Advanced Optical Communications
Prof. R. K. Shevgaonkar
Department of Electrical Engineering
Indian Institute of Technology, Bombay

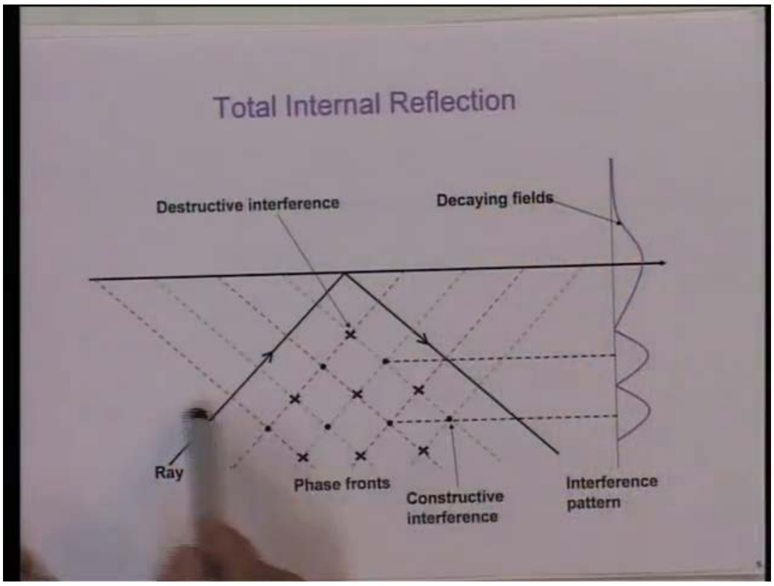
Lecture No. # 04

Ray Model - II

We are investigating propagation of light inside an optical fiber. In the last lecture we saw that optical fiber has a solid glass road what is called core and a glass shell surrounding that road what is called cladding. We saw that if the light is incident on this optical fiber from the side, this light cannot be guided inside the optical fiber.

So, only light can get inside the optical fiber, if light is launched from the tip of the optical fiber. Then we saw that depending upon the launching angel, either the light ray can remain confined to the plane containing the access of the optical fiber. which we called as a meridional ray or ray which does not lie in the plain containing the axis of the optical fiber. This rays spirals around the axis and these rays where called as skew rays. Then we said the light can have sustain propagation inside the core of the optical fiber through multiple total internal reflections on the core cladding boundary. Then we also saw something more in depth about the total internal reflection and all these we were doing by the ray model, which is the simplest possible model for light.

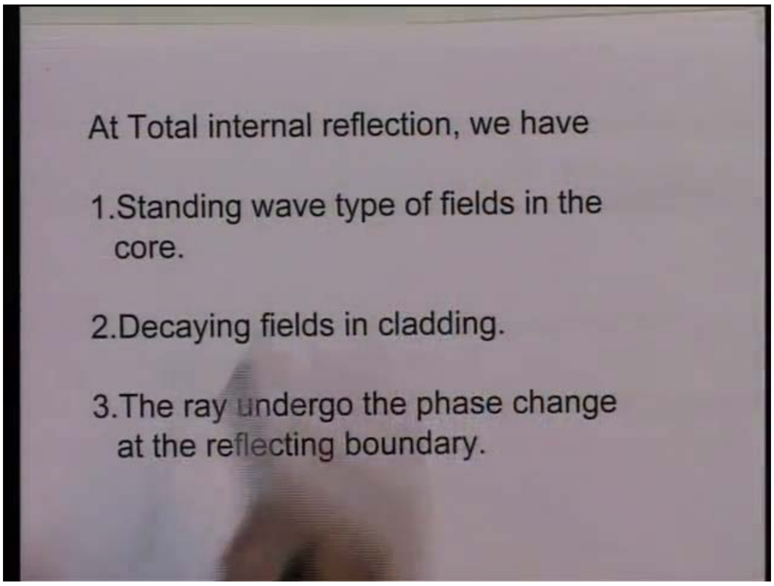
(Refer Slide Time: 02:16)



Total Internal Reflection

So, today let us see little more inside into the propagation of light still using the ray model. So, yesterday we are seen for total internal reflection in the medium where light is total internal is the reflected. You have the super position of this phase fronts which give you the constructive or destructive interference and because of that you have standing wave kind of pattern. In this region is same as the core region of the optical fiber and then we have exponential decaying field in the cladding and this field theoretically at least extents up to infinite. Then we have said that for total internal reflection three things are to be noted one is the standing wave type of field inside the core, decaying field inside the cladding and when the phase under goes at a total internal reflection that is the certain phase change at the boundary.

(Refer Slide Time: 02:49)

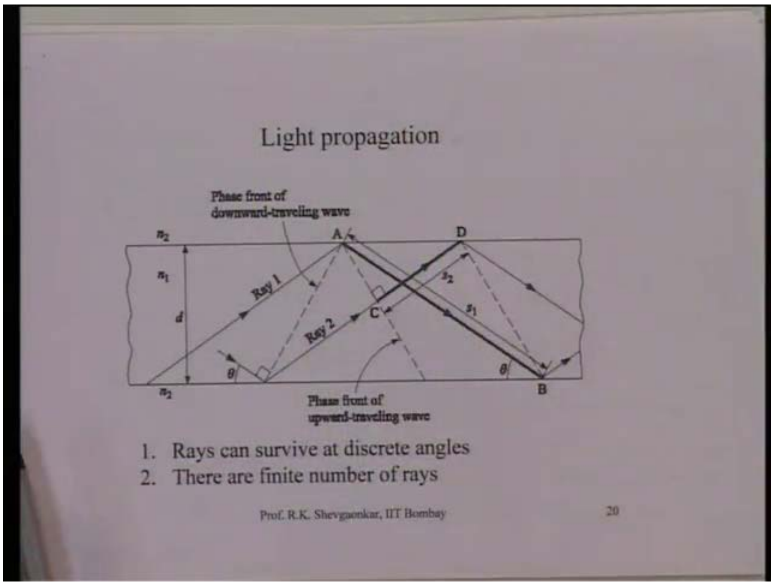


At Total internal reflection, we have

1. Standing wave type of fields in the core.
2. Decaying fields in cladding.
3. The ray undergo the phase change at the reflecting boundary.

