**Advanced Optical Communications**

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**Module No # 01**
**Lecture No # 37**
**Raman Amplifier**

In last few lectures, we have been discussing the non-linear effects in optical fibers. We saw that in glass fibers the nonlinearity is because of the third order susceptibility and then we have taken the special case of that which is the Kerr nonlinearity. In which the refractive index depends upon the power density. So, we saw that in the presence of Kerr nonlinearity there is a effect what is called the self phase modulation. That means, when the pulse travels on the optical fiber, the phase of the pulse is changed continuously and the change in phase depends upon the power inside the pulse.

We also saw that this phase change is a function of time within the pulse because this is coming due to the amplitude of the pulse at that instant and as a result you have a change in frequency within the pulse. So, we saw there is some kind of a frequency modulation which takes place within the pulse and that phenomena is what is called the self phase modulation. We also saw the effect of group velocity dispersion that means, when the pulse travels because of dispersion at different frequencies travel differently and then again you have some kind of a frequency modulation inside the pulse.

And depending upon whether you are in the normal dispersion regime or non anomalous dispersion regime, one can get the frequency chirp which is positive or negative, the frequency chirp which is coming because of self phase modulation is always positive. And therefore, if we operate at the anomalous dispersion regime then the chirp created by the group velocity dispersion is of opposite nature then what is produced by the self phase modulation. And in that situation if we adjust the parameters then these two chirps can cancel each other and then the pulse can travel without broadening for long distances on optical fibers and that phenomena we call a soliton.

So, then the pulse travels almost like a particle and in last two lectures we investigated the characteristics of solution. And then we noticed that when we are dealing with solutions the most important aspect is that the nonlinearity should be maintained when the pulse moves inside the optical fiber. Now, we all know that there is a loss on the optical fiber. So, when the pulse starts travelling on optical fiber the amplitude of the pulse reduces because of the attenuation on optical fiber. And do the pulse amplitude reduces the effect of nonlinearity reduces because the nonlinearity depends upon the power density.

So, we saw that at any point of time if the non-linear effects become weaker than the dispersion effect, then the pulse broadening phenomena will dominate. And when the pulse broadens the peak amplitude comes down so, nonlinearity becomes further weak and then the pulse further broadens. So, at any point of time if the dispersion dominates over nonlinearity then the gain is lost. Iin the sense that now the broadening phenomena will dominate and there will be some kind of a regenerating mechanism that more broadening of the pulse will further weaken the nonlinearity. And which will again help in broadening the pulse because of dispersion. We also saw that if you increase the power in the pulse significantly to large value.

So that the other end of the optical fiber still the non-linear effects are dominating over the dispersion. Then at the input end of the optical fiber there is a possibility of excitation of higher order solutions which do not have a simple pulse shape and also their propagation behavior is quite complex. So, we saw that if we wanted to make a solitonic communication a reality then the better option is not the lumped amplification, but the distributed amplification. That means, as the pulse travels on the optical fiber whatever is the loss on optical fiber there should be some mechanism which just compensates for this loss.

We also saw that in the optical communication system most of the communication at the moment is taking place in 1550 nanometer window. And there is this amplifier what is called the erbium doped fiber amplifier which is EDF and which has about 30 40 nanometer bandwidth around 1550 nanometer. But as the time is moving, there is a possibility of transmission over a much wider wavelength range that is from almost 1270 nanometer to about 1600 nanometer. And then the EDFA does not really give you amplification in the entire window so, there is a need to have an amplifier which can work in a wider frequency range.

So, we have now two motivations to create a new amplifier, one is an amplifier which is not of lump nature which has a distributed amplification. And other one an amplifier which has a much larger bandwidth than what the EDFA can give and this kind of amplifier is what is called the Raman amplifier. So, Raman amplifier is based on the principle of Raman scattering. So, in this lecture we are going to discuss the fundamental of Raman scattering the very basic equations of Raman scattering. How amplification takes place in a distributed fashion and then we will see its application for optical communication.

We also see the effect of Raman amplification on WDM optical system and then if there are any limitations coming because of this amplification that also we will investigate. We will also see the use of Raman amplification for sustenance of the solution on optical fibers.

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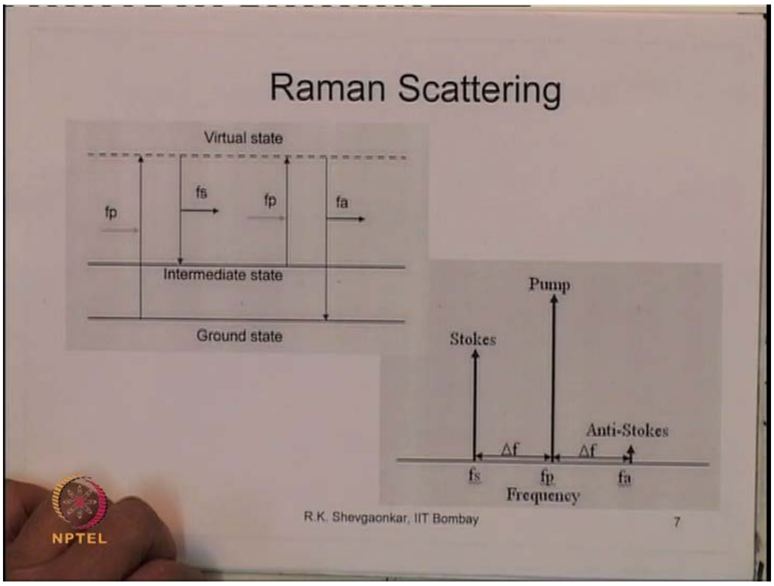


So, let us look at the very basic phenomena of Raman scattering. Now, Raman scattering phenomena is as follows that if you consider a material which are having a energy levels. You have a ground state, this is virtual state and this is a intermediate state which are essentially vibration states. So, if you excite the material from the ground state to this virtual state these excited electrons will jump to this vibration state here. And in this process a frequency is emitted which is smaller in value compared to this value and the difference in the energy essentially is equal to this which is fixed. That means there is a fixed change in the frequency compared to with which the material is excited.

