light, so we are saying I am illuminating with this frequency let us just talking terms of frequency, this is my mu naught then when I look at my scattered frequency I can have multiple components, nu s1, nu s2, nu s3 and so on right I can have multiple components each of those components are representative of a particular molecule in that material and let us say I have mapped out all the phonon energy corresponding to all molecules in general then I have a clear finger print for each molecule, so if I say I am seeing a peak around this point then you say this must be this molecule right so you can identify what are the different molecules that are present in that material and not only that you can also tell the concentration of those molecules, how?

Student: (())(26:57).

Professor: You look at the relative peaks, the amplitudes of those relatives peak that tells you what is the concentration of those molecules, so now I have you give me one material I will tell you that these are the molecules that are present and these are the concentrations at which they are present, so I can completely map out that material, how amazing is that, right? So it is extremely powerful technique in spectroscopy and that is clearly one application that it is good for spectroscopy okay and we also talked about sensing, temperature sensing it is a very nice tool for that, we can use for sensing applications and we have one more application which is communications.

So in complications it could both be bad as well as good, it could be bad because let us say I am sending information in different frequencies like in wavelength (())(28:17) in different wavelengths. If nu naught and nu s are both different channels in my communication system this Raman's scattering what it does is, it takes energy from nu naught and deposits it in nu s right that means the information that you are sending in one frequency, in one channel is actually you know imprinted on another channel.

So that can give rise to crosstalk right, so that will be a major limitation in communication that it can give rise to crosstalk but it can also be used to your advantage, how can you use it for your advantage? Now what is at the same time the photons is coming to this molecule you have another photons h nu s also coming in there. If I have both of these there then I am stimulating the transition and I am going out with 2 photons which are clones of each other just like what we did in stimulated emission right.

So you have a possibility of stimulating this Raman's scattering, why is stimulation important because when you talk about spontaneous scattering, spontaneous scattering can happen to anyone of these energy levels okay but stimulated scattering, what that means is whatever photon energy you are coming with the same photon energy you are going out, you are getting a clone of that incoming photon right so in that case you are able to amplify a particular wavelength channel okay, so that is one amazing… So you have a question there.

Student: What is wave number…?

Professor: The question is what is the wave number for this phonon energy essentially? So the wave number, I cannot remember the exact wave number it is some 1000 centimetre something like that or 500 inverse centimetre, I think it is above 500 inverse centimetre in few silica, the phonon energy in few silica which is amorphous medium around 500 inverse centimetre is I think the peak. Actually what I do is the phonon energy frequency, the shift in frequency that you have where you have maximum phonon that corresponds to 13 terahertz okay, 13 terahertz would be roughly about 100 nanometres in wavelength okay you figure out what is it in wave numbers and you can do that right.

So this is for SiO2 and of course you would expect this to be different for different material okay but what I was saying is you can get stimulated Raman's scattering and what does that mean, if you are able to get stimulated Raman scattering what does that mean from this optical process amplification is possible here. So this can give rise to amplification of light and there is a very important aspect to this amplification, how do you differentiate this from what you did in this erbium doped or ytterbium doped fibres those rarest material.

You see a difference between the 2? So yes there are photons that are controlling your transitions and here there are vibrations that is partially correct but there is one more important thing that we have here which is key, so there it is a nonlinear process right so you need certain number of photons to activate this process, so beyond that threshold only you can have this process is happening in a consistent manner but the key differences…

Student: (())(33:40) can be greater than the incoming.

Professor: Okay the scattered frequency can be greater than the incoming frequency if you are looking at the anti-Stokes process which is also a good point but the key difference is that here we are talking about virtual energy levels okay we are talking about virtual energy levels here. In erbium, ytterbium, neodymium whatever the rarest ion we were looking at before we were talking about God given physical energy levels from this orbital you can go only to this orbital you cannot go anywhere in between right it has some very specific energy levels that you can go to.

Of course there was an advantage in doing that in the sense that once it went to that energy level there was a finite time it could stay there, that energy was actually stored in that orbital for a finite time which is in the order of 10 milliseconds for some of this rarest elements. Here there is no physical energy level, it is a scattering process it happens instantaneously, so there is no storage of energy happening anywhere okay so that you would say is a disadvantage because when we talk about stimulated emission we say we want to build a population inversion right and the inversion you can build with very high level if you hired a very long excited state life time remember those were the basics concepts that we learned while ago.

