# Introduction to Photonics
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Good morning and welcome to new session on introduction to Photonics, so next couple of lectures we going to sort of switch tracks to a new module and before I do that, I thought we should go back and review what we have seen so far, so we started looking at science of light as far as this course this is concern from the prospective of ray optics, where we look at propagation of light in terms of straight lines that we call as rays.

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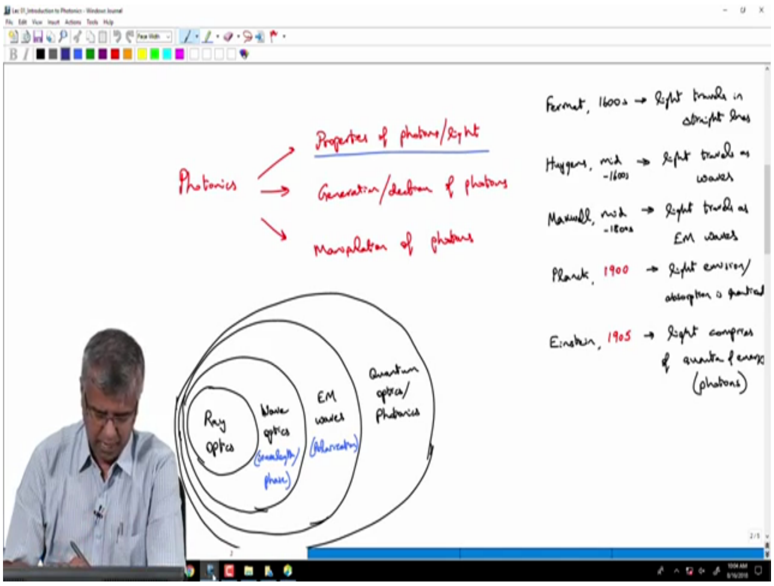


And then we said okay, that is going to be limited in terms of with its utility because light may be treated as waves in which case you have a face and you know wavelength that can be used to describe light and so we would be looking at wave optics and we are at a point where we are at sort of at a crossroads between wave optics and actually treating it as you know, particles in terms of photons.

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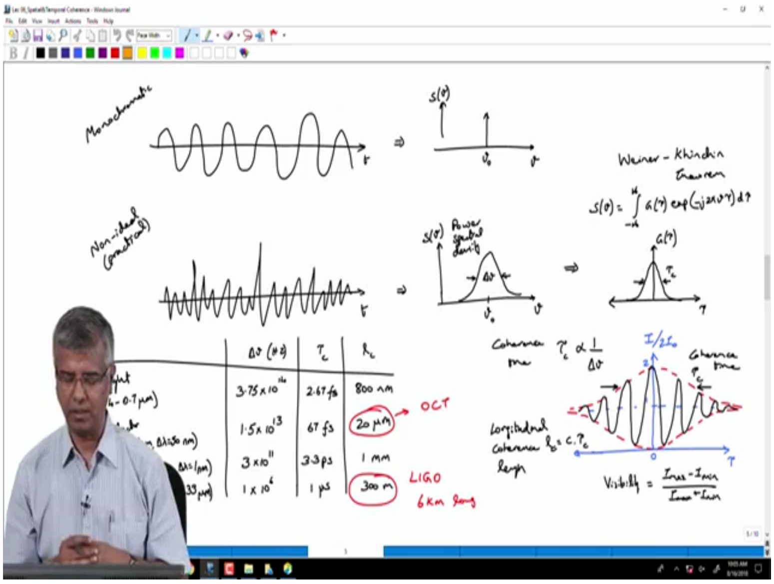


I say that because as you know in the last few lectures we have been looking at the concept of coherence of light and we defined what temporal coherence and spatial coherence means and that is to say in practical light sources, there is a certain level of randomness associated with the propagation of light, the certain level of randomness associated with the generation of light itself, we will come back and look at that in the next few weeks, but as of now, we are just characterizing light propagation and we are saying that, you know, quantifying that randomness is what we are trying to do in terms of temporal coherence where we say okay, light may actually be polychromatic, may have multiple colours and because of that, you may not be able to get perfect correlation when you take one way front and interfere with another, a delayed way front right, that is what we have been seeing with Michelson interferometer and of course we saw that we could define a coherence time and through that a coherence length and of course some of you there are taking this course here have been able to do this experiment in the lab where your actually experiencing or figuring out how to quantify temporal coherence.

