Introduction to LASER
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Lecture - 12
Er Doped Fiber Amplifier (EDFA)

Welcome to this MOOC. In the last lecture, we discussed about Nd: YAG Laser Amplifier and today, we will take up Erbium Doped Fiber Amplifier. Erbium is also a rare earth element which is doped in silica fibers and erbium doped fiber amplifier is a very important practical amplifier used in optical fiber communication, alright.

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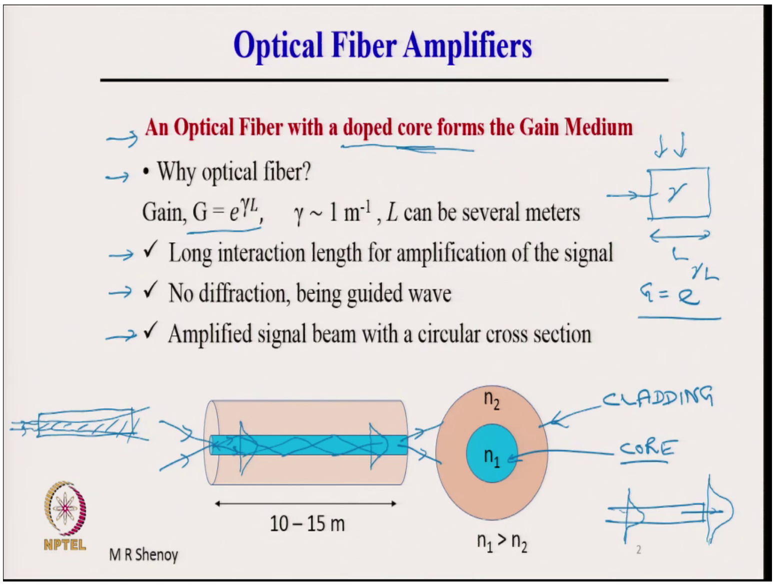

First optical fiber amplifiers; an optical fiber these comprise of an optical fiber with a doped core, core is the central region of a fiber core forms the gain medium. The doped core in an optical fiber forms the gain medium. So, for example, here we have shown the cross-section of an optical fiber for those of you who are not familiar.

This has a circle two concentric cylinders one fused into the other and the inner region of higher refractive induction n 1 is called the core and the outer region is called the cladding. So, this is the core and this region outer region is called the cladding. So, the core is doped with the rare earth ion erbium in the case of erbium doped fibers and we call it as erbium doped fibers.

So, because the core is of higher refractive index those of you who are not aware light which is launched into the optical fiber will propagate by total internal reflection. In its simplest picture light propagates through total internal reflection at the core cladding interface because it is a boundary between high refractive index medium and a lower refractive index medium. And therefore, light propagates in the core through total internal reflection.

It is this core which is doped. So, doped core here refers to this core which is doped with erbium ions in this case. Now, unlike the Nd: YAG amplifier where we had a amplifier rod or a medium why optical fiber. We know that the gain the total gain is given by e to the power of gamma L. If we have a gain medium; so, this is a gain medium which is pumped let us say and there is a signal which is entering this.

So, if this material is of length L and if gamma is the gain coefficient in the medium then the gain G gain is equal to e to the power of gamma into L. G is gain gamma is the gain coefficient that is per unit length. So, gain is given by G is equal to e to the power of gamma L.

Typically gamma may be of the order of 1 meter inverse may be anywhere from 0.1 meter inverse to several meter inverse, then L can be several meters long if we use an optical fiber. And therefore, the term e to the power of gamma L the coefficient the exponent gamma L becomes large and therefore, we can get relatively large gain by using an optical fiber because they provide long interaction length for amplification of the signal.

So, all along the length of the fiber there is gain provided therefore, in materials when the gain is very small we can have long interaction length by using an optical fiber. Second there is no diffraction being a guided wave, what do we mean by this? The light which is propagating through here propagates as a mode or as a guided wave like this with a certain field distribution.

But, this field distribution remains the same all along the length, there is no diffraction. If we were to consider instead for example, the Nd: YAG laser, Nd: YAG laser amplifier then if you launch a beam a signal beam into this then every finite beam will diffract and therefore, there is a finite amount of diffraction which is taking place.

And, this diffraction limits the length of interaction in the amplifying region whereas, in the case of a fiber because light is confined to the core light propagates as a mode of the wave guide. Then we have no diffraction effects and light can get amplified throughout irrespective of the length provided there is sufficient power and that is the second advantage.

And the third is that the amplified signal beam which the signal which is launched here because being of circular cross-section you will get at the output also here a circular a beam of circular cross-section. Many times this is important that if we want to further focus the light or if we want to couple this light into a cylindrically symmetric system, then we would like a perfect circular cross-section.

And, we will also see that if you use a single mode fiber that is a fiber which supports only one type of mode distribution or mode field, then we can have a pure mode coming out of the other end. Here I am referring to the mode as a spatial distribution, the transverse distribution of energy.

So, if it is a single mode fiber then it is characterized by a single field distribution for example, if I were to show it here the in a single mode fiber there is only one field distribution which propagates which looks almost like a Gaussian. And therefore, when it comes out after amplification you will have a nice single Gaussian type of field distribution coming out.

And, this is important in many applications and therefore, fiber amplifiers have also the advantage of giving out beams with circular cross-section. At the input the signal beam may not be perfectly circular, but what you get at the output because it supports cylindrically symmetric field distributions. And therefore, it gives out it gives out a circular cross-section of the beam output beam.

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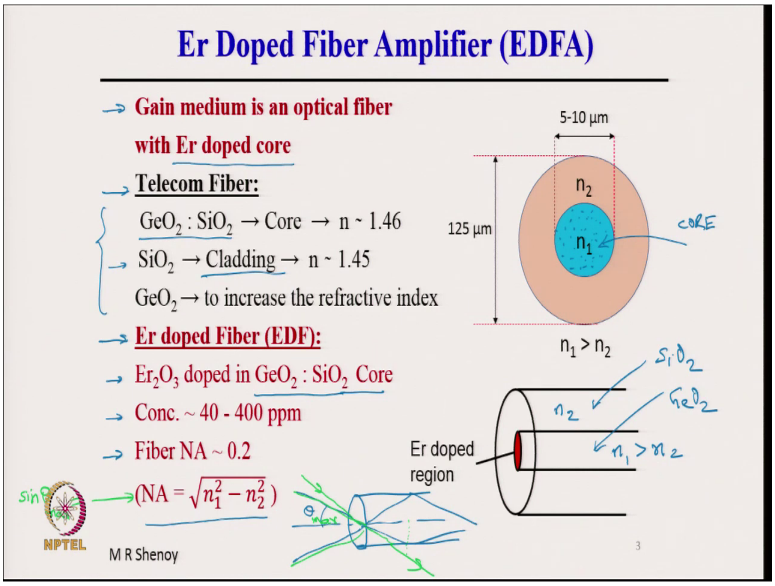

Now, let us come to erbium doped fiber amplifier that is about general fiber amplifiers. Erbium doped fiber amplifiers where the gain medium is an optical fiber with the erbium doped core. So, erbium is a rare earth element, normally in telecom fibers. So, erbium doped core means again we have shown here the cross-section whereas, where this is the core and therefore, this core is doped with erbium.

So, the core I am just showing now as dots here, but they are actually not visible, but just to schematically illustrate the core is doped with erbium ions. Normally, the telecom fibers, fibers used in optical fiber communication have ours germanium oxide doped silica fibers which means, the outer cladding the cladding here is pure silica SiO_2.

Generally, there are some variations here and there, but pure silica is the cladding and the core we dope with germanium oxide GeO_2. That is because by doping germanium oxide the refractive index here becomes larger n_1 becomes greater than n_2. So, n_2 is the cladding which is that of pure silica.

So, when the core is doped with germanium oxide before fabrication at the time of fabrication then we can get the refractive index of the core greater than the refractive index of the cladding. And, therefore, the core is germanium doped silica. Typically, the refractive index is of the order of 1.46 it depends on the wavelength of operation and the cladding is pure silica refractive index about 1.45.

The numbers are shown to indicate that of course, core is of a higher refractive index, but the refractive index difference is very small. There are various reasons for having a small refractive index difference between the core and cladding. We will not go into that aspect of fiber optics. Now, germanium oxide is used to increase the refractive index.

