Fiber - Optic Communication Systems and Techniques

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Lecture - 11
Introduction to optical fibers

Hello and welcome to NPTEL MOOC on Fibre Optic Communication Systems and Techniques. In this module we begin are study of optical fibers, which continuous for a few more modules, because we want to really understand, how light is guided by the optical fiber and what kind of impairments does this fiber impose on the information that is travelling in the fiber.

So, we need to understand to answer this questions we need to first understand the geometry of the optical fiber, perhaps also look at different types of optical fibers not all optical fibers are used for communication, some optical fibers are used for sensors, some of them are used for biomedical imaging applications, some of them are used you know just for entertainment purposes, you take a bundle of optical fibers, then send light maybe you know just cut them off and make a lamp kind of a thing.

So, it is possible for optical fibers to be used for various applications, but since this is the communication course our main goal will be towards looking at those fibers and, their properties which are essential for communication purposes only. So, broadly we can classify this optical fibers as you know at least in the communication perspective, we normally classify them as single mode fibers and multimode fibers. Now, strictly speaking this classification should be there for I mean should be associated also with the specific wavelength range for example, a same fiber, which may be single moded, or single mode fiber for a certain range of wavelengths can become multimode for a different set of wavelengths however, in communication we do have specific wavelengths, or wavelength bands over which we communicate.

So, when we say it is a single mode fiber at 15 50 nanometre, which is the most popular you know band of communication wavelength band of communication something that we are going to study deeeply later on, then it is kind of understood that when we say single moded fiber, then it is used for or it is assume that for long distance communication it is being single moded, in the wavelength band of around 15 20 nanometre of course, you do get multimode fibers in that same wavelength or in a different wavelength region.

So, what exactly the single mode fiber and a multimode fiber are they same in terms of their construction, actually know their construction slightly differs and it is in fact, this construction, which gives it is you know property of whether it is single moded, or multimoded. To understand that we need to go back to our slab waveguide you know discussion, that we had in the previous module, where we said that when you have you know a slab waveguide, there are different modes that are possible and we actually talked about the even symmetric t modes and then there is or symmetric t modes right.

So, we talked about those modes and then decide that when the mode number nu which we were using, when that nu is equal to 0 you get essentially a single t mode and, then as that parameter kappa f times h, where h was the film thickness that we you talked about in the last module. As this parameter kappa f, which is the transverse wave number times this film thickness as it increased beyond a certain value, then the waveguide was now able to support not only the fundamental t e 0 and t m 0 modes, but it is also able to support the next higher order mode t e one or t m one.

So, we could of course, make it single moded slab waveguide by restricting the product kappa f into h, or more prominently by playing around with the film thickness for a given wavelength ok, because all this qualities are wavelength dependent kappa f depends on wavelength, everything depends on wavelength of course, h does not really but there is a specific relationship between h and lambda that we looked at in the previous ah module, which tells us that if I want to restrict my waveguide for a single moded operation, then I need to ensure that h does not exceed a certain critical value. The same kind of idea goes even with optical fiber so, once you fix lambda, then in order to make it single moded you have to adjust the core a core radius of the fiber ok.

So, we will look at that what happens when you change the core radius while keeping all the other parameters same, or when you have all the fibers manufactured what happens, when you change lambda. All these quantities are actually captured by what is called as V number of the fiber ok.

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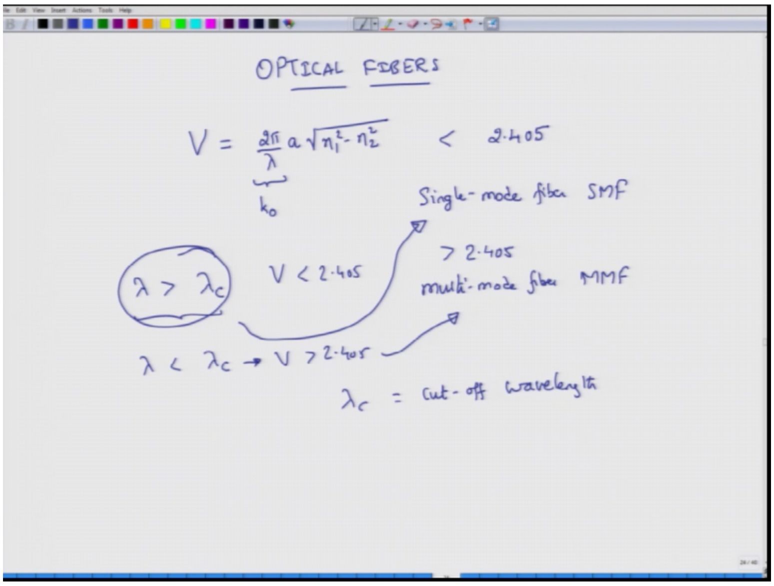