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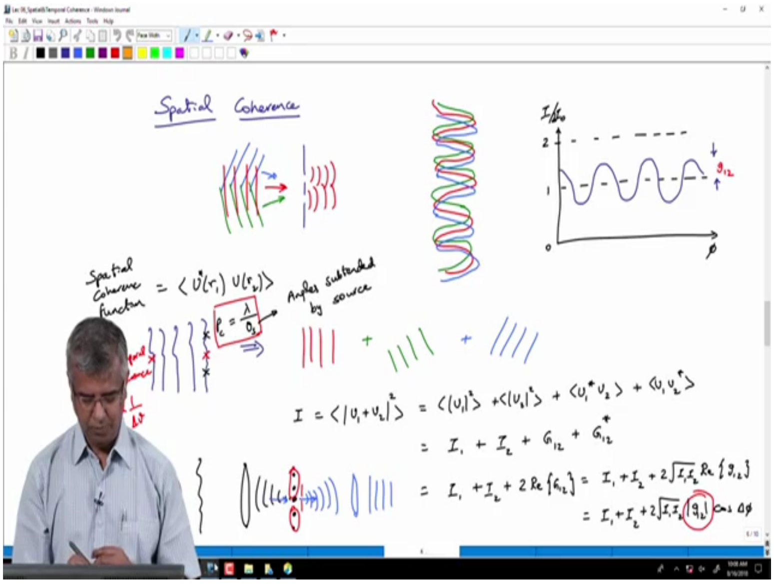


Okay, and you also looked at spatial coherence which essentially says that okay, your light waves not going to be a plain electromagnetic wave all times right, so there is no such thing as a perfect plain wave in practical sources so you typically, deal with a sub tension of wave vectors or sub tension of angles as far as the source is concern and we are trying to quantify that through this spatial coherence length which we have mentioned as rosy over here and that spatial coherence length determines is basically inversely proportional to the angles sub tender by the source, so in other words, we say if you have a large number of angles sub tenders by the source as in the case of a LEDs a very good example.

Then you may have very little spatial coherence that means it is far away from being a plain wave or on the other side, if you have very good collimated source which can be direction of, which can be, you know determine by particular angle, just one particular angle. Then, we say it is a highly spatially coherent light wave, so this is actually just talking about the randomness with which they are encountering this light and these are essentially measures of that randomness.

So what we will, what is a natural step from here is to essentially treat this light waves as consisting of photons. Okay, and each of those photons may have a sub wavelet and a particular direction and so on, so you may actually be able to characterise these sources a little more easily when you go to the photon picture, but of course that is founded by the fact that, when you are talking about light emission or absorption of light that tends to be quantized in nature. Okay, that is what Max Planck initially discovered, and then followed by

Einstein, who said okay, the propagation of light waves can be explained in terms of photons themselves right.

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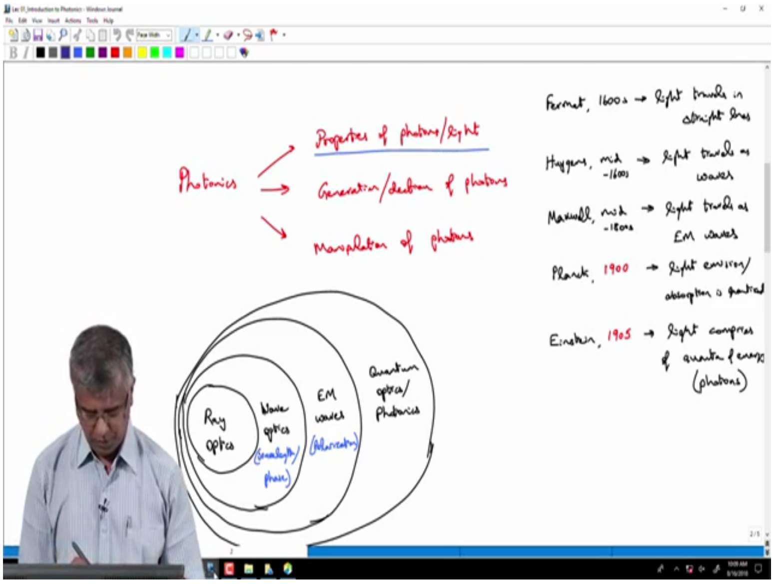


So we going to come to that, but before we do that if we look at what we wanted to do initially is to from the wave of this picture, we wanted to go to the electromagnetics picture right, so let us spend a little bit of time understanding that electromagnetic picture, and through that we will actually, you know, do one demonstration where you are quantifying the modes of an optical fibre and through that quantification you are also going to understand how an optical fibre can essentially act like a special filter, okay, so that is what we are going to do you know in this lecture is just capture a little bit of electromagnetic optics of course, that is actually a fairly large field once again, there are a lot of finer aspects to it, but we will just pick up some essential concepts from there before we move on to treating light as quantum, you know, consisting of quantum object called photons.

