Photonic Integrated Circuit
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Lecture 14
Waveguide Structure

Hello all. So, let us look at how waves propagate in a guided medium. So, that is our primary interest in exploring how one can confine light, propagate light and exploit this confinement. But light and free space we have seen it, right from our school experiments, physics experiments, in undergrad you must have done experiments in your physics labs and also looking at some laser used for some interesting applications and also experiments free space is reasonably well known laser light going through free space you do not see any divergence and so on.

But, they always follow a straight line, if you want to change the direction we use mirrors to do that but then it is okay to do that in setups on optical tables and so on that reasonable size that you can handle. Imagine that you want to send information that is like 10 or 20 kilometers from here or even add few zeros 100 or 1000 of kilometers from here, it is impossible to align your laser with the receiver there, maybe few tens of meters is still possible but then the alignment becomes very difficult once you go out and also the losses becomes beyond what one could accept.

So, the guided wave system is a much more sophisticated way of transporting light. So, in a guided medium meaning we take a dielectric similar to optical fiber you say is a good example and putting our photons inside. And once we designed it in an appropriate way we should be able to take this photon inside the medium to the other side, this other side could be tens of kilometers without losing them. So, we need to keep it inside, we know how lot of light matter interaction that can go on.

The two popular ones that we have seen is reflection and refraction and you could also scatter combination of this. So, once the refraction happens light goes out of the system. Is it possible for us to keep the light inside the medium of interest? Once you can achieve that we call that as a guided medium. So, you can guide the light where you want. So, let us look at what all the requirements we have in order to do this and also how are we achieving this what are the phenomenas that help us in realizing light confinement and guiding. So, let us dive in.

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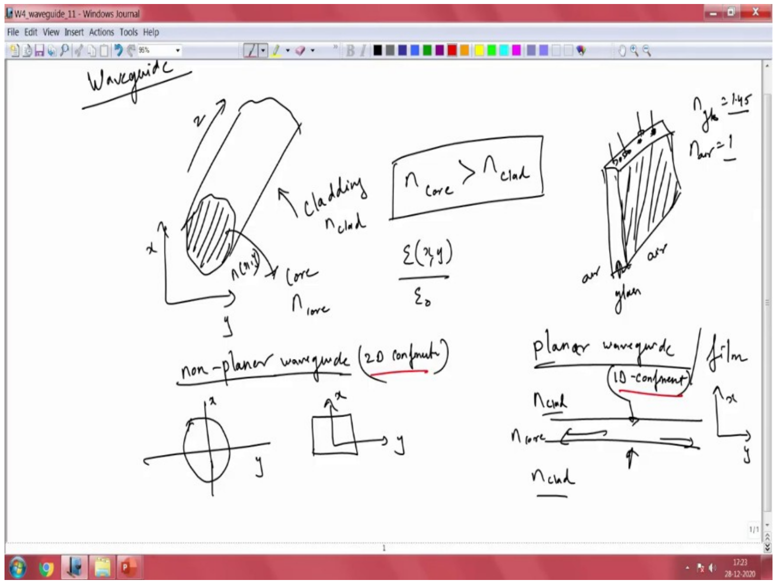

So, wave guides are three dimensional structures. So, these structures got what you call the dielectric waveguide, for example, consists of an arbitrary shape let us say, it is an arbitrary shape in x let us say x and y and this will be infinite length let us say.

So, they are along z and this material that we have where we are going to confine is called core and it is surrounded by a medium, this the surrounding medium is called cladding. So, optically if you want to differentiate these two. So, we can say n_{core} and n_{clad}. So, the n_{core} should have higher refractive index than n_{clad}, this is a requirement, we will see I mean from where are we saying this, I mean let us say you are arbitrarily saying that n_{core} should be greater than n_{clad} why not n_{clad} is greater than n_{core} why not?