Now, we come to erbium doped fiber EDF. This is the normal telecommunication grade fibers. The erbium doped fibers erbium oxide is doped in the core, the core is already doped with germanium oxide. So, GeO_2, SiO_2 core is further doped with erbium oxide and the concentration typical doping concentrations are about 40 to 400 parts per million.

And, the typical fiber numerical aperture used in erbium doped fibers is of the order of 0.2, numerical aperture is given by this formula here that tells us that what is the angle of the cone, that is acceptable. So, if you take the fiber here, so, let me draw the core only and you are launching light then numerical aperture.

So, if angles up to a maximum theta is accepted; accepted means what? So, if you launch up to this then they will get trapped. If I launch let me just change the color if I launch a ray let us say a ray coming at a higher angle then this will not be undergoing total internal reflection because it will not satisfies the critical angle condition and this will come out.

And therefore, light is accepted only up to a certain maximum angle which is called theta max and therefore, sin theta max. So, sin theta max is called the numerical aperture NA and you can show that it is equal to square root of n 1 square minus n 2 square. These are some of the specifications of the fiber. The important point is the core of a standard telecom fiber can be doped at the time of fabrication not after fabrication. So, before fabrication it the fiber can be doped by erbium ions, alright.

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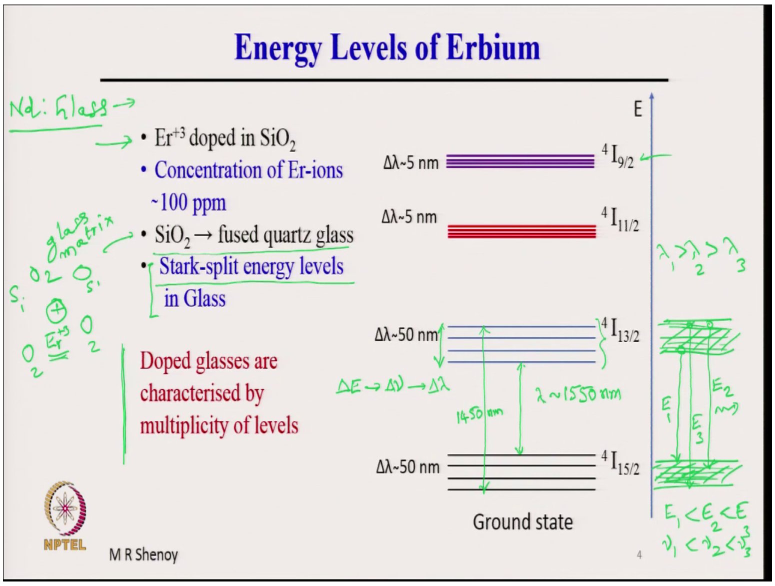

The energy levels of erbium. So, let us very quickly recall I had discussed in detail the energy levels, the nomenclatures in the case of neodymium doped YAG. And here I have directly written the erbium doped silica fibers or EDF where erbium appears as a Er plus 3 ions and these are the energy levels of the Er plus 3. So, as before you can see 4 which is 2 s plus 1 multiplicity of the levels and I is the orbital angular momentum and 9 by 2 in this here represents the j value.

So, the j values are shown here. This is increasing energy and 4 I 15 by 2 is the ground state of erbium. An important difference as compared to that of an Nd: YAG is that because of the doped glasses are characterized by multiplicity of levels. This is because silica is glass; silica SiO 2 is glass it is not a the atoms are not placed periodically perfectly periodically, but it is a glass matrix. So, this forms a glass matrix.

And therefore, when it is doped with erbium the energy levels of the erbium plus 3 ion split. They split these are called Stark split energy levels. The Stark splitting Stark here refers to electric field distribution. For example, if the erbium let us say the erbium Er plus 3 ion is here Er plus 3 ion.

Now, around this there is silica that is silicon SiO 2 and therefore, this is there is Si there is oxygen O 2 and there may be O 2 here, there may be Si here and O 2. So, the oxygen atoms so, I have shown as O 2, but actually it is O. So, the oxygen atoms Si atoms the distribution of these atoms are not uniform throughout the glass matrix.

And, therefore, the electric field experienced electric field because of the vicinity of these atoms the electrons of these atoms result in an electric field an environment of electrostatic field and the erbium ions experience different electrostatic field in different regions.

Because it is not a perfectly periodic crystals silica is glass and that results in what is called as Stark split energy levels. That is the splitting of the energy levels or permitted value of the energy levels are different in different locations locally they are different because of the variance of the electrostatic field.

The surroundings the surrounding electrostatic field of these erbium ions are different and therefore, this results in different allowed values of the energy levels which is called as Stark split energy levels in glass. This is the same this is also true in the case of we discussed Nd: YAG, but if we use Nd: ions in glass Nd: glass lasers and Nd: glass laser amplifiers are also very important.

Now, glass here is again a it is a matrix it is not a periodic positioning of atoms in glass and therefore, these are also characterized by broad Stark split energy levels. So, this explanation I have given because the energy level here is not one, but it comprises of many, many levels. And, typically the it looks like a band with typical width that corresponds to a wavelength chain, a wavelength difference we can write this width in terms of delta E.

Please see that this difference can be written in terms of delta E a spread in energy levels which means delta E is equal to h into delta nu and therefore, we can write it in terms of delta nu. But delta nu is related to delta lambda and therefore, this can also be relate write written in terms of delta lambda.

What it means is the energy difference is such that if for example, if it means delta lambda is 50 nanometer approximately and 50 nanometer here; that means. Let us say this energy difference corresponds to a wavelength of lambda the smallest difference corresponds to a wavelength of let us say 1550 nanometer I am just taking a number 1550 or 1650 nanometer.

Then the maximum here because this is about 50 nanometer wide this is 50 nanometer wide. So, this energy difference will correspond to 1450 nanometer in other words we can have transitions giving out wavelengths from 1450 to 1550. So, please see it is a certain delta E here a range and here it is like a band. So, a certain range of levels there are large number of levels here.

So, atoms which are sitting here may make a transition an atom may make a transition to this level or an atom sitting here may make a transition here or an atom sitting an in another place may make a transition here. What do we have? We have the energy difference if this is E 1, this is E 2 and this is E 3, the photon emitted if the energy of the photons are different then note that E 1 is smaller than E 2 is smaller than E 3 and therefore, h nu 1.

So, h nu 1 is smaller than nu 2 is smaller than nu 3. This means lambda 1 is greater than lambda 2 greater than lambda 3. In other words, the transitions from 4 I 13 by 2 the multiplets here of 4 I 13 by 2 to 4 I 15 by 2 can lead to the emission of a range of wavelengths.

This is the important point and this is very important because this is going to determine the bandwidth of the amplifier. There is amplification possible as I will discuss in more detail amplification possible for wavelengths over a wide range of wavelengths, alright. So, these are the four energy levels or bands which represent the energy of erbium 3 plus ions.

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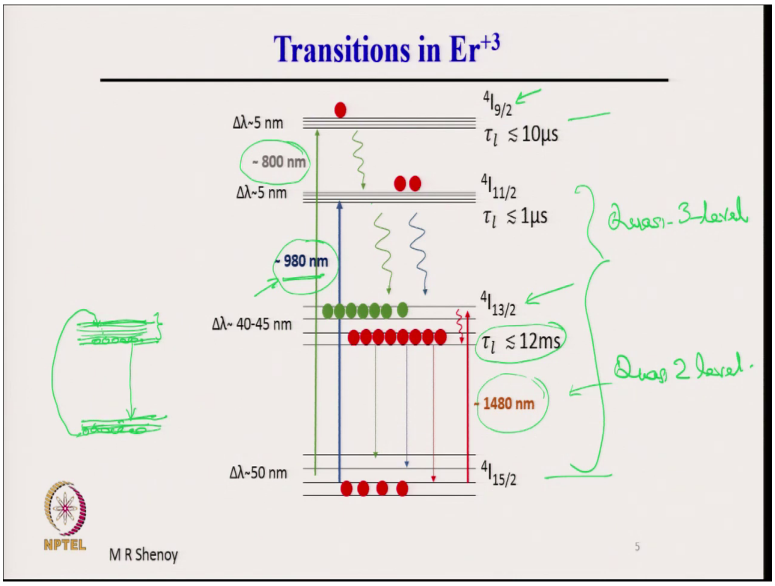

And therefore, the transitions will be like this the energy difference from the ground state 4 I 15 by 2 is the ground state to this level corresponds to a wavelength of about 800 nanometer this is the largest difference. And, this the difference here corresponds to 980 nanometer from ground state to the third level and the difference from here to the second level corresponds to 1480 nanometer. These three wavelengths can be used to excite atoms from the ground state to the upper state.