So, you have this three things happening when the total internal reflection takes place. Then we have taken this simple figure here saying that,

(Refer Slide Time: 03:21)



Light propagation

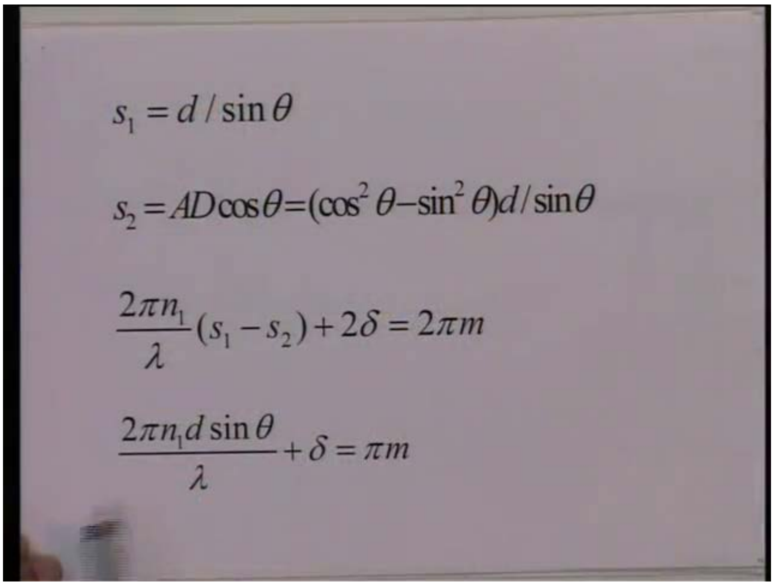
1. Rays can survive at discrete angles
2. There are finite number of rays

Prof. R.K. Shevgaonkar, IIT Bombay

20

if you consider the two rays which are parallel and these are the phase fronts. This phase front is common to this two rays. Similarly, this phase front is common to this ray and the total internaly reflected ray twice at this inter phase and that is inter phase, and then this inter phase. And then we said if you have a sustain propagation then there has to be this phase condition satisfied, that the light interferes constructively.

(Refer Slide Time: 03:55)



$$s_1 = d/\sin\theta$$

$$s_2 = AD\cos\theta = (\cos^2\theta - \sin^2\theta)d/\sin\theta$$

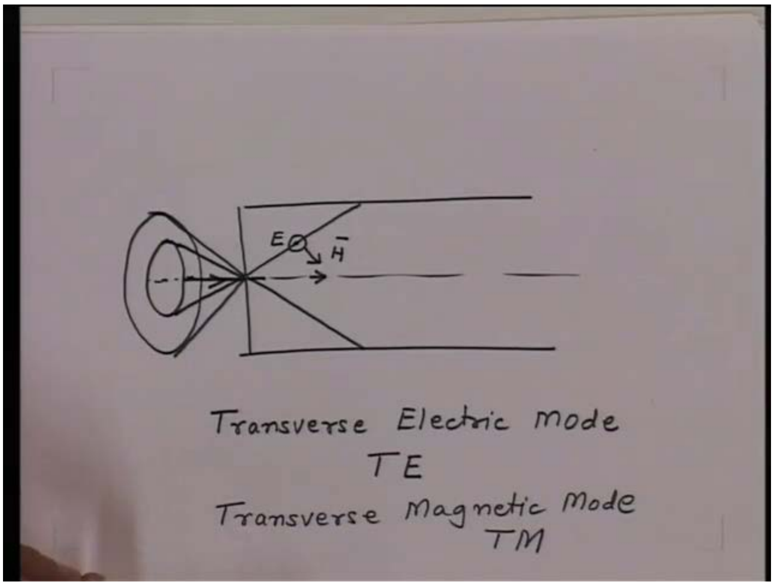
$$\frac{2\pi n_1}{\lambda}(s_1 - s_2) + 2\delta = 2\pi m$$

$$\frac{2\pi n_1 d\sin\theta}{\lambda} + \delta = \pi m$$

So, that you have a propagation of light inside the core and then by using the simple geometry. We got the phase condition that is, if this condition is satisfied then only the light can get launched inside the optical fiber. If this condition is not satisfied then the light is not launched inside the optical fiber.

So, we made very important observation that even within the cone of numerical aperture you will light ray is launched at an angel which does not satisfied this phase condition, then that ray cannot propagate inside the optical fiber.

(Refer Slide Time: 04:33)



Transverse Electric mode
TE
Transverse Magnetic Mode
TM

So, we have said that if we consider optical fiber like this; this is the cone which is the numerical aperture cone. Earlier when the phase condition was not needed any ray lying within this con would have totally internal reflection, and would have propagated through this core. However, now what we are saying is that only certain angel the ray can get inside the structure and any other angel, the ray cannot propagate inside the structure.

Now, where I mentioned earlier whenever we are saying particular angel we are essentially talking about all rays which make the same angel with the access of the optical fiber. So, when I say this ray, essentially this ray corresponds to the ring, which is making an angel this theta which is to the access. So, one thing to know here now is that if I consider a ray which is launch along the axis of the optical fiber. This ray does not require any condition to be satisfied because there is no total internal reflection for this ray. This ray essentially does not go to the boundary. So, one can say that if a ray is launched in this direction, without any special condition, this ray will always propagate inside this optical fiber. So, that means a ray responding to theta equal to 0 will always propagate inside the optical fiber.

However, the next ray which can be launch is inside the optical fiber has to satisfy this condition now. So, one can say that ray which goes along the axis of optical fiber, see there is no totally internal refraction, does not go to the boundary. Delta is equal to 0. You can take m equal to 0 that is the first ray which can propagate. So, you get theta equal to 0 that is the ray which is going to propagate.

