

hello welcome to this lecture module on optics in the last lecture we discussed about reflection and refraction at a plane interface and we discussed the snell's law today we will continue it further in particular we gave emphasis on light incident from air or from a rarer medium on to the interface at the denser medium and discussed about refraction and reflection today this is this one when light enters from rarer medium to denser medium that is when  $n_1$  is smaller than  $n_2$   $n_1$  is less than  $n_2$  it is also called external reflection today we will focus more on internal reflection internal reflection when light enters from a denser medium and is incident on the interface between the denser and rarer medium we will see some interesting effects today

so recall reflection and refraction at a plane interface

so today we are looking at internal reflection that is when  $n_1$  is greater than  $n_2$   $n_1$  always refers to the incident medium and  $n_2$  is the second medium here

so light consider a point source  $p$  which is giving out light rays the light ray which is incident normally on the interface

so this is the denser medium this is the rarer medium  $n_1$  is greater than  $n_2$  the light which is ray which is incident normally a part of it gets reflected and a part of it gets transmitted a ray which is making an incident angle  $i_1$  here when it goes from denser medium to rarer medium it bends away from the normal and we can see that  $r_1$  is greater than  $i_1$  this comes out from the snell's law

so if  $i_1$  increase the angle further that is if  $i_1$  consider a ray which is incident at a larger angle here  $r_2$  further increases  $r_2$  increases if  $i_1$  increase the angle of incidence here to a value which is  $i_3$  then  $r_3$  would just graze along the interface every time a part of the light is reflected and a part of the light is transmitted for the particular ray that  $i_1$  have shown here with an angle of incidence  $i_3$  the ray would graze along the interface snell's law says  $\sin i_1$  by  $\sin r_1$  equal to constant and similarly  $\sin i_2$  by  $\sin r_2$  equal to constant  $n_2/n_1$   $n_2/n_1$  is  $n_2$  by  $n_1$  the relative refractive index in this case  $n_2/n_1$  is less than one because  $n_1$  is the denser medium and  $n_2$  is the rarer medium

so  $n_1$  is larger than  $n_2$  and therefore  $n_2/n_1$  is less than one therefore when you write  $\sin i_2$  by  $\sin r_2$  equal to a quantity which is less than one obviously  $r_2$  is larger than  $i_2$  now we look at the case of  $i_3$  that is the ray which is making an angle of incidence  $i_3$  then  $\sin i_3$  by  $\sin r_3$  is also equal to  $n_2/n_1$  but  $r_3$  is 90 degree here  $r_3$  because the transmitted ray or the refracted ray is grazing along the interface therefore  $r_3$  is 90 degree which implies  $\sin i_3$  is equal to  $n_2/n_1$  because  $\sin r_3$  is 1 and therefore  $\sin i_3$  is equal to  $n_2/n_1$  which is of course less than one what would happen if the angle of incidence is increased beyond  $i_3$  that is if  $i_1$  have another angle  $i_4$  which is greater than  $i_3$  what would be the outcome let us see

so so here it is for angle  $i_4$  which is greater than  $i_3$  here  $i_1$  have not drawn  $i_1$   $i_2$  those rays  $i_1$  have shown the ray which is making an angle  $i_3$  here where the transmitted ray or the refracted ray is grazing along the interface now  $i_1$  am considering the next ray that is array which is making a larger angle  $i_4$  larger than  $i_3$  what would happen

so  $i_1$  have shown the reflected light here the reflected light is there always but  $i_1$  have not shown the transmitted light what would happen

so let us look at the mathematics snell's law says  $\sin i_4$  by  $\sin r_4$  must be equal to  $n_2/n_1$  but  $\sin i_4$  is greater than  $\sin i_3$  because  $i_4$  angle here is larger than  $i_3$  therefore  $\sin i_4$  is greater than  $\sin i_3$  equal to  $n_2/n_1$  but  $n_2/n_1$  is less than one and therefore  $\sin r_4$  must be greater than  $\sin r_3$  which is equal to one this implies  $\sin r_4$

