Indian Institute of Technology Kanpur

National Programme on Technology Enhanced Learning (NPTEL)

Course Title
Optical Communications

Week – IV
Module – V
Optical fiber-I

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Hello and welcome to the mook on optical communications we have seen optical transmitters we have seen optical receivers that was a big picture called context to see where optical communication system fits in of course optical commutation would not exist without the optical fiber itself and of course a laser source or a light source in order to send light but that is a different part of the sorry we will come back to that one later so the principle reason why we do have optical fiber communications is because we have low loss large band width optical fiber that is the optical fiber loss is so low that one can go considerable distance typically about 80 to 100 kilometer in the long haul links without outing up an amplifier.

So of course at that stage the signal quality would have degraded but this is a very large distance if this large distance can be compared to much shorter distances that you would have had to use if you where to use a copper cable in order to connect the whole wide world so optical fibers have low loss which means long distance propagation is possible optical fibers also support a large band width the operating frequency of the laser itself is terahertz so even if you were able to just tap point 10% of that terahertz signal then you're already looking at a very large bandwidth.

More over by multiplexing the channels you can actually an implementing spectrally efficient modulation techniques such as QPSK or higher order QPSK QAM as we discussed in the transmitter side it is possible for us to improve the data rate as much as possible now what we will do is we will began with consideration of optical fibers I will give a very brief over view of the optical fiber history and the quickly jump into what is called geometrical optic analysis of optical fibers this geometrical optics is kind of very simple analysis in the sense that it is actually a simplistic analysis it works under certain conditions but in general if you want to understand more about optical fibers the propagating modes and how will I it actually propagate inside the optical fiber then you have to study it from the electromagnetic theory perspective.

However we will of course we have already looked at electromagnetic review and I am assuming that you have done a course on the electromagnetic but geometrical optics provides a little bit of intuition which we will be gaining if we study with the geometrical optics approach and more over it is kind of simple we will understand a little bit about optical fibers and how the mode propagates in a simplistic way by looking at geometric optics ;later of course we will use electromagnetic to actually know how the light gets distributed inside the optical fiber okay so let me began by highlighting.

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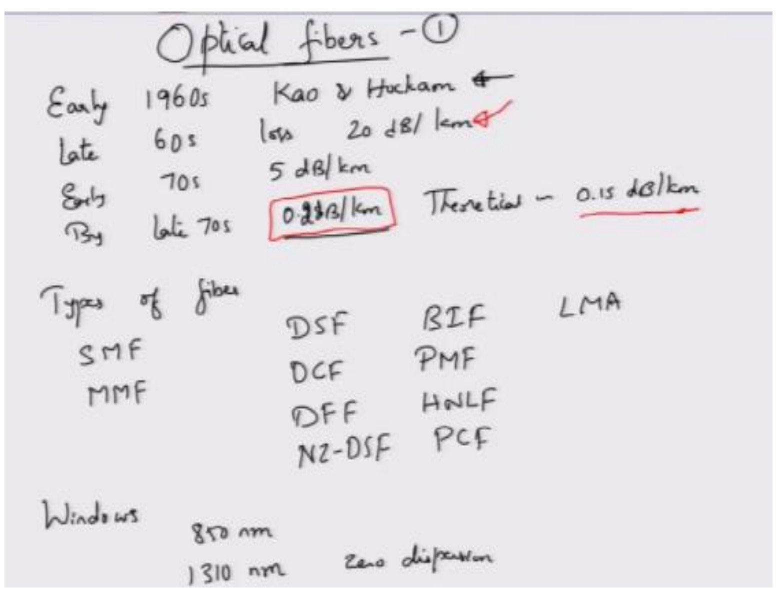

The kind of short history around here optical fibers the concept of an optical fiber was not knew it was there from the earlier times when light itself used as communication tool however the realization that silica made or silica dielectric rods which where what they were called earlier can lead tom optical fiber production and can lead to low loss optical fibers was actually made buy a couple people one is Charles kao he was working in the bell labs at that time when he made this kind of prediction or rather an nice case for optical fibers.

