Fiber Optics
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Lecture – 06
Transmission characteristics - I

In the next three lectures we are going to see what happens to optical pulses when they propagate through an optical fiber. And in these three lectures we will concentrate only on multimode fiber and see what happens to the pulses.

So, I will start with these transmission characteristics of an optical fiber, and part one and in this part I will concentrate on attenuation of signal.

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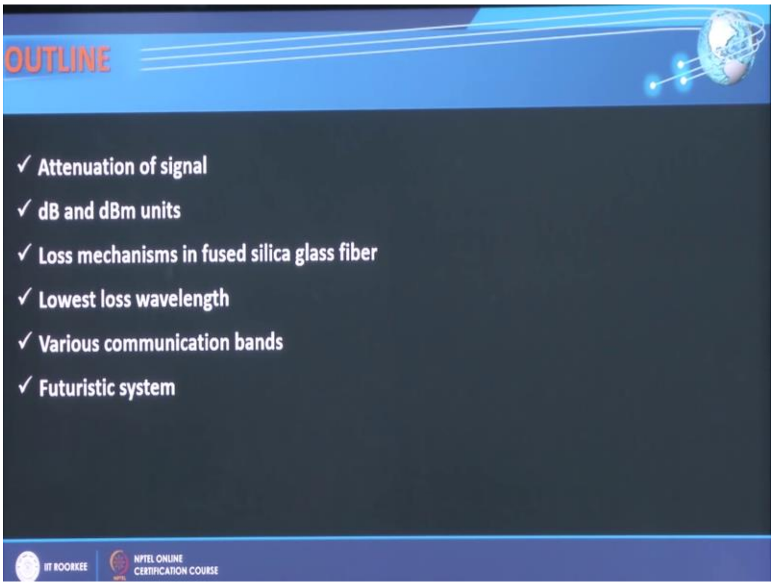

In order to understand attenuation of signal and do calculations, particular units dB and dBm units are very handy.

So, we are going to look into these units, then what are the lost mechanisms in fused silica glass fiber; at what wavelength you have the lowest loss, what are various communication bands and what is a futuristic system we are looking at. So, these things we are going to do in this lecture. So, let us look at the propagation of optical pulses through an optical fiber; so if I have my data encoded in a pulse train, your optical pulse train a sequence of 0s and 1s.

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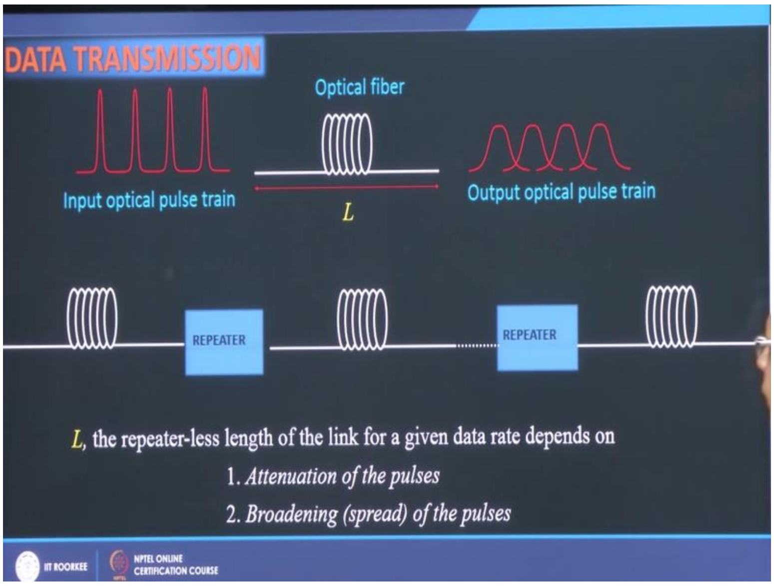

And when I send this pulse train through an optical fiber, then at the output end the shape of the pulses becomes something like this. What I notice here is the amplitude of these pulses the power level of these pulses it goes down, and at the same time the duration of pulses increases.

So, when I send these pulses through optical fiber and the pulses become like this, then I will have to pay attention I will have to take care that these pulses do not overlap; also the power level of the pulses should remain at such a level that, the optical detector should be able to detect them otherwise I will lose information. So, before these pulses are overlapped or their power levels go down to beyond a certain limit, I will have to reshape the pulses. I will have to bring them to their original form and this is done in a device known as repeater.

So, in a communication link you send pulses through optical fiber and then after a certain distance you will have to reshape the pulses, and bring them to their original form and then you again send it to the next segment and then to the next segment and so on. If L is the repeater less length of the link then this repeater less length of the link for a given data rate depends upon two things; one is how much the pulses have attenuated and what is the spread of these pulses what is the broadening in these pulses so that they do not overlap.

So, we are going to look into these two things in next lectures next few lectures, in this particular lecture I will pay attention to the attenuation problem. So, what is attenuation that the power at the input end which I sent through an optical fiber.