So, there is a reason for this we will see why we want this to happen. So, normally this is the requirement for guiding light inside the core. The light is propagating along z direction here and the electric field is in x and y which can be represented by your dielectric constant here $\frac{\varepsilon(x,y)}{\varepsilon_o}$.

So, this is the dielectric constant that we have, it could be your isotropic I am not going to differentiate isotropy and anisotropy here for all practical purpose let us now assume for all the further discussion they are isotropic.

So, wherever you move in the x, y plane the refractive index is uniform. So, that means your refractive index n(x, y) is uniform across this plane and it is extruded along the z direction. So, this is basically your arbitrary waveguide. So, there are two type of wave guides we have. So, one is a non-planar, it is a non-planar waveguide and then you have planar. So, in a non-planar waveguide we can already see that the name itself suggests it is not planar let me first explain a planar waveguide.

So, planar waveguide is where the light is confined only in one transverse direction. So, let us say you have x and y. So, the light is now confined in the x direction. So, along y direction there is no confinement. So, the core is nothing but a sandwich. So, it is sandwiched between the two clad. So, you have core you have two cladding. So, it is this is what we call a planar wave guide.

So, we can also call this as a film. So, it is a thin film waveguide this is nothing but a thin film for all practical purpose and you have a cover, cladding is our cover. Your glass window for example is a planar waveguide, you must have seen in some of the shops you will see when people put LED light on top of this, this whole window or this glass will glow as if you have light source or light emitting from this window.

So, you can put LEDs at the top and this glass slab will act as a planar waveguide. So, you have glass and then you have air, this satisfies our condition for wave guiding because the refractive index of glass is about 1.45 and refractive index of air is 1. So, that means n_{core} is higher than the cladding index. So, that is the reason why by putting LEDs on top we can make it propagate on shine.

So, that is a planar waveguide. So, this is a planar waveguide. So, let us look at non-planar waveguide. In a non-planar waveguide, so, light is confined in two dimensional, a true dimensional transverse optical confinement. So, that is called the non-planar waveguide. So, here the both in x and y, light can be confined, a good example is optical fiber and the other example is a wire wave guide. So, where light is confined both x and y. So, two dimensional confinements and here it is one dimensional confinement. So, this is the basic difference between a non-planar waveguide and a planar waveguide.

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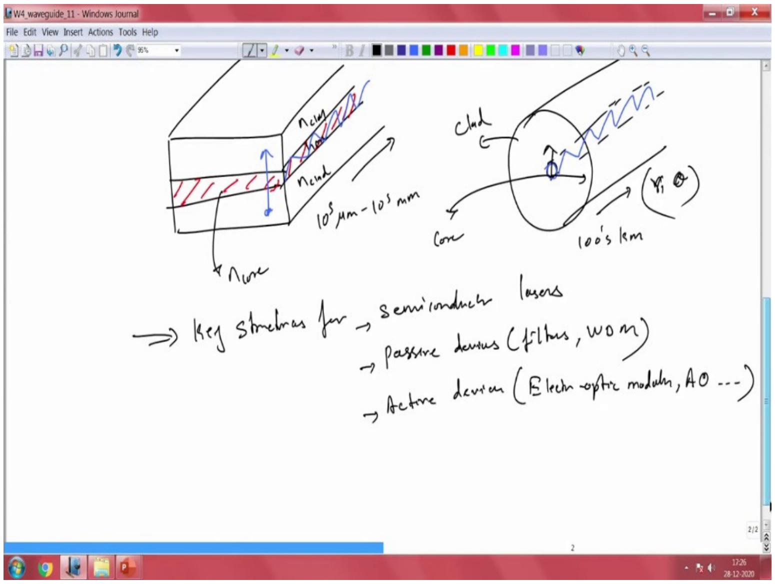

So, as I mentioned we could confine the light in two dimension and in one dimension, let us look at how one can do that. So, you can have a very thin film take a thin film and then you can extrude this and this is the part. So, now light can propagate inside the sandwich. So, you have clad n_{clad} and n_{core}. So, this is n_{core}. So, now when I put light can travel in this sandwich.

