Fiber Optics
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Lecture - 38
System Design Aspects

Now after having understood, most of the things that is the transmission medium which is an optical fiber the components devices in between optical sources that is a transmitter end and optical detectors that is the receiver end. So, we have now studied all the segments all the sections individually. Now it is time to put them together and look into system design aspects.

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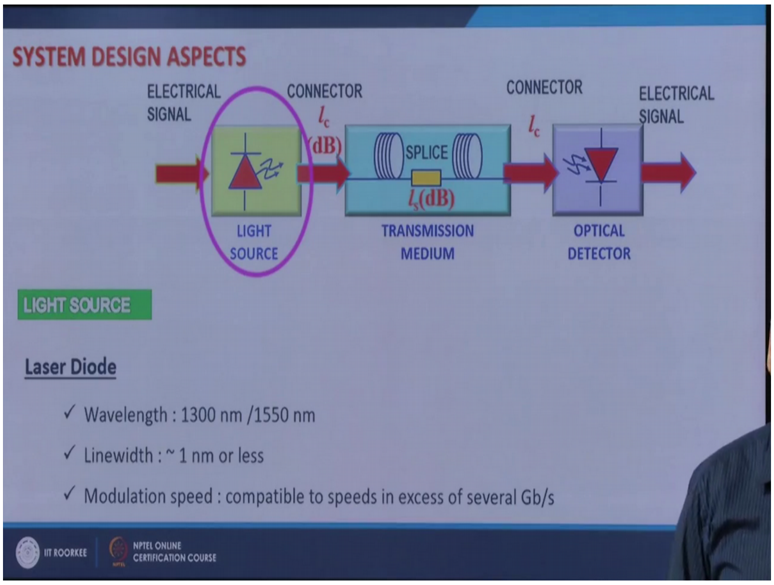

So, what we have the overall system that we have electric signal, which comes out from data, data is in the form of electric signal which drives light source generates optical pulses, then this optical energy is coupled to transmission medium which is optical fiber using connector, then in between we can have several optical fibers.

We can have different components and devices based on optical fiber itself, then at the receiver end we need to couple this optical energy into the optical detector. So, again we will require a connector and ultimately we will get electrical signal output from optical detector. So, this is the complete system, now let us look at the design aspects of this. So, the very first thing is light source for long haul telecom system one would prefer laser that laser diodes as light source, with operating wavelength 1300 nanometer or 1550 nanometer.

Line width should be one nanometer or less and modulation speed should be in excess of several Gbps or the light source should be compatible to modulation speeds which are in excess of several Gbps basically you can directly modulate the light source using the injection current or you can use external modulator. Directly modulating the light source has some consequences and it cannot go beyond few g b p s. So, for very high speed you will require external modulators and your laser diode should be compatible to that.

Another thing is that when we design the system, then we would have to look into what input power of light source would be needed taking into account all the components transmission medium and sensitivity of the detector.

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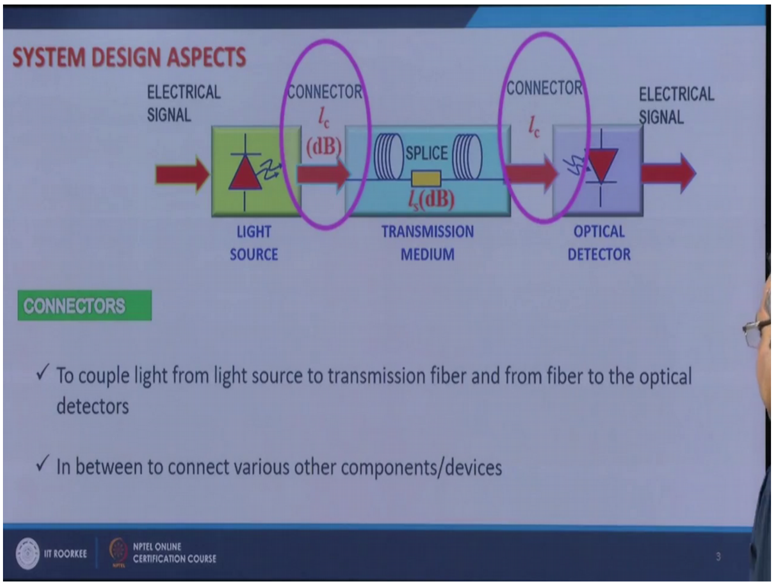

Then we have connectors at several places took up a light from light source to transmission fiber and from fiber to the optical detector, and in between also we put several optical fiber based components. So, we will require connectors. So, these connectors will cause some loss each connector will have certain loss. So, we will have to take into account that.

Then in the transmission medium we will have we may have to join several fibers together or we may have to join some specialty fibers for certain operations with the transmission fiber. So, we would require splices. So, we will have to take into account the loss at each splice then of course, the transmission loss of the fiber itself.

