**Introduction to LASER**
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**Lecture - 36**
**Lasers and Laser Amplifiers in Optical Fiber Communication**

Welcome to this MOOC on LASERS. We are in the last part of the course and in the last couple of lectures, I discussed about some laser systems and in this lecture and in the next lecture also, we will discuss some applications – laser applications. And, today we will discuss one of the important applications that is Lasers in Optical Fiber Communication.

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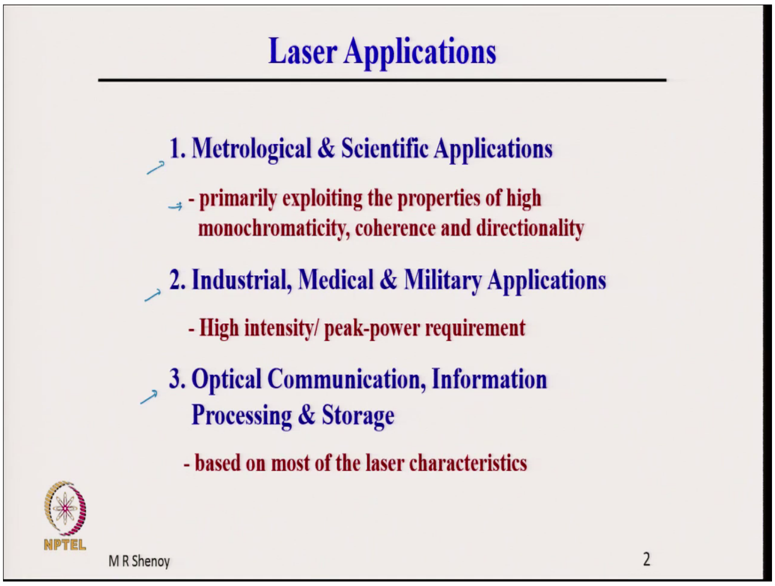


Laser applications are broadly classified into three categories. I have classified them here into three categories – metrological and scientific applications; industrial, medical and military applications and optical communication, information processing data storage these applications.

In the 1st applications mainly metrological and scientific applications, primarily it exploits the properties of high monochromaticity, coherence and directionality of the laser beams. In the 2nd application it primarily exploits the high intensity, peak-powers possible by using lasers because in industrial applications such as cutting, welding. And similarly in medical applications such as surgery and in military applications such as target identification and destruction. So, you need very high intensity or peak powers. In the last application optical communication, information processing and storage several of the important properties of lasers are exploited.

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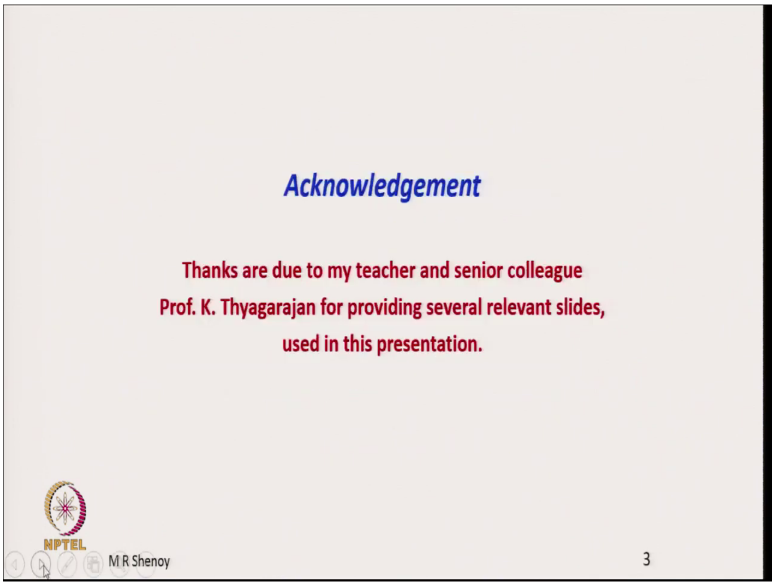

So, before I proceed with the optical communication is an acknowledgement. Thanks are due to my teacher and senior colleague Professor K. Thyagarajan for providing several relevant slides, used in this presentation. We worked together for more than 30 years and some of the joint works which we did are in this area.

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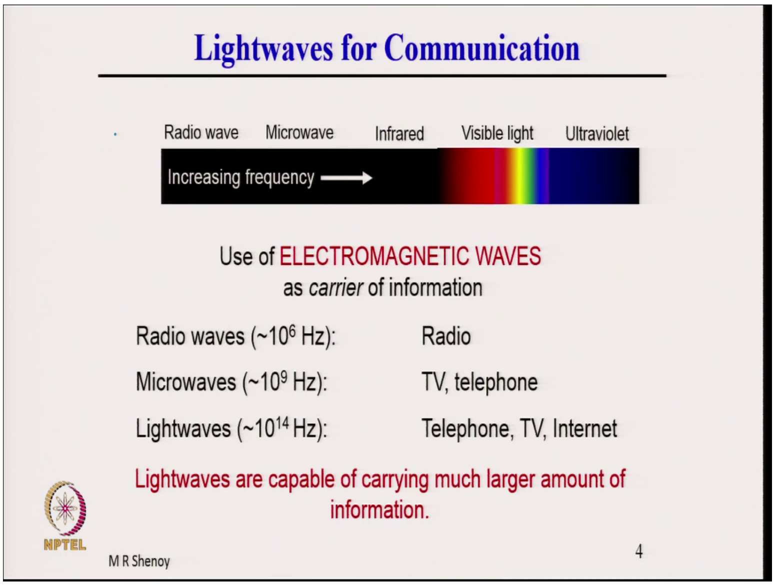


Light waves for communication: all are electromagnetic wave spectrum – radio waves, microwaves, infrared, visible light, ultraviolet. So, use of electromagnetic waves as carrier of information for communication: so, radio waves typically the frequencies in the range of 100s of kilohertz to several 10s of megahertz, so, of the order of 10 to the power of 6 hertz.

Microwaves which use frequencies in the range of gigahertz used for TV and telephone transmissions and light waves – light waves have frequencies in the range of 10 power 14 to

15 hertz again used for telephone, TV and most importantly for data communication and internet applications.

Light waves are capable of carrying much larger amount of information as compared to the other two. Primarily because as you can see the carrier frequency is much larger in the case of light waves as compared to radio waves and microwaves. And, the communication bandwidth usually depends on the carrier frequency; larger the carrier frequency larger is the bandwidth that is the information carrying capacity of the channel.

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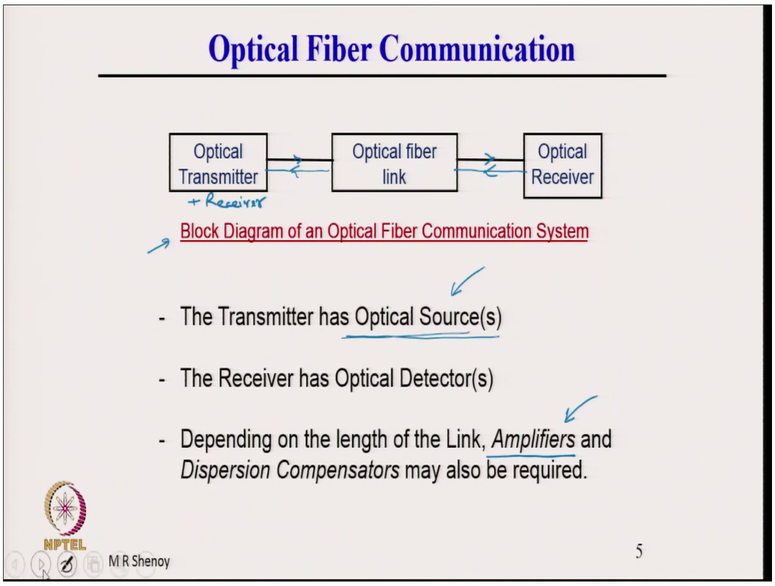


Optical fiber communication what is shown is basically a simple block diagram of an optical fiber communication system. It has an optical transmitter. So, this is one way shown, then there is the optical fiber link and the optical receiver. In a real system of course, it is a two way link. So, it is light going back and coming back; forward and backward.

The transmitter actually has transceiver it has a transmitter plus receiver. So, in a real system there is a transmitter and receiver. So, it is also called transceivers. So, that there is two way communication. Broadcast is one way, but communication is always two way.

So, block diagram of an optical fiber communication in simple terms can be shown like this. The transmitter has optical sources and the receiver has an optical detector and depending on the length of the link, there can be amplifiers there will be amplifiers and dispersion compensators.

We will discuss primarily the optical sources because in this course we are interested in lasers and these sources used in optical fiber communication are lasers and the amplifiers which are used here are also laser amplifiers. Therefore, these are the two focus areas for us in this talk.

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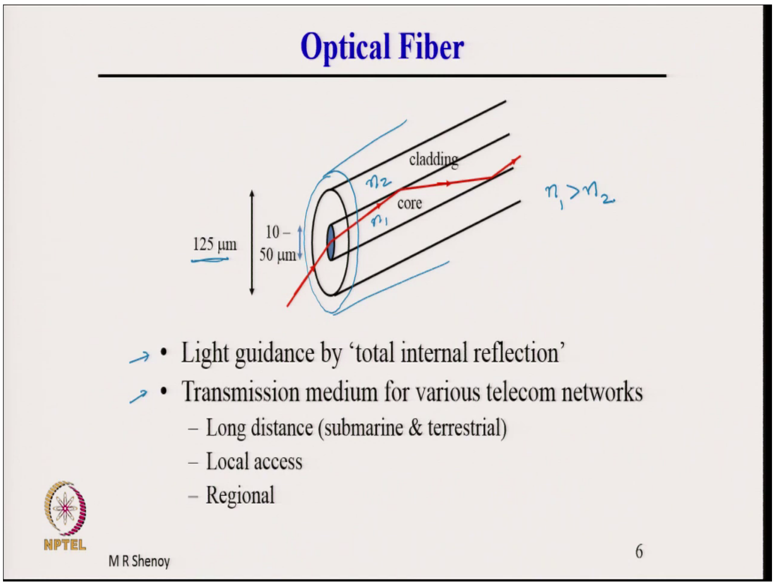

So, let us start with optical fiber: optical fiber first and then optical communication and then we will see the role played by the lasers in optical communication system. So, light guidance in an optical fiber is by total internal reflection in simple terms and it is used fiber forms the transmission medium for various telecom networks for long distance, submarine, terrestrial, local access networks, regional networks and so on.