So, if a pump wavelength of around 800 nanometer is used then the atoms from the ground state will be predominantly excited to the fourth level which is the 4 I 9 by 2 level and this both 4 I 9 by 2 and 4 I 11 by 2 have short life times. And therefore, the atoms rapidly come down to the lower levels and accumulate in 4 I 13 by 2.

This has a long life time 12 millisecond the lifetime of this band or this multiplets 4 I 13 by 2 is very large typically about 10 to 12 milliseconds. And therefore, if we pump from the ground state to 4 I 9 by 2 or 4 I 11 by 2 atoms will accumulate in this multiplet here. And as I already discussed because it comprises of a large number of levels the atomic de-excitation from 4 I 13 by 2 to 4 I 15 by 2 can lead to a emission of a range of wavelengths.

And, therefore, the picture tells us that we can use 980 nanometer as a pump or 1480 nanometer can also be used as a pump to raise atoms from the ground state to the top of the first excited state. So, this if we use 1480 nanometer as a pump then this is called a quasi 3-level pump quasi 2-level pumping. It is a is not 2-level, we have already shown that in a 2-level we cannot achieve population inversion.

But, it is not two-level because this level comprises of large number of levels and therefore, if you can raise atoms to the top of this then the atoms can come down and accumulate here. This within the same level within the same level which is a multiplet and from here we can have population inversion between this level and this level. Atoms from the ground state are excited to the top of the band as shown in the picture here.

So, using a 1480 nanometer pump we can create such population inversion here also this is not a 2-level system I repeat because it comprises of multiplets. But, normally there are various issues and the normal pump used is a 980 nanometer pump, where atoms are excited from the ground state to the 4 I 11 by 2 level, from there the atoms rapidly come down to 4 I 13 by 2 and from population inversion is created between 4 I 13 by 2 to 4 I 15 by 2.

So, here I was writing quasi 2 level, if we use a 1480 nanometer pump, but if we use a 980 nanometer pump then this scheme will be a quasi 3 level. We are using the word quasi because it is not individual single levels all comprise of multiplets and therefore, we call this as a quasi 3 level amplifier. So, we will discuss this the current amplifier the most widely used system is the quasi 3 level amplifier, where 980 nanometer is used as the pump. So, I will discuss this in a little bit more detail.

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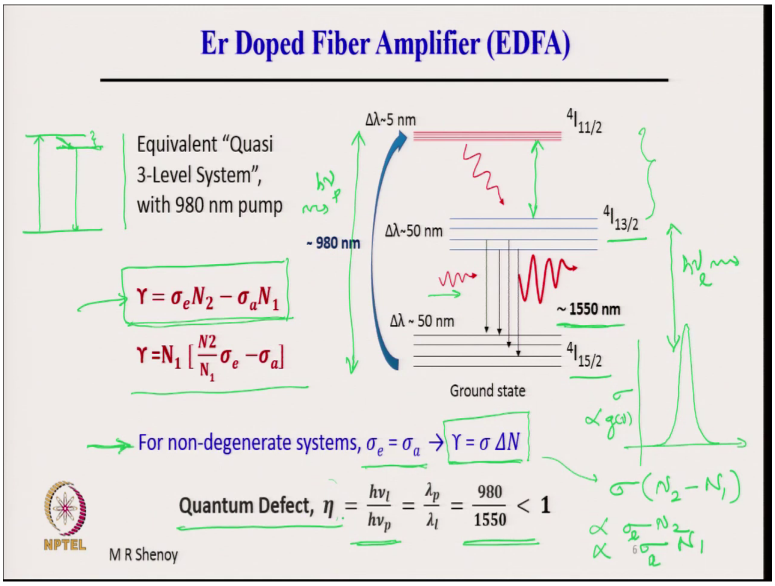

So, erbium doped fiber amplifier as I have discussed in the previous slide equivalent quasi 3 level system with 980 nanometer pump, atoms are excited to 4 I 11 by 2 from there they rapidly come down to 4 I 13 by 2 and a signal population inversion is created between 4 I 13 by 2 and 4 I 15 by 2.

A signal therefore, which is incident on to this amplifier can get amplified by stimulated emission of radiation and this band is around 1550 nanometer, over a range of wavelengths around 1550 nanometer, that is the first point. The second point is for a non-degenerate system when we discussed the theory of laser we considered non-degenerate systems and sigma e was equal to sigma a. This is the emission cross-section was equal to absorption cross section.

We may remember that the emission cross-section and absorption cross-section we call it as sigma we did not have a sigma e and sigma a, we simply had a sigma which was proportional to g of nu. And, therefore, we use the same g of nu or same sigma for both emission and absorption. That is how we got an expression for gain coefficient gamma is equal to sigma into delta N.

But, if the emission and absorption cross-sections are different, then we will have an expression for gain coefficient like this gamma is equal to sigma e into N 2 minus sigma a into N 1. This is very easy to appreciate. Please see that this has come because we had gain coefficient gamma is equal to sigma into N 2 minus N 1, where N 2 minus N 1 was population inversion extent of population inversion.

The emission probability the rate of emission was proportional to sigma into N 2 rate of absorption was proportional to sigma into N 1 and therefore, the net emission was sigma proportional to sigma into N 2 minus N 1. Therefore, we got the expression for the gain coefficient as sigma gamma is equal to sigma into N 2 minus N 1.

Now, the emission probability if we have sigma not equal to sigma a then the emission probability will be sigma e into N 2 absorption probability will be proportional to sigma a into N 1. And therefore, the difference is here gamma is equal to sigma e into N 2 minus sigma a or gamma can be written as N 1 into N 2 by N 1 into sigma e minus sigma a. This is an important difference because sigma e is not equal to sigma a.

A second parameter which is shown here which is characterizing all amplifiers is the quantum defect in all optical amplifiers which where it is defined as the emitted photon energy, the amplified in photon energy and the pump photon energy. It is a ratio of h nu l to nu p which comes out to be lambda p by lambda l because nu is c by lambda. Therefore, we have the quantum defect eta is in this case is 980 divided by 1550 which is less than 1.

This gives an indication what it means is if you supply this much energy for the pump, every photon which excides an atom by absorbing this much energy can at best give a photon of this energy difference. This energy is h nu l and this energy is h nu p. One photon can at best get excite an atom from the ground state to the upper state and atom subsequently would come down and from here it again gets de-excited and a photon is emitted.

Therefore, the absorbed energy there are many other ways the photon energy is lost, but the best possible is an input energy h nu p gives out a photon energy or the output of h nu l. And therefore, this quantum defect is a parameter which is like efficiency input by output, output by input so, h nu l by h nu p which is always less than 1.

The laser amplifiers are designed or lasers are designed such that quantum defect approaches 1 because if the quantum defect is much less than 1, it means the difference in energy which is given out as heat. For example, here in the given example energy is lost here this is the non radiative transition where energy is lost to the lattice as thermal energy.

Now, if we can minimize this difference if we can minimize this energy difference for example, if I add a 3 level system where the second third level is right here then a pump energy is absorbed is this much the signal energy given is this much. So, the difference is only this much. So, the difference lost as heat is very small and therefore, quantum defect here is very close to 1. A higher value of eta or quantum defect this is a parameter which characterizes the efficiency of utilization of the pump, alright.

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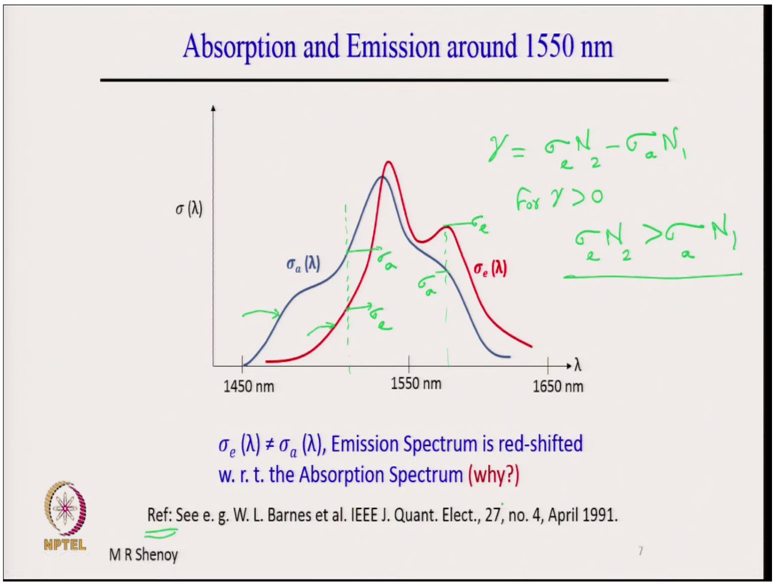

So, this is what is illustrated the actual absorption and emission cross-sections of the erbium ions in silica around 1550 nanometer. So, what is shown is the absorption spectrum. So, this is the emission cross-section of for absorption. So, the cross-section is of course, represents the strength of absorption at a given wavelength.

