Fiber Optics
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Lecture – 32
Optical Fiber Components and Devices – V

So, now in this lecture, we will look into some other components and devices based on optical fiber and these are basically pulse shaping devices.

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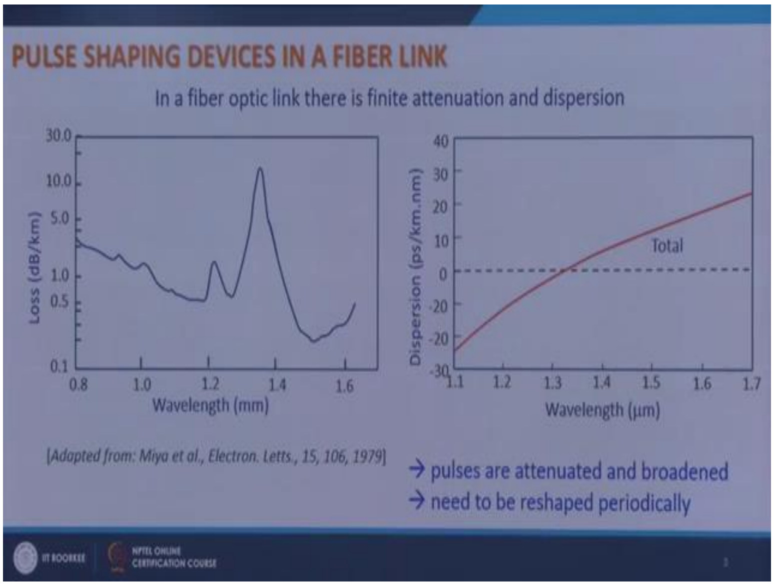

So, what happens when pulses travel through optical fiber? They get attenuated and they get dispersed. Typical attenuation curve; you know of an optical fiber is like this and a typical dispersion curve is like this. So, when these pulses are attenuated and dispersed then periodically we need to reshape the pulses.

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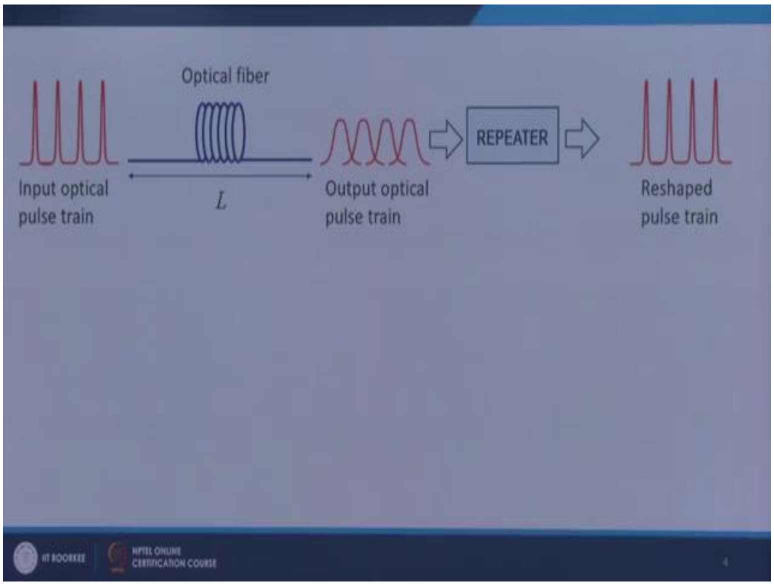

So, this is how it happens. You have an optical fiber. This is the input optical pulse train. The pulses get attenuated and broadened. So, before we lose any information which is embedded in this pulse train we need to reshape the pulses and this is done in a device which is known as repeater. This repeater reshape the pulse train and bring it back to its original form this repeater consists of an amplifier to take care of a renovation and a dispersion compensator or a pulse compressor to take care of the broadening.

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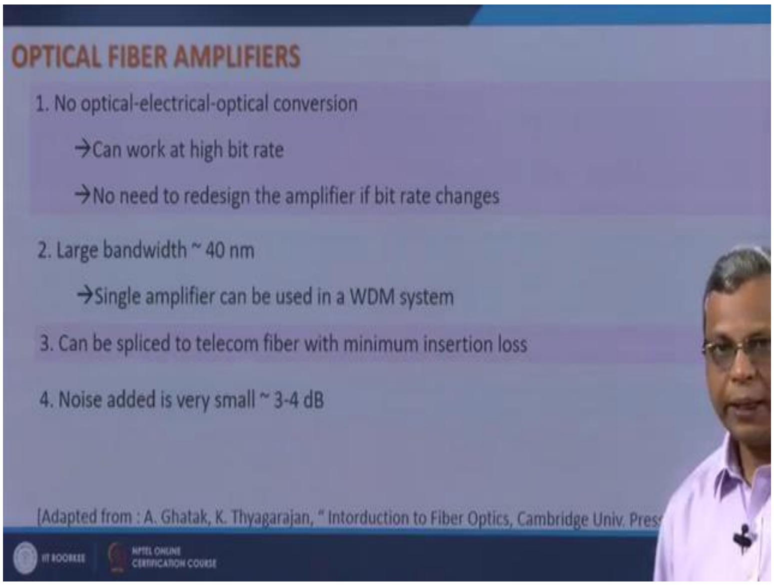

These amplification and pulse compression both are preferred to be done in optical domain itself because by doing everything in optical domain that us doing all optical processing, we will avoid this combustion process of optical to electrical to optical conversion and also we can work at whatever data rate we want.

