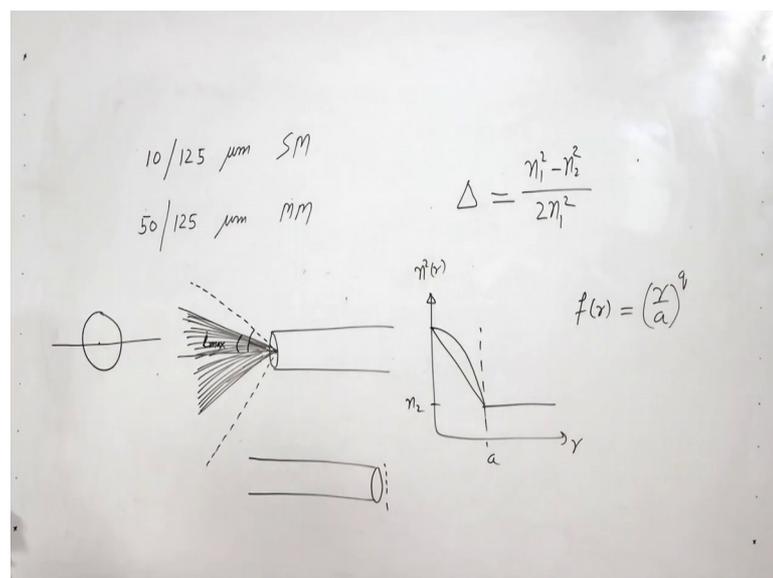


Fiber Optic
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Lecture - 39
Optical Fiber Measurements

Well, now it is time to carry out some measurements to understand the measurement techniques in optical fiber. When we have an optical fiber, usually the optical fiber is having core diameter which is 10 micron and cladding diameter 125 micron, this is single mode fiber. And multimode fiber may have a core diameter 50 micron and cladding diameter 125 micron.

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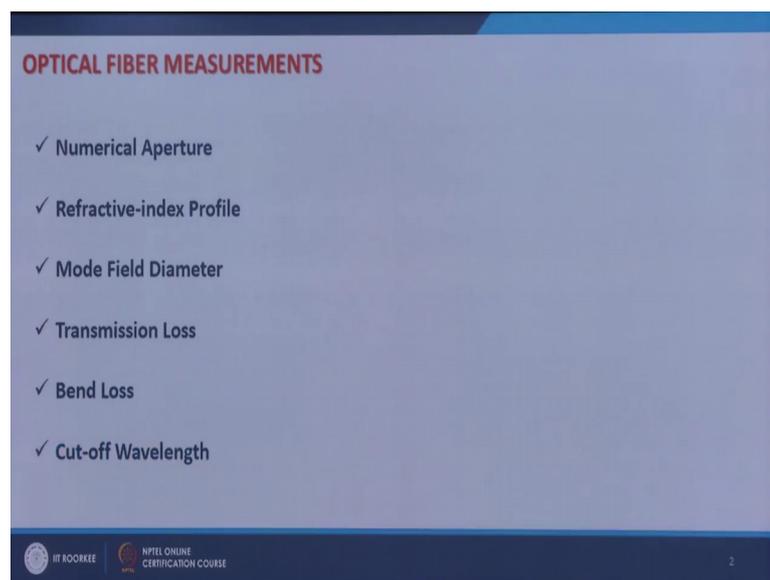
So, this is multimode fiber. And then there is acrylic coating, so the overall diameter might be 200 micron or 250 micron.

So if we look at this fiber, by just looking at it we cannot make out whether it is single mode fiber or it is multimode fiber. We cannot say what is the numerical aperture of the fiber, what is the cut-off wavelength of fiber, at what wavelength it will behave a single mode, at what wavelength it will behave as multimode, what is the losses of the fiber. So, when we have a fiber we need to know all these things. We need to actually characterize the fiber.

So, in order to do that there are certain techniques, and I will discuss in this lecture few such methods. First of all to distinguish between single mode fiber and multimode fiber of course it has to be at certain wavelength. So, what you could do is you just launch light of that wavelength. For example, if you want to know whether the given fiber is single moded or multimode at 633 nanometer wavelength. So, you can take a laser at 633 nanometer wavelength and launch light into it and observe the output. If you see in the output is speckle pattern, then it is a multimode fiber. If you see a clean Gaussian kind of pattern then it is a single mode fiber.