So, what is shown is a cross-section of an optical fiber here. Typically, the core diameter may be around 10 to 50 micrometer depending on whether it is a single mode fiber or a multimode fiber. And, the total diameter of the fiber is 125 micrometer for standard telecom fibres.

And beyond this, of course, there is a plastic jacket which will be there beyond this outside this there will be a plastic jacket for protection. So, light propagates by total internal reflection. This is refractive index n 1, this refractive index n 2; then n 1 is greater than n 2, so that there is total internal reflection, alright.

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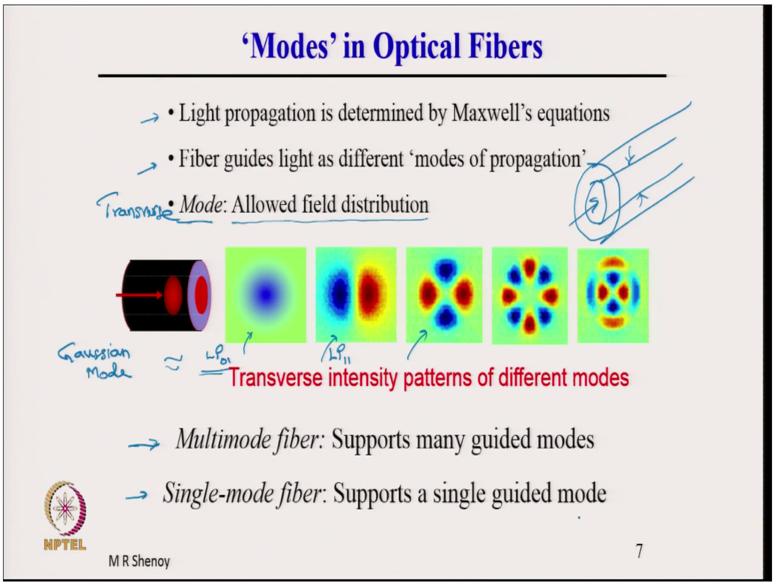


So, what is shown are the modes in optical fibers? We have discussed about the resonator modes both the transverse modes and the longitudinal modes of a resonator. So, the modes that we are now talking of in optical fibers are the transverse modes, that is, they represent the field distributions which propagate in the fiber.

So, light propagation in an optical fiber is determined by Maxwell's equations and when the boundary conditions appropriate boundary conditions are applied then they result in modes of oscillations that is fiber guides light as different modes of propagation and what is a mode? Mode is an allowed field distribution.

Here we are referring to transverse mode. So, these are transverse field distributions; so, transverse modes. So, when you take an optical fiber as shown and then apply the boundary conditions at the core cladding interface, if an electromagnetic wave propagates through this then it has to satisfy the boundary conditions at the interface. And, if we apply the relevant boundary conditions we get certain solutions which are called modes of propagation.

So, transverse intensity patterns of different modes are shown here. So, this is the fundamental mode which is almost like the Gaussian; this is the next mode, so, the 01 or 10 mode as we have seen in the case of laser resonators and then this is the 11 mode. So, in the case of optical fibers these are designated as LP 01, LP 11 and so on LP 11.

And, a multi mode fiber by name as the name indicates it supports many guided modes. Many guided modes can simultaneously propagate through the fibers. In the case of single mode fiber as the name indicates this supports only a single guided mode and this usually is the fundamental mode which is the LP 011 mode which is very closely resembling a Gaussian. So, approximately like a Gaussian beam. So, this is almost like a Gaussian beam.

In fact, there is a Gaussian approximation of this particular mode; so, Gaussian mode. Almost it is not exactly Gaussian, the exact field distributions are Bessel and angle field distributions, but the fundamental mode can be approximated by a Gaussian mode. So, single mode fiber, multi mode fiber as the name indicates they support many guided modes or support a single guided mode.

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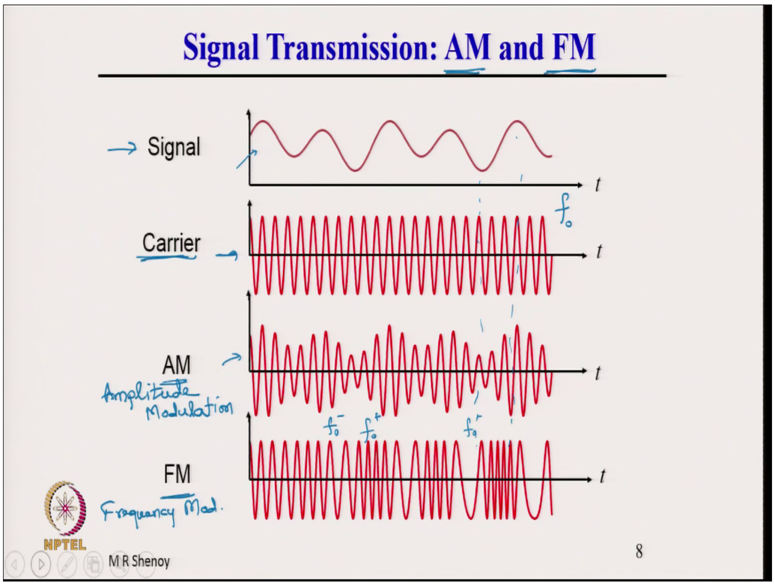


Now, we come to communication. So, in communication signal transmission is usually done in the classical signal transmission it is done by amplitude modulation or frequency modulation. So, in both the cases you have a carrier a high frequency carrier here and a signal to be transmitted when a signal has to be transmitted over a medium or over a link or through a certain distance, then the carrier is modulated according to the signal.

According to the signal means either the amplitude is modulated; so, the carrier here is a carrier with constant amplitude. The amplitude of the carrier is modulated in accordance with the amplitude of the signal. So, that is what is shown here this is an amplitude modulated signal; so, amplitude mod so, those of you who are not familiar with communication.

So, this is amplitude modulation; illustration in simple terms of amplitude modulation. As the name indicates the amplitude of the carrier wave is modulated according to the amplitude of the signal wave. In the second case, frequency modulation. So, this is frequency modulation, FM is Frequency Modulation. Many of you will be aware of these things.

So, in frequency modulation the frequency of the carriers we see here that this has a certain frequency let us say f c or f 0 is the frequency it is a constant frequency carrier. And what we see here is the frequency in some places is more here. So, this is f 0 plus and here we can see that it is f 0 minus. So, f 0 minus we can see and f 0 plus.

In other words, the instantaneous frequency of the carrier is modulated according to the amplitude of the signal. When the amplitude goes down the frequency goes down, we can see amplitude goes down then the frequency also goes down and when the amplitude goes up the frequency goes up. So, this is called frequency modulation. This is the classical modulation techniques used for signal transmission.

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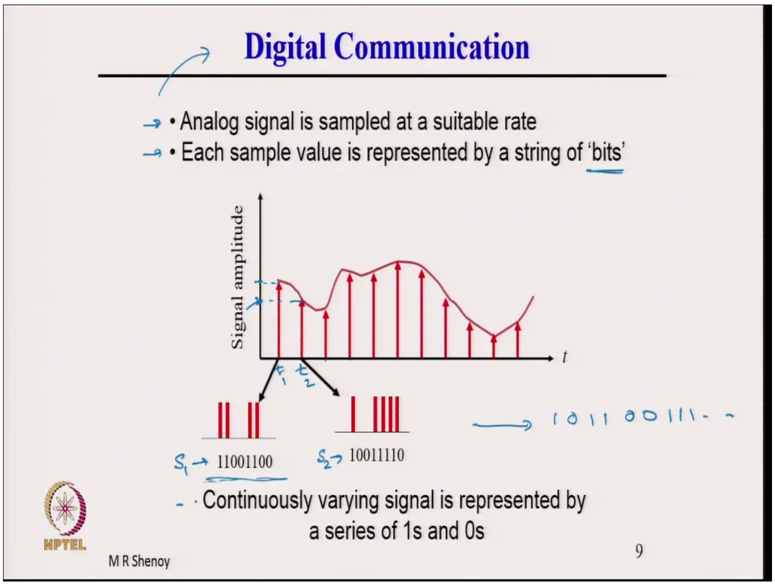

But, today almost all transmission are digital transmissions. So, digital communication where an analog signal is sampled at a suitable rate and each sample value is represented by a string of bits; bits stands for binary digits 1s and 0s. So, what is shown here is the analog signal which is sampled it is value is sampled. So, sample means this is the sample value at this instant.

So, this axis is time, at various instance at a certain rate which is called the sampling rate the value of the amplitude is sampled and the sample value is represented in the form of binary digits. For example, the sample value here is represented by a string of binary digits 1s and 0s and the sample value here corresponding to this time let say this is at time t 1 and this is at time t 2.

So, the sample value S 1, so, here if I say that this is S 1 which is at time t 1 is this one corresponding to this height and the sample value here is S 2 is at a later time. In other words, the analog signal is sampled and each sample value is represented as bits and what is transmitted is simply 1s and 0s. So, 1s and 0s – 1 0 1 1 1 0 so, a sequence of 1s and 0s.

