Integrated Photonic Devices and Circuits
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Lecture – 09
Fundamentals of Light Waves: EM Waves Principle of Optical Waveguiding

Hello everyone, so far we have just discussed also that there is a limitation in electrical interconnect transmission line in integrated circuit. So, it has normally they used transmission line for electrical interconnect and the transmission line you know that has a cutoff frequency that means it is considered as a low pass filter you cannot communicate high speed data. So, optical interconnect came into pictures.

And optical interconnect the fundamental building block is electromagnetic and this optical waveguide and optical waveguide basically to understand optical waveguide we have discussed a bit about electromagnetic theory, Maxwell's equation, plane wave propagation etcetera. And now today we will be discussing about optical wave guiding so electromagnetic wave in optical frequencies if it is operating then how to design optical waveguide.

You know normally we know that for higher frequency relatively bit higher frequency for example micro waveguide we use metal waveguides. So, we would like to discuss first why the same metal waveguide cannot be used for optical wave guiding. So, there would be some kind of limitations and I will discuss that first and then I will move on to actual wave guiding different type of optical wave guiding and their properties in details.

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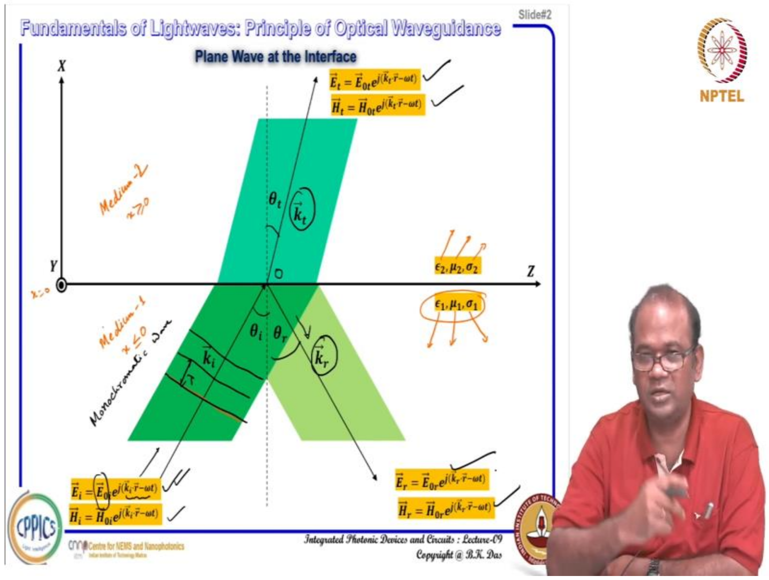

So, let us start you see let us consider to understand, the optical waveguiding we need to know how electromagnetic wave behaves in the interface between 2 media. 2 media means if I consider range of frequency of operation you are considering in electromagnetic domain electromagnetic wave, so you can think of that you have to deal with metal, dielectric, semiconductor all those type of things.

Here we are considering for example a reference frame here for example this is actually your medium 1 and this one below YZ plane in this figure below YZ plane this can be considered medium 2 according to this definition here and this can be considered as a medium 1. And medium 1 is characterized by its parameters, electromagnetic parameters that is permittivity epsilon 1 and permeability mu 1, conductivity sigma 1.

Similarly medium 2 your permittivity epsilon 2, permeability mu 2 and conductivity sigma 2. We are just considering 2 medium characterized by these parameters and they are meeting this 2 medium meeting at x = 0 YZ plane that means YZ plane you can consider in finite extended and for x greater than 0 you have medium 2 and x less than 0 you can consider medium 1. So, exactly at x = 0 here that is x = 0 you can consider that they are meeting interfaces there.

And you can imagine that electromagnetic wave propagating in medium 1 we think wave vector k i in this direction wave vector is a vector of course and it is propagating in this direction and it is a plane wave you can consider for example you can consider plane wave means you can just consider something like this maybe you can change the color. So, you can consider something like this these are the plane waves sorry.

So, parallel phase front and you can say that this is your lambda in that medium. So, if this is the plane waves making an incident at a normal say consider here region here. This dashed line is the normal drawn perpendicular to the YZ plane at O and the wave vector making an angle with this normal is theta i then what happens in the interface normally because 2 medium, medium is different one medium is creating one type of impedance, second medium will be another type of impedance.

So, what there is an impedance mismatch, so because of this impedance mismatch fraction of the power or wave will be reflected back with an angle theta r and rest it will be transmitted to medium 2. And corresponding your wave vectors are shown here k t and here k r. And also we can consider that since it is the plane wave we can define by electric field E i E 0i it is a constant and it has a vector and then phase factor k i dot r - omega t of course you are considering monochromatic wave single frequency monochromatic wave monochromatic plane wave.

So, it is making an incidence and corresponding magnetic field is this one. Similarly I can represent transmitted electric field and magnetic field k t it is defined by k t in this case k t is the proportion vector and it is k r similarly we can consider reflected 1. So, far so good we can see that there will be some situation can occur and plane wave remain plane wave in the transmitted second medium. And plane wave will remain plane wave when it is getting reflected if that type of linearity we have considerable the medium will consider linear.

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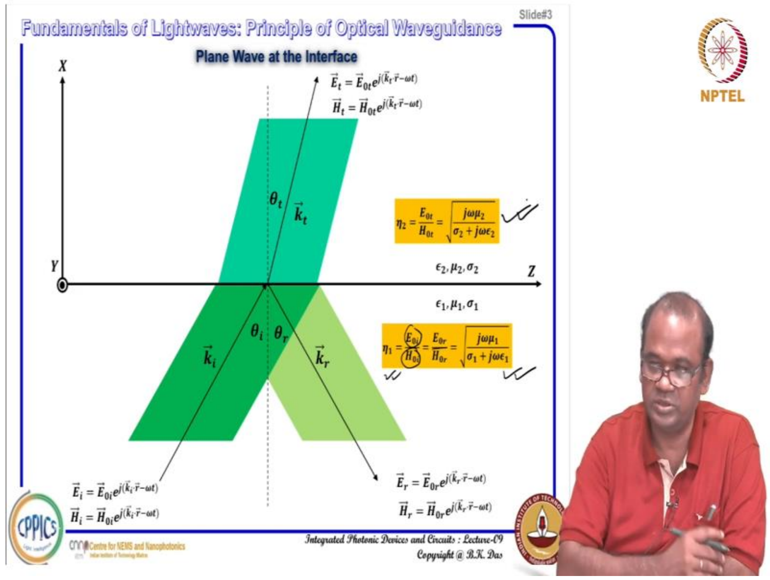

Now you see we have one more characteristics to define one is eta 1 that is the characteristics impedance that is nothing but you have to take the amplitude of the electric field and amplitude of the magnetic field, normally they are most of the time they are not in same direction they are orthogonal you take the ratio. And that is the amplitude divided by amplitude and that we have derived earlier in terms of frequency omega and conductivity sigma 1 permeability mu 1 and permittivity epsilon 1. Similarly for second medium eta 2 is this one fine.

