Indian Institute of Technology Kanpur

National Programme on Technology Enhanced Learning (NPTEL)

Course Title
Optical Communications

Week – X
Module-V
ASE induced limitations

by
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Hello and welcome to the mook and optical communications in this module we will look at some effects of amplified spontaneous emission noise in an optical amplifier and in ultra long hole communication links what effects would this ASE noise or ASE induced noise would have on the performance of the system we remember or we recall from earlier modules.

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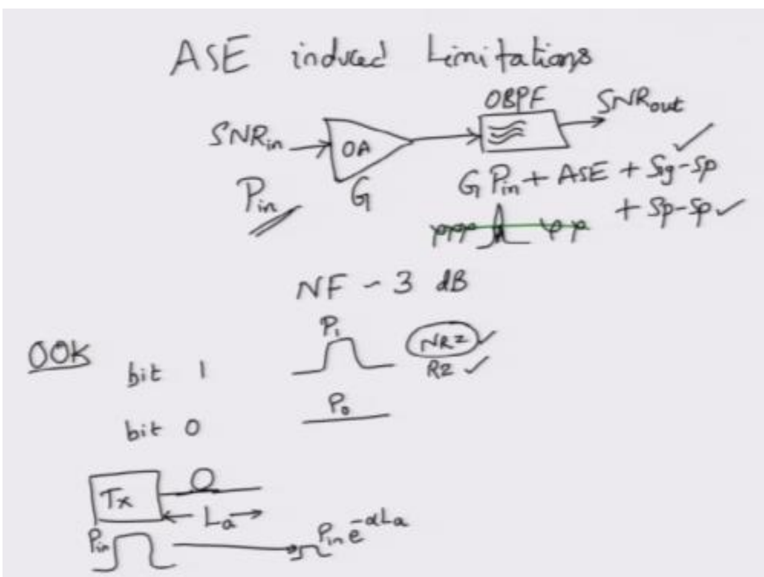

That an optical amplifier that would be a semi conductor optical amplifier or it could an Erbrim doped fiber amplifier is characterized by 2 things one it is the gain of the amplifier which means that if at the input terminals of the amplifier we have an input power of Pin optical power of Pin at the output terminals of the amplifier we get our power which is G times Pin as we said optical amplifiers are any other amplifier for that matter are not going to be ideal amplifiers in the sense that in addition to this signal there would also be a ASE noise right there would also be noise in the context of optical amplifiers.

It is ASE noise because that is primarily coming from the amplified spontaneous emissions so spontaneous emission in the active medium of the optical amplifier which then gets amplified and choose up as output amplified spontaneous noise compared to the signal which is usually a narrow band signal because it is modulated at a particular modulation rate on to a optical carrier the amplified spontaneous emission noise is white band okay therefore if you want to limit or if you want to work with the optical output.

That is coming out f the amplifier is somehow have to also limit the amount of noise that is entering into the subsequent devices or subsequent components of the optical link you do that by actually putting a output band pass filter so you actually have an output optical band pass filter in order to limit this amplified spontaneous emission noise only to the band width that the signal occupies okay so all these components of the amplified spontaneous noise outside the band width is all equal to 0.

Well we have looked at what happens actually you get this ASE not just as the ASE component you also get in addition to this the signal and the ASE betting which we called as the signal spontaneous we also see that the spontaneous emission or the ASE itself will bet with the ASE giving rise to spontaneous emissions okay in usual operating it is the signal spontaneous noise that is quite dominate compared to the spontaneous emissions noise or the spontaneous betting of the optical amplifier.

So this is essentially what is actually happening with an optical amplifier and a band pass filter the effect of the amplifier is to actually reduce the signal to noise ratio at the output or rather verse in the signal to noise ration but this is not bad because with it the amplifier you would not even be able to detect any signal okay so although the signal to noise ratio at the outputs seemed to be decreasing or to degrading this is of set by actually looking at the being in the signal the signal actually increases okay.

So this particular characterization of an optical amplifier or any amplifier for that matter is characterized by the noise figure of the amplifier and for the Erbrim doped fiber amplifier under reasonably best conditions we saw that the noise figure will be roughly 3 db now let us consider a slightly different problem we consider what happens on a ultra long hole optical communication link we will stick with ON OFF keying for the movement if you are wondering what ON OFF keying is probabably it is just a bit to easy to refresh your mind you have bits one and 0.

So when you want to transmit a bit 1 you transmit it by sending a pulse when you want to transmit a bit 0 you transmit nothing right so the optical power here will be P1 the optical power here will be = P0 again you can have the NRZ variety or the RZ variety for our purposes it does not really matter which one is which although we will consider the NRZ variety of the optical pluses in our discussion okay.