So, this frequency at which the energy is supplied to the material is what is called the pump and the frequency at which the energy is released this is called the stokes. Now of course it is not that the entire energy is going to get converted in to this frequency. So, about 10 to the power minus 6 of the total intensity of the light which is impinging on the material, comes out in the form of this stokes frequency. Then we also possibility that if the energy supplied to the material corresponding to this frequency and if you can make possibility of this transition. Then one can get a frequency which is what is called the anti stokes frequency compared to the a pump this frequency will be of higher value.

Again by the difference corresponding to this energy difference between the vibrational state and the ground state. So, that is the basic phenomena of Raman scattering that if a material is exposed to a beam of light then a small fraction of that energy is converted in to the frequency which are the stokes frequencies. Or what we say is that in the frequency is down shifted compared to the incident frequency by a fixed amount which is corresponding to this energy difference. So, if I look at spectrally in the spectral domain if I excite the material with this frequency which is the pump frequency.

Then we get a stokes frequency generated which is smaller than this and this change in frequency or decrease in frequency that is the parameter of the material. Because that corresponds to the energy difference between the vibrational state and the ground state. Similarly, if you could excite this mechanism then one can create anti stokes for which the frequency would be higher compared to the pump frequency. Of course this mechanism is more easily realizable, this requires special systems we are going to focus essentially on this mechanism. That means if the material is exposed to pump, we will generate the frequency, which is the stokes frequency, which will be down shifted with respect to the pump frequency by a fix amount.

And this difference as we said is decided by the material so, every material has this frequency fixed that is the characteristic of the material. So, if I look at the material glass then you will see that this vibrational energy states which you have got here they are not as discrete as it is shown here actually is the band which you see here. So, it is more like a diffused band. So, this transition can take place within that band anywhere. So, we do not get this frequency a monochromatic frequency even if the pump is monochromatic. So, you see a clear band of frequency generated here, when material is excited with a monochromatic pump.

So, now since the frequency in which we are interested now is not an absolute frequency it is a relative frequency with respect to the pump one can now get a relative a spectrum for Raman gain..

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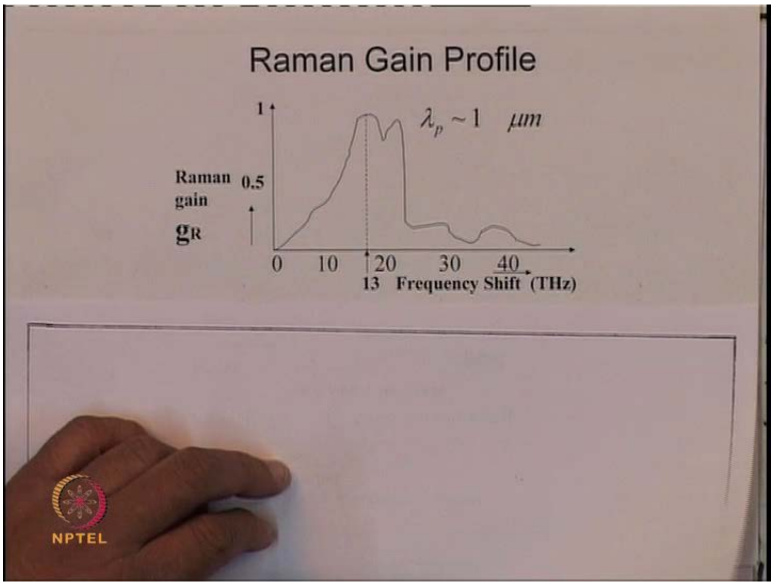


So, the frequency characteristic if I plot what is called the gain spectrum of Raman process, the spectrum looks like that and that parameter which decides this is what is called the Raman gain coefficient. So, this spectrum is drawn in the relative frequency domain that means, the pump is here at this relative frequency 0 and these are the frequencies differences which are plotted in terahertz. So, now what we are seeing here is that this gain peaks somewhere here and this is not an absolute frequency at which we have amplification or gain from the from the system. This is the relative frequency compared to the pump see if you put a pump if you shift the value of the pump the absolute frequency also will shift because this difference will be will be constant.

So, for glass around if you take the pump around one micrometer wavelength then we see that the peak of this Raman gain is approximately thirteen terahertz away from the pump frequency. Or we say that the signal is thirteen terahertz downshifted compared to the pump frequency which is a whatever value you take now. If you take this 13 terahertz and if you convert that into approximate wavelength, it will turn out to be 100 nanometer kind of wavelength approximately. So what that means is that, whatever wavelength you have for the pump, you will generate a frequency band or a wavelength band which are about hundred nanometer less compared to the pump wavelength.

So, if you excite the pump around 1500 nanometer, we will get something about 1350 nanometer or 1400 nanometer we will get the amplification. But the important thing to note here is that we have a band which is created because of the Raman scattering. So, it is not only one frequency which is excited, all these frequencies which excited here we have a more power, but actually it is the large bandwidth over which the frequency is get generated. That is the phenomena essentially we want to exploit now for the broadband amplification. We have also seen that this turns out to be almost like about 13, 20 terahertz. So, this can give very wide band amplification even if we consider this range.

So, what we are now going to do is we are going to make use of this phenomena of Raman scattering to see a broadband amplification which is not wavelength specific, but which is relative wavelength specific. That means if the pump wavelength is changed then this frequency also can be changed.

