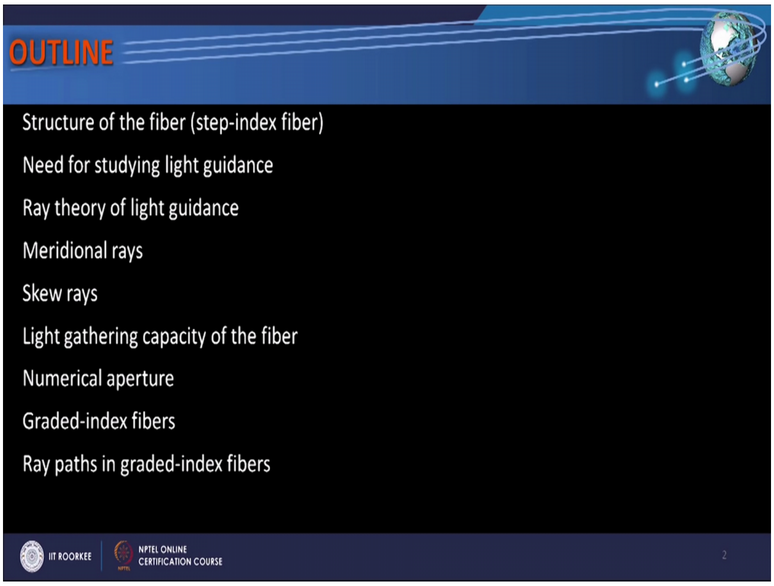
Fiber Optics
Dr. Vipul Rastogi
Department of Physics
Indian Institute of Technology, Roorkee

Lecture – 03
Salient Features of Optical Fiber – I

In the last lecture we had answered the question, why do we need optical communication, that is why do we require light waves for telecommunication. And the answer we found is if we utilize carrier wave communication through em waves for telecommunication purpose. And we had seen that in carrier wave communication if we increase the frequency of the carrier, the data transmission rate can be increased the bandwidth of the system increases. Light waves have much larger frequency as compared to the microwaves and radio waves, that is why light waves can give you a enormous bandwidth very large bandwidth, and this is the primary reason for using light waves for high data rate communication. If we want to use light for communication then we need to guide light across curves and corners, in the same way as copper wire conducts electricity.

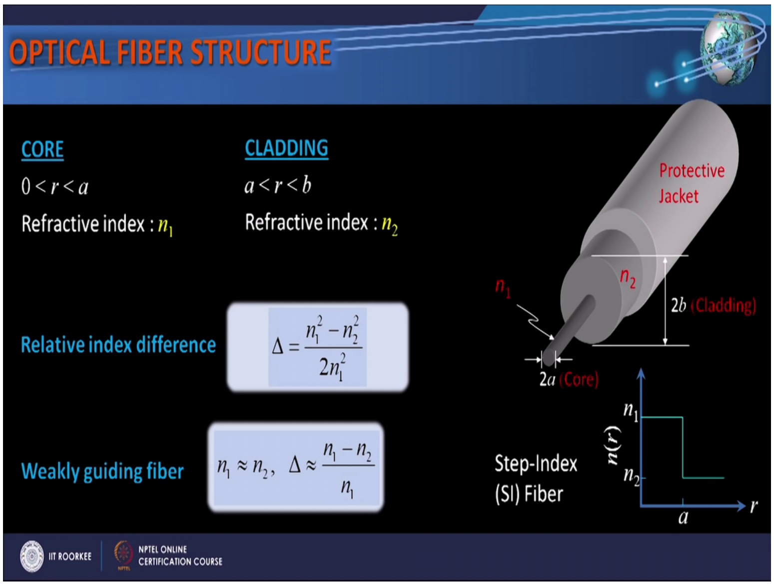
So, now in this lecture we will look at the structure which carries light along it around all the curves and corners, and this structure is called optical fiber, we are going to look into the salient features and characteristics of optical fiber in this lecture.

(Refer Slide Time: 02:17)



So, what plan we have for this lecture, we will look at the structure of a typical optical fiber which is step index fiber then we will understand what is the need for studying light guidance in an optical fiber. What is the ray theory of light guidance which is a very simple theory to understand light guidance in a fiber, fiber guides light through two types of rays one is meridional rays another is skew rays, then what is the light gathering capacity of the fiber, what is the numerical aperture of the fiber, then there are different type of fibers which have refractive index variation in the core they are known as graded index fiber, and we would look into how rays go in graded index fiber, what path they follow.

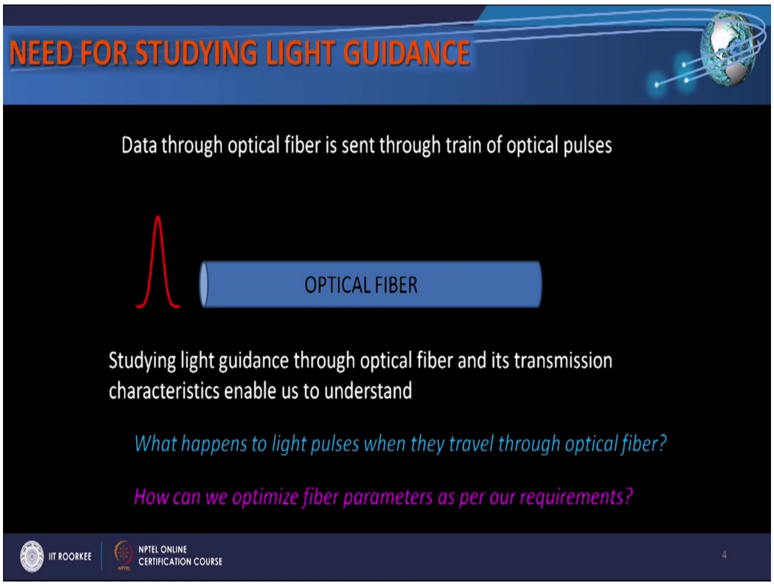
(Refer Slide Time: 03:40)



