Indian Institute of Technology Kanpur

National Programme on Technology Enhanced Learning (NPTEL)

Course Title
Optical Communications

Week – X
Module-I
Optical amplifiers-I

by
Prof. Pradeep Kumar K
Dept. of Electrical Engineering
IIT Kanpur

Hello and welcome to the moke on optical communications. In this module we will discuss optical amplifiers, these components or divisors if you would call them they are very important in a modern optical communication system. Now the reason why an optical amplifier is important is just as why an electrical amplifier is important when you are looking at communication systems.

Because amplifiers allow you to amplify the signal, so typically signals which are at the receiving end, so at the transmitting end when you transmit a modulated information on the carrier, and then send it out to the receiver, the signals are quiet strong. So if you were to look at the energy in the side band for example in a double side band modulation, then the energy would be significant at there as does the carrier energy as well.

However, as this double side band surprised carrier maybe for example, passes through the atmospheric channel, because of the losses and because of the noises that get accumulated especially at the receiver end, what will happen is right at the receiver side if you want to look at the energy, the energy would have been very small. A very similar thing happens when you take the optical carrier in the form of a laser and then modulate this laser in order to impress your data on to that.

And then this modulated carrier travels through the optical fiber and fiber introduces dispersion as well as loss. So loss is of course important because it basically starts to reduce the signal amplitude or equivalently the optical power. So it might come to a situation where the optical power that is received will be so small that it would essentially be buried inside the noise that you are going to look at.

So from the noise from which you are trying to extract the signal, we normally quantify how much the signal, you know is powerful compared to the noise by defining a quantity called as signal to noise ration. So you want at the receiver a very high signal to noise ratio, you want it because your signal which is very small in amplitude, if it is very small in amplitude then it is almost impossible for us to distinguish the signal from the noise, if the signal to noise ratio is very small.

Now one can of course mitigate this problem without the use of an optical amplifier. How would we do that? Suppose you have a carrier, so let us say this is there at your transmitter end, you modulate it, you send the information okay. So let us say your fiber has a certain length and then after a certain, after that particular length the optical power would have reduced to so much that you cannot detect it, that is your APDs or the photodiodes will have a detectivity which detectivity or the sensitivity below which the signal power would fall if the length of the fiber is large.

So if you do not want this length of the fiber, so if you do not want the signal to be lost in this, you know in this process and hence you want to recover the signal you can simply reduce the length of the fiber okay. So reduce the length of the fiber, detect the signal, amplify it okay and then maybe if you want to clean up the signal you can also clean up the signal, maybe the signal is also suffering from some chromatic dispersion so the bit boundaries have slightly enlarge.

So you can actually reshape the signal, so you can receive the signal, regenerate the signal, reshape the signal you do all that okay, and then send it on to the next span okay, Notice here what has happened you have not used an amplifier, so whatever that you have to work with you have to work with very possibly very low optical powers and moreover, the available or the span length that you are looking at will have to be limited.

Because if I increase the span length that is length between the regenerator, repeater and the transmitter or between two regenerative repeaters if you are in the mid span of the link then the distance between this span actually reduces you do not want this because reducing the distance means that you have to put in more and more regenerators the number of regenerators simply start increasing as the if you do not have an amplifier and you have to choose and you choose to work with this low amplitude or low power scenario okay.

So it is not advisable from the cost point of you more over if you do not have you know enough amplitude or enough optical power it is not just you cannot you know regenerate the signal you might also be suffering from other problems for examples if you have multiple wave length signals which you have multiplexed okay and then you have transmitted so at the transmitter there is sufficient power but at the receiver in order to regenerate the signal you have to first separately take each signal out through a each wave length out through wave length demultiplexer and once you have taken them through the demultiplexer.

And once you have take them through the demultiplexer then you have to separately put a regenerative repeater okay so you see that if you do not have an amplifier the length before which you have to you know regenerate becomes very small if you had an amplifier then you can go long distances without relay amplifying okay or without really doing anything and once the signal level falls right at the end of first span you can simply amplify the signal back to a desired level that you want and it is always nice to work with signals at this level you know where there is comfortable optical power.