I should say not prediction it was a nice case of optical fibers optical fiber type guide wave guides where already studied but the importance of them for communication was realized by kow where in he published a paper in the year around 1966 which was a very famous paper by these two authors kow and howcome so these two guys published a paper where they analyzed the existing silica dielectric rods what are the modes of propagation and they also predicted that if one could find a you know fabrication method which can cut down the law's then this can be used for optical communications.

Okay so it was it kind of realizations that even though it sometimes it is very obvious that if you simply cut down the law's in an optical wave guide you can you know use it for communication was it was not applicated at that time when kow and hiowcome made this analysis the people around them go so existed they started really working towards achieving the low's so at that time if you wanted to replace the existing copper cable network by an optical fiber the targets figure for the law's was 20 DV/ km because this is the typical law's that microwave links which used you know links which used copper cables where going.

So if you wanted to target we wanted to say that they know you see you throughout all the copper cables in the worlds and replace them with this very thin slice roods then it was necessarily to convince the industry that this target laws of 20DP/km can be met and this was made possible in the year 1970 by a process known as chemical wave predisposition which brought down the loss to less than 20dp/km once it was brought down to that level work intensifies so much that in the earlier 70's in the earlier to mid 70's the loss where already down to 50 dp/km which is way below what the copper cable can do and it was realized that the main contaminations to this was the water contaminations.

So it was you know people understood it very well and therefore they also came up with methods to remove this contaminations and eventually brought down EΠ the late 70's now just about start of the 80's the losses were brought down to 0.2dB per kilometer. Now that is an extremely small value compare to 20 dB per kilometer and remember this is the dB scale so if you go one order magnitude won you are reducing by 10 times you know you are going by that one, so you go that ways you are quickly building up to the DB scale you can appreciate very well that from 20 dB/km losses.

If we have come down to the existing optical fiber losses around 0.2dB/km and the theoretical predicted loss for the silica fibers where around 0.15 dB/km this one can obtain after looking at various type of scattering loss and material composition of a silica fibers, so this was the ultimate limit kind of a ting and it looks like we have even recently reached almost to the theoretical limit not even 0.2 it the losses have been cut down even further.

So the loss property of an optical fiber which is very low for fibers was made possible by tremendous efforts of so many researches where they started off from 20 dB/ km this was a magic figure to achieve from there the losses where steadily brought down to the existing levels of 0.2 dB / km, of course I have told you only one part of the loss story because loss is also wave length dependent.

So if you go to different wavelengths operating region then the loss also changes with that, with typically the lower wavelength regions having higher losses and the higher wavelength or the longer wavelength having lower losses okay, so based on that optical communications started operating in different kind of windows as we call them we will talk about that in the next few minutes. Now what different type of fibers are available in the market today? Fibers not only characterized by the loss they are also characterized by the area of the core.

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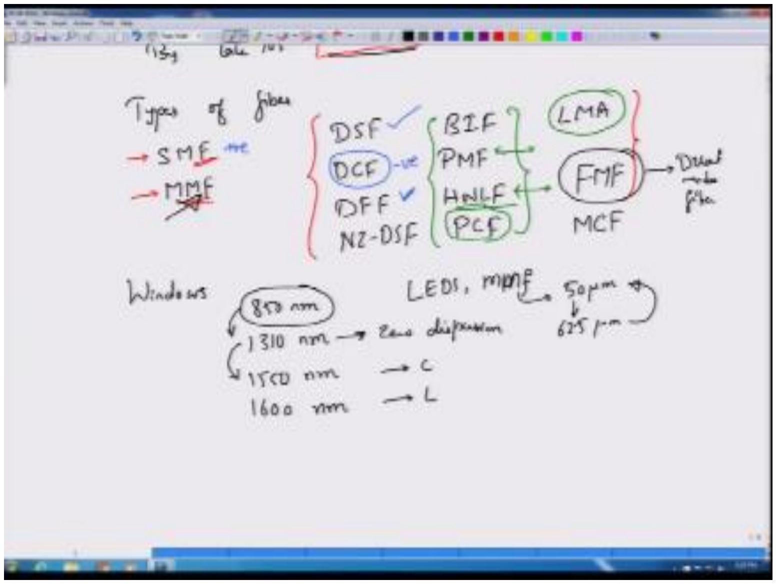

The total area of thee fiber itself and whether they are single more fibers or multi mode fibers and whether they can cope with dispersion or they cannot cope with dispersion, can they maintain polarization are they insensitive to bends can the non linearity in the fiber a topic which we have not test and non linearity in the fiber be increased, it is possible to you know come up with very interesting specialty type of fibers which will do.