So at the transmitter to have the ON OFF keyed pluses that are coming out and then the you have a fiber link through which these intensity modulated or ON OFF key modulated signals are passing through and after they have passed a certain length which let us call it as LA the level of the optical pulse would have reduced because of the attenuation in the fiber which is what we are only considering we are not going to consider the dispersion aspects so you start off with the pulse that would look like this at the end of the length L_a of the fiber the pulse amplitude would have decreased, okay. So you started off with say some P_{in} the power that you get here will be P_{in} $e^{-\alpha La}$ where α is the attenuation co-efficient of the fiber, La is the length of the fiber that you have connected.

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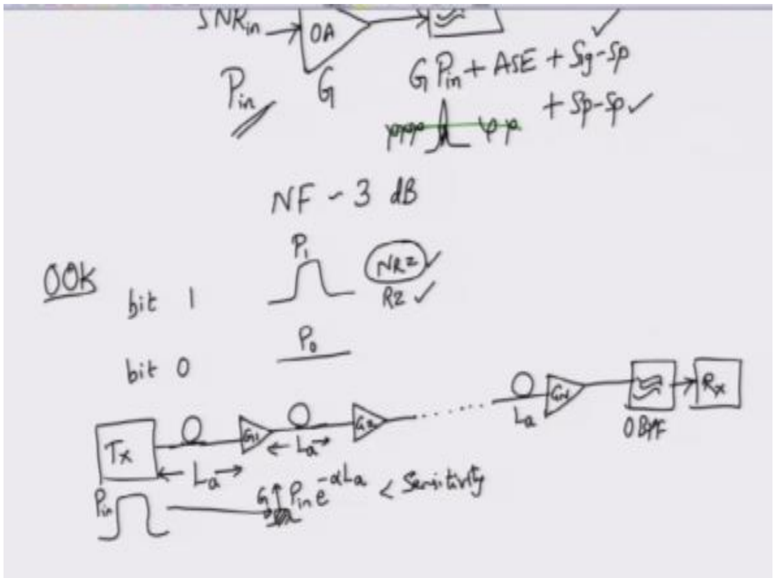

If this happens to be less than the sensitivity of the detector right then it would be not possible for us to realize that there is actually a pulse that has been transmitted so what we do here is to actually pull up the amplitude by giving an appropriate value of the gain, okay. So you actually have an amplifier with a gain let us call this as G_1 okay then of course you still have one more you know fiber link.

Let us for simplicity assume that the fiber link has the same length La before you give in the amplifier of a gain G_2 then you keep doing this until you come up to the last length, right. So here you actually have a length La and the amplifier that I am using will have a gain of G_n we will see that all these gains are normally equal okay you do not normally see the amplifier with different gains for various purposes.

But before making that assumptions let us also put down the optical band pass filter okay and then look at the output, so this is a system that I want to consider, so whatever that comes out of the optical band pass filter can go into the receiver so you can actually put a photo diode or you can put a coherent receiver and then amplify the signal but if in this system things seem to be very simple.

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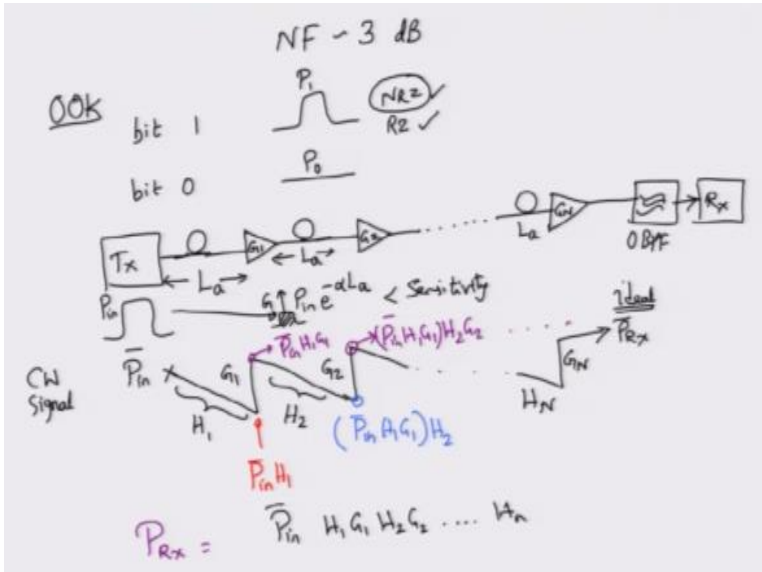

Actually things are not really simple, see you start off with the certain power P_{in} okay the average power that you start of here let us say is given by P_{in} and this is let us for now assume that this is the continuous wave signal that is P_{in} bar or the mean optical power is actually going to be constant, now due to the fiber there is an attenuation okay, so the power actually reduces by a certain factor.

But because have put in a gain the power actually comes back, okay. If you call the loss factor here which is $e^{-\alpha La}$ as H_1 okay H_1 denoting the loss in the first fiber link G_1 denoting the gain of a first amplifier that you are going to put in okay, then you again the power reduces because there is a loss factor H_2 because the optical signal is propagating in the second link as well and from here you again pull the output back.