So, as you can see it is confined only in this vertical direction, laterally it is not but then I can also take an example of optical fiber. So, here the light will stay inside this boundary this is the core and this is clad. So, now I can confine this in whichever direction I want x and y. So, this can extend or in other words if you really want it is r, θ. So, you can confine it in any direction angle you want.

So, this can confinement happens along the cross section and you can allow it to propagate let us say in an integrated photonic circuit it can be tens of micrometers to tens of millimeter or even centimeter in this case you can even have it for hundreds of kilometers for example. So, it is possible to do it. It is a, once you confine it, you should be able to allow this to happen and the optical waveguides both the fiber based and also the rectangular or the recliner geometries are fundamental or fundamental structures.

So, these structures are key structure for semiconductor lasers, passive devices such as filters wavelength division multiplexing and also active devices like electro optic modulators or acousto optic modulators and so on. So, this structure becomes really key to realize various functionalities that one can use it in many applications. So, the refractive index we defined here n_{core} n_{clad} but it need not be strictly that way there is a configuration for that. So, that let us look at how the refractive index should be.

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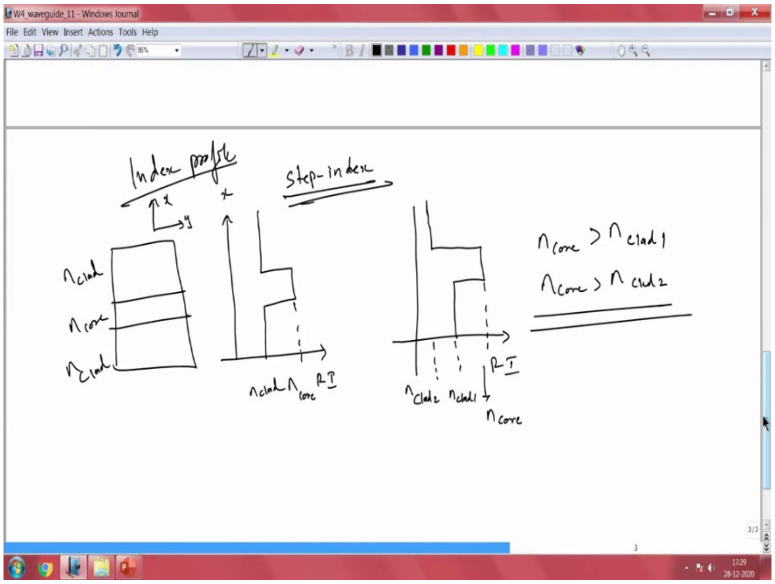

So, there is index profile. So, let us just simply take a cross section. So, we took a very simple sandwich here. So, n_{core}, n_{clad} and then n_{clad} let us say. So, like you can use other names as well. So, as a function of let us say the x and this is z. So, if I am going to draw the refractive index. So, this is refractive index function of distance. So, there is clad index and the core index like this. So, this is n_{core} and n_{clad}. So, this is what we call step index configuration, it is like a step you go from the clad to core.

So, I could have something different here. So, again refractive index I could have different indexes for core and cladding, the both, the cladding. So, I could have very low index here high index and something like this. So, here I have three refractive indexes you see. So, this is of course n_{core}. So, this is n_{clad1} and this is n_{clad2}. So, this is a top refractive index and bottom refractive index. Whether this configuration would work? Absolutely, the reason for this is the n core is greater than n_{clad1} and n_{core} is also greater than n_{clad2}.

So, this is the condition that we should satisfy if you remember that is the first thing that we stated your core refractive index should be higher than the refractive index of the surrounding then only you can confine light. So, this is step index. So, we have another form or another profile which is called graded index.