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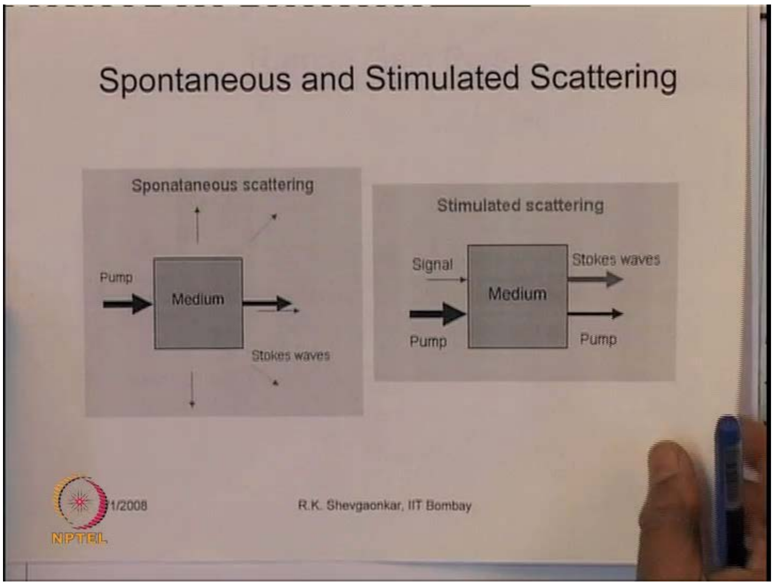


Now, when I am looking at this phenomena as we all know that the phenomena you have got a basic mechanism which is a amplification mechanism or frequency conversion mechanism. So, this phenomena if you do not put any seed signal inside, then this phenomena is like a spontaneous phenomena so, we have this spontaneous Raman scattering. And if we have a material then and if you pass an intense beam of light through this material, a very small fraction of that power actually will get scattered and that is a stokes wave which we talked about that phenomena is a spontaneous phenomena.

But as we know that if we have another signal pass through the material along with the pump and this signal frequency is such. That is, it coincides with the peak or the Raman gain then this process can be converted in to a stimulated process. So, here we were seeing a phenomena they when the pump beam propagates through the medium, there is a another frequency generated which is downshifted compared to the pump frequency. But here we are seeing that no if we put signal along with this then coherently the power from the pump can be transferred to the signal. The signal now is aligning with where the amplification is maximum.

So, this process now by using he stimulated mechanism can be used for the amplification of the signal. So, essentially we can create what is called the Raman amplifier, a broadband amplifier and the band will be decided by what is the pump wavelength. Say as we saw that if I change the pump wavelength then the entire band will be 13 terahertz down with respect to the pump wavelength. So, choosing the variety of pumps we can find the amplification in any desired band we like.

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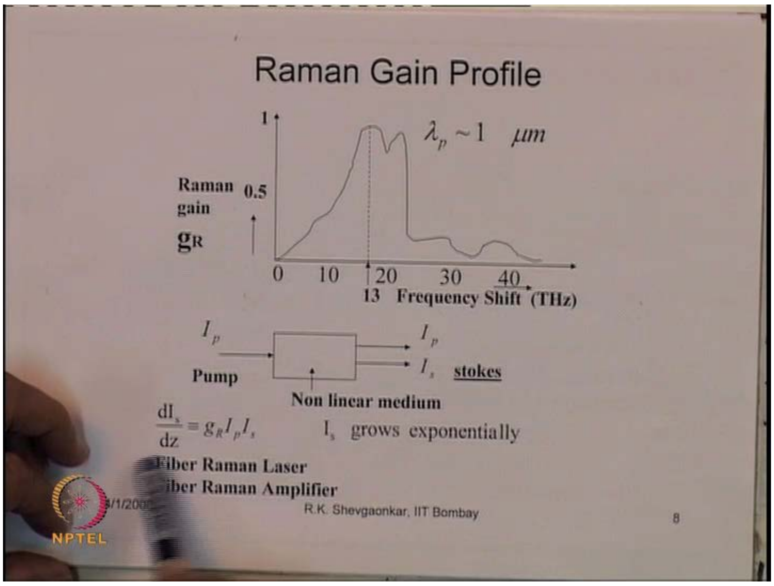


So, that is the basic process essentially we are investigating here now. So, Raman scattering phenomena and for glass this phenomena gives you a frequency shift which is about 13 terahertz away from the pump frequency. So, while once you are having a amplification mechanism where stimulated process is there, we can create the chord Raman amplifier. And then with proper feedback we can also create what is called the Raman laser. So, let us do a analysis of this in a in a most simplified fashion and one can also try to find out you know what are the threshold powers which you require in the pump to get a the amplification in to the stokes away.

So, first of all as we know that once you are having a gain coefficient like this, the radiation will grow exponentially with the gain constant which is given by Raman gain. So, let us say we are having the frequency and you are having intensities corresponding to those frequency.

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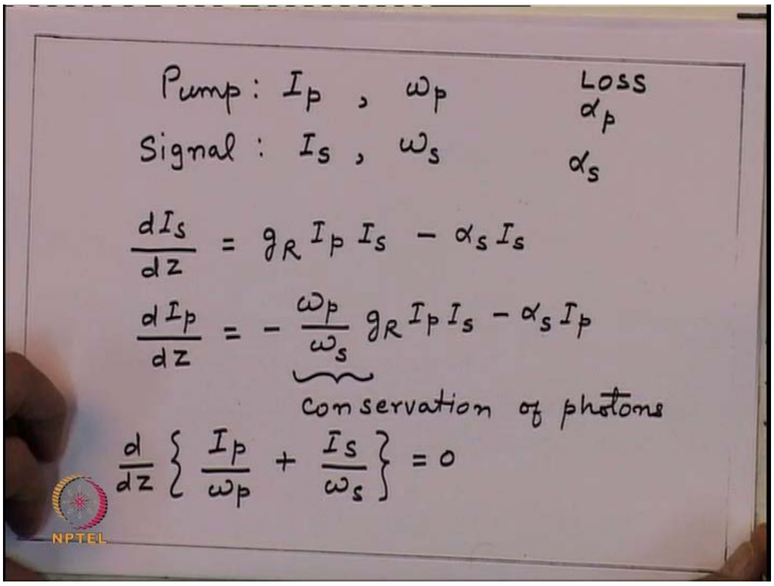


So, we have a pump which has a intensity I p and a frequency omega p. Similarly, let us say we have a signal which has a intensity I s and the frequency is omega s. Let us say on the fiber, we have the loss and the attenuation coefficient for the pump wavelength is given by alpha p and for the signal it is given as alpha s. So now, you see when the pump and signal travel on the optical fiber. You are having a mechanism which is the Raman mechanism which glows the signal and since the power is going to get transferred from the pump to the signal. The pump power will reduce and power will reduced both pump and signal due to the losses on the optical fiber.