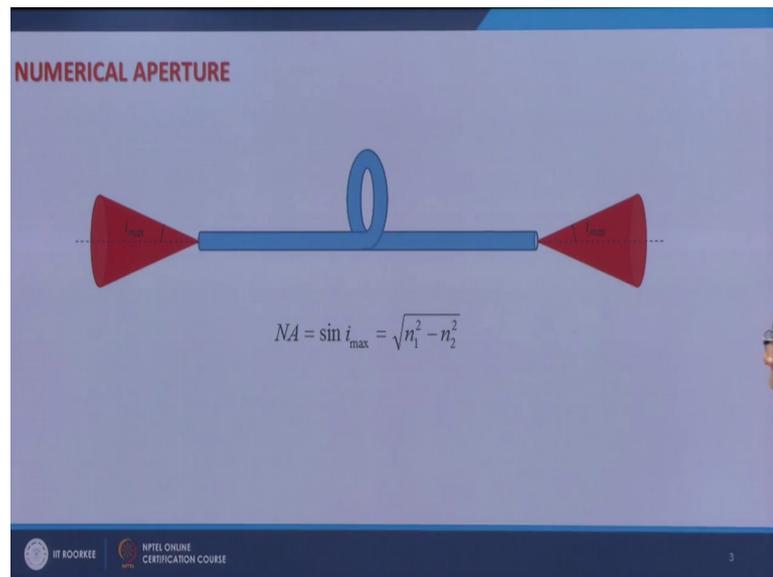
So, in this way you can make out whether a fiber is single moded or multimoded. What about the other parameters let us look at them? So, in this lecture we will understand the measurement methods for measuring numerical aperture.

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Refractive-index profile, mode field diameter, transmission loss, bends loss, and cut-off wavelength of the fiber. So, let us first look at numerical aperture. We know what numerical aperture is. It basically signifies light launched at what angles would be guided through the fiber.

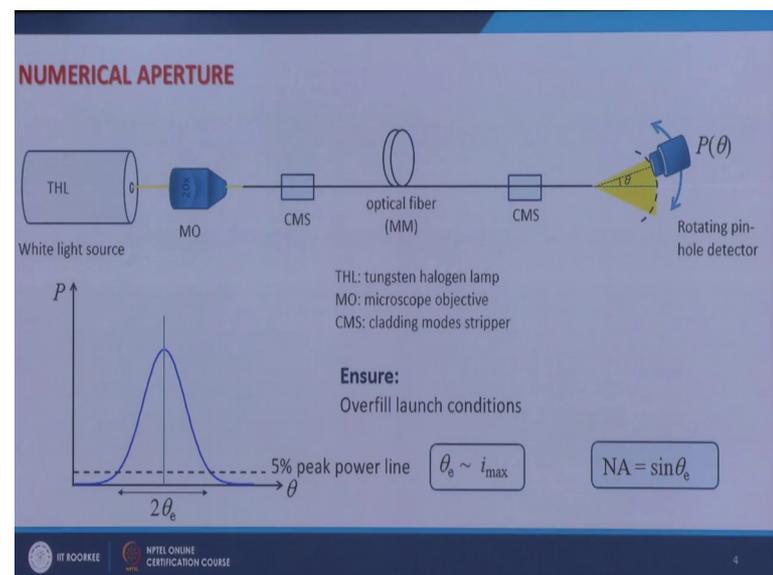
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So, there is a maximum acceptance angle. So, light launched only in this cone will be guide it, and correspondingly at the output and the light will emerge out of the fiber into this cone.

So, in order to find out the numerical aperture of the fiber what we need to do, we need to measure this angle i_{\max} at the output end of the fiber. And if we can measure this angle i_{\max} then we can find out the numerical aperture of the fiber by simply taking \sin of this i_{\max} .

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So, this method is very simple, but this can be used for only multimode fibers. So, you take a multimode fiber and use a white light source, and using this white light source you launch light into this fiber using a microscope objective of sufficiently high numerical aperture. This microscope objective simply works as a lens.

So, with the help of this you launch light into this fiber. And you also put cladding mode strippers in order to strip off light which is going into cladding modes. Otherwise there would be measurement error. Then otherwise at the output end you will collect light not only coming from the core modes, but also from the cladding modes. And numerical aperture is defined with respect to the guided light.

So, it is essential that you strip off these cladding modes. So, you can use cladding mode stripper which is nothing but you can put an index matching liquid on to either input end or output end or at the both at both the ends of the fiber so that your cladding modes are stripped off.

For white light source you can use a tungsten halogen lamp which has very broad spectrum. And why do we want to use a white light source? It is because with the help of white light source you can overfill the numerical aperture of the fiber. What do I mean by that? It is if you have a fiber like this and this is the cone of guidance. So, in order to fill this completely you can use a white light source so that this forms a continuum, otherwise you have guided modes which are discrete.