Similarly, the emission cross-section which is here represents the strength of emission because it is proportional to g of nu at for strength of emission here is given by the emission cross-section. The point to note is that sigma a at any given wavelength except where it intercepts here. So, any given wavelength for example, if we take a wavelength here this is the value of sigma e and this is the value of sigma a.

Therefore, it is important the expression which is written for gain coefficient gamma is equal to sigma e into N 2 minus sigma a into N 1. Therefore, it is not sufficient to have N 2 greater than N 1 what we need is for gain. For gamma to be greater than 0, we must have sigma e into N 2 greater than sigma a into N 1. N 2 greater than N 1 is not sufficient, sigma is not the condition.

In such cases, such non-degenerate systems where sigma e is different from sigma a the condition for amplification is sigma e into N 2; N 2 is the atomic population in the excited state to minus sigma a into N 1 greater than 0. And, therefore, we can see here this is sigma e and sigma a; here sigma a is greater than sigma e.

But, if you come here for example, sigma e is greater than sigma a here sigma e is less than sigma a at this wavelength at this wavelength sigma e is greater than sigma a. And, therefore, it is this condition which will tell us what is the gain, the what is the range of wavelengths where we can have gain. So, for example, you can see in this reference for the actual curves corresponding to erbium fibers.

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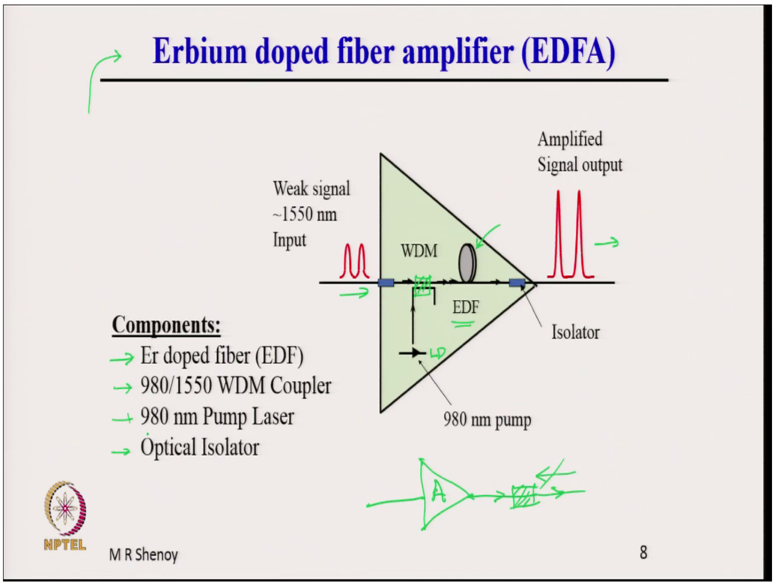

Now, I come to the erbium doped fiber amplifier a little bit about the amplifier system itself. So, the amplifier here is a schematic of the erbium doped fiber amplifier. So, what is shown is input signal weak input signal around 1550 nanometer. Why around 1550 nanometer?

For erbium doped fiber amplifiers we will get gain around this region we can see that emission and absorption are predominantly between 1450 to 1650. In this region only it is possible to get amplification for because that is the laser transition and emission over a range of wavelengths.

And, therefore, if we consider a weak signal as a input the signal can come out amplified at the output. So, what are the components involve? The component there is a erbium doped fiber shown here; there is a WDM coupler, I will discuss what is this. This is a combiner basically, there is a pump laser diode, a laser diode here at 980 nanometer which provides the pump radiation or the pump energy. This is the signal input and this is the output.

So, the components are erbium doped fiber, I have already shown which is written as EDF 980 1550 nanometer WDM coupler that is to combine the pump and the signal I will discuss in the next slide and the pump 980 nanometer laser had an optical isolator this is like an optical diode.

So, there are optical isolators here which prevent light coming back into the amplifier. If you have an amplifier here which is giving a certain output in this direction, then the isolator if you put an isolator it is like an optical diode. So, we will not go into the details of how it functions, but this is the diode which permits light to go in this direction, but does not permit light to come back.

The light which is coming back the light could be coming back because of reflections and scattering at various interfaces and those back reflected light can again go back to the amplifier and take away the energy of the amplifier. And, therefore, we stop to stop back reflections there are optical isolators which are used. So, these are the most important main components of an erbium doped fiber amplifier. Let me discuss the components one by one.

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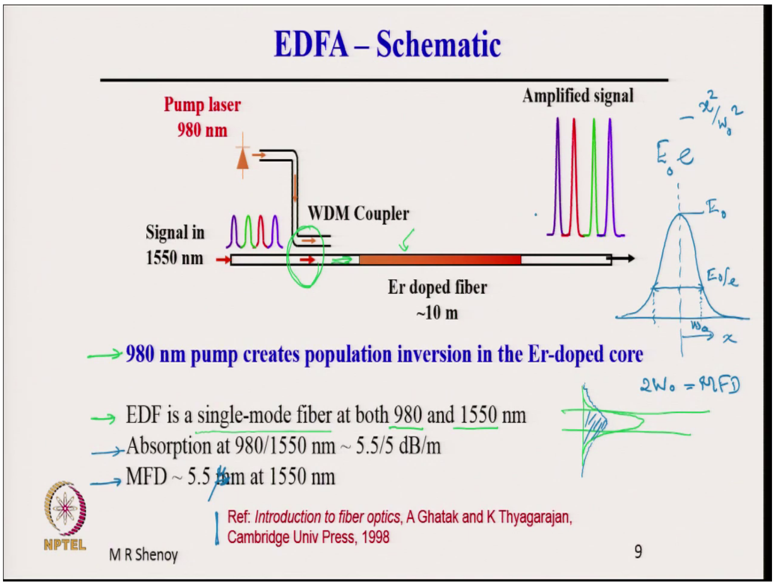

So, the schematic is represented here. So, you have a pump laser and this is again the coupler is here the WDM coupler which. So, the weak signal and the pump both are combined into one fiber which enters the erbium doped fiber. This red portion here is the erbium doped fiber may be typically 10 meters in length.

So, the pump energy is utilized in creating population inversion along the fiber and the signal which is coming along gets amplified and the signal comes out here. So, this is the basic schematic of the EDFA. The 980 nanometer pump creates population inversion in the erbium doped fiber and the erbium doped fiber which is used is generally a single mode fiber, means it supports a single transverse field distribution at both lambda equal to 980 nanometer and 1550 nanometer.

So that, if it is a single field distribution for example, the fundamental mode at 980 nanometer would look like this like a bell shaped curve and the mode at let me take a different color the mode at 1550 nanometer would be more spread of course, and therefore, it would look something like this.

But, you can see that the mode profiles overlap very significantly because overlap of the interacting fields is very important for strong interactions. And, that is why if both of them are single mode that is fundamental modes both of them are bell shaped one over the other then we get very good interaction. That is why the EDF used is single mode at both wavelengths.

The typical absorption is, absorption is given by about 5 or 5.5 dB per meter at this wavelength and the mode field diameter. For those of you are not familiar, the mode field diameter represents the extent of the field. So, this is a typical way of defining mode field diameter if you have a Gaussian field distribution; so, this is Gaussian field distribution in the transverse direction.

Then where the field drops down to 1 by E of its maximum if this value is E 0, then where it drops down to E 0 by e, if we take a Gaussian which is defined as e to the power of minus this is x. So, minus x square by W 0 square, then when x is equal to W 0 this exponent becomes e power minus 1 which is 1 by e that is why the amplitude.

So, if you have the an amplitude a Gaussian represented like this E 0 into e power minus x square by W 0 square, then at x is equal to W 0 the amplitude drops down to 1 by e. So, this value here so, this axis is x. So, this is W 0 is called the spot size. So, those for those of you are not familiar W 0 is called the spot size and 2 W 0 that is called the mode field diameter 2W 0 is the mode field diameter.