So, let us first look at the structure of a typical optical fiber. This fiber has a high index core of refractive index n 1 and radius a, it is surrounded by a cladding of refractive index n 2 and radius b. So, if I look at the refractive index variation in this region, then in the core which is defined by 0 is less than r is less than a, the refractive index is n 1 in the cladding which is defined by a less than r less than b, refractive index is n 2 and this is the refractive index profile of the fiber, nrs function of r where the refractive index is n 1 from 0 to a, and refractive index is n 2 for r greater than a for simplicity I have considered here infinitely extended cladding instead of a finite cladding because the cladding is much larger cladding dimensions are much larger than the dimensions of the core. So, we can consider it to be infinitely extended.

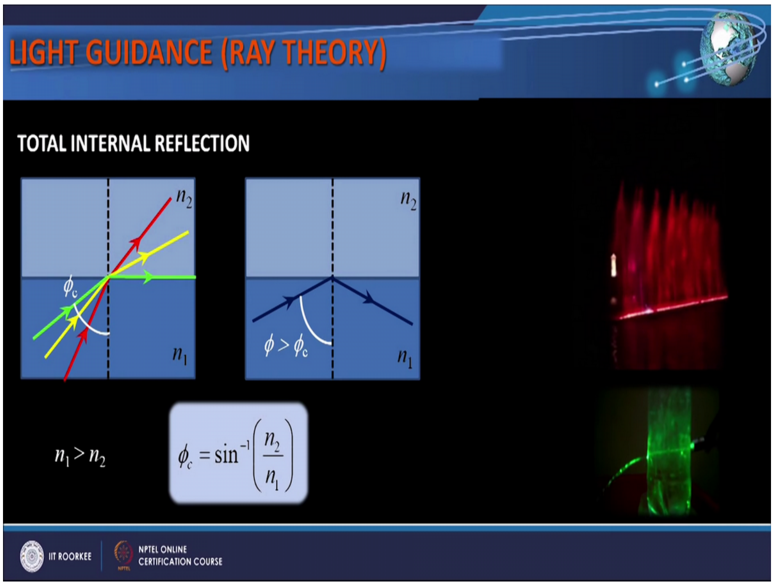
The index difference between the core and the cladding is defined by a parameter relative index difference, delta is equal to n 1 square minus n 2 square over 2n 1 square and for practical fibers, n 1 is close to n 2 the difference between n 1 and n 2 is small and they are known as weakly guiding fiber for such fibers delta can be approximated by n 1 minus n 2 over n 1. Now the question is what is the need for studying light guidance in the fiber. Well when we send data through optical fiber it is sent through train of optical pulses, and we need to know what happens to these pulses when they travel through optical fiber.

(Refer Slide Time: 06:03)



So, studying light guidance through optical fiber and its transmission characteristics, enable us to understand number one what happens to light pulses when they travel through optical fiber, and number two how can we optimize fiber parameters as per our requirements. How light is guided through optical fiber well to understand that.

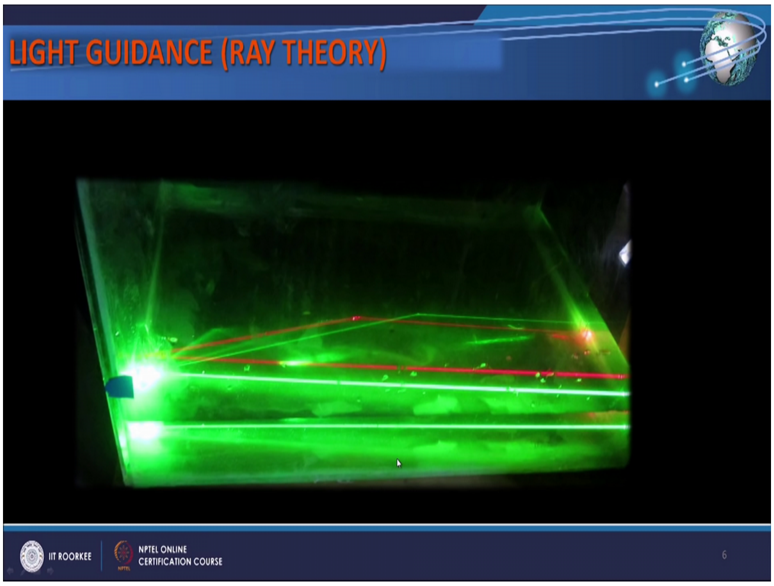
(Refer Slide Time: 06:43)



Let us have a look at this which is light at fountain here, and what we see that light is place somewhere here light source is place somewhere here and these streams of water they capture light they are lighted all over. How do they capture light how do they guide light along the stream how the light is guided along the stream. Another thing we can look at is we can perform a very simple experiment in which we fill a transparent bottle with water, pears a small hole in the bottle and let the water stream come out. Now if I launch light from a laser pointer on to this hole, then what I see that here the light travels in a straight line, but here this is stream of water captures light, and light is guided along the stream how this light is guided at all well. The answer is the mechanism of guidance here is total internal reflection what is the total internal reflection. So, to understand that let us have let us have these two media n 1 and n 2, this is a denser medium this is a rarer medium. So, n 1 is greater than n 2.

