Advanced Optical Communications

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Lecture No. # 09

Signal Distortion – II

In the last lecture, we started discussing one of the very important aspects of optical communication, and that is signal distortion.

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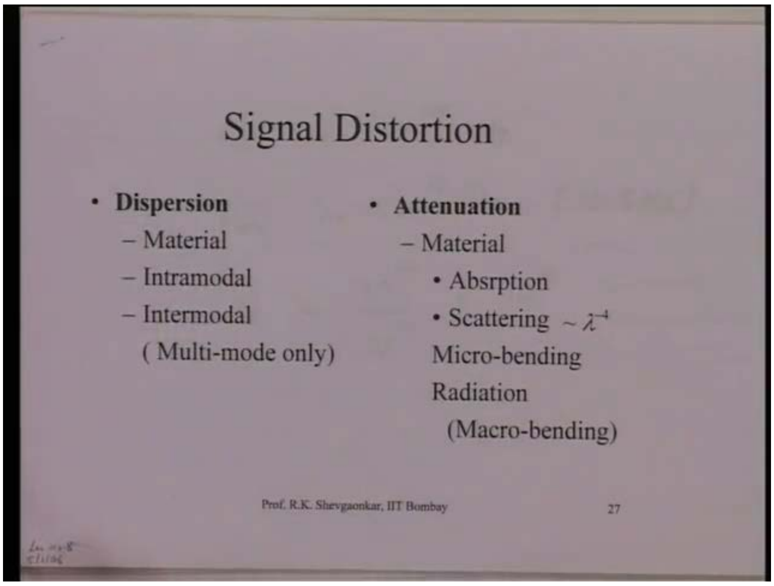

We saw that the signal is distorted, when it is sent on optical fiber for two reasons; one is what is called dispersion, which essentially is the pulse broadening as the pulse travels on optical fiber; and other one is the attenuation or loss of energy as the pulse propagates on the optical fiber.

Then we saw the dispersion could be due to various reasons, it could be intrinsically because of the material properties, we call it as the material dispersion or it could be because of the modal nature propagation inside the optical fiber, that we call as the intramodal dispersion, and then because of the multiple modes propagating on the optical fiber, we have what is called the intermodal dispersion. And then we saw that in a single mode optical fiber, we have material dispersion and intramodal dispersion present. Whereas in a multimode fiber all three dispersions are present, but intermodal dispersion is much higher compared to these two dispersions. The attenuation that is the loss of energy as the pulse propagates could be various reasons and we will discuss this subsequently.

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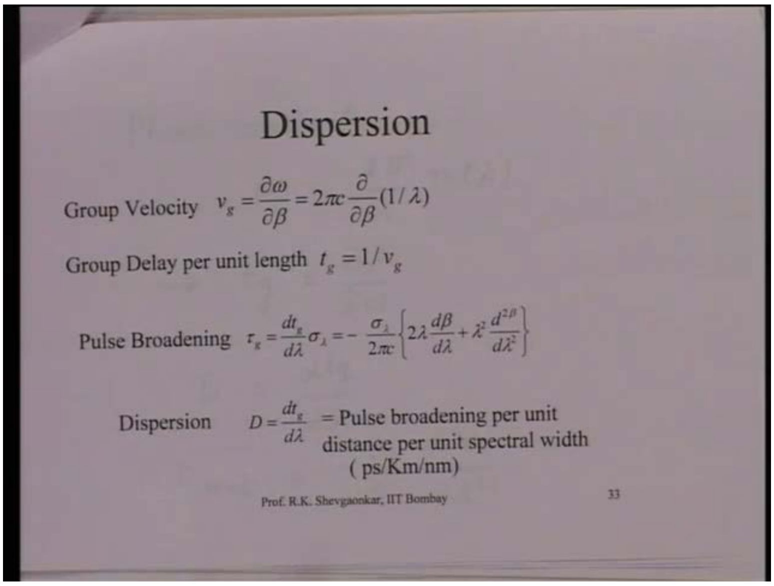

So, in last lecture we started discussing in detail this quantity dispersion. We define dispersion quantitatively and that we said if you have the relationship between omega and beta then from there we can calculate what is called the group velocity, that is, the velocity with which the pulse travels on optical fiber. Inverse of this quantity is what is called the group delay per unit length, that is this t g and then we said the dispersion is nothing, but dt g by d lambda that is rate of change of group delay with respect to the wavelength and then we got the unit for dispersion which is Picosecond per kilometer per nanometer.

With this basic mathematical formulation, then we started investigating dispersions one by one that is, material dispersion and then waveguide dispersion and intramodal dispersion. However, we said that since the dispersion is rather a weak phenomena. We quantitatively calculate the dispersion due to one phenomena at a time assuming that the other dispersion is not present and the then the total dispersion is sum of the two dispersions. So, when we started discussing the material dispersion, we assume that the wave guiding nature for the dispersion due to the modal nature inside the fiber is not present; that means, the energy is propagating as if it is propagating in infinite medium and then just due to because of the material properties, we have the dispersion that we call as the material dispersion.

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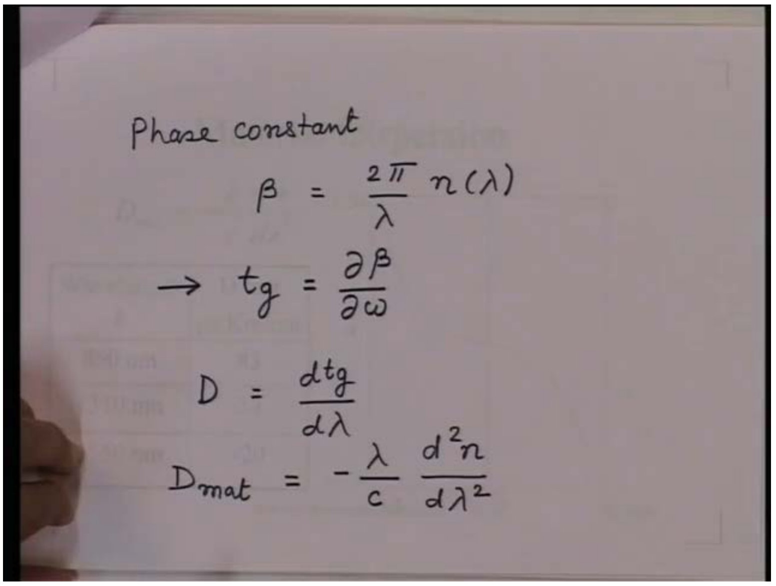

So, starting with the phase constant for a unbound medium and saying that now, the refractive index of the medium is a function of wavelength. We calculate the value of t g and then from there we got this quantity what is called material dispersion which is given by this and then we notice here that this quantity is proportional to this second derivative of the refractive index as a function of wavelength and then we plotted it the refractive index for material glass and realize that the second derivative of refractive index with respect to wavelength gives you the curvature of the function.

