Fiber - Optic Communication Systems and Techniques

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Lecture – 41
Erbium-doped fiber amplifier

Welcome to NPTEL MOOC on Fiber Optic Communication Systems and Techniques. In the previous module we talked about an optical amplifier which was able to amplify signals directly in the optical domain without converting the optical signal into electrical signal, right. While semiconductor optical amplifiers have many users and they have their own initia of application, it turns out that there is another amplifier which is by far the most widely used in long haul optical communications. And, in fact the one that combined with WDM technology started off this whole you know revolution in optical fiber communications in the late 80s and early 90s or some (Refer Time: 00:58) about 90s, ok.

And this amplifier operates on the same fundamental principles. You still have to have a gain medium and then you have to have a pump in order to you know excite these atoms from one state to the other state. And then you have to supply a weak signal typically a weak signal so that this weak signal will then induced stimulated emission causing the overall output to actually grow, ok.

And many of the things that we talked about in the semiconductor optical amplifiers such as the dependency of the gain on the input power magnitude of the input power applied would also apply equally well here. But there are very important and significant differences, between the amplifier that I have that we are going to study in this module versus the amplifier that we studied in the previous module.

And this amplifier is an amplifier which is directly realized in the fiber domain it is not an integrated optical amplifier. That is it is not formed as an integrated optical circuit or a photonic integrated circuit and then given to you to which you have to input and the output have to be coupled by fibers, ok. So, this is directly done at the fiber level itself that is the first primary significant or primary difference between the two amplifiers.

So, this amplifier is an all optical fiber amplifier, therefore, when the signal is coming in from the standard single mode fiber you do not need to take it out on to free space focus it, no couple it, the launch optics is actually quite simple. We just slice or connect to the amplifier with extremely low loss that is possible.

So, this is an important issue because it reduces lot of loss that actually goes away in the coupling mechanism. So, if the signal is already weak in reaching the amplifier then the extra losses that are usually introduced by the coupling optics in the case of a semiconductor optical amplifier is completely eliminated here that is the first advantage and first difference between this and the semiconductor optical amplifier.

So, the second difference is that in the semiconductor optical amplifier the pumping was done by the help of a current, right. So, we had the current which is forward biasing the amplifier and then forward biasing the semiconductor material. And then you had this carrier you know confinement and all the other things that we discussed, right.

In the case of this fiber amplifier we do not have a current pumping but we actually have an optical pumping. So, in that sense this is much more closer to what we talked about in the beginning of the laser basic. So, you have atoms at the ground level then you have atoms at the higher or excited states and then an optical pumping. So, photons actually have to be used at the pump to raise the atoms from one energy level to the other energy level. So that is the second crucial difference. So, this is optically pumped whereas, so as are simply electrically pumped.

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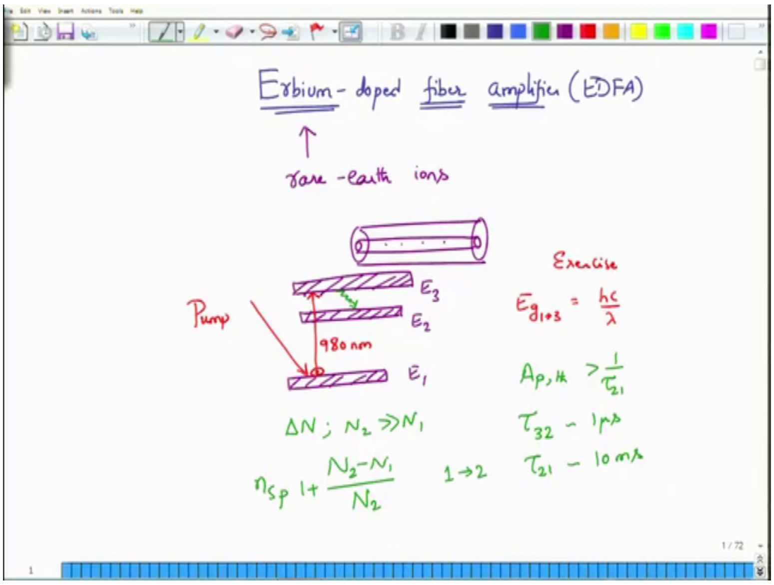