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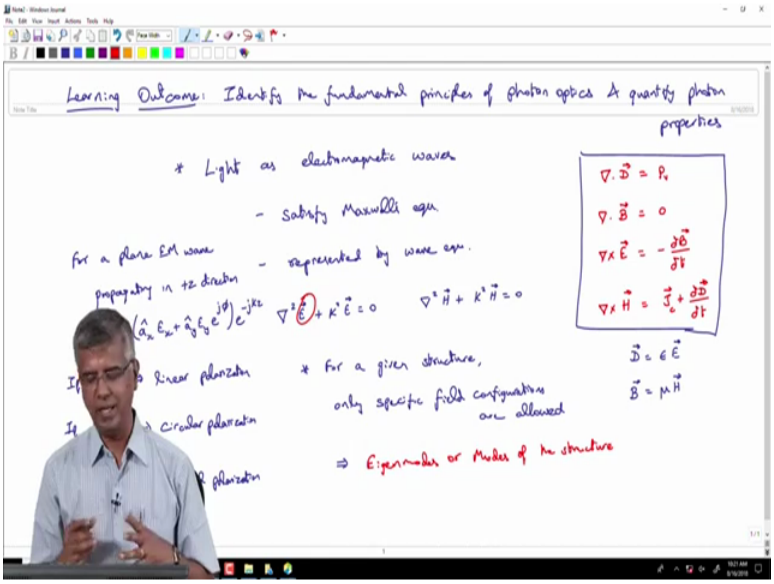


Okay, so let me start here the learning outcome for the next few lectures is actually identify the fundamental principles of photon optics and quantify photon properties, but before we do that let just look at electromagnetic properties of light. Okay, so now we are treating light as electromagnetic waves right, so, and of course if we are treating a light as electromagnetic waves, what is this I have to satisfy? It has to satisfy the Maxwells equation, so you first of all have to satisfy the Maxwells equation which you know is probably remember from one of your electromagnetic courses consist of Coulombs law diversions of the electric displacement current density is given by Robey, your magnetic flux density is conservative, magnetic fields are conservative in nature, so the diversion of magnetic flux density is zero.

Then you have your famous Faradays law which says that you have a circulation of an electric field whenever there is a time varying magnetic field and then you have Amperes law which was modified by Maxwell to include displacement current density, because originally, Amperes was looking at only from a perspective of explaining the circulation of magnetic fields through the current carrying conductor, but of course Maxwell completed this picture, saying that it could actually be through a displacement current as well, right, so all of this constitutes the Maxwells equation with of course the constuents relationships which says that your electric displacement current density is related to the electric field intensity in terms of through this constant, sorry through this parameter called Epsilon which is permittivity and similarly, we said the magnetic flux density is related to the magnetic field intensity through mu, which is the permeability right.

So in other words, permittivity and the permeability constitute the response of a given medium to an applied electric or magnetic fields right, so that is what is, it has to satisfy and of course this is represented by the wave equation right in the wave equations are essentially for the electric and magnetic fields can be written in terms of is called the Helmholtz equation del Square E Plus, K square E equals to zero and del Square H plus K square H equals to zero, where K equals to omega root mu abs lone, we that before represents the wave number for a given medium right, so what we understand from this, now of course , one of the things that we are starting to incorporate here is the fact that we are considering this electric and magnetic fields okay which was previously represented by certain wave.

You know we said wave having a certain amplitude and phase but now we are talking about electric and magnetic fields and there is a specific notation that I have used vector notation right which essentially says okay there could be a specific orientation for this electric and magnetic fields and if we look at that more carefully let us say for the case of for a plain M wave, let say is propagating in a positive direction, which is essentially a solution of C wave equations, you will find that the electric field vector can be represented in terms of, if it is a plain wave, propagating along a positive these direction where are the field components X and Y right.

So it can be X plus in terms of AX, EX plus AY, EY and you could have a certain face difference between the two components also in a generic case, so you say, if J5 and this is propagating in the positive C direction so it is going to accumulate face as it propagating and once you express the electric field like this, than you have specific conditions where if 5 equal to 0 that is EX and EY are in face, what do you get, you have a certain polarisation, certain orientation with which the electromagnetic wave is propagating, so that corresponds to linear polarisation or if 5 equals to + -5 x 2 and EX equal to EY, then that electric field vector is going to propagate like this, is going to go around and you know the terminus of the electric field is going to draw a circle.