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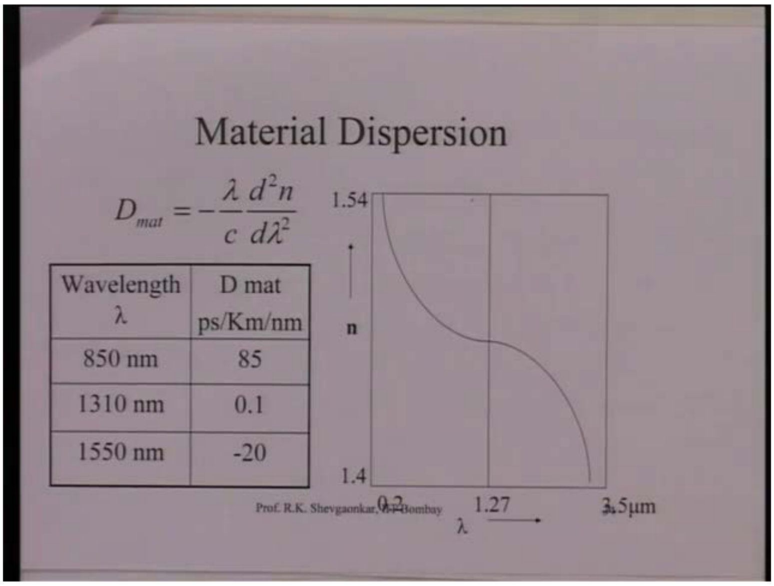

So, here we are drawing a curvature of one type here we have a curvature of opposite nature. So, curvature must be going zero somewhere, here and that wavelength we found out to be 1.27 micrometer or 1270 nanometer. So, these are the quantitative numbers which you saw last time that at 850 nanometer wavelength the material dispersion is rather large it is 85 Picoseconds per kilometer nanometer. If you go to thirteen ten then you get 0.1 and if you go to fifteen fifty you will get 20.

Now, we have here a positive sign and a negative sign. So, if I look at the sign of this, what does the sign really mean, the dispersion is a parameter which tells you by what factor the pulse is going to broaden when it propagates on the optical fiber. So, does that mean that when we have a dispersion negative the pulse is shrinking or it is becoming more and more narrow as it propagates. The answer is no, the negative sign does not mean the compression of the pulse, but it rather tells you the way different frequencies are going to travel inside the pulse.

Let us look at thing this thing in little more detail.

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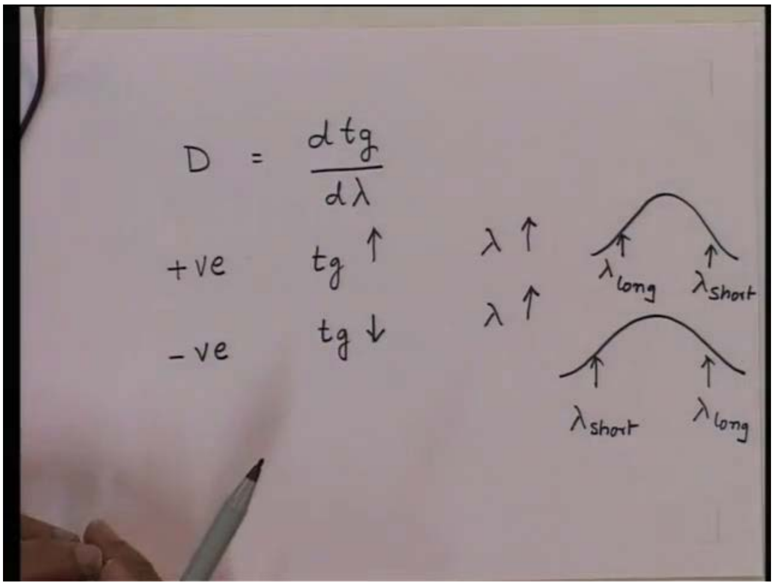

So, let us ask what is dispersion which you have defined this quantity, this quantity is d t g there is a group delay by wavelength. So, it is the rate of change of group delay as a function of wave length that is what gives you dispersion. So, if this quantity is positive, what that means is that, the slope of this time t g as a function of lambda is positive; that means, as the wavelength increases the t g also increases. Whereas, if you have this quantity negative the slope is negative; that means, as the wavelength increases the t g decreases.

So, as I go to longer and longer wavelength if this quantity is positive the delay will be more and more; that means, the longer wavelength will take longer time to reach the same distance. So, for positive sign the t g increases as lambda increases. Whereas, if you have a negative sign then you have t g decreasing as lambda increases. What that means, is that if you are having a dispersion which is positive, the longer wavelengths since they take longer time they are travelling with lower speed. So, the group velocity essentially decreases as the function of wavelength, as the wavelength increases the group velocity decreases. Whereas, if you have a negative sign then as the wavelength increases the group delay decreases; that means, the group velocity increases.

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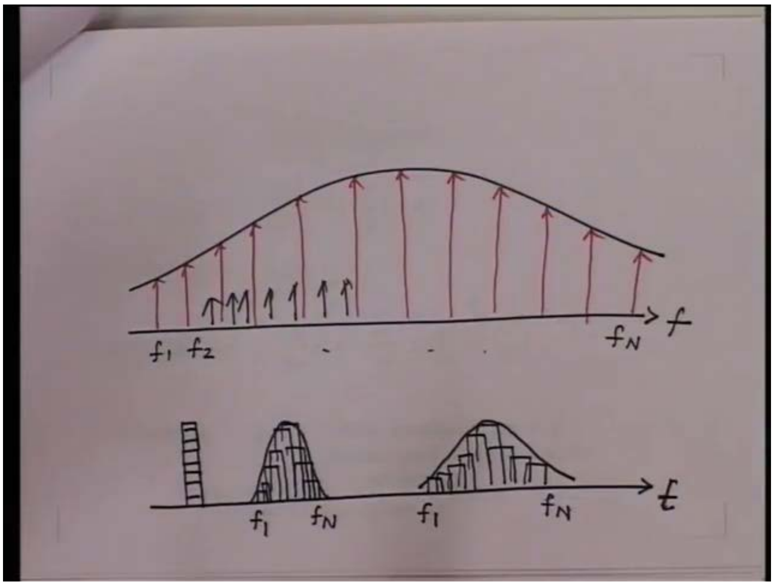

Now, you recall when we talked about the dispersion we said that the phenomena can be visualized as transmission of multiple signals propagating on the optical fiber. So, you have this white spectrum of your source carrier and these are the different component, which are present in the carrier and we said, the scenario of propagation can be visualized as the pulse is riding on each of this carriers and reach on the other side and total thing what you see is again a combination of the different pulses which you are travelled on different carriers.