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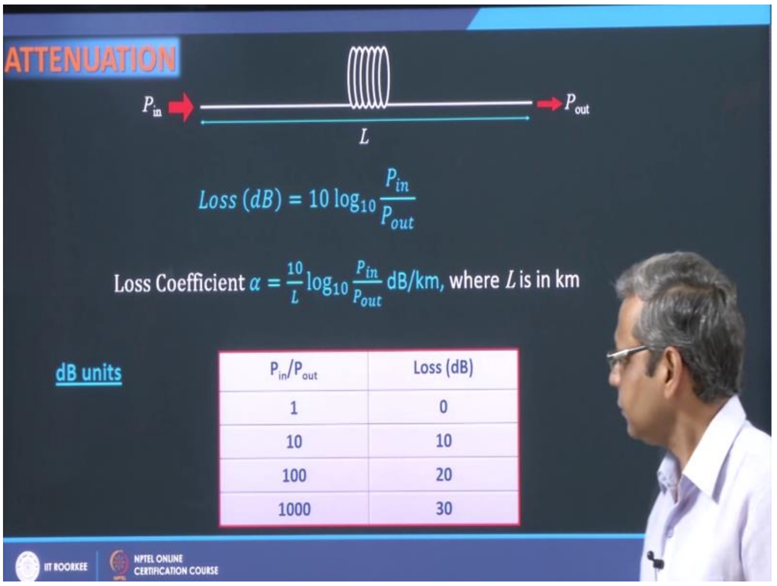

If it is P_{in} , and the power that I receive at the output end is P_{out}, then I define the loss of the link loss of this fiber through length L as in dB units $10\log_{10}(\frac{P_{in}}{P_{out}})$. So, this is the loss in dB through L length of an optical fiber, it is often convenient to represent this loss in terms of loss coefficient, which is loss in dB per kilometer length of the fiber. So, I divide this thing by L and I get this loss coefficient α in dB per kilometer units where L is in kilometers.

It would be nice to have a conversion from linear to dB units. So, if P_{in} over P_{out} is one then there is no loss, the loss is 0 dB if it is a factor of 10 then it is 10 dB a factor of 100 means 20 dB and a factor of 1000 means it is 30 dB loss. To facilitate calculations, it is also convenient if I represent power also in terms of dB units, but dB units involve log and I can take log of only a ratio. So, how would I represent power which is in milli Watt or power in watt into dB units, for that I take a reference.

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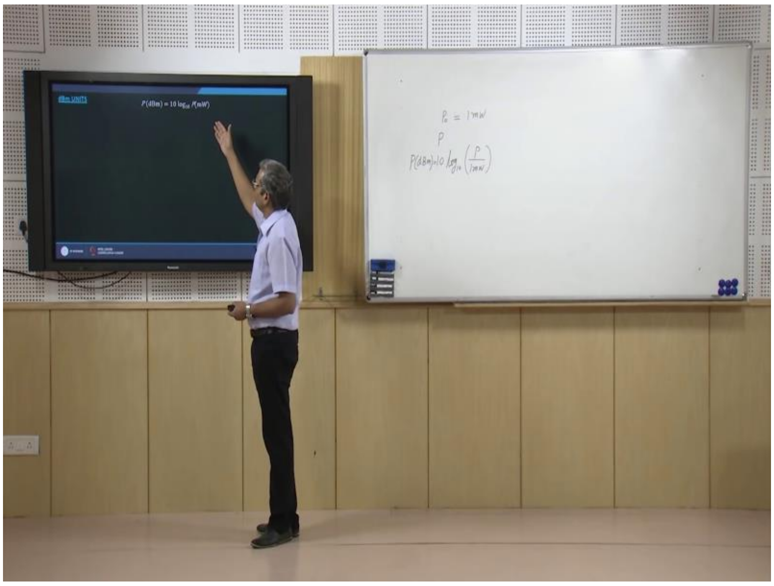

For example if I take a reference of 1 milli watt. So, if I say that P_0 reference is 1 milli watt, then I can whatever power I want to now represent in dBm that I can take with reference to this. So, I take ratio of this P with my 1 milli watt and then take its log at base 10 multiply it by 10, then it becomes power in dBm units. So, here it is the same that if I want to represent power in dB units.

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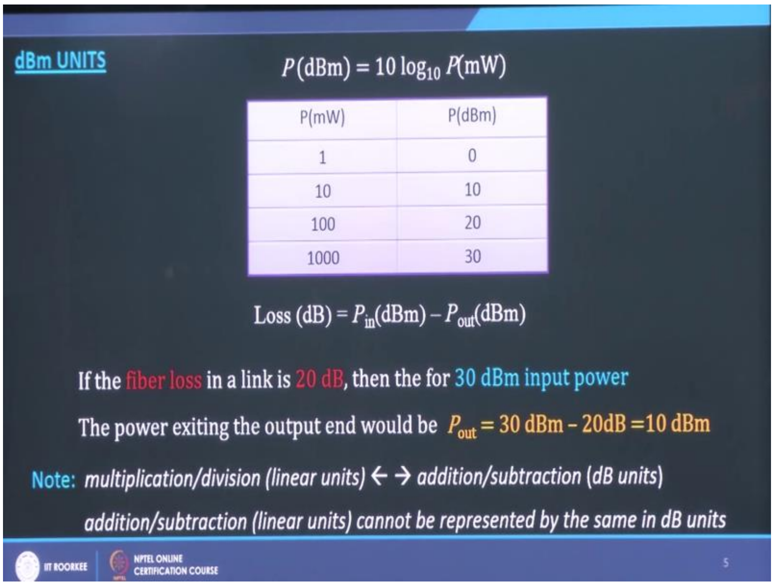

So, I can represent it as log of power when I represent power in milli watt and then multiply it by 10, then it is dBm units m stands for milli watt that is I am taking the reference as milli watt you can also have dBw units when the reference is one watt. And this is the conversion if the power is 1 milli watt then it is basically 0 dBm, but 10 milli watt of power is 10 dBm, 100 milli watt power is 20 dBm and 1000 is 30 dBm and so on.