We know the advantage of digital communication that this usually leads to higher signal to noise ratio for those of you who are familiar you know that digital communication usually has a higher signal to noise ratio because you are transmitting only two levels – 1s and 0s.

So, either it will be a 1 detected as 1 or detected as a 0 that is far better than detecting different levels of amplitude, alright. So, a continuously varying signal is represented by a series of 1s and 0s. So, this is in brief digital communication.

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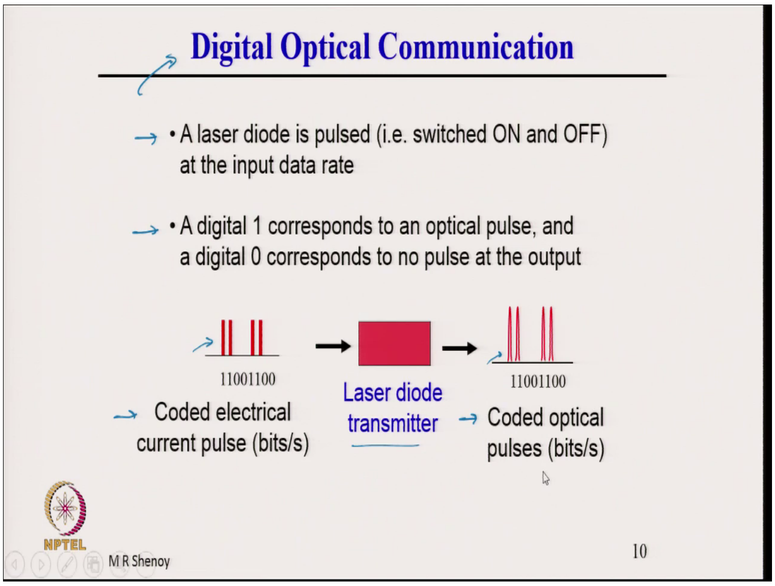


Now, in digital optical communication, we are interested in optical communication and it is digital communication a laser diode is pulsed that is switched ON and OFF at the input data rate; the input data is a digital data which comprises of series of 1s and 0s. It is electrical data 1s and 0s and a laser diode is pulsed in accordance with the data.

So, a digital 1 corresponds to an optical pulse the presence of an optical pulse and a digital 0 corresponds to no pulse at the output. So, what is illustrated here is a laser diode transmitter here. At the input we give coded electrical current pulses this is current electrical current pulses. So, 1s and 0s that is high current, low current, high current, low current 1s and 0s. And, depending on the current the laser diode gets gain modulated or gain switched to give out the output in the form of pulses 1s and 0s.

So, you can see that we have shown here rectangular pulses, the digital pulses, current pulses and the output pulse is not exactly rectangle because of the nature of the optical source. But they are in the form of nice pulses. So, a digital 1 corresponds to a pulse output and when the digital input is 0, there is no pulse at the output. So, coded electrical current pulses are converted to coded optical pulses and then these are transmitted.

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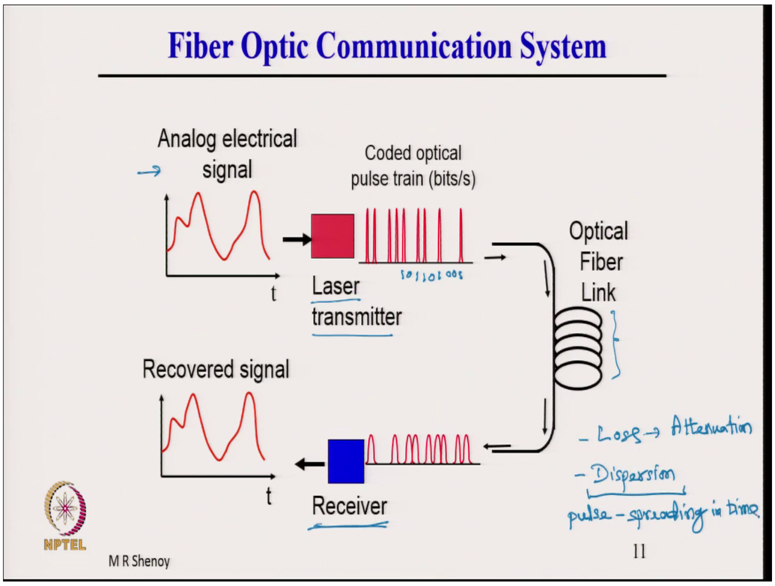


Therefore, in a fiber optic communication system, so, now, we are combining everything and showing a schematic of the fiber optic communication system. You have an analog electrical signal at the input which is coded, sampled and coded in binary sequence, binary digits and it is fed to a laser transmitter here.

And, the output is coded optical pulse train, bits per second which is then coupled to an optical fiber for transmission over the optical fiber link. This may be several kilometers or several 10s of kilometers depending on the length of the link. And, at the output what we get is a digital stream of optical pulses which is received which is detected by a photo detector; this receiver has the first component as the photo detector.

Photo detector generates equivalent current corresponding to the optical pulses and then the signal processing is followed which leads to recovery of the original signal. This is the schematic representation of a complete fiber optic communication system. What we note here is the input pulses are sharp and pulses of large amplitude; at the output we see that the pulse amplitude has dropped and the pulses have become wider.

They are completely separated here for example, this is a 1, this is a 1, this is a 0, this is a 1, there are 0s, then 1, 1, 0, but we see that the 1s are very very close they tend to overlap. So, this is deliberately shown because the fiber link has two important characteristics one is loss and the second is dispersion. Every medium has loss and dispersion.

So, the loss is responsible for the drop in the amplitude of the pulses and the dispersion. Dispersion is for example, temporal dispersion; here in the case of pulses we call temporal dispersion means dispersion here refers to pulse spreading. In this context dispersion here refers to pulse spreading.

And loss here corresponds to pulse attenuation. So, this corresponds to attenuation. So, this loss in the medium in this case fiber leads to attenuation that is the amplitude is attenuated. And the dispersion in the fiber leads to pulse spreading, spreading in time spreading in time.

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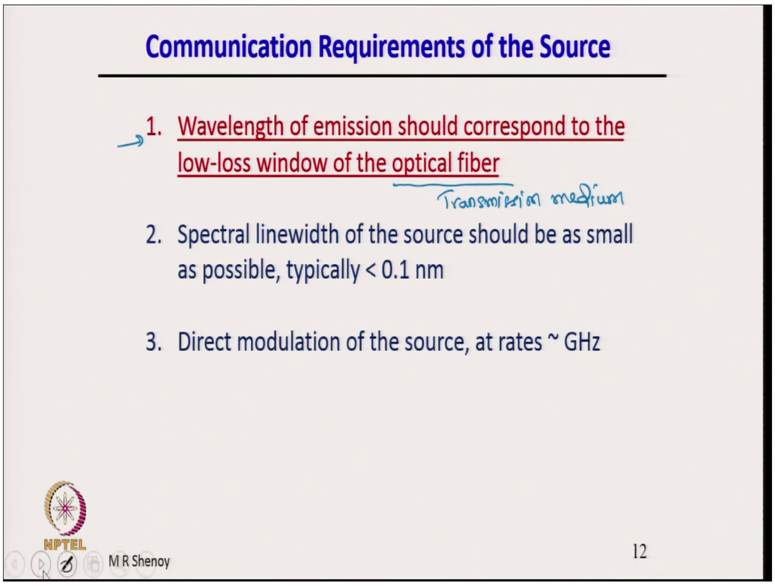


And, we will discuss this a little bit more. So, the communication requirements, so, we will discuss about these a little bit later. So, first let me look at the requirement of the source which is used in the transmitter. So, what is the requirement of the source? 1st the wavelength of emission should correspond to the low loss window of the optical fiber. Remember this is the transmission medium. So, transmission medium optical fiber is the transmission medium. And therefore, the wavelength of the source must correspond to the low loss window of the optical fiber. What is this? Let us see here.

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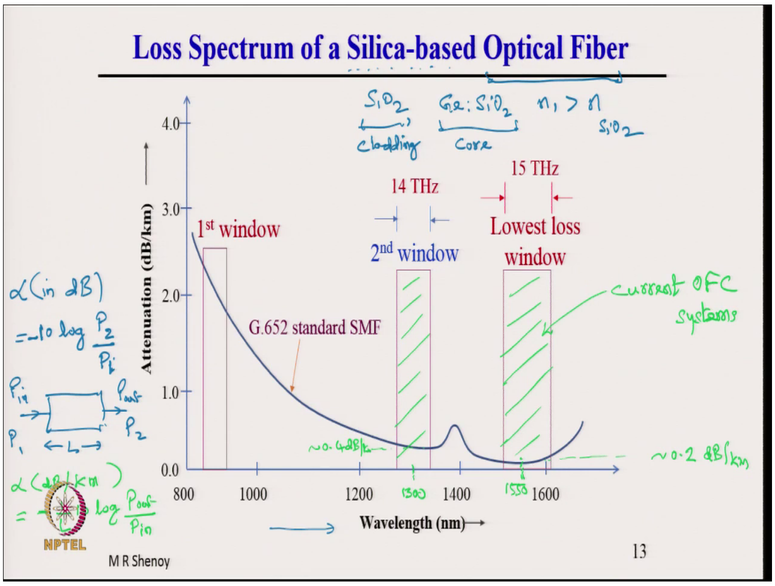


So, if we see the loss spectrum of a silica based optical fiber the optical fibers used for fiber optic communication are silica based. So, silica based means they are SiO 2 based; based is used because they are also dopants which are used to change the refractive index. For example, germanium doping is done to increase. So, germanium SiO 2 has refractive index n 1 of the core which is greater than of just silica.