Even things which are not a typical fiber can do and can it also be possible to reduce the non linear non linearity in the fiber, is it possible to excite multiple modes in the optical fiber if we case do that what type of a fiber should we have so all these parameters determined the type of fibers that are available in the market, the primary type of fibers that you can find in the market are the single mode fiber and the multi mode fiber.

And all these other fibers can come In the versions of single mode and multi mode fibers, what we mean by single mode fiber is that, for the given frequency of operation there is only one mode electric field pattern and magnetic field pattern together is called as a mode, so there is only one mode which will propagate inside the fiber, okay. So when it comes to multi mode fiber as you could have easily guessed.

Multi mode fibers will have multiple modes it can support multiple modes although it seems that this idea of multi mode fibers is very interesting rather than restricting our self to only one mode carrying the information signal why not use a multi mode fiber and have many, many modes carried information signal, it turns out that in the 70's, 80's 70's it was quite popular 80's it was already beginning to go down.

90's it was not 2000 it was not the reason for why MMF was not popular for long hall communications was because it introduce us what is called as intermodal discussion, okay. These signals which are carrying with each other they start to talk to each other and then they will be distortions and the total error rate of the system increases and therefore this was not a preferred choice.

Of course MMF can be easily excited by coupling it to achieve Led and this MMF operating in the 850nm was white popular for short distance communications such as Ethernet, today multi mode fibers have made come back in some specialized areas where people have learnt how to Un-couple these couplings that exist between the most inside the multi mode fiber. So this uncoupling is done not in the optical domain.

But that is done in the digital signal processing domain, so having said that we will concentrate for the theoretical purposes or for the course purposes to understand the properties mainly of the single mode fiber we will go to mufti mode fiber as and when that is required. I said that dispersion is a major factor in optical communications, infact we will later see that dispersion limits the bandwidth or the bit rate of the system.

In order to cope with dispersion there are lot of ideas people have come up with over last 30, 40 years one is the so called dispersion shifted fiber which has a 0 dispersion wavelength located in the Fee band I will tell you what this bands are later, so this is the one where we are operating at 1550nm and the dispersion shifted fibers has a 0 that is 0 dispersion at 1550 nm you also have a dispersion compensating fibers.

Suppose you have a single mode fiber which is characterized by positive dispersion whereas DCF are characterized by negative dispersion so if you put one after the other you can see that dispersion can be compensated if you choose the appropriate length and hours there is also what is called as dispersion flatter fiber here the dispersion cure is almost is almost constant with respect to wavelength.

So this is used in other specialized applications where we know the amount of dispersion or rather we want to minimize amount of dispersion that over a wide band of information barring signals are subjected to rights like though kind of a band over which the dispersion remains constant therefore all the signals within this band are unaffected by dispersion or rather they are affected by dispersion with the same value it was also realize that having DSF would increase non linearity because non linearity and dispersion are like you know in and young one goes up the other goes down the other goes up one goes up so if dispersion goes to 0 that is where the area where non linearity is can really, really take of and create lot of troubles therefore it was realize that well we do not want to make the dispersion 0 let us just raise the dispersion a little bit.

So that the overall efficiency of non linear generation comes down okay so this type of fibers are called as non 0 dispersion shifted fibers and this non zero dispersion fiber have a small amount of residual dispersion which will then allow it to counter act the non linearity's these are some of the specialty fibers that you can get in the market BIF is called as bent intensity of fiber and this is majorly applied for the fiber to home networks where in it is you know the fiber has to go from home from say your room do your a parents room for example there as the cable goes there will be bending around the edges because no one likes to have a fiber hanging out like this right so you want all the fiber lines

.