So here there is no storage of energy so there is no concept of building an inversion and all that right, so that is a disadvantage but the key advantage is because your energy levels are fixed in rarest ions you could get amplification only at very specific wavelengths. If you use erbium you get amplification at 1550 nanometres if you wanted application at 1 micron you needed to go to ytterbium if you wanted the amplification at 1.3 micron we have to either go to neodymium or praseodymium which has specific energy levels corresponding to that, so you could not do it at whatever wavelength you want but what about this?

Where you get amplification is determine by what? Your pump energy, your pump wavelength, I said 100 nanometre shift we have right, so if I want…so this is actually lower frequency 13 terahertz is lower frequency compared to the incident frequency or in terms of wavelength it corresponds to 100 nanometres, so this corresponds to 100 nanometres in wavelength right so if I want gain at 1550 nanometres what pump water use? 1450 nanometres, if I want gain at 1560 nanometres I come in at 1460 nanometres.

If I want gain and 1300 nanometres I would come in around 1200 to 1220 nanometres or so on right because 13 terahertz is a frequency shift but that corresponds to a delta lambda that is different depending upon what wavelength range you are operating at but the key point is I can get gain at whatever wavelength I want provided I have pump photons which has a frequency that is down shifted by or rather higher frequency that is up shifted by 13 terahertz… There is a question there.

Student: Why would the (())(38:13).

Professor: The question is what about the phase? Well we are talking about stimulated process, so if it is actually stimulating like this the outgoing photons will be both of the same phase it is highly coherent process.

Student: (())(38:30)

Professor: So the energy is transferred provided you have incoming photon with h nu naught arriving at a molecule with the phonon energy of h nu bh right, at the same time you have this h nu s also coming okay the signal photons also coming. If all of this happens together then you have stimulated Raman scattering.

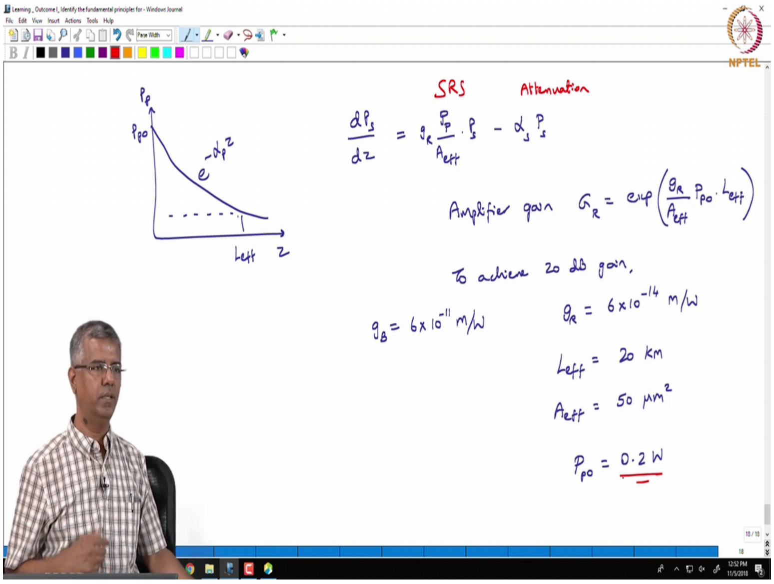
Student: The base is that of a (())(39:09).

Professor: The signal itself that is right the phase is corresponding to the signal right. Now what is the probability of something like that happening are right you are talking about a material with zillions of molecules, you come in with trillions of photons at h nu naught, h nu s what is the probability that both these photons come to a location at the same time that is a very low probability right.

So to increase that probability you need to have large number of photons of both your pumps and stokes right like you cannot have one photons of pump going into this material another photon at stokes going into the material and that you can expect them to come to a location at the same time to have this process happening. So you say more number of photons the better, the better the probability that you will have the stimulated scattering but then that is counter-productive right with a signal you do not have more number of photons I mean signal is already weak why would you want to get to an amplifier because you lost all your power and attenuation so you want to boost that signal right.