Refractive index of silica if it is doped by germanium it leads to a higher refractive index and that is why the silica based word is used. It is not pure silica very often the cladding is pure silica, but the core is germanium. So, very often there are other dopants also used. So, this is usually the core and this is the cladding pure silica is used as cladding

Now, typical loss of silica what is plotted is loss spectrum; spectrum means wavelength versus loss attenuation in dB per kilometer. So, for those of you are not familiar dB decibel refers to dB per kilometer refers to if L is the length of the link. If we have an input power P in and output power P out then loss in dB alpha, if I denote this as alpha, alpha in dB this is for those who are not familiar is defined as.

So, simply 10 log P 2 by so, P 2 output by input. Because it is a loss so, this is P out that is P 2. So, P 2 and this is P 1 or P out by P in. So, we use a negative sign otherwise alpha will come out to be negative. So, this is loss in dB, but what is shown is loss in dB per kilometer if L is the length therefore, alpha let me use different color. So, alpha in dB per kilometer is calculated as equal to minus 1 by L into 10 log P out by P in.

The minus sign is used here only. So, that the loss comes out as a positive number. So, this is the definition of alpha in dB per kilometer. So, please see that the loss here around 1300; so, this is 1400 this is 1200 therefore, around 1300. So, around 1300 the loss is low and around. So, this is 14, this is 16, so, this is 15.

So, this minimum is around 1550. The loss is minimum around 1550. And, therefore, there are two windows here; window refers to a range of wavelengths over which the loss is very low. So, this is centered around 1300 and this one is centered around 1500. So, we call it as a low loss window.

And note that the loss around 1500 is the lowest. So, the loss here actually is approximately 0.2 dB per kilometer and the loss here could be about 0.4 dB per kilo 4 or 4 5 dB per kilometre. So, the lowest loss occurs in the window around 1550 nanometer. This is very important and today's communication all communication optical fiber communication is in this window the current communication systems.

The current OFC Optical Fiber Communication systems, use the low loss window centered around 1550 nanometer. So, the point is the source must have a wavelength in this range. So, the source should be chosen such that it corresponds to the lowest loss of the optical fiber, so that the signal attenuates least when it travels through several kilometers of the fiber.

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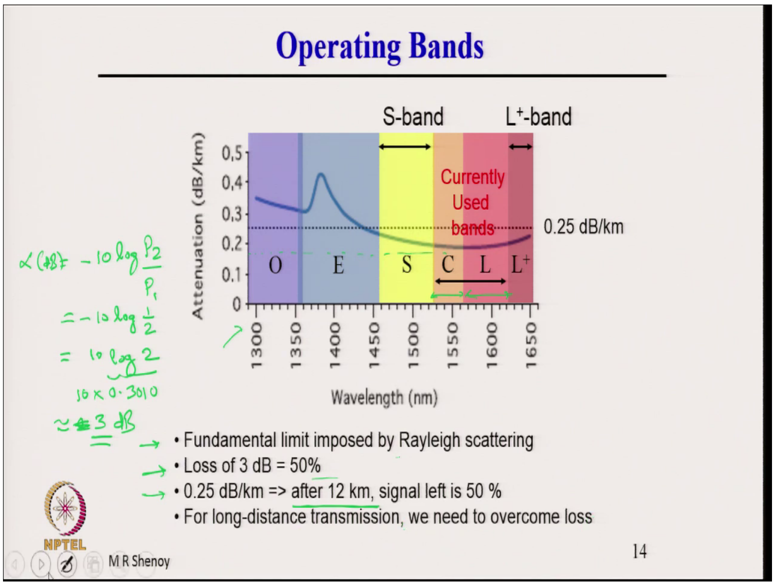


So, let us see this further. So, in the communication technology these are also called different bands. So, there is a band C band, which is called the conventional band, this is called the long band which are C and L are currently used there is a L plus band is a beyond the long band and there is a short band S band and there is a old band initially the communication was around 1300 nanometer, there was a reason for that.

Because the silica based optical fibers show 0 dispersion wavelength around 1300 nanometer and E is the extended band. The fundamental limit on the loss; so, this is shown so, it is below is less than 0.2 dB is the fundamental limit is imposed by the ever present Rayleigh scattering in the medium. A loss of 3 dB, so, I had already discussed corresponds to 50 percent.

If the loss is 50 percent; that means, it corresponds to 3 percent. So, we can see that. So, for example, alpha in dB is equal to minus 10 times log P 2 by P 1. So, P 2 by P 1 if P 2 is half, then we have this equal to minus 10 log half P 2 by P 1 is half the output is half of the input this is equal to 10 log 2 this log is to the base of 10 and we know that log 2 is 30 10 this part is 0.3010.

And therefore, multiplied by 10 is approximately equal to 0.3 is equal to 3. That is why this is 3 dB. That is what is written here loss of 3 dB corresponds to 50 percent loss. And, if the loss is much smaller like 0.25 dB per kilometre what it means is for the signal to become 50 percent of it is strength that is to get attenuated by 50 percent the signal can travel 12 kilometers this after travelling 12 kilometers the signal will become half of what has been input at the input end.

For long-distance transmission we need to overcome loss. This is ok 12 kilometers it becomes half, half is fine, even if it becomes one fourth, one tenth it is fine. But, if the loss becomes much higher when the length of the link becomes very large then the loss would become higher and then for long-distance transmission. Long distance means we are talking of 100s of kilometers then we need to overcome loss. So, how to overcome loss is by the use of amplifiers.

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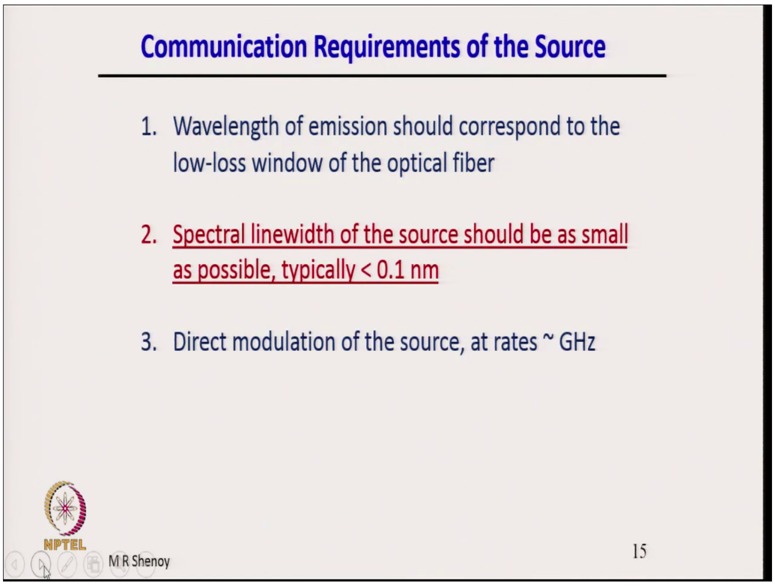


We will discuss that a bit later. So, we have discussed the 1st point wavelength of emission should correspond to the low loss window of the optical fiber. 2nd point spectral line width of the source should be as small as possible, typically less than 0.1 nanometer, why is this?

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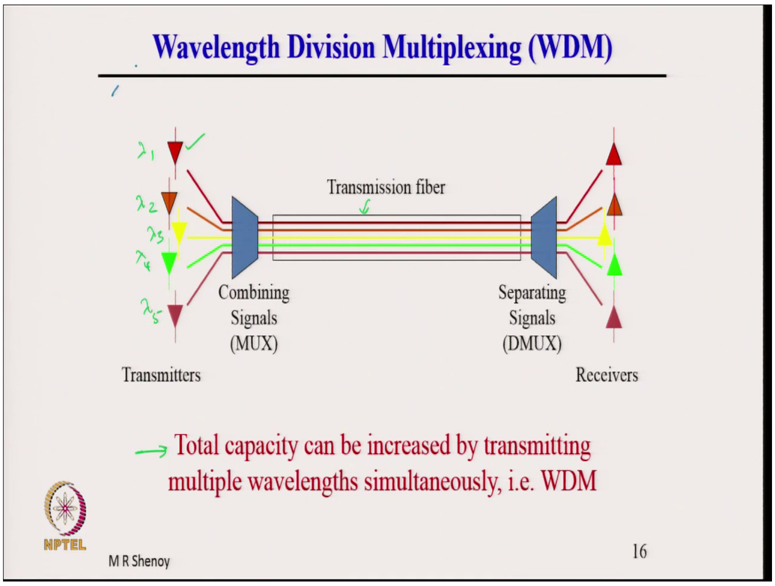


So, let us look at this 2nd point the current systems which are used are Wavelength Division Multiplexed systems WDM systems. WDM means in the same fiber in the same transmission fiber different wavelengths lambda 1, lambda 2, lambda 3, lambda 4, lambda 5 and so on. You can have several wavelengths lambda 5 and so on coupled into the same fiber.

There is a combiner which is called MUX a multiplexer which combines these wavelengths and launches into the same fiber and at the output there is a DMUX that is demultiplexer which separates these wavelengths again and each wavelength can carry a large amount of information. And, therefore, by using let us say if we use 100 wavelengths, then the total capacity of the system is increased by transmitting large number of wavelengths.

If we transmit 100 wavelengths then the total capacity is increased 100 times that is why wavelength division multiplexing systems are currently used. Now, how does this correspond to the discussion that we have that is namely the point 2 here which says the line width of the source should be very small? So, let us discuss this ok.