In order to completely fill this numerical aperture you should use a white light source. Also, if this is i_{max} then you should use a lens of sufficiently high numerical aperture. So, the microscope objective or the lens should have numerical aperture which is larger than this; which is larger than the numerical aperture of the fiber. So, we will have to ensure that. Now what you do at the output end the light emerges out in this cone and you put a detector on rotating stage which is rotating about this end of the fiber. So, this end should be at the centre of the rotation stage and then you move this, you rotate this pinhole detector about this centre; about this end of the fiber. And at different angles you can scan the intensity or the power. So, you measure power at different angles. Your pinhole detector should have a hole which is very small in order to have good resolution.

So, when you do this and you plot P as a function of θ you will get a variation something like this. Now the question is where is this boundary, I need to find out this i

max and i_{\max} corresponds to the boundary here the boundary of the cone the semi vertical angle of the cone. But when I see this it does not drop down to 0 abruptly, but it slowly goes to 0 and it will $P=0$ at θ is equal to infinity for example.

So, we have to stop. We have to define this boundary for that usual way is that you draw a line which corresponds to 5 percent of peak power. So, whatever power is here you take 5 percent of that and get this line. And then find out what is this angular width. If this angular width is $2\theta_e$ then your i_{\max} is θ_e , and then you just take the sin of this and this will give you the numerical aperture. So, in this way you can measure the numerical aperture of the fiber.

Next is, if you have a multimode fiber. Usually a multimode fiber has dimensions 50 by 125 micron and for local area networks you have a fiber which has nearly parabolic index profile. If you want to find out this refractive index profile of the given fiber then you can use a method which is known as transmitted near field method.

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REFRACTIVE INDEX PROFILE : transmitted near-field (TNF) method

Let the fiber has the refractive index profile given by

$$n^2(r) = \begin{cases} n^2(0)[1-2\Delta f(r)] & r < a \\ n^2(0)[1-2\Delta] & r > a \end{cases}$$

Where, $f(r)$ is the profile function

If all the modes of this fiber are equally excited, then the near-field power distribution $P(r)$ is given by

$$P(r) = P(0) \frac{n^2(r) - n^2(a)}{n^2(0) - n^2(a)}$$

So, measurement of the near-field power distribution $P(r)$ can give the RI profile as

$$f(r) = 1 - \frac{P(r)}{P(0)}$$

[Adapted from: Ghatak and Thyagarajan, "Introduction to Fiber Optics," Cambridge Univ. Press, 2009]

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So, if the fiber has a refractive index profile given by this that is n is square is equal to $n^2(0)[1-2\Delta f(r)]$ in the core and $n^2(0)[1-2\Delta]$ in the cladding; where Δ is the relative core cladding index difference. And you remember the definition of Δ ; Δ is $n_1^2 - n_2^2$ over $2n_1^2$.

And $f(r)$ is the profile function; it tells you whether the fiber has refractive index profile if this is r and this is $n(r)$ or $n^2(r)$. So, this is core-cladding interface r is equal to a . This is the cladding refractive index; let us say it is n_2 . Now in the core whether the refractive index is this or whether the refractive index is this it is defined by this function $f(r)$. For a power-law profile $f(r)$ can be written as r^q/a^q this we had seen earlier also; q is equal to 1 corresponds to this triangular profile q is equal to 2 corresponds to the parabolic profile.

So, $f(r)$ is the profile function and then it can be shown that if all the modes of the fiber are excited equally then the near-field power distribution $P(r)$ can be given by this. What do I mean by near-field distribution? Near-field distribution means you launch light into the fiber. And at the output end you capture the light coming out of the fiber as it just comes out, very near to the fiber, very close to the fiber so that the final number is much much smaller than 1, the distance from the fiber is very small; within a couple of millimetres.

So, the near-field power distribution is given by this. And then if I am able to measure this near-field distribution then from this near-field distribution I can find out the refractive index profile $f(r)$.

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Experimental set-up: TNF method

THL: tungsten halogen lamp
MO: microscope objective
CMS: cladding modes stripper

White light source

Translating pin-hole detector

$P(r)$

$f(r) = 1 - \frac{P(r)}{P(0)}$

Ensure:

- ✓ Overfill launch conditions
- ✓ Capturing near field at the output end

Limitations:

- ✓ Measurement resolution is primarily limited by fiber NA
- ✓ Errors due to leaky modes propagation
- ✓ Valid only when all the modes are equally excited

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So, how do I implement this? Again I take light from white light source which is tungsten halogen lamp. Use a 20 x microscope objective which has sufficiently high

numerical aperture. Then I launch light into this fiber using this and put cladding mode strippers. Then at the output end I use a 40 x objective whose focal length is very small about 2 millimetre or less, so that I can capture light from the output end as it just exits. I do not let it propagate. If I let it propagate then whatever I will capture would not be the near field, but it would be the diffracted pattern. So, it would be the far field.