Just like the power cables are buried inside your house you want along that same lines your fiber also to be buried or you know guided by the walls rather than by just hanging around which invertabily leads to bend in the fiber and bends in the fiber reduces the I mean the bend in the fiber actually increases loss a lot of it increases loss it will also alter the dispersion so in order to hope with this problem bend in sensitive fiber or bend managed fiber are used which will have little bit of less sensitivity compare to typical single mod fiber for bending you have a polarization maintaining fiber.

Which will maintain the x and y polarizations inside the fiber suppose you launch a signal x polarization then at the end of the fiber your guarantee to have the same polarization by the polarization mod dispersion if you want to perform some non liner optics non linearity is not always bad it is good in many cases of optical signal processing so if you want to use your fibers for that you want your fibers to have a high non linear coefficient and those fibers are called as h and lf that is highly non liner fibers and this last fiber which I mentioned you know can do very interesting things this is called as photonic crystal fibers so these are kind of fibers plus filters integrated together I mean this is a very simplistic definition that I am giving but is photonic crystal fibers can do lot more interesting things and what I have just told you now finally large mode area fibers are available which have a larger more area.

And non linearity bring inversely proportional to the area if you increase area non linearity comes down I also forgot to put one more fiber here this is called as a few mode fiber of few more fiber you know ahs typically like only one to say 6 or 1 to 7 modes sometime there is a specialization of the few more fiber called as dual mode fiber or too more fiber in which there are only two modes okay so these few more fibers have much less modes they can support much less number of modes compare to the multi mode fibers whereas multimode fibers can easily support up to 15 to 20 modes.

Few mode fibers can support say about 6 or about 5 and that already is very large for this finally you have what are called as multi core fibers rather than having a single fiber with a single core you now get multi core fibers the idea here is like you know you have taken a multi core fiber each of this core is can then carry information signal okay so it is like your pitting some parrelisim you are having an antenna and then your beaming it into 4 different areas so it is kind of broadcasting thing that is being looked at so these are all the different type of fibers and these fibers all are characterized by different geometries they are characterized by different core areas their characterized by different cladding diameters.

You know clad cladding there also characterized by the refractive index profile so some fibers have a trench in order to make them be less Benn sensitive than others and some have no trench some have a step index fiber some have a graded index fiber some have a very interesting fiber profiles in order to achieve this DSF DCF DFF properties okay so we will see some of those later when we discussed the summary of different of fibers after we have learned the modes okay now one last point about the operating wave lengths in optical communications the early optical communications was.

Made with the help of Led's and multimode fibers it was easy to couple up LED and multimode fibers for which the core diameter or I think core radius or core diameter I am not very should which one it is was 50micon became 62.5 micron and then it was pushed back to 50 micron in order to make it comparable with the LED so this 850 nanometer is was the first window of operation where much of the optical communication was taking place this of course was in the LED 60s or earlier 70s then people figured out that if you go to a higher wave length 1310 loss goes down so the next window.

Of operation was 1310 nanometer it also had a bonus because the 0 dispersion wave length of the fiber was the 0 dispersion of the fiber which is Silica material depended was at 1310 nanometer so it was made up of Silica and this Silica had a 0 material dispersion at this 1310 nm, so it was quite interesting to work with both low loss as well as 0 dispersion. However, people realize that 1550nm you see even less loss than 1310 nm and loss is sometimes very important because you do not want to put too many amplifiers in between you are willing to take a little bit of hit on the dispersion and reduce your bit rate, but you do not want to increase your infrastructure cause by putting up your amplifiers at a smaller repeaters spacing.

So loss was very attractive so 1550 nm was has become the operating wave length for optical communication.

