Indian Institute of Technology Kanpur

National Programme on Technology Enhanced Learning (NPTEL)

Course Title
Optical Communications

Week – VI
Module – III
Wrapping up fiber parameters

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Hello and welcome in this module we will continue and rape up our discussion on dispersion and then we will also talk about attenuation very briefly and that would be the end our fiber parameters as for us this particular course is consider a few of the remaining fiber parameters like non linear effects will be consider as an and when they are required in the later half of the course you might have studied in the earlier module about dispersion and we have talked about it.

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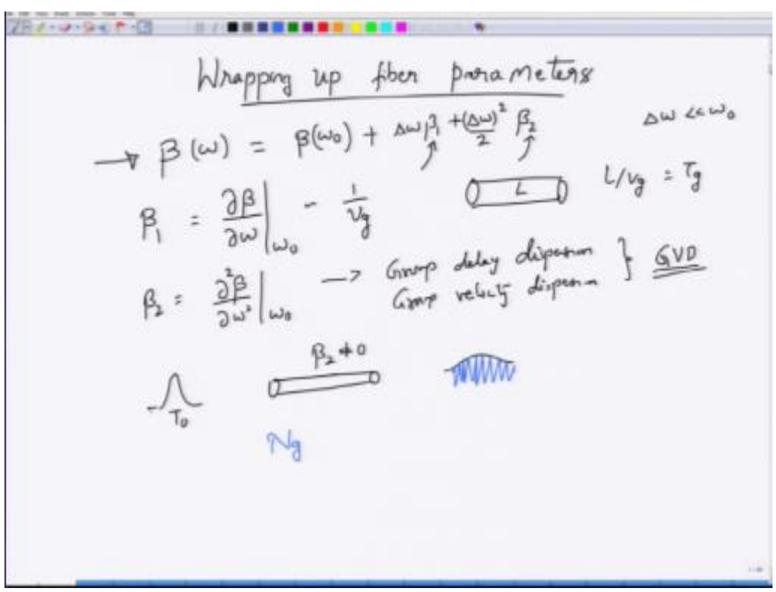

Dispersion is a very general name for the dependence of the propagation constant β inside a fiber with respect to ω if this was a linear relationship as in for the case of a free space where we know that β is given by ω x $\sqrt{}$ of μ ε and assuming that μ and ε are constants right with respect to frequency then β will be a linear function of ω and we have seen that the derivative of β with respect to ω is basically the inverse of the group velocity so this group velocity will be equal to a constant because δ β/ $\delta\omega$ will actually be a constant.

And we have also seen that this $\delta\beta$/ $\delta\omega$ evaluated at the carrier frequency ω_0 is denoted in a short hand by writing this as β_1 we have also seen that you can expand $\beta(\omega)$ around the carriers so you would actually get the first term ω_0 + we know ω $\omega(\beta 1)$ where $\delta\omega$ is the deviation of the frequency from the carrier frequency ω_0 we can also expand this to the second order so getting δ ω^2 (2) multiplied by β_2 where β_2 corresponds to the second derivative of the propagation constant with respect to the frequency evaluated at again at $\omega = \omega_0$ of course in writing these equations we are assuming that this spectral with $\delta\omega$ is very small compare to the carrier frequency ω_0 itself.

Okay so as long as this is true you can expand $\beta(\omega)$ and you will see that the presence of non zero values of $\beta 1$, $\beta 2$ is the reason why you get dispersion okay $\beta 1$ tells you how the envelope gets delayed while $\beta 2$ tells you how the envelope actually gets spread for that reason this $\beta 2$ is called as the group delay dispersion term or the group velocity dispersion okay because β is inversely propositional to $\beta 1$ is inversely propositional to 1/vg if you consider a length of L the L/ vg will correspond to the group delay okay.

So this term $\beta 2$ can then be through of as the variation of group delay with respect to frequency and therefore this can be consider as group delay dispersion how does τ_g vary as a function of ω as well as because 1/ τ_g is corresponding to vg the group velocity you can call this as group velocity dispersion in parameter as well okay, so it is sometimes not specified which one you are talking about but the context should make you clear this is typically called as GVD parameter okay.

Although strictly speaking β2 should be called as group delay dispersion and 1/ β2 should be called as the group velocity dispensation okay any the pint to note here is the dispersion whether it is material desperation or the wave guide dispersion which we talked about in the earlier modules can be encapsulated into this formalism where β is a function of frequency okay we have also seen what happens to a input Gaussian pulse of certain width T_0

What happens to this pulse as it propagates through the fiber you know of certain length where β2 non zero is that the amplitude decays and the width also increases in addition to that there will also be a chapping right the carrier frequency will start to increase or decrease depending on what whether the GVD parameter is positive or negative okay so this positive or negative chapping would happen and we have seen a certain expression for obtaining this pulse width as a function of β2.

Now let us get back to the dispersion in terms of material dispersion rape up that discussion we have looked at the group velocity Ng which we had defined right now we will actually look at the reasons why you get Ng okay so material dispersion is actually the property of the material itself okay so material dispersion is a property of the material itself so we have discussed Ng the group index we have discussed now let us look into that reasons why we get.

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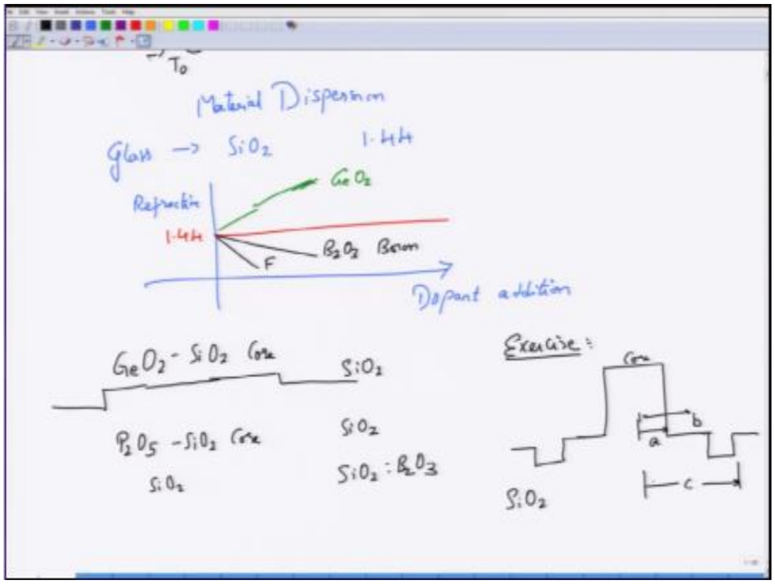

Material dispersion in order to understand material dispersion we need to know what is the material that is that forms the optical fiber and it turns out that glass is the material that is used glass is sometimes called as the host material because you will be doping this glass with certain other dopant materials in order to increase or decrease it is refractive index glass or silicon dioxide SiO2 is the fundamental material or the major material that is used to made make fibers glass fibers or silica fibers.

And this as a typical refractive index of about 1.44 now we know that the core part of the glass as to have a higher refractive index compared to the cladding and in order to increase this refractive index you have to dope this material with certain dopants and these dopants can be increasing the refractive index certain dopant and certain dopants actually decrease the refractive index okay.

So if you look at the refractive index as a function of the dopant addition so how much in percentage or in how much in mole you're actually adding this dopants and what happens to the overall all refractive index you see that glass as certain base refractive index of say 1.44 and if you certain materials such as boron or florin these will actually reduce the refractive index so this is basically for the fluorine and this is the boron dioxide or boron trioxide I am not very sure byt this is boron atoms okay.

So if you dope your silica with these atoms fluorine or boron you are going to reduced the refractive index okay and the amount of reduction of the refractive index depends on how much the doping that you are going to add of course when you add this dopants you are actually creating certain you know mixture of the glass host and the dopant atoms and the structural properties of the material will also change by structural properties I mean the tensile stress the strain and the bending effect all those property the elastic properties in elastic properties.

In the elastic properties the internal absorption properties these are all actually changing so you have to be careful in adding the required amount of the dosage or the dopant and not change the structural properties of the glass to much okay if you want to increase the refractive index well you have to do something like adding germanium which will increases the refractive index so this is for increasing the refractive index you can also add certain other materials in order to increase the refractive index.