So, I am go to describe this V number now and then we will derive all this V number and other parameters, that I am going to talk about in this module in the coming modules ok, here in this module we are going to look at the high level you know characteristics of or a birds eye view of an optical fiber of optical fibers, but we need certain parameters I am basically going to write them down do not, worry if you do not understand this parameters right away, the understanding comes in the later modules ok.

So, anyway so this V number which is a very critical parameter in optical fibers is defined as 2 pi by lambda, where lambda is measured in free space, that is it is measured in not in the material medium which is made out of optical fibers, but it is measured in the free space. So, you have 2 pi by lambda of course, you do remember the this 2 pi by lambda is the free space wave number of a plane wave that we were considering so, that is represented by k 0, times a where a is now the core radius times square root of n 1 square minus n 2 square, where n 1 is the maximum refractive index in the core n 2 is the maximum refractive index in the cladding ok. So, we will talk about what is the core what is the cladding shortly, but this parameter essentially governs whether my fiber is single moded or multimoded.

So, when this parameter is less than this value 2.405 ok, then the fiber will be a single moded fiber, or single mode fibre, we shorten this as SMF and, there is a standardized version of this SMF that is used a communication industry that is called as standard single mode fiber ok.

That is specified by certain standard so; g 656 is the standard that specifies the properties of the single mode fiber that is used for long distance communication purposes. Now, when this V number exceeds 2.405 ok, which can happen in what is called as multimoded fibers, or simply multimode fibers ok.

So, this is shortened or abbreviated as MMF, M stands for multi, then M stands for mode and F stands for multimode fiber ok. Now, fiber which has a single mode fiber for a certain wavelength lambda, if I start reducing that lambda value then clearly the value of V increases, because V is inversely proportional to lambda ok.

So, there is a certain lowest possible value of lambda which we call as lambda c, if the wavelength lambda is greater than lambda c, then and for which V is less than 2.405, then over this wavelength region then the fiber will be single moded, or it will be a single mode fiber. However, when lambda becomes less than lambda c ok, we automatically becomes greater than 2.404 this causes value of V to increase and, if V increases beyond 2.405, then this fiber becomes multimode fiber.

So, it is possible for the same fiber to become single moded fiber over a certain wavelength region ok, beyond what is called as lambda c right. So, beyond lambda c for all those wavelengths if the fiber you know is ensure that it is single moded at lambda c, then for every lambda that is greater than lambda c the fiber will remain single moded however, if you reduce the wavelength lambda, then the fiber will not be single moded it becomes multi moded, because V is inversely proportional to lambda.

And this magical value of lambda c which is the design parameter that you can choose of course, you cannot fabricate it you have to go to a optical fiber manufacturing plant, to get this optical fiber with whatever magical lambda c that, you want but this lambda c in optical fiber communication systems, or optical fiber system is called as the cut off wavelength ok. It means that for all lambda greater than lambda c, then the fiber will be single mode fiber and when lambda is less than lambda c, then the fiber will become multimode fiber ok.

Now, let us look at we have already seen the picture of optical fiber, but for our purposes and understanding of how light propagates inside the fiber this simplified picture might be sufficient.

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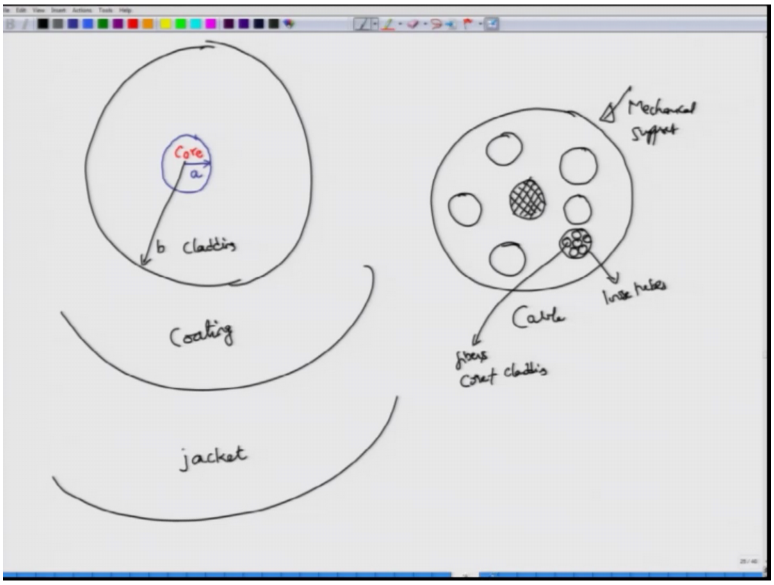