Erbium-doped fiber amplifier (EDFA)

↑

rare-earth ions

Exercise

$E_{g_{1\to3}} = \frac{hc}{\lambda}$

$A_{p,th} > \frac{1}{\tau_{21}}$

τ_{32} - 1μs

τ_{21} - 10 ms

ΔN ; $N_2 \gg N_1$

n_{sp} $1 + \frac{N_2 - N_1}{N_2}$ 1→2

So, what is this magic amplifier that we are talking about on and on? That amplifier happens to be the erbium doped fiber amplifier erbium is a rare earth ion, ok. It is not usually found in large quantity. So, there are certain classes of materials which are called as rare earth materials, ok. So, there as their name suggests they are not quite common, but out of these materials erbium has a very interesting and intimate history with optical communications. Because when you dope a regular fiber, so this is your standard fiber or a single mode fiber let us say and then you put some erbium ions throughout this amplifier.

So, when you do that then what you create because the erbium states actually are no many states are you know possible with that one the ground state is N 1 or E 1 let us say that is the energy of the ground state. And then you have the next higher order state there are actually many more of this and in fact, it turns out that these are not discrete isolated states, but rather bands that we would have to look at in the spectroscopic details of erbium ions is something that we are not going to look at in this course. The basic idea is that you have a band of energy that one level called E 1, then there is band of energies at E 2 and E 3, ok.

And the rest of the process is kind of simple you know already this one, you do not need a cavity here because you are not making a laser therefore, that requirement is gone. So, what you need of course is a pump. Since there are 3 levels what are the energy gaps between these two and what is the wavelength at which we need to pump that is the question. So, if you are using a pump which will take electrons which are ions in the state E 1 to the state E 3, then you need to have a pump of 980 nanometer wavelength.

So, you can of course, calculate what would be the energy gap between 1 and 3 by using this equation since I know h, I know c lambda is given to you as 980 nanometer you can easily calculate what would be the energy gap. And I will leave that as an exercise to you, ok.

So, what you do is when you pump it then you have these atoms or ions sitting in the energy state E 1, which will be raised to the energy level E 3 by this absorption of the pump photons where they will quickly decay in a non-radiative manner, they will quickly decay in non-radiative manner to energy level E 2, ok. This is very crucial. And we have seen what are the conditions that are necessary for this, in fact we have seen that the absorption has to be greater than a certain or the absorption cross section have to be greater than a certain critical or a threshold value which is more or less given by 1 by tau 21, where tau 21 is the lifetime from 2 to 1 assuming that the lifetime from 3 to 2 and 3 to 1; 3 to 2 is actually very small and 3 to 1 is somewhere in between them, right.

So, the typical numbers for erbium doped fiber is that tau 32 is about a few microseconds or maybe less than that one whereas, tau 21 happens to be just about 10 milliseconds. So, we can see that most ions which have reached energy level E 3 they have the tendency to just drop to the energy level E 2 which without emitting any photon. So that is all, right because we do expect the photons to be generated when atoms undergo transition from E 2 to E 1, ok. So, but the point is that they quickly go back to level E 2 and start populating the level E 2.

In a laser operation we would actually want a complete inversion correct we want delta N to be such a way that N 2 should be much larger than N 1, right and we want almost all of the atoms that are then the ground level to be pumped up to the intermediate level to create the population inversion. However, because we are not really looking for a laser but we are looking for an amplifier this condition is not normally satisfied the degree to which it is actually pumped is usually given by this ratio and we denote that ratio as n s p or the filling factor. So, when you fill completely you will see that N 1 will be equal to 0, and N 2 and N 2 will be there and then n s p can go all the way to 1 or maybe this is actually 1 plus N 2 minus N 1 by N 2, ok.

So, the filling factor can be in such a way that it can go from 1 to 2. So, I have to adjust these numbers in any way but does not do not really worry about this but the idea is that you are not going to fill completely but you are going to fill it with a certain factor, ok. So, usually I think this definition of n s p is wrong but the does not really matter to us you just assume that the fraction of the filling can go from 1 to 2, 2 indicates complete inversion, 1 indicates no inversion, ok. So that is how this particular inversion thing is characterized.