That is this ray which is along the axis. if I now go to the second value of m which is m equal to 1, then now I require certain value of n 1 d for given lambda. So, that this condition is satisfied. What that means, is now that the next angle which can propagate inside this structure could be this angle. another mention this angel essentially means all the rays is which are making the same angel which is fact to axis. So, essentially it is this ring which is going to propagate inside this optical fiber.

So, one ray is the one which is going straight like this, second is the ensemble of rays which are making this angel, third could be this one and that is all. So, what we find now is that, there are discrete and ensemble of rays which can be launched inside the optical fiber and when we take the ensemble of the rays the collection of this ensemble of the rays that gives you interference pattern inside the core. And as a result you have a very definite intensity patterns formed inside the core of the optical fiber.

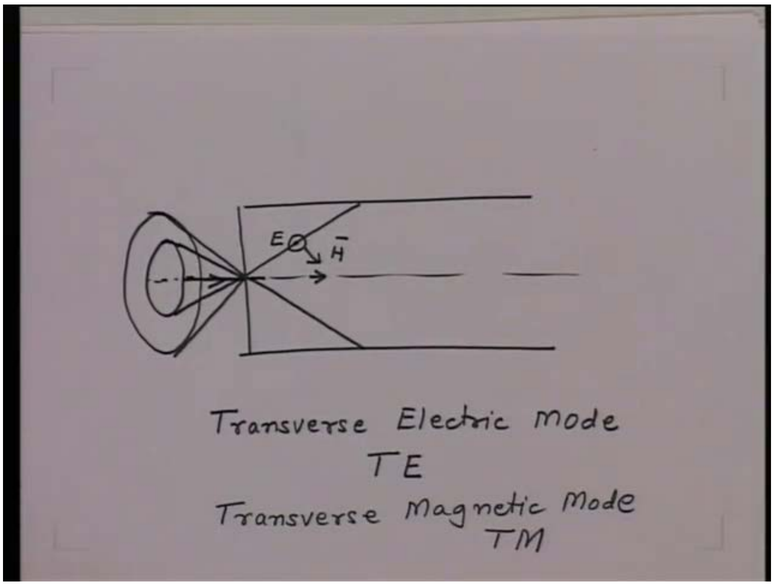
So, for every value of theta you have a unique intensity pattern created inside the optical fiber and this unique intensity pattern essentially what is called the mode of the optical fiber and as the angel increase a higher and higher we say that the order of the mode increases. So, the mode which created inside optical fiber corresponding to the ray which is launched along the axis, that mode is called as the lowest order mode, then there will be next mode and beyond the numerical aperture the ray cannot be launched inside this. So, you have finite number of modes which can propagate inside the optical fiber.

So, two things should be noted at this point, one is your having discrete intensity patterns which can survive inside the optical fiber any arbitrary distribution cannot survive inside the optical fiber. And secondly, these patterns are discrete and they are finite in number because any ray which is having an angel greater than the numerical aperture angel that cannot be launched. So, if we can literally count the angel at which the rays can be launched inside the optical fiber.

So, now we see that even if you have a numerical aperture cone which is larger then this. The light launching efficiency is further reduces because every ray which is lying within this cone cannot go inside the optical fiber. So, fiber chooses only light coming at those angels and any other light essentially is rejected. So, the efficiency of launching inside the optical fiber is further restricted. So, if I know consider this variation of the intensity inside the optical fiber because of the constructive or destructive interferences. We may get various kind of patterns you may have maximum at a center and then the field may die down slowly towards the end of the h of the optical fiber or is possible it may be maximum at a center goes to 0 again raises towards the walls of the optical fiber and so, on.

One more thing one can note in this point is that, let us say when the rays launch like this, if the ray goes along the axis of the optical fiber and now slowly try to put the wave phenomena behind this. So, let us say this ray is a transpose electrons magnetic wave now. So, you have a electric field and you have a magnetic field. So, if I consider this ray then the electric and magnetic field are perpendicular to each other and they are perpendicular to direction of propagation of this ray.

(Refer Slide Time: 04:33)



Transverse Electric mode
TE
Transverse Magnetic Mode
TM

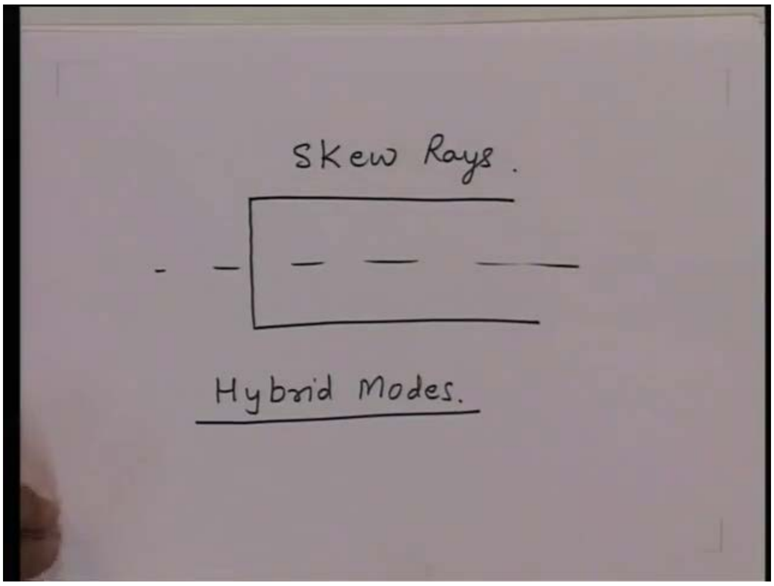
So, let us say the electric field lies in the plane of the paper. So, for this ray it will always lie in the plane of the paper and since the net propagation is along the axis of the fiber, you have the electric field which will be always perpendicular to this. If I consider a ray which goes at an angel like that and if I consider know the electric field let us say it is coming perpendicular to the plane of the paper then this is the direction of the electric field then E cross h should give me through direction of the power flow.

So, you have magnetic field. So, the electric field is perpendicular to direction of propagation, for all the rays which are going to be lying on this surface. Whereas, the magnetic field has a component which is in direction and which is in this direction. So, in this situation we find that the electric field component is always perpendicular to the net propagation of light inside the optical fiber. And this propagation therefore, we call as a transfers electric propagation, because the electric field always remains transfers to the direction of net propagation of light inside the optical fiber.