So that the further parts of the communication link are satisfactorily working so what you need is an optical amplifier and we are specifying something like optical amplifier what is the difference between an optical amplifier and electrical amplifier except that they work at two different wave lengths in theory there is no difference between an electrical amplifier and optical amplifier however for optical communication systems the development of optical amplifier was a very significant step. In fact before the optical amplifiers the system would normally look like this so you have transmitter here.

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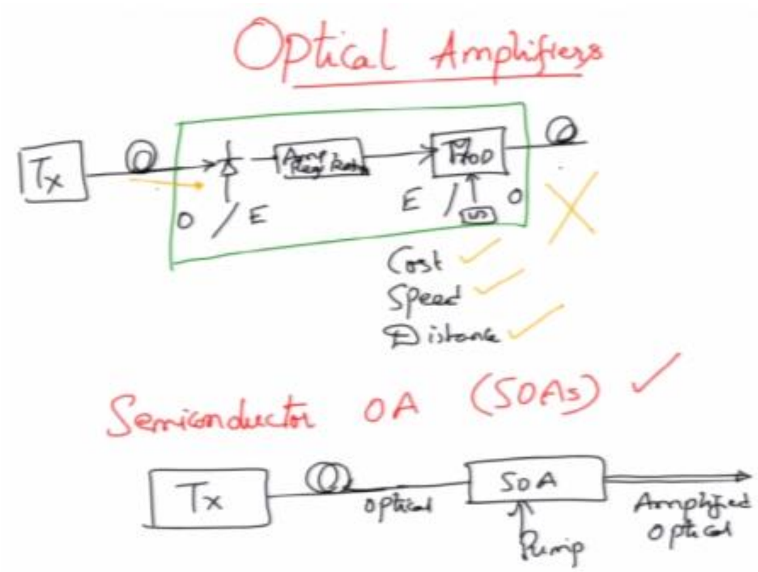

And from the transmitter you launch on to the fiber it would propagate now notice there was no optical amplifier so what you had to was you had to put photo detector right so you had to put a photo detector form the photo detector receives once you have the photo detector you convert from optical signals over here to the electrical signals on to the photo detector then you would amplify regenerate and then amplify regenerate and reshape okay.

So you would do all these process in the electrical domain because it was kind of easier to develop or it the technology for microwave amplifiers or electrical amplifiers was very mature in the early 80's you know because of the development in the microwave technology so you could convert from optical to electrical and do all the processing in the electrical side and then put one more optical transmitter or an optical modulator so let us just put an optical modulator and then transmit once more okay.

So this block which you can you know encapsulate from the receiver side on to the modulator side would perform optical to electrical conversation amplification and other process you know clean up the signal and again from electrical to optical signal back so you have of course at this point an optical signal and at this point signal but in-between there as been bottle neck why is there a bottle neck because you are optical to electrical conversation is a slow process depends on the photo diode.

And the associated circuits and whatever the amplification regeneration reshape that you have to do you will have to do that in the electrical domain and it is cost in effective because you have to after doing the electrical signal after getting a reasonably clean electrical signal you then have to re-modulate the optical carriers so of course you would also require a laser diode at this point.

So you have to you see that at every span you have to put a laser diode you have to put a modulator you have to put all this things, so clearly giving us a problem in terms of cost giving us a problem in terms of speed or the distance between the spans, right.

So the distance was also an major factor because you could not go far too long because if you went far too long then you see that the optical power would have dropped considerably over here, so the lessen out here is that around 80’s people realize that if they have to you know increase the speed of operations so at that time the optical speeds was not very high okay, however if they the demand for speed was always there.

And if you wanted to go to a larger speed then it was necessary to circumvent this bottle neck, okay. So optical to electrical and electrical back to optical is something that we would not want to have it because it will increase cost it will decrease speed and it will also limit the distance so what is a solution, so interestingly two kinds of solutions came up one was called as semi-conductor optical amplifier, okay.