Now typical optical fibers that you find in market are made up of germanium silicon core okay so that refractive index is actually higher here in the core region and it reduces slightly if you had silicon dioxide cladding at the outer end or silica are the classing okay you can of course also make another one phosphorus say suppose and then you can add or dope that one in the core and then in the cladding you keep SiO_2 itself you also make the core consisting of only SiO_2 right and then add a dope end in the gladding region.

So that you made for example try SiO_2 B_2O_3 addition okay so you can have possible variations in order to come up with the refractive index profile that you want these are what we have shown for the step index if you want to obtained greeted index then you have to also add impunity so the function of radial distance right.

So that is a little more complicated than the refractive index profiles but you can actually obtained refractive index of almost any shape and you will see that most modern fibers have for different applications have very complicated refractive index profiles okay and that is one coming basically by taking the glass host as the main material and the adding required amount of dopants at certain regions in order to change the refractive index.

The local refractive index changes by the addition of dopants here is an exercise for you I will consider one of very interesting profile which is used to flatten the dispersion okay we will talk about dispersion later the dispersion coefficient but this structure is used to flatten the dispersion and this called as trench in the cladding okay or sometimes called as the dispersed cladding structure so you can imagine that this radius is a and let us say this one is some b know all distance are measured with respect to the center of the fiber and let us say this edge is at a distance c so you see that there are certain areas right.

So you have a core and then you have a clad and then there is also trench in the cladding right so there is also a dip or the trench in the cladding the excise is that assuming that you have SiO_2 material as the core then can you come up with the required dopants you know depending on what ever doping you want it is not that you have to give the exact percentage but I just wanted to identify which dopants would be good in order to obtained the structured in the cladding in this fashion okay.

Then you assume that I am not even specifying the core okay this exercise two part one you assume that the core is SiO_2 then do not assume anything about the core then you come up with your own material okay in order to realize the refractive index profile that is shown here okay. Now what you can see is that you can add dopants which in the refractive index but is this refractive index constant well you are earlier studies in optics would have kind of let you think that refractive index is an quaintly that is independent of frequency because when we talk of geometrical optics problems.

We say that your ray of light as been incident on glass at 30 degrees right and then there is a reflection there is refraction we calculate all those angles no vary kind of seem to talk about the frequency or the wave length but in fact it turns out that refractive index is the response of the materials it is the response of the material to the external electric field and how the material rearranges itself which is defined by what is called as dielectric permittivity or the dielectric constant although it is not constant because it depends on the frequency so this dielectric permittivity is the root cause of the refractive index.

In fact refractive index is given by square root of the relative permittivity of a dielectric medium okay and this dielectric permittivity is a function of frequency so clearly frequency or wave length so clearly this refractive index is also function of wave length and that is what is you know going into the group index NG if you look at the group index term which we looked at the in the last class there is a term which says $dn/d\lambda$ tells you how the refractive index n is varying with respect to λ and factor is the one which causes.

The group index and the group velocity and you can imagine now that since $dn/d\lambda$ can exist $d2n/ d\lambda2$ can also exist that is a second order derivative for the refractive index can exist and you write and that would again cause the group delay dispersion in fact that is related closely to the group delay dispersion okay so we have already seen let us recap starting by.

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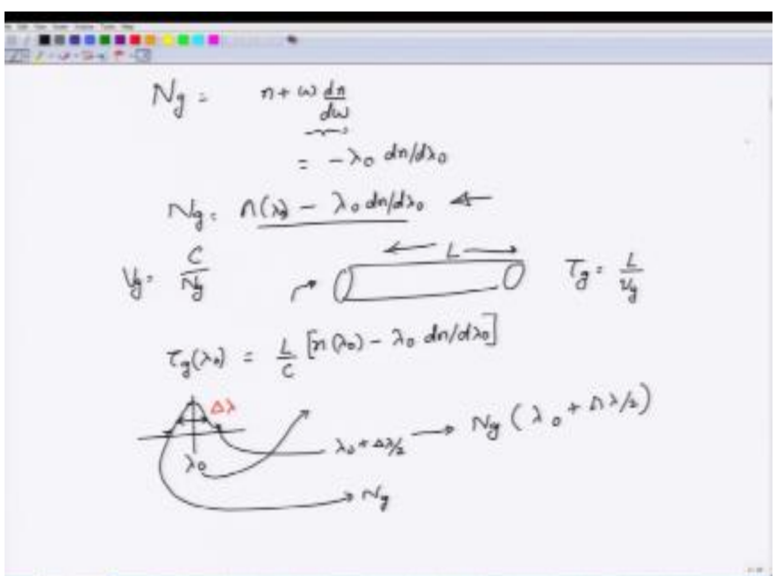

Ng we have already seen that Ng is given by n+ω dn/dω indicating clearly that you have to consider the refractive index variation as a function of frequency you can of course write this ω in times dn/dω in terms of the wave length and write this as – λ0 dn/dλ0 where λ0 is the free space carrier wave length right, so this is the expression you can substitute into Ng and then recognize that n can be written has a function of frequency or as a function of wave length we can write this has n of λ – λ0 dn/dλ0 rather n of λ0 again so this will give you the group index.

Okay so this is the one that is actually to the group index and the group velocity Vg will be given by C/Ng okay and if this is the group velocity if you consider a fiber of a certain length L then if you consider you know sending a pulse of certain envelope here then the envelope would arrive at a group delay of L/Vg okay group delay can be rewritten as L/C because Vg is C/Ng and remember what is Ng, Ng is nothing but this follow so you can write this as n of λ0 – λ0 dn/dλ0 so this is the group delay that you are looking at and this group delay is dependent on the material now this is the group delay of a particular wave length λ0 now suppose instead of having one single wave length.

Which would not be possible even if you consider an ideal laser what you actually have is a spectrum around λ0 so most sources have a certain spectral width okay, so this spectral width or the bandwidth of the laser or the light source that you are considering can be denoted as Δλ and now you want to find out what is the overall delay for a case whether the light source has a certain spectral width right now this λ0 travels at a certain group index this part which is λ0 + Δλ/2 will travel at it is own group velocity so you will have Ng λ0 + Δλ.

So this would have a different value compared to the value for Ng at λ0 and clearly even this lower edge would have very different value of the group index Ng okay so you can find out what would be the overall delay here by writing this one or by looking at the overall delays which we can call it has Δτ.

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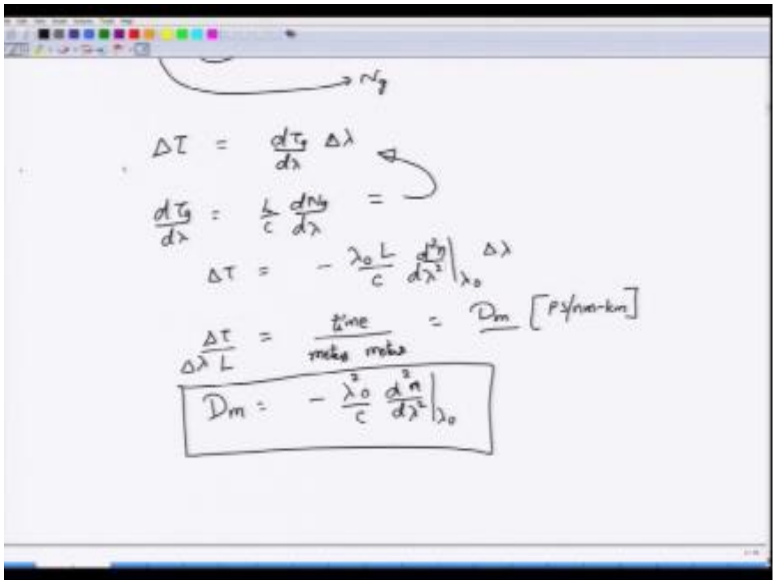

And writing this has dτg/dλ which would tell you how the group delay is varying with respective λ and multiply this one by the spectral width Δλ okay so you can calculate this one so what would be dτg/dλ so will can be obtained by differentiating the expression L/C dNg/d dτg/dλ I will leave this as a small exercise for you to calculate what is this dNg/d dτg/dλ and then it turns out that if you calculate this and then put that value into this Δ τ you will see that Δ τ is given by – λ0 L/C $d^2n/d\,\lambda^2$ okay which has to be evaluated.