$r_4$  must be greater than one please see this  $\sin i_4$  is greater than  $\sin i_3$  and  $\sin i_3$  is equal to  $n_2/n_1$  that is the right hand side and therefore if this quantity has to be less than 1 if this ratio has to be less than 1  $\sin r_4$  must be greater than  $\sin i_4$  and that implies  $\sin r_4$  must be greater than 1 this is not possible for any real angle  $r_4$  since the maximum value is one for ninety degree and therefore  $\sin r_4$  greater than one is not possible for any real angle  $r_4$  that implies there is no refracted ray possible while reflection is always possible no refracted ray is possible because there is no real angle  $r_4$  which can satisfy this and therefore the entire incident light energy is reflected back into the first medium that is why I have not shown any refracted ray because no refracted ray is possible for all angles below  $i_4$  there is a reflected ray and a refracted ray as we have seen earlier there is a reflected ray and refracted ray for  $i_2 < i_1$  and

so on but when for an angle  $i_4$  which is greater than  $i_3$  where the refracted ray was grazing along the interface we do not have any refracted ray and therefore the entire energy has to be reflected back and this is called total internal reflection  $\sin i_3$  was equal to  $n_2/n_1$  we have seen in the last sheet that  $\sin i_3$  was

so here  $\sin i_3$  by  $\sin r_3$  was  $n_2/n_1$

so  $\sin i_3$  was equal to  $n_2/n_1$  which is  $n_2$  by  $n_1$  and therefore we have  $\sin i_3$  is equal to  $n_2/n_1$  and the angle  $i_3$  for which the refracted ray is grazing along the interface is called the critical angle it is called the critical angle because for any angle larger than that there will be no refracted ray and the entire energy or entire light energy is reflected back into the medium whereas below this angle below for angle smaller than  $i_3$  we have both the reflected ray and the refracted ray and therefore this  $i_3$  is a critical angle a threshold angle below which refraction is possible above which refraction is not possible and that is why this angle is denoted by  $i_c$  called the critical angle and therefore  $i_c$  is equal to  $\sin^{-1}(n_2/n_1)$   $i_c$  is nothing but  $i_3$  in this case

so  $i_3$  is equal to  $\sin^{-1}(n_2/n_1)$  but that angle is identified as the critical angle and therefore the critical angle is given by  $\sin^{-1}(n_2/n_1)$  ok let us go further the critical angle  $i_c$  therefore this was  $i_3$  in my first figure  $\sin i_c$  is equal to  $n_2/n_1$  which is equal to  $n_2/n_1$  and therefore  $i_c$  is equal to  $\sin^{-1}(n_2/n_1)$  with of course  $n_2 < n_1$

so typical values of  $i_c$  for the medium air interface we have a medium and the other side air

so this way the medium air interface is given by  $i_c$  is equal to  $\sin^{-1}(1/n_2)$  because  $n_{\text{air}} = 1$   $n_2$  is an air which is 1 and therefore  $i_c$  is  $\sin^{-1}(1/n_2)$  by the refractive index of the medium

so I have taken three different values here

so three different media crown glass water and diamond

so for crown glass the refractive index is 1.52

approximately glass is a very generic word and even within crown glass there are different different varieties with the different refractive index but this is a typical value of crown refractive index of crown glass the corresponding  $i_c$  calculated from here is approximately 41 degrees for water with refractive index 1.33

the critical angle is 48.

degrees and for diamond with the refractive index of 2.42

the critical angle is 24.