So, we want to have amplifier which is in optical domain itself and an optical amplifier which is in fiber geometry itself because then it is easier to splice the amplifier with the transmission fiber. So, if we use optical fiber amplifiers then there is no optical to electrical to optical conversion, it can work at high bit rate and when the bit rate changes you need not to redesign the amplifier as you will have to do in an electronic amplifier.

Second advantage of optical fiber amplifiers is in particularly of an amplifier which I am going to talk about which is known as erbium doped fiber amplifier, EDFA. It has got very large bandwidth in the conventional band itself, its bandwidth is about 40 nm which means that I can use it in WDM system in which you send several wavelengths together simultaneously to send your signal. So, each wavelength works as an independent wave, independent data channel.

So, all these wavelengths can be amplified simultaneously by a single amplifier because it has got very large bandwidth since it is in fiber geometry itself. So, you can simply splice this fiber with the telecom fiber with minimum insertion loss and the noise added by this amplifier is very small typically it is 3 to 4 dB also the gain of the amplifier is polarization insensitive.

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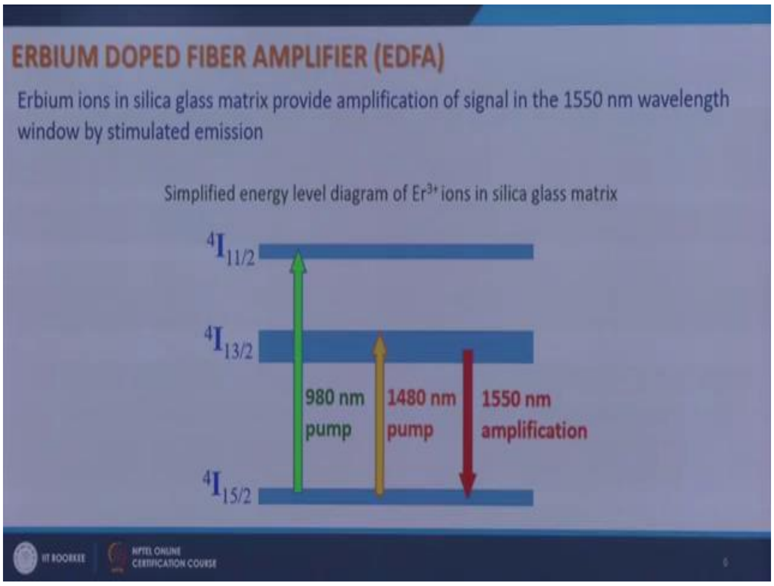

So, how do we amplify this signal in an optical fiber amplifier? We make use of erbium ions in silica glass matrix and do amplification by stimulated emission of radiation the principle which is involved in the laser itself.

So, these erbium ions in silica glass matrix provide amplification of signal around 1550 nm wavelength. This is a simplified energy level diagram of erbium ions in silica glass matrix. So, you have these bands here energy bands, this band corresponds to about 980 nm wavelength, here you can have about 1480 nm and this corresponds to 1550 nm. This is shortly band and this is metastable. So, what you do you use a 980 nm wavelength pump to lift atoms from this state to a higher state here and since these states are short lived, so they decay back to this state very quickly through non-radiative transition and populate this level. So, in this way you create population inversion now if large number of atoms are available in this state then they can decay back to this lower state and give you amplification how because this is metastable state.

So, you will have a spontaneous emission which will have small fraction and then you have stimulated emission this stimulated emission will give rise to amplification of the signal at 1550 nanometer wavelength you can also populate this level by using 1480 nm pump.

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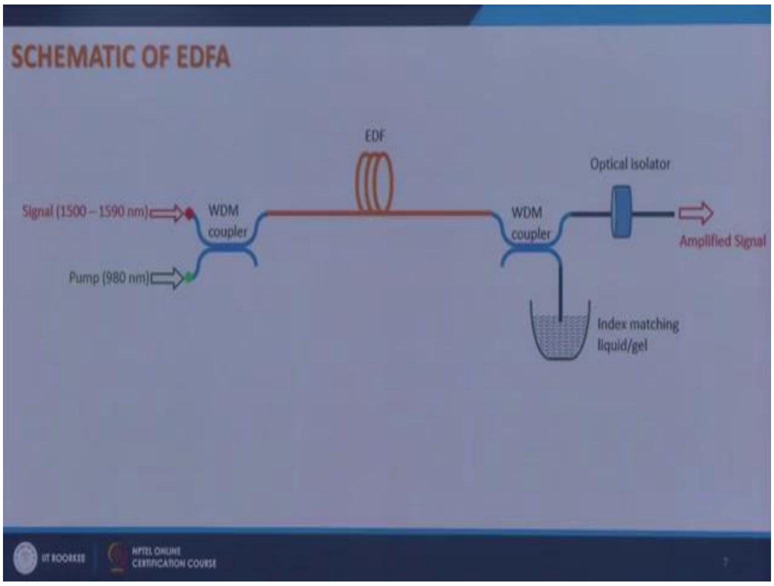

This is a schematic of an EDFA. So, you need to know what you want to do; you want to amplify signal which lies in this wavelength range with the aid of the pump which provides energy for amplification of signal and this pump is at 980 nm.