So signal is already weak I have very few photons coming in the signal, so how do I compensate for that? I need to have a much larger number of pump photons than what is normally necessary in the case of rarest ion, rarest ion or erbium doped fiber you guys did this experiment where with pumps of even few 10s of Millie what you were gain getting games of 20 db and so on right here that is not possible you need to have much more number of pump photons so you have much higher power levels that are required to achieve that same gain okay, so let us just quickly do that calculation I am realizing I am running out of time so but just quickly do this and then see.

(Refer Slide Time: 41:46)



SRS Attenuation

$$\frac{dP_s}{dz} = g_R \frac{P_p}{A_{eff}} \cdot P_s - \alpha_s P_s$$

Amplifier gain $G_R = \exp\left(\frac{g_R}{A_{eff}} P_{po} \cdot L_{eff}\right)$

To achieve 20 dB gain,

$g_B = 6 \times 10^{-11}$ m/W

$g_R = 6 \times 10^{-14}$ m/W

$L_{eff} = 20$ km

$A_{eff} = 50\ \mu m^2$

$P_{po} = \underline{0.2\ W}$

So if I am tracking the signal photon along the length of the fibre that obviously is going to get depleted at the rate of minus Alpha s Ps where Alpha s corresponds to the attenuation in the fibre right that is just the background attenuation that is going on but it is going to be enhanced the number of signal photons, so the Stokes scattered photons it is going to be enhanced at the rate of gr and it depends on the pump intensity, so you have Pp over an effective multiplied by PS okay, so this corresponds to the SRS process, the stimulated Raman scattering process okay.

So it is getting enhanced at that rate and you are losing photons due to just the attenuation in the medium okay and similarly you can write an expression for the pump power in which case you will be depleted by both your gain as well as your background attenuation in the fibre but based on this small signal approximation you can actually come up with an expression for the amplifier again basically you neglect the attenuation component okay if you have enough pump power you can get gain through this process in which you can neglect that other component.

So your amplifier again due to this Raman process can be given by exponential of gR over A effective multiplied by Pp naught, Pp naught is the power that is launched into the fiber in the beginning of the fibre multiplied by L effective. Why does L effective come into the picture because the power is getting depleted, the pump power as the function of z it is going to get depleted, Pp naught is the power here.

So this will go down as e power minus Alpha p Z so the total gain is over certain effective length okay and of course if your actually length of the fibre is lesser than that of the effective length, effective length we calculated to be in the order of 20 kilometres but if your actually length of fibre that is available to you is much less than that, that physical length is what you would put here okay, so if you do some quick math to achieve 20 DB gain which is a typical requirement, so GR needs to be 20 db right.

So we have gR in few silica is 6 into 10 power minus 14 metre per watt. I should give your perspective the brillouin gain gB give you a perspective 6 into 10 power minus 11 metre per watt, so brillouin gain is actually 3 orders of magnitude larger than the Raman gain right but nevertheless even with this number we can still get some work done because if you say you have a fairly long fibre let us say the L effective is 20 kilometres okay and like we calculated previously the A effective can be in the order of 50 microns square.

If you put all of this together to achieve 20 dB gain if you calculate Pp naught, Pp naught would work out to be about 0.2 watts right it is about 200 milli watts over 20 kilometres long fibre okay, so if you have a much lesser length of fibre right let us say if you have only 20 metres, if you have 20 metres of fibre then the corresponding pump power you need is 0.2 into 10 power 3 that is 200 watts you need. Here to get 20 DB gain, you understand?

So there is actually much higher requirement of power in an erbium doped fiber if you had 20 metres you could get 20 dB gain with may be something in the order of 4 or 5 milli watts of power but here you are having to go to much higher power levels mainly because of the fact that stimulated Raman scattering is not a highly probable event, so you need to have both your pump as well as the signal photons coming to a location the same time, so which is possible only when you flood that material with huge number of pump photons okay so that is the… if you want to call that as a drawback but the big plus point is that this amplifier can be setup at whatever wavelength you want because we are dealing with only virtual energy level.

So we are not limited by specific energy levels and is in the case of rarest ions okay I think we have run out of time. I wanted to actually speak a little bit about acoustic optical modulator but I can keep going on and on for another month so I will stop at this point. I think this is enough, what do you think? You are worried about studying all this for your final exam, so let us stop here and we will meet again like a said later this week for the tutorial session on Thursday and if you want any lab visits if you think that is going to help your understanding of some of these things or if you want a review sessions we will schedule that sometime later this week okay, we will communicate over WhatsApp on this. Okay.