So, if dispersion is positive then we say that since now, the longer wave lengths are travelling with low speed, a longer wave lengths means smaller frequencies. So, if these frequencies travel with lower speed and compare to these frequencies then we have a dispersion which is positive. On the contrary, if these frequencies travel slower compared to these frequencies then we have a dispersion which will be negative. Now, whether these frequencies travel faster or this frequency travel faster, the dispersion is because of the spreading of the pulse because of differential velocity with different frequencies.

So, if the pulse has to remain intact all the frequencies must travel with the same speed. In one case this frequencies travel faster so this frequencies go ahead this frequencies left behind; in the opposite sign for dispersion this frequencies travel faster this frequencies are left behind. In either of the case there is going to be a pulse broadening, there is no shrinking of the pulse. So, if I look at internally the pulse if the dispersion is positive then the longer wavelength would be left behind within the pulse and shorter wavelength would go ahead.

So, in this case, if I look at a pulse spectrum and ask internally, how the frequencies are going to look like. So, if I this is my pulse which is transmitting originally all the frequencies were together at every point in this pulse. Now, we will see that there is a accumulation of the longer wavelengths more time they will be getting accumulated on this end. So, you have here lambda longer wavelength and here you get a lambda which will be shorter wavelength.

So, the frequency separation is going to take place inside the pulse because of this dispersion and for positive dispersion, the shorter wavelength will go ahead and the longer wavelength will be telling behind. If you take a negative dispersion then exactly opposite would happen again as far as the envelope is concerned it will be exactly identical to this. So, you again get a pulse broadening exactly by the same amount, only thing is now lambda longer will come here and lambda shorter will go here.

So, the sign of dispersion essentially changes the distribution of frequencies of the carrier inside the pulse. But if you look at the envelope as a whole, the envelope is effected exactly the same way whether dispersion is positive or negative. So, in one case the plain is shifted like this; in the other case the plain is shifted like this, but if you look at a projection in time it will give you exactly the same kind of broadening what; that means, is that the pulse broadening is actually given by the modulus of this quantity D. So, though we define this quantity dispersion as d t g by d lambda, as far as the pulse broadening is concerned that is given by modulus of this quantity D.

So, until and unless one is interested in finding out how the frequencies are separated inside the pulse, the sign of the dispersion does not matter whether dispersion is positive or dispersion is negative, as long as the magnitude of the dispersion is same it gives you the same broadening irrespective of the sign of the dispersion..

So, this is the material dispersion now. The next dispersion which you want to investigate is what is called the waveguide dispersion and as I mentioned earlier. When we now, discuss the waveguide dispersion; that means, this is the dispersion due to the modal nature inside the optical fiber.

We have seen this diagram the b - V diagram, where V is the V number of optical fiber and that is proportional to the frequency, we have this quantity b which is normalized propagation constant which is related to the phase constant of a mode. So, from this diagram we would like to find out what would be the group velocity and how it would vary as a function of wavelength. We also recall that the b - V diagram is not a linear diagram. So, b V relationship is not linear there is a non-linear function there. So, as a result we expect that there would be some kind of a pulse broadening because of this wave guiding nature.

So, as we mentioned earlier we take one dispersion at a time. So, now when we investigate the wave guide dispersion, we assume that the material dispersion is zero; that means, the core and cladding material do not have intrinsically any dispersion. Only dispersion which is going to be there is because of the guided nature of optical fiber. So, essentially we would like to find out this parameter dispersion in terms of the parameter which is b and V. So, let us do a small derivation to get a relationship between a dispersion and the parameter b and V.

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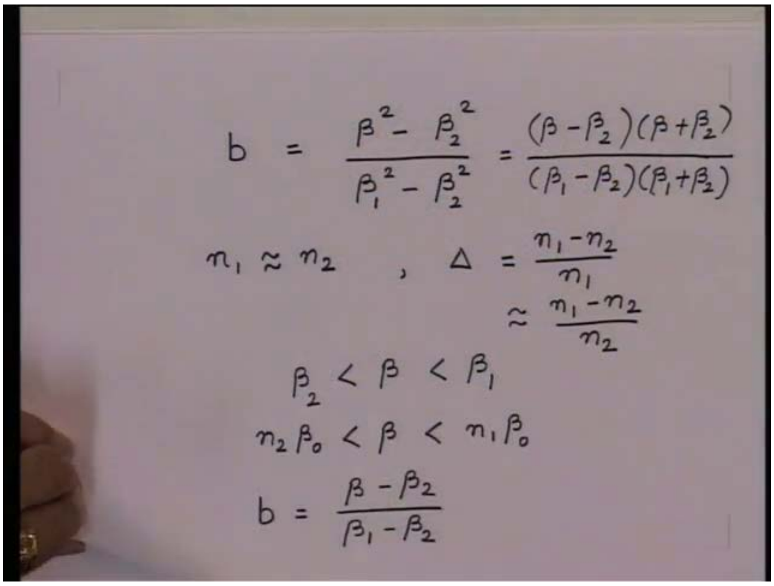

So, you recall we had define the quantity b which is equal to beta square minus beta 2 square divided by beta 1 square minus beta 2 square, where beta 1 and beta 2 are the phase constants intrinsically in medium core and cladding and beta is the propagation constant of the particular mode.

Now, recall that we also have in practice the optical fibers for which the refractive index n 1 and n 2 are very close to each other; that means, for a practical fiber what we call as the weakly guiding fiber, we have seen that n 1 is approximately equal to n 2 where the difference between them is typically of the order of about 10 to the power minus 3.

We also recall that we had define a parameter delta that is equal to n 1 minus n 2 divide by n 1 and since n 1 is approximately equal to n 2, I say approximately this quantity is also n 1 minus n 2 divided by n 2. We have also seen that when a mode propagates the phase constant of a mode is bounded by beta 1 and beta 2. So, beta lies between beta 2 and beta 1 which is nothing but n 2 multiply beta 0 and this is n 1 multiply beta 0 since, n 1 and n 2 are very close to each other the range over which this beta changes is extremely small

So, what; that means, is that this quantity difference quantity which we have, beta beta 1 and beta 2 are there almost equal. So, if I can factorize these two we can write this as beta minus beta 2 and this is beta plus beta 2 divided by beta 1 minus beta 2 and beta 1 plus beta 2. Now, since this beta beta 1 and beta 2 are very close to each other this beta plus beta 2 is almost equal to beta 1 plus beta 2. So, we can say that this is approximately equal so, this can cancel. So, we can linearize this relation b as this is beta minus beta 2 divided by beta 1 minus beta.

So, to do a simple calculation for the what is called the waveguide dispersion, first we linearize this quantity b under the assumption that the fibers are weakly guiding fibers; that means, the refractive indices of core and cladding are almost same. The different between them is very very very small.