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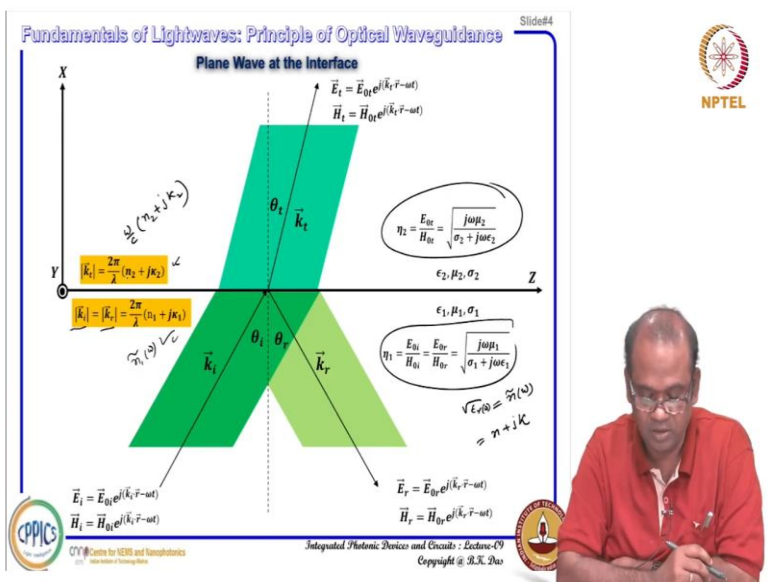

Now we also know that what is k t and what is k i? k t is actually you know 2 pi / lambda it can be written as omega / c and n 2 + j kappa 2 you know because of this all these parameters are there we know that refractive index normally we can represent square root of epsilon r, if it is a lossy medium or so epsilon r normally we consider something like this, if it is omega frequency dependent do you write our frequency dependent.

And that is normally we represent that n real part of the refractive index and imaginary part of the refractive index called extinction ratio. So, k t will be 2 pi / lambda can be written as a frequency by velocity of lights c and n 2 that means a real part of the refractive index in medium 2 and real imaginary part of the refractive index in medium 2. Similarly k i and k r must be same because they are in the same medium 1 we can here n 1.

So, this can be written as n 1 omega complex refractive index n 1 + jk 1 kappa 1. So, since k i and k r in the same medium they are absolute value would be same that is what we have written here and for k t we have written only their direction is different and their value will be also different for k t and k i if you can compare fine.

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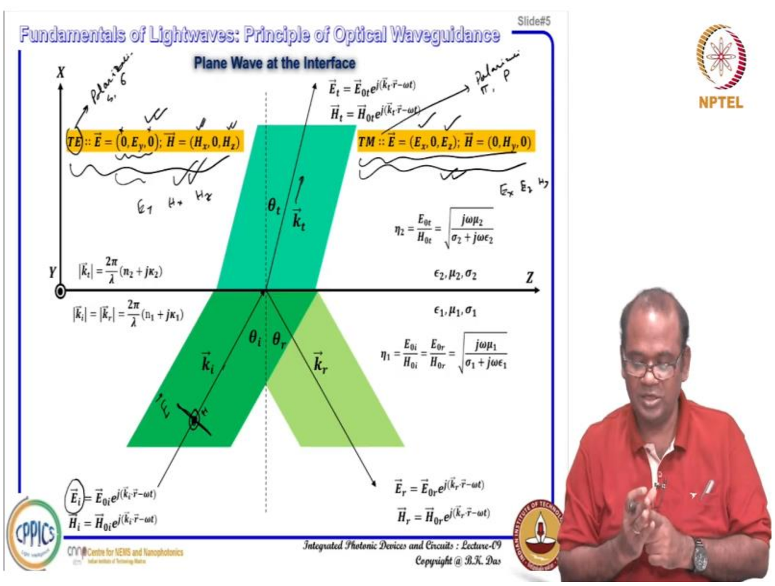

So, now we can consider let us concentrate a little bit on our electric field vector we know that we have already represented the wave vector direction of the wave vectors for incident wave, this is incident wave, reflected wave and transmitted wave we have represented already. Now we know that this is plane electromagnetic wave associated with the electrical field and magnetic field. We have the liberty to consider a special case for understanding purpose.

Which is called TE polarization we can call it is as a TE polarization sometimes you can consider TE polarization sometimes, it is called sigma polarization, sometimes it is called S polarization. If you have S polarization for that with this reference frame we can consider electric field will have only oscillating along Y direction only y component will be there. So, electric field will be oscillating perpendicular to the screen and no x component, no z component of the electric field represent.

So, called electric field is in the this is your E y in this direction perpendicular to the screen the magnetic field can be perpendicular to the both k i vector as well as perpendicular to the electrical vector electrical field E y. So that means magnetic field this one H, H can have the components are H field can oscillate in XZ plane meaning H field will have x component and z component.

So, if this is the situation then absolutely fine a plane wave can propagate along k i direction. So, if a wave if an electromagnetic wave has a electric field component oscillating along Y direction and magnetic field is oscillating in the XZ plane but both are perpendicular to the wave vector k i then we can ensure that wave which propagating energy can be carried in this direction so far good. Similarly we can consider another combination where this field, this electric field will be oscillating this can be your electric field.

And this can be your, this is your electric field and this will be your magnetic field. Magnetic field will be in the Y direction and electric field will be in the XZ plane. So, I have written here XZ plane electric field E x component is there E z component is there, y component missing and y component of magnetic field will be there and that also another kind of situation you can assume show that electromagnetic wave can carry energy in the k i direction.

So, what we made confirmed that if k i propagation direction is there that means electric field and magnetic field can be perpendicular to the k i and they are combination can be decomposed into TM polarization or TE polarization any polarization, any direction electric field is oscillating perpendicular to the k i you can decompose into these 2 different combination and you can treat them independently.

And at the end you can just check them what is the resultant effect. So, sometimes again likewise TE polarization TM polarization also sometimes it is called TM polarization of course and sometimes it is called pi polarization and sometimes it is called what you call that pi P polarization. So, this is sometimes S polarization, sigma polarization. So that way different textbook normally they define like that.