Now, when a light ray is incident on the interface of these two media, the light ray gets reflected. If I increase the angle of incidence from the normal, then the since it is going from denser to rarer it moves away from the normal. So, if I increase the angle it will further move away from the normal and at one particular angle phi c this reflected ray basically grazes the interface between the two media. Now what is this phi c. This phi c is called the critical angle for total internal reflection and it can be given by sin inverse n 2 over n 1. Now if I incident a light ray which makes an angle larger than phi c then this light comes back into the same medium this is known as total internal reflection and the condition for total internal reflection is that phi should be greater than phi c the critical angle.

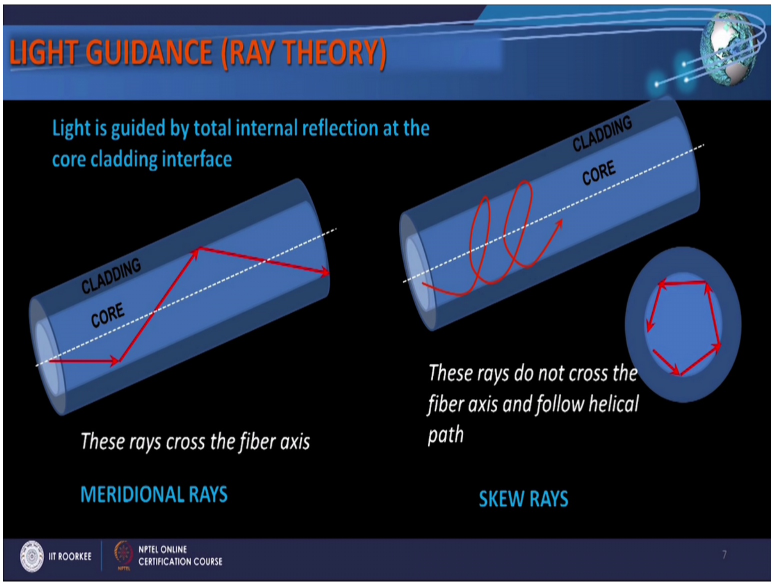
(Refer Slide Time: 09:35)



This is one very simple experiment that you can do you can fill a transparent tank with water and then you send the laser beam at different angles, and you find that if the angle of incidence is larger than the critical angle there is total internal reflection at the interface of water and air.

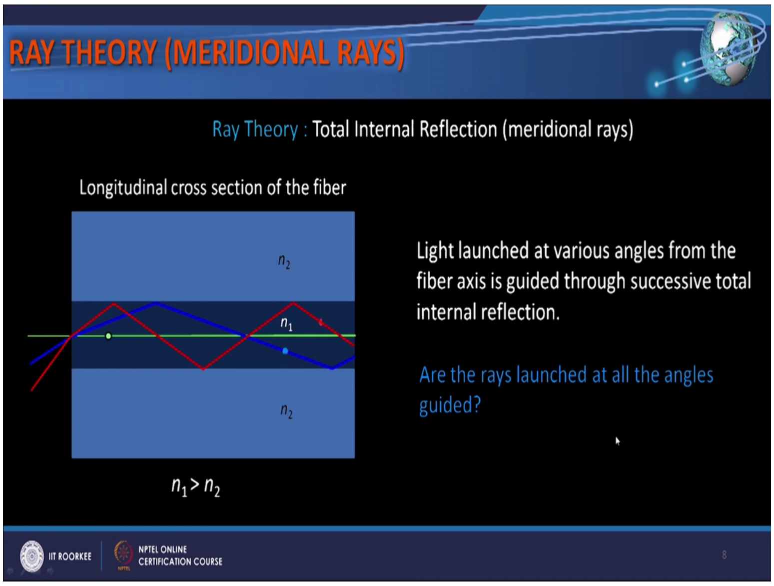
Now, if I look at the ray theory of light guidance in optical fiber, then light is guided by total internal reflection at core cladding interface.

(Refer Slide Time: 10:08)



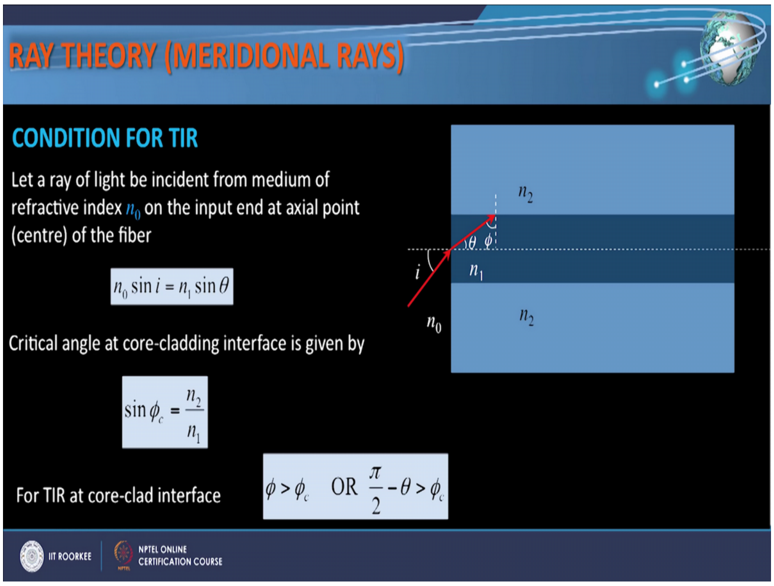
So, if I launch a ray of light into the fiber it goes like this, and if this angle this angle which it this ray makes with the normal to the core cladding interface is larger than the critical angle, then it will be total internally reflected and it would be guided. What we can see here is these rays they cross the fiber axis and these are known as meridional rays there can be another possibility that depending upon the launch conditions, a ray can never cross the fiber axes, but it will be totally internally reflected it will undergo TIR, but it will follow on a helical path it will never cross the fiber axis. If these would be clear when we see the transfers cross section of the fiber, if I look at transfers cross section. So, these rays go like this and they never cross the axes. So, these rays are known as a skew rays. So, light guidance takes place via meridional rays as well as a skew rays in an optical fiber.