So these are for short known as SOAs okay and these work essentially on the principle of very similar to a principle of a semi-conductor laser infact we will very shortly see the relationship between a laser and an amplifier, these semi-conductor optical amplifiers was made out of the same materials as the semi-conductor lasers more or less they were made of the materials are the semi-conductor lasers.

And they were excellent in amplifying a signals optically so what is a significant difference over here, you have an optical signal coming from a transmitter passing through the fiber so you have a signal that is completely optical and then if you give this one to a semi-conductor optical amplifier what you would get would be an amplified optical signal, okay. And this amplified optical signal you would get in the optical domain itself.

So there is no conversion of optical to electrical and back from electrical to optical, so this in principle would have been a very nice solution and in fact it was proposed as a nice solution except that it did not work very well, okay.

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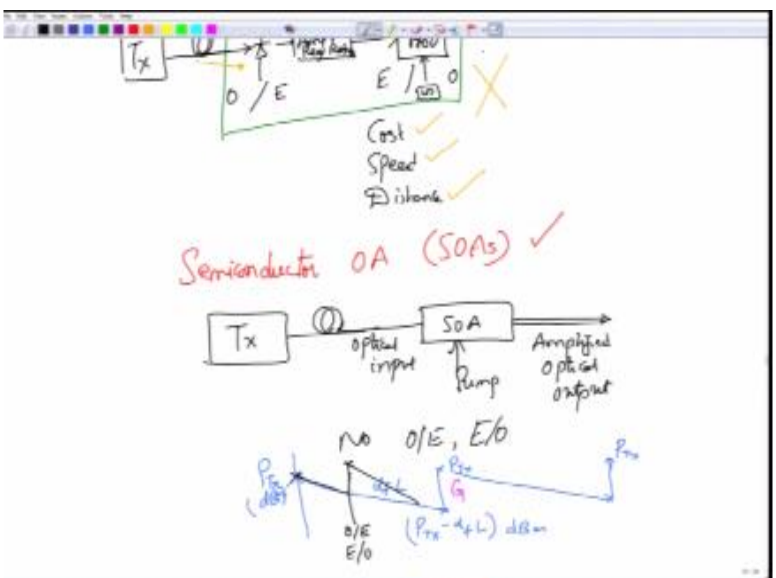

For various reasons that we will comment on later but if you had this semi-conduct optical amplifier you give an optical input and what you get would be an amplified optical output, so no electrical to optical or optical to electrical and electrical to optical conversion and therefore the speed could be increased tremendously as for as the cost is concerned again the cost well you know in this case it is just doing the purpose of an amplifier.

If you want to clean up your signals you still have to do something else onto that one but if you clean up this not what you are looking for then this would also reduce the cost, more over you can now increase the distance between the transmitter and the point where you put in the amplifier because at that point you still have a little bit of an optical power which can then be amplified.

So if you where to follow up on how the optical power would go let us say you launch a certain power PT_x over here, okay. So this is the launch power may be you could call this as P_{in} but I just arbitrarily called this as PT_x because of the fiber there is a linear attenuation up there, correct, so the power basically goes down I am plotting all the powers in the dB scale and what is a loss here? α_F L so the slope of this one would be α_F .

At this point of course the power that you are receiving will be $PT_x - \alpha_L$ all measured in terms of dBm, how many mille watts above this particular thing will exist, now this one can be amplified okay so let us say at this point we put in a semi-conduct optical amplifier of an appropriate gain so that I can bring back the optical power to what it was originally to begin with, okay. So at the transmitter side we have PT_x and because of an SOA which has applied a gain G now the total power has gone back to P_{Tx}, okay if you have the next span launched the power would again reduce at this point you would put one more amplifier to pull the power back on to P_{Tx} and that is how you would able to transmit the optical signals.

If the optical amplifier was not there then the launch P_{Tx} would have to be stopped much before, because if you had let it go all the way here the sensitivity or the detectivity of the APD or the optical receiver would not be sufficient, so I have to interrupted the process right before here and then do an optical to electrical conversion back from electrical to optical conversion and then pull up the power, okay.