So, we can consider 2 different types of polarization for our understanding purpose for our analysis purpose. The actual reason to consider this type of components set of components all the 6 components can have an electromagnetic wave propagating in k i direction all the 6 component can have but out of these 6 components I can make ensure that these 3 components E y component H x component and H z these 3 component are good enough.

Another set you can consider E x, E z and H y component good enough to ensure energy propagation in this direction you can independent thing TE polarization, TM polarization as I mentioned region actual reason to consider that thing is that to utilize the boundary condition what is that?

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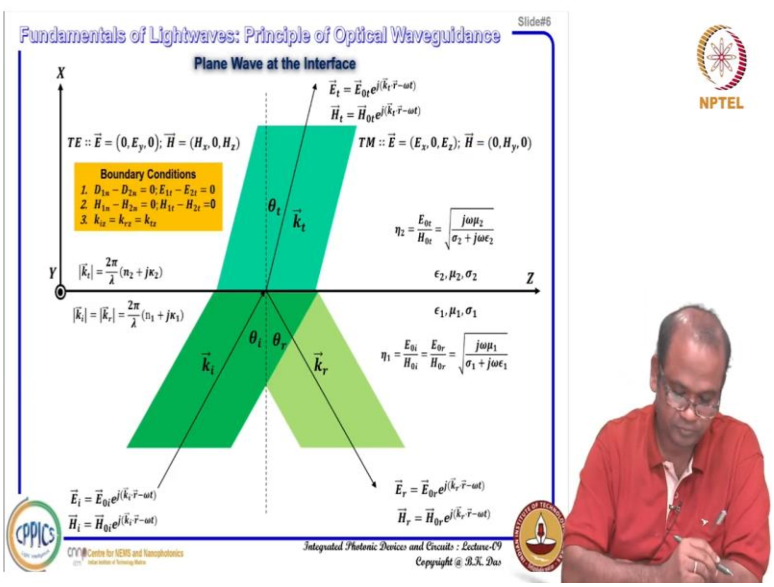

Boundary conditions according to our Maxwell's equation, Gas Law etcetera we can derive a set of boundary conditions that is you know how to derive that in basic electromagnetic book you can find. That normal component of displacement vector you know displacement is nothing but displacement vector is epsilon E. So, if you see displacement vector wave propagating from medium 1 and it has some part is medium 2 and something reflected back here.

So, you can see that exactly you just consider x = 0 minus coordinate and x = 0 plus coordinate this 2 ordinate point just above the interface and just below the interface. If we just compare for example here exactly at o if I consider x 0 plus and x 0 minus I can find out what is the total displacement vector in medium 1 and I can find out what is the total displacement vector in medium 2 when I say the total displacement vector in medium 1 that means I have to consider incident wave as well as reflected wave their resultant.

So, they are some of their displacement vector you take the normal component. And normal component the second medium displacement vector normally they are continuous. So that is one boundary condition we can that means normal component means that is normal to the YZ plane if we have a component of displacement vector normal to the YZ plane in medium 1 and medium 2 exactly at x 0 + 1 and x 0 - 1 they must be equal. Normally they can be some value if in the interface there is a charge available.

We are considering there is no charge in the interface. So, we can consider that and if you see the tangential component of the electric field in medium 1 and tangential component of the medium 2 they must be also equal E 1t and E 2t. E 1t in medium 1 I have to consider electric field total electric field of incident wave and total electric field of reflected wave and medium 2 only transmitted wave.

So, they should be also continuous similarly for magnetic field normal component and a tangential component when there is no current flowing across the interface. So, if we just use these 2 use this boundary condition it would be easier if I have electrical only E y component meaning that is the exactly tangential component in the interface and for TM polarization only component magnetic field H y that is tangential component to the interface.

So, it would be easier to analyze the all the ray all the waves reflected and transmitted to how they behave how much packs and it will be reflected how much packs and will be transmitted that will be easily can be derived. So, this is a main reason of considering the TE type and TM type thing so that you can treat them independently you have to use the boundary condition and using this boundary condition one more important thing you could find out here.

k iz that means k iz if I have a theta i k iz = k i so called theta i this one is theta i. So, this is 90 – theta, so k i sin theta I, k iz = sin theta i and similarly if I just tried to find out k rz it is nothing but k r sin theta r and if I just find k tz Z direction this component k t sin theta t. So, these are actually we are assuming that is the tangential component of the wave vector in incident wave this one, reflected wave this one and tangential component of the transmitted wave this one.

According to the boundary conditions they must be equal. All are of equal amplitude that is actually boundary condition hence used. But you can see that overall k t vector k r vector they are in different direction compared to k i if you will compared with this one why that happened? That happened because of the k ix component and k rx component and k tx component they differ normal component of the wave vector the differ.

So, because if the normal component defaults so that this is k tx, k tz and k tx if it is their variation is different. So, you can think of that their angle will be different. So that is the reason the reflected wave transmitted wave they can have can occur differently, their angle can be different good so far so good. So, we have defined that electromagnetic wave plane electromagnetic wave in the interface of 2 medium, what can happen mathematical setup already established and known.

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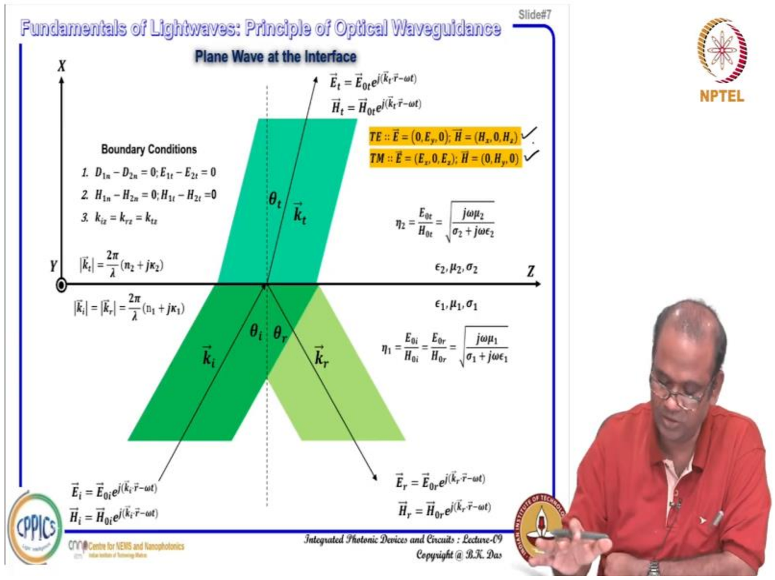

Then what we should think now next thing is that well we just again picks that either we are considering TE polarization, TM polarization I just mention here all the things are refreshed here now. So, all the parameters we know where from they are coming how to derive that that must be known to you.