So that is what we called as circular polarisation and of course we can go into very specifics and say if it is +5 x 2 that corresponds to a left circular polarisation -5 x 2 that corresponds to a right circular polarisation and any other case, you probably have an elliptical polarisation, so the whole concept of polarisation of light comes about, you know, when you go into, when you start treating this light waves as electromagnetic waves. Okay and there are certain manipulations you can do, you know depending upon the response of your medium, if it is a isotropic response than the polarisation remains the same but if you are going into a material which responds differently for different directions or response differently for different electric field vectors, then you may start having, you know certain polarisation changes and some manipulation that we could possibly do, all of that will come back to it later on, you just enough to understand at this point that light actually could have polarisation, could carry a certain polarisation, right.

This is all stuff that you would have seen in one of your courses in electromagnetic fields, right. Basic courses in electromagnetic fields, now what we understand by solving this wave equation is that, this key point that for given structure, you have certain field configurations that satisfy Maxwells equation, so everything as far as electromagnetic waves are concerned as to satisfy Maxwells equations and so for a given structure it has to satisfy Maxwells equation as well and that is what is being represented by this wave equation, so what will we find is for a given structure only specific field configurations are allowed, okay, are allowed by the Maxwells equations, so what do we called this specific field configurations, so these are called the Eigen modes, okay, or simply modes of the structure. Okay.

So you have this concept of Eigen modes or modes of a structure that come into the picture because these electromagnetic fields will have to satisfy Maxwells equation within that structure, okay.

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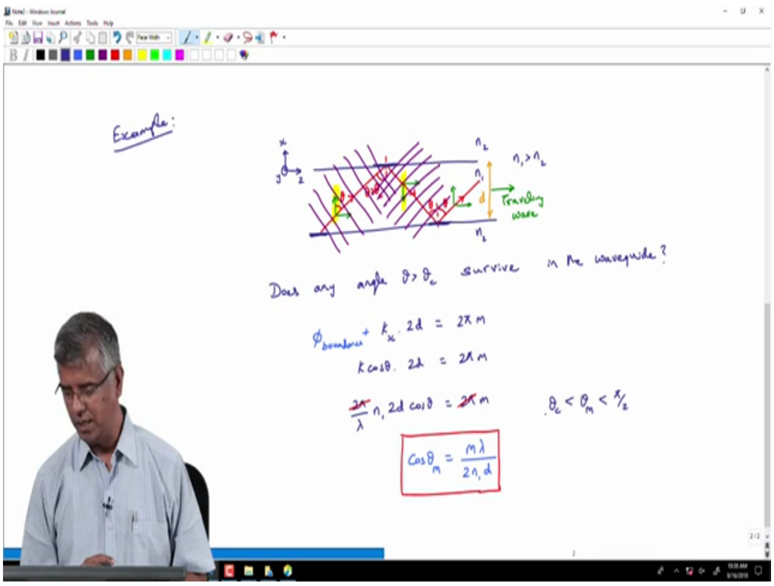