At λ0 then multiplied by the spectral width Δ λ right so it is simply telling you that difference between the group index at the upper portion of the spectral width that is a largest frequency component or the wave length component and the smallest wave length component here okay that is what determines the overall pulse width so that pu7lse width turn out to be Δ τ and clearly this Δ τ by L will give you the pulse spread per unit length and sometime this is also divided by the spectral width Δ λ.

In order to obtain the pulse spread which is measured in time and Δ λ which is measured in meters okay and length which is also measured in meters okay so this quantity is what is called as the material dispersion coefficient Dm and this quantity Dm is typically measured in units of

Ps/nm km okay it simply tells you that if you know what is Dm at a particular wave length $\lambda 0$ and you also know what is the spectral width $\Delta \lambda$ around that carrier frequency $\lambda 0$ or the carrier wave length $\lambda 0$ and then.

If you propagate a certain distance L through the fiber then you can calculate what would be the overall pulse spreading okay and that factor Dm depends directly on this factor D2n/d λ^2 right that is one of the major factors which give you the value of Dm of course this is Dm would be equal to 0 that is no pulse spreading when D2 n/d $\lambda 2$ would actually be equal to 0 okay so writing down what is Dm the material dispersion you have to divided this $\Delta \tau$ by l and $\Delta \lambda$ you get $- \lambda 2$ 0/C $d^2n/d \lambda^2$.

Evaluated at $\lambda 0$ so this expression for Dm tells you how the pulse would actually change what would be the delay of the pulse or sorry what would be the pulse spread in terms of ps/nm km for a pure silica fiber you can actually show that by properly measuring.

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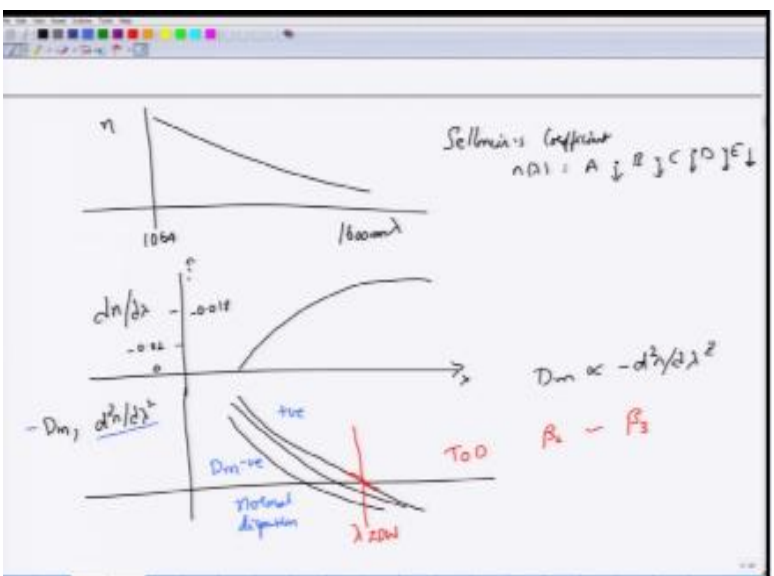

This refractive index n is a decreasing function of λ okay for the region of interest that we are looking at say around 1064 to 1600 nm this n as for the pure silica fiber would actually be a decaying function and attempts have been made to capture this empirical measured sorry captured this measured data using some empirical formulas these are known as sell mayors coefficients okay that is you expand this n of λ in terms of certain coefficients a b c d e I believe five coefficients are sufficient.

And this would actually be some powers of λ okay these are all multiplying some powers of λ the exact way in which this formulas you know the coefficients A B C D E come from or actually determine by the experimental values there is hardly any kind of good theory in order to find out the values of A B C D and E but once you know this coefficients for the given glass hose that you are working with then you can construct n of λ as a function of λ okay this is the very good approximation to the measured refractive index profile.

Once you have the refractive index profile n which is actually decaying function you can then take a look at what would be dn/d λ so let us plot dn/d λ and it turns out that this would be all negative okay so better way would have been to write this in under the access so this would actually be at 0 this is actually – point 02 this is – point 018 and so on okay so this is how this dn/d λ would go and it kind of make sense because n is decaying with respective λ therefore dn/d λ should actually be.

Negative now more importantly because dn/d λ is okay but my dispersion coefficient Dm is proportional to – $d^2n/d\lambda^2$ correct so I want to know how the second derivative of n with respect to λ looks like and that will look very interesting so it will actually look with the positive value until certain region and then it goes to a negative value and if you dope this one with different materials then you can control or you can shift the positions of where the 0 occurs and little bit here okay this is for the different materials.

You observe one thing over here you have $d^2n/d\lambda^2$ or equivalently Dm because they are proportional to each other there is consider any one of those curse so there is a certain critical λ which you can call this as λz D_w at this λzdw the material dispersion actually has gone to0 correct which means that there would not be any pulse spreading if you want to send only one wave length signal at this z 0 dispersion wave length and if you want to sending a very narrow pulse or you send in a pulse with very narrow bandwidth.

Then around this 0 dispersion wave length then because this dispersion itself is very small around that region there would not be significant material dispersion caused pulse broadening okay of course that would not be possible in the practice because you then will be working with only a very short region around that and then wasting much of the other regions so you cannot afford to really do that one.

So you do send in signals at various wave length not just at 0 dispersion wave length not just at zero dispersion wavelength, but it is good to know that the zero dispersion wavelength is going to 0 at some particular wavelength, okay and around that wavelength the value here is kind of quite small and the slope of that one will what is called as a third order slope or slope of β2 is actually giving you the third order dispersion parameter β3, okay and if you can also further evaluate you will be able to find β4, β5 and so on.

Now the other interesting part that you have to observe here is that in this region that is below zero dispersion wavelength, this $d^2n/d\lambda^2$ is actually a positive quantity, right because this is positive Dm actually is negative, right. So I should actually write this as not Dm but rather write this as –Dm because Dm is proportional to $-d^2n/d\lambda^2$ so while where $d^2n/d\lambda^2$ is positive Dm is negative, okay and this is what is called as the normal dispersion regime in the normal dispersion regime the characteristic is that the longer wavelength actually arrives at a shorter time.

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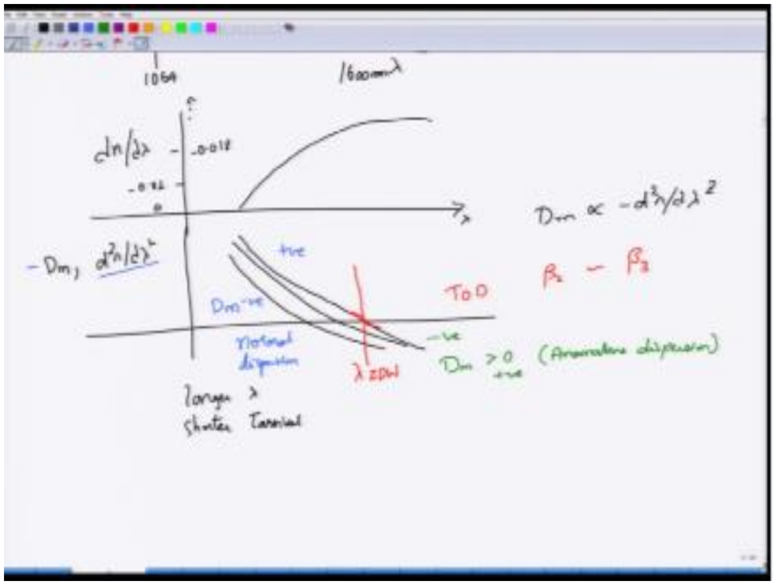

So actually the longer the wavelength that is contained the shorter will be the arrival times, okay shorter time of arrival. Now go to the other region where $d^2n/d\lambda^2$ is actually negative, right while $d^2n/d\lambda^2$ is negative the corresponding value for Dm is greater than 0 that is to say Dm is positive here, this region is called as anomalous dispersion, okay an anomalous dispersion is very important for pulse compression because in this region if you were to operate the pulse actually does not expand but rather contracts, okay.

Of course initially only if you take the length of anomalous dispersion to be very large then eventually, okay because of the chirping then you will start to see that the pulse actually becomes broadened, okay but at least in the small section of the fiber you can actually compress the pulses in fact this is quite widely used for pulse compression and it is also the region where you can find solid on propagation in the fiber, okay.