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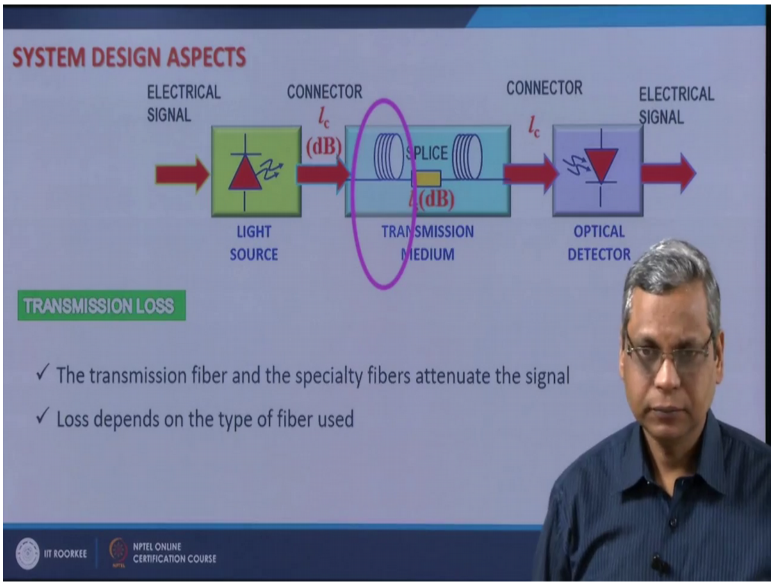

So, whatever fiber we are using we will have to take into account the loss of that fiber at the operating wavelength. So, this loss depends upon the fiber used and of course, the wavelength of operation.

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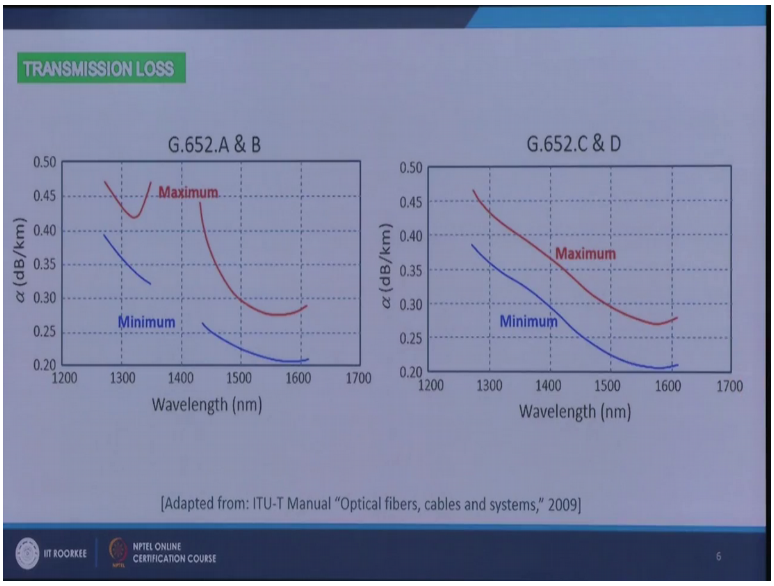

If you look at certain fibers which is G 652 a and b, and this is G 652 C and D.

So, the loss coefficient as a function of wavelength which is admitted is like this, which has been adapted from I t u t manual on optical fibers cables and systems. So, where I can see that if I look at 1550 nanometer. So, the maximum loss that can be admitted is about 0.275 d B per kilometer and minimum is around 0.2d B per kilometer; however, if I look at this. So, at 1550 the loss limits are similar, but if I compare this fiber with this fiber this fiber also operates near 1380 nanometer wavelength where this fiber does not operate.

So, here you have water peaks in this fiber. So, this fiber cannot be used here; however, this fiber can be used in the entire wavelength range from 1300 nanometer to 1600 nanometer.

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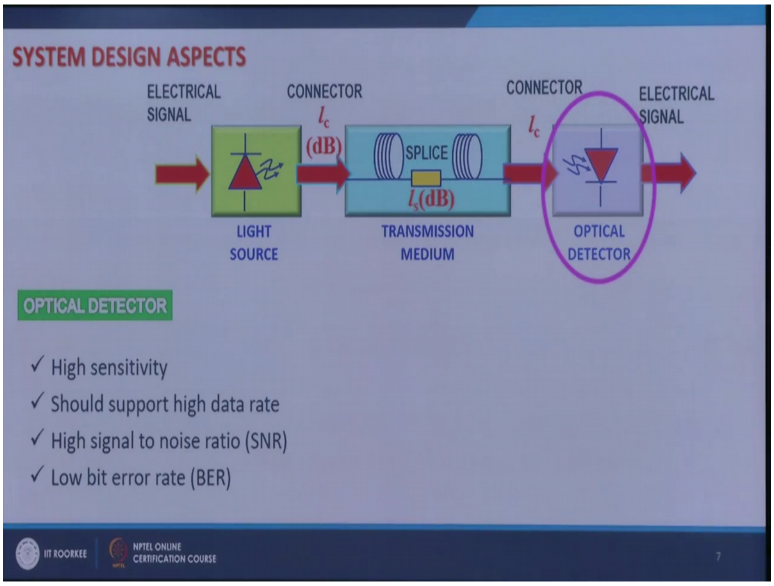

Then another very important aspect is to design or to choose optical detector and look into various characteristics of optical detector. The detector should of course, have high sensitivity should support high data rate and should have high signal to noise ratio so that we can fish out signal from the noise. So, that the signal is tends out quite well from the noise and it should have low bit error rate. So, very important aspect of any detector is how well it can distinguish signal from the noise, and that is particularly when your signal levels drop down to very low levels. So, the noise should be as low as possible and in fact, the ratio between the signal and noise should be as large as possible.