So, I capture the near field. And I image that near field on to this pinhole detector. So, what I will have? I will have my spot like this and then with the help of pinhole detector I scan the intensity across a diameter which is given by this $P(r)$. So, $P(r)$ is the intensity distribution; near field intensity distribution. When we plot it, it comes out like this.

So, on either side of the centre the intensity decreases. And what I see that at this centre I have a small dip. This is small dip is because of germanium or diffusion when the pre-form is collapsed, when you raise the temperature to a very high value and to collapse the pre-form then there is germanium or diffusion. And because of that there is a small dip at the centre. So, I can just correct it by extrapolating it or interpolating it like this. And then of course, I can correct it by leaving these points and extrapolating these. Well, with the help of this now I can immediately find out what is $P(r)$ over $P(0)$ and then r .

So, while doing this measurement again I should insure over fill launch conditions; that is the numerical aperture of the lens which I am using here is larger than the numerical aperture of the fiber. And I use white light source to fill the complete mode volume. And I also should ensure that I am capturing the near field. What are the limitations? The limitations of this method are: the measurement resolution is primarily limited by fiber NA. And there might be some leaky modes propagation, so the light which is going into leaky modes also contribute to this $P(r)$. And another very important one is that this whole method is valid only when all the modes are equally excited. So, I should ensure that. Then another important parameter of a fiber particularly of single mode fiber is mode field diameter.

So, the first two parameters were for multimode fiber and this method is for a parameter of single mode fiber which is mode field diameter. So, I know that for a single mode fiber the fundamental mode can be very well approximated by a Gaussian. And what I do in this method as this Gaussian mode comes out of the fiber I let it propagate over a

small distance. And what I see then is the far field; I let it propagate maybe a centimetre or two so that I am in far field, a couple of centimetres.

So, when this Gaussian exits from the fiber end and propagates in free space, so it is diffracted and since it is a Gaussian mode then diffraction of a Gaussian beam is another Gaussian; so in the far field if I scan the intensity along a theta then.

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MODE FIELD DIAMETER: far-field method

For a Gaussian mode, the far field is given by

$$|\psi(\theta)|^2 = |\psi(0)|^2 \exp\left[-\frac{2\sin^2\theta}{\sin^2\theta_f}\right], \text{ where } \sin\theta_f = \frac{\lambda_0}{\pi w_0}$$

For a small θ and θ_f

$$|\psi(\theta)|^2 \approx |\psi(0)|^2 \exp\left[-\frac{2\theta^2}{\theta_f^2}\right] \quad [\theta_f \text{ is the angle at which the intensity falls to } 1/e^2 \text{ of its peak value}]$$

Mode field diameter

$$d_f = 2w_0 = \frac{2\lambda_0}{\pi \sin\theta_f}$$

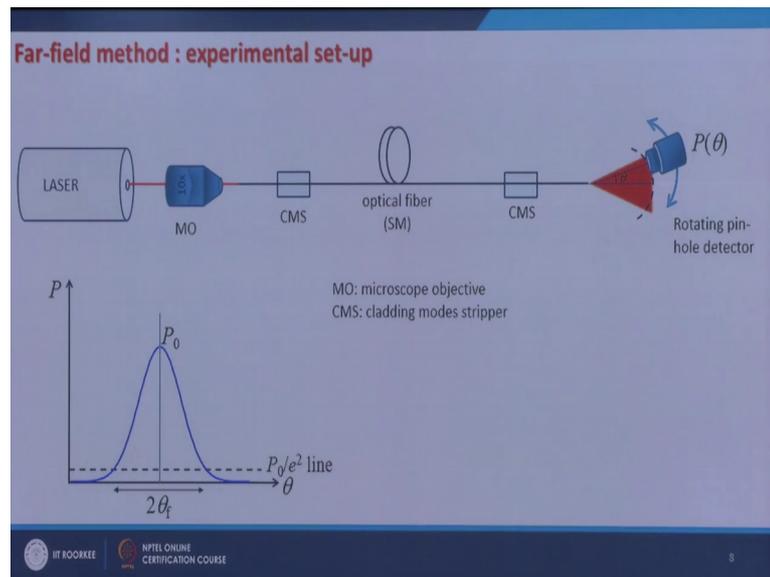
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Psi theta is given by psi 0 square exponential minus 2 sin square theta over sin square theta f. Where sin theta f is lambda naught over pi w naught. This can be shown by diffraction of a Gaussian beam.