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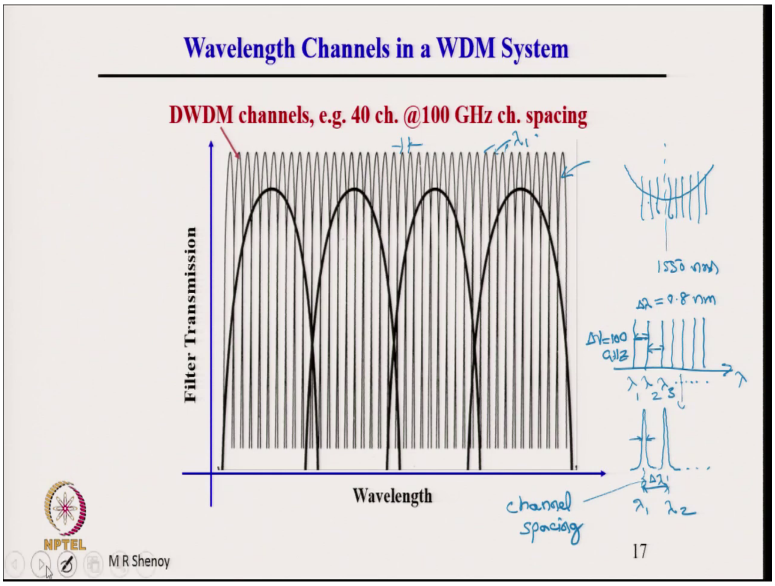


So, now within the low loss window, so, what I am showing is the low loss window centered around 1550 nanometers. If we want to pack in a large number of wavelengths closely separated wavelength, so that is what is shown here. So, these are the wavelengths which are shown.

So, this is if I may call these as lambda i so, these are the wavelengths lambda i's, different i. And, what is shown is the filtered transmission. It does not matter do not bother about the darker line which is shown here this corresponds to coarse WDM, but what is important to recognize is the wavelengths are packed very closely within this low loss window.

Larger the number of wavelengths closer they are packed, that is in the wavelength spectrum if I show lambda versus the position of the wavelengths, then the wavelengths are very very closely separated.

So, how closely are these separated let us put some numbers and see lambda 1, lambda 2, lambda 3 and so on. These are the different wavelengths which are packed into one single fiber in a WDM system. Let us put some numbers and get a feel for these, alright.

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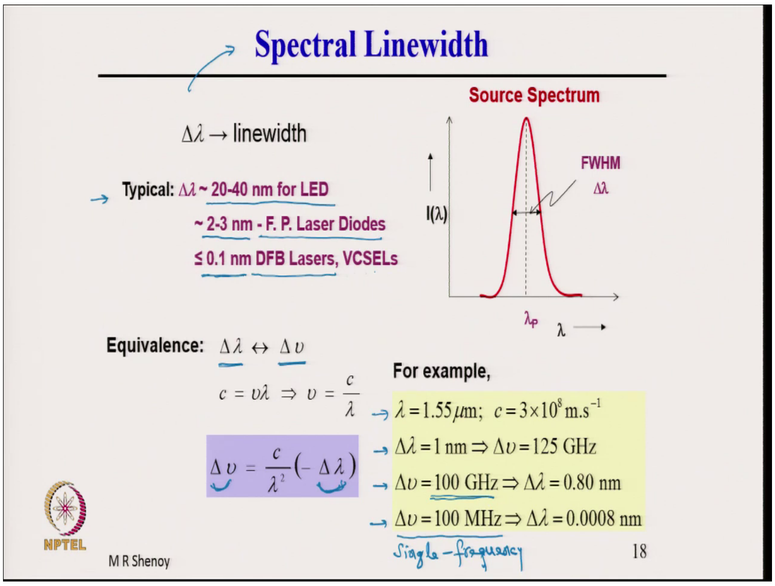


So, first the spectral line width of a source we have discussed about this full width at half maximum of the source and we also know that typically the line width of the source is about 20 to 40 nanometer for a light emitting diode. It is about 2 to 3 nanometer for a normal semiconductor laser diode which is called the Fabry Perot laser diode and it is much smaller, smaller than 0.1 nanometer for single frequency lasers.

In the last lecture, I have discussed about DFB lasers which are single frequency lasers and wick cells referred to vertical cavity surface emitting lasers. Let us not go into that, but what is important for us is single frequency lasers have much smaller line width first point.

Second point normally in communication engineers discuss in terms of the frequency bandwidth and channel spacing in terms of frequency which should be linked to corresponding wavelength separation delta lambda. It is very simple, if you write c is equal to nu into lambda this is not v this is nu frequency into lambda, then the frequency nu is equal to c by lambda.

And, therefore, delta nu is equal to c by lambda square into delta lambda which means if you know delta nu that is the line width in frequency then you know the corresponding line width in terms of wavelength. This is very important to appreciate. For example, if we use lambda is equal to 1.55 micrometer in the low loss window and c is of course, the velocity of speed of light.

Then for delta lambda is equal to 1 nanometer the corresponding delta nu will be 125 gigahertz approximately or alternatively if delta nu is equal to 100 gigahertz, then delta lambda comes out to be approximately 0.80 nanometer around 1.55 micrometer. If delta nu happens to be 100 megahertz, then corresponding delta lambda is much much smaller.

Now, why these two numbers I have taken if you take a single frequency laser delta nu is typically. So, this is for single frequency laser 10 megahertz to 100 megahertz for single frequency laser. So, in the case of a single frequency laser, the line width of the source is much much smaller of the order of 0.0008 nanometer.

And, why did I take 100 gigahertz? The international telecommunication union sets that the standard the separation between these channels here. So, the frequency separation, this the separation between these. So, this is the delta lambda separation between the channels is equal to this corresponds to a delta nu is equal to 100 gigahertz 100 gigahertz or it could also be 50 gigahertz. There are standards for that.

But, if it is 100 gigahertz then the corresponding delta lambda will be equal to 0.8 nanometer, which means the wavelengths have to be separated by approximately 0.8 nanometer when you pack a large number of wavelengths in the low loss window of the optical fiber. And therefore, if the line width if I now show this more realistically, please see that every source has a finite line width. So, here we have this is lambda 1 and this is lambda 2.

So, this is the line width of the source delta lambda of the source and this separation is delta lambda the separation is called channel spacing. So, this is called channel spacing, that is spacing between different channels every wavelength corresponds to one channel communication channel and therefore, the separation between the wavelengths is called channel spacing. Now, with this, let us go back.

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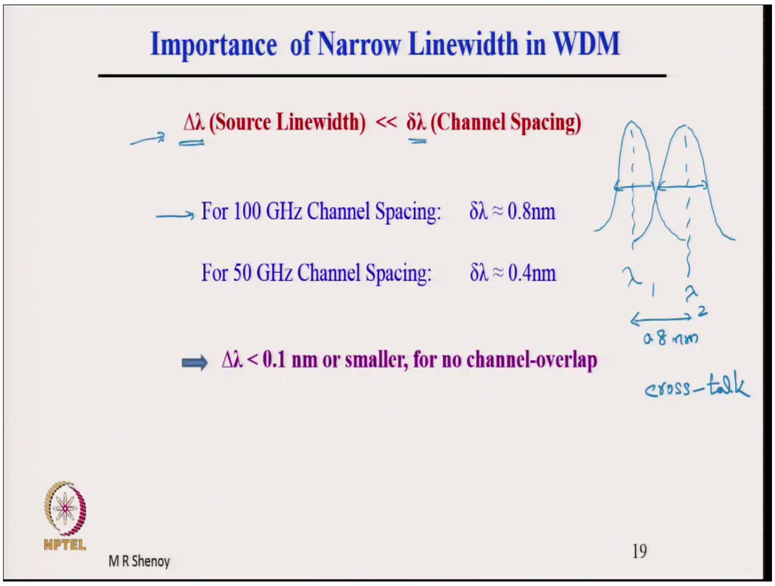


Now, if we come here therefore, for a 100 gigahertz channel spacing delta lambda is 0.8 nanometer this is between two carrier wavelengths it is 0.8 nanometer. Now, for a 50 gigahertz channel spacing delta lambda will be 0.4 nanometer. What about the line width? So, this delta lambda here is source line width, this delta lambda is channel spacing.

Now, the source line width must be much smaller than the channel spacing, otherwise the channels will start overlapping. Let me exaggerate it. Let say, you have one channel like this. So, let say this is lambda 1. The other channel is like this. So, this is lambda 2 of course, this separation is 0.8 nanometer this is as per standards, but if the line width here this one is larger than 0.8 nanometer then the two channels will overlap.

Once they overlap then there will be crosstalk between these channels. So, this would lead to crosstalk when the channels overlap this will lead to crosstalk. And, therefore, if you do not want interference of one channel with another channel, then the line width of the source must be much smaller than the separation between the two channels.

So, that is the statement here that delta lambda of the source line width must be much smaller than the channel spacing. Now, note that for 100 gigahertz channel spacing delta lambda is 0.8 nanometer and therefore, the line width delta lambda must be 0.1 nanometer or even smaller for no channel overlap. That is the meaning of this statement. Hope, I have been able to make it clear.

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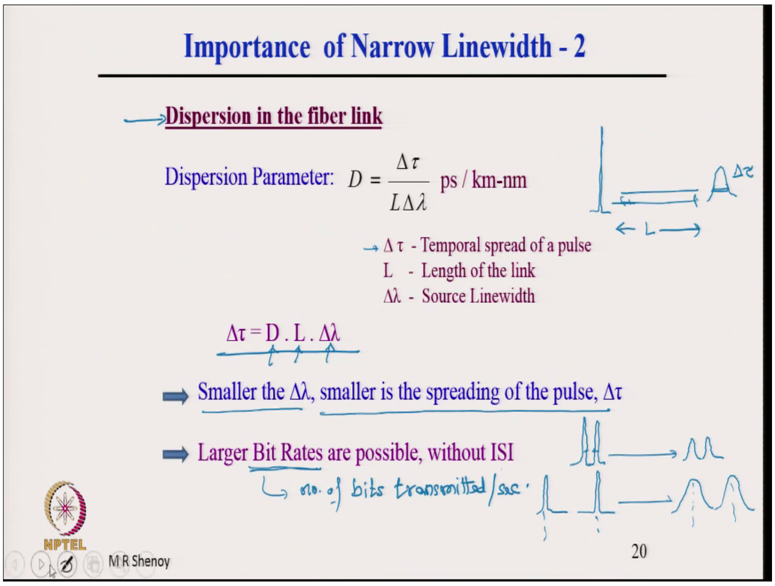


So, that is one of the primary reasons for having small line width of the source because in WDM systems DWDM systems this is the situation. Now, there is a second reason I mentioned dispersion in the fiber link. Those of you have not studied fiber optics it is all right, but just to mention in fiber optics there is a dispersion parameter D which is given by delta tau divided by L into delta lambda, where delta tau is the temporal spread of a pulse.