(Refer Slide Time: 11:53)



Now, let us look at light guidance by meridional rays. So, if I launch light at various angles into this fiber this is a longitudinal cross section of the fiber, then what happens is that the rays launched at different angles will be guided through successive total internal reflections. Now the question is are the rays launched at all the angles guided or there are only certain range of angles that would be guided.

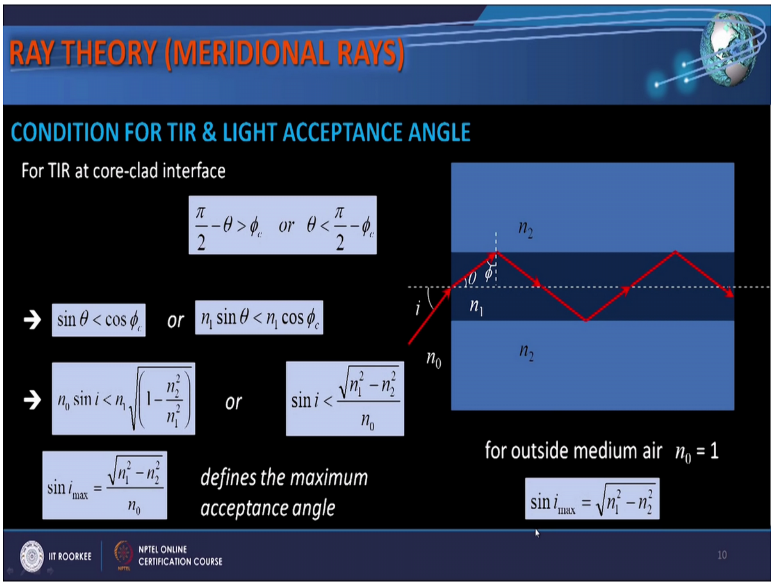
(Refer Slide Time: 12:29)



To understand that let us apply the condition for total internal reflection in the fiber. So, again this is the longitudinal cross section of the fiber, you have a core with refractive index n 1 and cladding of refractive index n 2 this is the fiber axes, and the refractive index of the outside medium is n 0.

Now, let me launch a ray from outside medium onto the input end of the fiber, let us say at an axial point and it makes an angle i from the axis of the fiber. Now when this ray enters the fiber it is refracted, and like this reflected ray make an angle theta from the fiber axis and correspondingly an angle phi with the normal to the interface of core and cladding. Now from Snell’s law I know that n 0 sin i should be equal to n 1 sin theta, and the critical angle at core cladding interface is given by sin phi c is equal to n 2 over n 1. Now it is clear that for TIR at core cladding interface this phi should be greater than phi c and correspondingly pi by 2 minus theta should be greater than phi c because this pi is equal to phi by 2 minus theta. So, if this phi is greater than phi c or this pi by 2 minus theta is greater than phi c, then this ray will undergo TIR successive TIR at core cladding interface and would be guided.

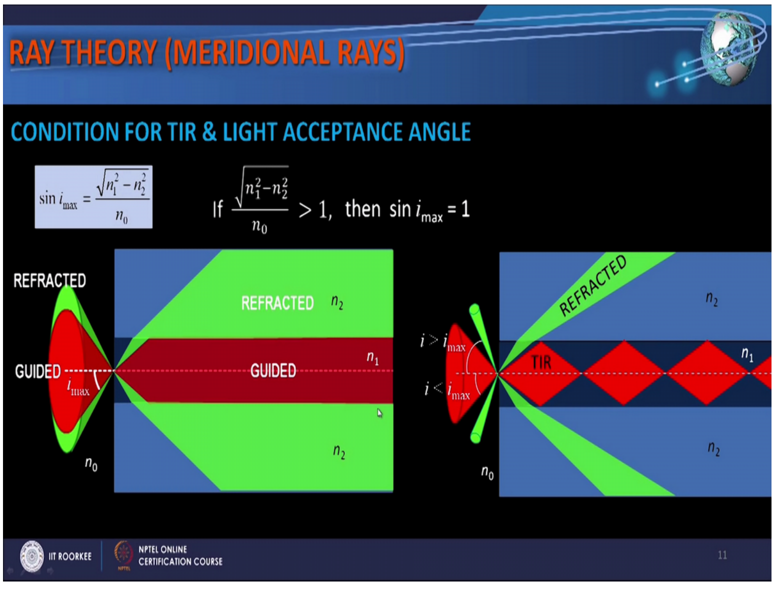
(Refer Slide Time: 14:45)



This condition for total internal reflection can also be written as theta is less than pi by 2 minus phi c, and now if I take sin of this then sin theta should be less than cos phi c and if I multiply it by n 1 then n 1 sin theta should be less than n 1 cos phi c, since sin phi c equal to n 2 over n 1. So, cos phi c would be equal to square root of 1 minus n 2 square over n 1 square, and n 1 sin theta is equal to n 0 sin i. So, this equation will now give me n 0 sin I should be less than n 1 square root of 1minus n 2 square over n 1 square or sin I should be less than square root of n 1 square minus n 2 square over n 0. So, for a limiting case if I consider the limiting case, this sin imax is equal to square root of n 1 square minus n 2 square minus n 0 defines the maximum acceptance angle; which means that if this I is less than I max then there would be total internal reflection at core cladding interface and light could be guided through optical fiber.