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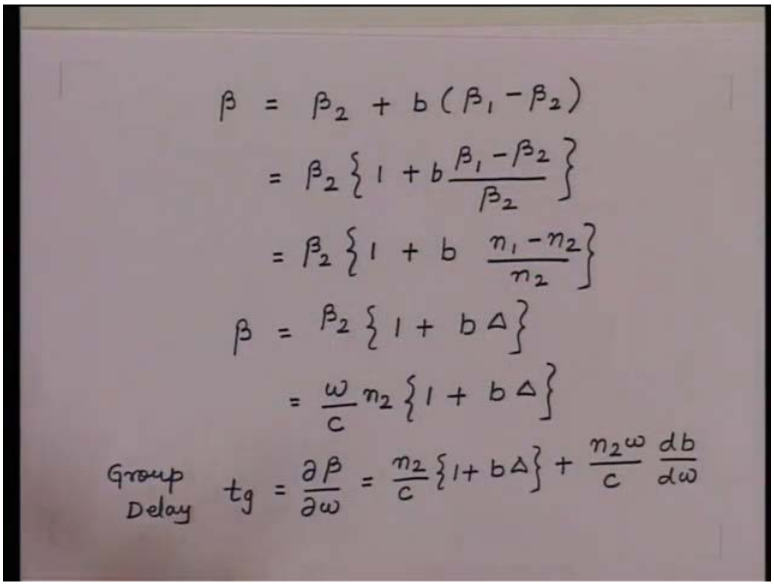

Once you do that then I can invert this relation and I find out this quantity beta which I can do as beta that is equal to beta 2 plus b into beta 1 minus beta 2. So, I just take this beta 1 minus beta 2 here bring beta 2 on the other side. So, you get this now phase constant beta for mode which is given by beta 2 plus this one. Now, I can take this beta 2 common from here since you get beta 2, 1 plus beta 1 minus beta 2 upon beta. Now, this quantity beta 1 is n 1 into beta 0 this is n 2 into beta 0 and this will be n 2 into beta zero. So, beta 0 will cancel. So, this quantity will be n 1 minus n 2 upon n 2. So, is you can write here this is beta 2 which is 1 plus b n 1 minus n 2 upon n 2.

And this quantity is nothing, but the fiber parameter what is called delta. So, we can write this expression now, in terms of beta 2 one plus b into delta. So, after linearizing we get the phase constant of a particular mode which would be essentially given by this and now, I can write down this quantity beta 2 explicitly in terms of frequency and the refractive index. So, this could be omega by c into n 2. So, it is beta 0 into n 2 where omega is the frequency multiplied by 1 plus b into delta.

Now, note here this quantity b which is the normalized phase constant or propagation constant that is a function of omega or that is the function of lambda. So, how to find out dispersion as we have done in the basic formulation; first you find out what is called the group delay which is d beta by d omega. So, we have group delay t g that is equal to d beta by d omega. So, if I differentiate this with omega we get is equal to n 2 by c, 1 plus b delta plus n 2 omega by c, d b by d omega.

We want to finally, derive the expression in terms of b-V diagram. So, what we want to do is we want to change derivative d b by d omega, in terms of the derivative with respect to the V number because once you have a b - V diagram we can find out the slope or the curvature of the b V diagram. So, essentially we can find out the derivatives of b with respect to the frequency omega.

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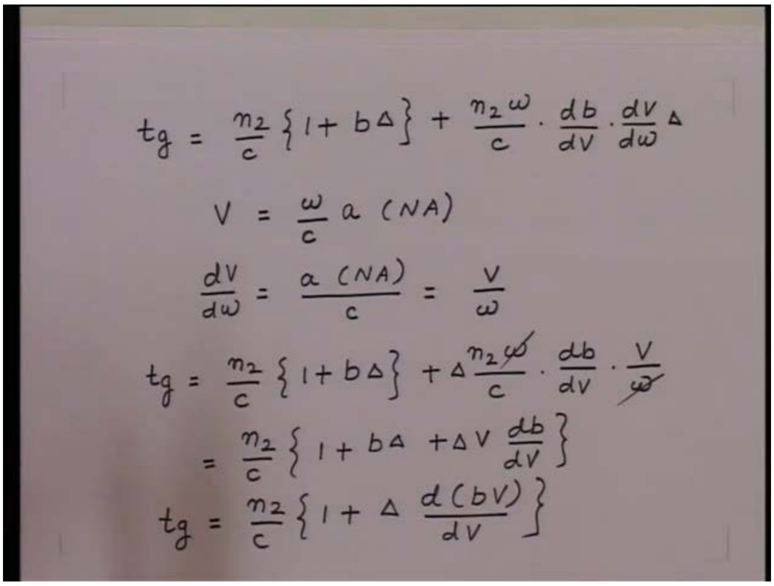

So, what we can do is we can write this expression differently. So, we can get here t g which is equal to n 2 by c, 1 plus b delta plus n 2 omega by c, this one we can write down as d b by d V into d V by d omega.

So, the derivative which we have here d b by d omega, we can write here as a d b by d V into d b by d omega. Now, recall we have this number V number which is defined as, omega by c into a into the numerical aperture. So, if I calculate this quantity here d V by d omega that is nothing, but a into numerical aperture divide by c. So, that is equal to if I can multiply this by omega divide by omega, if I multiply by omega the whole quantity will become V. So, this is nothing, but V upon omega.

So, I can substitute in to this to get the group delay that will be equal to n 2 by c 1 plus b delta plus n 2 omega upon c d b by d V into d V by d omega which is nothing, but V upon omega where V omega, this omega cancels with this. So, here you get a quantity here n 2 upon c which will be common with this. So, you can rewrite this n 2 upon c into 1 plus b delta plus V d b by d V, there has to be delta here is you got a quantity here delta here delta. Now, taking the delta common from here you can combine these two to write more compactly. This is n 2 by c into one plus delta d b V by d V.

Note here, if I expand this it will be d times b V by d V which is one. So, that gives you delta into b the second term will be b into or V into d V by d V which will be this term. So now, the group delay in terms of the b - V diagram parameters is essentially given by this. Now, note here this quantity n 2 by c, if I see this is nothing, but the group delay which the signal will undergo if it was travelling in the medium cladding of a refractive index n 2.

So, this parameter is a constant delay where signal will undergo anyway, this is the quantity essentially which is telling you the differential velocities. So, this is the term which essentially will give you something which we are interested in that is dispersion. So, every signal is going to undergo a delay which will be this thing which is constant which is not a function of wavelength or frequency, this is the term which is going to give you a differential delay and that is what will give you a dispersion.