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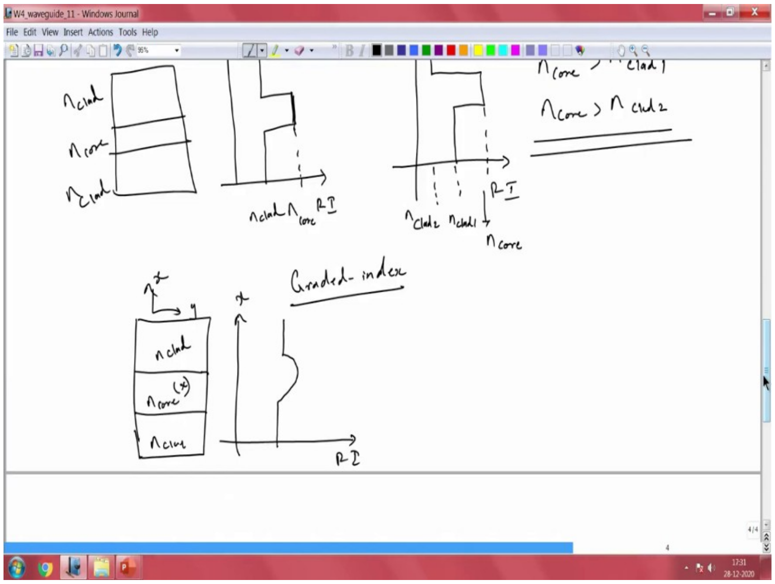

So, there is a graded index profile, we can take the same configuration here. So, there is n_{clad}, n_{core} and then n_{clad} the only difference here in in the graded index is this n_{core} is now a function of position. So, it is not any more uniform refractive index as we saw here. So, now the refractive index profile. So, here n_{clad} is uniform no doubt about it and now this n_{core} is now as a position dependent one. So, it could have anything in this case let us say it follows a parabolic function like this and then. So, here the refractive index is profiled it is graded we call it as graded index wave guides or graded index profile.

So, why graded index is important? Later on we will see once we understand light propagation and how light propagates through this thin slabs with the different refractive indices, we will attempt to understand why one would think about grading which is not easy to fabricate unlike the step index we just sandwich different layers and we should be able to get it all. So, for a non-planar waveguide. So, this is in planar geometry you can also have this refractive index profiles in non-planar geometries as well, let us start by understanding what are all these non-planar waveguides.

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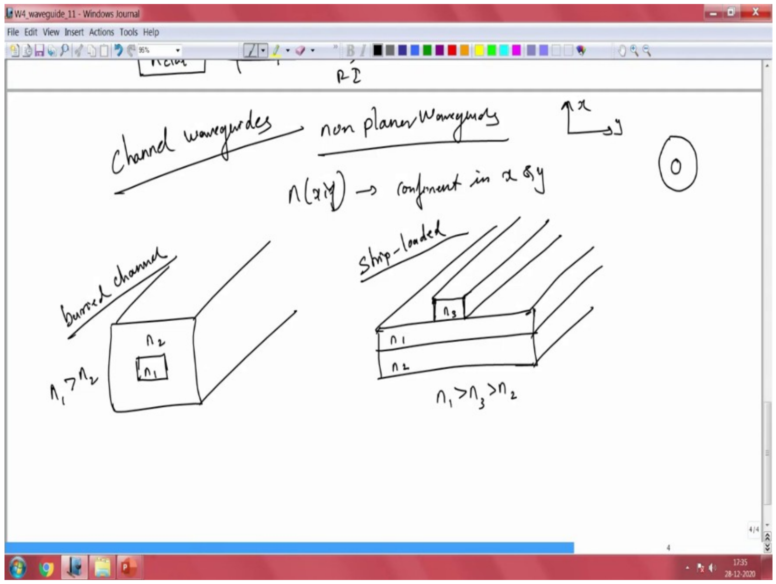