So, I have a mode what is called transverse electric mode, which we denote by T E. And then you put some index for this mode essentially telling us how many maximum minima with the interference pattern would create inside the core of the optical fiber. Issue of electric field perpendicular to this, if the magnetic field was like that, then the electric field will lie in the plane of the paper and then we will have they electric field components in the direction of propagation and the magnetic field will remain always perpendicular to the direction of propagation. So, as we got transfer electric mode we will also get the transpose magnetic mode and again depending upon the variation of the intensity we will have some index defining the transpose magnetic mode. So, you have a mode which will be transverse magnetic mode or we denote by T M mode.

So, as we know see that if you consider the rays which are meridional rays, because these ray which are drawn here are meridional there lying in the plane which is containing the axis of optical fiber. The supper position of all this ray is which are going at certain angel would create a electrician magnetic field patterns, which could be either transfer electric in nature or which could be transpose magnetic in nature. Compare this now with thus skew rays which are going the certain angel which is respect to this meridional plain.

(Refer Slide Time: 14:35)



Skew Rays.

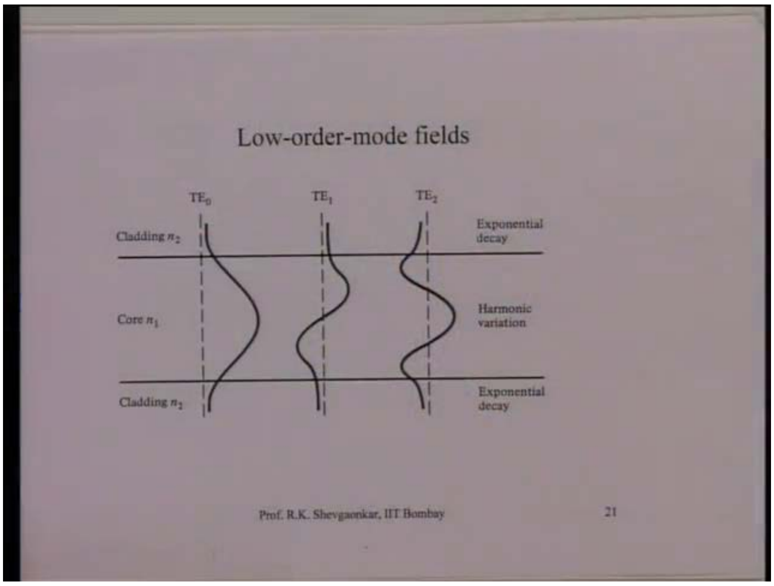
Hybrid Modes.

So, if I consider let us say optical fiber like this and they ray goes at an angel which is node in this plain is something like this. If that happens as we seen these ray essentially spirals around the axis of the optical fiber, and as a result you show that in no circumstance you will have a configuration which will have purely transverse electric in nature or which will be purely transverse magnetic in nature.

So, if we consider skew rays they would have electric and magnetic field both components in the direction of net propagation of light. Then this is neither electric, transverse electric in nature or not transverse magnetic in nature. That is the reason if I consider the skew rays, they essentially give raise to phenomena what are call the hybrid modes. Those of few we have done wave guides earlier they know that in metallic wave wide you have the electric and magnetic field distributions which are either transverse electric or transverse magnetic, there is the nothing like hybrid mode which exists in the metallic wave wide; however, when we come to optical fiber which essentially is the dielectric wave wide, there in addition to transverse electric and transverse magnetic modes. We also have another set up mode, what are call the hybrid modes and later on we will see hybrid mode is the lowest order mode, which essentially propagates inside the optical fiber.

So, infect the ray which goes along the access of the optical fiber when we do the regress analysis will find that mode is neither transverse electric nor transverse magnetic, now it is transverse electromagnetic, but it is the lowest hybrid mode which essentially propagates or which corresponds to their ray which goes along the axis of the optical fiber.

(Refer Slide Time: 17:31)



Low-order-mode fields

Prof. R.K. Shevgaonkar, IIT Bombay

So, now you find that just from the ray model and just putting phase fronts behind this rays we get a reasonable indepth understanding of propagation of light inside the optical fiber. And that is we have discreet intensity patterns created because of interference of the phase fronts, and these intensity patterns could be transverse electric in nature, could be transverse magnetic in nature or could be hybrid in nature.

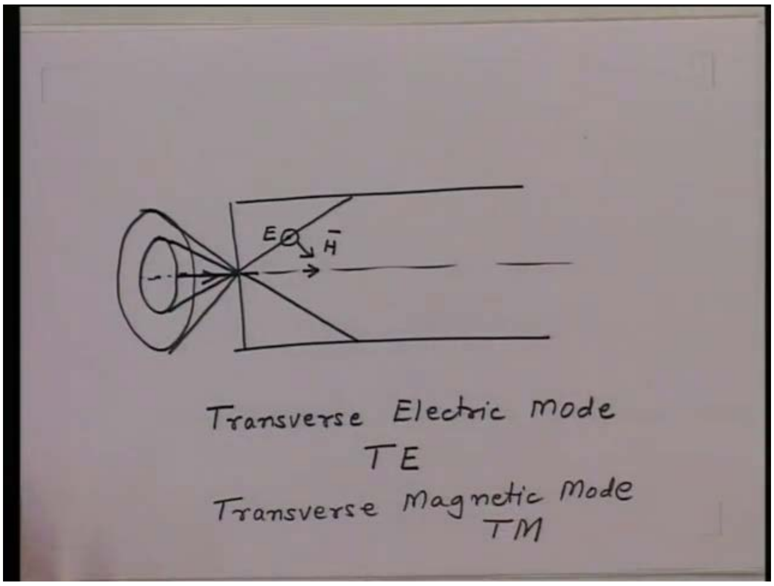
So, now if I look at know the intensity patterns which are created we may have situation something like this, if the angel at which the ray is launch is reasonably low with respect to the axis then you will get maximum at the center and slowly the field will decrease because of the reduction in the constructive interference and by time you reach to this core cladding boundary the field is to this value and beyond this the speed exponentially it has down in the cladding. If I have the angel further increase then there is a possibility now that you will have a maximum at a center field goes to 0, again increases with reverse direction in the field and then reaches to the core cladding bound the exponentially dies down.