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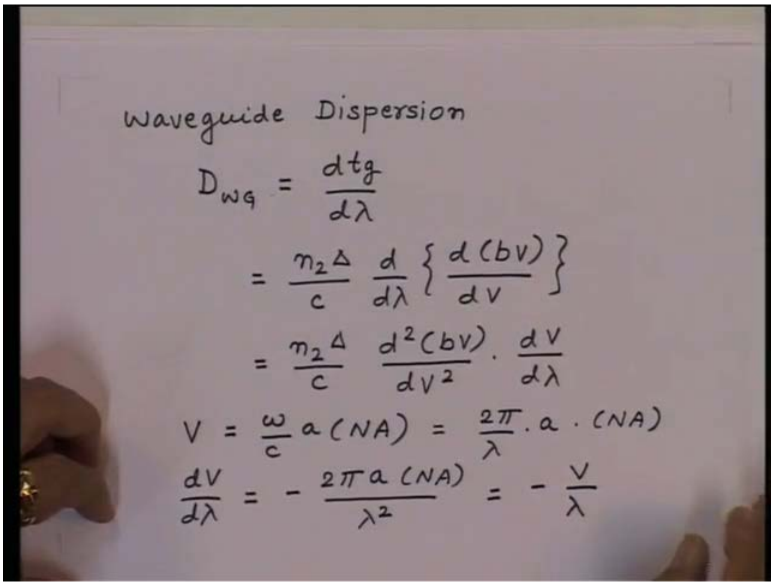

So, now having got now this quantity here t g then the next step is the dispersion which is t g by t lambda. So, we can get now the waveguide dispersion let us call it d w g that will be equal to d t g by d lambda. So, I can take this quantity d t g and differentiate with respect to lambda. Firstly, this quantity is constant so, that derivative is 0. So, what I get is equal to n 2 delta by c d by d lambda of d b V by d V. Again, we can do the same thing as we did in the previous case this I can write as d by d V multiplied by d V upon d lambda. So, you can write here this n 2 delta upon c. See, if I write this d by d V this will become d two b V by d V square. So, I will here d two b V by d V square into d V by d lambda. Again writing the V number now in terms of wavelength rather than in terms of omega we know, that V omega by c a in the numerical aperture that is the V number, but omega we can write as two pi have and c upon f will give you wavelength. So, this also can be written as 2 pi by lambda into a into numerical aperture.

So, d V by d lambda will be equal to minus 2 pi a into numerical aperture upon lambda square, if we give one lambda here and one separate out 2 pi a numerical aperture upon lambda will be nothing, but again the V number. So, this quantity can be written as minus V divide by lambda. So, we can substitute now, this quantity into this, we get what is called the waveguide dispersion in terms of this b - V diagram parameters. So, we get d w g that will be equal to minus n 2 delta upon c, V upon lambda d two b V upon d V square.

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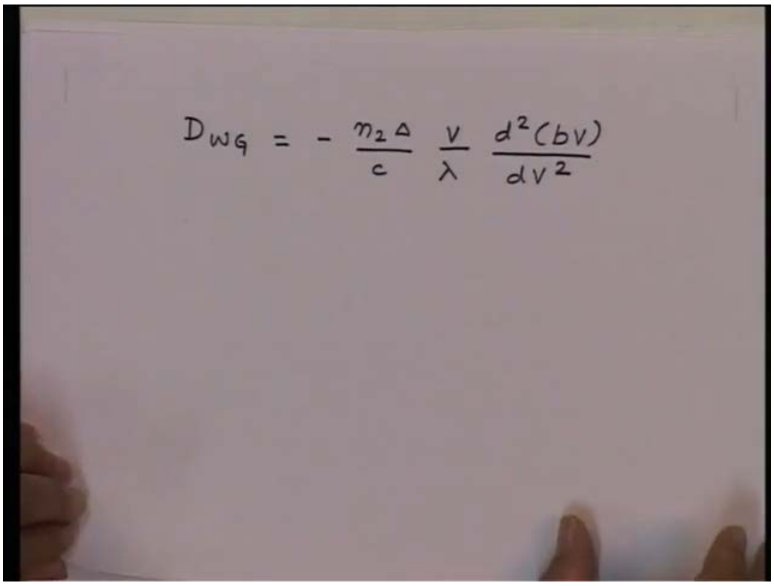

$$D_{WG} = -\frac{n_2 \Delta}{c} \frac{V}{\lambda} \frac{d^2(bV)}{dV^2}$$

So, once we have the b - V diagram known, then from there we can calculate this quantity b into V and then we can calculate second derivative of this quantity and from there we can essentially calculate the waveguide dispersion. Of course, in the b - V diagram does not have any analytical form, this derivative has to be obtained numerically. So, firstly you should have a very accurate value of V measured or calculated as a function of V number and from there then you can calculate what is called the waveguide dispersion.

Now, again looking in to the expression one does not get a feel what should be the V number for operation so, that I get this waveguide dispersion as small as possible. So, again one has to go numerically to find out from the b - V diagram.

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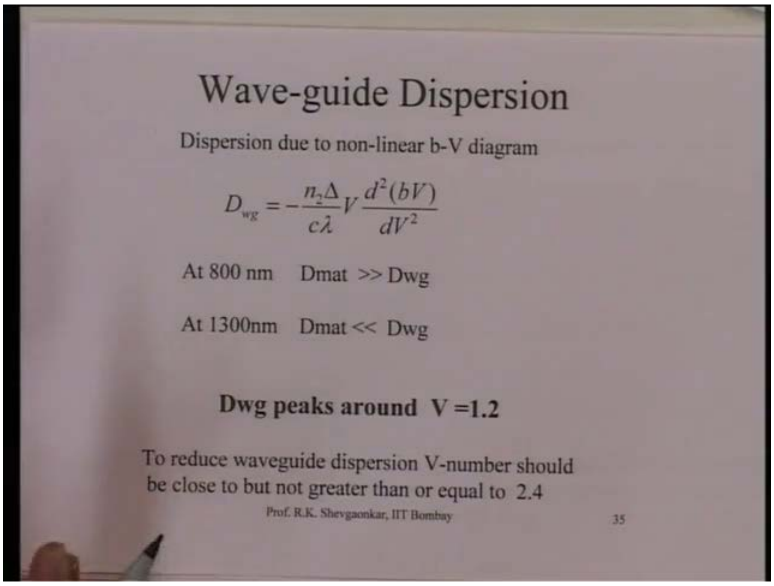

So, if I now consider the b - V diagram and from there I find out this waveguide dispersion, we find that for the Lp zero one mode or HE 11 mode that is the first mode which can propagate. The waveguide dispersion peaks around V number around 1.2. So, if I go on either side of V number 1.2, the dispersion reduces so; that means, if we want to have waveguide dispersion then either I have to operate at a V number much smaller than 1.2 or at a V number which is much larger than V 1.2; obviously, if I go to a V number which is much less than 1.2 then since, the V number is very small either the numerical aperture has to be very small or the radius of the fiber has to be very small. So, that is not a very good option because both of these essentially are going to affect the launching efficiency of the optical fiber.

So, ideally we should operate at a V number as large as possible as we have seen earlier and now, we are saying that we should operate at a V number which is much larger compared to 1.2. So now, you have restricted the operation range for V number still further that we cannot go to a V number more than 2.4 because, if the V number is increases more than 2.4 the fiber does not remain single mode. So, for single mode operation V number has to be less than or equal to 2.4, but now the V number has to be more than 1.2.