So, now you need to couple the signal and the pump into the same fiber EDF which is erbium doped fiber which provides amplification for that you use WDM coupler, we already talked about that. So, with the help of this WDM coupler you send both the wavelengths in this erbium doped fiber where the signal gets amplified and after amplification you decouple the pump and your signal goes through this is the amplified signal in order to avoid any back reflection into the system you can use optical isolator.

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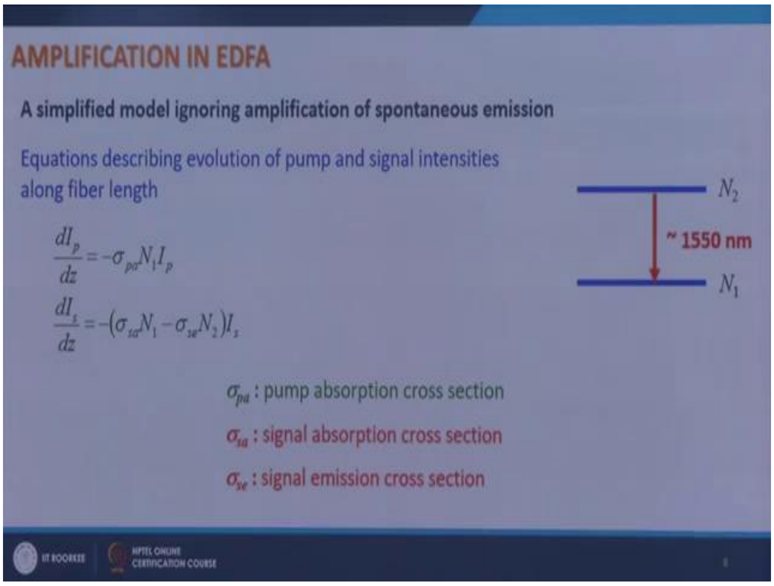

So, a simplified model for this amplification of an EDFA can be given by these 2 equations which tell the evolution of the pump and signal intensities with the distance z the propagation length. So, what we have here we have a simplified 2 level model here this state or this band has been populated via a higher band using for example, 980 nm pump or directly from here to here using 1480 nm pump.

So, you create a population inversion N_2 is the number of atoms per unit volume in this band and N_1 is the number of atoms per unit volume in this band. So, the pump intensity and the signal intensity would vary according to this your $\frac{dI_P}{dZ} = -\sigma_{pa} N_1 I_p$. *Ip* is the intensity of the pump σ_{pa} is the pump absorption cross section. The $\frac{dI_s}{dZ} = -\sigma_{sa} N_1 + \sigma_{se} N_2 I_s$ where σ_{sa} is signal absorption cross section while σ_{se} is signal emission cross section.

So, you can see that this *dIp*/*dz* would be proportional to the number of atoms here and what is the intensity of the pump. Similarly, this will depend upon how many atoms are here and what is the emission cross-section and what is the intensity of the signal. So, with this very simple model I can understand how the intensities of the pump and signal vary and what is the gain of the amplifier; although this is very simplified picture just for understanding at elementary level.

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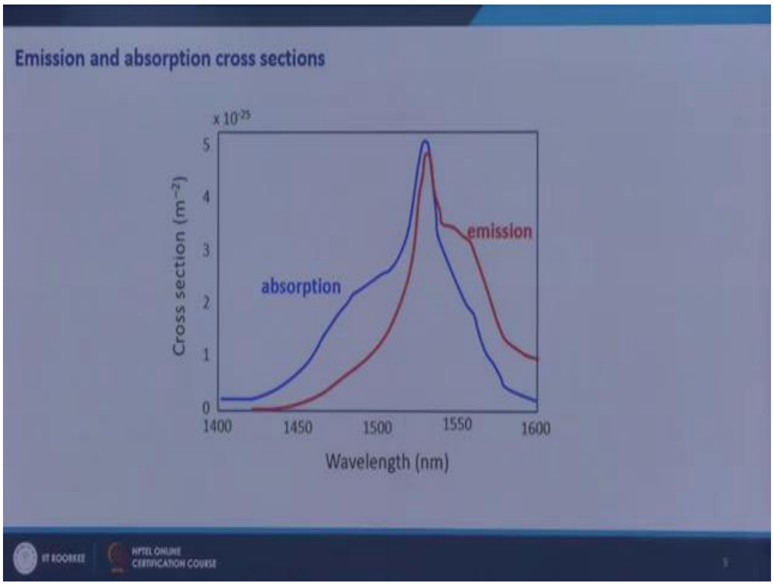

These are absorption and emission cross-sections with respect to wavelength. So, we can see the absorption cross-section is like this and emission cross-section is like this in the wavelength band near 1500 nm wavelength. Apart from this there is absorption at 980 nm wavelength which is very strong absorption. So, here I can see that in this region emission cross-section is larger than absorption cross-section. So, the emission will dominate over absorption and I can readily have the gain. However, in this region I will have to do something very special to obtain the game.