By supplying a gain of G_2 and this process keeps on reducing until you come to the last stage where again there is a factor H_n because of the n^{th} fiber span and then you pull the amplitude back upto get the total gain of G_n okay and this would be filtered let us assume an ideal band pas filter which means that it is not decreasing the amplitude of the signal so this goes to the receiver side okay.

So the mean received power can be obtained by looking at the loss and the gain and then multiplying each of these components right because the power at this point is simply given by P_{in} bar H_1 while the power at this point is given by P_{in} bar H_1 G_1 correct and the power here is given by P_{in} bar H_1 G_1 which is a power from the previous stage times the loss factor H_2 and finally the power here will be given by the power at this stage which is P_{in} bar H_1G_1 H_2.

And then pulled up by the gain G_2 okay and therefore if you come all the way upto the receiver side you see that the power at the receiver should then be given by product of all this, right So you actually have P_{in} bar which is the input power times H_1G_1 H_2 G_2 ….. all the way upto H_n G_n right.

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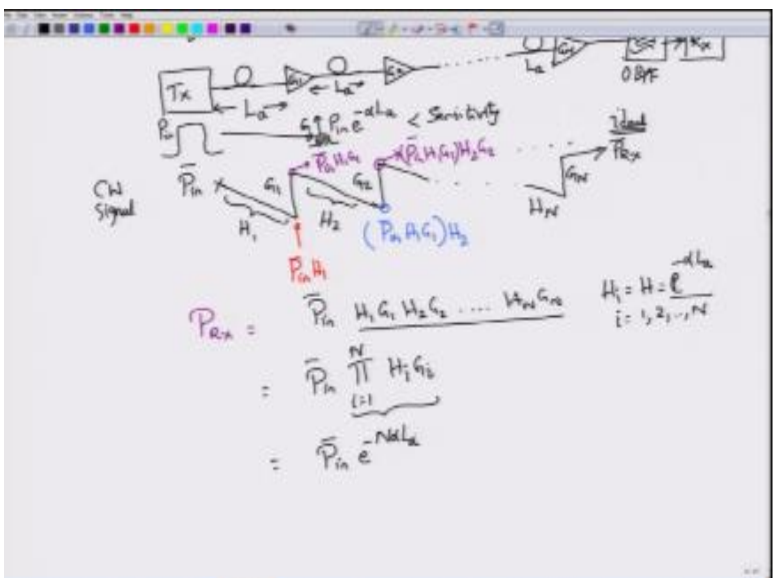

So the loss factor and the gain factor are both getting multiplied with each other okay and in general one can always assume that H_1 is different from G_1, H_2 is different from G_2 and so on but normally that is not what is done because then the amplifier spacing becomes unequal the saturation power of the amplifiers become different, so in order to avoid all these problems you normally take ball the amplifier losses to be the same.

That is H_i is equal to the same value of H which is given by $e^{-\alpha La}$ this you can do by putting all the amplifiers at a equal distance from each other, so the spacing La which is called as the amplifiers spacing is kept constant and of course how many stages we have, we have I = 1 to all the way upto n, okay so you can write down what is the power that you have receiving in a short hand way by introducing this symbol called as π symbol and then write i=1 to N it simply means that you have to take a product of the terms of the form H_iG_i, okay so this is a short hand notation to write down this particular factor, okay.

So this is what you get at the receiver side and we have already said that all the loss elements H will be the same so you can pull that H element because it does not depend on the index i outside of this case, so you simply write down this as $\bar{P}_{in}$ and then H of course you are going to multiply this factor N times, correct. So what will happen although that is not dependent on i it is actually what we mean is that this is actually constant and independent of the value of i, but this factor gets multiplied N times so what you get here is $e^{-N\alpha La}$ does this make sense.

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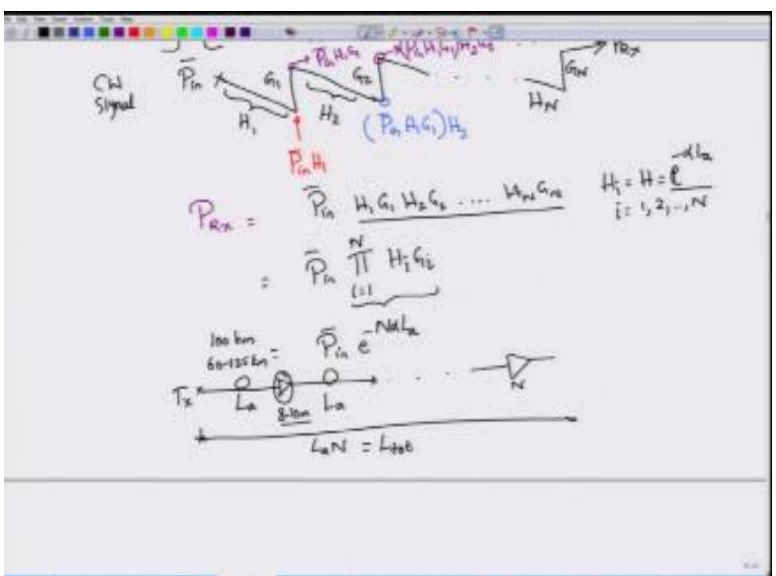