Now this theta and theta f they are very small. So, I can approximate this by psi 0 square exponential minus 2 theta square over theta f square. So, from here I can immediately see that if theta f is the angle where this intensity because mod psi square is corresponds to intensity. Where the intensity falls down to 1 over e square of the intensity at theta is equal to 0 and at theta is equal to 0 you have the maximum intensity. So, if I am able to measure this theta f then I can find out the mode field diameter by this; it is 2 lambda naught over pi sin theta f which comes from here itself.

So, the problem only reduces to measure the specular intensity distribution in the far field.

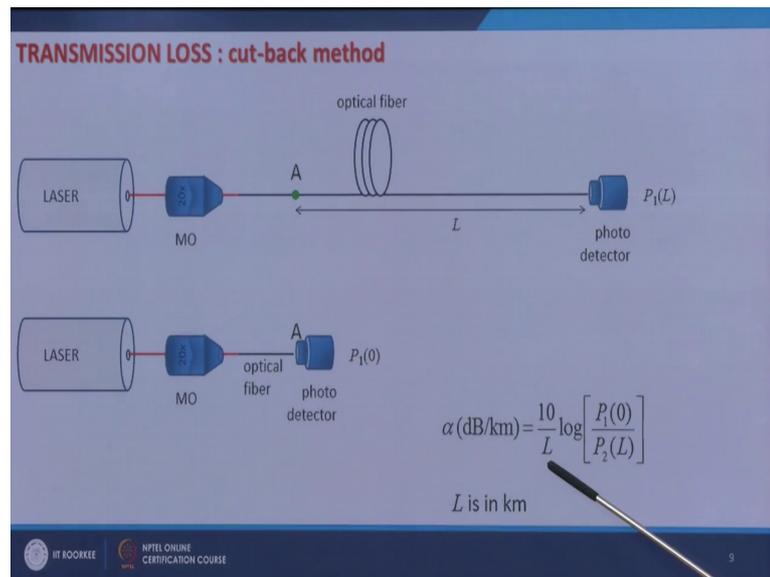
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So, for that I take a single mode fiber, launch light laser light into this using a microscope objective. Again I use cladding mode strippers to strip of whatever light might go into the cladding modes. And then I let the light come out propagate over a small distance from the fiber and then I scan again the intensity at different angles using a rotating pinhole detector. When I plot it, it looks like this. And then to find out theta f I draw a line which corresponds to P_0 over e^2 where P_0 is the peak intensity here. And I measure this angular width; this is $2\theta_f$ and from here I can get d_f which is the mode field diameter.

Then, I also need to find out what is the loss in the fiber. For this the method is very simple; you again launch light into the fiber.

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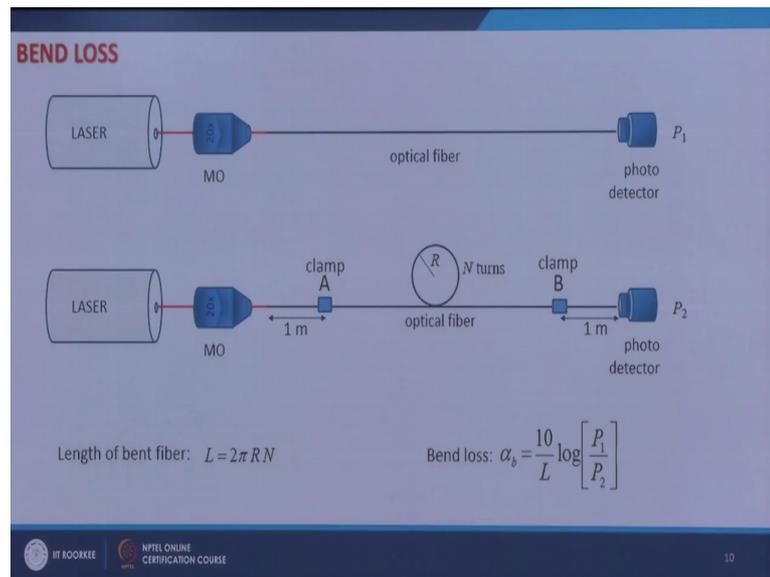


From a laser using a microscope objective to you take a long fiber it might be a kilometre long fiber and identify one point very near to the input end mark it. And from that point you might know what would be the length of the output end. So, this length should be known. And then you measure the power at the output end of the fiber, using a photo detector and let this power v P 1 L.