If I take outside medium as air then n 0 is equal to 1, and sin I max is equal to square root of n 1 square minus n 2 square. Now we have seen that sin I max is given by this the question is if n 1 square minus n 2 square over n 0 is greater than 1 then what would be I max or sin i max.

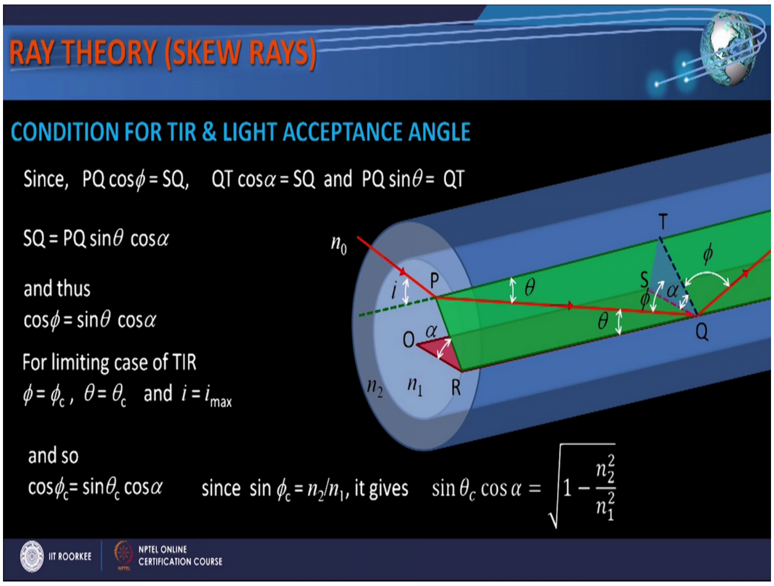
(Refer Slide Time: 16:33)



As I know that sin i max, i max cannot assume values greater than 1. So, even if it is greater than one then sin I max will be kept at value one because I max cannot be greater than ninety degrees. So, now, if I launch a cone of light into the fiber, then what I see that all the light which lies in the cone of semi vertical angle imax will be guided through the core of the fiber and the light which makes angles larger than imax would be refracted. I can see it in this way also that if this cone of light has semi vertical angle which makes with which is smaller than imax, then this light will be guided through total internal reflection and if I launch light in this region where the angles are larger than imax then this light will be refracted, and it will not be guided through optical fiber.

The second kind of rays which we talked about is skew rays. What is the condition for total internal reflection and light acceptance angle what for skew rays for that let me launch a ray of light somewhere here on to the fiber end and it makes an angle I with the fiber axis in the outside medium n 0 when it enters the fiber this ray makes an angle theta with the longitudinal direction of the fiber, and it is reflected here.

(Refer Slide Time: 18:22)



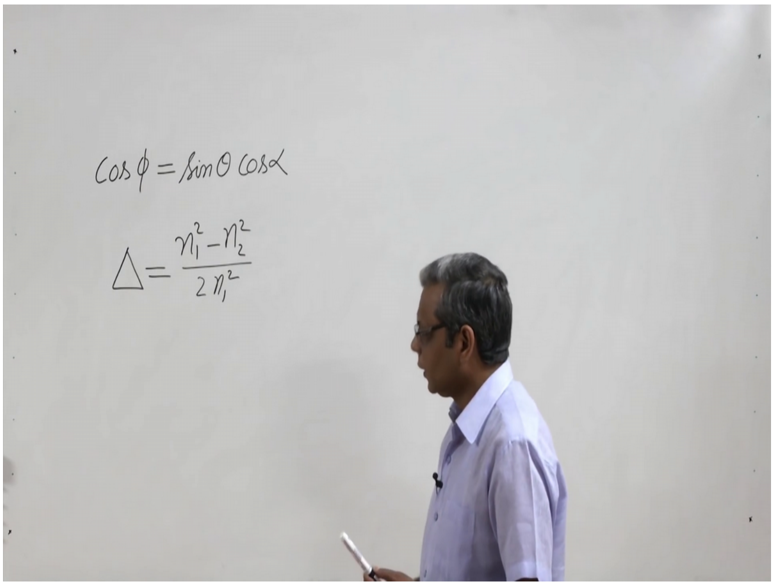
It is incident it hits the point Q at core cladding interface and then it is reflected. Let me make this plane consider this plane which contains this incident light and reflected light which is represented by green here, and this is the normal QT is the normal at the core cladding interface and then let me also consider another plane which is a longitudinal plane, but which contains this line this longitudinal line which passes through Q.

So, basically this plane makes an angle alpha from this longitudinal plane, if I consider a transverse plane here which is SPQ, then this transverse plane makes an angle phi from this incident ray and this is the reflected ray that also makes an angle phi with this. Now what I can see here is that this PQ cos phi is nothing, but SQ and QT cos alpha is also SQ I also find that this PQ sin theta is QT. So, if I considered these two then I find that this SQ is nothing, but PQ sin theta cos alpha, because QT cos alpha is equal to SQ and QT is PQ sin theta here.