degrees what we observe is that as the refractive index of the medium that is the denser medium increases the critical angle decreases we can see from here as

the refractive index increases the critical angle decreases for smaller values of  $n$  two one the critical angle will be smaller let's see a couple of examples here first let me take out the reflection by a prism

so what i have shown here is a 90 degree prism with its an isosceles prism with 45 degree and 45 degree angles here a laser beam which is entering from here laser beam that is entering will subtend an angle of 45 degree here because a laser beam entering normally this angle is 90 degree and therefore this angle has to be 45 degree this is 45 degree and therefore this angle of incidence is greater than the critical angle critical angle we just calculated it was 41 degree and the angle of incidence  $i$  is 45 degree therefore  $i$  is greater than  $i_c$  this implies the beam will have to go undergo total internal reflection

so there is the beam undergoing total internal reflection and this is now deflected into 90 degree angle that is the direction of the beam has changed if we keep the prism in this way then we see that the incident angle is again 45 degree here this is 90 degree therefore light gets transmitted of course there is a small fraction which is getting reflected here but we are looking at the transmitted light most of the light is transmitted a small fraction is reflected it undergoes total internal reflection therefore again the angle here is 45 degree therefore it undergoes total internal reflection here and the beam is reversed in direction

so it has come like this and now it is reflected back along the same direction that is why it is also called retro reflectors retro reflectors

so these are used widely in various applications

so i will just show you the prism and we will discuss about this a little later so here is the prism

so let me keep the prism here

so we can see i hope will be able to see like this

so it has two reflecting surfaces one here and one here and the third one here along the hypotenuse

so in the first example i launched the laser beam along this direction and the beam would come in this direction and if we launch the laser beam like this that is along this direction it would undergo total internal reflection at this point and again undergo total internal reflection and come back along this direction there are various applications of these beam deflectors because many times the laser cannot be moved laser is ah fixed at a particular location particularly ah higher power lasers and then you have to deflect the beam to another direction to perform maybe another experiment and then we easily use such prisms to deflect the beam in the required direction of course one could use mirrors but all mirrors have a finite amount of loss therefore the reflected light gets lost somewhat and a fraction only is reflected back whereas using this prism we are having 90 degree reflection but it is total internal reflection therefore the entire beam is reflected back that is why people use such prisms for deflecting beams rather than mirrors ok let us go further lets extend the example further now to a slab internal reflection in a glass slab

so i have taken this glass slab here

so this is the glass slab earlier we discussed internal reflection at one interface now basically i have added one more interface therefore this is a denser medium glass light is now not entering i am not considering the case of light entering from here because if light enters from here it will pass through with a small lateral shift but we are looking at light entering from the edge of the glass slab

so this is the glass slab and light is entering from one of the edges

so look at the rays one two three i marked one two three the ray one which enters from here bends towards the normal because this is air this is glass

therefore it undergoes partial reflection

so it bends towards the normal

so the refracted ray comes here if the angle of incidence here is greater than the critical angle it will get totally internally reflected because on the other side there is air

so glass air interface and therefore total internal reflection can take place here total internal reflection cannot take place because it is rarer medium to denser medium that is external reflection whereas this is internal reflection similarly if i look at a slightly i am increasing the angle of incidence

so this was the angle of incidence now if i increase the angle of incidence look at the ray 2 it also bends towards the normal however now it is subtending slightly larger angle  $i_2$  smaller angle compared to  $i_3$  here  $i_2$  is smaller but if  $i_2$  is greater than the critical angle then it will also undergo total internal reflection and if it subtends an angle  $i_2$  here it will also subtend an angle  $i_2$  and it will undergo total internal reflection because these are two parallel lines and therefore if this is  $i_2$  then this will also be  $i_2$  which means if it undergoes total internal reflection here it will also undergo total internal reflection here and the light will get transmitted inside the slab if we look at the ray 3 which is now coming at a larger angle of course the ray bends towards the normal but now it is incident at an angle  $i_1$  it is shown here  $i_1$  this angle angle of incidence is such that  $i_1$  is smaller than the critical angle then a part of the light will be refracted i have shown it as 3 dash ray 3 entering here and it is three dash is the refracted light and it also gets reflected

so a part of the light is getting reflected it will subtend the same angle  $i_1$  which is less than the critical angle therefore again a part will be transmitted or refracted and a part will be reflected