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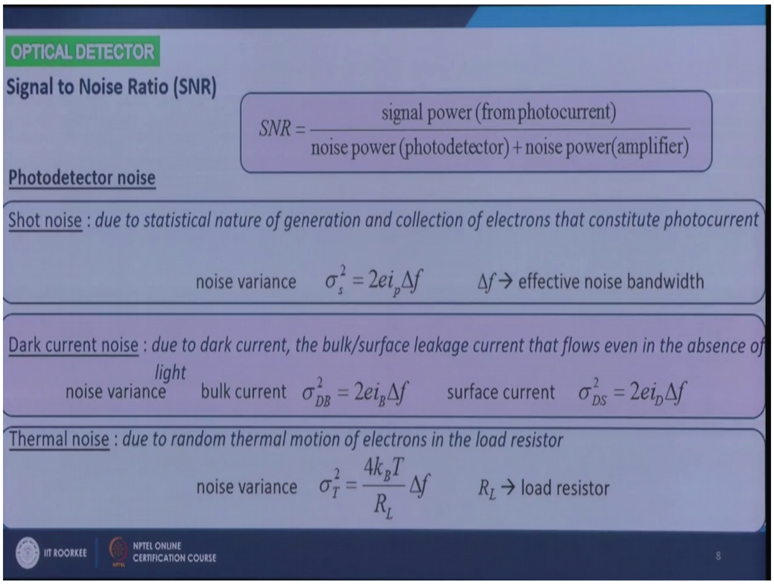

So, it is defined in the form of a ratio which is known as SNR signal to noise ratio which is nothing, but the ratio of signal power which comes from photo current divided by photo detector noise power plus amplifier noise power. So, the total noise signal power divided by total noise power. In a photo detector you have various processes by which the noise is generated; one is short noise which is due to statistical nature of generation and collection of electrons that constitute photo current. So, photo current is because of the stream of electrons which is generated and these electrons are generated at random times and collected at random times.

So, because of that there is a variance in the current and this leads to noise because of the random nature of this. So, the noise variance is given by sigma s square is equal to 2 times e times IP. I P is the photocurrent times delta f where e is the charge of an electron delta f is the effective noise bandwidth. So, this is an ampere square. So, the square root of this basically gives you the noise current corresponding to short noise then another process is the dark current. So, even if there is no optical energy if you do not incident any light on photo detector, then in the bias circuit you will still have certain current bulk current and surface leakage currents and these kind of currents are known as dark current because of this you will have noise variance.

Noise variance corresponding to bulk current is given by sigma DB square is equal to two e i b delta f, where i b is the bulk dark current and because of surface dark current it is given as sigma d s square two e i d delta f where i d is the surface dark current. Then in the photo detector circuit you will have to put a load resistor and when you put a load resistor then there is thermal noise which is generated and it is because of random thermal motion of electrons in the load resistor. Because of this the noise variance is given by sigma T square is equal to 4 K B T divided by R L times delta f where K B is the Boltzmann constant and R L is the load resistor.

So, you have all these processes by which the noise is generated and your signal should be very high as compared to these noises. Let us work out an example and see what kind of noise currents or noise variance we get in a typical semi conductor photo detector.

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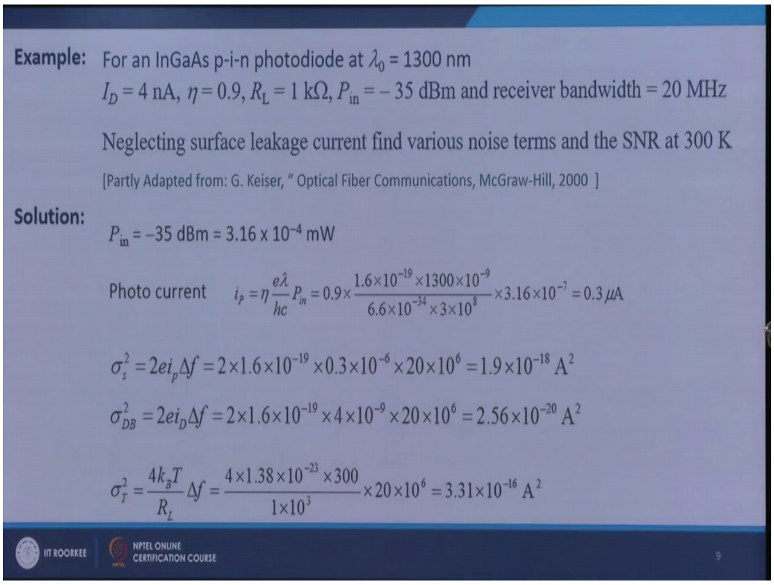

So, I take an example of indium gallium arsenide P i n photo diode at lambda naught is equal to 1300 nanometer, which has I D is equal to 4 nano amperes, quantum efficiency 90 percent, load resistor is 1 kilo om and P n is minus 35 d B m and receiver bandwidth is 20 megahertz. So, I would like to find out various noise terms and SNR at 300 k neglecting the surface leakage current.