Temporal spread of a pulse means if we have an impulse at the input of an optical fiber link, then at the output the pulse may spread and the pulse width might have become delta tau and then this delta tau is called the temporal spread of a pulse. Spreading of a pulse in time L is the length of the link and delta lambda is the source line width about which we have been discussing.

Now, note that delta tau that is how much the pulse spreads here delta tau is dependent on D, the dispersion parameter this is a characteristic of a given fiber the length of the link and delta lambda line width of the source. Therefore, the spread will be smaller if the line width of the source is smaller. Smaller the delta lambda smaller is the spreading of the pulse.

And, therefore, if the pulse spreads less than larger bit rates are possible without inter symbol interference. So, what it means is if the spreading of a pulse after travelling let say let me show only two pulses which are very closely separated after travelling it would become this, but they are still well separated. Then the separation between them can be quite small, if the separation was more then I had to keep the two pulses well separated at the input.

Then only if they spread like this in order to avoid overlap we have to keep the separation larger between the two pulses, which means the number of pulses, which can be transmitted per second would be smaller and that is called bit rate. Bit rate refers to number of bits transmitted per second ok. Let us proceed further.

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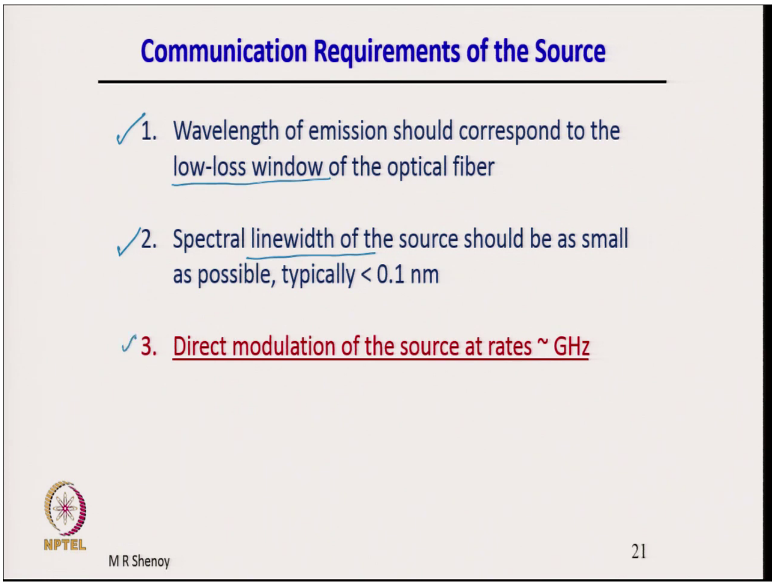


So, we have discussed the 2nd point also now, the 1st point we have discussed about low loss window of the fiber. 2nd point the line width of the source should be as small as possible and the 3rd point is direct modulation of the source at rates of gigahertz should be possible. If you want to use them in high speed communication, this is the 3rd point.

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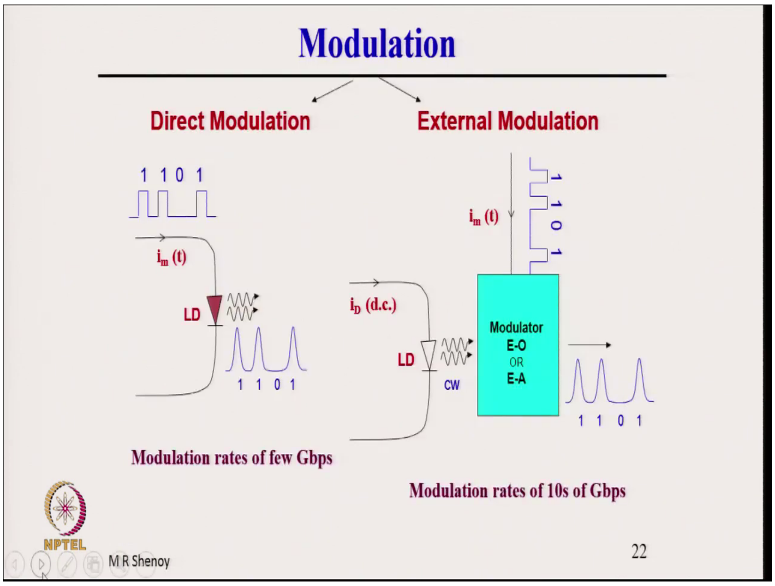


So, this we had discussed earlier that the modulation has two methods one is called the direct modulation and another is called external modulation. In the case of direct modulation the laser diode is directly modulated by a current signal which is riding on the bias, and corresponding to 1s and 0s the laser diode would give pulses. And, the modulation rates can be few giga bits per second by direct modulation.

As I mentioned earlier no other laser can be modulated directly at this rate this kind of speeds of course, when the speed becomes 10s of gigabits or 100s of gigabits per second, then one has to necessarily use external modulation technique, where you use electro optic or electro absorption modulators to modulate the input signal as per the signal to be transmitted.

This is the modulating signal which has to be transmitted in terms of pulses. So, direct modulation refers to this and only diode laser can be modulated at that speed.

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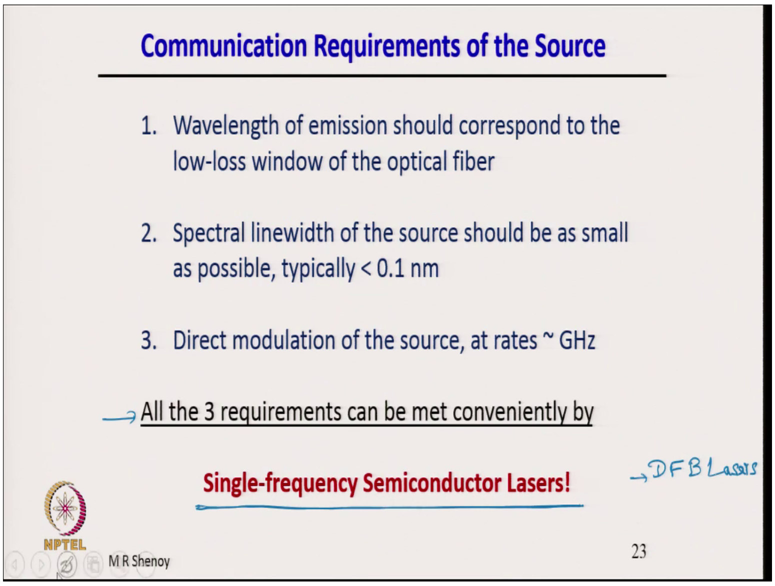


Now, if we look at all the 3 requirements here then we see that all 3 requirements can be met conveniently by single frequency semiconductor lasers. We have discussed about single frequency lasers and in the last lecture I also discussed about one of the single frequency semiconductor lasers, which is the DFB laser Distributed Feedback Laser. So, most of the lasers used in high speed optical communication are distributed feedback lasers, ok.

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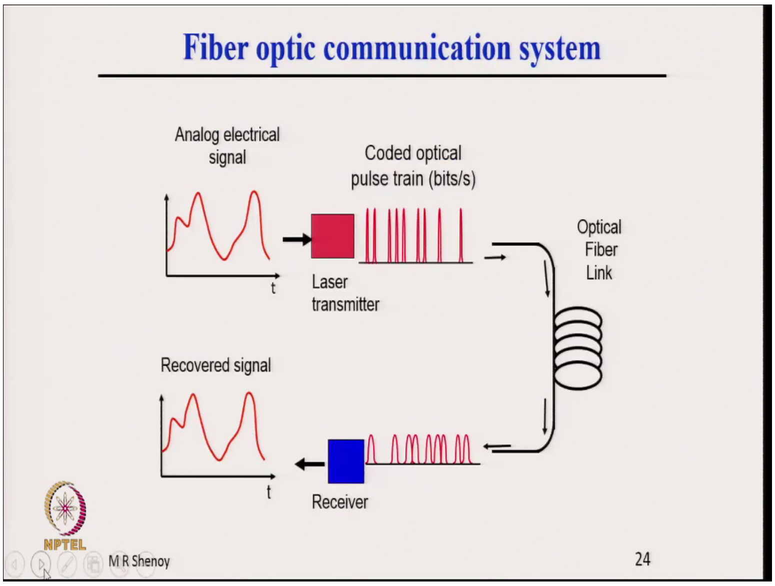


Let us now come back to the fiber optic communication system. So, here is the system and I have been discussing about the requirements on the laser in the transmitter. Similar conditions are required for the receiver which I will not go here because our emphasis is on lasers and sources. The next thing I want to discuss is about importance of laser amplifiers in communication.