So, how many 0 as crossed in the transverse direction, that essentially defines what is called the index for the more. So, the distribution which will look like that no 0 is crossed. So, we can call this distribution is transverse electric, 1 0 is there we call this distribution as T E1, this we call T E 0 and here that two 0 are there. So, we can call this distribution as T E 2.

So, like that as the angel of launching increases you see more and more 0s in the intensity pattern and that essentially use reflected into two this index which is put along with T E or T M. So, although figure shown here is for transverse electric case, the arguments are also true for transverse magnetic. Now coming back to again the launching of the rays inside the core of the optical fiber, the thing which we noted is that there are only discrete rays which can go inside the optical fiber one ray which is along the axis is always guaranteed because it does not require any phase condition to be satisfied, but the next ray which can go will depend upon whole lot of parameters. So, as we saw it depends upon the quantities which are the fiber parameters like the diameter of the fiber d, the wave length of operation, the refractive index of the core material.

So, these are the parameter which essentially will tell us at what angel will be the next launch inside the optical fiber corresponding to m equal to 1. So, one can ask very simple question, is it possible that only the ray which goes along the axis of the optical fiber is launched, but the next angel which satisfy the phase condition is more than the numerical aperture cone? Why do ask this question because we are seen that when a pulse of light is launched inside the optical fiber. And if large number of rays can propagate inside the optical fiber the pulse energy get divided into different rays different rays effectively travel with different velocity, because they go by different paths and because of there is pulse broadening.

(Refer Slide Time: 19:33)



Transverse Electric mode
TE
Transverse Magnetic Mode
TM

So, as we saw earlier that the pulse broadening is related to the number of rays which can be go inside the optical fiber. So, if I could reduce the number of rays inside the optical fiber; obviously, the first broadening also going to reduced that is the reason we are asking the question the suppose I make a condition. So, that only one ray which goes along the access of the optical fiber is launched, but the next ray we is satisfy the phase condition cannot be launched because that angel is more than the numerical aperture angel. Then there is no question of no pulse broadening because entire pulse energy is going to go only by the ray which is moving along the axis of the optical fiber.

So, we see that if I reduce this quantity d or if I make this quantity n 1 small enough, but n 1 we cannot change too much because we already identified the material glass. So, only this quantity d upon lambda or for a given value of lambda, the diameter of the fiber, if I reduce the d to a substantially low value than for any angel you cannot certify the phase condition even for the next value of m which is equal to 1. On the other words, what we are saying is if I make the optical fiber core thin enough, such that only this ray which goes along the axis can be launched, but even the second ray we certify the phase condition cannot be launched because this angel is greater than the numerical aperture angel. By doing this essentially then one can avoid that pulse broadening on the optical fiber, this phenomenon of pulse broadening later on we will see is what is called dispersion on optical fiber.

So, essentially by reducing the number of rays or creating situation were only one ray can go along the axis of optical fiber, that dispersion on the optical fiber can be eliminate. And that is very attractive thing because we know that the dispersion on the pulse broadening has direct implication on the data rate. So, if I could create a situation where only one ray goes then I can transmit a very high data rate on the optical fiber.

So, now I have situation where large number of raise go and energy propagates on the optical fiber or second situation will only one go along the axis and there is no dispersion on the optical fiber. Since we have seen that each ensemble of ray launched certain angel creates definite it density pattern which we call as mods. When many angels are possible inside the optical fiber we call that fiber as the multimode fiber. And by the same token when only one ray goes along the axis of the optical fiber, we call that fiber as the single mode optical fiber.

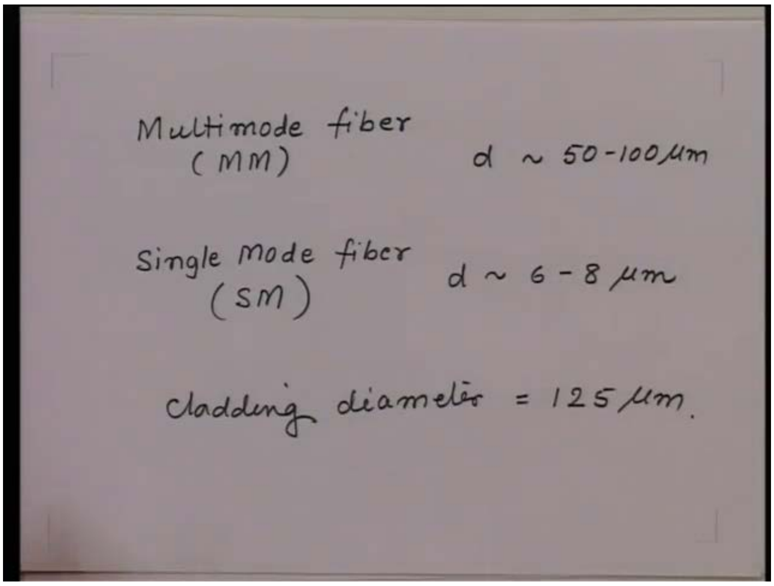
So, one thing is clear if I have the diameter of the fiber reasonably large compare to the wavelength then I have large number of rays going inside the optical fiber and I have a multimode of the optical fiber. If I reduce the diameter of the core to a reasonably low value, then I may get one ray launched inside the fiber or one mode will propagate inside the optical fiber and that fiber we call as single mode optical fiber.

So, then from dispersion point of view the multimode optical fiber is very bad fiber, because a it has a very large pulse broadening and single mode optical fiber is the best optical fiber, because it does not have any dispersion only one ray goes inside optical fiber; however, one would notice that if the diameter of the fiber is reduce to a substantial small value, then the numerically aperture cone also will reduce in this process, only one ray can launch along the access.