Similarly, if I go below 1 milli watt let us say I have 0.1 milli watt power, then it is minus 10 dBm. So, in this way we will represent power and using dB units the and dBm units the calculations become very easy for example, I can now represent loss by simply this P in dBm units minus P out in dBm units. So, if I have a fiber in a link and the loss is 20 dB, and I have the input power into the fiber 30 dBm, then the power at the output end would be simply 30 dBm the input power minus the loss 20 dB. So, it would be simply 10 dBm.

But I should be very careful that I know that if there is multiplication or division in linear units, then it would correspond to addition or subtraction in dB units. However, if I have addition or subtraction in linear units I cannot represent it in dB units. So, I should be careful while using this. Now let us look at loss in glass, how the transmission in glass evolved over time. So, here I have plotted optical loss in dB per kilometer with time which has been taken from IEEE circuits devices magazine 1989.

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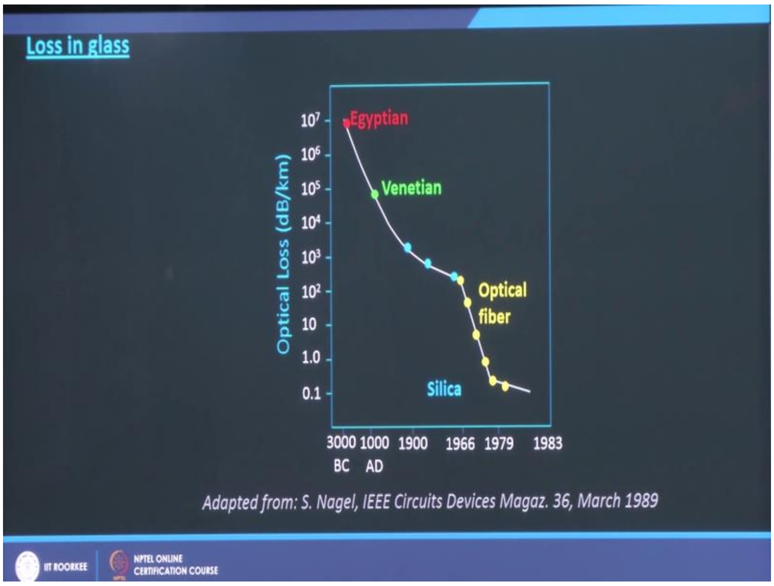

So, if I look at it you please look that on x-axis, it is not equally divided years equally divided scales.

So, see if I look at Egyptian aged around 3000 BC, the loss in glass was something like 10 to the power 7, 10 to the power 7 dB per kilometer. When you come down to Venetian age then the loss is about 10 to the power 5, the glass was almost opaque you cannot see through this then in 1900 around 1000 dB per kilometer, and if you look around late sixties or in mid-sixties the loss was around 100 dB per kilometer, that is where Charles K Kao proposed that the loss should come down to 16 dB per kilometer for the fiber to be used in telecommunication.

So, it was that point from here now you see the optical fiber came up low loss optical fiber came up this is the point representing 1970, the fiber produced by Corning glass work which was having a loss of 16 dB per kilometer, and then you see a sharp fall you see here it is 3000 BC 1000 AD and then 1900, 1966 and you see the time difference is much smaller here. From 1966 to 1979 within 13 years you can see how much advancement has been done, and how much the attenuation could be brought down in an optical fiber, and now we have a fiber which has a loss of 0.2 dB per kilometer.

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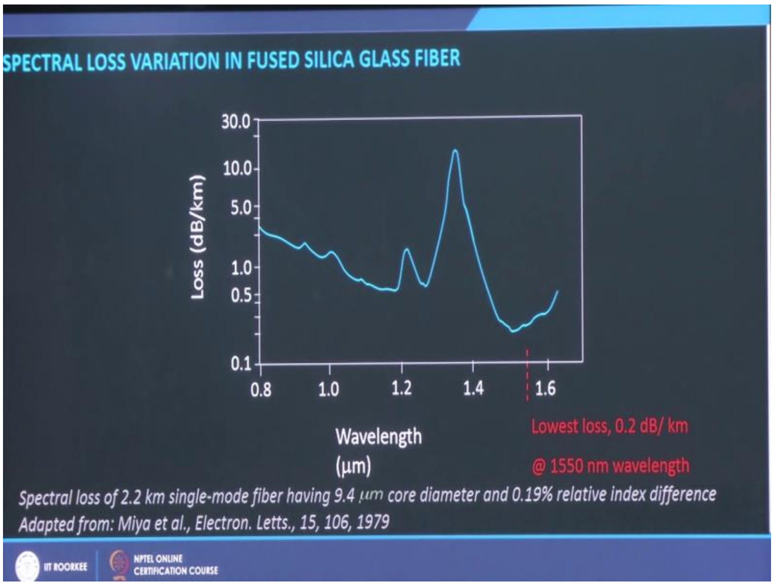

And if I look at the spectral loss variation in fused silica glass fiber it looks like this, this is the spectral loss of 2.2 kilometer single mode fiber with core diameter of 9.4 micrometer and about 0.2 percent relative index difference.