So, we have every fiber with having a normally circular cross section ok. So, this circular cross section has an inner radius of a this is actually a rod ok. So, except that these roads are not big once that you can imagine, but they are very very thin wire like structures, as I have shown you in the introductory class. So, in case you have forgotten how an optical fiber looks it is perhaps better to go to the intro video and, then look at how the optical fiber actually looks in a practical version of it right.

So, you have a core refractor I mean you have a core of an optical fiber, with radius of a ok, I will tell you the typical parameters of this core radius shortly, surrounding this core is what you have is called as a cladding ok. So, surrounding the core with a radius of b is what you have a cladding and of course, surrounding the cladding you will have a coating ok, which is an acrylic coating that is just so, that does not get accumulated on the cladding and, then you know cause problems on to the light transmission properties. So, it is essentially a shielding kind of a thing. So, you just put a small coating and you cover this entire coated fiber with what is called as jacket.

So, if this is the single optical fiber that you are selling it to consumers, or customers, then this is a typical fiber that you are going to sell them of course, as I have told you no fiber is in a big telecom industry no fiber is actually lade, individually underground or overhead ok, because that is just not economically feasible to do.

So, so what we actually do is we form multiple fibers into what is called as a cable structure ok, there are various styles of cables that are used so, this is just one style we are going to look at optical cables later on, but each of those circles that have drawn here are not really cores they are actually what are called as loose tubes ok.

So, inside this loose tube you have individual fibers so, these are the individual fibers here this fibers just have a core and a cladding ok, they do not normally go with the coated and this loose tubes are also differently coloured for you know for visual inspection later on, but this is how an optical fiber cable looks like.

As I told you this is not the only cable design there are many designs that are possible and this central member ok, does not really carry anything this is just for a mechanical support around, which you have this particular cable with typically about six of them I probably missed one circle so, I am going to put one circle out there. So, there are about six of them not exactly there actually completely surrounding them, I have not shown it nicely and each of these loose tubes themselves will have about 6 or 7 fibers so, individual fibers.

So, these are the thick cable that are actually lay down underground and, when you see those optical you know, you see those in whenever there is an optical fiber installation will see those the big drums right and this big drums have this black cables. So, these are the cables that are actually bound on the big drum.

And then that drum moves you know some kind of vehicle takes them along and then the cable actually get is laid underground of course, the cable also has additional things to not just been holding the fibers. And also gives all the fibers a mechanical support right, I mean you might lay of fiber cable underground crossing one road to another road, but then you have a concrete road on top of it, where the vehicles actually keep moving, then you know if you just had the fibers below, then this fibers would not be able to take that mechanical stress they would just break.

So, instead of that one if you encapsulate it with thick cables this cables, themselves are encapsulated in bigger cable. So, you do need to take kind of all those issues, because you want the fibers not to break, because you have to use this fibers for communication anyway. As far as mathematical analysis is concerned, if I were to do a complete mathematical analysis of this entire system, which involves the core, cladding, coating, jacket, including their material properties, including their thermal properties, mechanical properties, you know all those things fluid mechanical properties for example, if there is some fluid in between.

So, the entire mathematical model become too big to understand and perhaps not required for a initial course like this of course, there are specialist who sit and work on the entire mathematical models, the reason they work on this mathematical models is to understand the impact of coating thickness say maybe the jacket, whether I can reduce the coating thickness, because it is economically feasible to do. So, should I increase the coating, because maybe I can decrease the mechanic I mean decrease the cost of the fiber, but if the fiber keeps breaking, then my overall cost will actually increase?

So, what is the optimum value of coating which can kind of compromise between how what is the mechanical support, that the fiber requires versus you know how durable that it can be so, all these questions are answered by looking at detail, in detail every property that is possible to study about this optical fiber cables and most fiber manufacturing plants do have specialised people working on all these.