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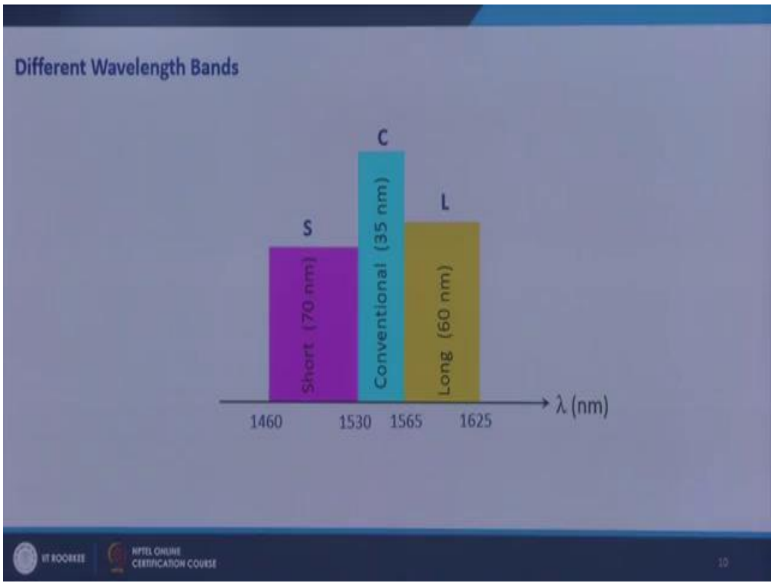

So, these are the different wavelength bands you have conventional band which is about 35 to 40 nm wide, you have long band which is about 60 nm wide. So, commercial erbium doped fiber amplifiers are available in these bands C band and L band and some special techniques can be used to amplify signal even in the short band.

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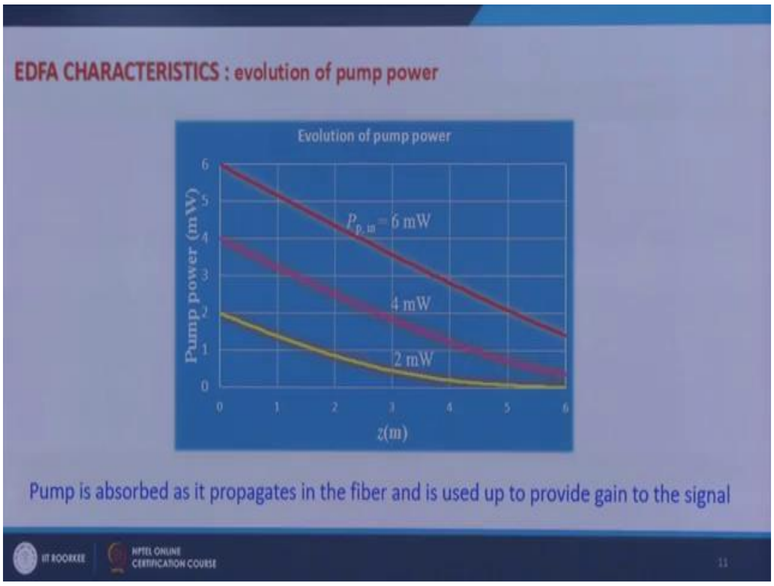

Let us look at typical characteristics of an erbium doped fiber amplifier here I show the evolution of pump power how the pump power varies with the distance in the fiber.

What I see here is that the pump power decreases with distance and it is obvious that because this pump is being absorbed and it provides energy for the amplification of signal. So, as you go along the fiber the pump intensity will decrease and the signal intensity will increase. These are the curves at different pump powers. So, this is at input pump power $P_{p,in} = 2mW$ input pump power $P_{p,in} = 4mW$ and input pump power $P_{p,in} = 6mW$ and that is how their intensity would vary with z, then this is the evolution of signal power.

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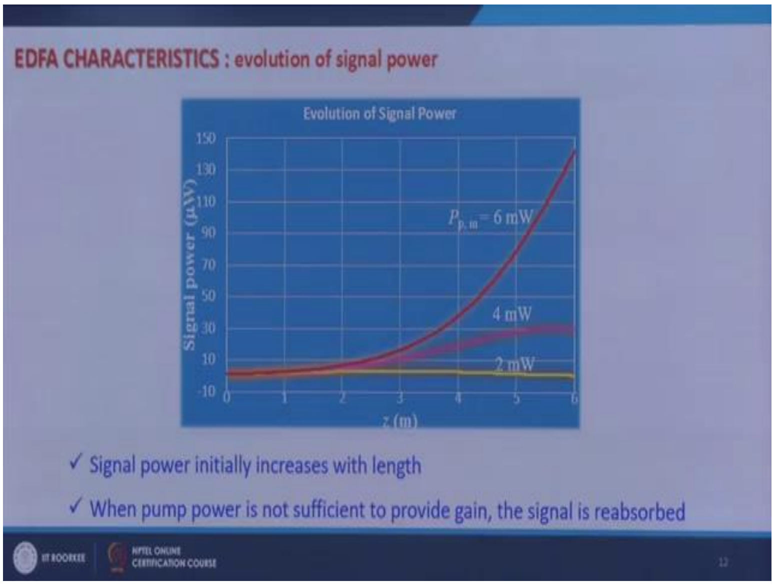

So, as you go along the length of the fiber the signal gets energy from the pump. So, pump energy decreases, but signal energy increases. So, you have a signal power signal power increases with distance when the pump available is not enough to compensate for losses or to provide the population inversion sufficient population inversion, then this gets saturated. So, even if you do not consider any losses, but if the pump power is not sufficient to provide you enough population inversion then gimp gets saturated here and then after that it may even fall because then the pump gets then the signal gets reabsorbed this is how the signal gain varies with z.