In a sense, yes it does make sense because you started of with the transmitter here and then you started placing an amplifier at each positions, right so you placed an amplifier between there is a fiber and so on we did until we ended up with the last amplifier. What is the total length from the transmitter to the receiver side here it would be equal to L_aN does it make sense, yes because the amplifier lengths, okay if you are using an erbium doped fiber this amplifier length is about say 8 to 10 meters.

Whereas this L_a is typically from anywhere between 60 to 125 kilometer with frequently the values being at 100 or 80 kilometers, okay so at 100 or 80 kilometers that would be very, very large compared to this small 8x10 meter loss, okay. So you can either absorb the loss in this erbium doped fiber amplifier or the semiconductor optical amplifier back into this factor H and then work with it or you can simply ignore the losses at this point they are not going to be very large and then realize that the distance from the transmitter to the second amplifier is about $L_a x2$ and after N amplifications the distance would be $L_a xN$.

Let us call this factor as total length, so what we are seeing over here is that the factor e^{-NLa} simply tells you what is the total fiber length, this fiber length is different from the amplifier fiber length or the amplifier length of a semiconductor optical amplifier if you were use that one, okay and the total loss over that total length L total is giving by $^{e-N\alpha La}$.

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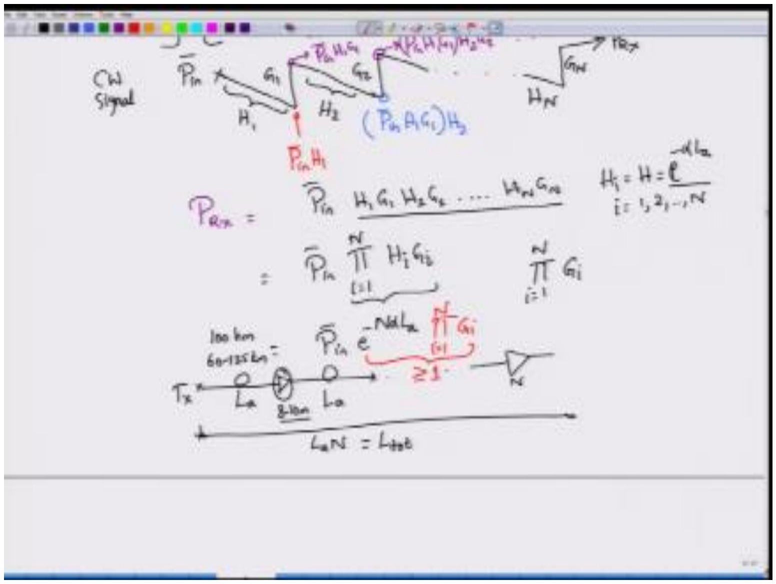

Okay, this factor we have obtained what about this factor G_i, now it is in principle as I said possible to actually have varies values of this G_i, okay so you can actually make this G_i values so of one stage be different from the other stage in an overall effort of either increasing the power beyond this $\bar{P}_{in}$ which is what at the transmitter side would be or you can reduce the power of course you would not normally reduce the power, so the design criteria at this stage seems to be that you choose this product i=1 to N G_i in such a way that this term, okay overall will be either greater than or equal to 1.

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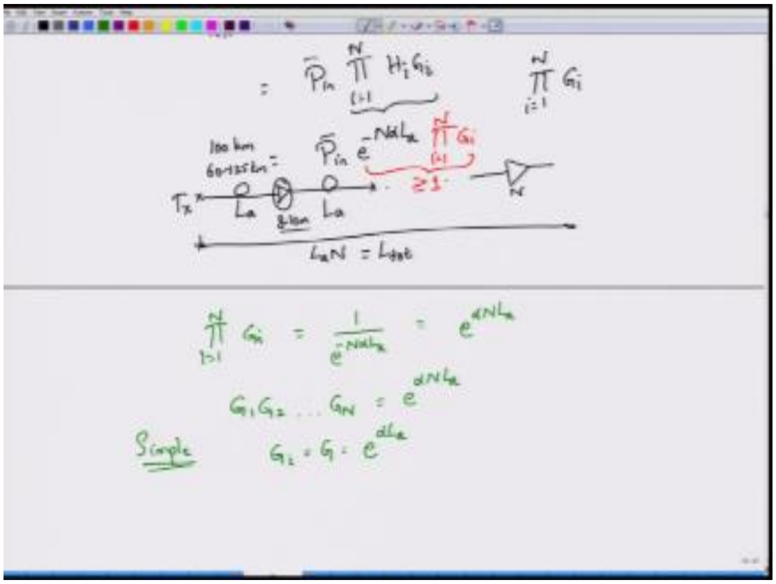