so it will undergo reflection partial reflections at every interface and at every interface it will lose a part of the energy a part of the energy and the remaining part proceeds further whereas ray 1 and 2 do not lose any energy when it undergoes reflection and therefore they get trapped inside the slab that is what is being written here  $i_1$  is less than  $i_c$  for glass air interface undergoes partial reflection while  $i_2$  comma  $i_3$  are greater than  $i_c$  which undergo total internal reflection all rays like 1 2 for which  $i$  is greater than  $i_c$  at the glass air interface propagate totally inside the glass slab this is the principle of light propagation in optical fibers

so we will see optical fibers what are optical fibers this is our next topic so optical fiber here

so an optical fiber comprises of two cylinders here that is a central core surrounded by a cladding both are glass cylinders which are fused into one another they are not separable its not a hollow core this this is also glass this is also glass which are fused one into another and the refractive index of the core here is greater than refractive index of the outer medium which is the cladding cladding is something which is covering

so that is why it is called cladding the refractive index  $n_{\text{core}}$  is greater than  $n_{\text{clad}}$  typical dimensions are given

so the dimension of the core is typically 50 micrometer and the cladding diameter is approximately 125 micrometer for standard fibers there are different types of fibers which are used and they will have different dimensions different refractive indexes but in general the material used particularly for communication fibers the material used is core is of doped silica glass silica is  $\text{SiO}_2$  or fused quartz doped silica glass and typical refractive index of about 1.48

and the cladding comprises of pure silica glass and the refractive index is

approximately 1.

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so light propagates by total internal reflection at the core cladding interface

so what i have shown here is a longitudinal section of this fiber

so a section here longitudinal section

so this is the end phase here

so light input undergoes total internal reflection along its length at the core cladding interface and therefore light gets trapped obviously if i launch light at a larger angle here the incident angle then a  $\theta_i$  it may not be able to meet the condition for total internal reflection at this interface in this case a part of the light will go out that is will refract out and only a part of the light will get transmitted

so there is a range of angles a range of angles  $\theta_i$  can show here a range of angles

so i can show a range of angles for which light gets trapped

so it forms a cone like this here and light gets trapped inside

so lets there are large number of applications of optical fibers and i have just listed a few of the applications here applications of optical fibers

optical fiber the most important application which we are all familiar is the optical fiber communication as a transmission medium for multi gigabit signals audio video telephony conversations in all major cities and major cities are now linked by optical fibers and each fiber able to carry is able to carry gigabits of information and that is the primary main application of optical fibers and there are many other applications optical fiber sensors for a variety of sensors for industrial and scientific applications optical fiber lasers to develop high power laser sources high power sources high power optical sources for industrial and military applications and endoscopy which is one of the earliest applications of optical fibers as a fiber guide or a tube for image transmission image transmission these are fiber guides used to observe internal parts of the body and that is called endoscopy and of course there are large number of applications i have not listed here ah each one of the application is a very important technology now

so here i have a laser and a prism and i just want to demonstrate to you the retro reflector see if i switch on the laser here we can see the beam is completely getting reflected back here because its undergoing total internal reflection at both the interfaces that is here as well as here and this is the principle of a retro reflector we can see here that its following exactly the same path this is the input beam which i have blocked now and this is the reflected beam and there is no output light here there is no laser beam on both the sides here however if i change the angle of incidence

so that the angle of incidence is

so we can see

so it is continuously reflecting now i am changing the angle of incidence

so that it does not meet the condition then immediately you see the light reflected light has dropped down and there is transmitted light which is here the transmitted light coming from the other side

so we have refracted light as well as the reflected light both of them however if i bring it here such that the angle of incidence is 45 degree this is an isosceles triangle then all the light is reflected there is no light on the other side i can also demonstrate this here that is the beam deflector

so i keep it here actually the prism is a little bit bigger size of bigger size but we can see here clearly that here it is and the reflected line is here and the incident beam is completely deflected at 90 degrees there is nothing on the other side we can see here there is no beam entire energy is reflected because