Now, if I consider these two equations I compare them then I immediately get cos phi is equal to sin theta cos alpha. So, in this way what I have got I have got phi, in terms of theta and alpha theta is related to i. So, I can relate it to I and then I can find out what is the condition of total internal reflection I know that for total internal reflection phi should be greater than phi c, and if I consider this limiting case for TIR then phi is equal to phi c correspondingly theta is equal to theta c, and let us say i is equal to imax. Then I have from here cos phi c is equal to sin theta c cos alpha, and since phi c is equal to n 2 over n 1 it gives me sin theta c cos alpha is equal to square root of n 2 square over n 1 square from here.

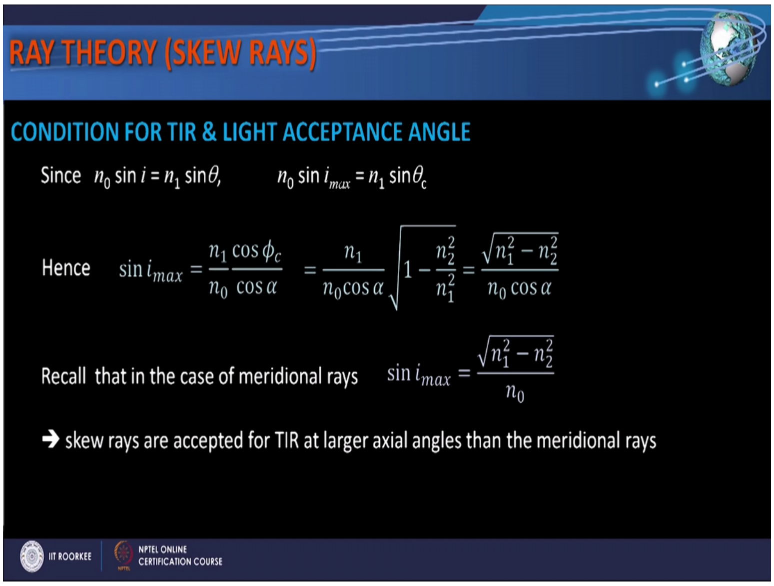
So, let me write this one down which I will use later also that cos phi cos phi is equal to sin theta cos alpha. So, cos phi is equal to sin theta cos alpha.

(Refer Slide Time: 22:15)



Now, since from Snell's law, I have already seen that n 0 sin I should be equal to n 1 sin theta. So, n 0 sin imax should be equal to n 1 sin theta c correspondingly.

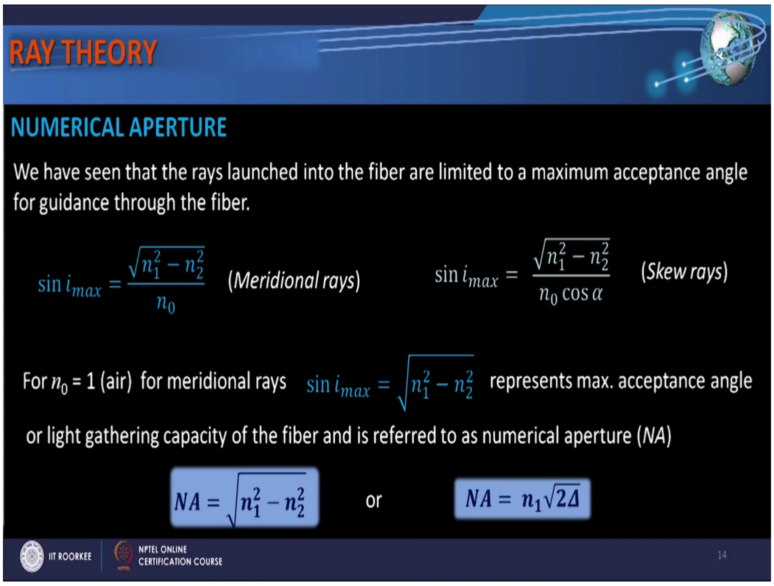
(Refer Slide Time: 22:37)



And hence sin imax would be equal to n 1 cos phi over n 0 cos alpha, because sin theta is equal to cos phi divided by cos alpha. So, and cos phi is square root of 1 minus n 2 square over n 1 square. So, this gives me sin imax is equal to is square root of n 1 square minus n 2 square over n 0 cos alpha. You just recall that in case of meridional rays this sin imax was a square root of n 1 square minus n 2 square over n 0. Now I have an extra factor of cos alpha in denominator, and cos alpha has maximum value one and that is the limiting case. So, since cos alpha is less than one for is skew says. So, skew rays are accepted for TIR at larger angle then the meridional rays.

What happens is that these skew rays are confined to the rim of the fiber, they never cross the access and therefore, they do not fully utilize core for light guidance and because of this they are not very important to be considered in optical fiber design and communication.

(Refer Slide Time: 24:39)

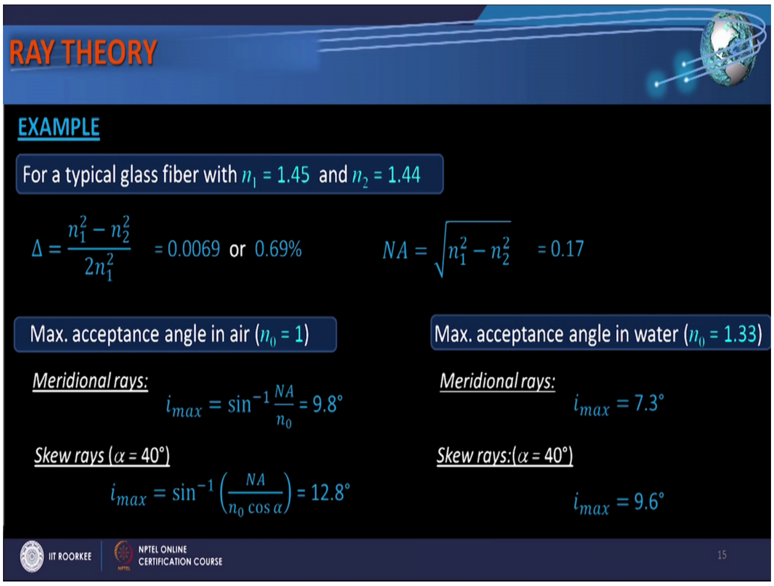


Now, let us look at numerical aperture of the fiber, we have seen that the rays launched into the fiber are limited to a maximum acceptance angle for guidance through optical fiber. For meridional rays this acceptance angle is given by sin imax square root of n 1 square minus n 2 square over n 0, and for skew rays it is square root of n 1 square minus n 2 square over n 0 cos alpha.