So, you understand that this has to be inverted but not complete inversion. So, there are some atoms in the ground level that are possible, ok. So, this is the 980 nanometer pump which takes the atoms from E 1 to E 3 where they quickly relax onto E 2.

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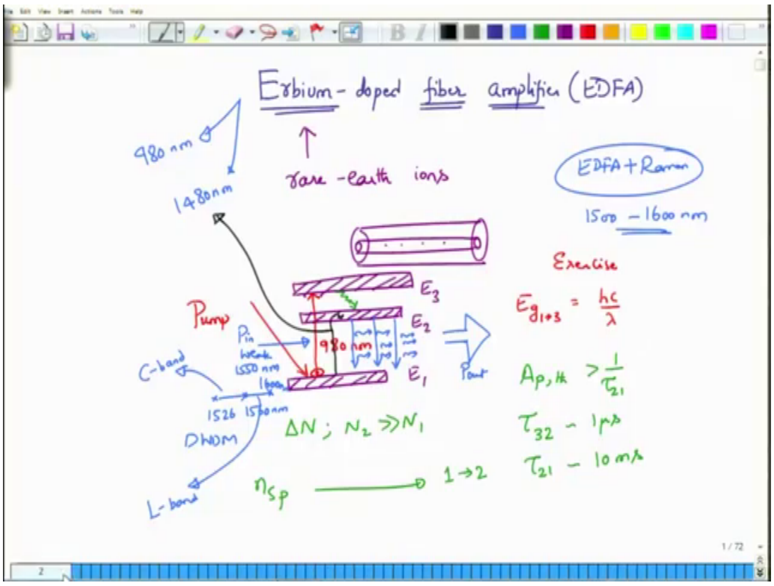

And now when you apply an external signal, ok, so this is a external signal which is weak and is in the range of 1550 nanometer there is actually a small band of wavelengths over which this particular signal has to be applied over which you actually get gain and that band is usually 1526 to 1560 nanometer, because of course, perfectly fine for us because most of the DWDM channels are also located in this band. Of course, there is also an extended band up to 1600 nanometer. So, this band from 1500 to 1560 is normally called as the conventional band of communication or the c band communication whereas, the range from 1560 to 1600 is called as the long wavelength band or the L band.

Of course, today it is not just erbium doped fiber amplifiers which are you know used to amplify signals in c band they are actually hybrid amplifiers which combine erbium doped fiber amplifiers with Raman amplification to obtain full range of operation from 1500 to 1600 nanometer. So, these hybrid amplifiers are the ones that are actually used simultaneously of you know amplify all of the WDM channels that are located anywhere between 1500 to 1600, ok.

So, anyway, the erbium doped fiber amplifier itself has a gain cross section that goes roughly from 1526 to 1560. These numbers can slightly change depending on various factors but this is the range over which you are actually supplying the weak optical signals here. And what will these weak optical signals do when you launch them with a certain launch power of P in? They will induce this stimulated emission because E 2 is kind of the reservoir holding many of the atoms at that level whereas, when the atoms drop down from E 2 to E 1, they will release lot of photons eventually amplifying the input that you have sent out. So, the output power will definitely be larger than the input power. So, this is essentially the basic idea of erbium doped fiber amplifier, ok. The pumping that is used is 980 nanometer.

Of course, that is not just the full story here we are going to look at a little more details on erbium doped fiber. One of the things that you should remember is that erbium doped fibers can be pumped at two different wavelengths, one is a 980 nanometer which is most efficient will result in larger gain and results in shorter amplifier lengths that is shorter fiber lengths in order to realize the same gain. However, there is another pumping level which is 1480 nanometer which takes these ions from the ground state directly and dumps them in the energy level E 2. So, it will go directly from E 1 to E 2 and this happens to be the 1480 nanometer, ok.