So, what we find is to reduce the waveguide dispersion essentially. We should go as close to again, the V number two point four. So, that the waveguide dispersion is small of course, it has not become very small it is about 20 percent of what we would get around the peak around the V number which is 1.2. So, you cannot make the waveguide dispersion very small because you cannot operate the fiber at a V number which is greater than 2.4. So, that is why as I mentioned earlier also, to guaranty the fiber to be single mode and to reduce the dispersion on the optical fiber the V number has to be very close to 2.4, but less than that.

So, now if I consider a single mode optical fiber we have both these dispersion present; one is the material dispersion and other one is the waveguide dispersion and total dispersion is approximately equal to sum of these two dispersions. Now, since both these dispersions are because of the finite bandwidth of the signal, this dispersion together we call as the chromatic dispersion on the optical fiber.

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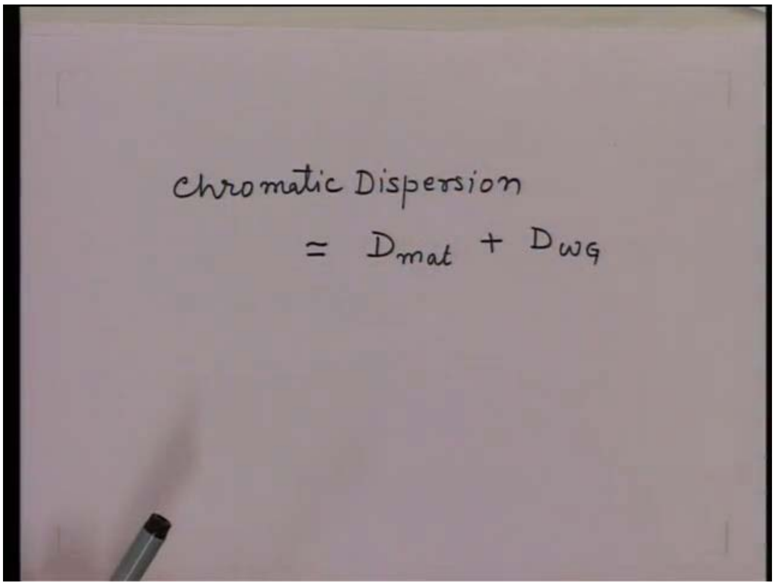

So, we have quantity what is called chromatic dispersion and this is approximately equal to the material dispersion plus the waveguide dispersion. So, we have now calculated now the material dispersion from the properties of the glass. We have calculated now, the waveguide dispersion and if we combine these two we will get the net dispersion on the optical fiber.

Note [however]; however, is that the material dispersion is a property of glass. So, it is completely out of your control, once you identify the material glass this d material is decided this quantity here; however, d waveguide that depends upon the b – V diagram and b – V diagram depends upon, the V number which depends upon, the size of the fiber the refractive index difference numerical aperture and so on.

So, this is the quantity which is the structure dependent quantity. So, if I change either the refractive index of the fiber or size of the fiber this quantity is going to change. So, d waveguide is a fiber based parameter, which can be controlled and later on we will see we will try to make use of this fact that the waveguide dispersion can be manipulated and as a result the total dispersion on the fiber can be manipulated, but at the moment it is enough to note that the material dispersion is almost like god given, but the waveguide dispersion can be manipulated by changing the fiber parameters.

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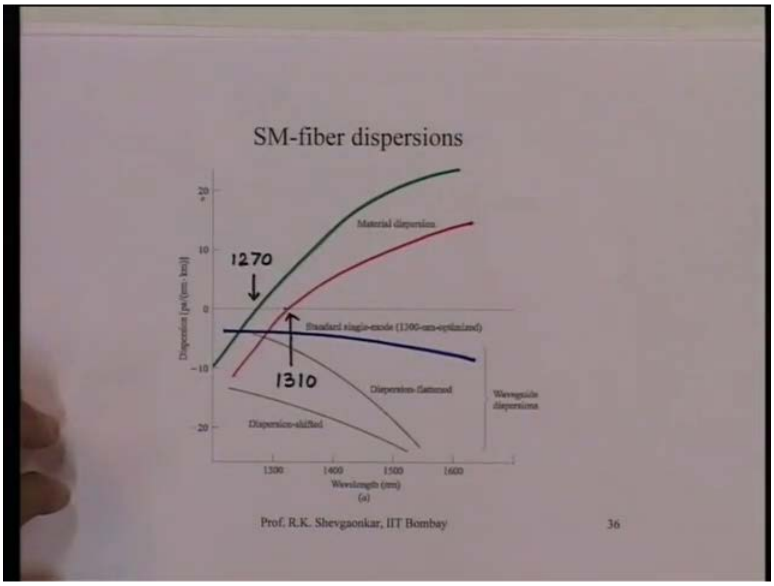

So now, if I take the total dispersion then as we mentioned it is sum of the two. So, here this green line gives you the material dispersion the blue line here is the waveguide dispersion for HE 11 mode in a single mode fiber. So, the total dispersion will be sum of these two. So, if I take these two curves and add them point by point, I will get this red line that is the total dispersion I will see on the single mode optical fiber. Recall when we talk about the material dispersion we have seen that the material dispersion goes to zero at a wavelength which is 1270 nanometer.

However, when I make a single mode optical fiber, I do not see this zero dispersion point at 1270 nanometer because we always see a combination of the waveguide dispersion and the material dispersion. So, effectively we will see this point, where the dispersion would go to zero and that point is 1310 nanometer. So, inside a single mode optical fiber the zero dispersion point is not 1270 nanometer, as it is for the intrinsic material, but it is around 1310 nanometer.

That means, if I take a single mode of optical fiber and illuminate this with a wavelength which is 1310 nanometer dispersion on this wavelength is almost zero; that means, it can really support a very large bandwidth or very high data rate at 1310 nanometer, if I go to a wavelength which is 1500 nanometer or 1550 nanometer again, the dispersion is a large.

So, pulse broadening is large and as a result the data rate is reduced. So, if you see from data rate point of view 1310 nanometer is the best wavelength in a single mode of fiber because that is the wavelength at which the dispersion is almost zero. Why I am using the word almost because as soon as you try to put a finite band of wavelengths we do not operate at a point where this curve is zero you will be having a very narrow region around it. So, one point of this curve is zero, but in the small wavelength range every point will not have zero dispersion. So, you will see some dispersion, but that dispersion will be extremely small compared to what you get at a point here, which is 1500 nanometer or you take a point here, which will be about 800 nanometer.

That is the reason 1310 nanometer, was immediately chosen window after the first generation because at that wavelength one could see a scope of sending extremely high data rates on the optical fiber. So, 1310 nanometer that is why the special window because it can support the highest possible data rate.