So, one can then write down the simple differential equations for this. So, we have now the change in intensity as a function of z which is distance on the fiber that is equal to now the gain coefficient the amplification coefficient is the gain coefficient multiplied by the pump power. So, we have here the Raman gain coefficient times I p is the pump power. So, this is now the gain coefficient, amplification coefficient with which the signal is going to grow on the optical fiber times I s and then there is a loss so, minus alpha s times I s. And as I mentioned now since the signal is growing and power is coming from the pump so, the pump will attenuate.

So, the differential equation for the pump would be d by d z that is equal to minus omega p by omega s, Raman gain I p minus alpha s times I p. This factor which you get here that comes essentially from conservation of photons.

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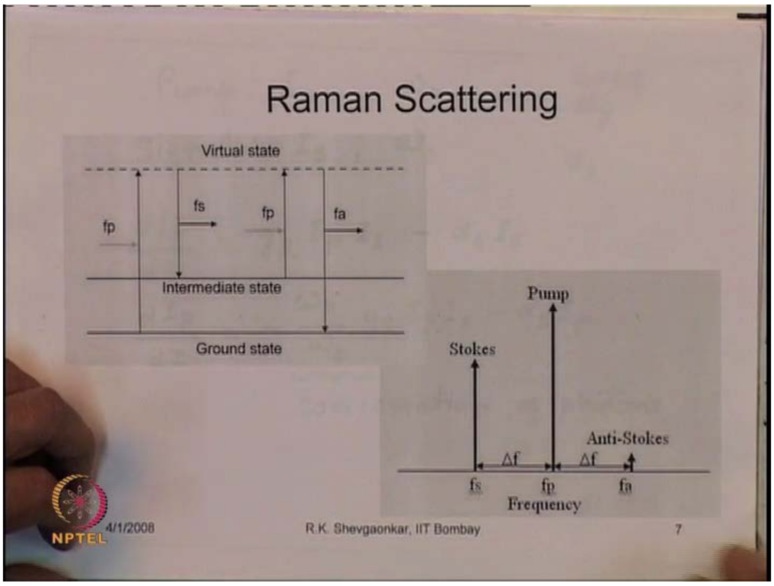


Because as we know in the Raman process what is happening that the certain transitions are made from this to this. So, a photon is absorbed inside the material is going inside the material and when it comes out actually reaches the this much energy has been taken away from the photon, but the number of photons which are gone inside they are conserved

So, we are saying that if the conservation of photon has to take place then the d by d z of number of photons combine together in the signal and the pump that change as a function of distance has to be 0. So, as we know the intensity if you take for pump the number of photons if I divide by the frequency plus if I take the signal intensity and divide by the frequency that essentially gives me total number of photons. So, rate of change of this photons as a distance that should be equal to 0. So, from there essentially we see that now that this coefficient has to be multiplied by this factor which is omega p by omega s. Now to analyze this first, what one can do is one can assume that the signal is very small.

Compared to the pump even if the power is transferred from the pump to the signal the depletion in the pump is negligible. So, we say that this term at least to start with is a not a very dominant term because the change in power because of this transfer is really small.

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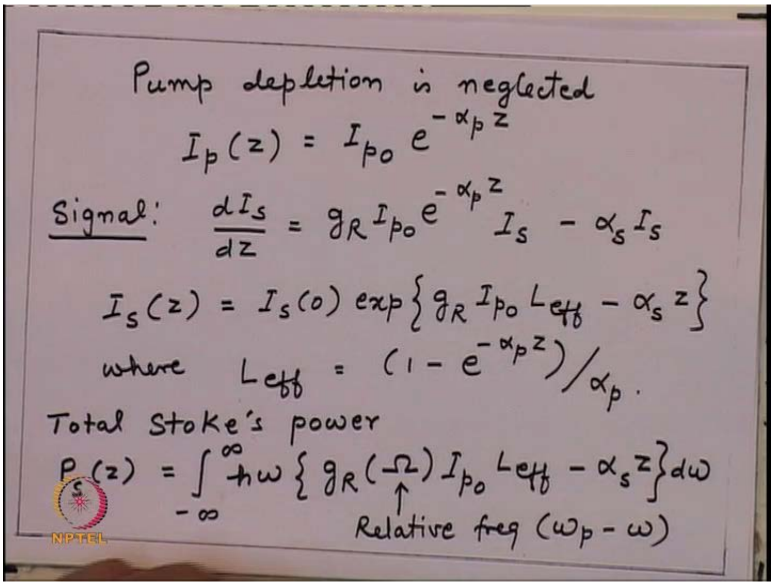


So, what we can do is, we can say that pump depletion is neglected. If I do that then this equation this term is not there. So, then the solution of this is very very straight forward. So, from here this should be sorry this should be alpha p is the pump attenuation constant. So, from here we have I p as a function of z that is, the initial pump value with exponential decay which is minus alpha p times z. And then I can substitute this I p into this to get the amplification of the signal. So, the equation for the signal then is d I s by d z that is equal to Raman gain coefficient, this quantity I p which is I p 0 e to the power minus alpha p z, times I s minus alpha s times I s.

Again as we have introduced the concept of the effective length on the optical fiber that means, there is a length over which the power is substantial. One can write the solution to this equation I s as a function of z that is I s at 0 exponential of this coefficients is g R I p 0 L effective minus alpha s time z. Where as we have defined earlier also the L effective which is the effective distance that is equal to 1 minus e to the power minus alpha p z divided by alpha p. So, now if you do not put any seal inside this material. So, if I take a system like this essentially what we are saying is that because of the thermal emission spontaneous emission is like a one photon is created in every frequency bin and then that photon essentially goes through this gain process.

So, there is amplification which takes place. So, if I wanted to find out what is the total power inside this stokes wave which is generated then essentially I can just take this expression. And if I integrate over the frequency, that will give the total power which is generated inside the stokes parameter. So, we can get here the total stokes power which function of z, that is if we integrate over the frequency h of omega with the Raman gain and now here we are looking for a frequency which is the relative frequency. So, I will write the frequency let us say is given by capital omega I p 0 L effective minus alpha s z, d omega.

So, what we have done? We have taken just this and integrated over the frequency to get the power which is generated in the stokes wave where this omega, capital omega is the relative frequency which is omega p minus omega. So, what one can do now is the since the Raman spectrum is peaky the spectrum is something like this, we can define some kind of effective bandwidth which the Raman spectrum has.