So, this is I D is the bulk leakage currents and here I am neglecting the surface leakage current. So, I know that this is P in, P in is minus 35 d B m which corresponds to 3.16 into 10 to the power minus 4 milli watts. So, this much P in will generate a photo current depending upon this value of eta. So, I can immediately find out what would be the photo current generated with this p n. So, the photo current generated would be given by i P is equal to eta e lambda over h c times P in. So, if I plug in all these numbers this comes out to be 0.3 micro amperes.

Now, if I look at short noise then it is given by two e times i p times delta f and i p is this much delta f is 20 megahertz. So, this gives me sigma s square is equal to 1.9 into 10 to the power minus 18 amperes square. Dark current noise variance is given by two e i d delta f and i d is 4 nano amperes. So, this gives me dark current noise variance is 2.56 into 10 to the power minus 20 amperes square. Thermal noise variance is given by this if I plug in all the numbers from here into this then it comes out to be 3.31 into 10 to the power of minus 16 ampere square.

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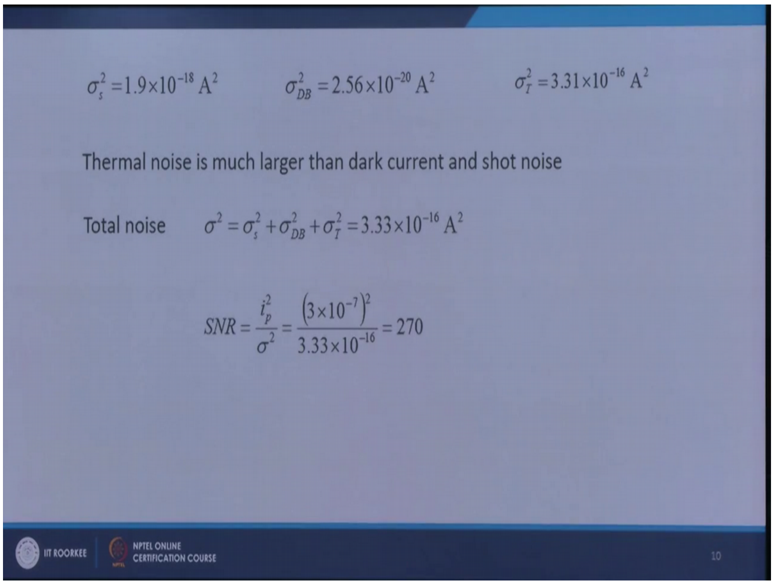

So, if I put all of them together then I have short noise, the dark current noise and thermal noise, and you can see that thermal noise dominates over dark current and short noise. So, what would be the total noise? Total noise would be the sum of all these and it comes out to be 3.33 into 10 to the power minus 16. So, most of the contribution comes only from thermal noise here from here I can calculate signal to noise ratio which is given by i p square divided by sigma square because this is equivalent to the photocurrent power and this is the noise power goes as I square.

So, when I calculate this then SNR comes out to be 270. So, this is how for any given photo detectors I can find out various noises and signal to noise ratio. Then this kind of noise can lead to errors in measurement there is I want to measure one a high bit comes a bit one comes, then there is a finite probability of detecting it as 0 and when a 0 comes then there is a finite probability of detecting it as one. So, because of this there is error in the measurement, and this is defined as bit error rate which is a way to measure the rate of error occurrence in a digital data stream.

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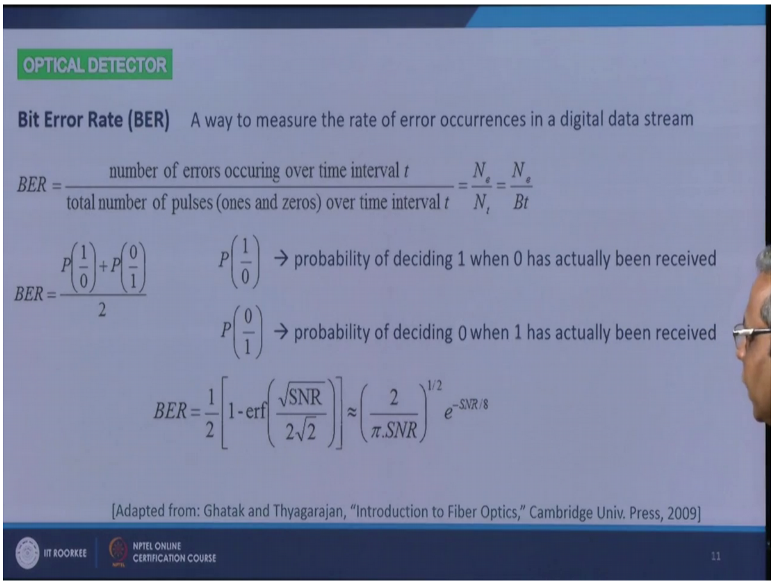