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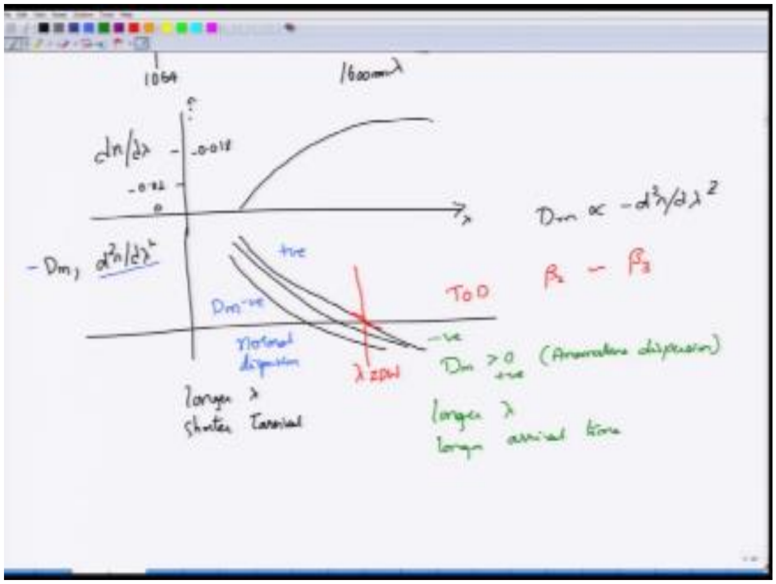

So this anomalous dispersion region is characterized by having a positive values of Dm or negative value of $d^2n/d\lambda^2$ okay, here what you can see is that the longer the wavelength, the longer will be the arrival time so longer wavelengths will arrive at a longer with a longer arrival time. So this is the characteristic of the anomalous dispersion in the materials.

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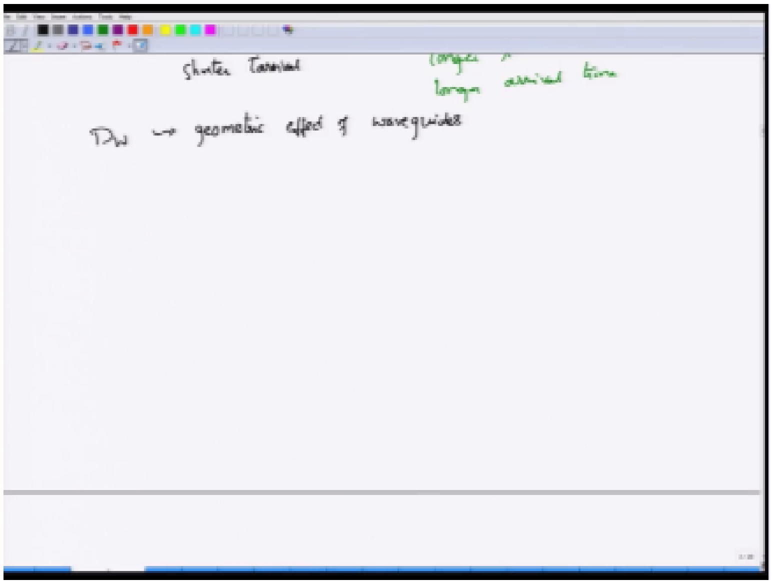

Now we will stop with material dispersion, we will look at another dispersion quantity called as the wave guide dispersion, now wave guide dispersion arises as I said in the previous module because of the geometric effect of wave guiding, so you are electromagnetic waves are not propagating in free space inside an optical fiber they are actually being confined because of the boundaries that exist for the core and the cladding they are actually propagating us confined modes inside the fiber.

So as they propagate in the confined mode remember you can have multi mode fibers or single mode fibers, right. Consider first the single mode fiber because multi mode fibers are typically having larger amount of dispersion and they are obtaining the characteristic of the dispersion is also slightly complicated to obtain a qualitative understanding of dispersion you will imagine a single mode fiber. Now one of the critical parameters that tells you how much energy is contained inside the fiber is the v parameter and remember how the v parameter changes with respect to the propagation constant.

It is not a linear region, it is I mean linear relationship it is actually a curved relationship, correct so this is how if you remember the normalized propagation constant verses the normalized frequency for the fundamental mode.

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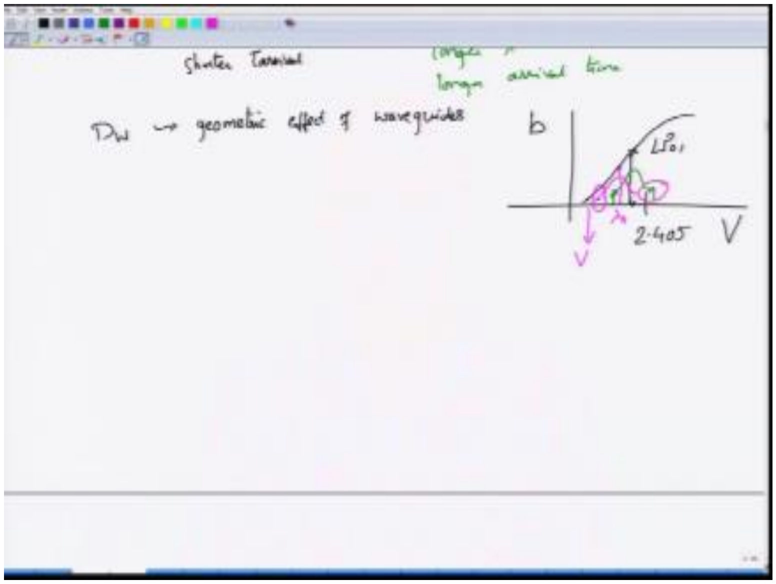

Would go like this, so this is for the LP01 mode, right. So you see that there is this curvature for the propagation constant and this curvature is the result of directly having certain core radius, right certain core cladding interface so it is actually the geometry. Now if you turn around and then make a rectangular type of an optical fiber then the b verses v curve, right will not be like this it will be different, okay. if you take for example, a free space then b verse v would been a straight line.

If you take b verses v for a metallic wave guide, then it would be slightly different it would look like this, okay. So depending on what geometry and what parameters you are looking at this particular curve b verses v would actually be changing. Now what is it mean look at this, we have this cutoff value for single mode it, right it is around 2.405 and we have mention that if you want to have a tighter confinement of the energy inside the core then the corresponding v number should be very close to 2.4, right it has to be as large as possible of course it cannot be larger than 2.4 then the fiber would not be single mode it would become multimode fiber. But larger v means a smaller λ also means tighter confinement.

Now this point we okay, as long as you had a single wavelength to consider but you actually do not have a single wavelength, you actually have a spread of wavelengths to propagate, correct. Because your modulating something and the shorter the pulse that you are modulating the larger will be the spectral band width and larger band width means that you have to consider all wavelengths over this region, it might so happen and it will happen certainly the larger the spectral band width is that the v number drops of significantly for a certain lower end portion of the spectrum and v number might increase more than 2.4 for a certain spectrum.

You might avoid this condition, you can avoid this condition of having larger values of 2.405 by actually moving the carrier frequency down in such a way that you do get a reasonable approximate I mean you do get a reasonable value for v at some $\lambda 0$, but at the same time the spread is more important, you can move it closer to avoid the higher end portion of spectral with being greater than 2.405 by moving the $\lambda 0$ closer to this one. But then you will see here that the corresponding lower end regions are actually having a smaller values of v number, okay.

Which means that these modes do not or the mode associated with these frequency components actually we will spend a lot of time in the cladding or we will have a appreciable quantity in the cladding and we know that the cladding refractive index is actually smaller, which means that portion of the energy actually travels faster, while the central portion which is smaller for smaller wavelength or rather for the larger wavelengths will actually be travelling slower, because v is inversely proportional to λ.

So you see that there is a difference between cladding and the core velocities and this difference depends on what wavelength you are considering and that is why you get wave guide dispersion and you can tailor this one by adjusting the core cladding refractive index distribution also changing this you know core radius a, you can tailor that dispersion by changing the refractive index profile do not consider the single mode profile. Consider making the core area very small, okay or consider having multiple tranches in there, so you do all this design, okay and in order to change the geometric dispersion effect and that is what is called as the wave guide dispersion. It turns out that for standard single mode fibers.