So, this diameter represents typically the extent of the field the size of this field distribution and that number MFD is typically about 5.5 micrometer. This is not millimeter; so, 5.5 micrometer at 1550 nanometer, typical numbers of the single mode fiber which is used. There is a reference which is given here. So, you can refer to Introduction to fiber optics by Ghatak and Thyagrajan for more details on the EDFA.

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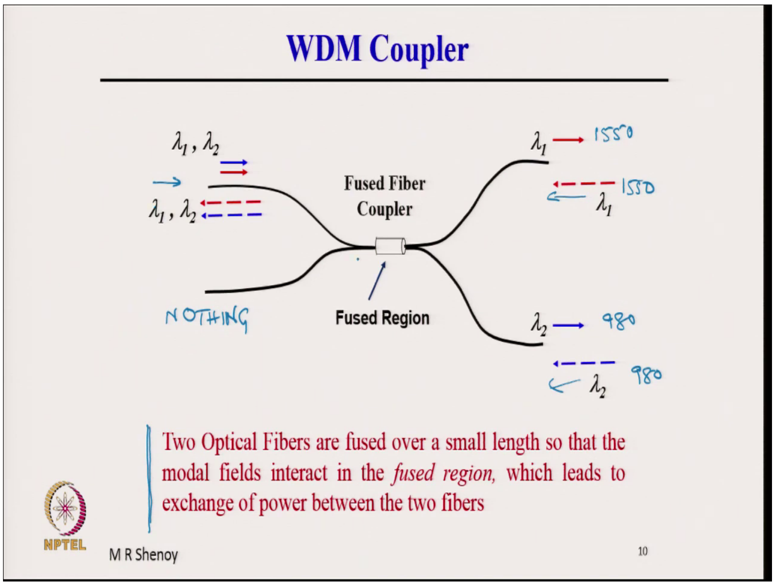

The coupler is this, the WDM; WDM means wavelength division multiplexed coupler or multiplexing coupler which means if you have one wavelength launched here another wavelength launched if the. So, this comprises of two optical fibers, the coupler comprises of two optical fibers single mode optical fibers which are fused over a small length.

So, this is the region where it is fused. This is the two fibers, they are glass fibers they are fused by a high temperature flame or a electric arc fusion technique. So, they are fused over a small length, so that mode fields interact in the fused region. This leads to exchange of power between the two fibers between the fibers.

The wavelength which is travelling here wavelength which is travelling here, they can exchange power in this region, so that the design is such that all of them both the wavelengths combine here and ideally there is 0, here nothing. So, nothing here, just writing nothing, but in practice a small fraction would also come there, but all of them would go in this direction.

On the other hand, if you input from this place both 980 and 1550 at the output they will separate out. So, this will become this will be 1550 and this will be 980. If you put 980 input and 1550 input then both of them will come here. So, it is a combiner or a splitter that is why it is called a WDM coupler.

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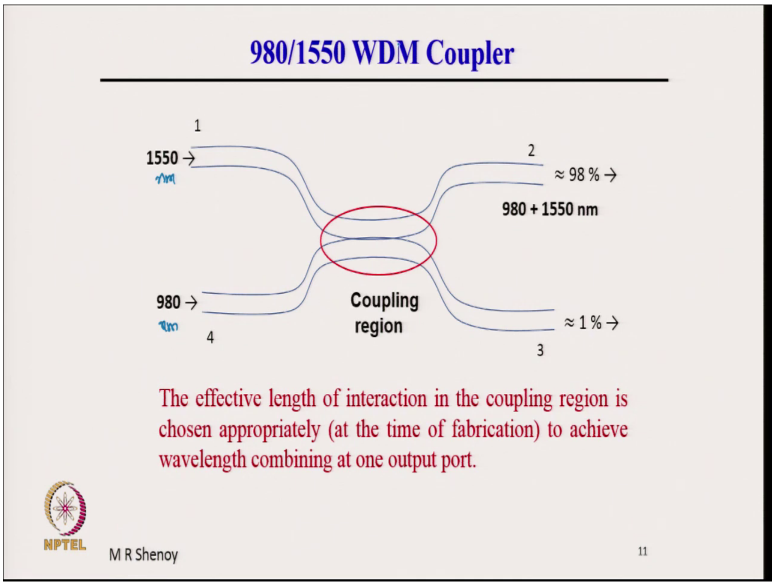

So, you can see the diagram more carefully if you put 980 from here this an optical fiber component a very compact component. So, if we put 1550 nanometer wavelength here that is the signal and the pump wavelength 980 nanometer here, then they will combine at one of the ports. A very small fraction may appear at the other ports. Ideally we would have liked a 100 percent all of them to come here, but in general there may be a small fraction which is coming there.

So, this is the WDM coupler. This is the coupler which is used to combine the signal and the. So, that is what is shown here. So, the pump for exciting the erbium atoms and creating population inversion in the fiber and signal which will draw energy from the population inversion and build up to have an amplified output, that is the erbium doped fiber amplifier.

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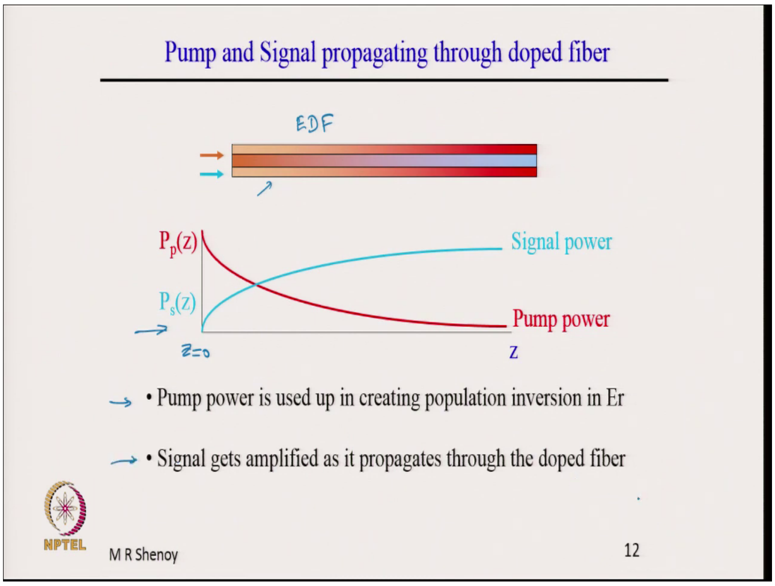

Now, the evolution of the pump and signal are schematically shown here. So, this is the optical fiber. Both pump and signal are input at this end, this is the doped fiber EDF. So, this is the EDF erbium doped fiber. The pump as you see the red color continuously reduces because the pump got absorbed in creating the population inversion.

The blue color the signal goes on building up and therefore, it is also shown qualitatively here this is the input end here that is Z equal to 0 and this is the output end with Z. The pump power continuously decreases as it propagates along the length because the pump is getting absorbed 980 nanometer radiation is absorbed in creating the population inversion or exciting the atoms to upper state.

The 1550 signal is building up by drawing energy from the population inversion. So, that is what is written here pump power is used up in creating population inversion and signal gets amplified as it propagates through the doped fiber.

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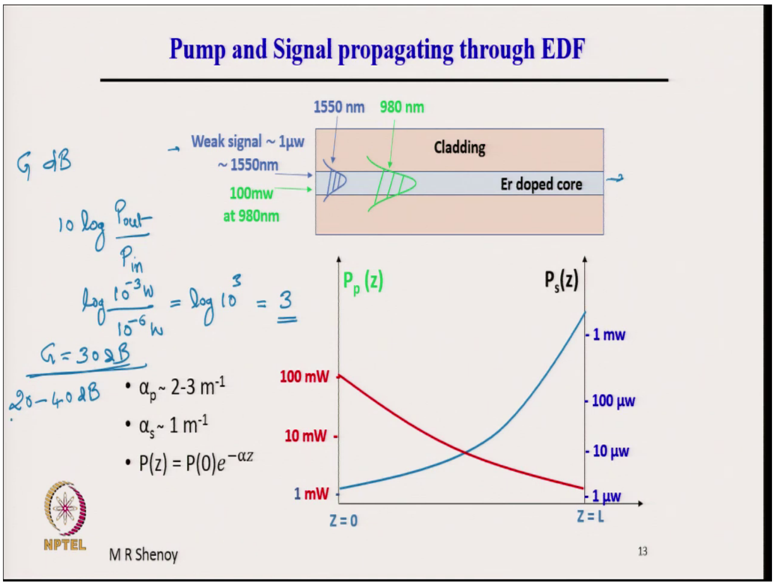

Now, it is again illustrated here with some more numbers as you can see the 1550 field here shown with small amplitude because it is a weak signal. Because the purpose of the amplifier is to amplify input weak signals to get sufficiently strong signals at the output. And, if we have put some numbers to give a better feel 100 milli watt pump at 980 nanometer is input from here and 1 microwatt a weak signal at 1 microwatt power is entering in this same port.