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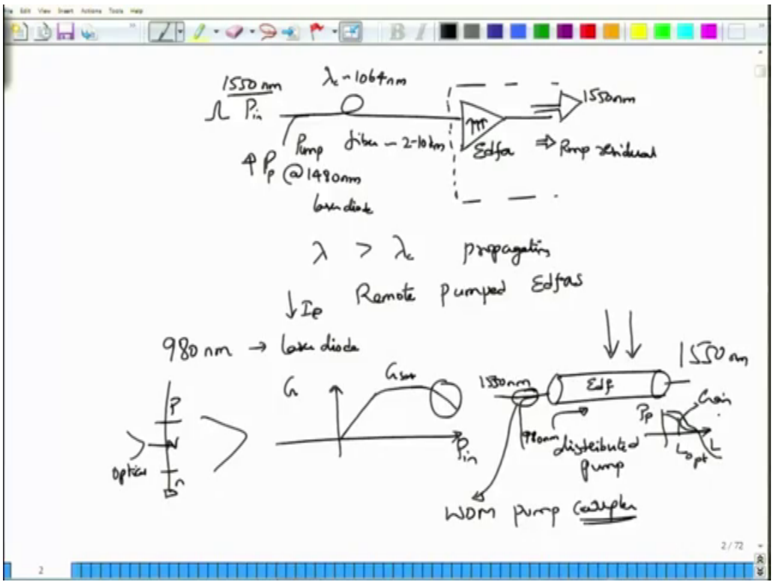

So, why do not we use 1480 nanometer? Well, we do use 1480 nanometer in situations where let us say I have a span of fiber here, and then I have an erbium doped fiber amplifier at this position. So, let us say the fiber is about 2 to 10 kilo meters, ok. But the erbium doped fiber is located here and I do not have access to this amplifier, somehow the access to this amplifier is cut off maybe because you know this 2 to 10 kilometer is actually going into the c and then there is an amplifier requirement. So, we have actually kept the fiber based amplifier here this is my erbium doped fiber amplifier but because it is under c, I cannot really go and you know put some equipment at 980 nanometer to actually pump here.

In that case I can send the pump, right away at 1480 nanometer at the input side itself. So, this is the input that you are sent out. However, at the same side you can also send in the pump power which let us call it as P with a subscript of P to denote this is pump power this pump is now at 1480 nanometer the advantage here is that if this input power is around 1550 nanometer. And this one happens to be a fiber which is say a standard single mode fiber or any other fiber the cutoff wavelength of these fibers is usually 1064 nanometer which means that for all lambda greater than lambda c those wavelengths actually are propagating, ok. Because of this condition both 1550 nanometer which is actually carrying some information or some sort of a light pulse will travel alongside 1480 nanometer. So, 1480 nanometer pump can undergo some loss through because it is propagating through the fiber without any amplification.

But if you keep the initial power to be quite high, then this 1480 nanometer will co propagate with 1550 nanometer reach the erbium doped fiber where they will start to excite the electrons or excite the atoms, at which when the 1550 nanometer light comes in what we will you get at the output will be an amplified version of 1550 nanometer. And of course, a diminished version of the pump itself, the pump will still be there the residual pump that you are going to get but that residual pump will be almost 0.

So, this type of an amplifier is used in cases of what is called as remote pumped erbium doped fiber amplifier. So, when you are pumping them in the remote without any access use 1480 nanometer which takes atoms or which takes ions from energy level E 1 and directly deposits them on to the energy level E 2. So, this is the remote pumping that we normally use.

If we examine the 980 nanometer pump itself that is actually realized as a laser diode. So, you are back to the situation where you want even the 1480 nanometer is a laser diode itself, ok, usually it is a laser diode not an another optical signal. So, you are back with having some current requirement for the pumping, ok. But that is all right, I mean this is for the laser to generate energy at 980 nanometer or 1480 nanometer but the actual pumping to the erbium doped fiber is done in the optical way. So that is the optical pumping.

The characteristic of this lase, I mean this amplifier with respect to the dependency on the input power that you have launched is as the same as that of the semiconductor optical amplifier. Initially when the power is launched the gain kind of rises linearly, so as the input power rate increases the gain also increases, but quickly it reaches a saturation value and in some cases may actually even drop, ok. It may drop provided the length of the fiber is quite long.