Now, the total dispersion which we have seen here since is the combination of these two the material dispersion and the waveguide dispersion this curve is fixed as I mentioned, but this curve can be changed either it can be changed like this or it can be shifted up or down and as a result the total dispersion on the fiber can be manipulated. We will come to this aspect little later, thereby changing the waveguide dispersion, what way the total dispersion characteristics can be modified and what way we can get much more broadband systems by manipulating the waveguides on the single mode optical fiber.

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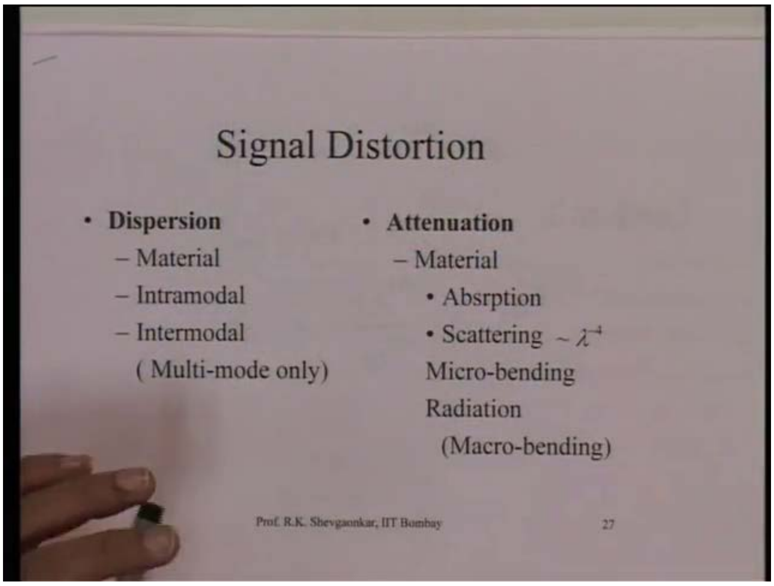

Let us now, turn our attention to the second important parameter which causes distortion on the fiber and that was the attenuation. So, we saw for the attenuation we have various mechanisms, the signal on the fiber can be attenuated due to intrinsic material properties.

So, like any other material you have absorption of energy as it propagates. So, intrinsically you may have a loss because of absorption, but more strong absorption which you see inside the optical fiber is what is called the scattering loss. Now, what is the scattering loss when I consider the optical fiber initially we said, that the refractive index of core is n 1 and refractive index of core is n 2 and there is absolutely constant inside the core and the cladding.

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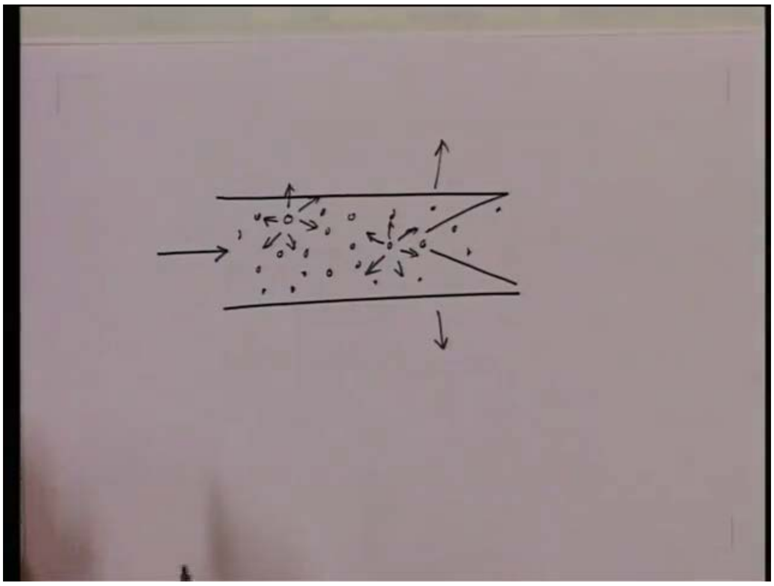

However, when I manufacture an optical fiber you will see that there are very small microcenters which are developed, which have a refractive index little different than the average value. In other words, we have a some kind of regions which are created inside the optical fiber which are distributed all through its length, and these sizes are very very small fraction of a micron.

So, when the light tries to propagate through this, it sees a small perturbation in the refractive index this phenomena is very similar to when the microwave signal tries to propagate in the atmosphere and we are a raindrops that microwave signal gets scattered by the raindrops.

Precisely same phenomena which you see here, that these microcenters have sizes smaller than the wavelength. So, you see scattering of light taking place because of this and that scattering is what is called the Rayleigh scattering. So, essentially due to very tiny fraction of light gets scattered in to all directions at everywhere. Now, recall that for a sustained guiding of light, the light must be confined within the numerical aperture cone. So, let us say if the numerical aperture cone was was this, any light which is scattered outside this numerical aperture cone will not get guided and will be lost from the sides of the fiber, that is what is what is called the scattering loss and the Rayleigh scattering is a very strong function of the wavelength.

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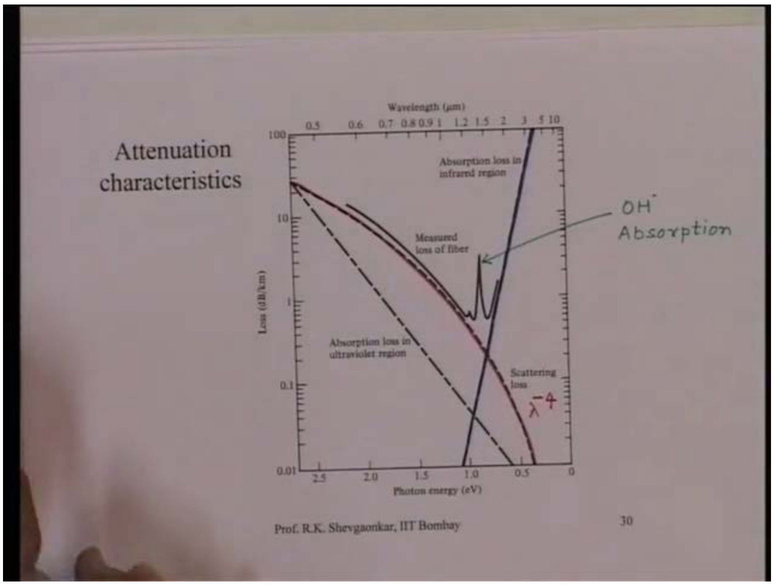

The Rayleigh scattering goes as lambda to the power minus 4; that means, for every doubling of wavelength, the Rayleigh scattering loss would reduce by factor of 16, it is lambda to the power minus 4 say wavelength is doubled it is 2 to the power minus 4. So, you will get a reduction in the loss by 2 to the power 4 which is 16.