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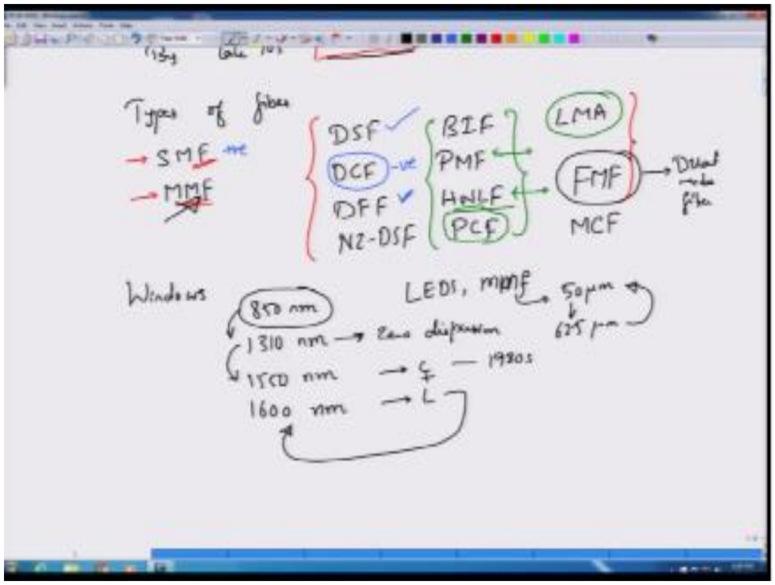

Since the 1980s, okay so this band is conventionally known as the conventional band or the C band, there is also long band at 1600nm where in we are looking at how to use different technologies in order to communicate at 1600 nm there is not much of a success yet but C+L band is expected to satisfy the customer needs for at least next 10 to 15 years.

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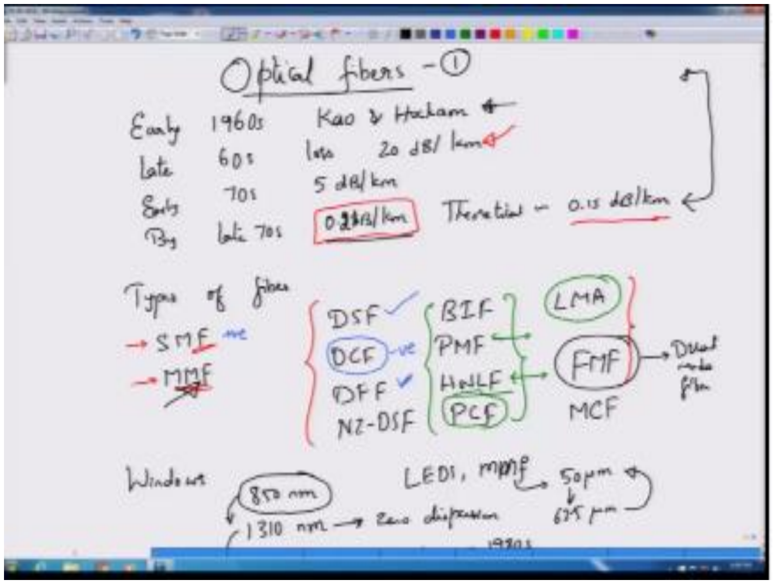

So this was just a brief about optical fiber history you know started as to what was the magic figure of 20dv per kilometer and then what was the theoretical limit and then to show that we have in fact achieved theoretical limit, so this in terms of the loss has been reduced considerably.

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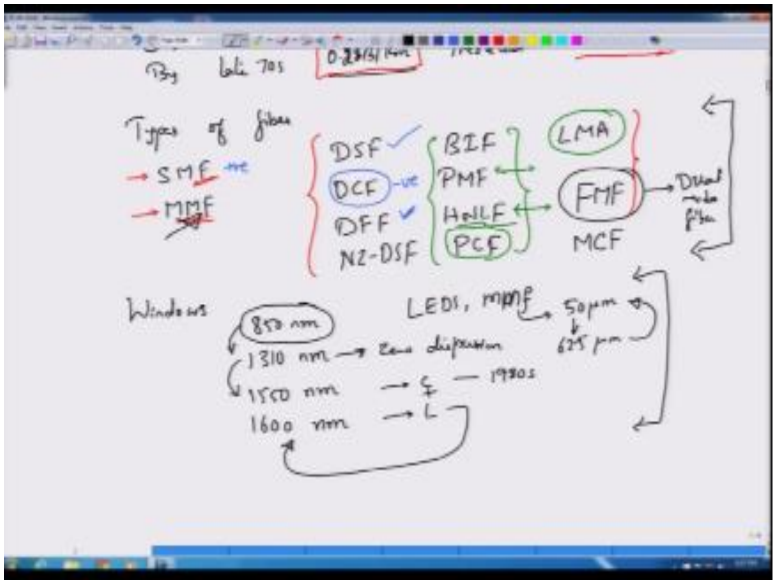