So you can see very well that whereas you know this is not exactly to the scale but you can clearly see that you would require multiple such optical to electrical and electrical to optical elements before you would be able to go to the same span length as something that an optical amplifier would provide.

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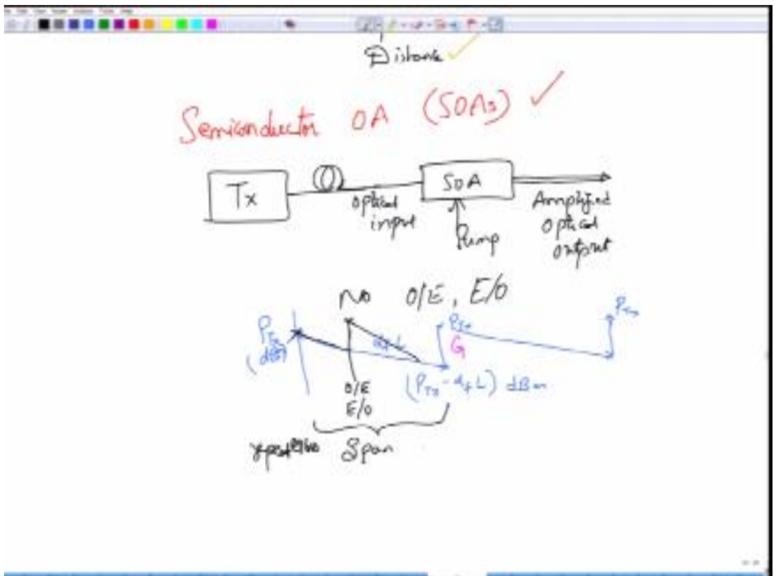

This distance before you put in the first repeater or you distance before you put the first regenerator is called as a span or sometimes called as a repeater less span, so what would be the span or what would be the length of the fiber before you put in the first repeater so this is something that an optical amplifier would provide an advantage, okay.

Now semiconductor optical amplifiers was one possible solution, but however it emerged that there was one more solution which was much more robust then the semiconductor optical amplifiers and it possessed a lot of other advantages that SOAs did not possess, okay.

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This amplifier was actually made from a fiber material itself it was actually made from a fiber and in the regular silica fiber you took what are called as this erbium ions, okay these are, these belong to what is called as a rare earth material or these are in the periodic table they are in the rare earth column, so these erbium ions where doped on to silica fiber, so silica was the host here and erbium ions where the once that were being doped the symbol for erbium is an Er^{3+} these are the ions that you are actually looking at, so which means that they do come with some electric field, okay.

So or they will at least part of the electric field of the silica host changing the overall energy levels, okay. So these amplifiers which were made of what are called as erbium doped fibers they became very, very popular in fact these are the reasons why the WDM era simply took off, so what is that erbium doped fiber amplifiers had that SOAs lacked well, erbium doped fiber amplifiers was very efficient fiber coupled amplifier, okay.

So you did not have to go from a fiber input which was coming from the transmission fiber convert that fiber into a free space version in order to launch on to the optical amplifiers semiconductor amplifier because semiconductor optical amplifier is a waveguide so you have a fiber and we have a waveguide, so from fiber to waveguide if you want to couple there are going to be losses, so this fiber coupled amplifier or this erbium doped fiber amplifier did not have a such problem although there is a different kind of a problem this problem is largely mitigated because your input is fiber and the amplifier material is also in the fiber domain, okay so it was very efficient fiber coupled device.