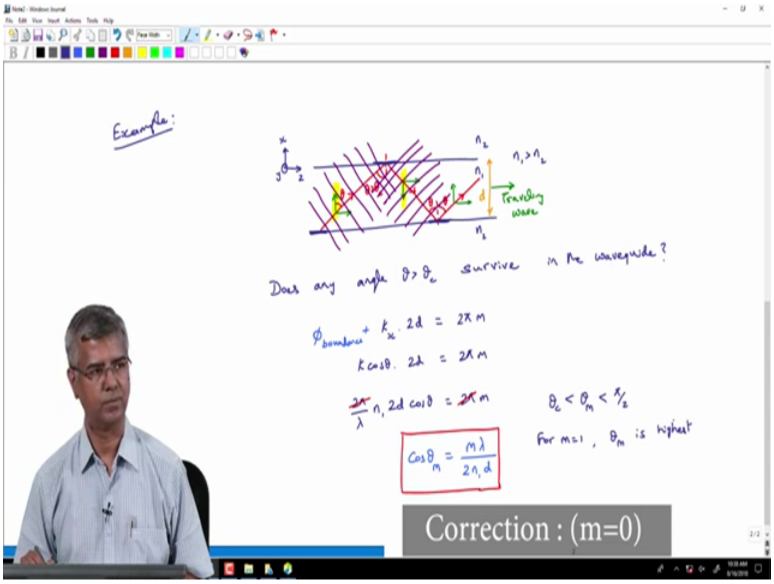


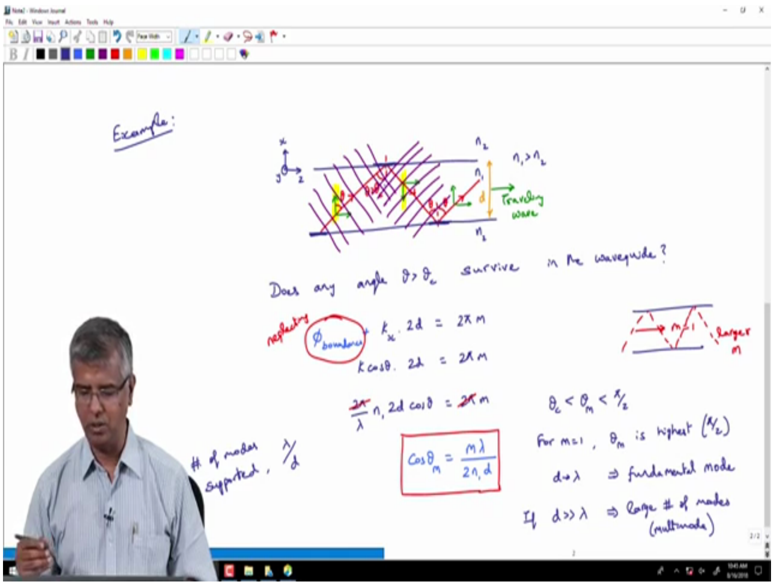


So let us take you an example, a very very simple example of how this happens, what is the implication of this? Okay, for a specific structure, so let us take the example of a total internal reflection, a waveguide, so we already saw in ray optics, we took an example of an optical fibre, right, to say that the optical fibre can be used as a guide, where did we use that ride? In that case, we used that for endoscopy, right, so we defined basically a largest guide which can be designed to support endoscopy right, so let us take a similar example, let us go back and revisit that example and now we will revisit it from the perspective of modes of the waveguide okay.

So let us say you have, once again like we done before, you have a medium with reflective index N1, another medium with reflective index N2, such that N1 is greater than N2, you going from a denser medium into a rarer medium and we saw that if we come in with a light ray which is a greater than a specific angle, right, theta greater than theta C, theta C defined as sign in words of N2 over N1, right, so if we come in with that, what happens? You have total internal reflection and then we said okay, if I put another parallel interface over hear and outside of that interface, once again you have this medium N2, then you could support these bounds right and you can make a waveguide out of it right.

Now, of course that is because, that is theta, this is also theta, right and the reflected angles also theta, so that same condition is maintained as long as those two interfaces are parallel to each other. Okay, so we say that could act like a waveguide, now the question is, the key question is, this seems to suggest, does any angle theta greater than theta C right, according to this picture, any angle greater than theta C should be guided right, any ray with an angle such that theta is greater than theta C should be guided, so it is that true, does any angle theta greater than theta C, survive in this waveguide.

Okay, so let us examine that a little bit and to examine that let just go back and look at this propagation little more closely. Okay, so clearly this wave vector over here can be, you know decomposed into two constituent wave vectors right, one pointing up and one pointing to the right side, right and similarly when we look at this wave vector this will have a component, that is pointing down another component pointing to the right side and similarly over here also you have the same case.

So after every bounce, we see that there is one component pointing consistently along the direction of the waveguide, okay and that component is called that travelling wave component, okay because it is pointing to a wave that is travelling in that direction, but what about this other component, what about this component? Now, when we look at that component, we see that before the bounce it is pointing up and after the bounce it is pointing down, right.

So essentially the fields, there are these two different fields that are interfering with each other in this region, so we are defining a particular ray right, so what is that mean, that essentially means that we are having these wave fronts, if I have to draw this wave fronts, so we have these wave fronts like these and these wave fronts after the bounce go like this, right.

So essentially we are saying this incident, the fields corresponding to do incident wave and the reflected wave are essentially interacting with each other. Okay, so when the interact with each other what happens, depending upon their relative phase, they will have to have constructive or destructive interference and key point here is for an electromagnetic waves to be supported in the structure, it has to satisfy Maxwells equations and Maxwells equations says that, I have to satisfy certain conditions at this boundary, but that same condition would have to be satisfied at this boundary as well because the angle is the same, angle of incidence is the same and then this material is the interfaces are the same right.