You normally choose the option of being equal to 1 which means that your product i=1 to N $G_i=1/e^{-N\alpha La}$ but $1/e^{-x}$ is nothing but e^x so just pull this up to the numerator side you get $e^{\alpha Nla}$. Now there are factors which are, there are in factors here, right so you actually have this factor G_1, G_2 all the way up to G_N this should be equal to $e^{\alpha Nla}$ one simple way of doing this or satisfying this constrained is to simply make all the amplifier gains equal to the same value which is equal to $e^{\alpha NLa}$, correct.

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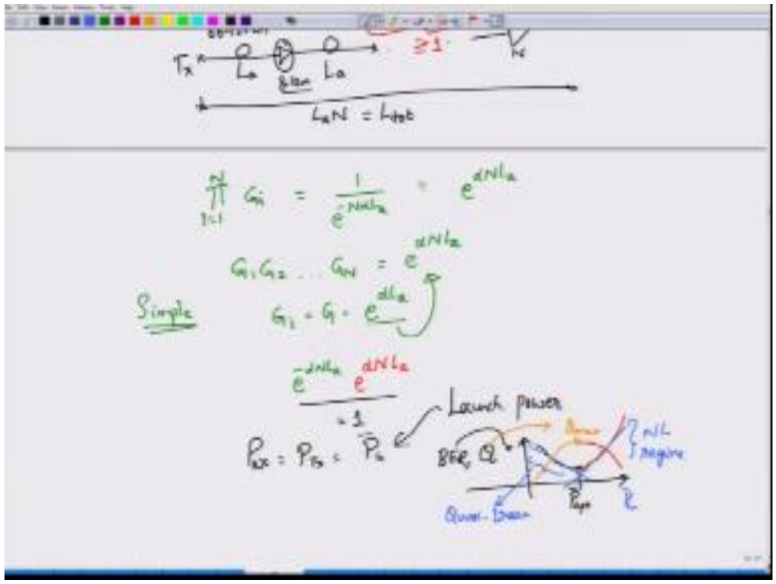

If I do this then the product of N such terms, product of N $e^{\alpha La}$ terms is obviously going to be equal to $e^{\alpha NLa}$, correct. So if this is equal to that then you have the loss factor total loss factor as $e^{-\alpha NLa}$ whereas the total gain factor also being exactly equal to $e^{\alpha NLa}$ with a plus sign of course in the exponential argument. The product of these two will be equal to 1, correct and the received power will be then equal to the transmit power which is equal to the mean power that you have launched.

So this power is called as the launch power and launch power is very important because if frequently in the literature find the performance of the systems wither by giving the quality factor cube which we have defined in the earlier classes or by giving the bit error rate which again we have defined in the earlier modules and then looking at what happens to this Q factor or the BER curves as a function of Pin.

Considering this as the function of the BER this is what you normally get okay so there is a certain optimum launch power for which the BER is small, of course in terms of the Q factor this would be the opposite situation so there is a certain value at which the Q factor is maximum okay which corresponds to the optimum launch power well the BER is at the minimum okay so this is for the Q factor.

Interestingly optical communication links kind of a very non intuitive way of behaving to with respect to Q and we behaving with respect to the launch power because as a launch power inc reassess you would actually think that well I am increasing the input optical power which means that my signal to noise ratio is might be very high why to stop at say1mw of the input launch power or the 1mw of the launch power why not I make it in to 1 w when you do that interestingly as you start increasing the launch power as a function of I mean increasing the launch power okay.

Beyond the optimum launch power what you see is that this curve actually starts to raise the BER starts to raise again and the quality factor starts to drop this fact which is not normally seen in a typical communication system in the non optical communication system is called the non linear region and this happens because as you start increasing the launch power so this is the launch power that we have as you start increasing the launch power various non linearity will take over which will then introduce an additional noise which will then bring down the Q factor or ion crease the BER.

Okay so the optimum launch power is the point where a linear region which is this fellow okay so this is some time called as Quacy linear as well it is not exactly linear but for all practical purposes it is linear so where this Quacy linear term meets the non linear region this is where you get the optimum launch power okay. We will not be able to look at much of this region in this course but do not worry you can actually take up additional courses an optical communication if you are really interested as to why the q factor or the BER actually behaves in a very different manner.