Then for different applications you know where you want to highlight some factors you do not want to highlight certain factors you can find many, many types of optical fibers, so you can find many types of optical fibers finally I also give you a brief overview of the windows of operation which means that we are selecting different operating wave lengths based on certain parameters such as loss and dispersion.

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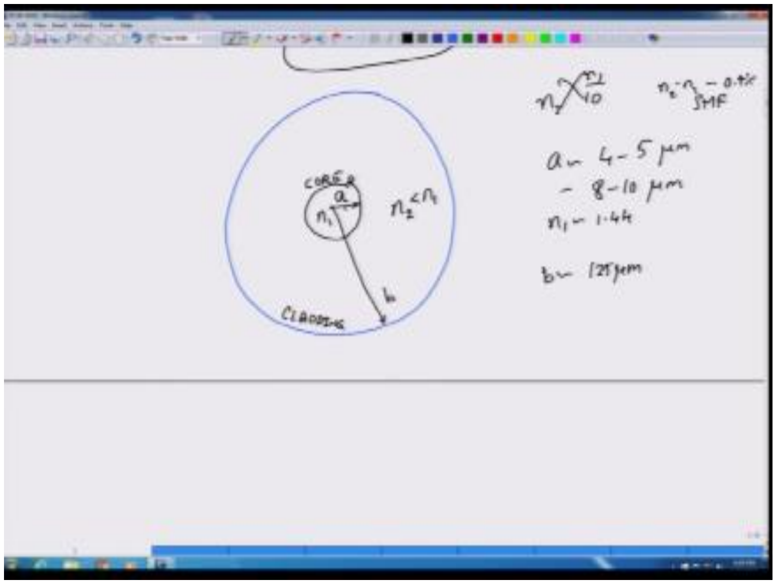

A typical single mode fiber will have a certain core radius, okay this is around 4 to 5 micron core radius and the diameter is about 8 to 10 microns and then it is also topped with certain materials the basic material is silica but it is topped with certain materials in order to raise its refractive index to n1, so let us call this as refractive index n1 and let us call the core radius as a, so this a is typically 4 to 5 micron making the diameter as a 8 to 10 microns.

The refractive index n1 is in the order of 1.44 something, okay. Now surrounding this is a cladding which is you know actually standardized at 125 microns so this radius is standardized at 125 micron, if you can call this radius as say b, so b is typically 125 micron and the region outside the core so this of course is the core and this is the cladding, okay. So this is the core and this is the cladding surrounding the core is the cladding and the cladding has a refractive index of n2 which is less than n1, I will tell you why to n2 has to be less than n1 in a moment.

But this is how it is done, but you might ask whether n2 is less than n1 is a very broad state might is there any particular difference between the two it turns out that n2 is not like say ten times lower than n1, okay it is not like this n2-n1 is typically about 0.12, 0.4% I think it is about 0.4% is the refractive index difference for standard single more fibers, okay. So such small refractive index difference is required in order to make the fiber single more it for the given core radius and the refractive index that is surrounding them.