So, if you look at this, then I see certain trends here. One is Rayleigh scattering you can see that towards shorter wavelengths the loss increases and if I see this trend carefully then I will find out that it goes as one over lambda to the power 4. So, it is Rayleigh scattering, another trend that I see is infrared absorption, it is the tail of infrared absorption which extends into this region, and these two are water peaks. Now these two very high peaks are water peaks OH ion absorption and here I have the lowest loss at 0.2 dB per kilometer which occurs at 1550 nanometer wavelength.

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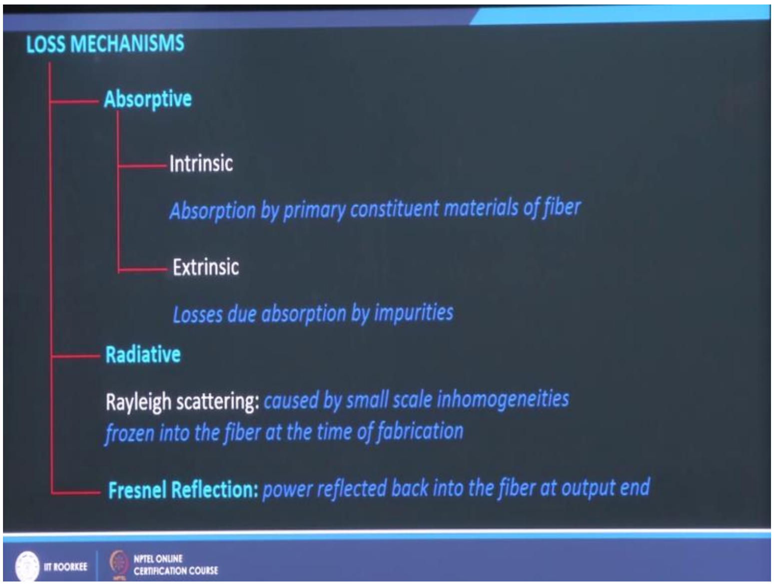

Now, what are the lost mechanisms in an optical fiber what causes loss?

So, there are various mechanisms, I can divide them broadly into three, one is absorptive, another is radiative, and yet another is Fresnel reflection. In absorptive loss mechanism I divided into two intrinsic which is the absorption by primary constituent materials of the fiber, and an extrinsic which is the losses due to absorption by impurities. In radiative it is primarily Rayleigh scattering and then we have Fresnel reflection which is caused by index contrast at the output end of the fiber. So, let us first look at intrinsic loss.

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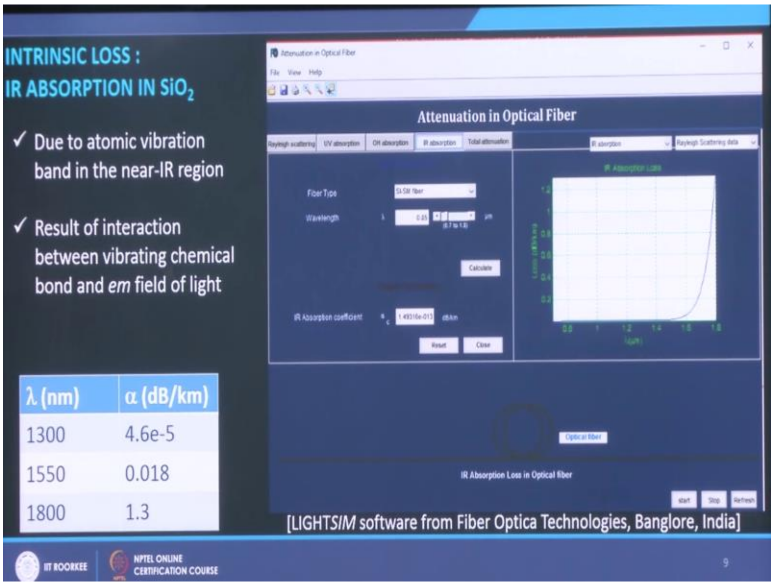

So, it is IR absorption in SiO_2. So, first I look at IR absorption it has SiO_2, which is this. So, what I can see is that as I go towards longer wavelength side, the IR absorption in silica glass increases it has a peak beyond two micron. So, it is the tail of that peak which comes into this wavelength window, and this ~~I~~ IR absorption is due to atomic vibration band in the near IR region and it is the result of interaction between vibrating chemical bonds and electromagnetic fields.

So, these electromagnetic fields give energy to these vibrating chemical bonds, and this causes attenuation in this wavelength range. I have marked here three wavelengths at 1300 nanometer it is very small 4.6×10^{-5} dB per kilometer, at 1550 nm, it is 0.018 dB per kilometer, and as I go towards two micron at 1800 nanometer wavelength it becomes 1.3 dB per kilometer, and beyond that it even increases, it further increases. This is the snapshot of a software LightSim which is available with fiber Optica Technologies, Bangalore.