To understand the difference as to why this is happening in an erbium doped fiber amplifier while it does not happen in a semiconductor optical amplifier you have to realize that the pump is not you know sent in a cross sectional way the pump is actually co propagating. Therefore, this is called as distributed pumping, distributed pumping versus the lumped pumping that you actually use for the semiconductor optical amplifier, right. So, in the semiconductor optical amplifier the pumping was done by a P junction and an N junction maybe some other N material out there and the pump was directed in this manner while the optical signal propagated in this direction, right. So, optical signal propagated and then eventually amplified.

However, in this case the 980 nanometer pump has to be coupled along with the light that is propagating. So, clearly if 980 nanometer has to be coupled the cutoff wavelength of this erbium doped fiber must be different than that of the single mode fiber, in the sense that it has to have a lower cutoff wavelength. So that it can support 980 nanometer on one hand, and of course, 1550 nanometer also on the other hand.

So, this is your signal and this is your pump and the special device which is used to couple signal at 1550 nanometer and a pump which is at 980 nanometer is called as a pump WDM coupler or WDM pump coupler. WDM simply refers to the wavelength around 1550 nanometer, whereas pump refers to the wavelength at 980 nanometer, ok.

So, we will see what a coupler is in one of the other modules shortly, but bear in mind that this coupler is used to combine 1550 nanometer signal with a 980 nanometer pump. And then both will propagate through the erbium doped fiber with a result that 1550 nanometer light will be amplified and pump.

What will happen to the pump? Well, that is what we were discussing what actually happens to the pump is the pump is strong initially, right and then as the length of the fiber I mean as the pump propagates along the length of the fiber there will be absorption of the pump. Of course, because there is a signal it will continuously perform the stimulated emission and the pump which is now powering many of the atoms at E 1 to go to E 3 and then subsequently to E 2 would start depleting because it is giving up many photons. So, initially the pump is quite high and thereafter the pump is actually quite small and then reaches down to 0, ok. Rather quickly after a few meter it will go down to 0. So, this is how the pump along the fiber would look like.

So, clearly the gain would also be high here and then eventually drops and maybe even become negative indicating that the signal instead of being amplified will is now start to absorb or the signal will be absorbed, ok. So, you do have a certain optimum length, in order to realize your erbium doped fiber amplifier at that point whatever the gain that you will get will be the optimum gain that you are going to use, ok.

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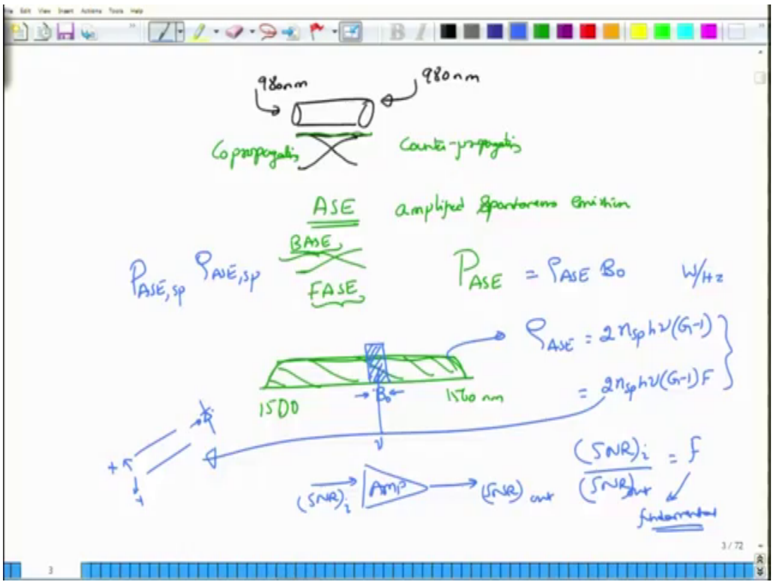

This also indicates another idea that one can use. While the forward pump drops down is it possible for us to actually use a secondary pump and in the backward direction while the forward direction pump starts off initially being very strong, and then eventually falls off. What if we could actually have another pump in the backward direction which could then start off strongly here and then go down as it goes?