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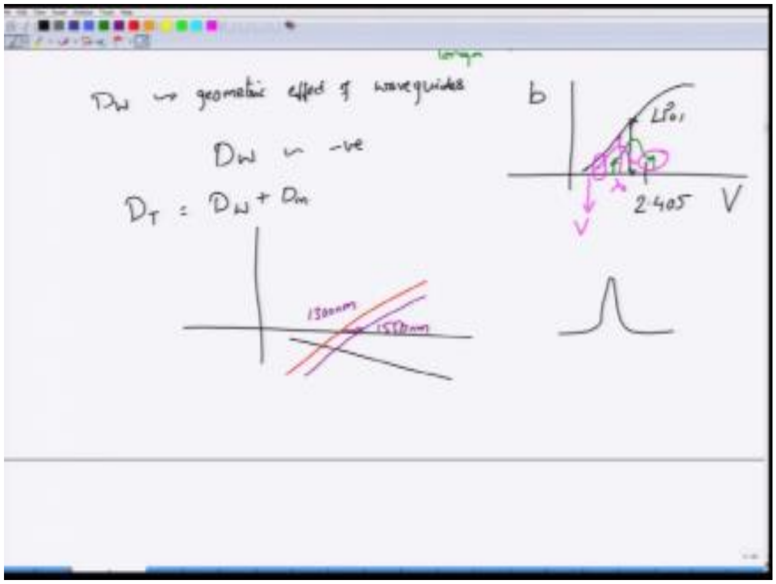

The wave guide dispersion Dw is mostly negative, okay and the total dispersion in the fiber comes because of the wave guide as well as the material dispersion, okay and material dispersion we know that would be initially positive up to certain frequency and then it becomes negative, correct. When Dm is positive this is called as a normal dispersion regime and when Dm is negative it is called as the anomalous dispersion regime. Now the total dispersion would be a quantity that is positive so this is how my Dm should go and then once you add Dm as well as Dw your overall dispersion curve would be going around something like this, okay.

My pictures are not really nice, but what has happen is that the zero dispersion wavelength has been slightly shifted from the material zero dispersion wavelength parameter, so it has been slightly shifted and in fact you can shift this zero dispersion wavelength from the 1300 nm which actually is a material dispersion for the pure silica fiber you can shift this zero dispersion wavelength to 1550nm which is the window for optical low loss optical window for the communication purposes, right.

By appropriately tailoring the refractive index profile, for example when you make the core area very small right, then you will get a larger Dw which allows you to shift this zero dispersion wavelength, but the drawback of this profile would obviously be that there is only one zero dispersion wavelength, so you have to perform all your modulation only around that wavelength in order to take advantage of zero dispersion which obviously cannot be done because you have a larger you know number of users so you have multiplex you have many channels and you cannot just transmit everything only at one channel, so in order to overcome that defect.

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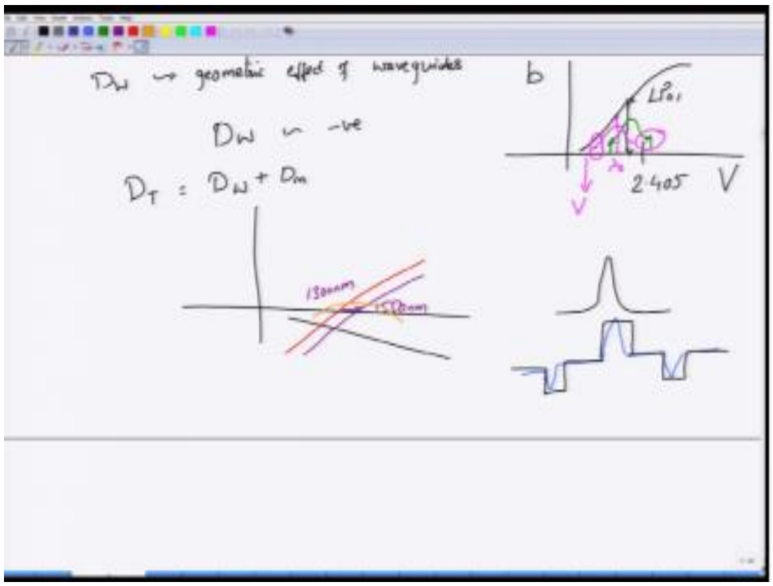

You introduce this trench kind of a refractive index profile, okay the trenches I have shown are the kind of practical trenches but for analysis purposes you can assume them to be step trenches and step index profile, okay. So this would be the index profile for a dispersion flatten fiber, what is dispersion flatten fiber here your dispersion actually will be zero over a certain band width, okay so this would be the dispersion curve. I am not showing anything to the scale, okay you can look at the actual data sheet of the fibers in order to find out where this dispersion flattening is happening, what is the range over which it is happening, okay.

But this is essentially the idea, so you can create dispersion flatten fibers which are extremely important for communication purposes. Now one of the things that commonly comes up when we ask questions to students about what light sources are used for optical communication, most students without asking further questions or without giving further thought would answer LEDs.

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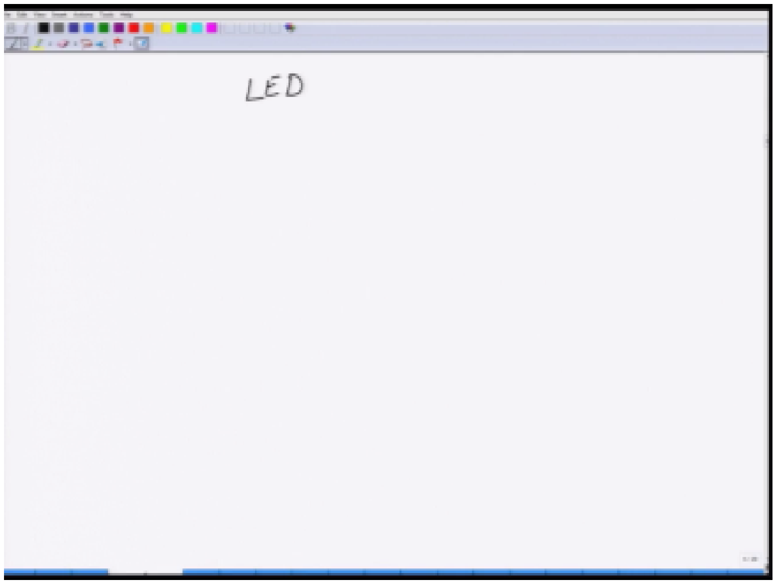

True, LEDs are cheap they are economical they are available at a very low cost at all places and LEDs are easy to recover a circuit they are also easy to modulate, you know data is easy to modulate you know that is easy to modulate on a led circuit, you don't have to worry about modulation de modulation the only drawback is that led is don't really work for long distance communication, there perfectly fine if you want to work with say about 100,200 meters of may be push it with great difficulty about 1 kilometer, okay.

But if you want to communicate over to your friend at the other part of the country there simply not suitable, so modern optical communication does not use led's, for long haul communications, okay for shorter and very short hall communications like this within the room lighting or wireless optical communication, these are all performed by led's because there cheap and they can be used their okay.

But they are not used for long haul communication and the reason is very simple, we will talk about that reason by looking at what would be the maximum data rate with which you can transmit? Okay which in turn is governed as you know by what is the delay that or the group delay that this, that we have to tolerate right? The,

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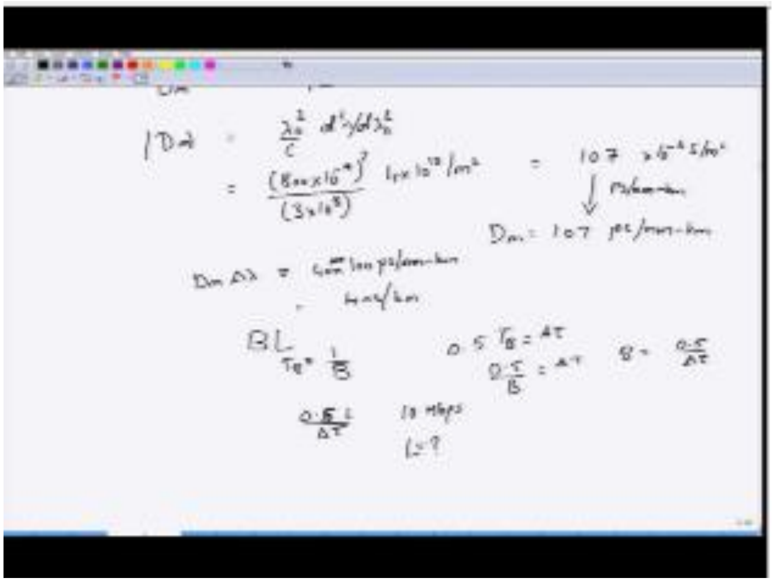

Larger the group delay, or the larger the pulse spreading the shorter will be the bit rate of transmission, right? so consider the typical led which has the typical spread ,Δλ are about 40 nanometres, you can actually find Δλ of up to 100 nanometres in practice , but these is a very good quality grade led which has a Δλ of about 40 nanometres.