Now what you do? You cut the fiber here where you had marked it at point A and remove this and put your pinhole it is not pinhole you use the photo detector it is large large area detector so that you can collect all the light coming out of the fiber. Now you measure the power here, and why you do this you ensure that the input launch conditions are not disturbed at all. Now when you measure power here let us label it as P 1 0, then by taking the ratio of this P 1 L at P 1 0 I can find out what is the loss. So, the loss in dB per kilometre can be defined as 10 over where L is the length of the fiber in kilometres times log P 1 0 over P 1 P 2 L; it should be P 2 L it should be P 1 0.

So, by measuring the power here and by measuring the power here you can find out what is the loss coefficient. Then what is the bend loss, because when you install this fiber in the field you have instances where you need to bend the fiber. So, it is important to find out the bend loss of the fiber also.

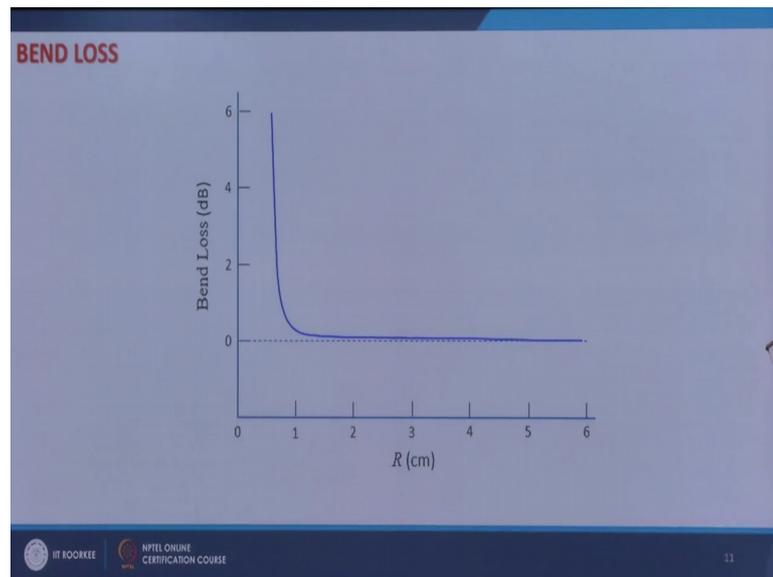
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For doing this what you do you take a fiber and keep it straight, and measure the power P_1 . And then what you do you identify two points near the input end and output end of the fiber which are almost 1 meter away from these input and output ends and clamp them here. Then, you make a loop of radius R here you can make a single loop or to have sufficient change in power; you can make n loops, you can make n turns of radius R . And then you measure the power here let this power be P_2 .

Now what is the length in this bend fiber? Length of the bend fiber is $2\pi r$ times n . And so the bend loss can be calculated now as α_b again in dB per kilometre if you express this L in kilometres is equal to $10 \log \frac{P_1}{P_2}$. So, with the help of this you can find out the bend loss. You can change the radius and then see; what is the effect of bend radius on the bend loss. And when you plot this it looks like this.

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We have this bend radius is in centimetres and this bend loss is in dB. So, when the bend radius is large that it is not a tight bend it is a big loop, then the loss is 0 dB there is no loss. And as you make the bend tighter and tighter you see that the loss increases. And around this value if you make it very tight the bend radius is even smaller than or close to 1 centimetre then the bend loss increases drastically.

The last parameter that I would like to discuss here is the measurement of cut-off wavelength. I know what cut-off wavelength of a fiber is. It is basically the wavelength at which LP 11 mode is cut-off.

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CUT-OFF WAVELENGTH

$$\lambda_c = \frac{2\pi a \sqrt{n_1^2 - n_2^2}}{2.4048} \quad \lambda > \lambda_c : \text{single-mode}, \quad \lambda < \lambda_c : \text{multimode}$$

practically due to various perturbations like macro-bending, micro-bending and twisting the fiber becomes effectively single-moded somewhat below λ_c . This wavelength is called effective cut-off wavelength and is denoted by λ_{ce}

Measurement through bending technique

Near $\lambda = \lambda_{ce}$: large fraction of guided-mode power is in the cladding mode

For $\lambda > \lambda_{ce}$: only LP₀₁ mode is guided and is well confined in the core