So, eventually creating a kind of a overall gain that is possible for us to do. So, this is called as co-propagating pump and this of course, is called as counter propagating pump. Both pumping mechanisms can be used, but it turns out that amplifiers are not perfect they actually add some amount of noise as we have called in the as we have seen in the previous module this noise is called as amplified spontaneous emission noise.

Why do we call it amplified spontaneous emission noise? Spontaneous emission is something that we already know, right it occurs without any external agency being stimulating that one. So, atoms naturally just fall down after a characteristic life time in a spontaneously on their own and of course, these photons that are released under the spontaneous emission are completely incoherent and they do not normally have any relation to the signal photons.

But their photons at the end of the day you are only caring about or the erbium doped fiber only cares about the energy. So, what would happen is as these so spontaneous emission induce photons falls down it will also induce some amount of stimulated emission photons to follow through. So, with the result that the noise level which starts off small will eventually build up into a reasonably large level, the amount of noise power that you are going to get will be denoted by P with an underscore ASE. And because this noise is building in the forward direction this is sometimes called as forward amplified spontaneous emission clearly there will be a backward amplified spontaneous emission which we can call as backward ASE. So, you have a total ASE resultant because of forward and backward amplified spontaneous emission noise.

The combined ASE would actually be quite a bit of a power. If you look at what is the average power that is because of the ASE that is spread out over the band that we were looking at, the average power depends on the spectral density of the ASE noise which actually has to be quite sharp and flat actually and has a range which is quite wide. So, it can cover all the way from 1500 to about 1560 nanometer which is the range which we are normally interested in.

Of course, you do not really use the entire range for a given channel; each channel will have a certain band as we have talked about in the previous module so you do have a certain band out there. But over that band what would be the total and if the band width is say B 0. The total noise power that is present in this band is actually given by the spectral density of the noise which we may write it as rho ASE. And this rho ASE is given by 2 n s p h nu, where h nu is the central wavelength of that particular channel you are considering. And if the amplifier is giving a gain power gain of G, then you have this factor of G minus 1 to n s p h nu G minus 1, B 0 for an ideal amplifier. However, most amplifiers are not even ideal in this sense that is then further degrade the signal to noise ratio by a factor called F, which is the noise figure of the amplifier.

So, if you actually look at any amplifier, so you might have some input signal to noise ratio at the input side and then you have a signal to noise ratio at the output side. Usually it turns out that because amplifiers are adding their own signal, the signal to noise ratio actually kind of worsens and how much does it worsen is given by the noise figure or the noise factor, ok. So, this is the further degradation that you would expect because most amplifiers are not going to be ideal amplifiers and they induce noise and they have this noise figure.

It turns out that noise figure is actually very fundamental property, it is something that can cannot be just wish the away saying that you know I can throw this out it is not possible to do so. So, this noise figure is something that comes fundamental from the fundamental physics point of view and therefore, cannot be thrown out.

Now, this was actually the power spectral density power spectral density will be measured in so and so Watts per Hertz when you multiply the power spectral density with the bandwidth you will get the total power. And in case of a non-ideal amplifier or an amplifier with some noise figure F this is the power spectral density.

Notice the factor of two appearing here, two actually indicates that you are looking at two polarizations. Remember this is a fiber. So, you have one polarization which is along say x and then you have another polarization which is along y and there is noise because of both polarizations x and y. So, when you put up the photo detector which is a subject of our next module, we will see that this noise will combine together will be detected and contributes to the factor of two here. However, if you are asked what is the total noise power or the spectral density per polarization per polarization will be denoted by s p which stands for single polarization in that case you drop the factor of two, in that case we simply have n s p h nu G minus 1 or n s p h nu G minus 1 into F. The bandwidth of course, is given by whatever the filter bandwidth that you use, ok.