Now, if outside medium is air then for meridional rays sin i max is equal to square root of n 1 square minus n 2 square, and this represents the numerical aperture of the fiber. So, if the fiber is in air, then what is the maximum acceptance angle that gives you the numerical aperture of the fiber. Because this maximum at maximum acceptance angle basically tells you the light gathering capacity of the fiber and that is why it gives you the numerical aperture it is known as numerical aperture of the fiber. So, numerical aperture or in short NA is a square root of n 1 square minus n 2 square and it purely depends upon the refractive indices of the core and the cladding.

If you remember that I had defined relative core cladding index difference delta is equal to n 1 square minus n 2 square over 2 n 1 square. So, I can represent this n a also in terms of delta. So, you get it as n 1 is square root of 2 delta. Let us consider an example for a typical glass fiber with n 1 is equal to 1.45and n 2 is equal to 1.44 delta is equal to about 0.69 percent and n a is equal to 0.17.

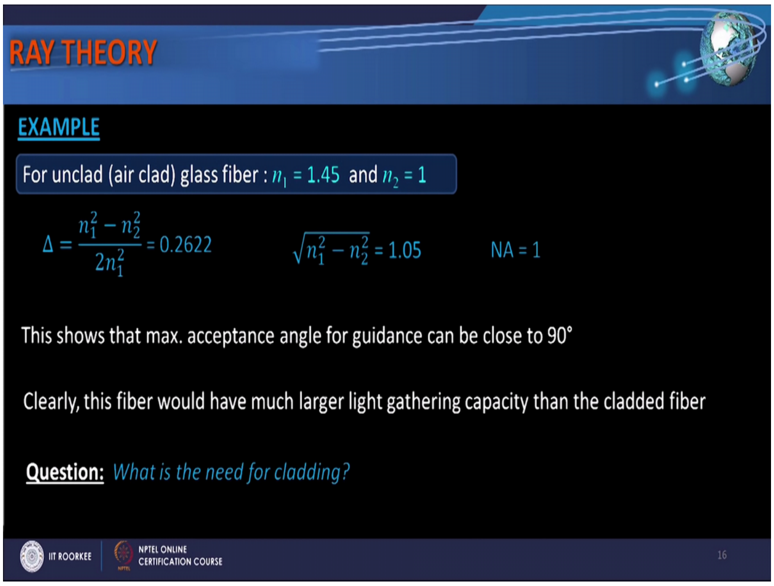
(Refer Slide Time: 27:16)



The maximum acceptance angle in air is can now be given by for meridional rays as imax is equal to sin inverse n a over n 0, which is about 10 degrees 9.8 degrees and for skew rays for alpha is equal to 40 degrees it is about 12.8 degrees. If I put the same fiber in water where the refractive index is 1.33, then for meridian rays imax becomes 7.3 and for skew rays it is 9.6.

So, what do I see here that for any given outside medium the a skew rays have larger imax than meridional rays, and if I change the outside medium if I increase the refractive index of the outside medium, the light acceptance angle goes down.

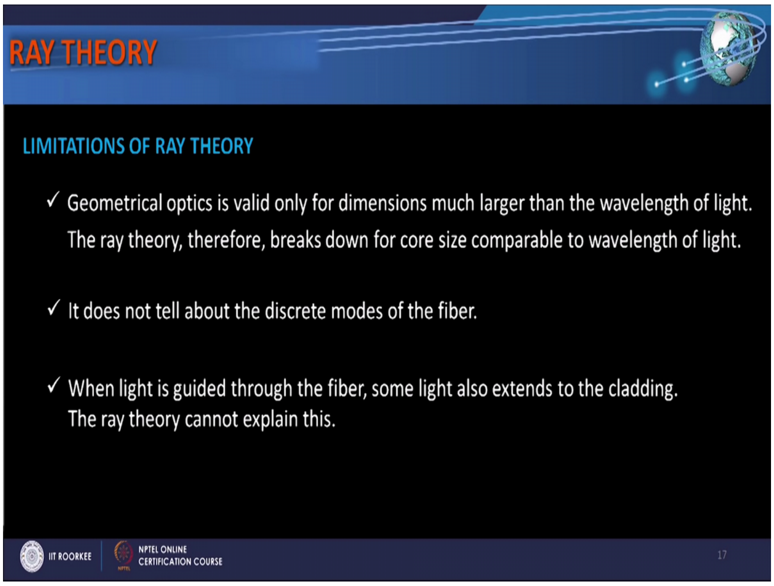
(Refer Slide Time: 28:38)



If I consider an unclad fiber than n 1 is equal to 1.45 and n 2 is one which is basically air then delta is 0.26 and square root of n 1 is square minus n 2 square minus is equal to 1.05 which means n a should be equal to 1. This shows that the maximum acceptance angle for guidance can be close to 90 degrees because n a is equal to 1 sin imax is equal to 1 clearly this fiber would have much more light gathering capacity as compared to cladded fiber.