So, BER is defined as number of errors occurring over time interval T divided by total number of pulses 1s and 0s over time interval T. If the number of error occurrence says is N e and the total number of pulses or total number of bits in time interval t is N t then BER is e over N t and of course, this can be written as N e divided by b t where b is the bit rate. You can also define it as BER is equal to P 1 by 0 plus P 0 y 1 divided by 2 where P 10 is the probability of deciding one when 0 has actually been received and this is the probability of deciding 0 when one has actually been received.

You can write in write BER in terms of SNR as 1 over 2, 1 minus error function is square root of SNR divided by 2 root 2 or you can approximate it to 2 divided by pi times SNR to the power half times e to the power minus SNR by 8, and from here I can immediately see that for BER is equal to 10 to the power minus 9, SNR should be approximately equal to 144.

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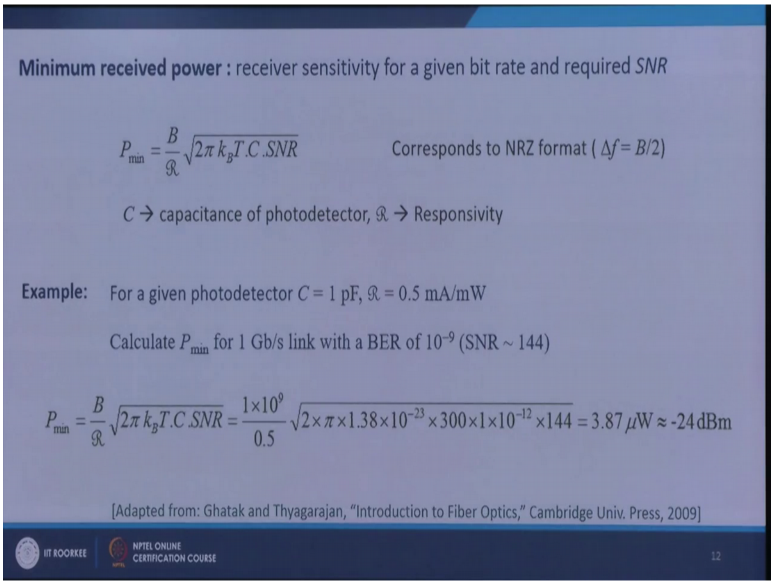

So, what is the sensitivity of a detector for a given bit rate and SNR so that I can distinguish my one from 0 very well. It is given in terms of minimum received power what should be the minimum power that a receiver should receive, and it is given by b divided by responsivity bit rate divided by responsivity times two square root of 2 pi k B T times C times SNR.

Where C is the capacitance of photo detector T is the temperature and of course, SNR is the signal to noise ratio and here this particular expression corresponds to NRZ format non return to 0 format where delta f is b by 2. Let us see an example for a given photo detector the capacitance is one pic farad, responsivity is let us say 05 milliamps per milli watt then what would be the sensitivity of the detector or minimum received power for one Gbps link if I want to have a BER of 10 to the power minus 9 which actually corresponds to SNR of 144.

So, if I plug in the numbers then P min can be given by this expression, and I put all the numbers here then it will come out to be 3.87 micro watts or minus 24 d B m. What is the ultimate detection sensitivity? And this ultimate detection sensitivity is provided by short noise limited system. If I take an ideal detector where there is no thermal noise no dark current noise and the quantum efficiency is one then bit rate is given by e to the power minus N p divided by 2.

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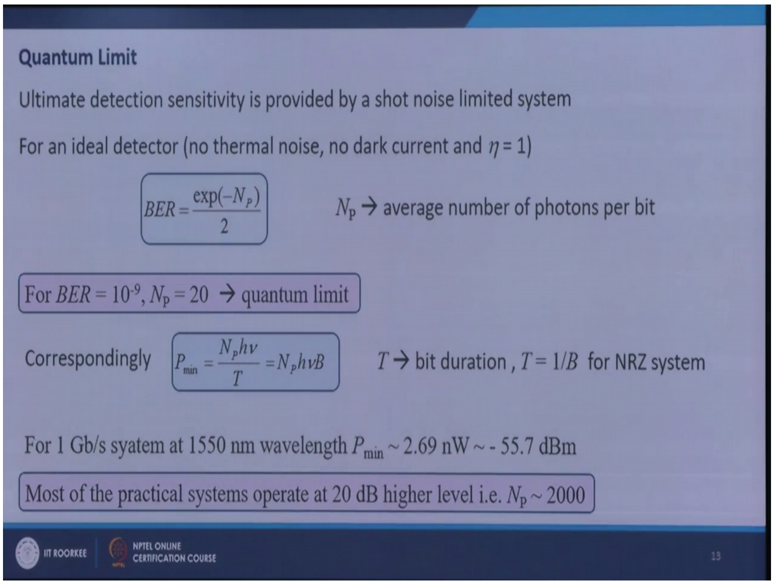

Where N p is the average number of photons per bit for BER is equal to 10 to the power minus 9, if you put it here then N p will come out to be about 20. So, this is the quantum limit and corresponds to the ultimate detection sensitivity.