So whatever interference condition or whatever boundary condition that I am satisfying at this boundary is the same boundary condition that I will have to satisfy here, the same boundary condition that I will have to satisfy here every time it goes through the bounce. Okay, in other words the electromagnetic field configurations that I am satisfying in this structure is symmetric about the centre and it is got to be consistent on either of these boundaries, one way of saying consistency is that, if I am having constructive interference over here, I should have constructive interference over here as well, okay, so over the round trip I should have constructive interference criteria, if I am looking at the incident wave and the reflected wave, the phase that I have accumulated between the two has to satisfy the constructive interference criteria. Okay, so that can be simply written as, so what is the wave component corresponding to this, let us say, we said this is actually, let us say this is the Z direction, the travelling direction and X and Y component are perpendicular to that, so let us define this as X and Y is actually coming out of the screen, right.

So that would be Y, now what we are saying is that the phase accumulated for this vertical component, over a round trip has to be integral multiples of two pie, so that it satisfies constructive interference criteria, so I can write this as, if I say KX corresponds to the wave component in the vertical direction and let us say this waveguide is got a dimension D, so KX multiplied by 2D has to be integral multiples of two pie, so it has to go through constructive interference criteria, so the same pattern, essentially the same field configuration is consistent as this wave is going across.

Now, if I were to write KX in terms of K, let say K represents this direction of the wave vector, right, that is going, so if this is K, what is KX? If this is theta, this angle, what is this angle? That is also theta, so what is KX in terms of K? That will be K cost theta right and so I can just write it as K cost theta multiplied by 2D, is what you have on the left hand side. Okay, K sign theta would correspond to the other vector, the traveling wave vector, but this one that is pointing upwards will be this K cost theta right.

So this can be written as two pie over lambda and the it is not the free space lambda, it is not the free space wavelength, what is the wavelength of light in this medium? Lambda over N1, so you have N1 here 2D cost theta, so those is equal to two pie M right and I can cancel this, so I get this expression which says cost theta would have to be M times lambda divided by 2 times, N1 times D right, so that has to be satisfied, so there is a yes, so there is a phase change at the boundary, that is a good point, somebody is just pointing out, but we are neglecting that for, you know, for a fact, but yes that is actually there is a component that basically says, there is a phase change at the boundaries also that has comes into the picture, right.

So we will have to take that into account also, but I am neglecting that just to drive home a particular point, so I am not being completely regress about this, okay, but the key point is only certain angles theta M right, so only certain angles theta M which satisfy this condition, will actually survive this waveguide, so it will survive in the waveguide, everything else will have to be just radiated out, okay or it will not even enter the waveguide, okay, so that is what we are talking about, so we are saying only specific angles are supported within this waveguide and this is different from the picture that we had just looking at ray optics, if we say, you know it just goes through total internal reflection, it can bounce and there we say any angle theta greater than theta C should go through these bounces and it should survive, but what you will find his only certain angles are supported and this is something that could be demonstrated, so what we will do, is will send red light through these waveguide and will show that, the field configurations that are corresponding to only specific angles are existing within that waveguide. Okay.

So that is actually a beautiful demonstration we will do today, okay, but come back and let us look at this a little more closely, so what we are saying is, theta M is different for different values of M. Okay, when M equal to 1, right, that would have to correspond to the smallest value of cost theta M, right, because as M goes greater and greater, then you will have, you know much more solutions that are possible and cost theta M correspondingly will be lesser, right, because cost theta M goes to 1 when theta equals to 0 and cost theta M when it is 5 by 2 that goes to 0, right.

So what we are saying here is theta M can take values, what are the boundaries for theta M? It has to be less than pie by 2 for sure, right, but what is the lowest value it can take, theta C, right, because anything less than theta C is not even totally internal reflected, so it will escape out, so theta M is bounded within these values and if we looks specifically for M equal to 1, cost theta M has to be the lowest value or in other words theta M is highest, right and for it to satisfy this equation for larger values of theta M, for larger values of M, theta M will have to be smaller and smaller. Okay, until it gets to theta C.

So and take, highest is 5 by 2, so what is that condition correspond to 5 by 2, so if this is my waveguide, 5 by 2 corresponds to a condition where I am almost going straight down that waveguide, right, so your fundamental, so your, for M equals to 1, when we say, you are going straight down the waveguide, that will correspond to, what is call the fundamental mode of the waveguide. Okay, and for, so that corresponds to M equal to 1 and for as you go to larger values of M, the theta M value gets smaller and smaller, so that will correspond to bouncers like this, so this will happen for larger values of M and the largest M that would be supported in this waveguide will just satisfy this condition of total internal reflection. Okay, that is theta C, okay, so do you understand that is fairly simple way of looking at modes in a waveguide and specifically we are talking about modes in an optical fibre.