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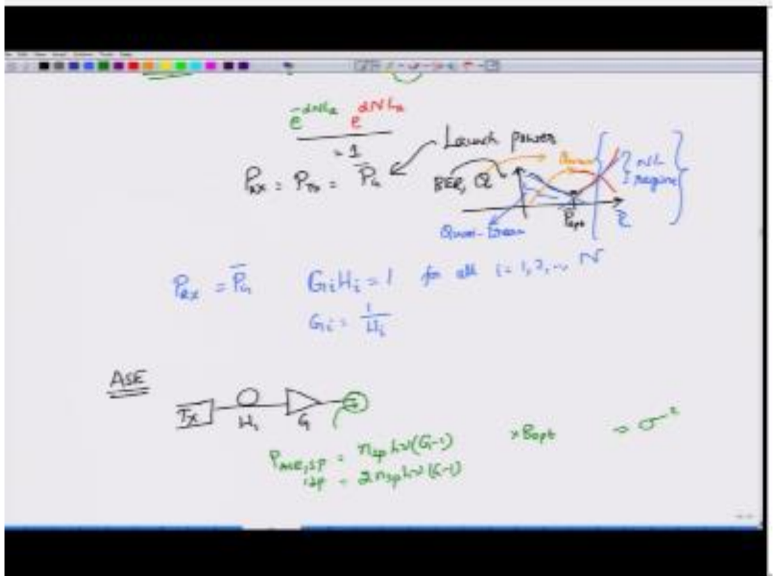

Coming back to our problem we have seen that the received power has been made equal to the launch power Pin correct so this is what we have done we have done this by choosing the factor Gi x hi =1 for all values of i from 1 2 3 all the way up to N where in the gain of each amplifier is equal to 1/ loss factor Hi okay so this is something that we have done with respect to the signal if this is all that we had our life would have been so easy unfortunately what we have is just one part of the solution we have not looked at what happens to the amplifier spontaneous emission, that is what we want to look at.

Go back to the circuit that we had or go back to the systems that we had you have a fiber well the fiber is not introducing any amplifier spontaneous emission so do not need to worry about that the loss factor associated with the first fiber span is H1 so this is my transmitter okay and art this point I put in a gain of a first amplifier right so this is the gain of G now you recall that we had looked at the noise power spectral density correct for a single polarization.

Or for a duel polarization this noise spectral density for a single polarization was given by nsp h η of course being the main optical frequency or the carrier optical frequency in our case times g-1 correct nsp h η g-1 this was the power spectral density if you multiply this one by the optical band width Bopt you are going to get the total noise component right or noise power or the noise variants right so this is what you would have obtained over here for a single amplifier.

For a duel polarization instead of one nsp you get a two times in nsp cause there are two polarization modes but the power spectral density at this point it still given by 2nsp h η x g-1 okay. Now this power spectral density okay in addition to the signal noise power actually you know would see the same thing as the next stages the noise is also seeing h2 g2 h3 g3 the first stage noise is actually seeing h2 g2 and so on and eventually it will come to the optical band pass filter, at which it gets limited, so the spectral density and the noise power of the first

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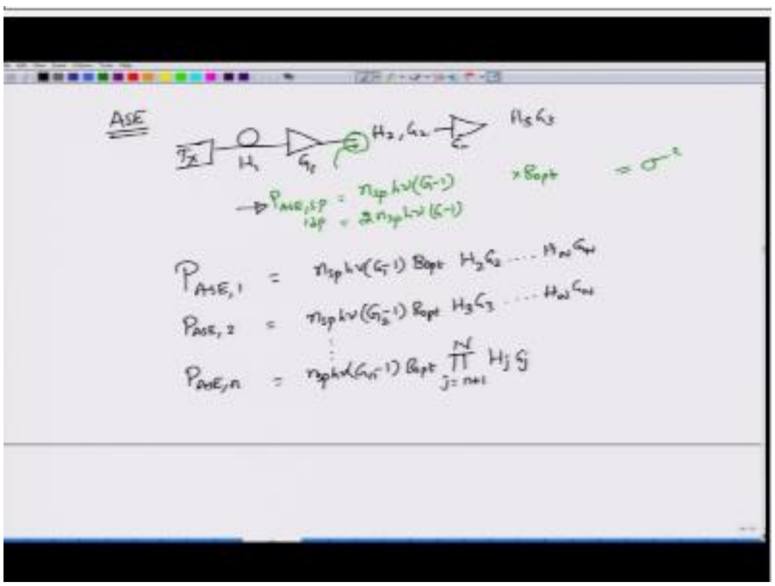

Amplifier grows as the least of the ling link curves, why would it grow? Well as per as the amplifier is concerned whether the photons are coming because of the signal, or whether the photons are coming because of the amplified spontaneous emission noise, they are exactly the same, they both are equal to each other, as per as the amplifier concern.

However because of our problem they would not be equivalent, because for me signal is not the same as the noise, but an amplifier doesn't really care, and the fiber also simply does not care it will start attenuating any optical power, one the optical power is launched in to the fiber, so based on this fact that both amplifiers as well as the fiber sees noise as well as signal with the same way.