What is the corresponding minimum power on the detector? Well if I know the minimum number of photons per bit then I can find out the corresponding power. So, these are the number of photons divided by the bit slot. So, number of photons per second times energy of one photon. So, this would be the P min and since T is equal to 1 over b for NRZ system then this can be written as N p times h nu time B. Let us see how much it is for one Gbps system at 1550 nanometer wavelength, if I work this out from here it comes out to be about 2.7 nano watts or minus 55.7 d B m which is really very small.

But most of the practical systems operate at 20 d B higher level that is instead of N p is equal to 20 which is ultimate quantum limit, we operate them at 20 d B higher level which is 100 times. So, N p is equal to 2000 typically, now let us power budget our optical fiber link.

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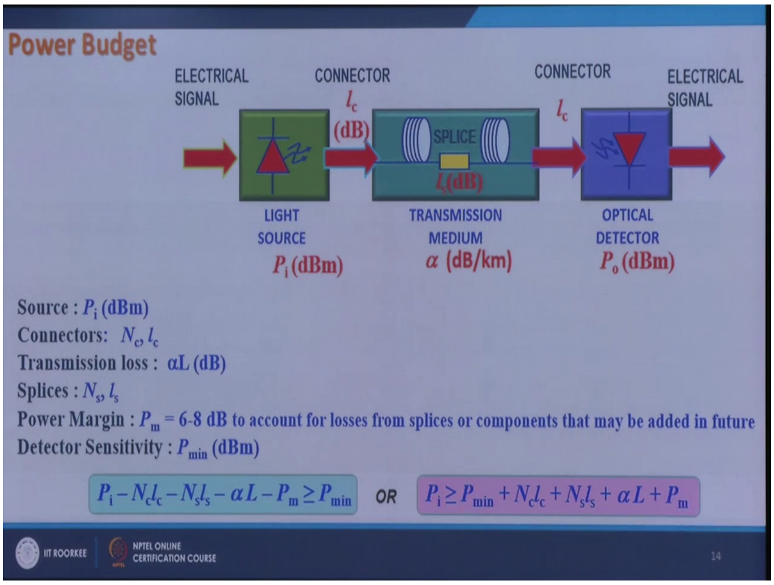

So, as we have seen that we have the light source then we have connector splices loss due to transmission medium, then sensitivity of the detectors and so on. So, how much power my light source should have or what should be the sensitivity of the detector if I take into account all the losses.

So, let us power budget it. Let me have the source power as P i in d B m everything I will I will write in d B units here for easy calculation, let us say there are N c number of connectors with l c loss each loss is again in d B, and the link has length l and transmission loss coefficient is alpha. So, transmission loss is alpha times L, they are n s number of splices with l s d B loss each then one has to keep certain power margin of about 6 to 8 d B to account for losses from a splices and components which might be added later on in the system, and if the detector sensitivity is P min in d B m, then what should I have that the source power minus losses due to connectors, minus losses due to splices minus transmission loss minus the power margin.

So, if I subtract all these losses from my input power, then this is what the power is left at the output end, and it should be greater than or equal to the sensitivity of the detector which is P min. So, I should be able to fulfill this condition or I can say that the source power should be greater than this which is one or the same thing, let us understand it with the help of an example.

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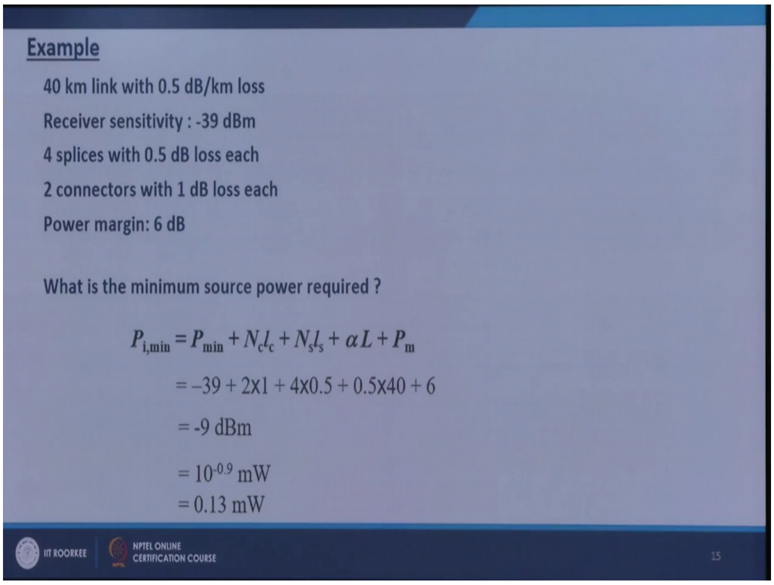

Let me have a forty kilometer link with 0.5 d B kilometer 0.5 d B per kilometer loss receiver sensitivity is minus 39 d B m.