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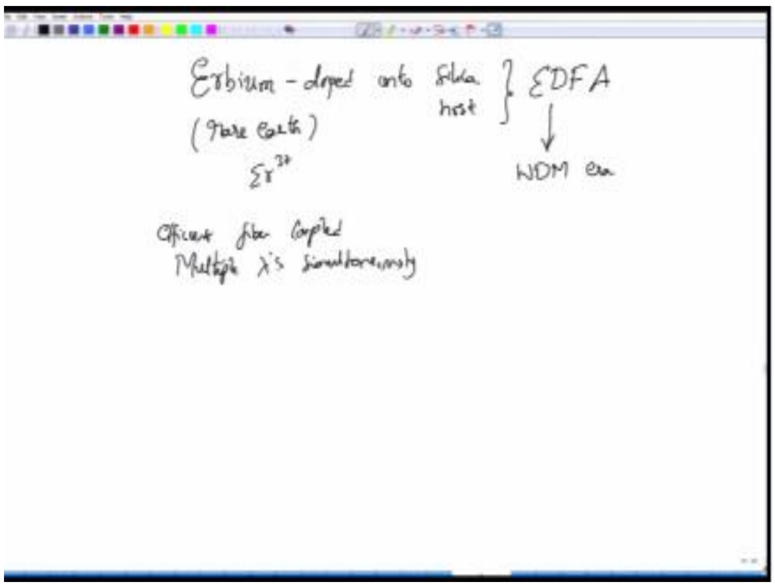

And more importantly it could amplify multiple wavelengths simultaneously, okay although semiconductor optical amplifier can also do this multiple wavelength amplification it does suffer from certain problems, so it mainly suffer from the problem of cross talk and it also suffers from what is called as the gain burning you know so the, we will talk about that one slightly later, okay. But erbium doped fiber amplifiers could actually amplify multiple wave length simultaneously the gain of these wave lengths for not always the same okay but that was a problem that was solved very quickly after the erbium dock fibers were introduced, so before that the point to note here is that they were able to amplifier all these wave lengths in the so called C band.

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Simultaneously thus giving rise to no requirement of a de multiplexing and then separately amplifying everything okay. So you just put one know so whatever the incoming fiber that is there you just couple it erbium dock fiber pump the erbium dock fiber and you get is an amplify signal all wave lengths are amplified simultaneously okay more are less there all amplified simultaneously more over erbium dock fiber amplifiers for more or less intensity of the pulverization changes of the input.

They were also insensitive more or less to the fluctuations in the pump power whereas these two qualities are completely opposite in the semi conductor optical amplifiers, so what will do here would be to first talk about the erbium docked fiber amplifiers in the next few minutes then talk about the remaining amplifiers in the next module okay so let us begin by looking at what an erbium dock fiber amplifier is and how it would amplify the signals.

We will not going to a too detail theory at this point because although the actual working of an erbium fiber amplifier is quite complicated and there are good number of text books available for you to fill up that knowledge from the big picture perspective and erbium dock fiber amplifier or a semi conductor optical amplifier both operate on the principle of stimulated and spontaneous emission.

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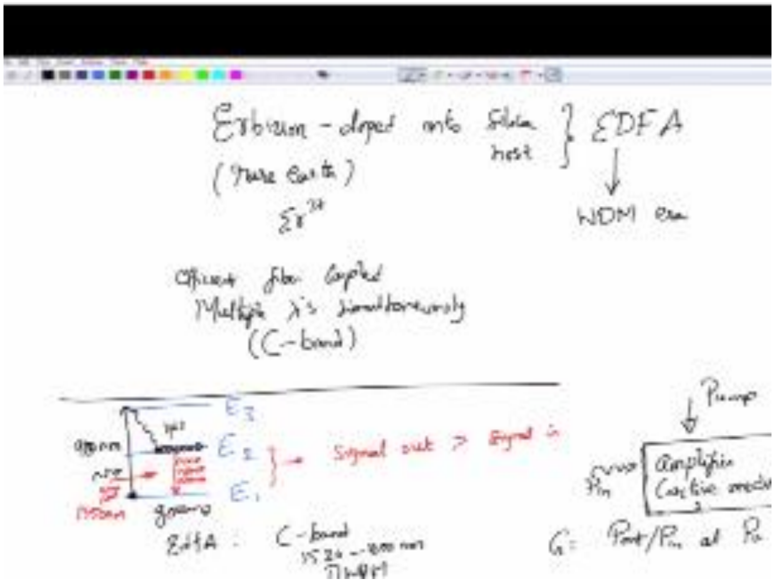

If you recall what the stimulated in spontaneous emissions were if you remember you had materials which had certain energy level so let say this material had an energy level e1 energy level e2 and an energy level e3 so I am showing three energy level because that is what is typically found in a erbium dock fiber. So to these energy levels you want to pick two of those energy levels and create a population in version.