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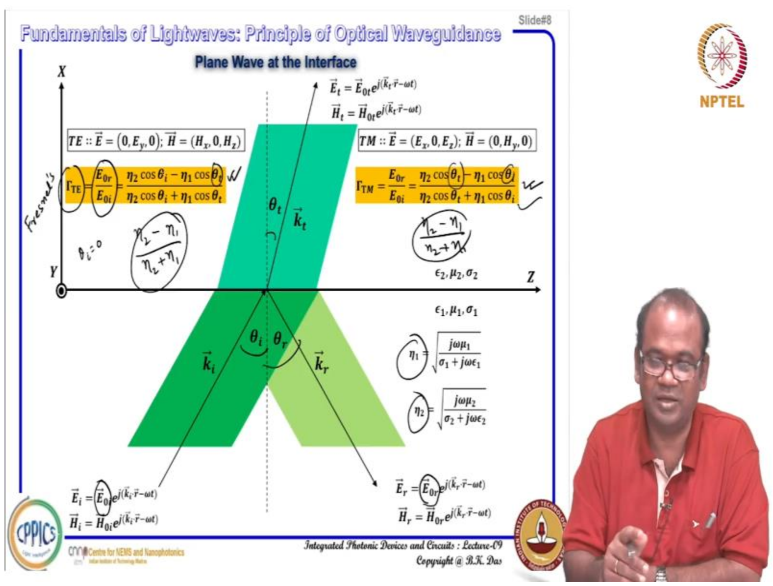

Now using the boundary condition I can find out for TE polarization that what is the reflected amplitude coming here and what is the incident electromagnetic wave amplitude if you take the ratio reflection by incident that will be called as a reflection coefficient, amplitude deflection coefficient we call it as a gamma TE because TE polarization if we just consider TE polarization will have certain boundary conditions, E y is the tangential component using that we can find what is the reflection coefficient for TE polarization.

Similarly utilizing the boundary condition that is a few steps you can do any electromagnetic textbook you can find those things. So, here also for TM polarization I can find this thing. You see if you just compare they are almost identical looking only thing is that theta i and theta t they are interchanged, the first term theta i was there and here first term is theta t. Theta t, theta i otherwise numerator denominator you see they are same plus minus only.

So, reflection coefficient for TE polarization and for TM polarization we can derive in terms of characteristics impedance, so called intrinsic impedance of the medium to media eta 1, eta 2 and they are of course theta i dependent. Obviously these are actually first time derived y using boundary condition it is Fresnel. So that is why they are called a Fresnel equation Fresnel’s law of reflection or Fresnel’s equation for reflection.

Obviously you can find theta equal to so called 0 degree normal incidence suppose this theta is normal incidence. So, theta t also will be 0 theta r will be same direction it will be reflected all will be 0 then that case for normal incidence theta i = 0, then this reflection coefficient will come eta 2 - eta 1 divided by eta 2 + eta 1 and here also eta 2 - eta 1 divided by eta 2 + eta 1. So, they are identical both the polarization for normal incidence.

The reflection coefficient the same this one and this one same for normal incidence only they will differ if they are making an incident with an angle and if it is angle if you see theta t here and theta i that way you can just try to TE polarization TM polarization can see different types of reflection coefficient fine.

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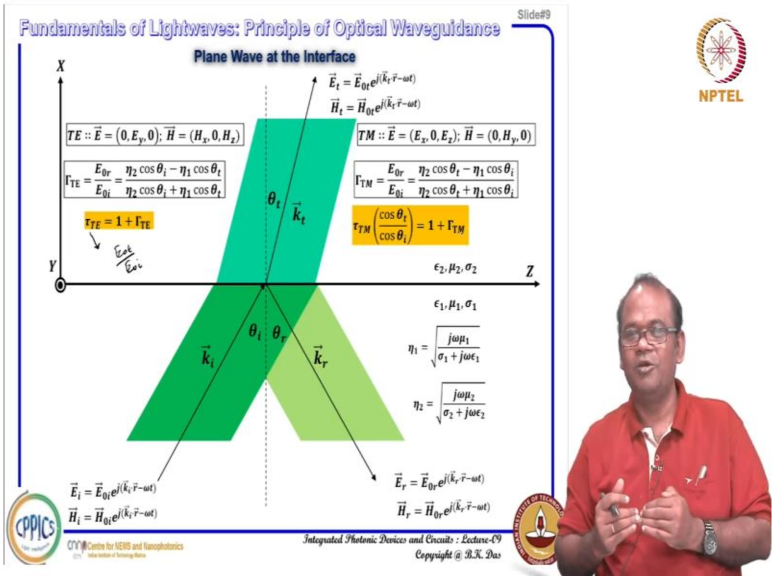

Now reflection coefficient is there if I am considering that YZ plane in the interface nothing is being lost absorbed, no absorption loss nothing is happening in that case we can find out what is the energy is conjunct. In that case we can see that how much energy how much transmission is there transmission coefficient. Transmission coefficient means this transmission coefficient I can say that it is nothing but E 0t / E 0i transmission coefficient for TE polarization it is simple.

If you know the reflection coefficient you add 1 then it will be transmissions coefficient and that is also can be derived from the boundary conditions. Similarly for TM polarization it is same but apart from that you have to multiply for the transmission coefficient cos theta t / cos theta i again if theta t and theta i = 0 theta t = 0, theta e = 0 that is 1. So, it will be normal incidence they are same basically only if it is angle is different then only your transmission also will be different.

So, now we know that how much fraction of amplitude is transmitting how much fraction of amplitude will be reflecting. So, if you have both mixture of TE and TM polarization you will see one of the polarization will be reflecting more and another would be reflecting less depending on the angle as long as this angle is not 0 normal incident.