So, the launching efficiency of this fiber is extremely is small. So, a launching light inside a multimode optical fiber is easy, because it as large diameter it has large numerical aperture cone. So, you can launch light very easily. If I consider fiber which is single mode optical fiber then the light can be launched only along the axis. So, you require a source which can give you a highly beam light or highly collimated light, there and then only light can be launched efficiently the single mode optical fiber.

So, single mode optical fiber gives you advantage of dispersion, but at the expanse of the launching efficiency of light. So, you require very special kind of sources like lasers. So, that like can be launch in single mode of optical fiber, but any other source like L E D are quite suitable for multimode optical fiber. If you take source like LED it does not give a very collimated beam and if you put a single mode optical fiber in front of L E D, hardly any light will get launched inside the single mode optical fiber.

(Refer Slide Time: 27:00)



Multimode fiber (MM) $d \sim 50\text{-}100\,\mu m$

Single Mode fiber (SM) $d \sim 6 - 8\,\mu m$

cladding diameter $= 125\,\mu m$.

So, now just to give you numbers a typical multimode optical fiber would have a diameter. So, you have multimode fiber it has typical diameter of the order of about 50 to 100 micrometer and if I consider a single mode optical fiber then we have a diameter typically in the range of 6 to 8 micrometer. So, you can see that when we have a single mode optical fiber the diameter is really very small and that is the reason the light has to be very precisely focused on the core.

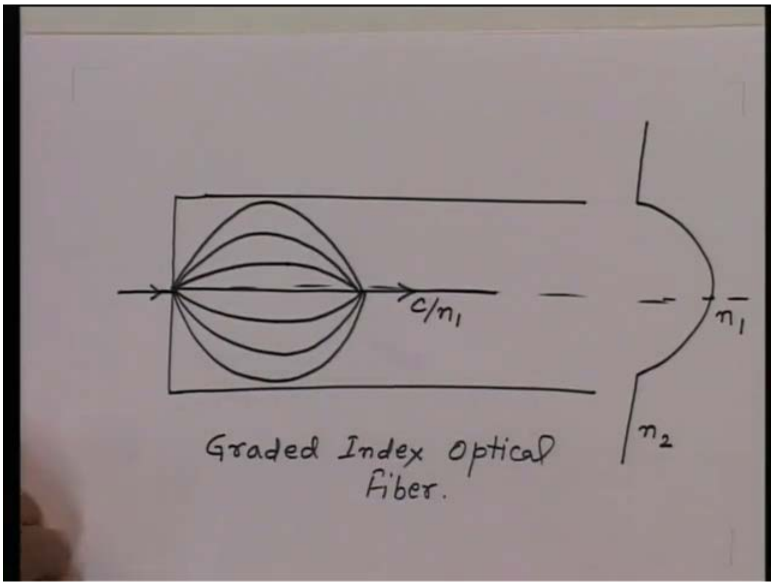
So, that it can get efficiently guided inside this fiber, though the diameter of core is different for the single mode or multimode optical fiber. The diameter of the cladding is always standardized to 125 micron and the reason for this is very simple, that whether we have a single mode fiber or you have multimode fiber, ultimately you would like to put a connecter on this fiber. So, fiber has to go inside the connector. So, the inner diameter of the connecter should decide what should be outer diameter of the fiber which goes inside this connecter.

So, irrespective of what is the diameter of the core the cladding diameter is decided by the inner diameter of the connector which are going to put on the fiber. And that is the reason the cladding diameter has always means standardize to 125 micrometer.

So, irrespective of whether I am using a single mode optical fiber or using a multimode optical fiber the cladding diameter is always will be 125 micrometer. So, now we will introduce nomenclature for fibers, the multimode optical fiber which carries large number of modes has a diameter of 50 to 100 micrometer has a very large dispersion, because large number of rays are going to propagate in this. And then we have a single mode optical fiber which has diameter of 6 to 8 micrometers has no dispersion, because only one ray propagates on this and it has a very low logic efficiency, but has a very good dispersion performance and the cladding diameter is standardize to 125 microns.

So, when we start using the single mode optical fiber we get the dispersion advantage, but at the same time we have a difficulty in launching the light inside the fiber because the size of the fiber is become very small. One can then ask a question can we do something. So, that I still have the size of the fiber still is reasonably large, but the dispersion on the fiber is reduced. So, to answer this question again go back to the basic ray model inside the core and ask if I do reduce a dispersion what is to be done to the ray propagation.

(Refer Slide Time: 30:45)



So, let us say this is the fiber core a ray which is launched along the axis will go like that. Nobody saw if the ray of launched at an angel which goes like this, it travels larger distance and because of that, the effective distance traveled along the excel the fiber is less does the angel become a larger and larger since the velocity of this ray and this ray is same and this ray a longer distance. So, there is a prime difference created between this ray and this ray, this is what essentially gave raise to will dispersion phenomena or pulse broadening phenomena.

So, suppose we can create a situation, where the ray which travels a longer distances with a fastest speed. Suppose if it is possible, then the ray which is going by this path will travel longer distance, but will have the speed which is higher than the ray which is going by this path. So, now there is compensation in time.

So, we will not have a separation of the rays as they use to be, when the velocity of this ray and this ray was same. So, if we can create a structure where the ray which travels the further distance travels with the fastest velocity and the ray which travels the shortest distance travels with the lowest velocity. Then the dispersion is reduced on the optical fiber because there is the type of compensation which is taken place.

So, essentially we are looking for a mechanism by which the velocity of light can be manipulated. And as we have seen earlier, this is very simple because the velocity of light depends upon the refractive index of the medium. So, if you can change the refractive index of the medium inside the core, then the velocity of light will change and if I want the ray which have going to the higher angels. If they have travel faster essentially the refractive index must reduce for region which is somewhere here and the refractive index should be highest here.