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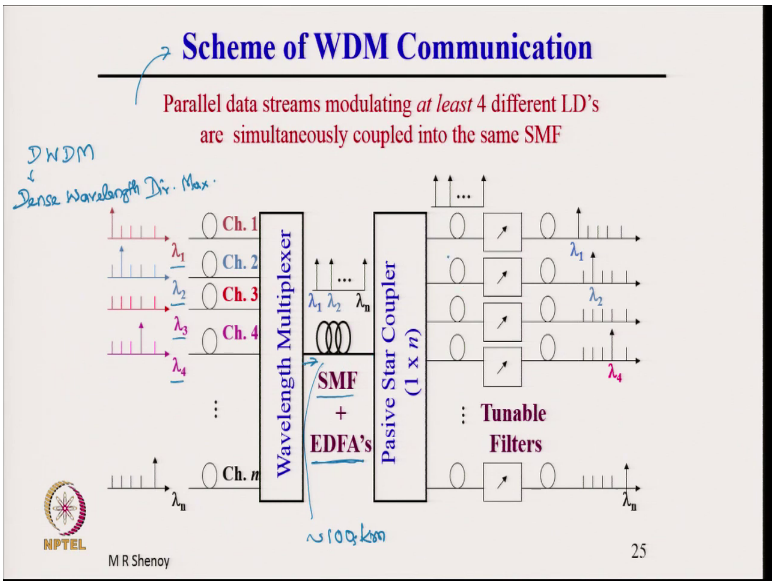


To see that let us come to the scheme of WDM communication there are several things which are shown we do not have to bother about it. Let me put it in simple terms. This is a DWDM communication system DWDM means DWDM stands for dense wavelength. So, this stands for Dense Wavelength Division Multiplex; dense wavelength division multiplexing.

There are several wavelengths lambda 1, lambda 2, lambda 3, lambda 4 and so on lambda n wavelengths transmitted they are all combined and launched into the single mode fiber and then this is the fiber link. This could be of the order of 100s of kilometers so, 100s of kilometres.

For example, a link between two cities such as Delhi and Mumbai the link could be about 1500 kilometers long. So, 100s of kilometres, then as we discussed in addition to the single mode fiber we need amplifiers in between to boost the signal when the signal drops down to small amplitudes it is required to amplify these signal.

And, then the signals at the other end will all be DMUXed that is de-coupled and there are different filters which are used and the wavelengths are separated. What we are interested is, to see that the link fiber link do not worry about these parts. The fiber link in a long distance DWDM system has single mode fibers and EDFA's Erbium Doped Fiber Amplifiers which we have discussed in detail, alright.

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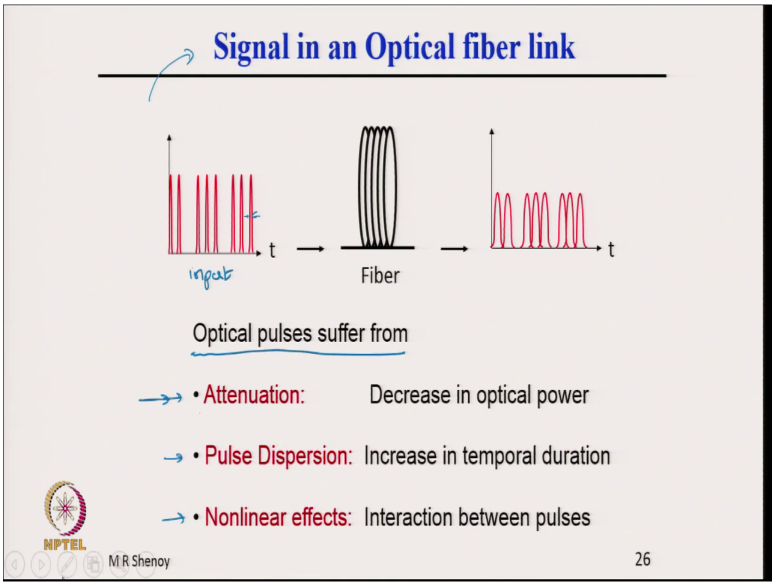


So, let me now discuss this last aspect of communication which is signal in an optical fiber link I have already mentioned that the input signal here. So, this is at the input after travelling through the fiber gets attenuated the amplitude decreases and the pulses start overlapping.

And, therefore, the optical pulses suffer from three problems attenuation, pulse dispersion and non-linear effects. So, this non-linear effects in communication is beyond the scope of our discussion here, but I will try to bring out some non-linear aspects in the next lecture. So, let us look at attenuation and pulse dispersion. Both we have discussed.

Attenuation decreases the optical power at the output, pulse dispersion increases the temporal duration which means spreading in time. So, that is what is shown here. Here you can see the pulses are sharp. So, this in time here the pulses have spread out and therefore, these two important aspects of the fiber affects a communication link.

Now, the first one attenuation can be overcome by amplifiers I will not discuss the second aspect of overcoming pulse dispersion, but let us just discuss how to overcome attenuation by using laser amplifiers and the amplifiers used are erbium doped fiber amplifiers which we have discussed in detail.

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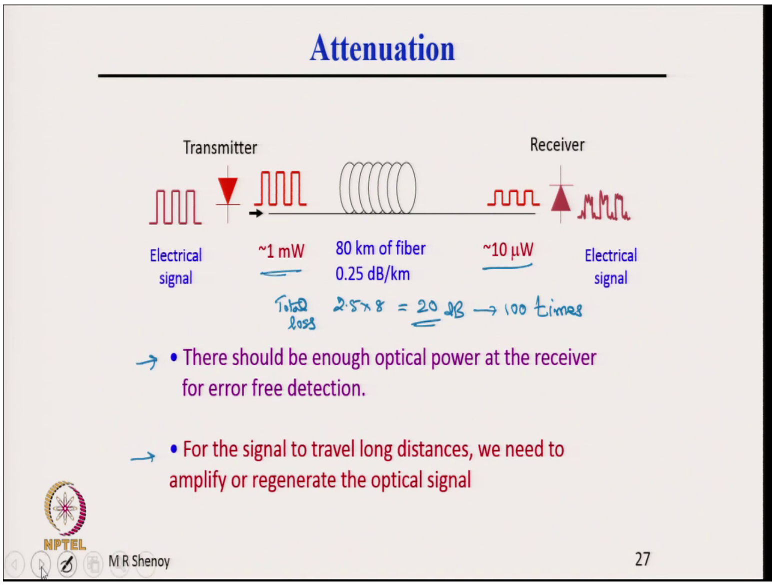


So, attenuation very quickly, so, the electrical signals let us say the power is of the order of 1 milliwatt at the input after travelling 80 kilometers of a fiber with a loss of 0.25 dB per kilometer the output will come down to 10 micro watt, 1 milli watt to 10 micro watt because 100 times. So, if we multiply 0.25 by 80 it is 2.5 into 8 and that is equal to 20. So, this is 20 dB total loss 0.25 dB per kilometer. So, total loss is 20 dB. So, 20 dB means 100 times; this is 100 times.

If P 2 by P 1 is 100, you get alpha as 20 dB. So, 100 times lower 1 milliwatt becomes 10 micro watt here and it is detected by a photo detector at the receiver and the detected electrical signal looks like this. Now, if the power goes much smaller than the output will be full of noise and therefore, there should be enough power at the receiver for error free detection. Therefore, for the signal to travel long distances we need to amplify or regenerate the optical signal.

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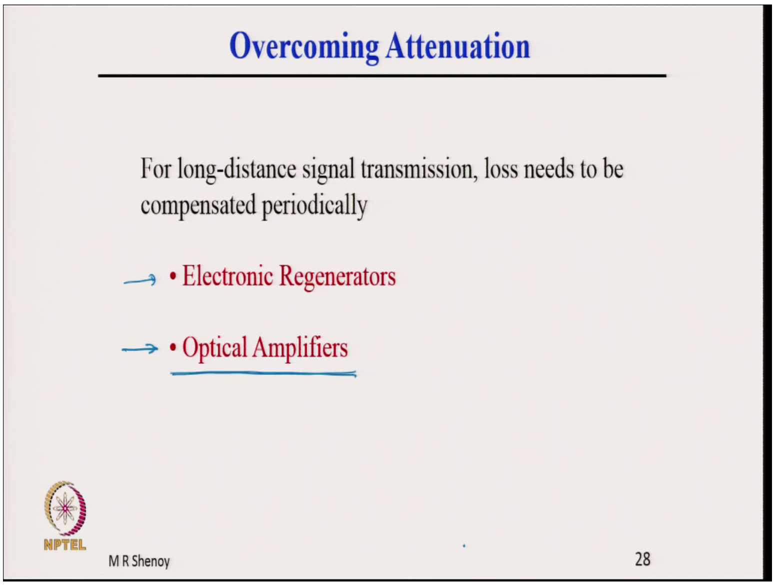


So, there are two ways of regenerating the signal – one is electronically regenerating the signal and the second one is optical amplifiers. So, currently the systems use optical amplifiers in an optical fiber communication system, alright.

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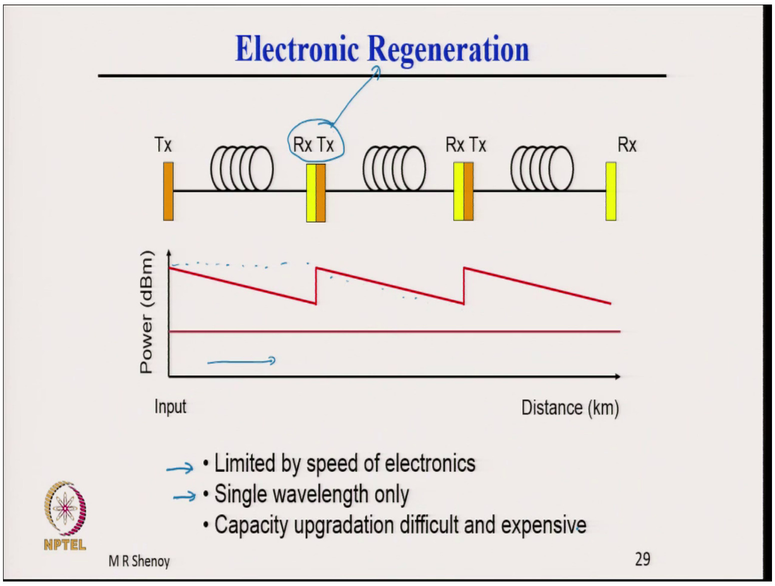


Very briefly in electronic regeneration the input as it propagates this is the propagation distance. So, distance in kilometer is the propagation distance; input drops down this is the power level we have not put any numbers here, but the input is dropping down at this place that is where it is received receiver transmitter. So, this is a regenerator this is regeneration. The signal is detected, the power level is boosted again back to the same level and then retransmitted.