Its spectral operation is around say 800 nm which was what the original or the first transmission window of optical communication was, this was way back in 1970's,okay, so today off course we are in 2016 and we don't really use 800mn for long distance communication .

So λ0 is 800 nm. Δ λ is 40 nm and someone has measured this quantity $d^2n/ d \lambda 0^2$ and have given as this value of $4*10^{10}p/m^2$, i hope the units of per meter square is evident, because n does not carry any units, λ carries a units of meter so this one is $1/ m^2$ now can you calculate what is dm also calculate what would be the pulse spread Δ τ , so you have to calculate what is data to u p/l , remember $\Delta \tau$ is the pulse spreading, in order to get the pulse spreading you don't really have to know the sign of this Dm.

So you can just look at the absolute value of Dm, which will turn out to be $\lambda 0^2/c * d^2 n/d \lambda 0^2$, that $\Delta \lambda$ *l has been thrown away in this particular case, because Dm is actually a quantity which is per peak of second per nanometre and kilometre, okay, so you first find out dm, you can substitute the values here this is 800nm, or 8 micro meter, so you can put that one there.

The velocity of light is $3*10^8$m/s and $d^2n/d \lambda^2$ is given as $4*10^{10}m^2$, so you plug in all these values you will get the absolute value of dm as $107*10^{-6}s/m^2$, converting this in to the units of pea co second per nanometre, kilometre will give you 107 pea co second/nanometre km, okay.

So this is the material dispersion for the led that has been measured now this is by itself not very important, what is important is what is the product dm *$\Delta \lambda$, and what is that product this is roughly 40*100 pea co sec/nm km, so this is 40 nm, so nanometre goes away over here, you get around 4000pea co seconds / km or 4 nanosecond /km, remember we have talked about this B*L product right? So B*L is the bandwidth into L product.

And we have talked about that if you want to transmit at B you transmitting 1 pulse every 1/b seconds, so you are transmitting this and if you ask that no this is the rate at which the pulses are coming out or this is the time period of the pulses. And if you say I can tolerate about 0.5 time is the pulse spreading, right? I can tolerate the inter symbol interference of about 5 times! I mean 0.5 times a pulse spreading.

Then 0.5 times db= $\Delta \tau$, that we have calculated right $\Delta \tau$ is the pulse spreading ,it can be about 50 % of the original pulse period let us say, like that okay, then you can substitute for db in b here this becomes $0.5 \pi b = \Delta \tau$, you can say $b=0.5/ \Delta \tau$, put this relationship back in to the expression , and then you get $0.5/ \Delta \tau$ *L this would be the bandwidth in to time product.

And we have seen that this $\Delta \tau$ is around 4 nanoseconds /km, so here you have 4 $\Delta \tau$ as 4 nanosecond /km you can substitute this and then say if I want to obtain data rate of 10 mbps what should be the value of L? So ill just leave it for you guys to calculate this one, this would be a small exercise to you.

So with dm turning out to be this value and if you want to data rate of 10mbps, find out what is this length over which you can propagate, okay so this is for the led now consider a laser.

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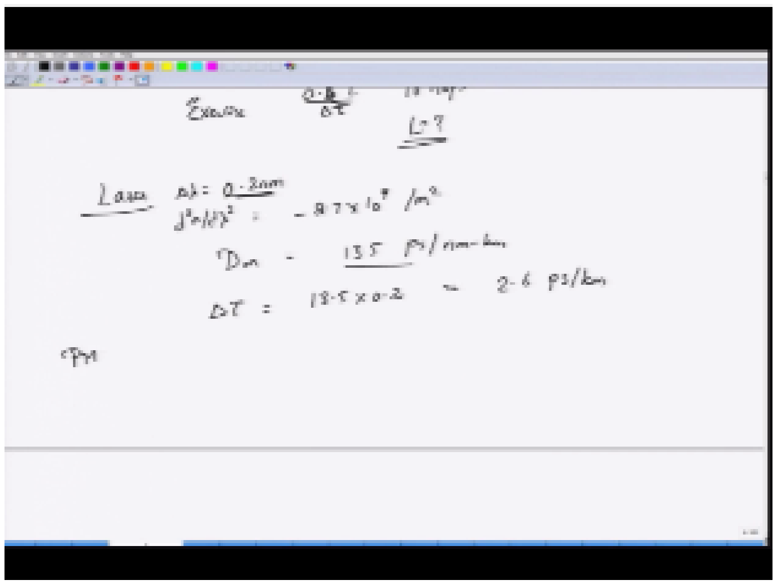

Okay a typical laser has a line width of 0.2nm, okay this is of course not the best of the laser the best kind of a laser s today have about 100 to 200 KHz of line width, these are extremely small line widths that you actually get, but this $\Delta \lambda$ will be around 0.2mn, there is a typical about tem twenty years ago what would be the laser okay.

So let us take that value there , and the value of $d^2n/d \lambda^2$ is slightly less for this laser it is one order of magnitude less and this is given by $2.7*10^9$ $/m^2$ you can substitute foe dm and calculate that this will turn out to be 13.5 pea co sec/nm km , if you compare this value it is not very large, mean it is not very drastically difference, it’s just one order of magnitude lesser then dm for the led, for the led you have 107 pea co sec/nm km or about 100, here you have 13.5 pea co sec, which can be third of its strength .

So there is just one order of magnitude reduction in dm but this is not what gives us the advantage of a laser the advantage comes here because of this 0.2 nm, decrease in the line breath why ? Because you calculate $\Delta \tau$, $\Delta \tau$ turns out to be 13.5*0.2, right? So many pea co seconds/ km this is actually around 2.6 pea co seconds /km. Which is a 1000 times less then what you had for the led case, you know it's in order of three magnitude less compare to the case of a led, therefore the data rates can be tripled at the very least you can triple the data rates using a laser.

So you can propagate much larger distances you can propagate with a larger bit rate using a laser therefore the reason why we use lasers for long haul communications or any communication that has to take place more than a kilometer or a about 10 km, is because you can transmit at larger data rates using lasers have a smaller $\Delta \lambda$, smaller spectral width, okay.

So next time when someone asks you what kind of a light source is used for optical communication I do hope that you are going to ask the questionnaire back saying that are you taking about very short hall or indoor wireless kind of a transmission a system or a long haul system, if it is long haul then it has to be a laser okay, so lasers are the reason why you can have this long haul communication.

The final dispersion that we wanted to talk about is what is called as polarization mode dispersion, now this polarization mode dispersion is kind of very difficult to model analytically okay, it was initially discovered in the decades of the 90's where people started going from 2.5gbps systems to 10.10gbps systems. So when that upgrade happened then they figured out that PMD was one of the mail limiting factors for you know, for not being able to go from 2.5 to 10gpps systems.

And lot of studies where done but still a thorough theoretical reason has to why PMD arises is not possible to as not been found but excellent studies have shown that the spread because of the PMD $\propto \sqrt{L}$ (length of the fiber) this square root of length can be thought of some kind of a random walk, you know a typical random walk is one where you take with a certain probability ,one step towards the right and a certain step to the left with a certain probability, okay once step to the left to the left with the certain probability and if you wait for large number of steps you would see that you are actually not just sitting at the initial point, as you would expect you in to be, but you would actually be arriving at a point which is a √n. So that's the average position after taking a large number of steps.

You know sometimes to the right, sometimes to the left so in that context which is called as the random walk problem, so you can think of this PMD as power exchange or the mode exchange between x to y and y to x, with a certain probability and over certain length, we will later give you mat lab exercise to realize all these things there is a nice way of formulating this problem, okay, using simple matrix approach called as Jones matrix approach.