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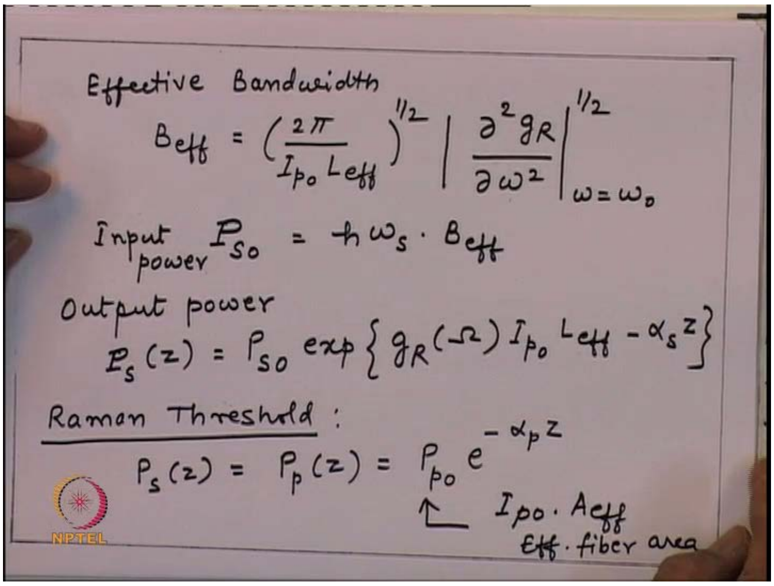


So, let us call effective bandwidth b effective and that is given as two pi divided by I p 0 L effective to power 1 by 2, d square g R by d omega square, square root at omega equal to omega 0.Where omega 0 is the is the is the location here where the Raman is maximum which is for glass is about 13 terahertz away. Then if you are considering only the spontaneous emission, then the input we are assuming that every frequency bin is having one photon. So, the input of the fiber the intensity is I s 0 and that is simply given by h into omega s, multiplied by the effective bandwidth. Because that is the energy which we got in each frequency bin, if I multiplied by the effective bandwidth that is the total power I have which is going inside the optical fiber.

So, then at the output we will get power that will be I know make it p for the power p s of z that is equal to p s 0, because this is of the since we are multiplying here by this. Let us call this as the power so, this is power so, p s 0 and then you will get from the previous expression as we have got here, we integrate this you get the total power which will be this I p 0 L effective minus alpha s z. Now there is a parameter what is called the Raman threshold and this parameter is the power level at which the stokes power becomes equal to the pump power. Say as we know that when now this amplification is taking place the material is excited only with the pump and as the signal starts travelling inside the spontaneous photon which were there they get amplified.

So, the power now gets transferred from the pump to this spontaneous emission or rather Raman spectrum. And then one can ask what should be the input power level in the pump so that, the pump and signal they become equal for the given length of the optical fiber. That power level is what is called the threshold power for Raman, it does not mean that unless the power exceeds the Raman threshold the Raman amplification or Raman scattering is taking place it is not saying that. It simply saying that that power level the power in the stokes will become equal to the power in the pump, but even if one is operating below the threshold level, some power is going to get transferred to the stokes waves.

So, this process will take place at every power level only thing is when the power increases in the pump then the stokes power will become as large as the pump power that is what may happen. So, we can define what is called the Raman threshold, that is at which the pump power for a given length of the fiber that becomes equal to the pump power which is initial power e to the power minus alpha p into z. And this quantity because the since you are talking about power essentially this is the intensity I p 0 multiplied by the effective area of the fiber.

So, this is a effective is effective fiber area as we know the loss profile for the fiber the loss does not change very significantly if you are in the around 1550 nanometer range then the loss coefficient for glass at 1550 nanometer and 100 nanometer below that will be approximately same.

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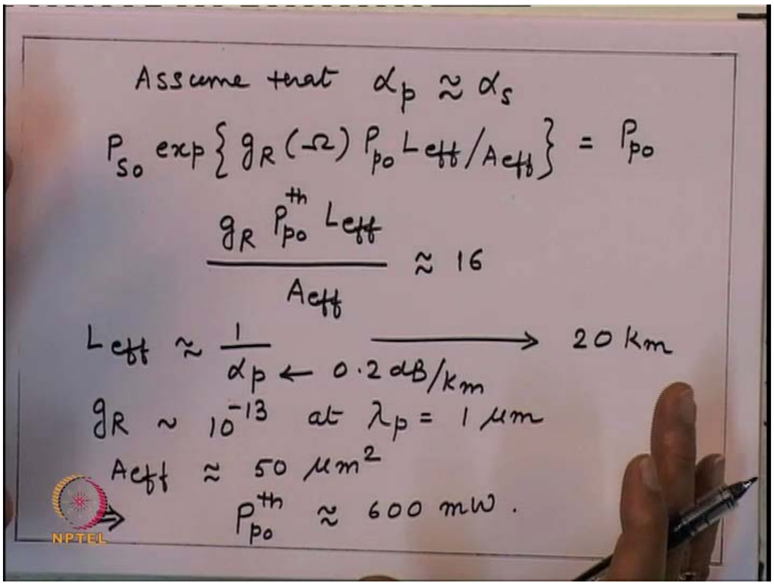


So, one can very safely assume that alpha p is approximately equal to alpha s. So, what we can do is now one can just make this approximation and then use this condition. To say that, now the signal power which is the Raman gain P p 0 in the in the pump L effective divided by A effective that should be equal to P p 0. So, from here than one can get the threshold power in Raman gain which is g R P p 0 Leffective upon A effective that is approximately equal to 60 for the parameters which you have chosen.

Now, if you take the typical the optical fiber parameters the l effective is approximately one upon alpha p and if you consider this quantity to be about 0.2 d b per kilometer. This will lead to L effective approximately about 20 kilometer. The Raman gain coefficient is of the order of about 10 to the power minus 13 at lambda p is equal to one micrometer and A effective which you see for a typical fiber is of the order of about 50 micrometer square. So, that gives us the P p 0 and we say we have threshold power. So, we say this power is a threshold power Pp 0 thresholds that is approximately equal to 600 mill watts.