The noise power of the first stage, so let us call this as P_{AC1} Noise power because of the first amplifier, and let us assume for now just we are working with single polarization, because for dual polarization you can always add another factor of 2, right? so this would be equal to n_{sp} h ν G (1-1), right this is the noise power that is coming of that is because of the first one multiplied by the optical band pass filter, this then has go through the stages H_2 J_2, all the way up to H_n, G_n, this is the noise power that you are going to get.

What about the noise power added by the second amplifier? Will the second amplifier also has the same spectral density, this would be given by (G2-1) P_{OPT}, the optical band pass filter, but it does not see H_2 right? Because H_2 is now previous, so this one is H_1 J_1, this J_1 sees H_2 and J_2, where as the second amplifier, with again J_2, could only see H_3 and J_3.

For this H_2 has already gone back, so this would be H_3 G_3, all the way Up to H_n G_n, so if you continue all this and recognize that you are at some point on the th amplifier stage, the power spectral density is still the same, the gain of the N^{th} stage, amplifier is G_n, the optical band pass filter is assume to be ideal as the same band value for everything, and this portion , this whatever the remaining factor that it sees , can be re written as j=n+1(N H_J G_J) okay.

I hope this short hand notation is now familiar, if not you just go back to the beginning of the module and you will see what this term is, but you might question, when we have already seen that H_2 J_2, must be equal to 1, $H_{n,}$ J_N, must be equal to 1 and so on, right? And you are right this is all, these factors are all equal to 1.

But these by themselves are not the totally AC noise components, the total AC noise is obtained by adding up all this elements, and you basically add up.

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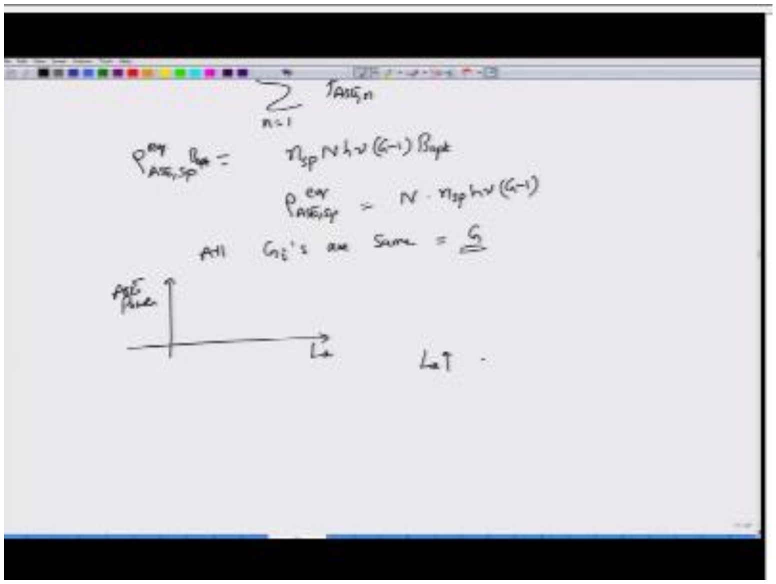

The N[th], stage amplifier noise, okay n=1 to N , there are N amplifiers, and you simply sum all the N_{ac} noise components, and when you do that because these factors are all going to be equal to 1, so this factor is 1, this factor is , infect this factor is also equal to 1.

Then what is actually happening? Well this is one factor, plus this one, plus this one, and there are n such factors right, so what you get is $n_{sp}Nh\ \nu$ (G-1), because all the gains are also the same right, for each stage the gains are also the same, times the optical band pass filter, so if you see this expression you can think of this as the AC power spectral density of a single polarization mode.

And an equivalent version of that multiplied by the optical band pass filter, where for a cascaded stage of n amplifiers, the equivalent AC noise is given by N times the noise for the, or noise spectral density for each amplifier, okay having the same gain, of course it is very very important for me to stress again that, all the gains are the same, okay.

All G_I, is are same and they are equal to just a factor of G, okay there is one smaller thing that is associated with this one, okay if you look at the AC power we will not prove this one but you can see this one later, if you look at the AC power and then you see this one as a function of the amplifier spacing L_a, it turns out as the amplifier spacing increases, remember as $L_{a,}$ increases $e^{-\alpha a}$ decrease which implies that e^{-aLa} must increase which means the gain of the amplifier ha to be increased, Obviously if the loss is increasing the gain has to increase in order to compensate for the losses, but what happens to the ASE noise power is that actually starts to grow exponentially, okay.