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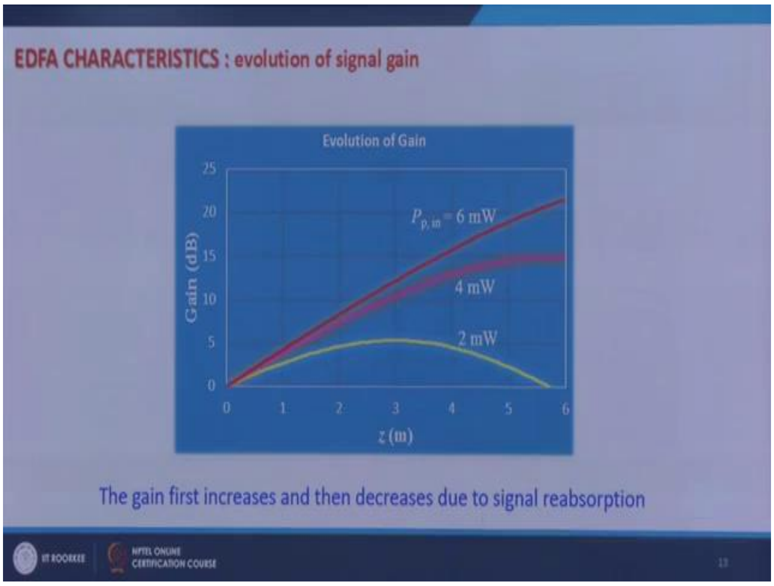

So, initially the pump is able to provide energy to the signal. So, your gain increases after that it gets almost saturated and then again it decreases because of signal re-absorption.

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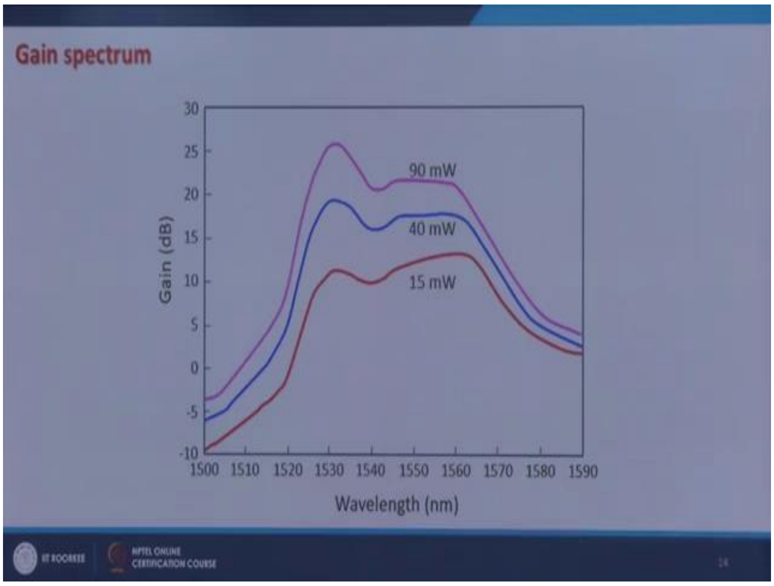

If you look at the gain at different wavelengths that is at the gain spectrum then it looks like this particular characteristic comes from the emission cross-section and absorption cross-section of the EDFA.

So, what we see that at different pump powers the gain of the amplifier varies with wavelength like this at sufficiently high pump power, I can have gain in excess of 20 dB if this is 20 dB line. So, I can have gain in excess of 20 dB over a wide range of wavelength, 20 dB means linear factor of about 100.

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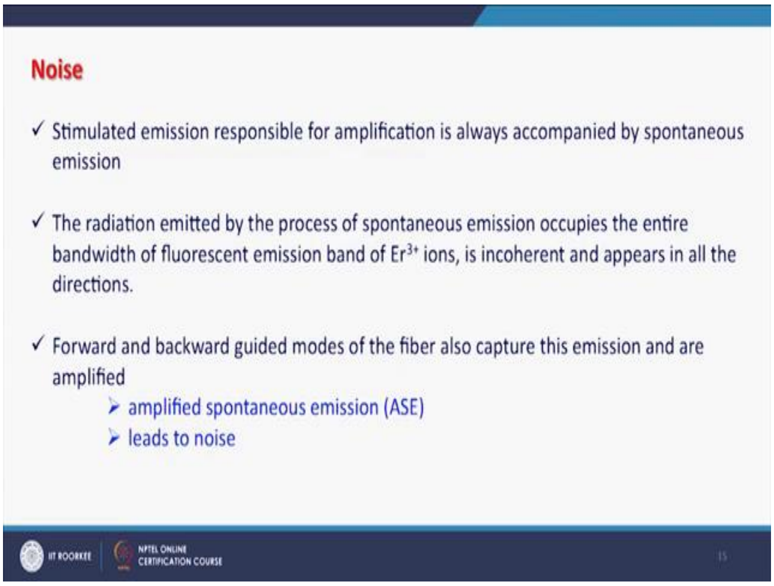

Then along with the amplification of the signal this amplifier also at some noise what is the noise added and what is the basic phenomenon behind the generation of this noise.

Since amplification is provided by stimulated emission and whenever there is stimulated emission it is always accompanied by spontaneous emission and the radiation emitted by the process of spontaneous emission occupies the entire bandwidth of the fluorescent emission band of erbium ions in silica glass matrix and since this emission is spontaneous emission. So, it is incoherent and it appears in all the directions. So, this works as a noise.

Now the forward and backward guided modes of the fiber also capture this emission and they get amplified this amplified spontaneous emission is also known as in short ASE and basically this is amplified spontaneous emission which leads to noise because it is incoherent and appears in all the directions.