If λ is now decreased below to λ_{ce} such that $V < 2.4048$, LP₁₁ mode would also be guided but is close to cut-off \rightarrow large fraction of LP₁₁ mode power is in the cladding and so bending the fiber would result in high transmission loss at this wavelength

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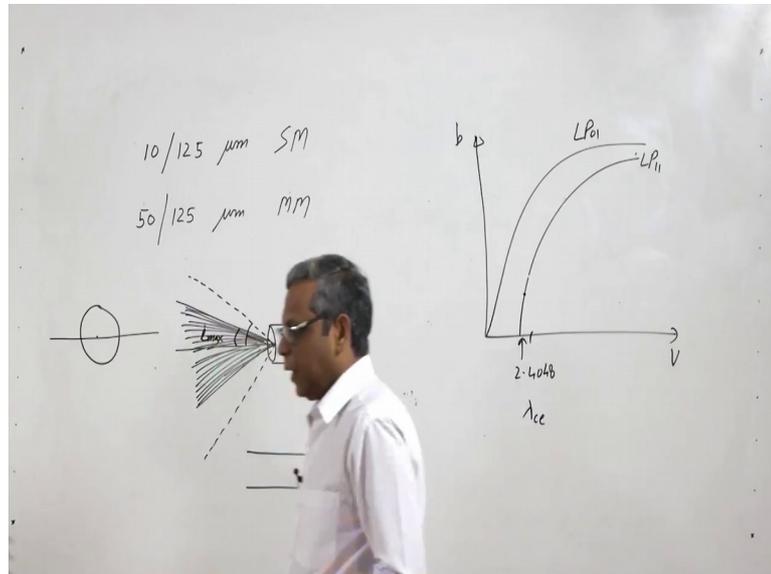
That is, if λ_c is the cut-off wavelength then for all the wavelengths longer than λ_c the fiber is single moded, while for all the wavelengths smaller than λ_c the fiber is multimoded. And this λ_c is given by this for a step index fiber it is $2\pi a \sqrt{n_1^2 - n_2^2} / 2.4048$, but this is theoretical. Practically there might be several perturbations it might be my micro bending, macro bending, twisting.

So, because of that the fiber effectively becomes single moded somewhat below λ_c and this wavelength is then called effective cut-off wavelength λ_{ce} . So, what you can measure is λ_{ce} and not exactly λ_c , but it is very close. How do you measure it? This is recommended by ITU- International Telecom Union itself. So, you measure it through bending technique. How does it work? If you have you launch light into the fiber using a broadband source maybe white light source and then measure the bend loss at different wavelength and then see how does it work.

So, if I am operating at wavelength which is equal to λ_{ce} the large fraction of guided mode power is in the cladding mode. And if you are slightly greater than λ_{ce} then only LP₀₁ mode is guided and is well confined in the core. Because then most of the power is an LP₀₁ mode, all the other modes are not guided; while here the power is going into LP₁₁ mode also and it extends to the cladding also. And also because this wavelength is shorter than this then LP₀₁ mode power also goes into cladding.

Now, if I decrease below λ_{ce} such that v is greater than 2.4048 then it should be greater than 2.4048, then LP 11 mode would also be guided. But it is close to cut-off.

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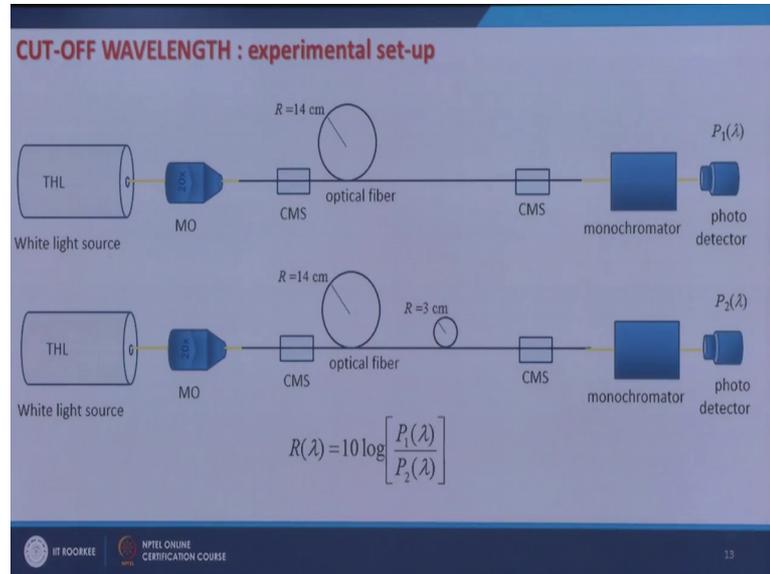
You see if you remember how does it work. If you look at b v cuts off fiber step index fiber then you have this as v this is b , this is LP 01 mode, and this is LP 11 mode. This point is 2.4048 and it corresponds to let us say λ_{ce} or λ_{ce} . So, when your λ is decreased below λ_{ce} that is v is slightly greater than 2.4048, then this is also guided but it is close to cut-off.