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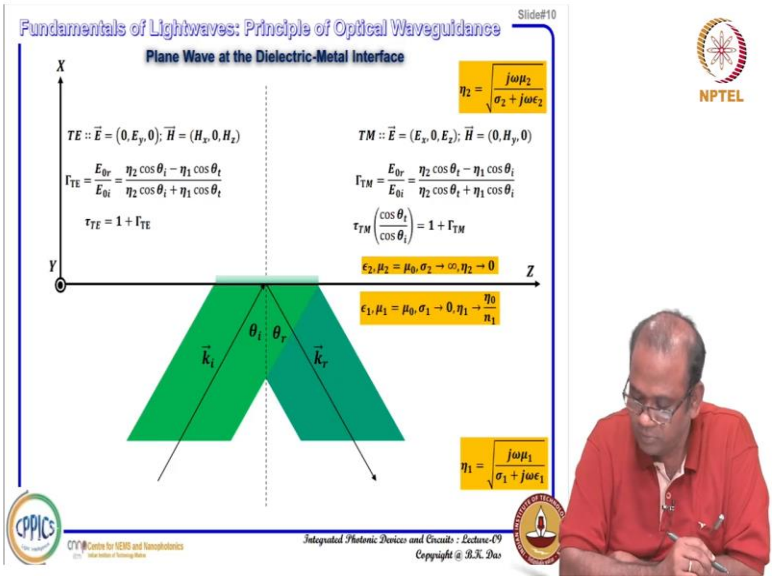

So, now little bit move on special case I have just moved eta 2 is same thing I have written here eta 1 here and special case we are considering, what we are considering? We are considering that first medium is a dielectric medium. So, it is a lossless sigma 1 = 0 if I consider and it is a non magnetic material mu 1 = mu 0 that means mu r = 1 non magnetic material, permittivity is there permittivity epsilon 1 you can say epsilon 0 epsilon 1r that is there.

So, it is a dielectric medium if you just insert all these in this equation then you will get eta 1 = eta naught / n 1 where n 1 = square root of epsilon 1r dielectric constant square root you take that was that is a refractive index that is actually called the refractive index that means I can characterize medium 1 if it is dielectric I can just represent eta value is eta naught / n 1. So, if you know refractive index then characteristics impedance you can just factor it then you can get the impedance eta naught / eta 1.

And medium 2 it is a completely different instead of signal 1 equal to tends to 0 we consider sigma 2 tends to infinity very large value high conductivity is a metal that means I am considering medium 1 equal to dielectric and medium 2 is a metal, what happens for that and also non magnetic metals are mostly non magnetic. So, mu 2 = 0, so mu r also here we are putting 0 and epsilon 2 we can just write again epsilon 0, epsilon 2r so far so good.

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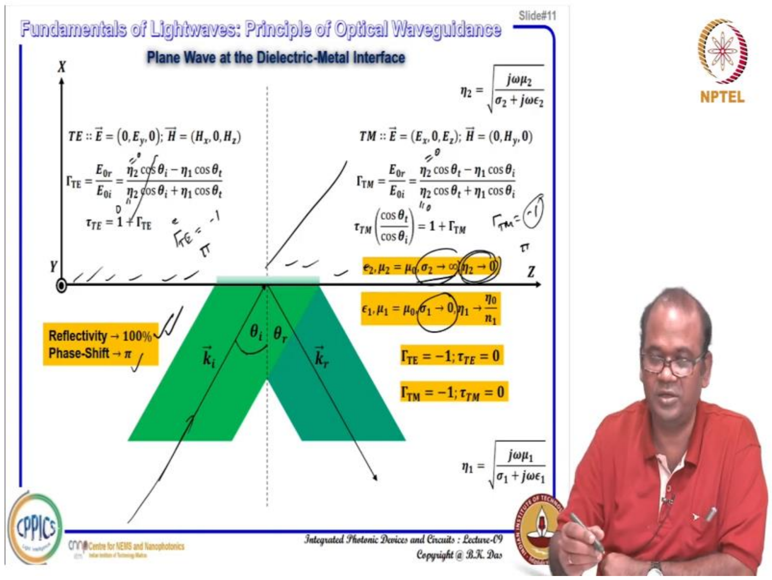

Now if you just put I know that in this case eta 2 will be equal to if you just put here sigma 2 infinity that means eta to tends to 0 something divided by very large value, so eta 2 tends to 0 I have written. So, eta 2 tends to 0 if we are putting 0 here, 0 here, 0 here, 0 here both the polarization what happens. Then gamma TE will be what? Gamma TE will be equal to you can write gamma TE will be equal to minus 1 because that one will be 0.

So, eta 1 eta 1 - 1 and here that is also gamma TM will be minus 1 that means reflections coefficients when it reflects both for TE polarization, TM polarization the reflection coefficient in what's that means completely reflected with minus sign that means pi phase shift, you are introducing pi phase shift upon reflects on both the polarization TE and TM. So, the first medium is the dielectric of medium.

And second medium wave it is coming from a dielectric homogeneous dielectric medium and then you have an interface of metal this is for examples and metal then what happens for any angle theta i can be anything your wave will be completely reflected and it will be phase shift pi phase shift will be optic. So, this is the beauty I am not considered any frequency here. With a low frequency, large frequency or whatever some arbitrary frequency as long as you consider at that particular frequency sigma 1 = 0 and sigma 2 = infinity.

For the second media then all the frequency to be reflected back. So, it can happen for micro wave guide also and it can happen also for the optical frequencies also microwave frequency as well as optical frequency this is valid if you can find a metal where sigma conductivity is very large. And you can find a dielectric conductivity is absolutely almost near to 0 so that type of situation if it is there then the electromagnetic wave can be reflected with pi phase shift both lower frequency as well as higher frequency only consideration is the conductivity.

The frequency were consideration at that particular frequency the conductivity should be large in the metal and very low towards 0 in the dielectric then it will reflect. So, I say that reflectivity nearly 100% and phase shift is pi that is why I am not shown any reflected wave rather I shown little bit here what is that you know what is that because metal if you have some kind of incident electromagnetic wave, metal normally because of the high conductivity you know it cannot propagate it normally attenuate.

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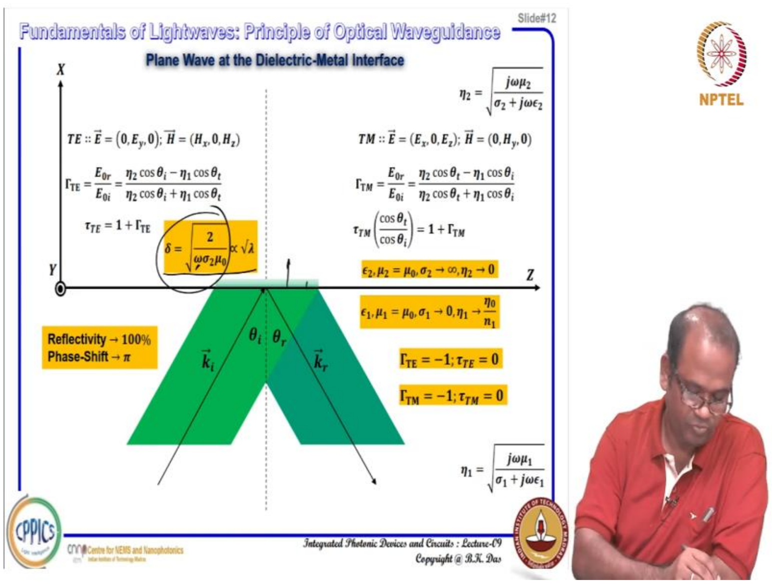

So, this attenuation you know up to this skin depth it can attenuate and then skin depth I can just derived it earlier already this is delta if you know frequency too why frequency and conductivity some conductivity will be there it is large but whatever value is there you can put down mu 0 that thing you get the bit it will be penetrated. So, if you just a little bit simplify here it is proportional to square root of lambda what does it mean?