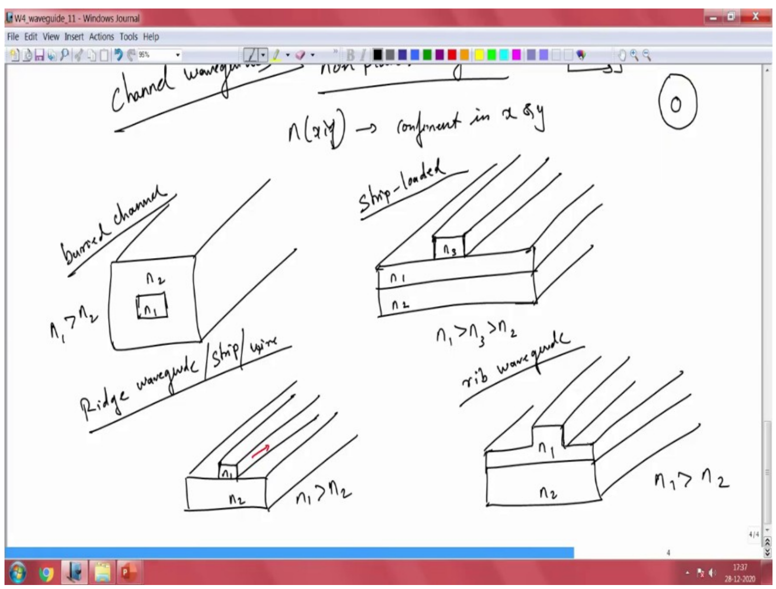

So, we call as channel waveguides. So, channel wave guides are mostly we are talking about non-planar waveguides here. So, they are all non-planar. So, that means the refractive index profile you have both x and y. So, that is n(x,y) and you have confinement in both the direction, confinement in x and y in both the direction we should be able to confine. So, there are different kind of, different types, varieties of such waveguides one can come up with one special type is this optical fiber the circular profile, the rest of the things are rectangular but this one is special type this is the circular type.

So, primarily we will only handle here non-planar that are channel waveguides. So, what are all those. So, let us start from a simple buried waveguide buried channel. So, here the core is buried inside the cladding here. So, this is n_1 surrounded by n_2. So, here n_1 is greater than n_2. So, this is called buried channel waveguide. So, the waveguide is buried inside a cladding material.

So, next is strip loaded, it is a strip that is loaded waveguide. So, the configuration looks something like this. So, you have a slab but then you have refractive index n_1 and n_2 this is slab you can quickly judge that this looks like a slab but it is a strip loaded. So, that means I am going to load this with a waveguide here. So, this has a refractive index n_3 let us say. So, here the refractive index of n_1 will be greater than n_2 which will be greater than, sorry n_3 which will be greater than n_2.

So, this configuration is called a strip loaded waveguide. So, in some of the waveguide material you will not be able to create such rectangular or square structure. So, that means you need to etch them and remove this in order to create this. So, if you are unable to do that we can have a thin film deposited and on top of that you could deposit your material of interest that is easy to process and create this kind of channel and this channel that you have, the strip that you have will allow the light to be confined in this region we will see how these confinements happen but for the moment this is how you can confine the light.

The next configuration is what we call a ridge waveguide, ridge waveguide. So, ridge waveguide or strip or wire. So, these are all the three names you can give it to this. So, here we can take plane index and then we have a waveguide defined on the top. So, this is n_1 and this is n_2. So, now the light will be confined within this region. So, light will be carried in this particular region. So, this is a strip a waveguide or a wire waveguide or a ridge waveguide. So, the next thing is a rib waveguide, a rib waveguide is a little interesting.