the ray enters from here the beam enters from the input end and it undergoes total internal reflection at this end and comes out as shown in this diagram i also want to briefly show you the optical fiber

so here is an optical fiber for those of you who have not seen an optical fiber maybe you will see this as a shining medium here and you can see this is an optical fiber and i can try to couple light into one end and see whether we can get some output at the other end

so what i am trying to do is i am keeping the prism as a paper weight do not look at the prism i am now trying to launch light from the other end let me just give it a try and if light enters the fiber then we should see a brighter spot at this end

so let me try this

so at some point when i am able to launch light you see suddenly a bright light which is coming there because i do not have an arrangement to hold it in position and therefore only when in some positions you can see that it looks bright because light enters through the fiber as at a certain position and we are able to see at the other end

so what you see is light coming from the other end of the fiber yeah

so there it is and let us continue now further let me now come to a naturally occurring phenomena a naturally occurring phenomena where we observe mirage

so what is a mirage mirage an optical illusion

so first i have shown here what is a mirage for those of you are not familiar when a person is walking through plains or desert or even walking or driving along a straight road such as highway on a hot sunny day he observes mirage he could observe mirage depending on his position

so what i have illustrated here is a tree a distant tree here is a person who is walking here is a distant tree the person observes a virtual image of the tree because of a phenomena called mirage

so how does he observe this we will discuss this in detail in the next slide but first

so he observes a virtual image and therefore he thinks probably there is water or some reflecting medium here on his way

so obviously on the way there may not be any mirror or anything

so he it appears as if there is a water body because of which he is observing the image of this tree but actually there is no water what is happening is a phenomena which we call mirage

so i have briefly shown here what is happening is the rays which come out or rays which start from the object take a curved path and it gives an illusion or it gives a feeling of apparent position of the tree which is here

so because the ray follow a curved path and they enter the eye from below after curving like this the person feels as if the rays are coming from here

so its like a virtual ray entering his eye

so its as if they are coming from here and therefore he sees a virtual image of the object

so why does the ray bend here because on a hot day the surface of the earth becomes very hot the air becomes hot the air in contact with the surface of the earth becomes hot and of course it rises up because of convection and the colder air comes down and after sometime there is a kind of temperature distribution here and we have hot air very close to the surface a little less hotter air a little less above a little above and a little lesser ah hot air above and

so on

so i will discuss this in more detail and this leads to a refractive index gradient and therefore the ray paths start curving

so i will explain this in the next slide on

so let's first look at ray paths in a graded index medium. I have taken two media uniform media which means uniform refractive index which means the refractive index is constant everywhere in such media ray paths are straight lines. Point P here let us say this is the source point from which rays are travelling and rays are emanated.

so the rays travel in straight lines in a uniform media. What would happen if the source is now in a graded index media graded refractive index media or graded index medium what I have shown here is the refractive index variation.

so this is  $n$  of  $y$  refractive index as a function of  $y$ .  $y$  is the depth here so as we come down the refractive index decreases.

so in this medium in this medium refractive index was constant everywhere in this medium refractive index is maximum here and as we come down the refractive index drops down refractive index comes down and such a medium is called graded index media. The consequence of this is a ray which is emanated from the point P starts curving starts bending or the ray paths are curved in such a graded index media.

so we can understand this here.

so here in another diagram what I have shown is the refractive index is highest here it is reducing continuously as we go down see this refractive index is maximum here near the surface and then it is continuously dropping down.

so if we consider this medium to be stratified if we imagine this to comprise of number of layers number of uniform layers that is each layer we can consider to be of uniform refractive index but this layer is of higher index compared to this layer and this layer is of lower index compared to the refractive index of this medium what would happen we can show that a ray which is entering here it satisfies the Snell's law.

so it bends away from the normal because this medium is of lower refractive index again it bends away from the normal.

so this we have shown piecewise continuous straight lines piecewise continuous straight lines because these media each one of them is of uniform refractive index but the refractive index of a lower layer is smaller compared to the refractive index of a higher layer a layer which is here and therefore at every interface the ray bends away from the normal.