Square root of lambda means inversely proportional to frequency of course omega is inversely proportional square root of frequency that is thing, so when lambda is increases then this delta will be increasing skin depth it will be penetrating more inside the material, but when lambda is small frequency is high towards optical frequency then this delta will be almost 0 nothing will be there inside little bit will be going inside.

So, for lambda penetrating more you can imagine that when it penetrates a little more there can be some kind of heating effect some kind of resistive loss, attenuation because of the attenuation some loss will be there but when very large sigma and very high frequency this delta will be less it will be less penetrating, so loss will be less. So, you can consider almost 100% reflectivity per optical frequency microwave frequency also you can see that loss is very minimal. So, if this is the case for micro wave particularly.

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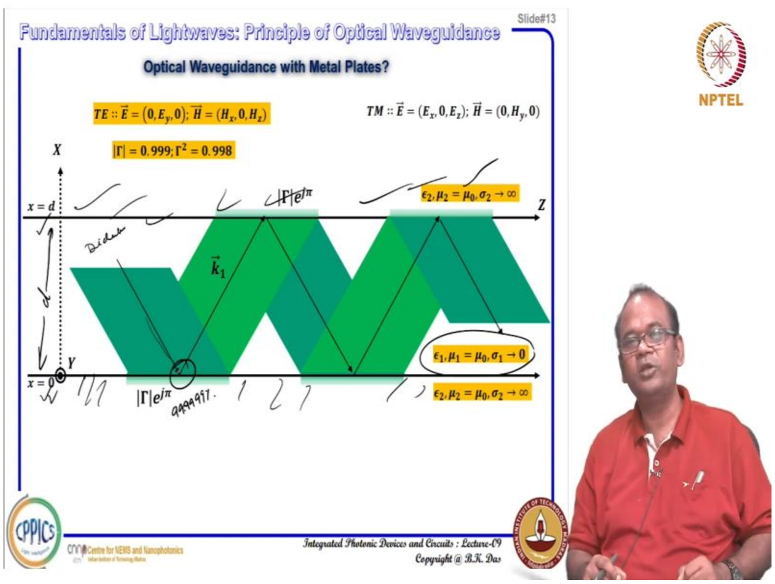

we use micro waveguides if you are using a 2 metal plate 1 metal plate here at x = d another metal plate at x = 0 then any wave comes here for any angle, this is a metal, this is metal and inside you have a dielectric medium just consider the dielectric medium with this definition. So, this metal and this metal may be identical metal, metal plate you are considering which is parallel to the YZ plane perpendicular to the X axis.

And you can make their separation as d, this is the d separation you can consider then any wave any angle you come that will reflect completely come back, come back and goes like this it can happen a little bit it can be some lossy it can happen that 99.999% maybe it will be reflected, little bit will be loss. So that is the principle used for microwave waveguide this is 1 dimension you can make like a box.

Inside the box you can actually you can launch microwave signal then it will be going back and forth reflection and it will be propagating that is the basic principle because metal reflects electromagnetic wave, so that is why you can design waveguide also dielectric insight and you can make a box that is a microwave guide. So, now my question is that what is the problem if we use same thing for optical waveguide for optical interconnect that is the important question now I want to discuss.

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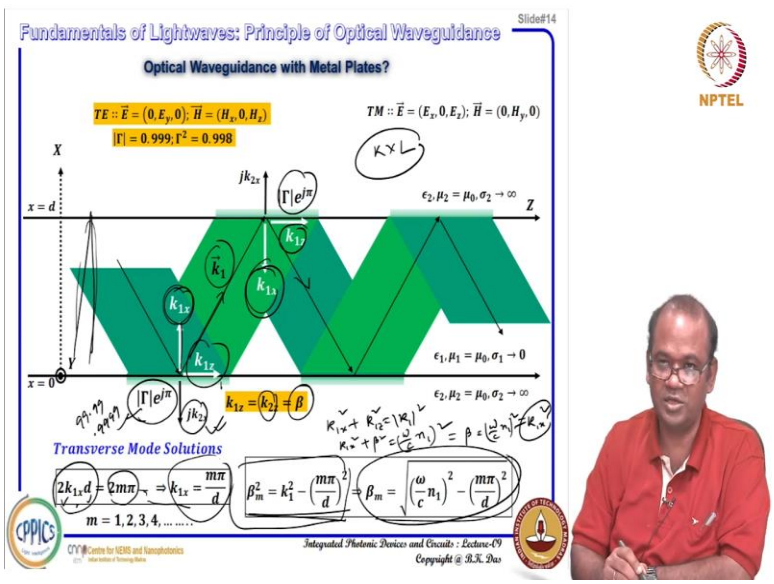

Just think about that, let us consider like this that wave vector this is k 1 wave vector coming and you know that this is k 1x dielectric material medium. So that is the x component that is the z component and when you reflects back x component that is the z component and we know that this k 1z, k 1z they are normally same and k 1x is just important and we know here reflection will be there some value reflections this gamma can be 99.999% or maybe 0.99999 you can put gamma value.

And you have e to the j by phase shift will be there, same thing will happen here and repeatedly go back and forth reflection which should happen like that and this here whatever it will be penetrating the skin depth. And you can imagine that something in the X direction completely it is imaginary. And that is why it is attenuate risk after the skin depth that is clear all at. Now you see you can actually decompose when we are propagating this direction and coming back this direction you can see only k 1x.

If you just consider k 1x you are considering they are actually counter propagating wave component. So, if this reflection is not the only condition for guidance one more thing you have to consider that this wave component propagating vertical direction after a round trip travel they should complete 2 pi phase shift 2 pi times integer. So, what is a phase shift k 1x if it is a wave component propagating in this direction some component wave vector component is this one.