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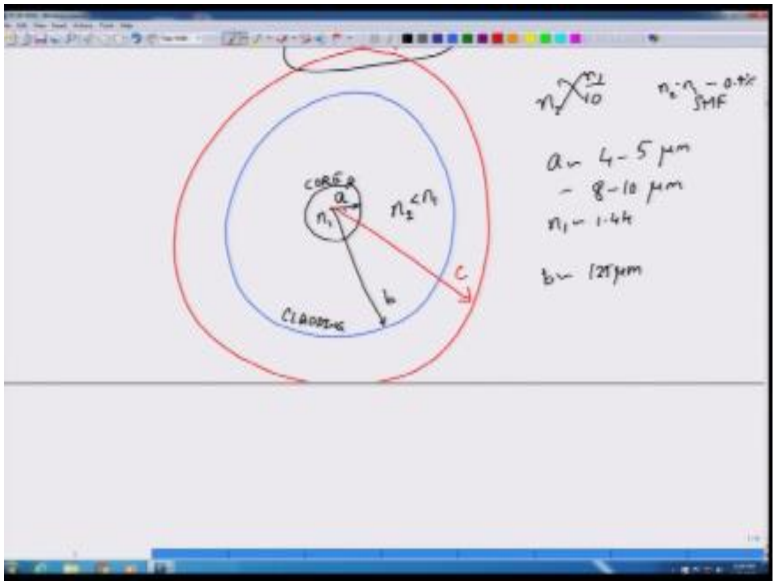

Surrounding all these would be a jacket which is typically at around 250 micron so you can clearly see that the way I have drawn this one is not really capturing the scales properly, so the jacket is typically around 250 micron this is further protected by a coating in order to make the mechanical properties of the fiber little better and then these are put in tubes and then these tubes are loosely bounded and then they are put into rods and this rods are located along the ducts. So this is how the fibers are taken up from and they are laid.

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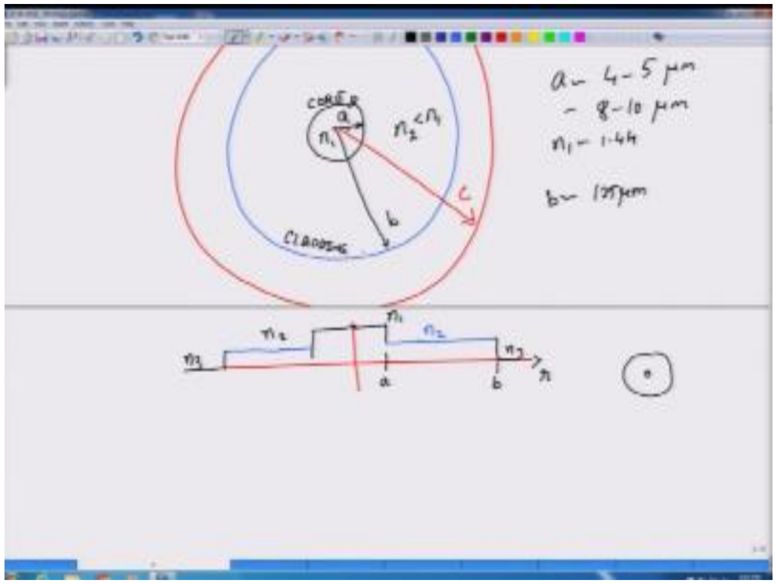

But the important point is that if you want to look at the refractive index distribution as a function of the different regions you will see that right at the core over the core region you are going to see refractive index of n1 assuming that this is what is called as the step index fiber then once you reach the cladding the refractive index becomes n2 which as I said will be less than n1, and finally when you reach to the coating outside or the jacket outside the refractive index goes to N3 so this is Ns so this of course has to be N2 and as I said N2 must be small compare to N1 okay so this is how the refractive index of the fiber looks like so if you call this as the radial axis r so the refractive index is N1 and till R = a it is equal to N2 and till r is equal to D okay.

Since this jacket is really for away from the region and does not really contribute much to the propagation property it is we kind of analyze an optical fiber as though it is consisted of a core and a cladding so this is kind of the relative scale accuracy that you are going to c. so that you can see that b is roughly 125 micron and a is around 5 micron let us say just to round of the number.

So clearly b is about 25 times larger than a so the region of the cladding is much, much larger than the core region okay so much of the properties are of the optical fiber modes are dependent on N1 N2 A and B okay we will see later that one.