So that means, if I consider a single mode optical fiber and if you put few hundred mill watts of power inside the fiber then the stokes frequencies which are generated they will have power equal to the pump power. Now, obviously if you consider a communication system which is single channel, typical power is going to be of the order of about few mill watts. So, it is no possibility of really reaching this condition of the threshold. So, that means, the stokes wavelength power will never be equal to the pump power.

However imagine a situation when we are having a WDM system and there are large number of channels are now transmitted inside the optical fiber.

In that situation then the total power which is going inside the fiber will could be easily fraction of this could become comparable to this. And in that situation then you will have the stokes wavelength generated must strongly compare to in a single channel system. Now since this phenomena is a natural phenomena which is going to take place on the optical fiber. Note here we have not done anything special to the optical fiber what we are saying is if the optical fiber is made of glass then it is a property of the glass that when the light travels to the fiber a small fraction of that light is going to be downshifted in frequency and that difference will be equal to about 13 terahertz.

That means, to create this amplification process we do not require anything to be done to the optical fiber simply we have to create a mechanism by which the pump can be inserted inside the optical fiber along with the signal. And then slowly the pump power will get transferred to the signal and then signal will starts getting amplified as they travel together inside the optical fiber. So, this phenomena actually going to take place on every fiber because this is the intrinsic property of glass. And then we already said that since we are to going to (( )) some device like a amplifier here. This amplification is going to take place all along the length of the fiber as long as the pump power is there the power will get converted into the stokes frequencies.

So, this is going to give us an amplifier which is the distributed amplifier that is what we are looking for. Another important thing to note here is that, no where it is said that, this mechanism of converting power from the pump to the stokes will stop. As long as the pump power is there, a small fraction of this power will go on getting converted to the stokes wave. Also it is never said that the pump and the signal have to propagate in the same direction. Is possible that inside the optical fiber signal may propagate in one direction pump may propagate in opposite direction and whenever they are having a common region the power from the pump will get transferred to the signal.

So, you can have the signal and pump co propagating, you can have the signal and pump counter propagating and the signal amplification will take place through the Raman scattering. So now, one can ask a question that having this basic mechanism given to us what are its implication for the optical communication system? We have already seen that in the single channel the power may not be very large. But when large number of channels are propagating then the power will become significantly large also as we said this phenomena actually is a one sided phenomena.

So, whenever there is a frequency you have a down conversion of the frequency. That means, when you are having a WDM kind of system every frequency is a pump because part of that is going to convert to another frequency which is 13 terahertz down. And every frequency is signal because this is going to receive power from a frequency which is 13 terahertz up for the peak. But in principle since Raman spectrum is distributed essentially what we are saying is in a WDM system every frequency receives power from its higher frequency and every frequency loses power to this lower frequency.

But this phenomena is a systematic phenomena, that high frequency lose power to the low frequency. So, if I having a band of frequencies, you will see the highest frequency will lose power to all its low frequencies. The second highest will lose power to the remaining low frequency and so on. That means, if I am talking about a WDM system systematically the power is flowing from the high frequency channels to the low frequency channel. Or in other words there is some kind of a crosstalk which is created in a WDM system because of the Raman scattering.

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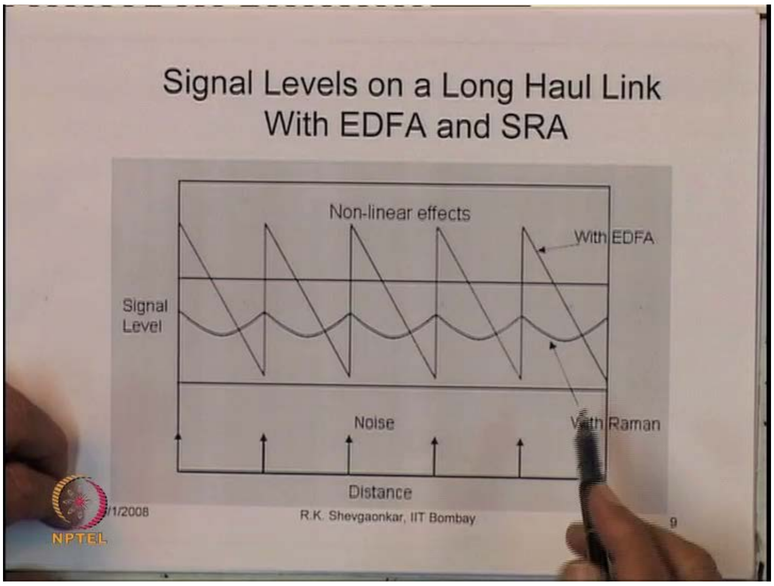


So, and that is what when I used to really worry about, but before we get in to that let us look at the mechanism of amplification, the distributed amplification say as we have seen. If I had let us say this link length from here to here and if I just wanted to maintain the signal level I wanted, whatever input signal is it? Its level should not change. It should remain just like this as a function of distance what would happen in a typical optical link where we use EDFA the signal will attenuate because of fiber, then we will put an amplifier which are here which is a discrete amplifier suddenly the power will jack up then it will go on attenuating then again put amplifier here I will jack up and so on.

So, that is the typical power profile I will see along the optical link, but if you have a Raman amplification which is a distributed amplification we can get a mechanism like that. So, if I create the Raman gain inside this, the power does not decrease significantly and then jack up. It sort of more or less maintains at certain level whatever level we are really looking for. So, you see that because of distributed amplification nowhere the signal was over amplified nowhere it has gone below the required level also. So, you got a reasonably good maintenance of the signal compared to the EDF as.