so if we now look at the overall ray path it has bend it is not a straight line path but it has curved like this keeping this in mind now we look back at the formation of mirage again.

so I briefly explained earlier now let us look back keeping with keeping this idea in mind.

so let's see I have now shown an object like this like a lighthouse here the observer is at a distance this is the earth and this is the atmosphere it's a hot sunny day therefore if we look at the air temperature it is hottest closest to the earth surface and then reduces.

so I have written this as warm warmer hot hottest the refractive index reduces as temperature increases cold air has a higher refractive index compared to hot air and therefore the refractive index here  $n$  as temperature increases refractive index decreases therefore the refractive index  $n$  of this medium is a function of temperature which means the refractive index here is lower is higher compared to the refractive index here because this is hotter and therefore refractive index is lower this is hotter compared to this and therefore the refractive index is lower.

so essentially I have a graded index medium with the highest refractive index here and refractive index dropping as I go below and I have picked up three points from the object.

so a ray 3 ray 2 and ray 1 starting from different points on the object.

so this is the object like a lighthouse seal for example the ray which travels from here travels it is travelling at an angle and therefore it is continuously bending towards higher refractive index and it comes here a ray which is travelling from here is going from higher refractive index to lower refractive index higher to lower and therefore it continuously bends away from the normal instead of going straight like this it bends away from the normal and finally it comes here to the observer now the observer sees as if the rays are coming from somewhere here because the ray which was coming like this is now entering his eye from below and therefore he looks at the object as if the object is here consequently he sees a virtual image because of the bending of rays there is no reflection there are no mirrors here but because of the bending of the rays the apparent position of the object the observer sees the apparent position of the object to be here which is like having a reflection

so if i had a mirror here then rays would have come here and it would have reflected back for example on the road if i instead of the road

so the observer is here if this were to be a mirror and if i had the object here

so i am trying to draw the same object here then if this is an object point ray which comes here would have reflected and gone to his eyes here then he would have seen that this as if the ray has come from a point here if i pick up another ray then this ray would hit some point and would get reflected and here and he would see as if the point is here the object point this is the object point this is another object point but they are now visible here if this was a mirror but these are all straight line paths now we do not have a mirror but we have a graded index medium

so the ray bends and enters his eye from below and this gives the same feeling as if he is seeing an image which is here and therefore it gives an it gives a feeling to the observer as if on the road there is some reflecting surface or such as water and that is why it is called a mirage mirage because there is no water but it gives a feeling to the observer as if there is water and as he goes closer and closer the water body the apparent water body moves away from him because actually there is no water

so this is the formation of image mirage using two concepts we have used one curved ray paths in a graded index media and apparent position of an object because it comes like this however please see that if the observer raises his head and looks at the tower here he will not see a mirage he will be directly able to see the object here if he looks is looks up and looks at the object he will be able to see the tree or the cloud but if he is looking down then he will also be able to see the image of the clouds or the tree because of the mirage let us take some examples now and make our concepts a bit more clearer

so first i have picked up an exercise here from the textbook at what angle at what angle should array of light be incident on the face of a prism of refracting angle  $60^\circ$

so that it just suffers total internal reflection just suffers total internal reflection at the other face the refractive index of the material of the prism is given 1.

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so i have here drawn the figure and try to explain this

so that we can comprehend the problem

so a ray of light is entering from here at a certain angle i it gets refracted into the prism and if the question is what is this i if there is refraction taking place at the other interface such that it is undergoing total internal reflection just just means our angle of incidence here is critical angle when this is critical angle the refracted ray will graze through the interface if i

were to take another ray here a deeper ray which is incident like this then it would have gone here like this and obviously it would not meet the ic and this would come here

so if  $i$  increase if  $i$  decrease this  $i$

so this was for a larger angle of incidence if  $i$  decrease this  $i$  then the refracted ray comes here and at one stage this angle here would be large enough so that it undergoes total internal reflection any further if  $i$  had reduced the angle here to a smaller value then it would have hit here