Next is UV absorption by primary constituent materials of the fiber which can be silica or germanium doped silica, and it is due to electronic absorption band in the UV region. So, it goes like this, and since the core is usually doped with germanium; if I look at that then I see that it increases with germanium concentration in the core, but this loss is much much smaller if I go to infrared region. At 800 nanometer wavelength the loss is 00.19 dB per kilometer which decreases to 0.036 dv per kilometer as I extend into infrared region at 1100 nanometer then at 1300 nanometer, it is even down 0.018 and at 1550 just 0.01 dB per kilometer.

So, I can see that if I look at 1550 nanometer wavelength which is lowest loss for fused silica glass fiber, contribution of UV absorption is negligible.

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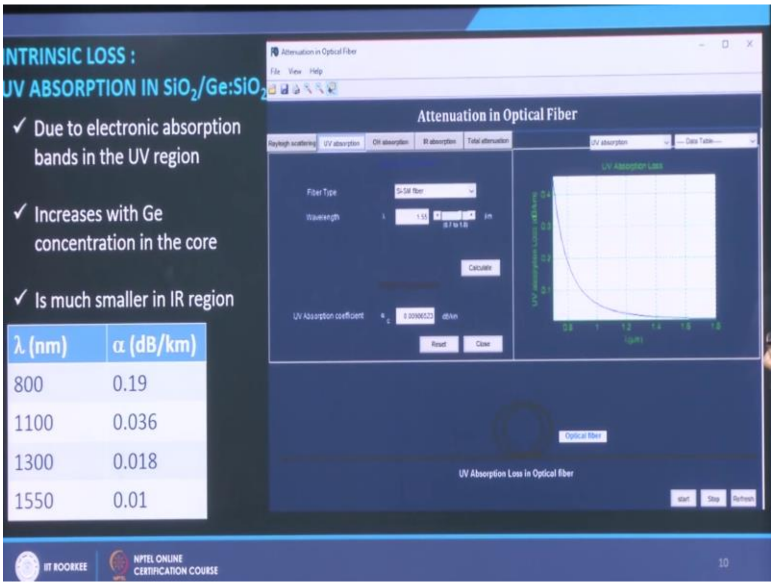

It is just 0.01 and I had also seen that at 1550 the IR absorption loss contribution is also very small 0.018.

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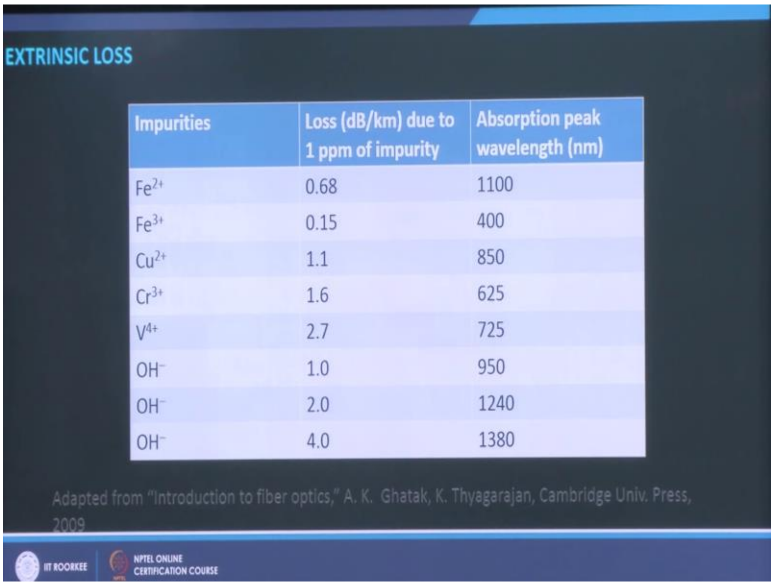

Next is the extrinsic losses in an optical fiber which are caused by various impurities in the fiber. So, here in this table we are showing what are the losses and at what wavelengths they occur due to various impurities of for example, iron, copper, chromium, vanadium and water.

So, this is the loss in dB per kilometer due to 1 ppm of impurity, and these are the absorption peaks. For iron I can see that for Fe 2 plus it is as large as 0.68 dB per kilometer which occurs at 1100 nanometer wavelength, for chromium it is 1.6 dB per kilometer at 625 nanometer wavelength, and I see two very large water peaks here out of three these two are very large at 1240, 2 dB per kilometer and at 1380, it is 4 dB per kilometer due to 1 ppm of impurity.

But now tremendous advancement has taken place, and people have now got rid of most of the impurities and even the water ok.

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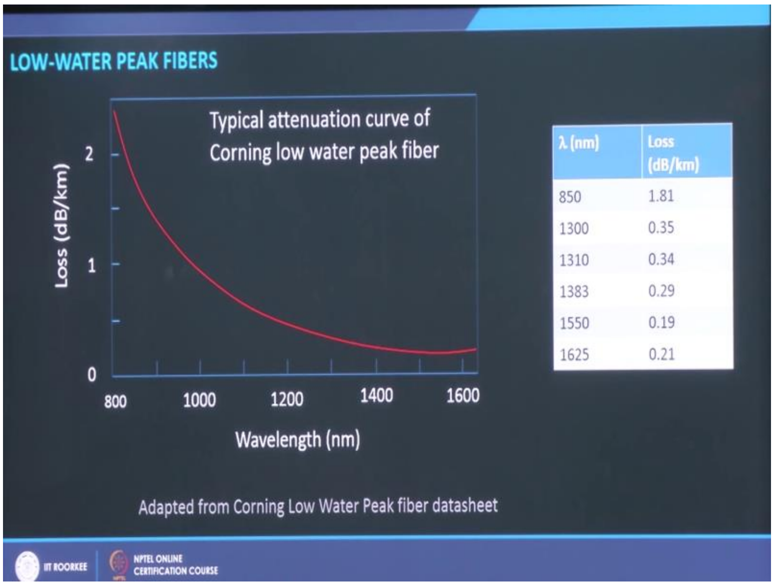