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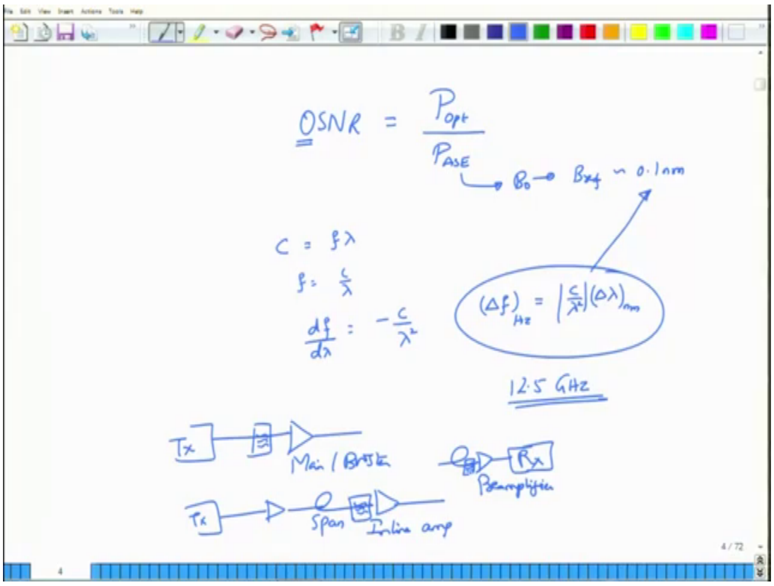

$$\underline{OSNR} = \frac{P_{opt}}{P_{ASE}}$$

$$P_{ASE} \to B_0 \to B_{xf} \sim 0.1\,nm$$

$$c = f\lambda$$

$$f = \frac{c}{\lambda}$$

$$\frac{df}{d\lambda} = -\frac{c}{\lambda^2}$$

$$\boxed{(\Delta f)_{Hz} = \left|\frac{c}{\lambda^2}\right|(\Delta\lambda)_{nm}}$$

$$\underline{\underline{12.5\ GHz}}$$

Associated with this erbium doped fiber is one last term that will come up very importantly in the cases when we discuss communication systems. So, when we start doing that it is called optical signal to noise ratio. That is if we were to able if we were able to directly measure whatever the optical power that is present in the signal, and then take the ratio of the total average noise power then this is called as optical signal to noise ratio.

Now, you might ask what about this P ASE bandwidth that we are going to take. You are right, if I start increasing the bandwidth the total value of P ASE starts to increase and the OSNR actually starts to decrease. However, this band width optical bandwidth is taken to be some reference bandwidth corresponding to 0.1 nanometer. Now, how do I convert 0.1 nanometer into delta F? I know c is equal to f lambda, right. So, I can write down f equal c by lambda differentiating both sides with respect to lambda assuming that they can be varied that way.

So, you get c minus c by lambda square and then the bandwidth delta f which is in hertz is given by c by lambda square magnitude of course, is what you are looking for times delta lambda in nanometer. So, you have you express lambda in nanometer c in say meters per second or nanometers per second and you can actually use this formula to find out what would be the appropriate value of the bandwidth in Hertz. It turns out and I will leave it as an exercise for you to show that this is roughly 12.5 Giga Hertz. So, 0.1 nanometer corresponds roughly to 12.5 Giga Hertz. So, this is about the erbium doped fiber amplifier that I wanted to discuss.

And what you will see is that these erbium doped fiber amplifiers can actually be used in two different ways, or many ways 3 different ways, in fact one at the transmitter itself. So, this is the transmitter and then you keep a amplifier, right away here. This arrangement is what is called as the main amplifier or sometimes called as the booster amplifier. Then you have a transmitter you have a booster or a main amplifier fiber, and then you have what is called as an inline amplifier after you have propagated after the pulse has propagated over 1 span, ok. So, this is also something that is possible.

And at the receiver you have just before the receiver comes in from the fiber after the last mile of the fiber just before you take the signal into the receiver sides you have one more amplifier which is called as the pre amplifier. Of course, that all these points you may have to or indeed you will have to put appropriate filters, so that you are limiting the amount of noise that comes in into the band of the signal of interest. So, this is about erbium doped fiber amplifiers.

And we will stop here. Many of the characteristics are quite similar to SOAs we have discussed, and many other things with the pre-amplifier we will discuss when we when we have all after all after we have introduced the photo detectors.

Thank you very much.