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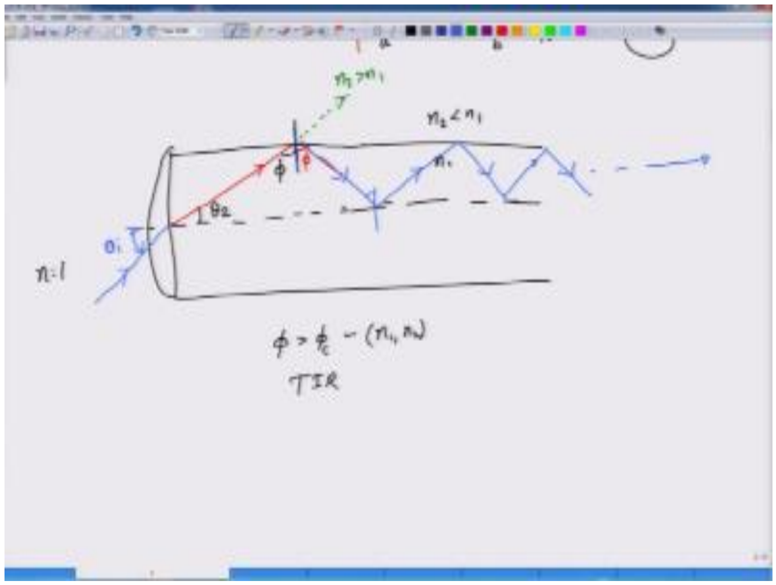

And since b is sufficiently large it does not really contribute much to the propagation so it is only N1 N2 and a that are primarily very important for the calculation of the optical mode. Now what I will do is in the next five minutes give you very, very simplistic view of how a mode is propagated inside an optical fiber. Let us assume that this is the optical fiber this has a nice syndical cross section and there is an axis of the cylinder along like this okay.

So this is the axis of the cylinder now what we do is we shine light at a certain incidents angle remember incident angles are to be measured with respect to the normal in this particular case the normal happens to be at along the axis of the cylinder therefore this is θi so this si the light that is coming in outside here the we will assume that this is air therefore the refract index here is n= 1.

Now as this ray of light comes and hits this particular axis right this particular inter face so you can imagine that this is the optical fiber that I have okay and then I have a normal to the axis so let us now just located like this so this is your normal to the axis and then we come in with light so maybe we coming with light like this okay. So now we can see that my hand finger is actually making a angle here and the angle that it is making with respect to the normal is θi.

So what should happen to the incident ray of light here well you see here is an inter face here this inter face is the core Area and the core which is separating the air and the core, core as a refractive index of N1 so in N's law applies here and what you will get her is a refracted ray so the ray basically gets refracted goes in to the core medium and then hits the cladding inter face at this point this ray refract and then hits this cladding inter face.

So maybe you know we will call this angle of angle at which this secondary refractive ray hits as 5 and this angle is $\theta 2$ maybe and this is 5 now this is one more interface here you have N2 < N1 here you have refractive index of N1, if N2 >N1 what would have happened it would have simply refracted again right so it the ray would have refracted again had N2 b > N1 so there is nothing happening out there.

There will have been of course some partial reflection back in to this region at the same angle 5 but the power would not have been completely reflected back so the transmitter wave or the refracted ray would have carried significant amount of power, however now suppose when you have N2 < n1 there will be no transmission in to the cladding but entire transmission will be along the along in to the first region itself provided this angle 5 is greater than what is called as the critical angle of the inter face.

The critical angle of the inter face is the function of N1 and N2 right as well as the angle of incidents 5 is actually he function of N1 and N2 and for a given angle of incidents 5 if it is greater than 5c total internal reflection takes place which will cause all of the power to be reflected back. So this is how once it is reflected back assuming that this angle is again larger so if this is larger than 5c this will also be larger than 5c ray will be reflected again and again.

There will be reflection and by this successive reflection is how the light propagates inside the optical fiber. So we will stop here and continue in the next module. Thank you.

<u>Acknowledgement</u>

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