I have four splices with 0.5 d B loss each two connectors with 1 d B loss each and let me put a power margin of 6 d B, then what is the minimum source power which I would require. Well the minimum source power would be P min plus N c l c plus N s l s plus alpha L plus P m and since everything is in d B unit. So, I just put them here and add them up. So, this gives me P i minimum equal to minus nine d B m which in linear units is nothing, but 0.13 milli watts. So, this much power I should have from my source.

Now, let us look into dispersion limited system and attenuation limited system what is the attenuation limited system? In attenuation limited system dispersion is not a major concern and repeater less length of the link is limited by attenuation.

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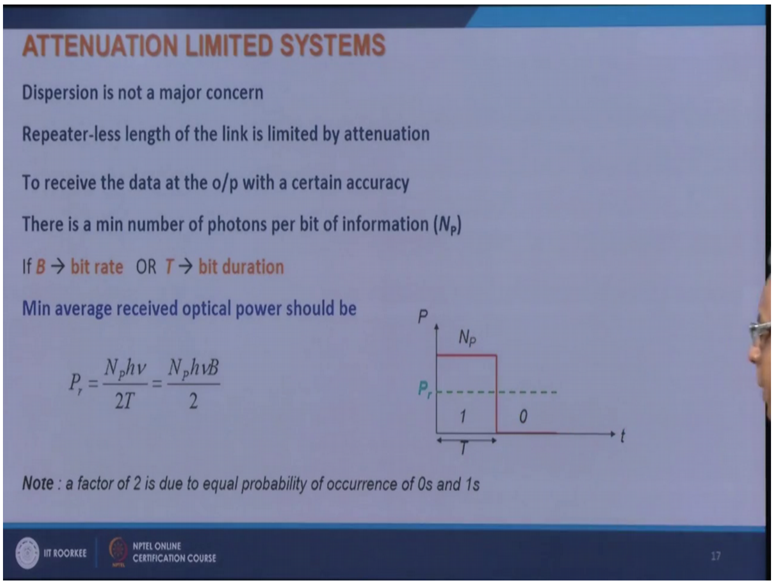

So, how do I get this? Well to receive data at the output end with certain accuracy, I need to have minimum number of photons per bit information and if B is the bit rate and T is the bit duration, then the minimum average received optical power should be N p h nu divided by 2 T which is N p h nu B divided by 2.

I will tell you why I have taken the factor two here as compared to in the previous slide, because I have in my system 0s and 1s. So, I have n number of 0s n number of 1s and I assume that all these 0s and 1s have equal probability of occurring occurrence. So, the average power per bit would be the power here divided by 2 50 percent of that. So, this would be the minimum average received optical power.

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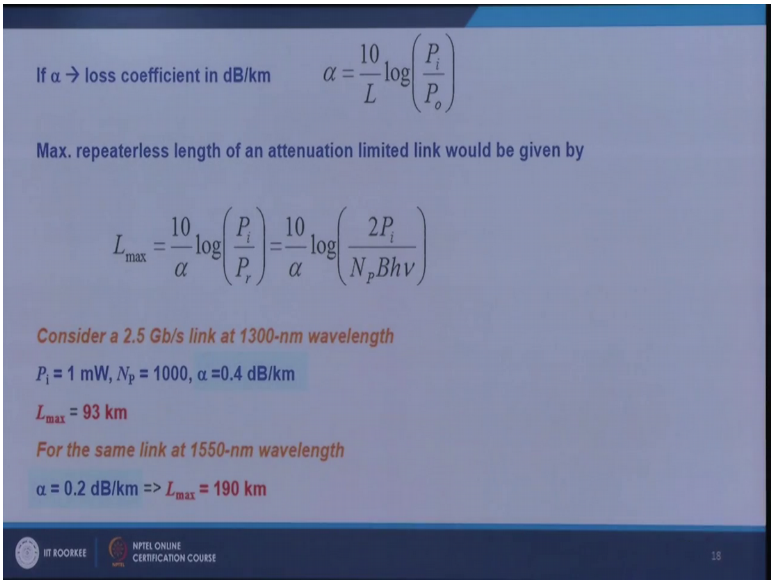

Now, if alpha is the loss coefficient d B per kilometer, then alpha is equal to ten divided by L log P i over P out and. So, the L max is equal to 10 divided by alpha log P i divided by P r which is minimum average received power, and if I put the expression for that from previous slide it comes out to be like this.