So, this is state of the art fiber from Corning glass works, which is low water peak fiber and I can see here that it is very smooth attenuation curve and it does not have any peaks and if I look at losses at various wavelengths, it is extremely small loss. So, you can see near 1380 nanometer wavelength, where we had very large water peak, now it has loss of only 0.29 dB per kilometer, at 1550 it has a loss of 0.19 dB per kilometer.

Apart from these absorptive loss mechanisms, we have radiative loss mechanism and this is primarily due to Rayleigh scattering and this is caused by wavelength scale in homogeneities which are frozen in the fiber during the process of fabrication.

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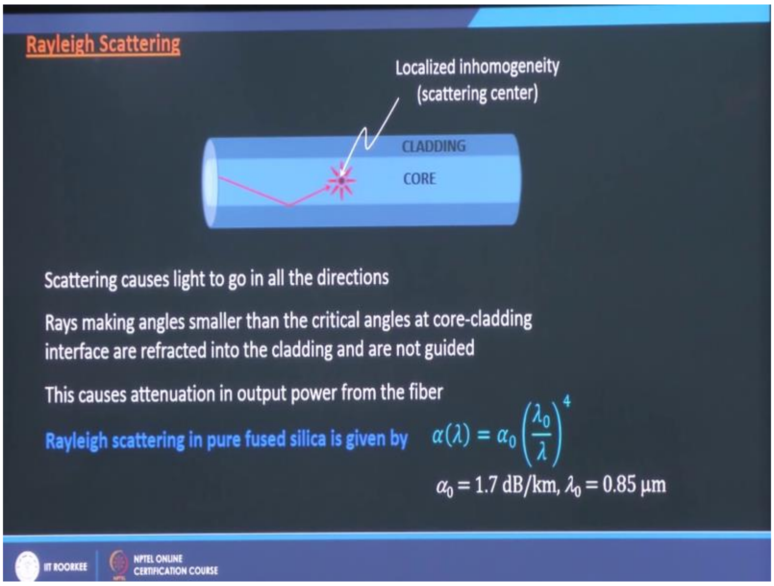

So, you have scattering centers which are developed during the fabrication process, and when light hits any of these scattering centers that it scatters light in all the directions. When its scatters light in all the directions, then only the rays here which make larger angle from the normal of core cladding interface, they are totally internally reflected and are guided, while all the other rays are reflected into the cladding and are lost. And this causes attenuation in the fiber in the output power from the fiber; and this Rayleigh scattering loss in pure fused silica is given by this relationship which has been obtained by empirical fitting alpha at any wavelength lambda is given by alpha 0 times lambda 0 over lambda to the power 4, where alpha 0 is 1.7 dB per kilometer, and lambda 0 is 0.85 micrometer.

So, if I know this formula I can find out loss at any wavelength. So, this shows how Rayleigh scattering loss varies with wavelength, and I can see that as I decrease wavelength the loss increases. Really scattering loss at three representative wavelengths at 850 nanometer it is 1.9 dB per kilometer, at 1300 nanometer wavelength it is 0.35 dB per kilometer and at 1550 it is 0.18. So, you can see at 1550 nanometer wavelength the Rayleigh scattering loss is 0.18, and total loss is around 0.2 dB per kilometer.

So, major contribution to loss at 1550 nanometer wavelength comes from Rayleigh scattering.

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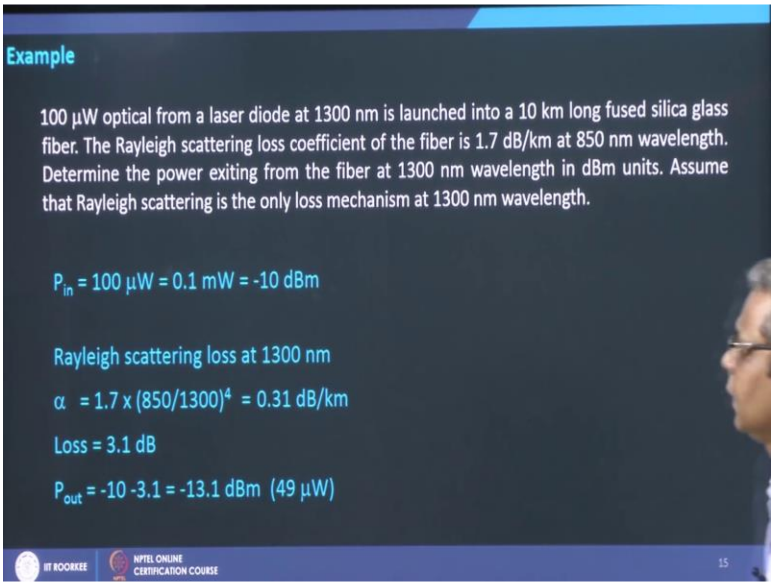

Let us take one example if I have a laser diode at 1300 nanometer wavelength and I launch about 100 micro watt of power from this laser diode, into a 10 kilometer long fused silica glass fiber, and if I know that the Rayleigh scattering loss coefficient of the fiber is 1.7 dB per kilometer at 850 nanometer wavelength, then what would be the power which would be exiting at the output end of the fiber.