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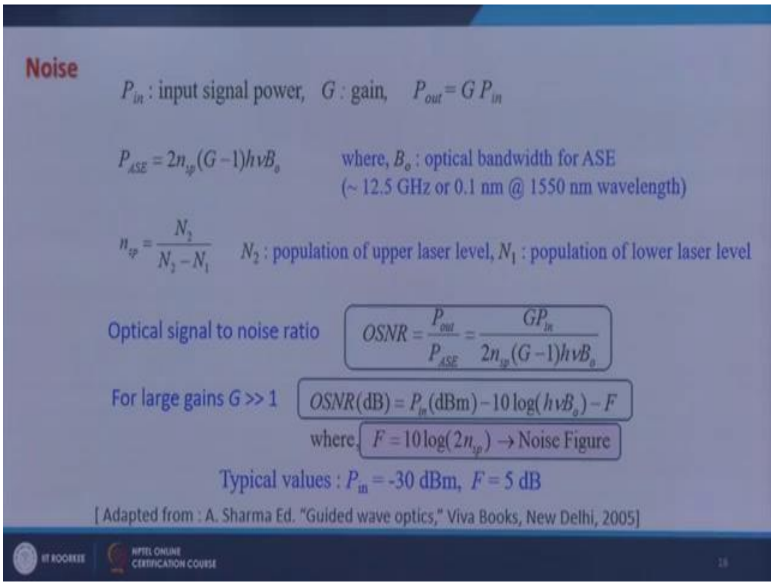

So, how much is the noise we can work out the expression from this, for this if P_{in} is the input signal power and G is the gain of the amplifier then $P_{out} = G\,P_{in}$ now our spontaneous emission also gets amplified.

So, this power in ASE is given by $P_{ASE} = 2n_{sp}(G-1)h\nu\,B_0$, where B_0 is the optical bandwidth for the ASE which is typically 12.5 gigahertz or about 0.1 nm at 1550 nm wavelength n_{sp} is given by $n_{sp} = \frac{N_2}{N_2 - N_1}$ which basically gives the inversion factor tells you how much inversion has taken place in the system where N_2 is the population of upper laser level and N_1 is the population of lower laser level. So, you can see that if $N_1 = 0$ then this $n_{sp} = 1$. So, there is complete inversion; however, if $N_2 = 0$, then there is no inversion then we can define optical signal to noise ratio as $OSNR = \frac{P_{out}}{P_{ASE}}$.

So, if I put P_{out} as GP_{in} and P_{ASE} from here. So, OSNR will be given $OSNR = \frac{P_{out}}{P_{ASE}} = \frac{GP_{in}}{2n_{sp}(G-1)h\nu\,B_0}$ for larger gains much much larger than 1, if I talk about 20 dB gain, then $G = 100$ which is much much larger than 1 then $\frac{G}{G+1} \approx 1$, then I can convert this into dB, as $OSNR(dB) = P_{in}(dB) - 10\log(h\nu)\,B_0 - F$, where $F = 10\log(2n_{sp}) \rightarrow \textit{Noise figure}$

and this is basically the noise trigger. This is basically the noise trigger typical values are you have input power about minus 30 dBm input signal power and this F is typically 5 dB the noise figure is typically 5 dB.

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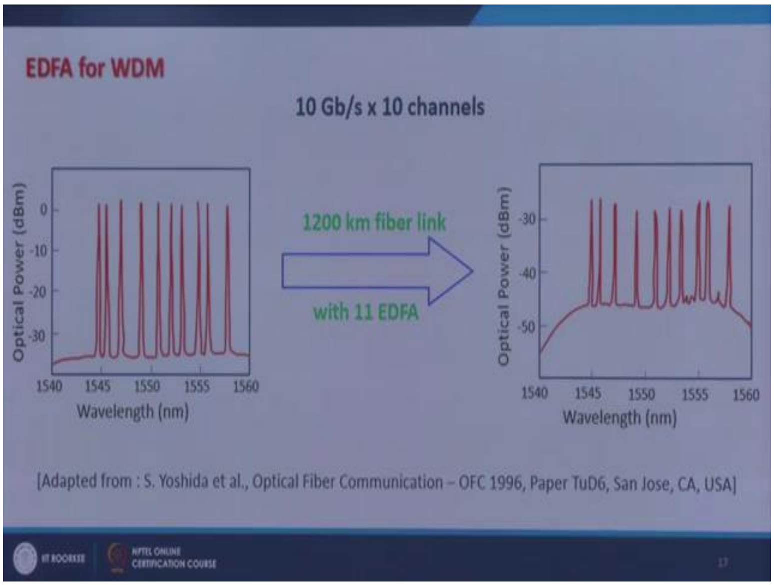

This is EDFA for WDM, you can use the same amplifier for different wavelengths. So, this shows a very exciting and very interesting system which has got a bandwidth of 10 GBPS in 10 channels. So, each channel has 10 GBPS and there are 10 wavelength channels and this has been carried out over a distance of 1200 kM in a fiber link using 11 EDFA in between. So, this is the input spectrum of the signal. So, you have 10 wavelengths 10 wavelength channels and after 1200 kilometer fiber using eleven EDFA this is the output.

So, you can see that that using WDM you can multiply the capacity of the same fiber many folds.