So, if I consider a 2.5 Gbps link at 1300 nanometer wavelength with P i is equal to one milli watt and P is equal to 1000, minimum number of photons which are required and at 1300 nanometer wavelength alpha is 0.4 d B per kilometer then L max from here will come out to be 93 kilometers. If I use the same link at 1550 nanometer wavelength then loss goes down from 0.4 d B per kilometer to 0.2d B per kilometer and L max will become 190 kilometers.

Next is dispersion limited system where attenuation is not a major concern and repeater less length of the link is decided by the dispersion in the system.

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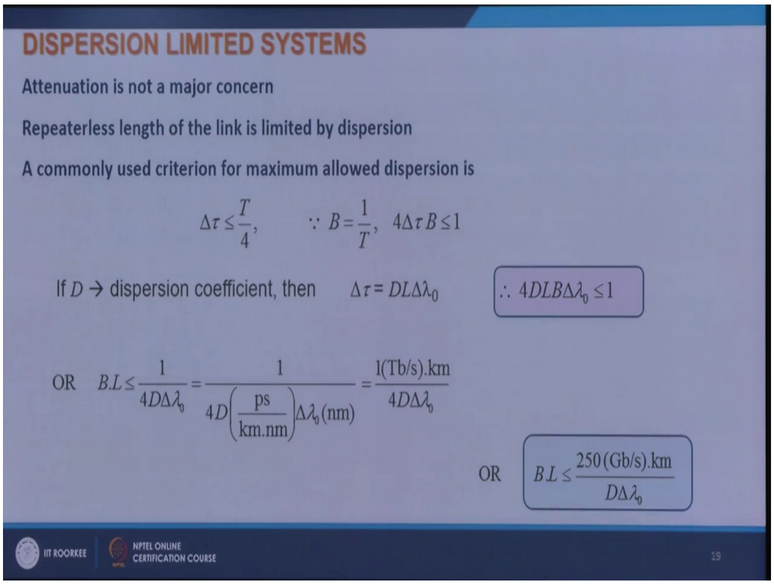

And a commonly used criterion for maximum allowed dispersion is that the broadening should be less than or equal to T by 4 where T is the bit slot or bit duration and since B is equal to 1 over T. So, I can write this as 4 times delta tau times B is less than or equal to 1.

Now, if I have a link which has a dispersion of dispersion coefficient D which is in pico seconds per kilometer nanometers. So, delta tau would be D times L length of the link times delta lambda 0 which is the spectral width of the source. So, if I put this one here then I get this is four times D times L times B times delta lambda naught should be less than or equal to 1, this gives me what is the bandwidth length product for a given dispersion. So, this bandwidth length product B times L should be smaller than or equal to one over 4 D times delta lambda naught, D is in picoseconds per kilometer nanometers delta lambda naught I put in nanometers.

So, this comes out to be 1 Tb p s kilo meter divided by 4D times delta lambda naught where D is in pico seconds per kilometer nanometers and delta lambda naught is in nanometers or I can write it down because one T b p s over 4 is 250 G b p s. So, it is 250 Gbps kilometers divided by d delta lambda naught, let us work out an example and conclude.

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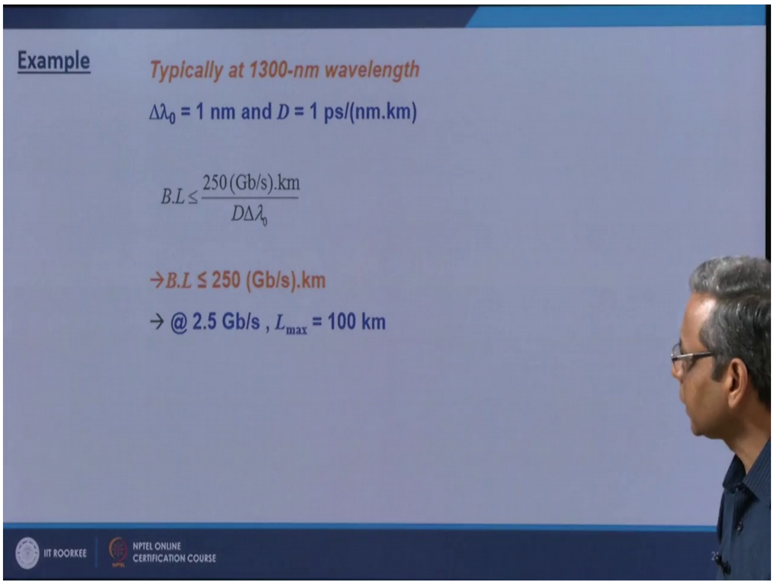

So, if I have a system with b is equal to 1 picoseconds per kilometer nanometer at 1300 nanometer wavelength with delta lambda naught is equal to 1 nanometer which is the typical system at 1300 nanometer wavelength you have very small dispersion.

Then b times till B times L would be less than or equal to 250 Gbps kilometer here because D is 1 delta lambda naught is one which means that which means that if I want to send pulses at the rate 2.5 Gbps, I can have maximum repeater less length of the link is100 kilometer.

So, this is all in system design aspects. In the next lecture I would look into certain measurement techniques in optical fibers.

Thank you.