This of course being the ground state will be the first natural part of the two level system and we have to chose between E2 and E3 it turns out that if you chose to pump this erbium dock fiber okay with 980 nm pump diode okay so this has to be a separate one this is a pump diode so if you want to chose pump then all the atoms that are there in the ground level or the ions that are in the ground level would absorb the photons at 980 nm and jump up to level E3 okay.

From this level they will very quickly within about 1 to 2 micro second drop down to level E2 so there is some sort of an indirect pumping going on so you take an erbium dock fiber and then you send in the 980 nm photon through a pump photo diode or pump laser diode this would then excite all the atoms from level 1 to level 3 where in the relax they would not emit anything they will simply relax I what is called as non radioactive DK.

Radioactive means they will emit some radiation non radioactive DK means they will not emit any radiation, so they will non - radioactively DK down to the level 2 and start increasing he population of level 2 ions eventually once you have signal input so let us solve this as the signal input or maybe this is my signal input then this signal input would also be in terms of photons these photons are then absorbed by the ions that are there in the second level and then they will drop down to the ground level emitting a photon okay.

The larger the number of input photons that you send to a certain extent the larger would be the number of stimulated emission photons okay so what would be the result of that the signal would then be amplified so the signal power would be larger than whatever the signal that went in, in this case the signal is actually a time domain or a time varying waveform which is coming in the 1550 nm band, so rbm dope fibers, amplifiers are widely used for C band amplification, okay C band is around 1520 to 1600nm.

So in this band your entire DWM technology is more or less located in this band, and the RBM dope fiber amplifiers can almost simultaneously amplify every wavelength out in this particular case.

Now you know from our discussion on a laser that there are three components to a laser, so there is actually an amplifier in between this amplifier is what we called as a active medium, active medium is the one where in we can create a population inversion, so RBM dope fibers are you know equivalent to an amplifier because or equivalent to an active medium, because when you pump this RBM ions, this ions will jump through the indirect process and create a population inversion between the energy levels E2 and E1, okay.

So you have an amplifier or an active medium which is where there, the second ingredient of this was that you put this amplifier inside a certain cavity, why would you put them inside a certain cavity such as fabric per a cavity in this case? Because you want to provide optical feedback, right? So you want to provide an optical feedback, and of course a laser does not really take in any external signals, it relies on the process of the spontaneous emission to start the process.

But once the spontaneous emission starts okay, because you have created population inversion each spontaneously emitted photon, would then induce a stimulated emission and this stimulated emission would further induced stimulated emission because they are all getting reflected or there all confined by this cavity.

So such a thing was essentially what you had for a laser, now all you have to do is, you take this same device okay, of course here there was a pump remember pump was necessary to create a population inversion, okay so without you creating a population inversion stimulated emission cannot take place, and whatever the emission that you are going to get will be spontaneous emission and it could not less.

To this laser what you now do is? you simply remove this feedback mechanism, or at least at any rate, make this feedback mechanism to be a very week one, okay so this is my attempted drawing a very week feedback mechanism, so I have converted a laser into an optical amplifier by removing the optical feedback, so I am removing the optical feed back or I am at least very minimalistic optical feedback, I have essentially minimized any optical feedback.

Okay instead stimulated emission brought about by supplying a external input signal, so I supply an external input signal so that I get an amplified external output voltage, okay. So what I have return over here is actually P_{out} , and the gain can be return in terms of P_{out} and P_{in} as how much optical power that you obtained the output compare to what optical power you gave, at a certain pump current or a pump value, okay.