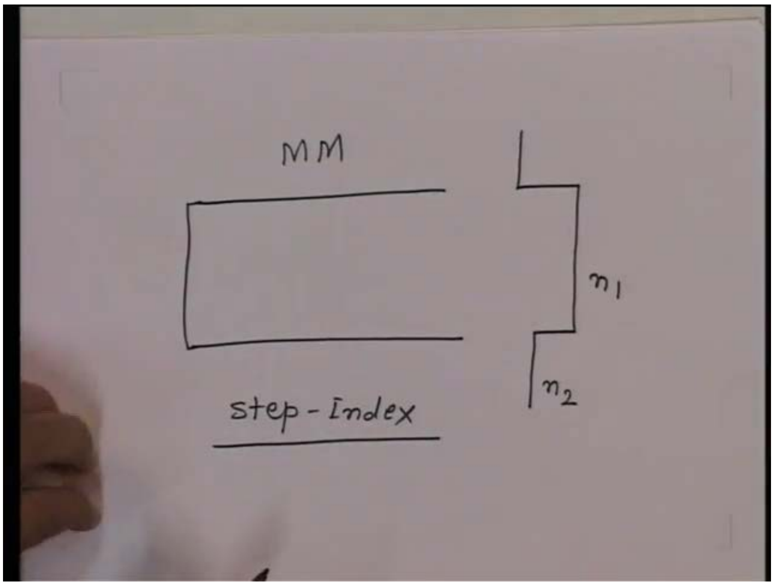
So, if I can create what is call the grading of the refractive index profile, then the ray which goes along the axis will be travelling with a slowest velocity. The ray which goes at an angel as your goes at higher and higher layers of the optical fiber, they will travel faster and faster and because of that the dispersion will be reduced. So, instead of having a refractive index profile which was constant in core and constant in cladding n 1 here n 2 here. Suppose I create a refractive index profile which looks something like that. So, this value at the center is n 1, this is the cladding where refractive index is n 2.

But the refractive index gradually varies from center of the fiber to the core cladding boundary, as a result what will happen this ray will travel which a velocity which is c divide by n l. The ray which is going at a slightly higher angel which will go like this and then now every ray will not go up to this point. The ray will go like that which are certain angel will come and join here the ray which is goes higher will travel faster and faster. So, will go like this come like this, the ray further goes go like this and comes like this.

So, essentially now the ray propagation is going to be like a projectile inside this fiber. So, the rays would start from here, they go like this. Since this ray will start travelling faster at faster by the times this we rays travel from here to here this ray would have again come and join here. So, it will start like this join like this like this like this.

So, since we have now graded the refractive index profile of this optical fiber. We call this kind of fiber as the graded index optical fiber optical fiber. So, inside a graded index optical fiber we have a large number of rays propagating the diameter of this fiber a same as the diameter of the multimode fiber, but the dispersion is much lesser compare to the multimode optical fiber. Of course, you can never have a perfect matching of the time for different rays, this will give you performance not as good as the single mode optical fiber performance, but it can give you performance much better than the multimode fiber performance. So, one can show with regress analysis that if you take this profile the refractive index profile which is parabolic in nature, then you get the best possible time compensation and you get the least pulse broadening on this optical fiber, graded index optical fiber.

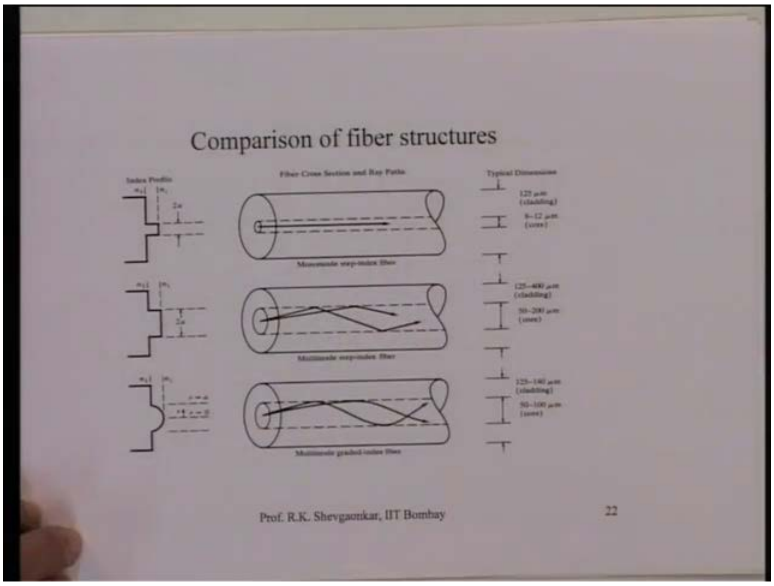
(Refer Slide Time: 37:29)



So, now we see in practice there are three types of optical fibers, the multimode optical fiber which has refractive index constant in the core and constant in the cladding and there refractive index profile is like step function. So, if I consider a simple multimode fiber the refractive index profile will look like that where this is n 1 this is n 2. So, this refractive index profile we call as the step profile. So, we can call this fiber as the step index multimode fiber. So, we can have here step index or we can have greater index fiber, multimode fiber or we can have a single mode fiber if you can create diameter typically of the order of 6 to 8 microns.

So, if I arrange them in the order of performance of dispersion. The multimode step index fiber is the worst fiber, because that has the highest dispersion much better than that is the graded index optical fiber which is multimode again, but for the parabolic variation of refractive index, it gives you dispersion hundred times better compare to the multimode optical fiber and the best full be the single mode optical fiber which is about ten times better compare to the graded index optical fiber.

(Refer Slide Time: 39:00)



Comparison of fiber structures

Prof. R.K. Shevgaonkar, IIT Bombay

22

So, now I summarize what we said we have three types of optical fibers in practice now, the best fiber is the single mode optical fiber, where the core is very thin here and the diameter is 48 microns, this is the refractive index profile have only 1 ray go this optical fiber this as the best optical fiber, because for this the dispersion is very low. This is the fiber which is multimode optical fiber where this core is 5200 microns. The refractive index variation is a step and it has to worse possible dispersion performance in between this 2 is the greater index optical fiber, where the refractive index profile is close to parabolic. And this gives you dispersion which is about hundred times better than this and ten times worse in this.