so let me show you the if  $i$  had taken let me take another ray if  $i$  had taken a ray here then it would have come here at a different angle and this would have undergone total internal reflection there would have been no refracted ray

so the question here is what is this angle  $i$

so that please look at the blue line only blue-ray

so that the refracted ray is just grazing the other surface

so identify

so what needs to be identified

so let me work this out

so let us work out the solution here

so solution

so let me draw the prism here

so what is given is this angle is  $60^\circ$   $60^\circ$

so we have a ray which is incident let me use a different color like this this is undergoing refraction and then this is grazing through this surface

so if  $i$  show the normals here  $i$  am drawing the same diagram again these are the normals then we have this is  $i$  let me show this this is the angle of incident  $i$  which we have to find out and what is the data that we have

so this there are two refracting angles here

so let me call this one as  $r_1$  and this angle here as  $r_2$   $r_1$  and  $r_2$  and let me draw this angle here as  $\theta_1$  and this angle  $\theta_2$   $\theta_2$

so look at the diagram here  $i$  hope the diagram is clear

so we can if required we can draw a bigger diagram

so here let me show a fresh a little bit bigger and grazing like this

so this is  $60^\circ$

so  $i$  have called this as  $\theta_1$  this is  $\theta_1$  this is  $r_1$  the refracted angle this is  $i$  and this is  $r_2$  because this will become the incident angle and this as  $\theta_2$

so lets look at the first it is given that it is just undergoing total internal reflection which means  $r_2$  is the critical angle this is the main point to be identified  $r_2$  is the critical angle critical angle for glass air interface

so critical angle refractive index is given 1.

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so it is here

so we have 1 outside it is 1 therefore 1 divided by 1.

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so if you calculate this this will come out to be  $41^\circ$  because we have already seen that the critical angle is about  $41^\circ$

so this is  $41^\circ$  actually forty one point some zero zero something like that

so we have got  $r_2$  once we know  $r_2$  we can find out  $\theta_2$  because  $\theta_2$  now is equal to  $90^\circ$  minus  $r_2$  which is equal to  $90^\circ$  minus  $49^\circ$   $41^\circ$  which is equal to  $49^\circ$   $49^\circ$  if we know  $\theta_2$  we know  $\theta_1$  because  $60^\circ$  is the angle is given therefore  $\theta_1$  is equal to

so it is  $180^\circ$  minus  $60^\circ$  minus  $49^\circ$  and therefore this is equal to

so  $180^\circ$  minus  $60^\circ$  minus  $41^\circ$

so this is  $120 - 49$  and therefore it is  $71$  degrees once we know  $\theta_1$  we know what is  $r_1$  because this is  $90$  degree this normal and therefore  $i$  is equal to  $90 - \theta_1$  which is equal to  $19$  degree

so we have got  $19$  degrees we have got  $r_1$  how to get  $i$  simply apply snell's law and therefore

so let me continue here in the sheet and therefore  $\sin i$  by  $\sin r_1$  is equal to  $n_2$  by  $n_1$

so one point five two four divided by one we know  $r_1$   $r_1$  is ninety degree therefore  $i$  is equal to  $\sin^{-1}$  i have taken this to the other side and then inverse of this

so  $\sin^{-1}$  of  $\sin r_1$

so this  $i$  had taken here  $\sin r_1$  into  $1$ .

524

so this is equal to  $\sin^{-1}$  of  $\sin 90$  degree  $\sin 19$  degree into  $1$ .

524

so this will come out to be  $29$ .