However, the fundamental fact that is used in all these optical fibers is to guide light and this guiding light is not by any arbitrary mechanism, but by this fundamental fact of total internal reflection. And to understand total internal reflection it is perhaps just sufficient for us to look at a simplified optical fiber structure, which consists of just a core and not even the cladding ok, we will assume that the radius is so, large compared to the core that we can kind of think of this cladding as being infinitely larger, you know or infinitely big medium.

So, you essentially have a single rod or a circular rod structure which is the core with all of its properties that are of interest for fiber light guiding and, then surrounded by an infinitely infinite medium of cladding of different material properties ok. There are some sophisticated mathematical techniques which one has to use, if the material properties are completely random, but luckily we do not have random material properties, at least those material properties which are of interest for fiber transmission are essentially the refractive index.

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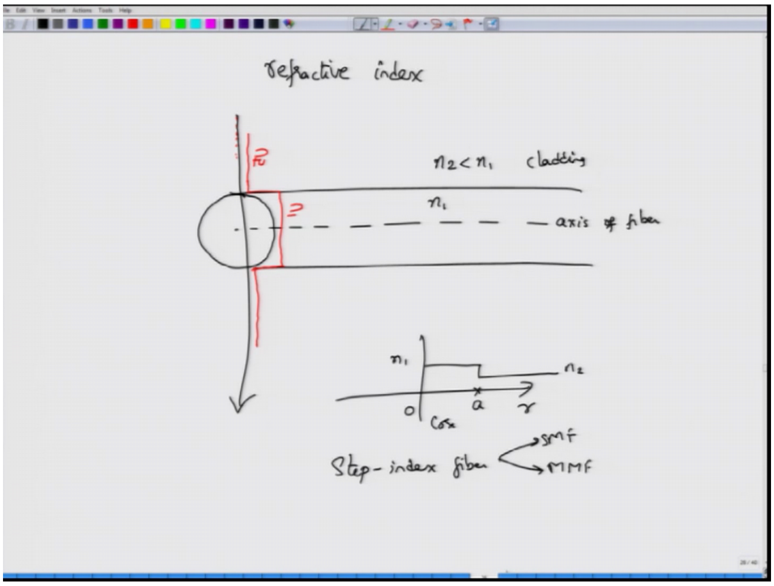

Ok and we make certain assumptions in our analysis just to simplify, it to get the crux of the idea you know, I want to understand how like propagates maybe one or two features that are important for communications, I would like to understand it in as much simple manner as possible of course, the detailed model if I want to know then I can always go for a detailed model ok.

So, the properties that are of interest for understanding light transmission is the refractive index, what kind of a refractive index does the core posses does the cladding posses, remember these are the only two layers that we are going to consider now, is this refractive index in the core can be less than the refractive index in the cladding. If it is less than the refractive index in the cladding will light be propagating inside it.

So, these are the questions that one would like to ask, when look when one looks at light transmission inside the fibers. And as I told you other material properties such as you know the structure of the fiber, or the mechanical properties of the fiber are not important, for the simplified cases that we are going to consider they will be important, at least we will going to discuss one particular case where the fiber is taken and bend it, in that case the mechanical properties what is the mechanical property of the material that the optical fiber is made out of how does it react to stress, how does it react to you know pressure those things will become important later on. For now we just need to know what is the refractive index and, and what is the core radius that may be at most required ok.

So, what we are going to do is to construct, or write a simplified structure of an optical fiber and this circle is essentially the core that, I am considering ok. So, this is the axis of the fiber and as you can see I am going to make certain assumptions, I am go to assume that the entire core has a constant refractive index n 1 where as the cladding outside right.

So, this is the cladding that I have this cladding has a refractive index n 2, which is also constant, but it is less than n 1 ok. So, if I were to match in myself being shunk down to the level of a single micro metre, or maybe nanometre scale person who is driving through this cladding and the core and, plot their corresponding refractive index what I will actually see is that if this is my axis hold on a minute.

So, if this is the axis that I have then the refractive index in the cladding will be about n 2 correct. So, this is n 2 refractive index, but when it comes to the core the refractive index jumps up slightly ok, becomes the core refractive index of n 1 and, then when you go outside it becomes again n 2 ok. So, if I were to plot this in the normal axis way.