So, round trip means d and coming back d so 2d. So, normally you know wave vector multiplied by l that is actually phase round trip phase. So, round trip means 2d, 2d times k 1x we multiply that is the phase round trip phase. Round trip phase if it is 2 m pi 2 pi times m integer m equal to 1, 2, 3 and so on. Then this round trip phase can cause certain kind of mood solution it actually ensures that round trip k 1x component actually creating certain kind of standing wave in the lateral direction X direction.

And that standing wave depending on k 1x value you can consider one mode. So, from here you can actually find out what is the k 1x? It is a micro waveguide these are actually you have learned earlier if you have studied any electromagnetic theory course. So, then from this equation you get k 1x = m pi / d. So, that means k 1x this x component will be discretized based on m equal to 1, 2, 3, 4 so on and depending on the d value d is the separation.

That is I am just considering only confinement here on the mode. Now you know you have this condition k 1x square k 1z square that should be equal to k 1 square wave vector. So, k 1z must be k 2z even if it is some field is in the skin depth that is k 2z is present this would be equal tangential component wave vector this would be equal that we define that as a beta. Now we can say that k 1x square + beta square = k 1 k 1 is omega / c n 1 square.

Now from here I can write beta value. So, this one I can write beta square = omega / c n1 square - k 1x square. So, this k 1x square I know this 1k 1x square. So, I can write v times beta m square equal to this one. So, since k 1x is discretized for a certain mode I can find that mode we have will have longitudinal propagation constant k 2z, k 1z that will be also discretized depending on the m equal to 1, 2, and so on. So, we have written down like this n is the refractive index n 1 here. So that means this k 1z also discretized, k 1x is also discretized to have a standing wave pattern along lateral direction X direction fine.

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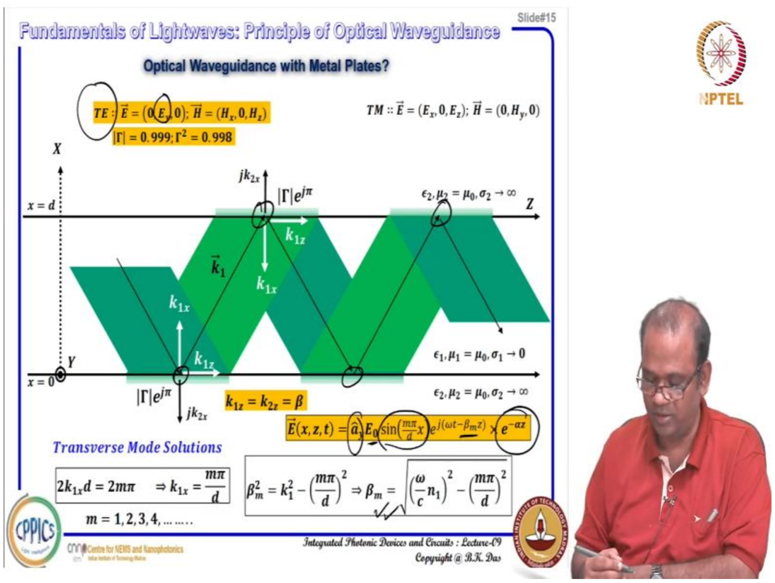

Now you see then any wave that mode can be expressed mode propagating along Z direction can be expressed that if it is just TE polarization only E y component present then I can say that E y component E 0 and standing wave I can define like the sin m pi / d x. So, x = 0 value will be 0 x = d that value m pi that will be equal to 0, m equal to 1, 2, 3, 4 so on different type of modes you can have.

And corresponding mode we can have that mode we will have longitudinal component beta m that is defined by this equation. So, this is your propagating mode along with that we just added one more part e to the power -alpha z that is basically as it propagates it will suffer certain kinds of loss were found that loss comes because every reflection you see it is a metal interaction, metal interaction some loss will be there. So that is why you can see some kind of little bit of losses will be there. So that you have to count for that loss is very important.

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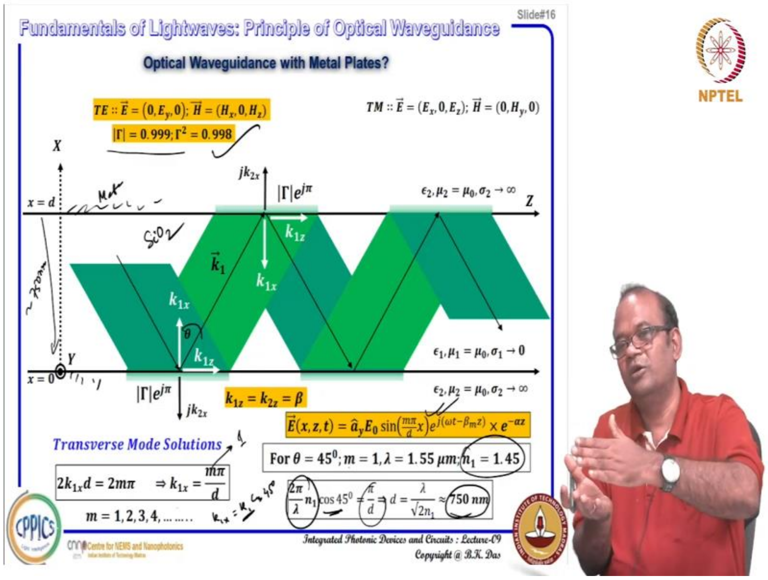

So, microwave normally if this way please consider the optical wave where lambda is very small. We can consider a typical example we consider say gamma equal to this one and gamma squared will be this one that reflectivity little bit loss is there in optical domain for example. And if we consider this theta equal to some 45 degree and for a mod m equal to 1 I am considering here 1 and optical wavelength is a third communication window optical communication window 15, 15 nanometer 1.55 micrometer I considered and if you consider this a S io2 just silicon dioxide then silicon dioxide at that particular wavelength diffractive indexes around 1.45.

So, this is your metal, this side is metal and this is metal for example I am just considering if I consider optical wave whether this can be useful for waveguide and that can be also this type of mode can be there or not that is the understanding. So, now we see that n 1 given lambda given m 1 I am considering 1 for fundamental mode for example m = 1 theta 45 degree then what do we get? We get this value k 1x, what is the k 1x? k 1x will be k 1 times cos 45 degree.

So, k 1x x component will be k 1 cosine 45 degree and k 1 = 2 pi / lambda n 1 propagation vector cosine 45 degree that k 1x if m = 1 you are putting that will be pi / d. So, k 1x means 2 pi by lambda n 1 cos 45 degree and m = 1 pi / d. This gives you all the value lambda and n 1 cos 45 degree value you put then d value comes 750 nanometer.