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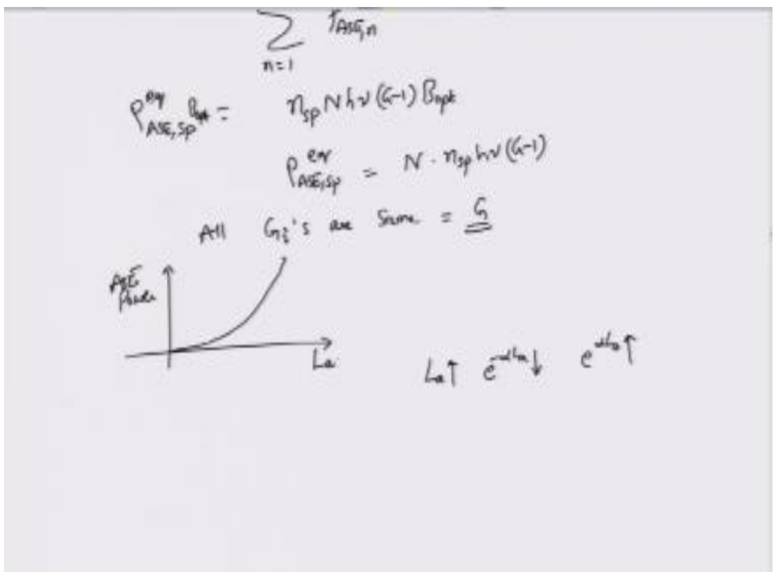

So as the amplifier spacing increases, the ASE noise power also, the local ASE noise power also starts to increase, associated with this cascaded stage or general in stage, is the quantity optical signal to noise ratio, this is exactly like a signal to noise ratio except that, this is talked in terms of the optical signals. So you have a certain mean power Pin that you have received, so this is especially at the receiver side that we need to talk about, so the received power is Pin bar, why should it be Pin bar? Remember we have chosen H and G, such that this is equal to 1.

And therefore all the amplifier are going to compensate exactly for the losses and the received optical power will be equal to large optical power Pin bar divide by what is the total noise variance that you have for a dual polarization if you want to look at, so this is OSNR for the dual polarization. Each amplifier has a prospective density of $2n_{sp}h\nu$ (G-1) in the bandwidth of B_{opt} times n, this would be the optical signal noise ratio. But what should I choose as B_{opt}, there is actually no specific value, kind of agreed upon value is that, this should roughly be 12.58 Giga hertz, which correspond to roughly about 0.1 nm, okay.

So this is the reference band width that you choose and within this reference bandwidth, whatever the signal power to the noise variance you get is called as the optical signal to noise ratio. So we have looked at what happens to the ASE, you know we looked at a optical communication system with what happens when you have multiple noise sources, what you can see here is that the noise spectral density, actually starts growing linearly with respect to n, if you want to actually to consider just this receiver side after a cascade of amplifier stages, if you just put a photo diode and then detect the signal, you will see that the q factor actually, you know depends on the square root of this n.

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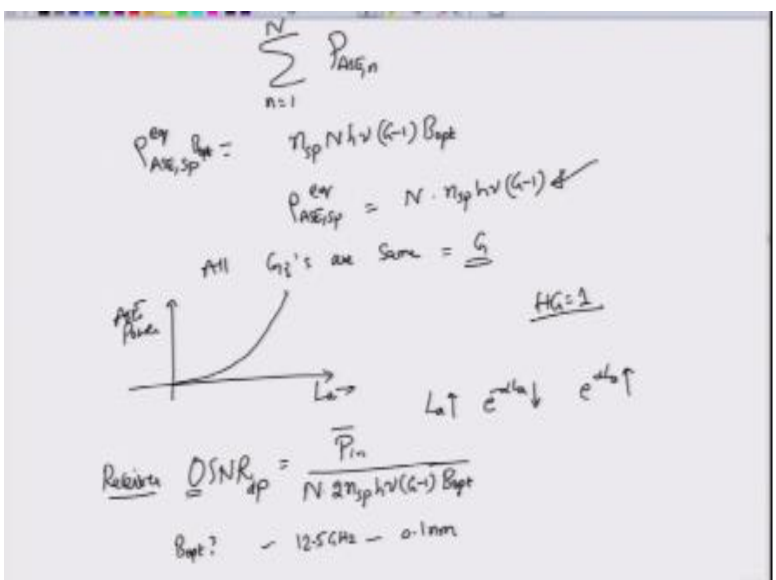

So inverse square root of n, as the number of stages n increase the launch power also must be increased, it's an additional side effect that happens here and this side effect that happens because, if you look at the saturation power that is the output, what this the maximum output power is that the amplifier can provide with an certain input power, the second stage saturation power must be slightly higher than the first stage, third stage must be slightly higher than the second one and so on. So because of, why should it be higher, because the first stage provides the input signal plus it adds a little bit of noise, therefore the total power that going into the second amplifier has slightly increased, right?

Therefore in order to deal with that, the noise saturation output power has to slightly increase and this actually happens all the way up to the end. Therefore this is not very advisable to tart reducing the number of; you know increasing the number of amplifiers and by reducing the amplifier spacing. So there is trade off here, reduce La, you reduce the ASE power, but at the same time you're going to increase n, which means the OSNR starts to dip. WE are going to look at, what is the coherent receiver, look at the amplifier with the direct detection receiver and what would the ASE noise do in the next module. Thank you very much.

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