Primarily, that is the reason why the fiber shows low loss at 1500 nanometer compared to 800 nanometer, because from 800 nanometer to 1550 nanometer the wavelength ratio is approximately 2. So, use a substantial reduction in the loss because of the Rayleigh scattering. So, if I take this and plot this loss as a function of wavelength, the Rayleigh scattering loss would go lambda to the power minus 4 which essentially is given by this red line. What we are showing here you is a plot as a function of wavelength, where wavelength is going from 0.5 micron to almost 10 micron here and that is a Rayleigh scattering loss, as you can see this drops very rapidly as the wavelength increases.

However, as we know that for glass there is another loss, what is called infrared loss. The glass is a very bad conductor for infrared. So, all infrared get very rapidly attenuated, when they propagate inside the glass. So, as you go to longer and longer wavelength the loss increases very rapidly. So, the blue line here essentially shows you a loss, which is because of the infrared absorption inside the glass. So, now, we see something interesting as we increase the wavelength, the scattering loss decreases, but as you go to very long wavelength much deeper in infrared then the infrared loss starts dominating and again the loss starts increasing.

So, the total loss profile if you see it is like a valley here which is created, the loss is decreased because of the scattering and started increase again and because of the infrared absorption. Let us also get a impurity what is called the OH molecules which normally remain inside the glass, these are the water molecules. Say even if you purify glass to a very high accuracy when the glass is exposed to the environment typically, the water molecules slowly get diffused inside the glass or even in processing time you cannot really move completely the water molecules. And water molecule gives you the absorption peaks at various wavelengths and one of the peak lies exactly on this valley, where the loss here is minimum.

So, this peak which you see here that is because of the OH absorption. Of course, now the technology has improved and people have removed this OH absorption loss. So now, we practically have a window which is just a corresponding with this valley, but because of this OH absorption loss essentially, this low loss window which is created by this valley has been split in to two and the so, precisely we find in the overall loss profile of the glass as we have seen in the earlier lecture. So, the dispersion here has been enlarged see, if I consider a region around this and if I enlarge this we get a large profile which looks like this.

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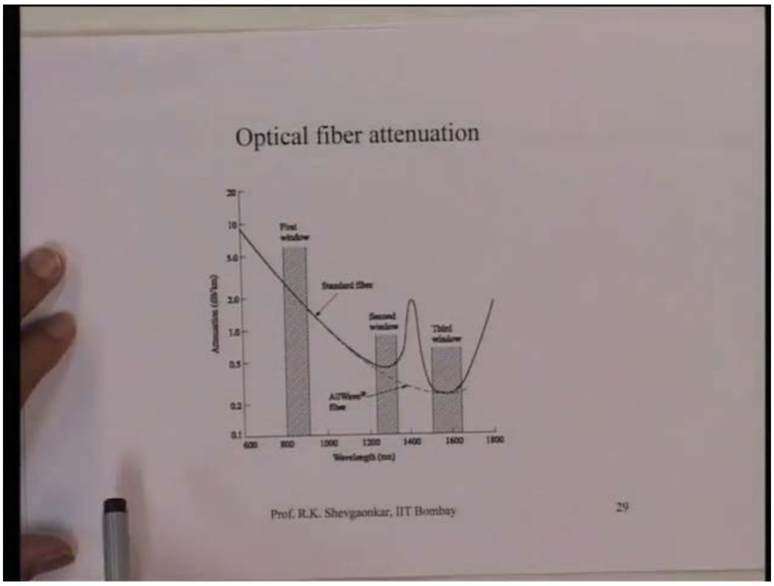

So, this is that OH absorption peak this is one of the windows, these are another window and this window is 1310 and this window is 1550. So now, it makes sense why this 1310 and 1550 windows, were chosen primarily they come because of the dispersion considerations and because of the loss consideration. Of course, this loss which we are talking about is intrinsically, because of the fiber characteristics; that means, as soon as a fiber is made you will always have a loss which is the absorption and which will be scattering, but in addition to that when the fiber is late in to the system, then the fiber has further loss incurred and that is because of the environmental or deformations of the fiber. So, either fiber can be deformed in to very small special scale or it will be defined at a very large special scale and both of these essentially contribute to the loss.

So, the scattering loss and the absorption loss are present inside the optical fiber, even in the ideal conditions; that means, even before laying the fiber in system.

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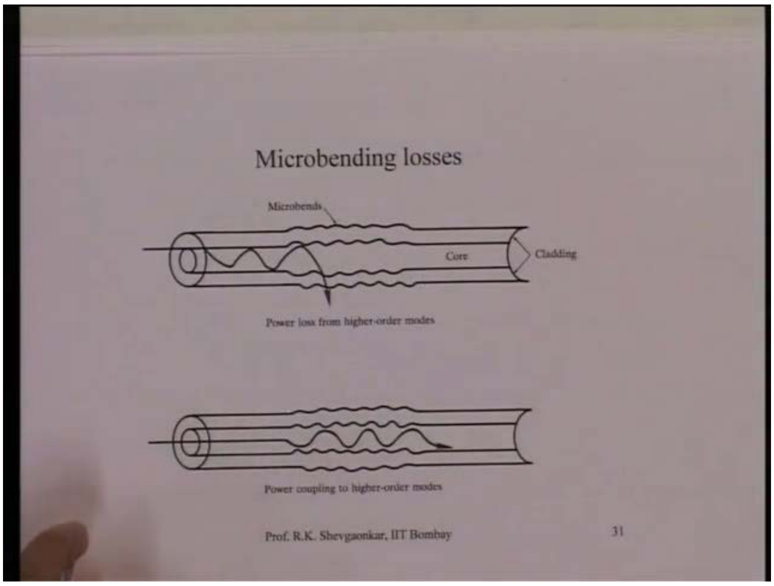

If I lay fiber; however, in the system and because of all the mechanical pressures, the fiber get deformed at a micro scale. So, ideally the fiber core and cladding should have remain absolutely straight, but because of this pressures you can have a micro deformations on the core and cladding of the optical fiber.

Now, these pressures are extremely tiny for example, even if you touch the fiber that kind of pressure is good enough to create this kind of deformations. Now, note here if the fiber was absolutely straight this boundaries are straight like this, ray will get propagated by total internal deflection, but if the (( )) is deformed like this then essentially, what is happening is locally now, the normal is changed this is normal now. So, the ray which was satisfying the critical angle condition when the normal was like this, (( )) no more satisfy the critical angle condition and as a result their energy essentially leaks out something like this. So, what we find now is that when the fiber has what are called the micro bending's then, there is a small amount of energy which leaks out from the fiber and this is what is called the micro bending loss inside the optical fiber. So, when the fiber is laid is commissioned in to the system in addition to the intrinsic loss which is scattering and absorption, you will also have the micro bending loss present inside the optical fiber.

There is one more loss which is there, which will be a fiber is bent gently and that loss essentially, we will investigate when we meet next time, that is what is called the radiation loss and then we will see as a whole, the attenuation and dispersion characteristics of the fiber to get some conclusions about the signal distortions and the optical fiber.