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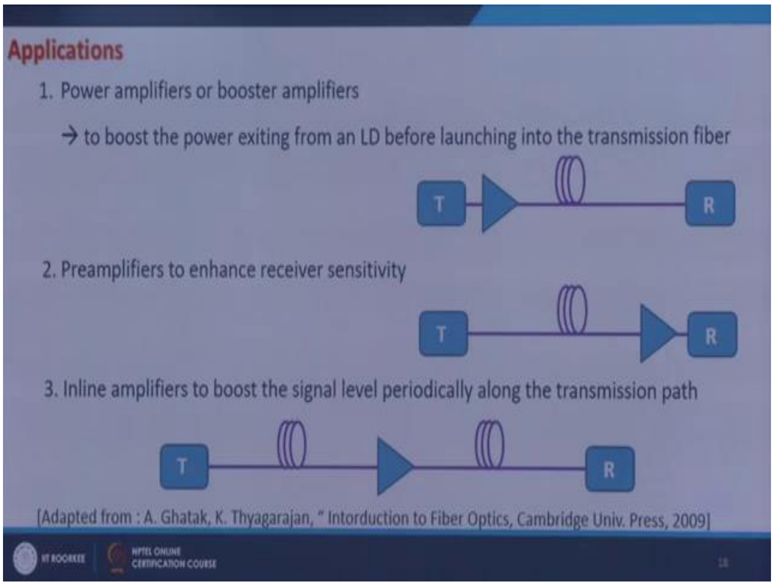

What are the applications? Applications of EDFA are in power amplifiers or booster amplifier what you can do before sending the signal into the transmission link fiber link you can first boost the signal using an amplifier then it is known as booster amplifier.

You can use it as preamplifier to enhance the sensitivity of the receiver. So, before sending the signal to the receiver you first amplify the signal and then send it to the receiver then it is used as preamplifier. And the most commonly used is the inline amplifier where you use an amplifier in between. So, here your signal gets attenuated after travelling certain distance through fiber then you amplify it and then you send it in the next section. So, apart from this EDFA which takes care of the attenuation of pulses we can also compress pulses using a device which is known as dispersion compensating fiber we can also change the dispersion characteristics of the transmission fiber to suit our needs.

So, let us now study the dispersion management in an optical fiber link.

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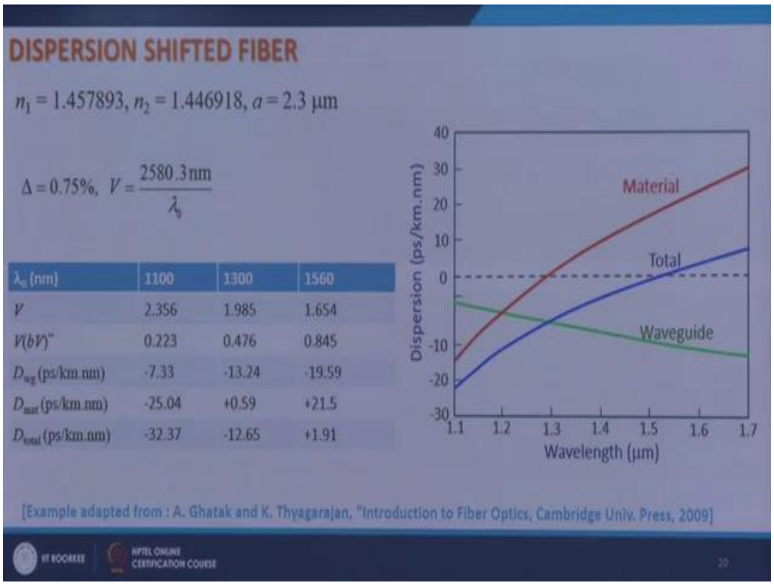

So, we have seen that in a conventional single mode fiber your 0 dispersion wavelength is around 1300 nm about 1310 nm. So, at 13 nm, you have minimum dispersion while your minimum attenuation is around 1550 nm. So, if you want to take advantage of both the minimum dispersion and minimum attenuation then you will have to shift the 0 dispersion wavelength to 1550 nanometer wavelength. How we can do this; we know that the total dispersion in a fiber is given by the waveguide dispersion and material dispersion it is the combination of these two, I cannot do much with material dispersion I cannot change the characteristics of the material; however, what is in my hands is to change the wave guiding properties of the fiber and change the wave guide dispersion and hence the total dispersion.

So, for that if I make a fiber design something like this where N_1 is this and N_2 is this which gives you delta about 0.75% in a conventional single mode fiber this delta is about 0.27%. Now it is 0.75%. So, to keep this fiber in single mode domain itself with this enhanced delta I decrease the radius of the fiber from 4.1 micrometer to now 2.3 micrometer.

Then V can be given by this and if I analyze this fiber over several wavelengths, then I find that at lambda naught is equal to 1100 nm my total dispersion is -32, at 1300 nm wavelength in a single mode conventional fiber, it was around between 1 and 2 ps/nm/km and now it is about -12 ps/nm/km.

However, it 15-16 nm wavelength with this design, I could bring down the total dispersion to much smaller value about 2 ps/nm/km. If I look at the dispersion as a function of wavelength, then I find that the total dispersion is 0 somewhere here which is around 1550 nm wavelength. So, with this design, I can change the waveguide dispersion considerably and shift the 0 dispersion wavelength from 1310 nm to about 1550 nm. So, this is dispersion shifted fiber. So, I can make use of both minimum dispersion and minimum attenuation; however, the price I have to pay is very high value of delta which of course, increases attenuation because you have increased the germanium concentration in the fiber and also *a* has become very small, so you are splicing this with other components gives you much larger loss and you will have to now work with much smaller dimensions. So, the cost of the components increases.