That is why it is called a regenerator and again the attenuation leads to drop in power which is again regenerated the entire sequence of bits 1s and 0s are regenerated and then retransmitted. But this part regeneration is done primarily by electronics. And, therefore, the speed is limited by speed of electronics. Further this can be done for one wavelength at a time and therefore, the capacity upgradation becomes very difficult and expensive.

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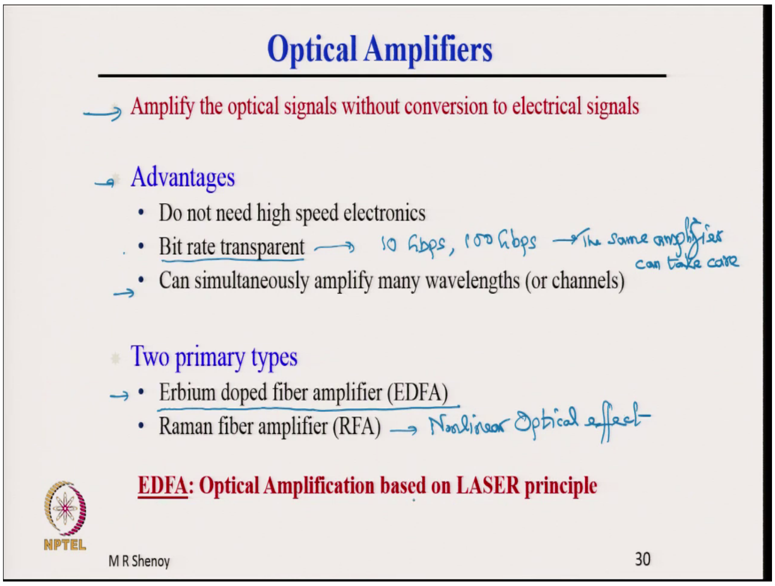


Now, if you go for optical amplification, it amplifies the optical signals without conversion to electrical signals. Therefore, the speed bottleneck is not an issue here. The advantages are indicated here it does not need high speed electronics it is bit rate transparent. Bit rate transparent means in this system you can put let us say 10 Gbps system 10 Gbps or 1 Gbps or 100 Gbps.

Whatever bit rate you put 10 Mbps, 10 Gbps or 100 Gbps the same system will work the same amplifier takes care, the same amplifier can take care which is not the case in electronic amplifiers can simultaneously amplify many many wavelengths. And, the two primary types of amplifiers used are one erbium doped fiber amplifier that we discussed in one full lecture in detail.

And the second one is Raman fiber amplifier this is based on non-linear optical effects. So, non-linear optical effects. So, the EDFA which we have discussed in detail is optical amplification in the current systems are based on the laser principle, the EDFA works on the laser principle which we have discussed in detail.

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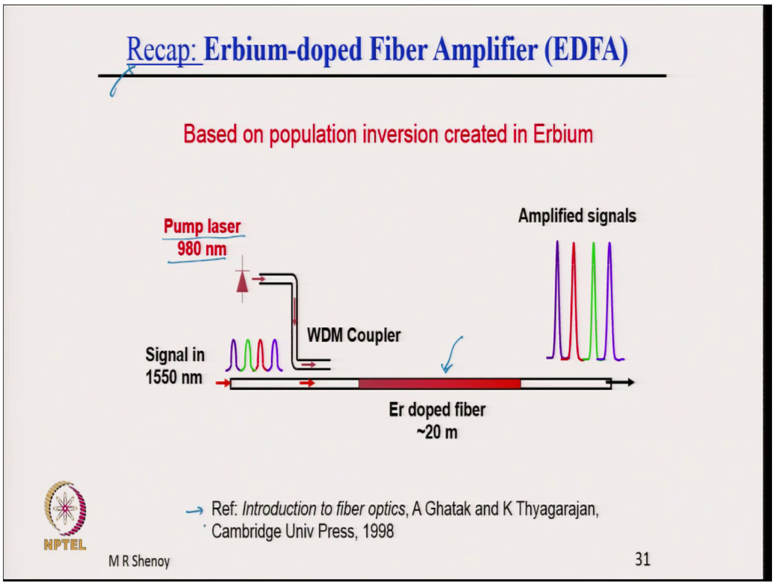


So, this is a very quick recap. We will not discuss in detail we have already gone through this a small signal can be amplified by having a pump laser to create population inversion in the erbium doped fiber. So, more details one can refer to the book here.

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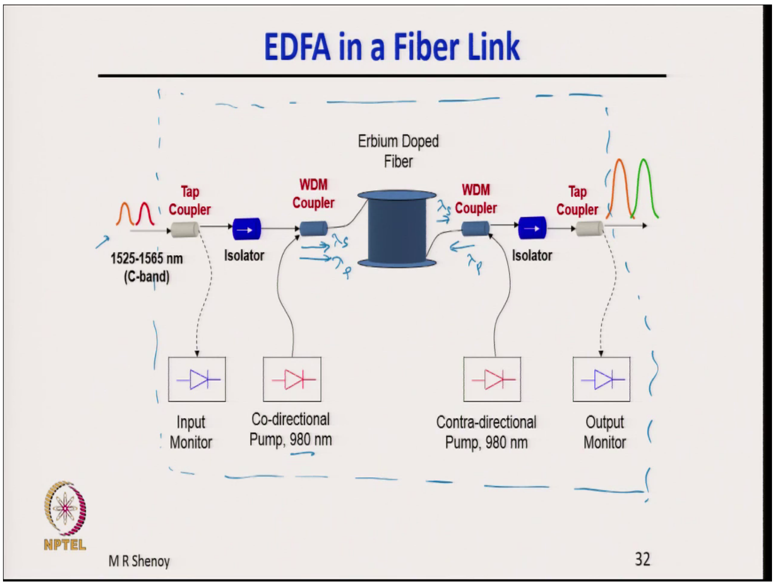


And, therefore, finally, the EDFA in a fiber link looks like this, you have low or weak signal which is entering the amplifier the whole unit is an amplifier. So, this whole unit is the amplifier here. So, the amplifier has a tap coupler to monitor the input power levels, there is an isolator which is like an optical diode, we have already discussed this.

There is a WDM coupler to combine the pump and the signal and then here is the erbium doped fiber maybe 20 meters kept in the form of a small spool and then there is a WDM coupler which is shown here because there are instances where you need to pump the fiber from both sides that is from the forward side and backward side if you want to get more output power from the doped fiber, otherwise this is not required.

The second part which is shown here that is the contra directional pumping which means pumping in a direction opposite to the direction of flow of the signal. This is called co-directional pumping because both signal and pump are travelling in this direction lambda S and lambda P.

In this case it is contra directional because if we use a second pump then the pump lambda P will go here and lambda S signal will continue in this direction and then this is called a contra directional pump. And that is a typical erbium doped fiber amplifier in a fiber optic communication link, alright.

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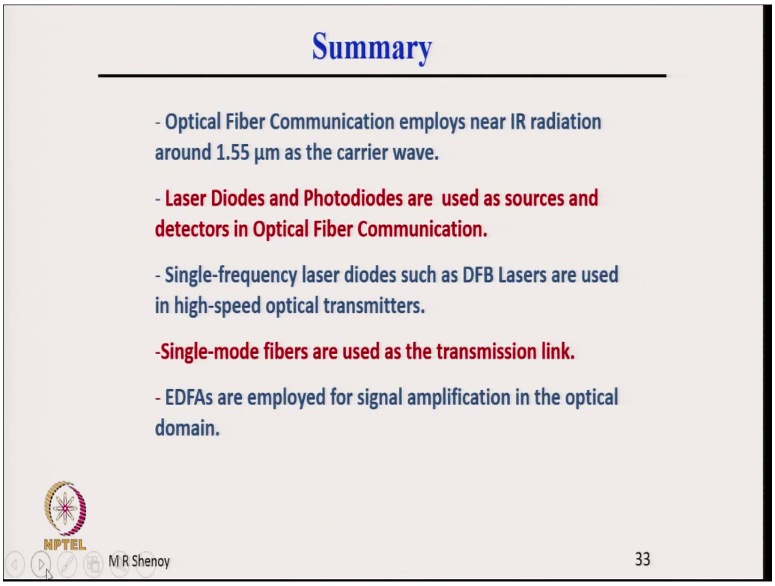


We summarize what we have discussed. Optical fiber communication employs near IR radiation because as we discussed it is in the 1550 nanometer window which is near infrared; so, IR radiation around 1550 nanometer or 1.55 micrometer as the carrier wave. Laser diodes and photodiodes are used as sources and detectors in optical fiber communication.

Single frequency laser diodes such as DFB lasers, which we discussed in the last lecture are used in high speed optical transmitters. Single mode fibers are used as the transmission link and EDFAs are employed for signal amplification in the optical domain.

So, this is the summary of optical fiber communication, very briefly. Our emphasis has been on the laser source and the laser amplifier which are used in the communication system. There are of course, lot of other details related to the communication system itself which is beyond the scope of our course.

Thank you.