In fact the effect of this 5 at the boundaries, which we are neglecting we can actually bring that back into this expression, we will actually pose that out as a tutorial problem for you guys to look at little more detail, so the number of modes supported, what do you think it depends on? It depends on this lambda over D value, right, so you will find that if D approaches lambda, okay, only one value of theta M can be satisfied and you will have only the fundamental mode propagating, so you will find that as D approaches lambda you will have only the fundamental mode, but if D is far far greater than lambda, then that allows multiple values of M, right and that would also allow multiple values of theta M to satisfy this expression. Okay.

So when D is far far greater than lambda, you have large number of modes another word it is called the multi-mode waveguide, right, so it is basically a multi-mode waveguide, as D approaches lambda, the size of the waveguide approaches a wavelength, you could do have only one mode propagating in this waveguide but as you open up the waveguide, you know it is much larger compare to the wavelength, then you have a large number of modes, that are propagating.

In this picture by the way is not very different from what you might have encountered in electromagnetic, in terms of rectangular hollow metallic waveguides, rectangular waveguides, cylindrical waveguides, they all have the same picture basically, but what we are considering here is an optical fibre, which is a dielectric cylindrical waveguide. Okay, but the principles are the same, since you have boundaries in the structure, you have this concept of reflection that comes into the picture and whenever you have reflection, you have interference and that interference actually gives the concept of modes of the waveguide. Okay, right.

Higher the order most cheaper the bounce, okay, so for example and this is something we can probably demonstrate also, you send red light through a multimode waveguide and then you bend the waveguide, okay if you bend the waveguide what happens, you are essentially changing this total internal reflection condition at this point, so when you bend the waveguide some of those modes steeped, the steepest modes that were guided in this waveguide, may not satisfy the total internal reflection condition, so they will escape out, so you will see red light, normally when you have a straight waveguide, you will not see any red light coming off because everything is actually guided within the structure, but the moment you bended, I am talking about a multimode waveguide, you will have some of these modes escape the waveguide and you can see that corresponding  radiation okay, so we will try to demonstrate that later on today.

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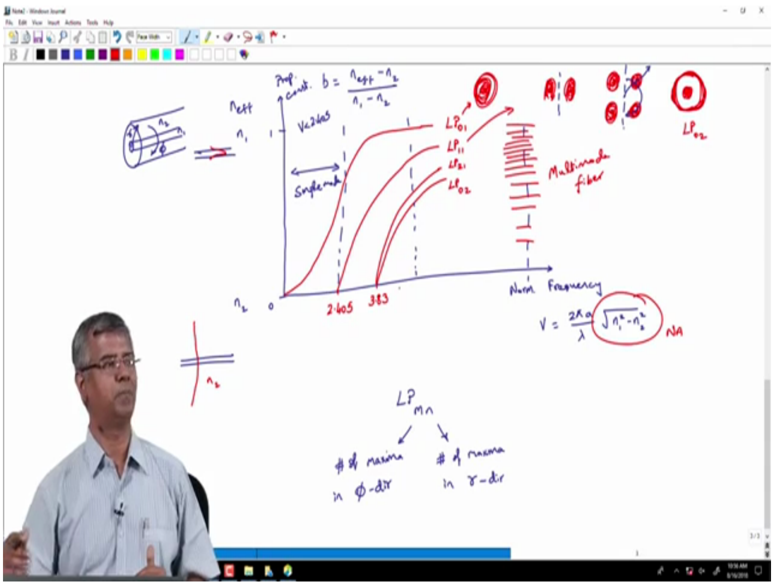

Okay, so let us move on, so let us try to, get to, a little more specifics and so when we are considering an optical fibre, we are considering a core with refractive index N1 surrounded by a cladding with reflective index N2, okay and if you analyse this optical fibre, what we want to understand is, what are the modes that can propagate as a function of different frequencies, so in one side I will write propagation constant okay, that takes a value of 0 to 1 okay, so 1 means it has got a very highly provolty that will be supported by the waveguide and zero means is very low provolty that will be going to be supported by the waveguide, we will that as a function of frequency, okay, if you look at this picture and this frequency, we will in case of an optical fibre, we will look at is as normalize frequency, what we call as a V number, which is defined as 2 pie A over lambda, it has got a 1 over lambda dependence end that is why it is called frequency term.