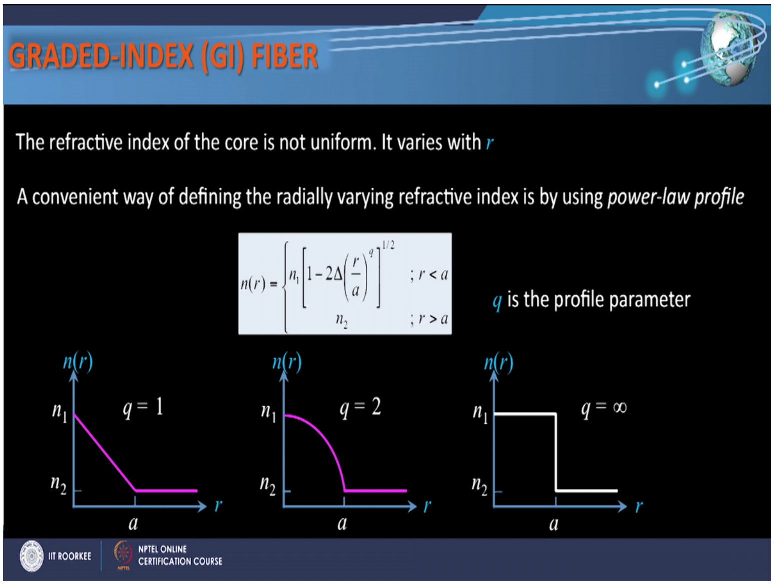
Then the question is what is the need for cladding and we will answer this question later in subsequent lectures. Now let us look at the limitations of ray theory what are the limitations of ray theory. Well ray theory is basically geometrical optics and geometrical optics is valid only for dimensions which are much larger than the wavelength of light. So, ray theory basic term.

(Refer Slide Time: 29:54)



When we consider fiber whose score is of the order or to the compare able to the wavelength of light. Second thing that it will not tell you the discrete modes of the fiber as we will go along we will learn that the fiber support certain discrete modes of propagation, but ray theory cannot tell you about discrete modes of the fiber. Third thing is when light is guided through optical fiber, some light also extends to the cladding and ray theory cannot explain this. So, these are some limitations of the ray theory.

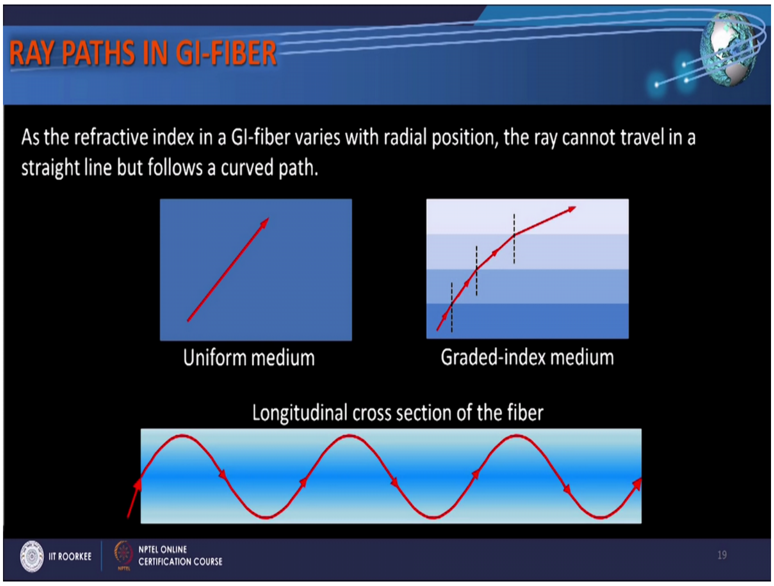
(Refer Slide Time: 30:51).



Then apart from step index fibers there are graded index fibers where the refractive index of the core is not uniform, it varies with r the radial position. And a convenient way of defining this radially wearing refractive index is using power law profile which is given as an r is equal to n 1, 1 minus 2 delta r over a to the power q whole to the power half in the core or less than a and it is equal to n 2 for r greater than a in the cladding. This q is nothing, but profile parameter, it basically governs the index gradation let us see what does it mean.

So, if I put q is equal to 1, then the refractive index profile would be something like this in the core as you move away from the axis, the refractive index will gradually decrease and this decrease is linear this is also known as triangular profile. If q is equal to 2 then this decrease is like this in parabolic fact fashion, then this fiber is also known as parabolic index profile fiber, and if q is very large if q is infinity then this is nothing, but a step index fiber. So, very large values of q will give you a step index profile.

(Refer Slide Time: 32:41)



How the ray paths look like in a graded index fiber. If I have a uniform medium and I launch a ray of light from here it goes straight, but in a graded index medium there is change in refractive index here the refractive index is larger than a smaller than a smaller than smaller, then what happens is if you consider an interface here like this then it will move away from the normal, then here again away from the normal here again away from the normal. So, light will not go straight, but it will be banned. So, it will follow a curved path and this is the ray path in a typical parabolic index fiber if the if the refractive index where is parabolic ally away from the axis, then the ray launched into the fiber follows a sinusoidal kind of part. So, the ray paths are curved.

So, in this lecture what we have understood it how light is guided through optical fiber via meridional rays, and skew rays what is the condition for light guidance, what is the light gathering capacity of the optical fiber, what is the numerical aperture of the fiber, what happens to the numerical aperture when the outside medium refractive index changes and what are graded index fibers.

Thank you.