So, with r as the parameter you know the radius of this one as the parameter and taking r equal to 0, because you know this is symmetric so, it is sufficient for me to take this as from r equal to 0 so, up to 0 to a the refractive index is actually n 1, because this is in the core region and outside of this the refractive index is n 2 which is of course, less than n 1 ok. This type of a profile where in the refractive index is essentially constant in the core, as well as in the cladding and experiences a sharp step like change, or a step like discontinuity is called as step index fiber ok.

So, again step index fiber can be single moded fibers, or can be multimoded fiber ok, it turns out that while this step index fiber is kind of simple to analyse in fine, it is simpler of the other type of profiles to analyse, this is not the only refractive index profile that is possible and it is in fact, you will find out many different type of profiles.

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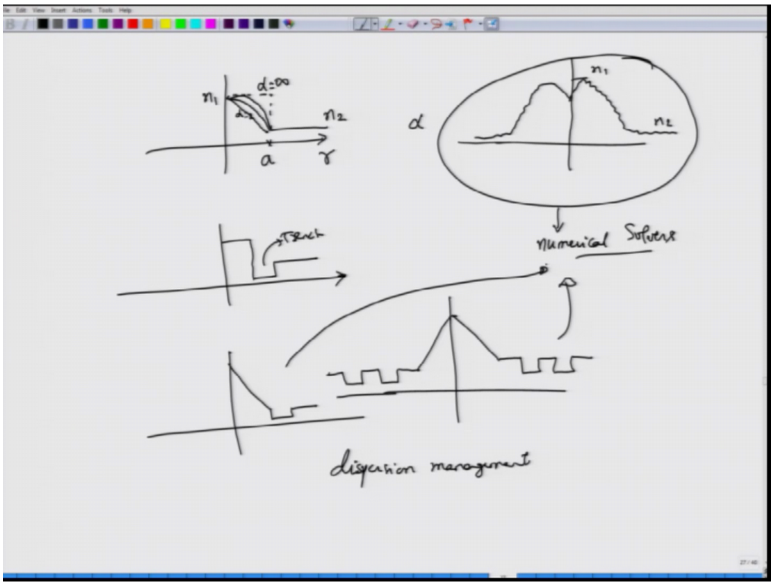

One of the profile that is very popular for eliminating intermoral dispersion in multimode fibers especially, is what is called as a graded index fiber. In this graded index fiber the refractive index of the cladding remains constant at n 2,

Whereas at the centre of the core the refractive index is n 1, but n 1 to n 2 transition does not happen like a step ok, but actually happens more like a graded profile ok, how is this bending this bending curve is characterized by the profile parameter called alpha, this is the usual case for alpha equals 2, and you know for alpha equals infinity you will actually get back to the step index profile you will also have additional types of graded index profiles that are possible by changing the values of alpha.

So, alpha equals 1 will give you the linear profile alpha equal to 2 will give the parabolic profile and, you know different values of alpha eventually alpha equal to infinity will give you the step index profile of course, this alpha is just a mathematical you know convenience that we are going to use, real refractive index profiles do not look anything like this. So, if I were to look at a real refractive index profile, you will actually see something like this ok. So, there is a central dip because of the manufacturing process and so, where it is supposed to be maximum its actually kind of minimum in the core itself.

So, this is n 2 and you can think of this as n 1 of course, this dip is unavoidable as I told you because of the manufacturing problem and, also notice that this is not a the refractive index is not going like a smooth curve, but rather has jacket edges that is because the refractive index profile, despite whatever the you know manufacturing improvements that we have made is not really giving you a smooth profile ok.

Those surface roughness if you go to examine them, would give you a jacket refractive index profile however, to analyse these type of fibers with this kind of complicated refractive index profiles, you cannot really do it with analytical means.

So, what we have to do is to put them on to some kind of a numerical solvers and, what I will do later on will be to tell you how to go about this numerical solutions ok, but I would not be able to show you how to write codes algorithms that will actually help you, solve this type of real world problems ok, for our course it is sufficient for us to consider things to be reasonably simple, but not too simple so, that we obscure the understanding of the fibers ok. Anyway we come back to this. So, this is a graded index fiber in communication you will also find other type of fiber profiles at least the ideal fiber profiles that are used.

So, you have what is called as a trenched fiber the number of trenches. So, this is a trench the number of trenches maybe more than one so, you will have a multiple trenches you will also have fibers, which you know have this kind of a fiber profile ok, you will also have fibers with the refractive index profile which goes something like this, with multiple trenches of course, this is symmetric right. So, I have so far not indicate the symmetry here, but this is just how it would actually look like ok.