So, if you do not want to sacrifices to much on the launching efficiency, then multimode greater index fiber is the better option, than going for the single mode. So, utility wise than one can say that if my data rate is not very large or if my distance is not very large, then multimode grater index optical fiber is a good choice, because it does not requires special kind of sources even a LED kind of sources would be good enough to launch light inside this fibers. Whereas, when we go to very long distance high speed communication, then one graded index optical fiber dispersion performance is not adequate.

So, will go with the single mode optical fiber; so, in fact the multimode optical fiber with step index is only for the academic interest and may be this kind of fiber will be used in the laboratories, but if you go to the small network like local area networks at least we will use the fiber which is the graded index optical fiber with refractive index profile very close to parabolic. And when we go to the long distance high speed communication the most of the time the fiber will be the single mode optical fiber.

So, this is now the basic understanding which we have developed from the simple model what is called the ray model. One can ask a question can we just stop here and need not go for the ray model. T he answer is no, because the ray model gives you some insight into the propagation of light inside the optical fiber, still it does not describe the complete propagation of light. And the reason is very simple suppose we are asking the question that the ray which is goes along the access of the optical fiber, does the propagation characteristic depend upon the wave length? If I just consider the ray model the answer will come no, because I am considering a ray irrespective of what is the frequency or what is the wave length of this wave, this is the ray which will go along the axis of the optical fiber. So, propagation of light does not depend upon the wave length of operation.

However, that is not correct when we talk about a bond medium like this then the propagation characteristic depend upon the wave lengths of light. So, the ray model gives us some understanding a propagation inside the optical fiber, but if you wanted to have a quantitative understanding or propagation of light or if you want to find out how much pulse broadening actually going a take place or would there be pulse broadening. If there is only one ray which goes on the optical fiber, but if the source had a finite bandwidth. These question cannot be answer by the ray model and that is the reason we essentially go in investigate in detail what is called the wave model of propagation of light inside the optical fiber.

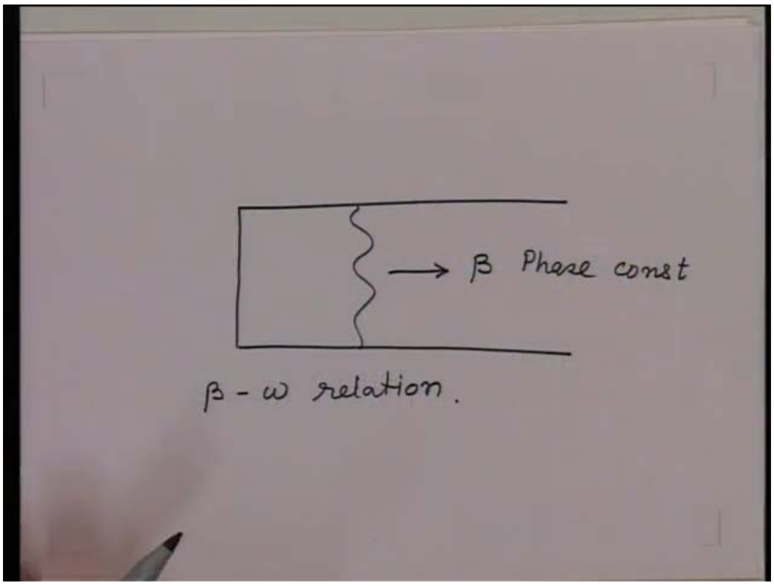
So, here now idea is that having a understood now, the propagation of light inside the optical fiber if the ray model make use of this physical understanding of propagation of light. And then try to go to the wave model put this physical understanding into the analytical approach and then to try to get the quantitative answers to the physical understanding which we developed here.

So, before we get into the propagation of light by using compliance wave model. Let us first ask why analyze the wave model, what are essentially we are looking for. So, first thing is we are asking if the structure is given to you, which is like an optical fiber. And the light is not propagating now in the form of rays suppose a light is launch inside this some kind of electric magnetic field patterns will be reduced inside the core this patterns are going to propagate in side this.

So, suppose we had now a. So, which is a finite bandwidth then the pattern of electrical magnetic fields would be created at all possible frequency, which are within that band. So, the question one can ask is if I change the frequency how much is the velocities which are going to change of this model pattern or the field pattern which are created inside the optical fiber.

So, the quantity essentially we are looking for is here, the behavior of velocity of the electrical magnetic field patterns as the function of wave length inside an optical fiber. So, the basic relationship which we have for the propagation of electromagnetic wave, light also is electromagnetic wave is the relationship between the phase constant which we defined earlier is beta and the frequency omega.

(Refer Slide Time: 46:06)



So, let us say if I had certain field distribution here, which travels with the phase constant beta and this phase constant now is the function of frequency. So, we have a relation which is the beta omega relation, this relation also called as dispersion relation. So, by using the electromagnetic theory and the wave propagation in this bound structure which is the optical fiber we find the relationship between beta and omega and once you get beta and omega then we can find the velocity of the field inside the core. And there as we know for a wave length there are two velocities one is called the phase velocity, other one is called the group velocity. So, we have V p which is phase velocity which is omega by beta and we have V g it is group velocity which is d omega by d beta.

So, inside the optical fiber since we are interested in sending light in the form of pulses, we are interesting in the velocity what is call the group velocity. So, in the next lecture when we meet essentially starting with the basic wave equation, we satisfy the boundary condition on the core cladding. From there we try to establish a relationship between the phase constant and the frequency omega. From there then we get a velocity which is group velocity for a pulse from d omega by d beta. And once you get a group velocity, then we can ask a question that if light pulse was launched inside the optical fiber, how different frequency component will travel and because of the variation in the group velocity, how the pulse is going to get deform inside the optical fiber.

So, this analysis of wave model is essential in finding out quantitatively the variation in the velocity of a pulse inside the optical fiber, which gives you information about the distortion of the signal on the optical fiber. So, when we meet in the next lecture we start with the basic Maxwell equations, treat the problem as a simple boundary value problem and then find the propagation characteristics of a mode inside the optical fiber.