Now, at the output here what would be the power? So, you can see that the pump power continuously drops down because it is utilized in exciting the atoms and the signal power builds up exponentially like e to the power of gamma z as the signal propagates along the fiber please note that the numbers are different. So, this is 100 milli watt and it drops down as it propagates through the fiber. And the blue scale here corresponds to the signal input is 1 microwatt and it is exponentially building up into 1 milli watt.

So, 1 microwatt to 1 milli watt a factor of 1000 amplification by a factor of 1000 that is typical numbers typically the amplification factor is about 30 to 40 dB. So, I hope you are some of you may not be familiar dB is defined so, gain or loss in dB. So, gain G in dB is defined as 10 log P out by P in, P out by P in.

So, in this example if the input is 1 microwatt, so, this is log of 1 microwatt that is 10 to the power of minus 6 watt and the output is 1 milli watt let us say 1 milli watt 10 power minus 3 watt. So, this is equal to log of 10 to the power of 3 which is to the base 10 this is log and therefore, this is simply equal to 3 and therefore, 3 into 10 is 30. Therefore, G is equal to 30 dB.

So, the typical numbers of gain that we obtain in erbium doped fiber amplifiers is anywhere from 20 to 40 dB. So, 30 dB means a factor of 1000, 20 dB means a factor of 100 and 40 dB means a factor of 10000 for the gain.

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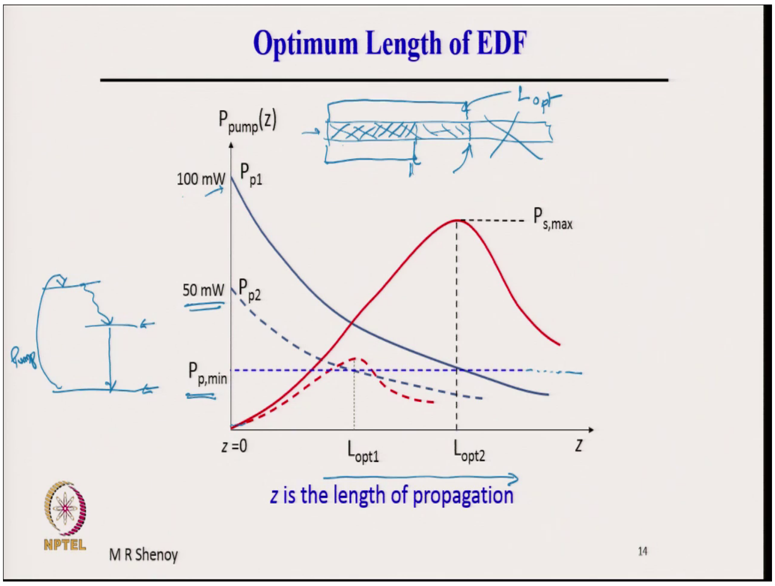

There is one important concept in this amplifier is the optimum length of EDF what is this. So, what is shown is the in this direction we have the length of propagation. Let us consider the input power as 50 milli watt at the input at Z is equal to 0. As I already explained the pump exponentially drops down because it continuously increases it continuously is absorbed and the signal from a small value here continuously gets exponentially building up.

Now, there is a certain minimum value of the pump power for the amplifier to provide net amplification. When the pump power drops down below the minimum required for amplification for creating population inversion. Please see that to create a population inversion it is a quasi 3 level system pump raises atoms here, from here it comes down and here is the population inversion created.

So, please note that the pump raises atoms to the third level from there it comes down and from here is the population inversion created between these two levels. To create there is a certain minimum pump power is required. So, that I have indicated by this blue dotted line here. When the pump power drops down this is along the length of the fiber; so, the fiber length is here. This is the length of the fiber, light is input. So, pump is continuously drop.

Let us say when it reaches some point here L the pump power drops down below the minimum amount required to create population inversion. And then there is no more population inversion is possible which means the signal there is no amplification and you see that the signal will start decreasing because there is no amplification and the signal will start getting absorbed in the fiber.

Amplification is possible only up to that length where pump is more than p minimum beyond that it is absorbing and therefore, the signal power goes down like this. If I had a higher pump power then the minimum up to which I can maintain could come up to a longer length and therefore, I will have amplification up to this length and after that it will been absorbed.

Therefore, the power will build up the signal power will buildup up to that length where the pump is above the minimum power required and what does this mean? This means that depending on the pump power you must choose an optimum length of the fiber. Because if I had chosen 100 milli watt I would get amplification up to this point that is up to this L and beyond that it will be absorbed and therefore, I do not want this portion of the fiber.

And, I will use only a fiber of this length and that length is called optimum length or L optimum and note that the L optimum will depend on the pump power if I had used 50 milli watt. I could have gone up to a certain length here where amplification is possible if I had used my input power as 100 milli watt, then the optimum length will be higher.

Now, therefore, if we choose if we want to get the maximum signal output power, then the length of the fiber must be chosen as the optimum length. So, this is the concept of optimum length. So, when an amplifier is designed it is designed for a certain pump power. So, for a certain pump power there is an optimum length of the EDF to be chosen, so that you get maximum output power.

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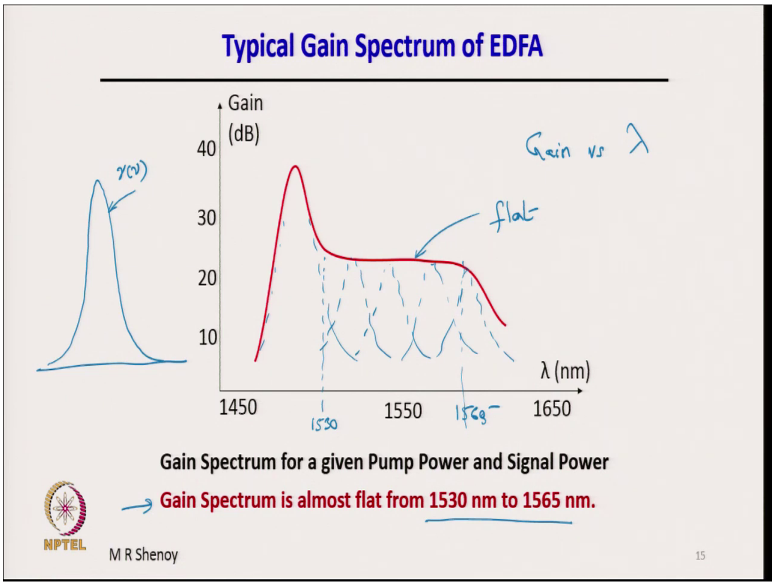

So, the typical gain spectrum of the EDFA is shown here. So, gain spectrum means, spectral dependence of gain that is gain versus wavelength. So, gain versus here lambda. So, that is what is plotted here gain versus wavelength. You see the gain is shown in dB. So, that means, typically 30 to 40 dB gain which is shown here.

The gain as you see is not flat unlike Nd: YAG laser where you in the Nd: YAG laser amplifier you had a nice gain spectrum where gain is the gain coefficient is gamma of nu is characterized by a homogeneously broadened Lorentzian. In this case, we see that the gain varies like this. It has a certain flat region and it is not one Lorentzian, it comprises of actually this can be modeled by considering several Lorentzians.

So, one Lorentzian here and then one here, one here. The point is because of the multiplets or multiplicity of the levels involved in amplification, the amplification band is spread over a range of wavelengths and the dynamics is such that the gain profile has a relatively flat region.

So, this is a relatively flat gain region over a range of wavelengths typically over a range of approximately from 1530 or about from 1530 to 1565 or 1570, 1560 you have a flat gain profile. This is how it is written 65 1565, you have a relatively flat gain profile. This is very important in wavelength division multiplexed optical fiber communication systems. I will discuss this if time permits towards the end of this course as an important application.