So, this complicated refractive index profiles are used for dispersion management ok, again understanding of these with you know using mathematics is kind of difficult for analytical solutions is kind of difficult So, what you normally do is to put them through some numerical solvers ok.

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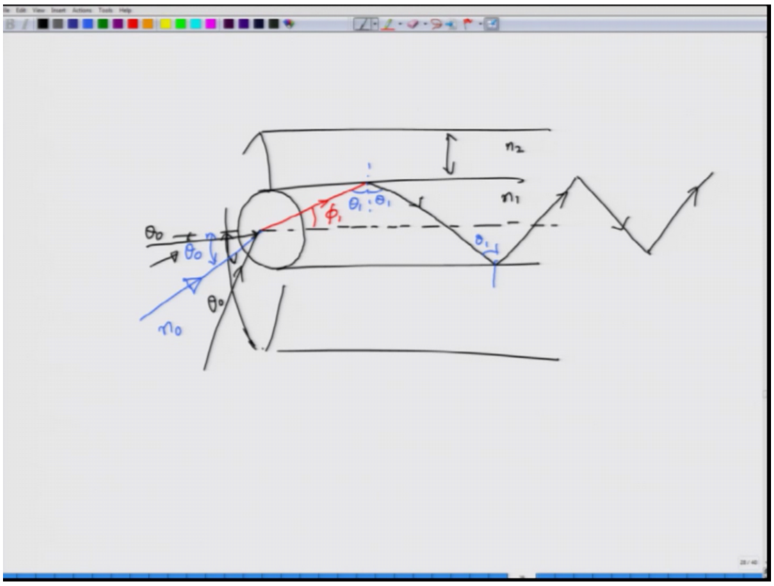

So, these are the different refractive e index profiles of optical fibers that you normally encounter and, what I am going to do as I was telling you is that I am going to look at a basic birds eye view of how light is guided by the fiber ok. And in order to do that it is sufficient for me to just consider.

So, this is the fiber, this is the core, and can also write down the cladding here see please note that this distance is not realistic ok, the core is usually quite smaller the cladding is usually quite a larger in circle, but just for our understanding, if I were to just imagine that this is my optical fiber, because I want to introduce the quantity called acceptance angle ok.

So, this is just the optical fiber with this axis I have exaggerated the core medium over here, what I have is that an incident light usually comes from outside the fiber right.

So, I wanted to indicate that one hence I have no indicated this optical fiber like this ok, this incident ray of light strikes the core cladding interface, you know the face of the optical fiber at an angle of theta 0 outside medium let us call the refractive index as n 0, inside the core has a refractive index of n 1 and the cladding has a refractive index of n 2.

Now, what happens when this ray of light is incident at this angle theta 0, clearly Snell's law will tell me that there will be a reflection into this one or as for a refraction into the medium. So, there will be some amount which is refracted of course, there will be some amount which is reflected, but we do not really worry about that reflected part.

So, the what we are concerned is the amount of light, or the ray of light that is refracted into the cladding now. So, the cladding now this axis is the normal to the interface right. So, the cladding is actually making an angle of let say I will call this as pi ok, maybe if you want I can put this as pi 1 and with respect to core and cladding now, this is the core and cladding correct, this ray of light which is travelling inside the core has made an angle of theta 1.

And now what I want to understand is that, if I were to have this ray of light the second ray of light which is travelling inside the core, hit the core cladding interface at an angle theta 1, what happens if this angle theta 1 is greater than the critical angle of the interface between core and cladding. If it is greater than the critical angle we know that this ray of light actually goes back ok, because it is totally internally reflected.

And now arrives at the lower interface of core and cladding, there is nothing special about this one, because if this has refracted by this angle theta 1, because of total internal reflection, this angle would also be theta 1 and we have already established that, this angle theta 1 is greater than the critical angle for the interface between core and cladding.

Therefore the ray of light further gets totally internally reflected and, then after passing through this zigzag paths light is guided from one point there is at the input of the fiber, to the output of the fiber, is it possible that there is any limitation on this angle theta 0 that is you know if I were to consider this angle theta 0, light at this angle theta 0 will this light be propagating inside the fiber, or if I consider light at this angle we know just very short angle theta 0, will light be propagated these are the questions that we will like to answer in the next module ok, when we discuss slightly more about this ray picture of light propagation inside the fiber so, until then.

Thank you very much.