So, here we have vertical and horizontal confinement but you can see here the material with refractive index n_2 is made as a wire but in this case of rib we are going to have a shoulder. So, we are going to have the shoulder of this waveguide. So, this is your n_1 and this is n_2. So, they form a very nice shoulder that allows the light to be confined within the n_1 region. So, again here n_1 is greater than n_2 here again n_1 is greater than n_2. So, this rip waveguide got these shoulders, there are few implications on having the shoulder, sometimes very useful which we will shortly discuss but this is again another class of wave guide where one can confine light

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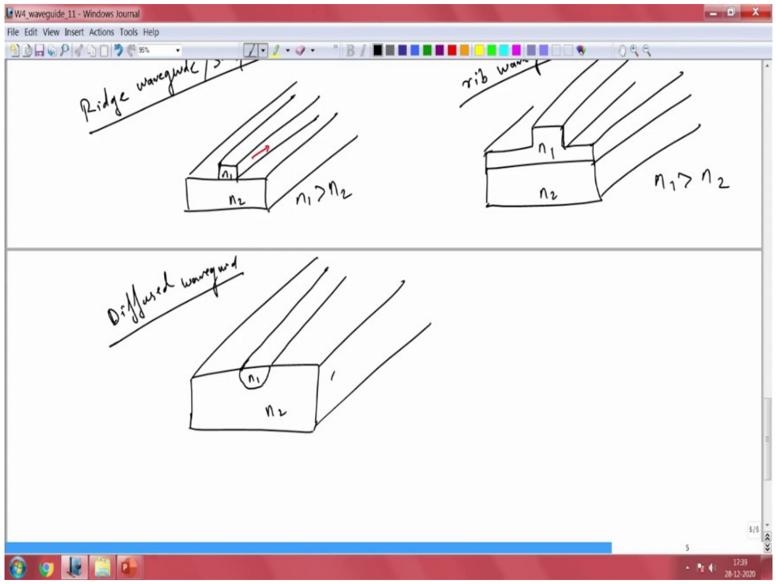

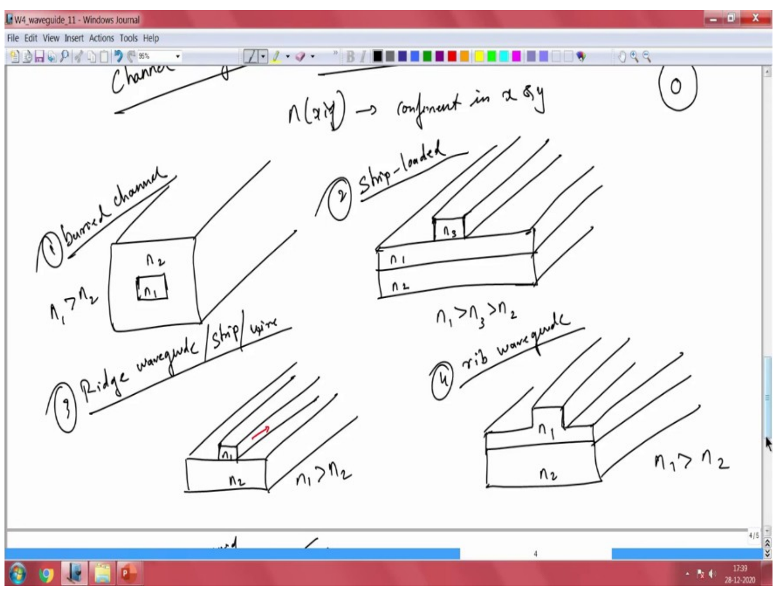

And there is one more waveguide configuration which is called a diffused waveguide which is very popular with the lithium niobate based system where you take the material and then diffuse a metal for example inside. So, there is a metal diffusion and this diffusion will cause a buried it is similar to buried waveguide but not fully buried you see in a buried waveguide, the wave guide is sitting completely immersed in the cladding but then in this case you have the surface.

So, the half of it is sitting inside and this is called a buried wavem sorry diffused waveguide where you could create this refractive index contrast by diffusing a material in lithium niobic it is titanium diffused diffusion that people use, there are other platforms one can also realize by this diffusion. So, primarily the popular geometries when it comes to silicon or silicon nitride or 3-5 semiconductors we will use one of these four configurations that we saw a buried channel waveguide, strip loaded waveguide, ridge or wire waveguide or rib waveguide.