But, right now the point to notice that the gain profile need not be Gaussian or Lorentzian always because it depends on the atomic energy levels. And in this case erbium doped fiber amplifiers, the erbium levels in silica comprise of multiplets multiplicity of levels and that leads to a broader gain spectrum.

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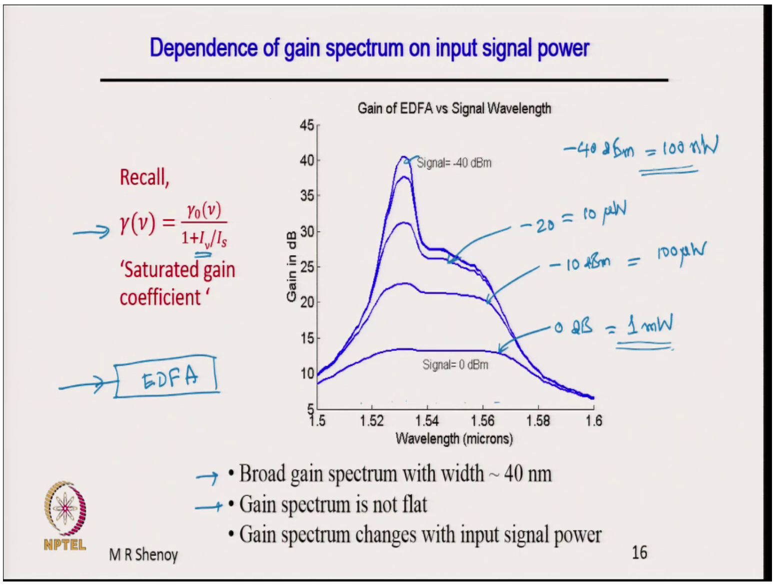

Here what is shown is the dependence of gain spectrum on the input signal power. So, what is shown first let me indicate what is shown. So, these are different curves for different signal powers so, different values of signal powers. So, this is the first one is shown here for minus 40 dBm minus 40 d minus 30 dBm is 1 microwatt.

So, this is minus 40 dBm. So, minus 40 dBm is equal to 100 nano watt as the input this is for minus 30, minus 20 and this is minus 10 and this is 0 dBm. So, for those of who are not familiar 0 dBm means 1 milli watt. So, these are the input power levels. So, the here is the EDFA.

So, this is the EDFA and there is the input power is what is shown here. So, a range of wavelength so, this is minus 10 dB dBm which is equal to 100 microwatt as the input power, this is 10 microwatt as the input power minus 20 dBm and 30 dBm is 1 microwatt and 40 dBm is 0.1 microwatt of input power.

The important point shown in this graph is that the gain profile depends on the level of the input power that is because we know that the gain coefficient depends on the intensity of the signal. If the intensity of the signal is signal level is higher, then the gain will be lower. So, the gain at various wavelengths is lower for input power of 1 milli watt as compared to the gain when the input power is very small. So, this is the dependence of the gain spectrum on input signal power

So, the gain of an amplifier depends on the level of the input signal power. This is because of gain saturation in the amplifier. So, what we have is a broad gain spectrum, but the gain spectrum is not flat and the spectrum changes the gain profile changes with the input signal power.

So, this is very important in the design of the amplifier that when an amplifier is designed, if it is designed to have a certain gain that gain is for a certain level of input power. If the input power ranges are very different then the amplifier will not be able to give that much gain because the gain saturation brings down the gain when the intensity of the input becomes higher.

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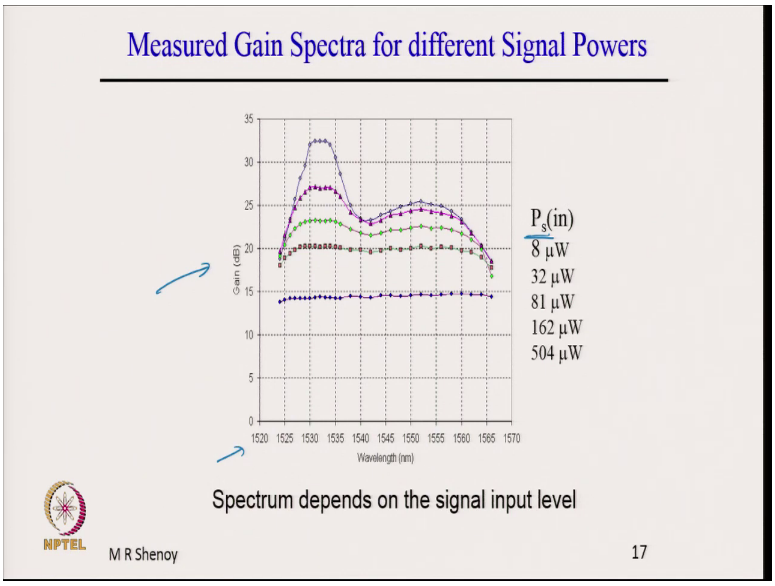

So, this is actually a measured spectrum in our laboratory. So, what is measured is wavelength verses gain as you can see different levels of input power. This is P s is the signal input power 8 microwatt 32 micro, as the signal power increases you note that the gain profile decreases.

So, the previous one here is theoretically calculated gain profile for different levels of signal input and this is actually measured in our laboratory that wavelength versus gain. And we can see that the numbers are similar to the numbers gain as I mentioned about 20 to 30 dB or 40 dB for an amplifier.

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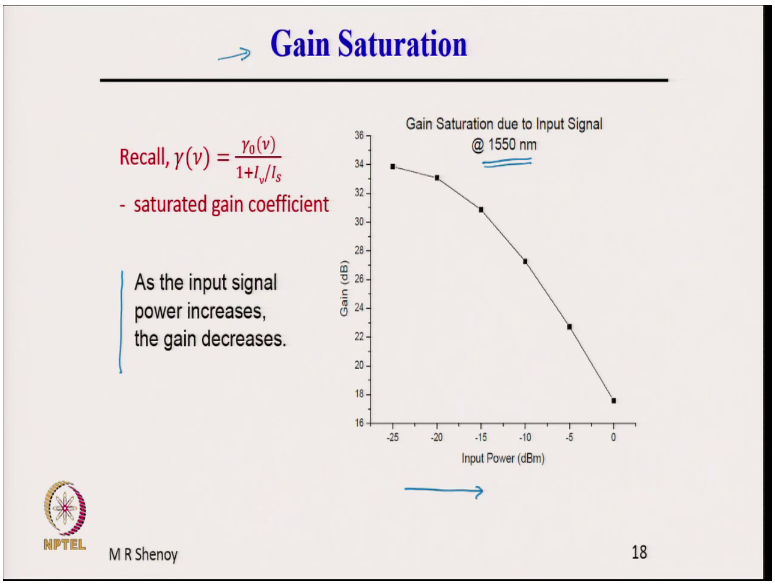

So, the gain saturation what is shown here is the input signal power at a particular wavelength. This is at the wavelength 1550 nanometer what is shown in the previous slide is at different wavelengths, the gain is measured for different input powers. Input power is varied at a given wavelength the power is changed and the gain is measured for different input powers and this is plotted for different wavelengths this is carried out for different wavelengths.

Whereas, here what is shown is at the wavelength of lambda is equal to 1550 nanometer as the input power increases we note that the gain drops this is the measured value. So, these points correspond to the measured gain spectrum as expected theoretically, as the input power increases the gain decreases. This is called gain saturation.

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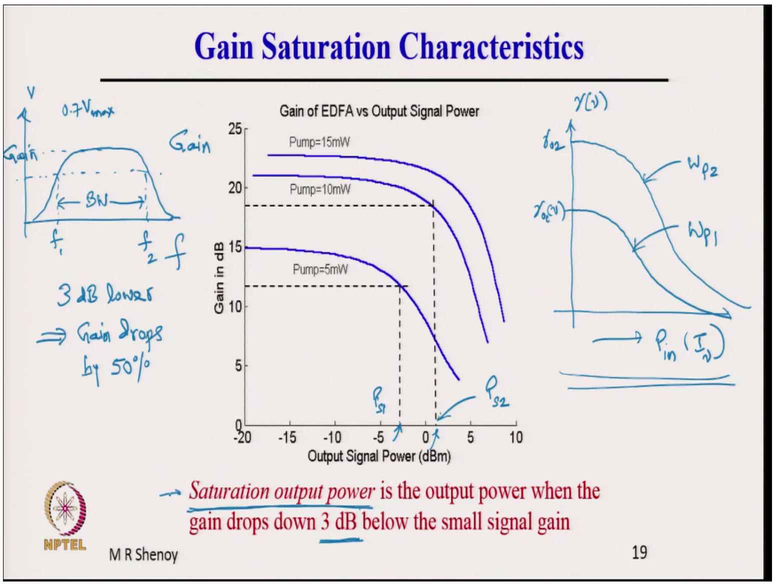

The gain saturation characteristics of an amplifier typically the gain saturation characteristics are shown here for three different values of pump power. As I mentioned if you change the pump power even at the beginning when we discussed about the gain coefficient you may remember that we had a saturation saturated gain varying like this.