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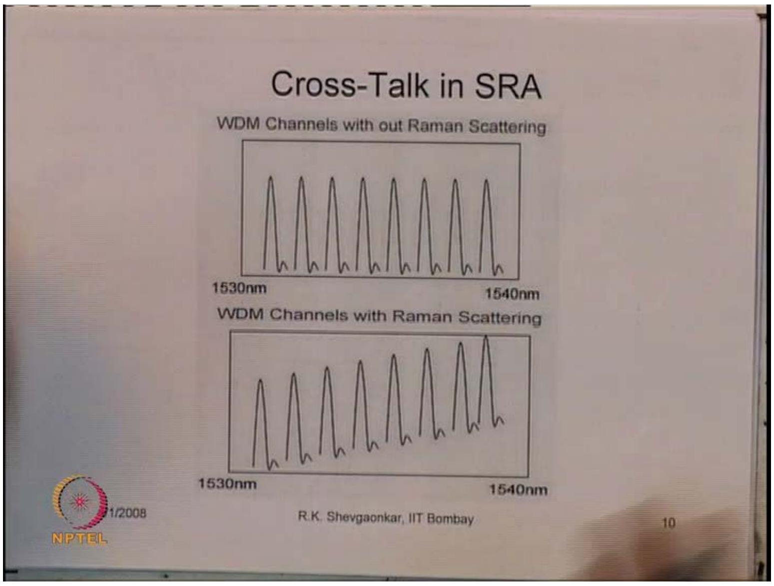


So, that is one aspect which we discussed second thing as we were discussing is that you are having now the multichannel transmission and. So, these are WDM channels which we are transmitting. So, if the Raman effect was not present, that is the way the channel would emerge at the output of the optical fiber. But if the Raman effect is present then as we have seen every high frequency now is going to put power in to low frequency. So, this put power in to this, this, this, this all of that this puts power in to this.

So, systematically you see that the power in the lower channel has grown up and power in the high channel has gone down. So, all channels without Raman amplification would have emerged like this. Now you see there is a systematic trend of having high power into low frequencies compared to the high frequencies and that is the phenomena which is a crosstalk which is created in the WDM channel because of the Raman scattering. So, one can then ask if this phenomena is going to take place in the in the optical fiber, what kind of power penalty would be there to get the same performance in the WDM channel?

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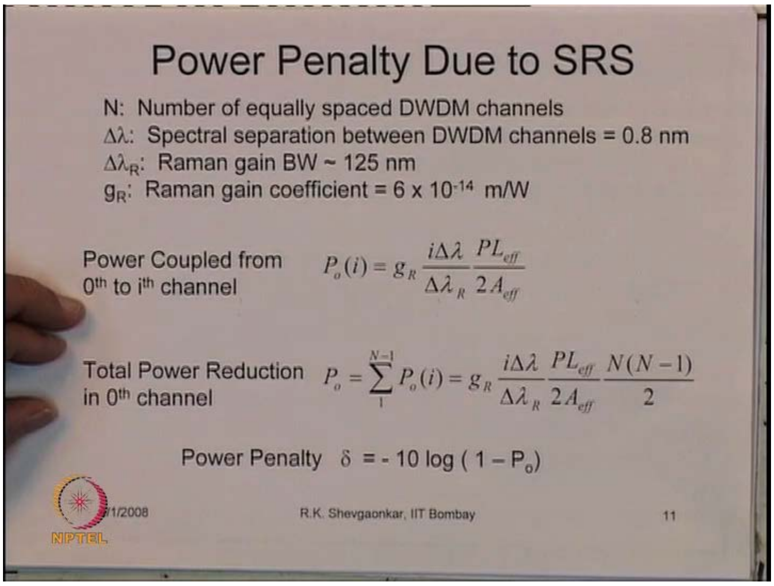


So, let us do a simple analysis let us say we have the n channels WDM channel which are equispaced. And as we standard thing which we take about 0.8 nanometer, this is the Raman gain bandwidth is approximately 125 nanometer which is about 13 terahertz. Raman gain coefficient is given approximately ten to the power minus 13. So, that is the coefficient which we get. So now, we see the power coupled from the 0 channel to any channel. So, we are numbering now the channels this is my 0 channel first channel second channel so on. So, this channel 0 channel is going to put power in every channel because of Raman.

So now, we see the power coupled from 0 th channel to I th channel actually is given by this is the same thing which we derived earlier. So, the total power reduction which I am going to get in the 0 channel is given by this expression. Here we have said that this channel is going to supply power to all the channels right which are the lower than that. So, then one can ask a question, how much power I have to increase in the 0 channel? So, that at the output I would still get the minimum power which I required in the channel from signal to noise ratio point of view and that is what is called the power penalty.

So, if I take this reduction in the power in the 0 channel the change in the power that is what 10 log of that is what is called the power penalty. So, we can get the power penalty in the Raman channel.

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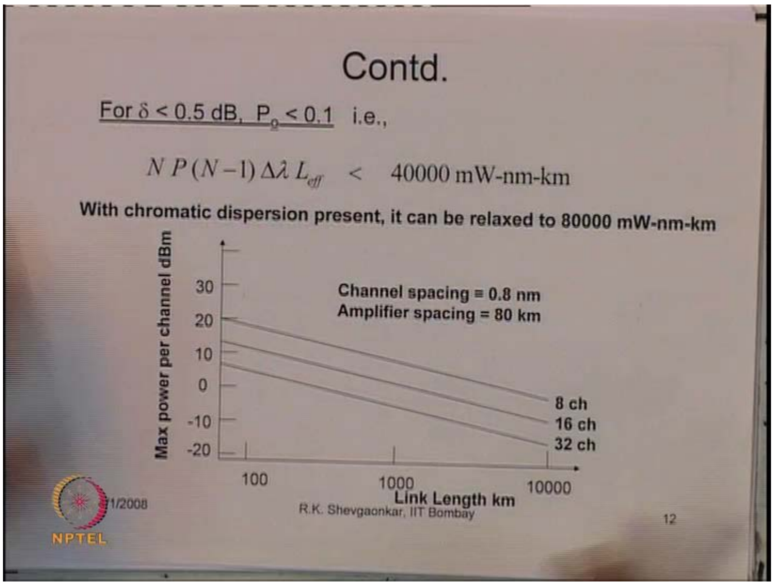


And then we can put certain numbers here to see that if I want the power penalty to be less than about 0.5 dB, then for this power which is less than 0.1 you get this quantity from here which is the number of channels which are n and the power that quantity essentially turns out to be approximately this. So, with chromatic dispersion present either this may be relaxed to about this quantity not 4000 not 40000, but about 8000. So, now what we see here is that if I plot this as a function of the link length for different WDM channel which are propagating. That is the maximum power per channel DBM I can transmit to avoid the Raman coupling between different channels.