So, these four are popular configurations that one can use. Let me quickly touch on why this strip and rib waveguide configurations are required. So, of course we understood strip loaded why because of the processing difficulty that you may have for this material the waveguide material that we have but rib, wire waveguide you want to confine the light in n_1 it is done perfectly well here but then in a rib waveguide you have a shoulder. So, the reason for this is in some of the application you want to apply some electric field.

So, you want to apply a field through this to change the material property let us say in order to realize electro optic or acousto optic effect from this material that you are using that n_1 material could be a non-linear material, anisotropic material where you want to exploit their property by applying external field, it could be electric field, it could be thermal it will be acousto, optic. So, any of those effect. So, in order to apply that you need to have this material extended, so that extension is given by this rib structure. So, those are all the different waveguide platforms that we can exploit.

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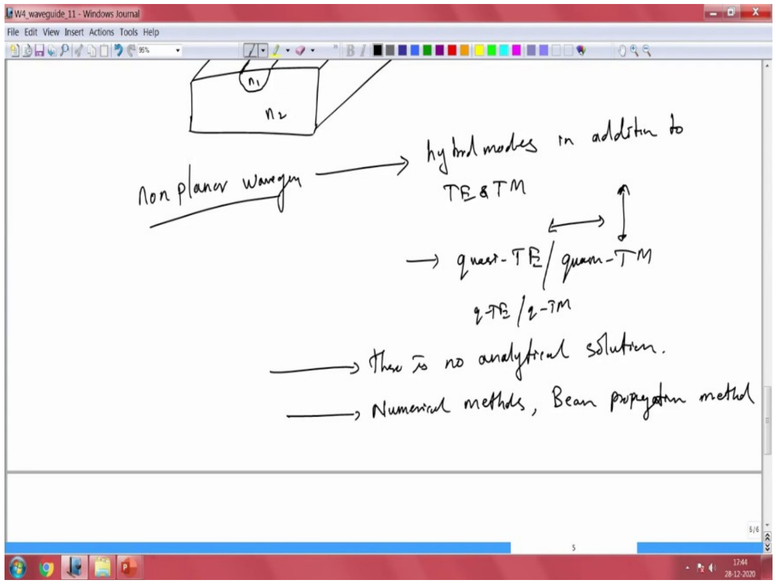

So, when it comes to the waveguides there are different polarization that you can allow in this particular system, in non-planar dielectric waveguides primarily they support distinctive modes or distinctive solutions into it. So, an important thing to understand is in non-planar waveguide you expect to see hybrid modes in addition to pure TE and TM modes. So, TE and TM are very distinctive electric field. So, you have orthogonal field here between TE and TM but in non-planar waveguide you will see hybrid modes. So, what do we mean by that is certain percentage of TE or certain percentage of TM in solution.

So, that is what we call a hybrid solution and that is the reason why we do not call it TE and TM anymore, we call it as quasi TE or quasi TM. So, we just say qTE and qTM. So, they are not purely electric or purely magnetic we will see this when we solve for our wave equation inside this but this is something that you should all keep in mind and understand that there is no pure TE or pure TM like in other waveguide systems, even in planar waveguide system you could have pure TE and TM but not in non-planar configuration and the other thing is for non-planar configuration there is no we do not have any analytical solution.

So, there is no analytical solution. So, to capture the nature of the modes here because of the structure itself. So, it is not possible to do that we have to do this numerically. So, we use numerical methods to solve this for example beam propagation. Beam propagation method is one such technique to solve this numerically and there are lot of approximation that one can do. So, one of the approximation method is effective index method and so on which we will see later on.

But this is brief description about waveguides and waveguides configuration. In the next topic we will look at waveguide modes, how light can be transported in this medium. So, right now we understand the geometry, what is the geometry required. So, for some of you are very used to the circular fiber based geometry. So, we also have planar geometries particularly for your photonic circuits. So, with that we have covered a different type of rather class of geometries we can use and in the following class we will look at what are the modes or what are all the solutions that can allow us to propagate light through these different geometries. Thank you.