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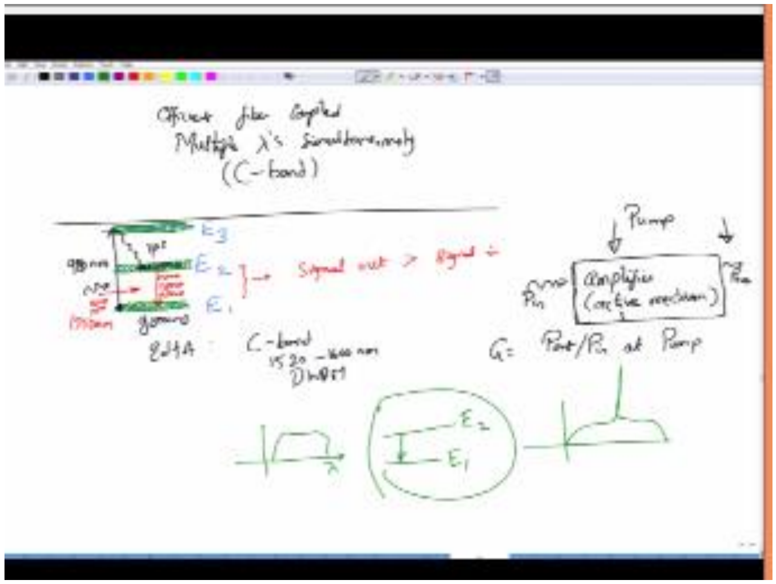

So this same idea is for both SOS as well as for EDFA, in EDFA this is the energy level that you are looking at, okay of course you have also seen that these energy levels are not really energy levels, they actually form a certain band there is a quasi contentious desecrate levels, they are form because of the! You know, the closely spaced atoms in a dense solid medium, as well as in this particular case you see that you have quasi contentious discrete levels.

And this quasi contentious discrete levels happen simply because each rbm ions introduced will cause the splitting of the energy levels, this splitting is called as torque splitting and to properly appreciate this torque splitting one has to look at quantum mechanics, we are certainly not going to do that , but just take it on the faith that if you have energy levels, this are not going to be discrete energy levels, but they are going to be certain bands around that discrete energy levels, infect band is something that is very important, okay if you had discrete energy level an active medium with just lines E1 and E2 so I am neglecting E3 because you can you are only looking at population inversion between E2 and E1, if you have just two lines then there was only one particular wave length which this could have amplified, okay.

So if you have such an amplifier, you know if you make such an hypothetical amplifier over here, and then you coming with a certain broadband signal so this is as the function of the wavelength you coming with certain broadband input signal, then what you would have obtained is only one wavelength that is getting amplified, so you do not want really to happen this, you don't want this to happen, what you want is, if you have band of frequencies, you know that is over which the gain can take place such a something can happen because of this tar splitting of these energy bands.

Then when you coming with the multiple wavelengths, then multiple wavelength can be amplified, so this is what you would actually observe in an erbium doped fiber and this bandwidth of the erbium doped fiber is essentially determined by what is the width of this cozy continuous band of energy level, that would be possible when you have a erbium ion doped into the fiber.

So this I how an erbium doped fiber would work except that I would like to mention. It not that necessary to have a 980 nm pumping, it is possible to actually have another type of pumping. Here this pump goes into a 1480m nm, which means that you can take a 1480m nm laser and then pump it so that the atoms don't go to the energy level E3 and decay, they directly go to the energy level E2.

However this is not initially done for communication applications, because 1980 nm pump is very low power case or essentially efficient process. For the same pump power the population inversion that is created with 980 nm is much higher, compared to 1480 nm, there is however the problem with 980 nm is that it's output power is low as well as, high power 980 nm is actually quite difficult to achieve that is to ay high power output I quiet difficult to achieve.