So, if I want to have a power penalty less than this, then each channel should be maintained with a certain power. So, that it does not draw much power from the lower channels or high frequency channels. So, you see here this plot which is a function of distance the link. And as you see that as the link length increases the power per channel goes on decreasing so, you cannot have a more power than this at any point of time. So, for the channel spacing and no number parameter which you have given here that is the typical sort of characteristics.

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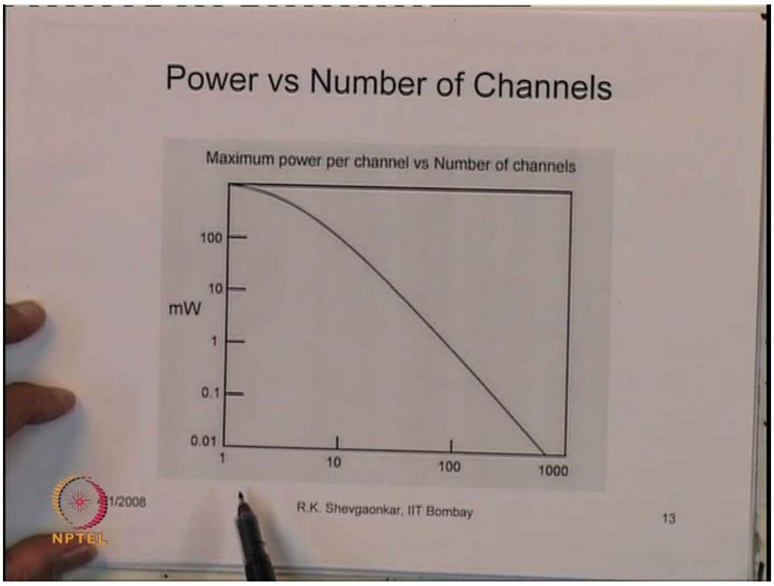


Which you will get for the amplifiers, the same thing can be plotted in a different way that the maximum power per channel versus the number of channels, which you are transmitting and that as you can see here the number of channels increase, the power per channel goes on goes on decreasing. And since the power per channel is going on decreasing, the link length also decreases because as we know from the signal to noise ratio point of view you require a minimum power to be to be there on the optical fiber. So, essentially what this phenomena is doing is in WDM system this is going to change the performance of WDM system is it going to introduce the crosstalk into WDM system.

So, Raman amplification is a distributed phenomenon which is a very good phenomena. If you wanted to have a communication which is a sol tonic kind of communication because that is where we are looking for the distributed amplification. But when we are talking about a WDM system, the same Raman effect introduces the crosstalk between different WDM channels and to avoid this crosstalk the power in each channel has to be kept below certain level and for that then the total power which you are transmitting on the optical fiber cannot be greater than certain value.

And that put the restriction on the length or the distance between the repeaters because for a given power for signal to ratio point of view you cannot send the signal beyond certain distance. So, you will get now a limitation on the length on the optical fiber. So, these are the issues which are related to the to the Raman amplification, it is a good mechanism because a distributed mechanism from sol tonic communication point of view it is very good,

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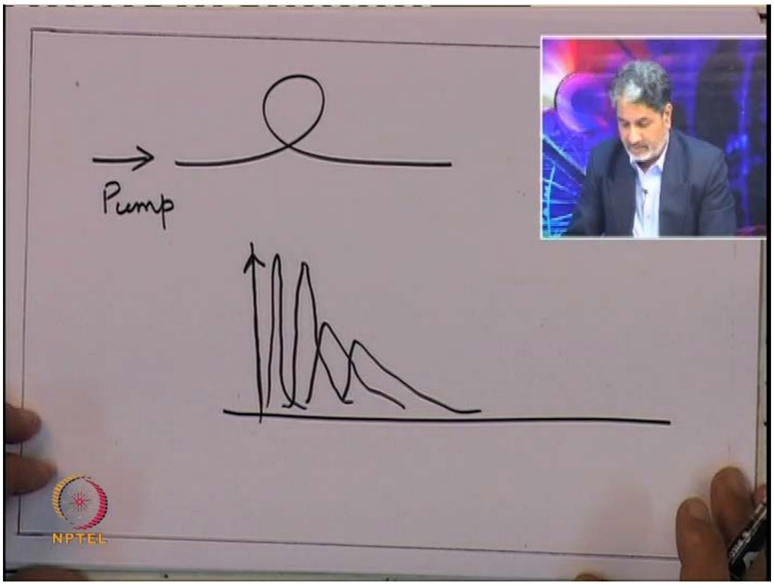


But at the same time it is going to introduce the crosstalk is also between different WDM channels. Before we close just one can ask a question that if I just take a long optical fiber and put a strong pump inside this what kind of spectrum I am going to get from the optical fiber at the output of the optical fiber. And you will see that at this point if you start with a pump which was a pump like this at this location. This pump is going to create a Raman spectrum which will be thirteen terahertz down approximately. As if you keep on propagating and if the power level is large even the power in the stokes spectrum will be large enough to give substantial following stokes.

So, this may generate one stoke which could be this, but here also power is very large so, it can generate now the further stokes to be this also power is large. So, it can generate further stokes we will see something like that. So, if you have a large power put inside the optical power, then you will see that not only the first stoke will get generated, but these power will be large enough to generate second stoke and then third stoke and so on. So, you may get a large spectrum which can be actually A obtained from the from the optical fiber. So, let me summarize what we have done we have just looked at the phenomena of what is called Raman scattering.

And we saw that this phenomena is a material dependent phenomena, also this phenomena use an amplification which is not at a given wavelength, but at a relative wavelength. So, by changing the pump frequency the band of amplification also can be changed. And therefore, Raman amplification can be obtained at any wavelength we like and difference between the pump and the signal amplification frequency that is fixed for a given material and for glass, that is about 13 terahertz. So, by using this mechanism one can create distributed amplification which is good for solitonic kind of communication, but this mechanism also introduces certain problems for WDM systems.

Because there is a systematic flow of power form one channel to another channel which introduces the crosstalk, but the systems are really exploring the possibility of using Raman amplification for long (( )) communication.