So, if I now calculate of course, the calculation would be simpler if I use dB units. So, I convert this input power which is 100 micro watt into dBm units. So, P_{in} is minus 10 dB m minus 10 dBm and now if I calculate Rayleigh scattering loss coefficient at 1300 nanometer wavelength, then it comes out to be 0.31 dB per kilometer. Since it is 10 kilometer long fiber so the total Rayleigh scattering loss would be 3.1 dB, and P_{out} would be simply minus 10 dBm minus 3.1 which is minus 13.1 dBm. If you convert it into linear units it will come out to be about 50 micro watt and it is obvious.

Since the loss is 3 dB then the power that will come out would be 50 percent of input power. Now the next is Fresnel reflection when light hits the output end of the fiber, then there is a there is an index contrast.

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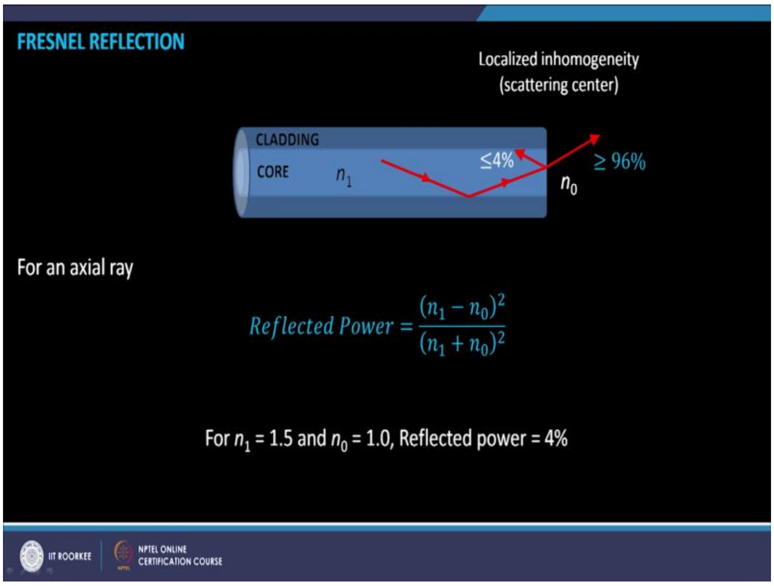

Here you have core with refractive index n_1, and here you have air and refractive index n_0 which is 1 basically. And I know that for an axial ray because of this index contrast if I calculate the reflected power, then it is given by n_1 minus n_0 whole square divided by n_1 plus n_1 whole square and if it is glass. So, for glass I if I typically take n_1 is equal to 1.5 and n_0 for air is one then the reflected power is about 4 percent.

So, here I will have at least 4 percent power will be reflected, and here I will have more than 96 percent power which will go out of the fiber.

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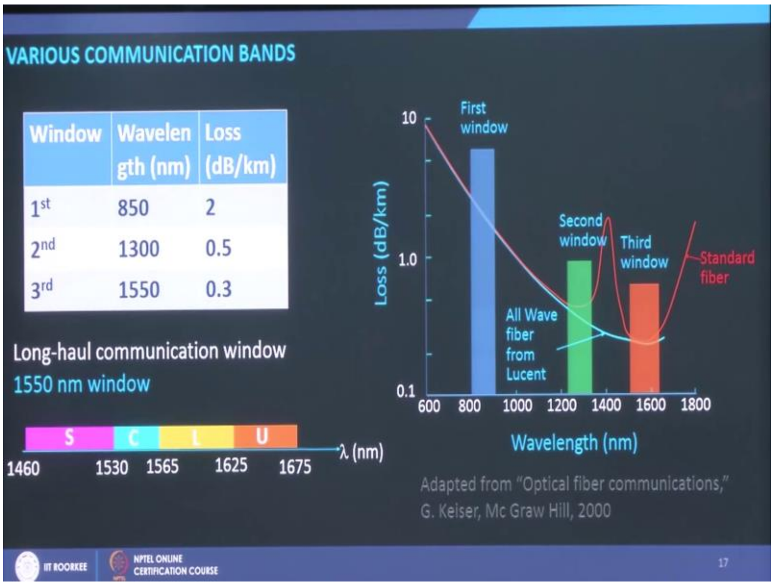

These are various communication bands here I can see the attenuation curve and various communication bands, this is the first window which is centered around 850 nanometer wavelength, this is the second window which is centered at 1300 nanometer wavelength, and has a loss of typically 0.5 dB per kilometer, and this is the third and latest window which is used in long haul telecommunication, which is centered around 1550 nanometer wavelength, and has a loss up to 0.3 dB per kilometer.

And in this 1550 nanometer window itself we have several bands, the conventional one which is also known as C band ranges from 1530 to 1565 nanometer, then there is a short band ranging from 1460 to 1530 nanometer wavelength, long band from 1565 to 1625 and U band which is ultra long 1625 to 1675 nanometer wavelength.