So, this is gamma 0 of nu at a given wavelength and then if you this is for a certain pumping power W p 1, then if I increase the pumping power then the gain would have gain coefficient. So, what is plotted is gamma of nu for so, this is gamma 0 1, this is gamma 0 2 for W p 2. So, this is gain coefficient, but what is plotted here is gain that is e to the power gamma l. So, the gain which is plotted we can see that initially for small input powers. So, here we have this is the input power P in.

So, P in versus gain coefficient P in or I nu, the intensity of input power or intensity at that frequency that is what we had plotted I nu versus gamma of nu. This is what we had plotted. So, it is the same thing here. Now, this is for one particular nu that is one particular wavelength, as the input power increases the total gain drops down. An important parameter which characterizes the amplifier is called the saturation output power.

So, the saturation output power is defined as the power where the gain drops by 3 dB; 3 dB because gain becomes half 3 dB below the small signal this gain is in decibels. So, 3 dB lower means 3 dB lower implies gain drops by 50 percent. This is for those people who are not familiar with the decibel scale. So, gain drops by 50 percent where the gain drops.

Those of you are familiar in electronics we have the standard amplifier gain versus frequency. So, gain versus frequency and we calculate the bandwidth, bandwidth at frequencies f 1 here and f 2. So, gain bandwidth in the calculation of f 2 minus f 1 is called the bandwidth of the amplifier. So, this is the bandwidth.

Now, what is f 1 and f 2? This is the cut off frequency lower cut off frequency and upper cut off frequency where gain drops by 3 dB or if you had plotted in terms of voltage then the voltage here output drops to 0.7 that is 1 by root 2 times. So, 0.7 times approximately 0.7 times V max. This corresponds to half the gain. It is the same thing here 3 dB where the gain drops by 3 dB, the corresponding output power is called the saturation output power.

So, note that as the pump power increases the saturation output power also increases. So, what is shown is this is P s 1 corresponding to 5 milli watt pump power; this is P s 2 saturated output power corresponding to 10 milli watt of pump power. All consistent this was the mathematics which we had done where gain versus input intensity was shown.

This is the actual input signal power as it increases corresponding output signal power will also increase. And, initially the gain would remain constant and as the intensity increases the gain drops rapidly and this power is called saturation output power.

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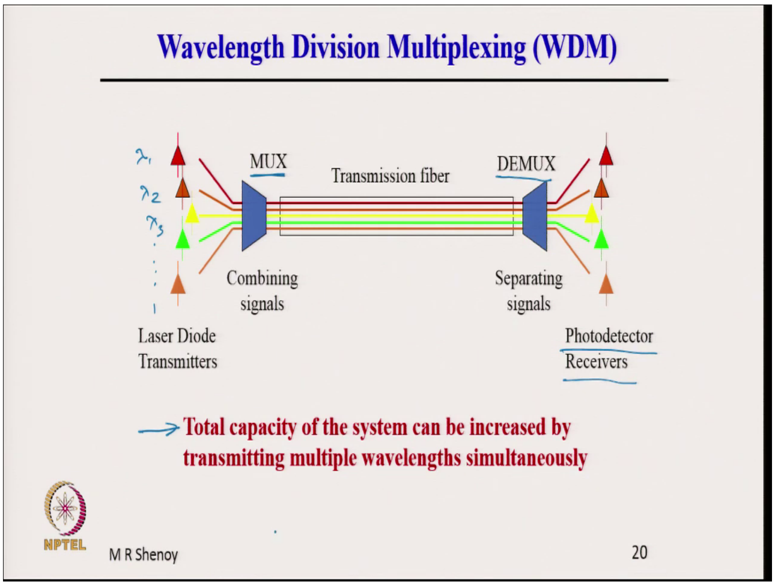

Finally, a very important application of the erbium doped fiber amplifier is in wavelength division multiplexed systems for optical fiber communication. An application which I would probably discuss towards the end of the course, but the point I wanted to show is the following.

In an wavelength division multiplexed system in the transmission fiber there are number of wavelengths. So, these are different wavelengths lambda 1, lambda 2, lambda 3 different wavelengths are input at the input end; MUX is a multiplexer which combines all the wavelengths here, so, different signals, so, different carrier wavelengths are combined into one single transmission fiber. This is one fiber.

And, at the output it is demultiplexed using a DEMUX the wavelengths are separated out and detected by using photo detectors such a system would lead to a higher total capacity of the system. The transmission capacity or the information carrying capacity of the fiber would be increased by using multiple wavelengths simultaneously through the fiber.

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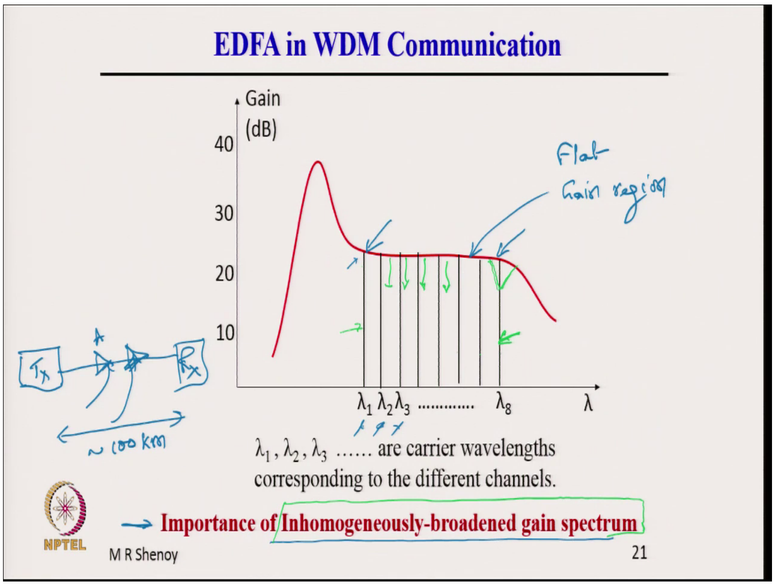

And, erbium doped fiber amplifier has this flat region, where the gain is flat. So, this is the flat gain region, flat gain region and if you include the amplifier with these wavelengths these are the multiple wavelengths, then all the wavelengths can be amplified simultaneously.

In a WDM communication system wavelength division multiplexed communication system, whenever you have a communication system you have a transmitter here then there is a receiver at the receiving end. In between there would be amplifiers required booster amplifiers. So, amplifiers would be required in between.

Depending on the length of the link if you have the transmitter transmitting to for example, this is an intercity link of several hundred kilometers then you need intermediate amplifiers to boost the signal. And, an erbium doped fiber amplifier can amplify simultaneously all the wavelengths or large number of wavelengths in the same fiber.

And, the here a very important aspect of inhomogeneously broadened gain medium would come. In a inhomogeneously broadened amplifier or gain medium, the gain at one part of the gain spectrum is not affected by the gain at other part. Because the gain profile at one wavelength is contributed by a different set of atoms as compared to the wave at a different wavelength.

Therefore, if there is some power variation, if there is some power variation here it is it does not affect the gain of another wavelength which is at a different value. In other words, any gain fluctuations or signal power fluctuations. For example, a power variation, we know that when the input power changes then the gain will be pulled up or down because of the saturation affect.

If the power varies for this channel let us say and due to which the gain drops down here then the gain at the other wavelength is not affected if the medium is characterized by inhomogeneously broadened gain spectrum. If this spectrum was homogeneously broadened characterized by homogeneously broadened gain, then a gain drop here would pull down the entire gain spectrum if this was homogeneously broadened.

This is not the case if it is inhomogeneously broadened. This is a very important implication of inhomogeneously broadened gain medium. So, I thought I will mention this at this point and here we will stop about the erbium doped fiber amplifier and as I mentioned we may discuss this more towards the end of the course.

Thank you.