75 degrees

so this was the angle that was asked to find out

so we see here

so what is this angle

so what we have done we have used two concepts here one total internal reflection here and snell's law here we have applied a total internal reflection and snell's law using these two concepts we can solve this and get the angle  $i$  such that it is grazing along the second interface let me take a second example now and this time let me take an example on optical fiber

so here given that the refractive index of the core of an optical fiber yeah the refractive index of the core of an optical fiber is four eight i just use this number earlier and that of the cladding is one point four six what is the maximum angle of incidence of rays angle with the axis of the fiber at the input that is at the input end of the fiber the maximum angle with the axis for which they are guided through the fiber the question is to determine what is the maximum angle for which the rays inside are guided if we launch a ray along the axis it will anyhow get into the fiber because it is normally incidence angle is zero if you increase this angle then it will start bending here and therefore one has to note down

so let me draw the cross section and show you this more carefully let me take a longitudinal section here and show this ah more carefully

so what is the data which is given

so we have here is the optical fiber

so is given that refractive index is  $1.48$

$1.46$  four eight and one point four six because this is the outer layer which is the cladding and this is the core layer

so here is the fiber axis

so this is the fiber axis array which is incident here

so we are looking for array let me use a different red color for this

so array which undergoes just total internal reflection it is bending towards normal because outside it is air

so we have air here and outside it is a therefore this ray is bending towards normal and it is just undergoing total internal reflection which means this is grazing along this in other words if i take another ray which is coming here

so this is this is the angle  $i_{\max}$  that we need to find out

so this is  $i$  or  $i_{\max}$  why do i say that that is  $i_{\max}$  because if i take array here then that is the second ray that will bend closer because that's at a smaller angle and therefore obviously for if this is the this is the critical

angle

so here i have the critical angle

so let me show the normal at this point then this angle here is the critical angle a ray which is travelling like this will obviously make an angle which is more than the critical angle here and therefore it will get totally internally reflected this is just like the diagram that i had already shown the diagram which i had shown earlier with when i discussed about optical fibers

so let me just place that diagram to make it more clear

so here here

so array which is incident at a deeper angle would undergo partial reflection whereas rays which are coming at shallower angles would meet the condition of total internal reflection

so the question is asking about the  $i_{max}$  for which there is graded grazing in grazing the refracted ray is grazing along the interface

so this angle must be equal to this angle here must be equal to  $i_c$  or the critical angle

so if we focus at this point

so let me draw that again just this point if i zoom that point

so here is the ray which is incident and this is grazing and here is the normal and this is  $i_c$  and corresponding to this i have an  $i_{max}$  here

so we know the refractive index here 1.

46 1.

48 and therefore we can determine what is  $i_c$

so  $i_c$  is equal to sine inverse of 1.

46 by 1.

48

so this will come out to be i think 80 point some number which uh 80.

57

so 80.

57 degrees

so the angle i see here is 80.

57 if this is the angle i see then we can determine what is the refracted angle

so this if i show this as my input input then i can determine the refracted angle here

so this is  $r$  this was  $i_c$  which is 80.

57 and therefore the refracted angle at the input corresponding to this  $i_{max}$  here is  $r$  is equal to 90 minus 80.

57 which is equal to 9.

43 9.

43 degree once i know  $r$  i can determine the  $i_{max}$  angle which is coming here

so this is  $i_{max}$  the angle  $i_{max}$  here we simply apply snell's law for this interface i know this  $r$  and therefore i can determine  $i_{max}$

so  $i_{max}$  will be equal to

so let me show here therefore  $\sin i_{max}$  by  $\sin r$  is equal to  $n_2$  by  $n_1$

so let me write here  $\sin i_{max}$  divided by  $\sin r$  is equal to  $i_{max}$  is equal to one point four eight  $n_2$  by  $n_1$  this is  $n_2$  is  $n_1$  this outside it is air 1.

0 and 1.

48 and therefore it is 1.

48 divided by 1.

0 and therefore  $i_{max}$  is equal to sine inverse this goes there

so sine inverse of  $\sin r$   $r$  is 9.

43 degrees

so 9.

43 degrees multiplied by one point four eight

so sine of nine point four three multiplied by one point eight  
so we should get this as about fourteen degree for fourteen point zero three  
degrees one can work out many problems and ah i will stop here and i encourage  
you to work out as many problems as possible thank you you

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