You will be solving that and you will you can see what will happen when the polarization mode dispersion actually occurs and the pulse basically spreads out, okay. So we have looked at these different dispersion characteristics it is time to wrap up this dispersion and then go to another factor which is called as attenuation.

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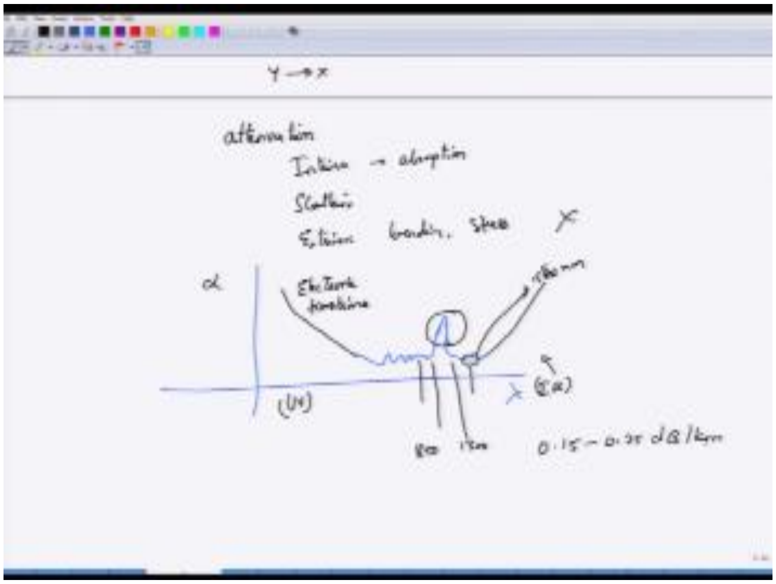

Attenuation again the mechanisms where by attenuation occurs in fiber can be intrinsic, okay, and this intrinsic includes absorption, it can scattering of light and it can be extend sick extend sick factors such as bending stress etcetera can cause attenuation we will not consider this attenuation now and we will of course not even be considering the full picture of why ad attenuation occurred this is something that is left best for materials and science people to explain better.

But if you look at the attenuation versus wave length curve for a silica fiber you will see that attenuation is very large at x ray wave lines it is not very short wave lines less than 400λ 400nm the attenuation is very large okay and this happens because of the electronic transitions at very small wave length the energy of the photons are quite high because energy is inversely proportional to λ it causes the materials in the lower state to go to the upper state okay.

There by inducing at transition so these electronic transitions cause attenuation of the signal you will see that at longer wave lengths there is an intrinsic absorption that is at the Ir region there is an intrinsic absorption here this is the uv region so this absorption keeps on increasing beyond around 2 to 2.2 micron for a silica fiber in between this is what is called as a low loss window which you will find some amount of vibrations okay these are because of some metals which are present in the fiber.

And then you will also see some water peaks which happens because of the impurities in the form of the hydroxyl ions which are used actually to when they are actually being use to fabricate when the fibers are being fabricated then connecting this would be the low loss window okay. In fact modern methods actually have almost eliminated this peaks hydroxyl peaks are the impurity ions water impurities and thereby lowering the losses.

So this region you know is called as the optical region right and in this region is where you communication windows are located earlier this was located at 850nm then it became 1300 nm and today your on this 1500nm window or 1550nm window where the loses are at its lowest. Over about 100nm the losses are pretty small the range from 0.15 to 0.25 db per km now what exactly is this attenuation loss.

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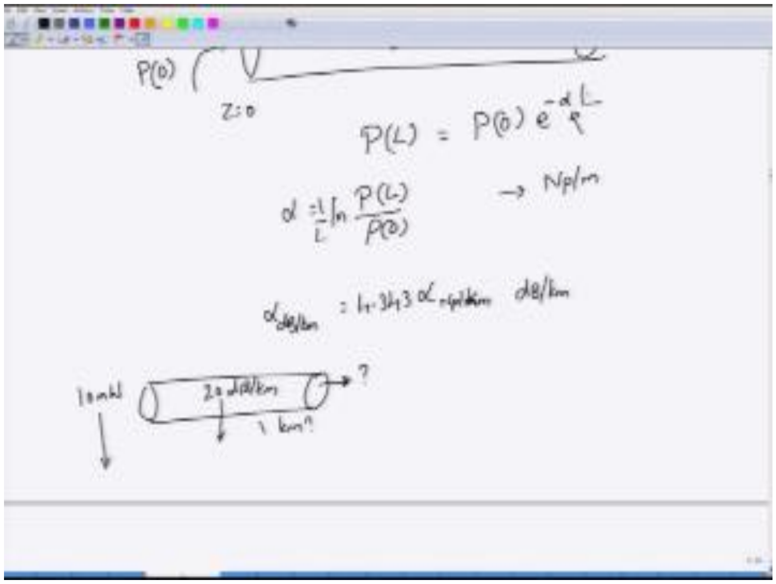

What it simply means is that if I take a fiber of certain length l and then send in a certain power which let us call it has p(0) at z=0 and then measure the power at the end of the fiber which we will call as p(l) it can be shown that this p(l) okay can be given as p(0) in to $e^{-\alpha x\ l}$ where l is the length of the propagation so this kind of a exponential relationship is empirical of course this is phonological relationship it does not come really from the fundamental physics are something.

But this is an excellent approximation for characterizing any loss in the fiber okay and loses are characterize by changing this value of α you can find out what is α, α is simply given by p(l)/ p(0) you take the natural log on both sides and divide this one by l okay so if you do this one then you will get the attenuation right this attenuation is measured in Np/ m or simply per meter but it is more common to actually specify attenuation in db/km okay.

So the relationship between α in db/km 2 α Np/m is this one so it is around 4.343 times α in Np/m okay Np/km I am sorry okay why this db/km thing is important let us considered simple example in the 1970 you had losses of 20db/km okay so this was the typical fiber in the yearly 1970 is where the losses about 20db/km suppose I send in 10mv of power okay what will be the power that you except at the output of say 1 km since the loss is 20 db /km and input is 10mv you can either express this 20 db/km in to np/m quantities or express this power into disable quantities and then subtract them and then you can get the corresponding expression. This is what we normally do.

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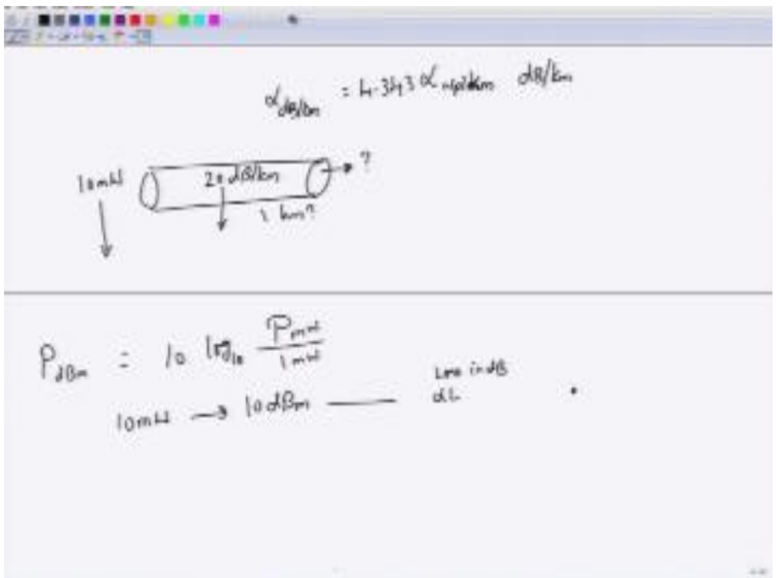

We consider how much power you are in suppose p is the power in mille watt divide that one by 1milli watt take then log to the base 10 multiply by 10 and what you will be defining is a quantity called power in dbm it is simply telling you how many disables above mille watt my particular power p is okay, for 10 mille watt this corresponds to 10 dbm okay so it is 10 db above one mille watt okay.

Now this power is launched and to obtain the loss at his point because you are working in the dp scales or you have to do is subtract this α x l when α is expressed in db/km times the length of the propagation will give you the total loss this loss will be in db right so this was at this level okay this power was at compare to 10mille watt so this, this is my base 1mille watt 10 mw means 10 disables above 1mw right.