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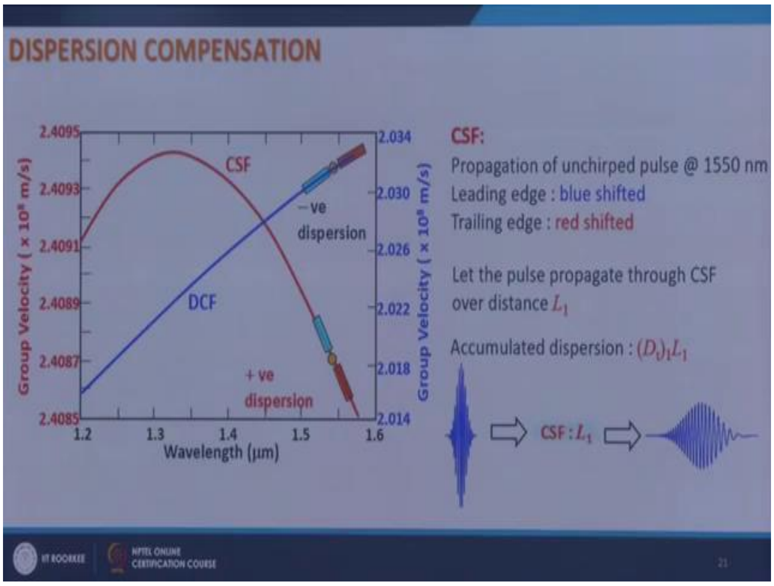

Another way of doing this is that you use the same fiber which is already laid millions of kilometer of such fiber is already laid which is optimized at 1310 nm wavelength. So, instead of replacing that fiber you use that fiber let use that fiber at 1550 nm wavelength let the dispersion accumulate and after that you compensate for this dispersion for that you need a dispersion compensating fiber how does it work let us look at it.

So, if you look at a conventional single mode fiber this is the group velocity dispersion of a conventional single mode fiber you work somewhere here at 1550 nm wavelength. So, here what you have that your longer wavelength components travel slower while the shorter wavelength components travel faster. So, as a consequence a pulse at 1550 nm if you send through this fiber then its leading edge gets blue shifted while the trailing edge is red shifted.

If I led this pulse propagate through distance L_1, then the accumulated dispersion would be dt_1L_1 where dt_1 is the total dispersion total dispersion of conventional single mode fiber. So, you input this pulse and in the output you get this, if I now looked at this fiber if I changed the design of my fiber in such a way that its group velocity dispersion curve looks like this then here what I see the longer wavelength components travel faster and shorter wavelength components travel slower, then the leading edge of the pulse gets red shifted while the trailing edge gets blue shifted.

If I let the pulse propagate through CSF through DSF, I am sorry this has to be corrected through DSF through DCF, if I let the pulse propagate through DCF dispersion compensating fiber over distance L_2 such that $dt_1L_1 + dt_2L_2 = 0$ where $dt_2$is the dispersion coefficient of this DCF dispersion compensating fiber.

Then this broadened pulse in the conventional single mode fiber will get compressed and you will get back the original pulse. So, accumulated dispersion is compensated and the pulse is compressed.

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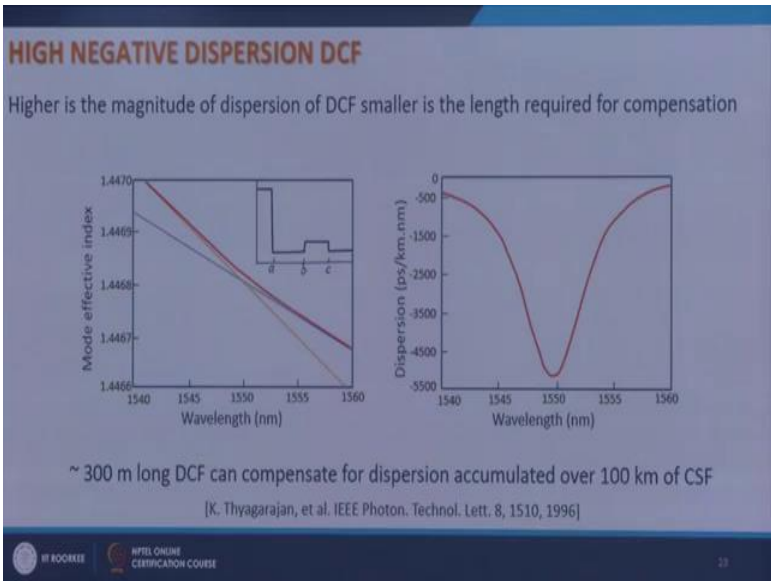

How do you achieve this kind of dispersion? There is a design which is given by Tyagarajan in 1996 where they have used this dual core fiber and this particular fiber gives you the effective index as a function of wavelength something like this which makes a turn which makes a turn somewhere here and the curvature changes here and because of the change in curvature at this point you will have very high value of the second derivative of an effective which gives you very large negative dispersion. So, you can achieve very large negative dispersion at a wavelength and the consequence of this is that with the help of this fiber only a 300 m long fiber can compensate for dispersion accumulated over 100 kilometers of CSF.

So, with this I finish discussion on pulse shaping devices in an optical fiber link. In the next lecture, I would look into the sources and detectors for optical communication.

Thank you.