Root of N1 square minus N2 square, okay, have we seen this before root of N1 square minus N2 square, that is the numerical approach, a very good, right, so you are familiar with that and 2A, A corresponds to the radius, so 2A corresponds to the diameter, which we have mentioned as D in the previous picture, okay and of course this function of lambda, now the propagation constant which we will mention as B is define as ineffective minus N2 divided by N1-N2, okay, so it is defined like this so that the analysis becomes little easier, the solving the wave equation becomes a little easier, okay, so that is why we are defining it in these two parameters but B going 0 to 1 can be represented in terms of ineffective, ineffective B is zero, ineffective would have to be N2, right and if B is 1 ineffective would have to be N1, okay.

So what is this represent, this represent a condition where you have a waveguide like this, with a core like this, but your wave is like this, so it is primarily propagating with the refractive index N2, whereas this condition corresponds to, if you have a waveguide like this, this condition corresponds to the fact that all your electromagnetic energy is well confined within this waveguide, so you are going from very poor confinement in which case all the energy is supported in the cladding to a condition, where everything is confined to the core.

If you do, if you solve the Maxwells equations, a wave equations and will look at specifically what are the different modes that are supported, what you will find is, something like this, you a fundamental mode, which is also called the LP 01 okay and then at a specific value of 2.405, where does that come from? It comes from the fact that when you solve the wave equation and look at field configurations, the field configurations will be expressed in terms of Bessel functions and 2.405 corresponds to the first 0 of the zero thought a Bessel function, so you will find that, the next mode comes about like this and that is called the LP 11 mode and then add another value of 3.83, you will see a couple of other modes come into the picture, one is called LP 21 mode and other is called LP 02 mode.

So essentially what we are saying is, if I manage to stay within this region, V number of less than 2.405, then I have only one mode gets propagated, okay or alternatively if I have a condition where D which is 2A in this case, 2A is much much greater than lambda, then the value of V is very high, right V could be 10 or maybe 100 also and if you have that region, so you were looking at somewhere over here and within that you going to have all these modes, they are going to be, you know 100 of modes here, so very high value of V would corresponds to a multimode fibre and then you could upvas have a fibre where, for a given wavelength, the V is define somewhere over here and you may be able to see in this case only these specific modes.

The interesting part is, these modes which are generally called as LP MN modes, M corresponds to number of Maxima in 5 directions, what is 5 here? 5 would corresponds to the azimuthal direction, okay and N corresponds to number of Maxima in R direction, R would corresponds to that radial vector, okay, that is pointing radially outside, so LP 01 for example, will have a field configurations like this, it will be fairly dense at the centre and then it will fall off as you go outside in the radial direction, so this will be LP 01, whereas LP 11 will look fairly dense in the centre bird it will fall off and then it will have two lobes.

Essentially those, so why is it called LP 11 because when you are looking at the azimuth direction, you look at the half azimuth plane okay, so within that half azimuth, because one is a reflection of the other, within the half azimuth plane, you will have one Maxima, right and radially outwards you have only one Maxima okay, so that is why it is called the LP 11 mode and so you can imagine what a LP 21 mode looks like, it is basically, it is got these four lobes like this, once again when we look at the half azimuth, you are going through two Maxima, so that is why you are calling LP 2 and then going radially out words you have only one Maxima, so this is an LP 21, so what is the LP 02 mode? How is it going to look like, zero means there is no variation in the azimuth direction, so it is all uniform but it has two Maxima in the radial direction, so how is that going to look like, you going to have one central peak here surrounded by another ring over here okay, so that will correspond to LP 02 and what will find is, this is not just some Wegh theory, you will find that you can see all these modes, if you choose a fibre with whose V number is somewhere, you know greater than four right, so and what we see here is the V number is not like a define quantity for one specific waveguide, any specific waveguide you have 2A and this NA defined, those are all material parameters and structure parameters, but wavelength depending upon the wavelength that which we use it, the V number can change.

In other words let us say you have 10 micron waveguide, you can come in with a wavelength of 10 micron and you will find that it actually like a single mode waveguide, you can come in with a wavelength of 1 micron and you will find that it has a different V value, it has got a higher V value, so it will actually support more, so you cannot generally call a fibre single mode or multimode okay, so it is single mode at a particular wavelength, multimode at a particular wavelength okay, so these are the concepts that will going to see in the demonstration today, so you overshot my time but let us stop here. Thank you.