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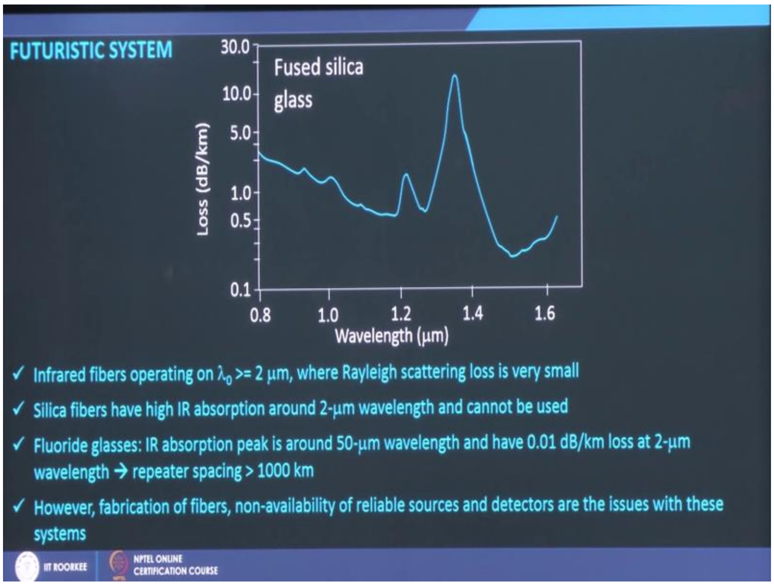

Then what is the futuristic system, can we still bring down the loss of the optical fiber. In silica glass fiber I have seen that the lowest loss wavelength is 1550, where the effect of Rayleigh scattering has almost diminished, and the effect and the tale of infrared absorption has also almost died down. I know that if I increase the wavelength further if I go towards longer wavelength, then I can still decrease Rayleigh scattering loss. For example, if I operate around 2 micrometer wavelengths, the Rayleigh scattering loss can be brought down too much.

But at the same time if I use silica glass fiber then infrared absorption is very high infrared absorption is very high at around 2 micrometer wavelength. So, I cannot use silica glass fiber if I work at 2 micrometer wavelength, then what to do. We will have to look for other materials where the infrared absorption is much smaller, and one option is fluoride glasses where the infrared absorption peak is at around 50 micrometer wavelengths, and a 2 micron wavelength the loss is infrared absorption loss is 0.01 dB per kilometer.

So, you see right now I have the loss of about 0.2 dB per kilometer, I can bring it down to 0.01 dB per kilometer, if I use fluoride glasses which means I can have repeater spacing's more than 1000 kilometers, which is presently around 100 kilometer. However, there are problems that there are fabrication problems of the fiber, then we need to have sources at 2 micrometer wavelength which we can use we should have detectors at 2 micrometer wavelengths. So, these reliable optical sources and detectors are still not available. So, work is going on, but still they are not fully commercialized.

So, these are some issues with fluoride glass fiber system. So, what are the points to remember in this lecture?

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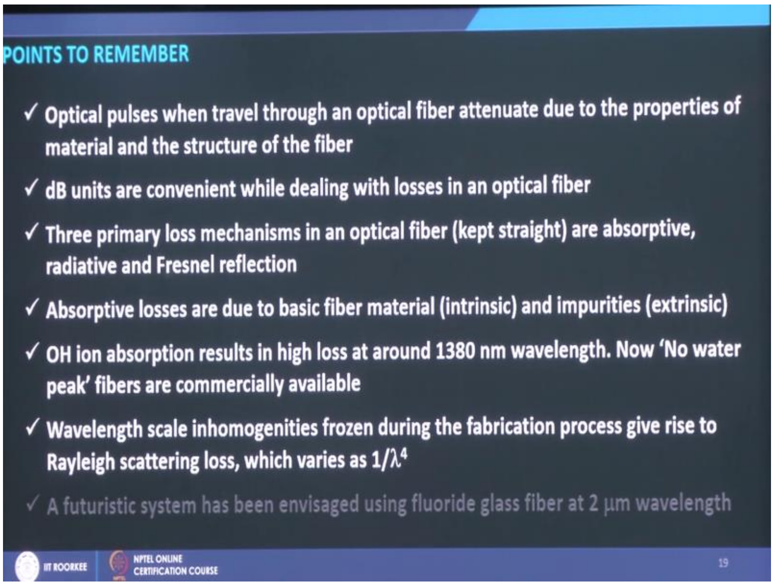

We have seen that the optical pulses they broaden and attenuate when they travel through an optical fiber, then we looked into dB units which become very handy while dealing with losses and optical fibers, and three primary loss mechanisms in an optical fiber which has been kept straight we have still not bent the fiber, these three mechanisms primary mechanisms are absorptive, radiative and Fresnel reflection.

Absorptive losses are due to basic fiber materials, it can be silica or germanium doped silica, and extrinsic are due to impurities, and in impurities OH ion absorption results in high losses at around 1380 nanometer wavelength, but now there are no water peak fibers are commercially available. And we had also seen that wavelength scale in homogeneities which are frozen during the fabrication process of an optical fiber, caused scattering and this is get Rayleigh scattering loss, and this Rayleigh scattering loss varies as 1 over lambda to the power 4. Then a futuristic system has also been envisaged using fluoride glass fibers at 2 micrometer wavelength.

Thank you.