And then losses would mean after subtracting the total losses you have to be at a certain above or below depending on how much loss you have in this case the total loss will be 20db so you started off with 10dbm then after losses you have gone down to 10-20 which is -10dbm. Which is 0.1 mw okay, so that is the kind of power you are looking at for a 1km transmission this is the power that you are looking at okay? If I turn around the problem and then tell you.

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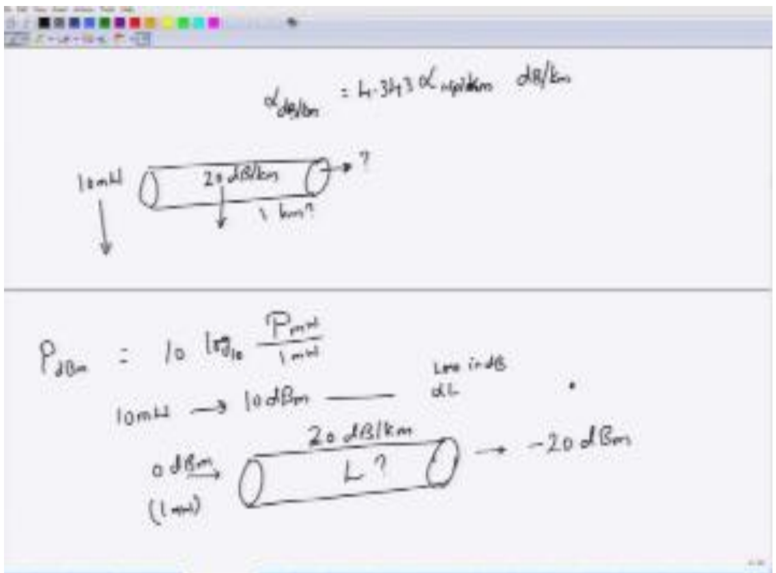

I can I do not know what is the length of the fiber that I want to use I know the attenuation is 20db/km however I am able to detect any power which is at least -20dbm can you find out what would be the length l well assume that the initial input is 0 dbm corresponds to 1mw okay.

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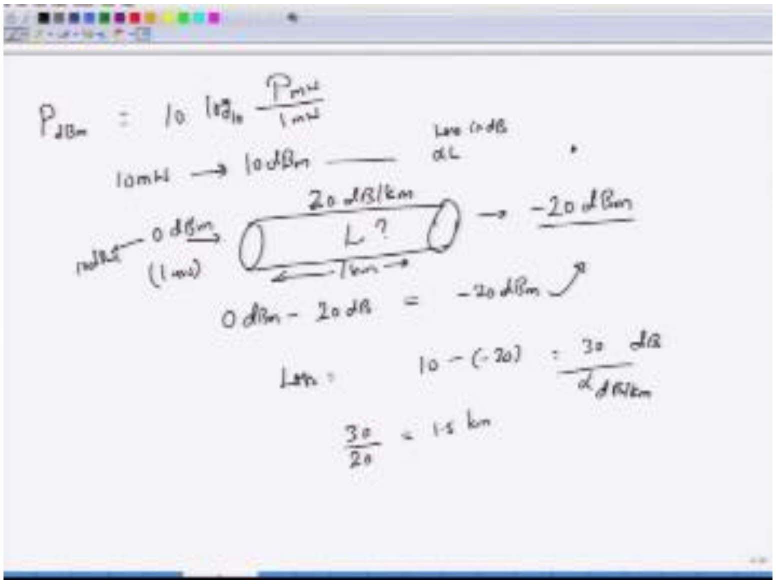

So you learn how to do all this conversion using those formulas which have given you so 0dbm corresponds to 1 mw and I can actually measure up to -20dbm using my photo detector circuit, what would be the maximum length of propagation that I can choose well the total loss is 20db/km right and if I consider 0dbm and add this loss which is -20db what I get is -20dbm which is just sufficient to measure the power.

So if I take 1km the total loss is 20db and I am actually able to transmit over 1km that is the maximum distance over which I can transmit, if I increase from 0 dbm to 10 dbm, then the length also can be increased because I am looking at a total loss of 10 so I have to started 10 dbm, to get down to -20 dbm I should have a loss of 30 db right so 10-(-20) is the total loss which is 30db loss .

But this loss divided by α will give you l because α x l is so and so db loss correct and α is measured in db/km so if you do that one you will get 30/20 which is around 1.5 km so if you start with 10mw power right and then you will still be able to go only up to 1.5km.

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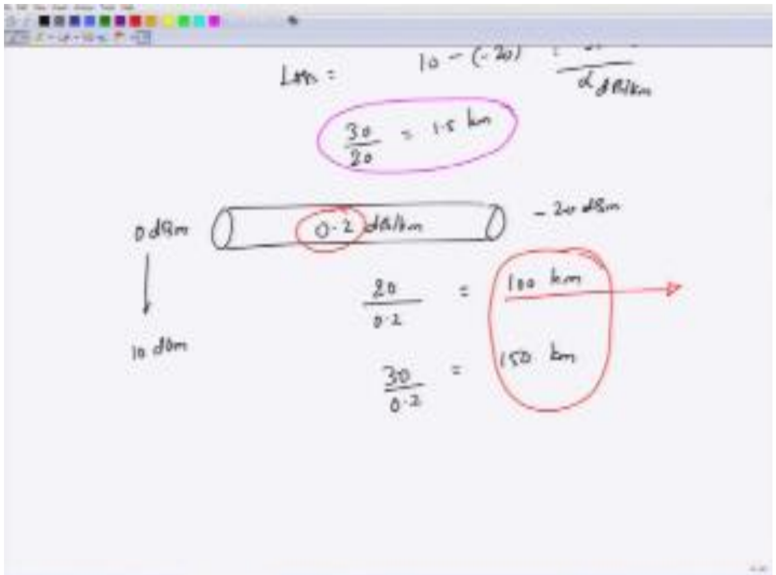

Consider this scenario and compare it with optical fibers whose losses are around 0.2db/km again the same -20dbm is my sensitivity limit or the minimum power that is required for the receiver I start with 0 dbm or 1mw optical power then what would be the length over which I can propagate well the losses total will be 20db so 20/0.2 which is about 100km correct. So this is the length over which I can propagate if I increase from 0dbm to 10dbm then the distance over which I can propagate will be 30/0.2 which I suppose will be around 150km right.

So you can see that remainders improvement from the earlier optical fibers which you could go only up to 1 to 1.5 km compare that same fibers today with losses as low as 0.2db/km the transmission distances have increase to 150 km in fact this transmission distance of 100 km roughly 100km is the span length so before which you will have to put in your repeaters in the optical communication systems.

So for a long hall communication system this 100km is the span length so this completes are parameters of the fiber to just deafly recap fibers are made of glass materials this glass material doped with appropriate doo pens in order to increase or decrease refractive indexes these doo pens and the glass material itself is the function of wave the refract index is a function of wave length and $d^2n/d\lambda^2$ which tells you how the refractive index is varying the second order refractive derivate of n with respect to λ will give tries to material dispersion okay.

Which simply means that the pulse are going to be spread and additional dispersion is the wave guide dispersion which occurs because of the geometrical aspects of the fiber and a third dispersion is the polarization mode dispersion which happens because of the random exchange of the power or field between that two modes of the single mode fiber okay, the overall dispersion is determine by all these three quantities in a single mode fiber.

For a multi mode fiber you also have to consider inter model delay that is delay between hE11 mode and TE 11 mode for example right, the first and the next higher order mode or between the higher order modes so multi mode fibers are typically much more prone to dispersion then single mode fibers finally attenuation is a mechanism we should reduce the optical power so this if you start with say 1mille watt at the input of the fiber what you get after 1 or 2km of the fiber will not be one mille watt.

There will be reduction in the power and how much power is reduced is determine by the attenuation co efficient of the fiber so this completes are parameters of the single mode fiber in the next module we will begin we will go back to communication concepts and study the simple module in order to put them together and we will then look at optical sources and optical detector later on. Thank you very much.

Acknowledgement

Ministry of Human Resource & Development

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Aradhana Singh

Sweta

Ashutosh Gairola

Dilip Katiyar

Sharwan

Hari Ram

Bhadra Rao

Puneet Kumar Bajpai

Lalty Dutta

Ajay Kanaujia

Shivendra Kumar Tiwari

an IIT Kanpur Production