So, the power goes into LP 11 mode, but a large fraction of LP 11 mode power is in the cladding. And this power which is in the cladding is very susceptible to bending it is strips off very quickly when you bend the fiber. So, if you now bend the fiber then there would be high transmission loss at this wavelength. If you further decrease λ then this LP 11 mode would be very well confined and then most of the power will now be confined in the core itself of LP 11 mode also. So, the bend loss will decrease.

So, what I expect is that if I start decreasing the wavelength then at longer wavelengths because most of the power in all the modes is in the core. So, it is less susceptible to bending so I will have low bend loss. As I decrease the wavelength the bend loss will increase. And when I keep on increasing and when I am near the cut-off then it will start increasing like this, and then if I keep on increasing it then the bend loss will keep on increasing. But further increase in λ will result the power confinement only due to

LP 01 mode and then it will decrease, because LP 01 mode is less susceptible to bending, because if most of the power is in the core. So, I expect a peak in the loss curve.

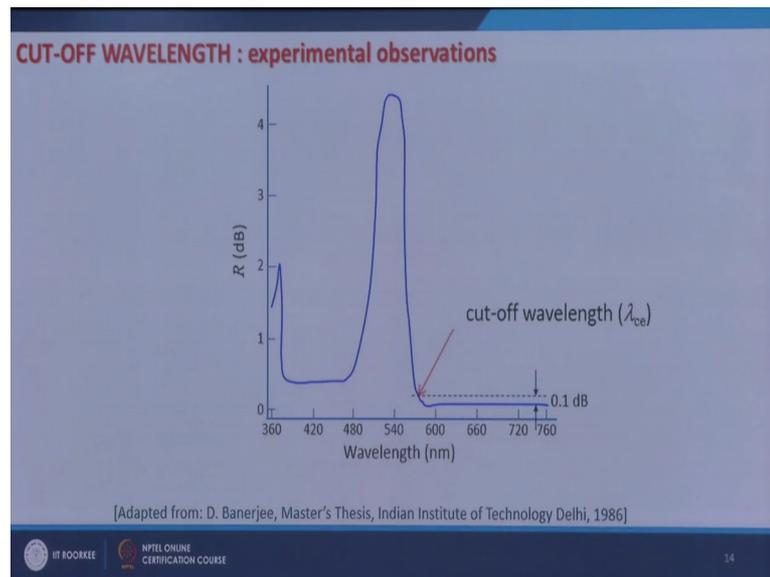
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So, how to now find out the cut-off wavelength, I make an experiment like this; I launch light into the single mode fiber using white light source which is tungsten halogen lamp again using a microscope objective I strip of the cladding modes. And then I make a loop, a big loop of 14 centimetre radius which does not cause large bending loss. And then I measure the power here at certain wavelength. I can change the wavelength and I can measure the power as a function of lambda and I change the wavelength with the help of monochromator. So, basically I pick particular wavelength using the monochromator and then I measure this $P_1(\lambda)$.

Then what I do? Apart from this now I make a small loop of radius 3 centimetre which can cause a large bending loss. And then again I do the same measurements and I measure the power P_2 as a function of lambda, then this ratio of $P_1(\lambda)$ and $P_2(\lambda)$ can give me the band loss; can give me the cut-off wavelength, I will show you how. So, if this ratio in dB is $R(\lambda)$ is equal to $10 \log \frac{P_1(\lambda)}{P_2(\lambda)}$ then I plot this ratio. When I plot this then it looks like this.

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So, at longer wavelength I have low bending loss, and when I keep on decreasing this wavelength then around this field and it start increasing because now the power goes into LP 11 mode which is spread into the cladding. And then further decreased in the wavelength will increase the bend loss and after that all the modes are confined in the core so bending loss will decrease.

Now if I identify a point here which is 0.1 dB above this long wavelength edge then this wavelength here will give me the cut-off wavelength. So, using this I can measure the cut-off wavelength.

So, with this I complete discussion on measurement techniques in optical fibers. And in the next lecture I would summarize the key points which we have learnt in this course. And, I will also give you what are the future trends, what are the speciality fibers coming up, and where we are heading in fiber optics.

Thank you.