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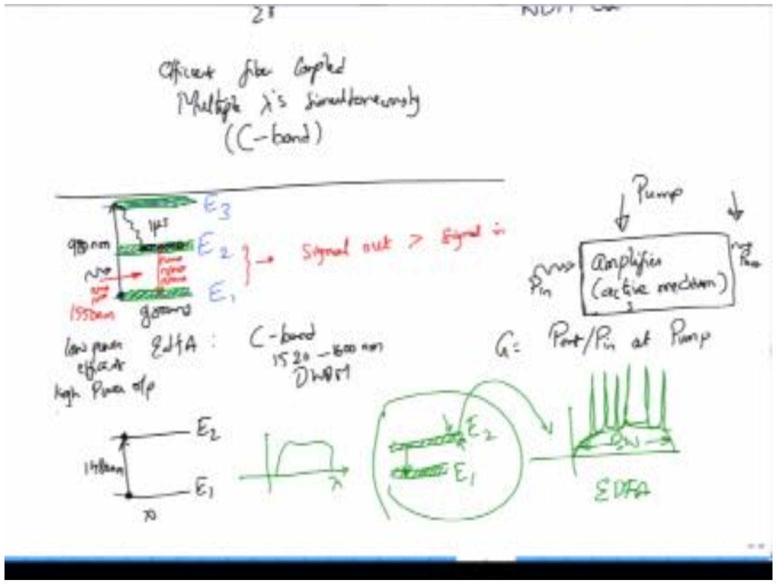

Moreover this requires a WDM pump coupler, pump coupler is a device which actually works something like this, so you have a 1550 nm, which is a signal input power and you have a 980 nm coming from a pump diode and this pump coupler actually couples these two very different wavelengths. So these are called as pump couplers and then you can give this one to the erbium doped fibers for amplification purposes.

So this is your erbium doped fiber, o this process is while very efficient and therefore widely used in communication purposes, 1480 nm actually have its use in high power lasers. So, when you want a high power laser to be fabricated using a fiber, erbium doped fiber, and then you see a 1480 nm pump. You also see this 1580 nm pump because you don’t require a WDM coupler or a pump coupler is not required because the same single mode fibers can be used. So you can just take the erbium doped fiber, you can just connect it to using a ordinary coupler which is very cheap compared to the WDM coupler.

And most importantly this can be remotely located, so you can actually pt this 1480 nm coupler at the transmitter side, so you have a 1480 nm pump and this pump co propagates along the signal. O no special coupler is required, it's an ordinary coupler is sufficient and if you put an erbium doped fiber here, then this would nicely amplify this particular input, for amplify this signal input generated amplified signal output, so this is all about erbium doped fiber amplifier.

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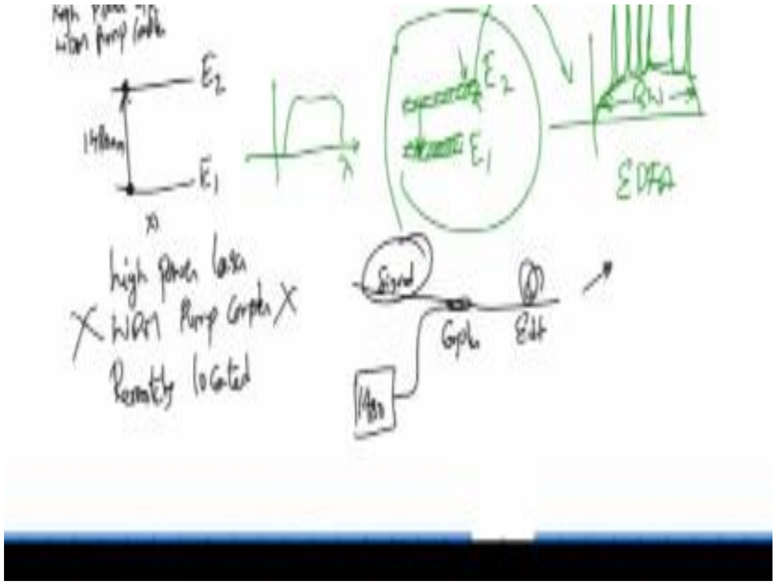

We are going to stop discussing this one and come back to the other aspects of erbium doped fiber in the next module. Thank you very much.

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