So, if you are interested to use optical waveguide metal optical waveguide the thickness of the waveguide this thickness this would be in the order of 1 micron or 750 nanometer depending on the wavelength fundamental mode if you are just confining in that direction 750 nanometers. Now suppose you are you can 750 nanometer and metal plate in between 750 nanometer oxide you can actually design without any problem that is fine but what happens?

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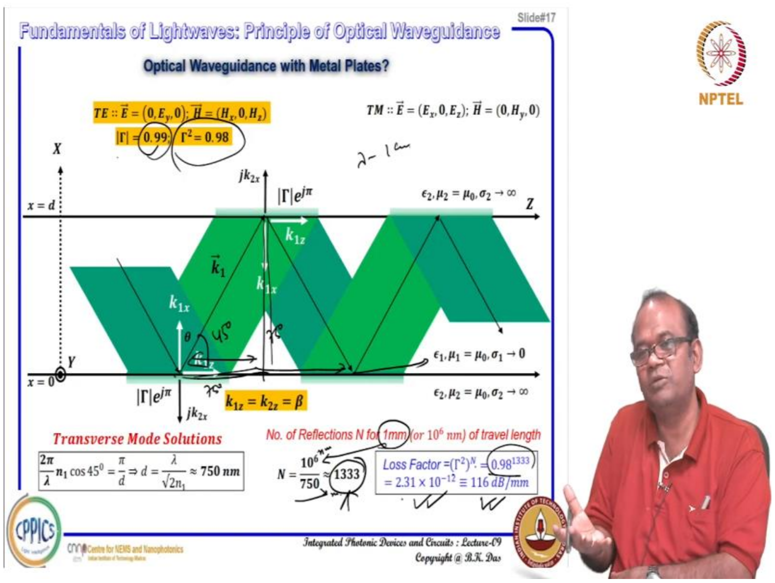

Let us consider that how many reflections and require to travel 1 millimeter of length you want to design 1 millimeter such waveguide optical waveguide. I would like to understand how many number of total internal reflection it is not total internal reflection, reflection taking place in every where there suppose if it travels this length then it is one reflection another length one more reflection one length one more reflection.

So, one reflects on how much length it travels along the waveguide this is 45 degree and this is 750 nanometers d, so this also will be 750 nanometers. So that means for 750 nanometer travel it needs 1 deflection and for 1 millimeter means 10 to the power 6 nanometer, 10 to the power 6 nanometer divided by 750 nanometer this is also nanometer 1 millimeter and then this is also nanometer.

So, you need at least 1333 the simple calculation it gives you 1333 reflections required just to travel 1 millimeter and if you are considering every reflection it contributes 0.99 reflection reflectivity these many number of reflections if it is happening so what will be the loss factor. So, loss factor will be this power if it is gamma square means power loss factor power is gamma squared equal to 0.98 gamma square to the power n.

If I just consider gamma equal 0.99 gamma square means power reflection coefficient is 0.98 and n reflection happens; every reflection you get 0.98 factors. So, 0.98 multiplied by this many number up to the power 1333 that gives you a very small number 2.31 10 to the power -12. So, basically these value actually gives equivalent to about 116 db loss per millimeter you imagine if you can design your; so called metal optical waveguide.

But you have to put this much loss which is very difficult you want to use this as a optical interconnect. So, this is impractical completely impractical but this is very good for microwave you know microwave you are considering maybe wavelength in the order of 1 centimeter so 1 centimeter 1 to travel few centimeter few centimeter, few centimeter length you can have a few reflections only, only few reflection you do not have much losses.

Whenever you are considering optical frequency you are dimension scale down once the dimension scale down number of reflections will be more and more reflections and more and more reflection means each time you are contributing the loss factor. So, ultimately you will be getting very less amount output. So, this is heavily loss so that this is not really possible to have your optical waveguide metal waveguide are completely not suitable. So, what is the solution?

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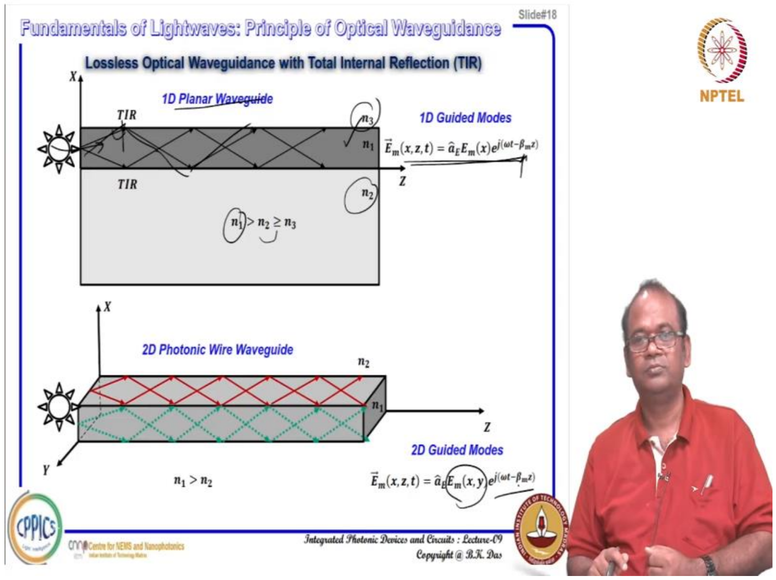

So, solution is that we have to rely on total internal reflection instead of metal we have to find out new type of things what is the optical fiber? You know all those types of things. So that is why we have to go for nearly dialectic here light higher frequency can undergo some kind of total internal reflection for a certain angle that angle must be greater than critical angle. So, we can have a layer one the plenary guide one higher refractive index n 1.

And then substrate can be lower diffractive index and top can be another refractive index dielectric all are dielectric 3layers of dielectric then n 1 if it is greater than both n 1 and n 3 then any light coming in it can undergo some kind of total internal reflection for a certain angle, if it is incident angle is more than critical angle. So, reflection so you can have the mode will be like this mode can be guided along z direction with a propagation constant beta m similar to electromagnetic microwave whatever we have considered.

And your field will be confined along the X direction because of the total internal reflection and if you can create this type of structure you can have 2D photonic waveguide. So, you can have total internal reflection in 2 dimensions both X axis as well as in Y axis, X direction as well as Y direction. So, in that case you can have a field distribution confined in XY plane well defined shape will be getting a mode and that mode will be propagating like this.

So, this type of waveguide normally we are looking forward to design optical interconnect in silicon or anywhere silicon on insulator for example.

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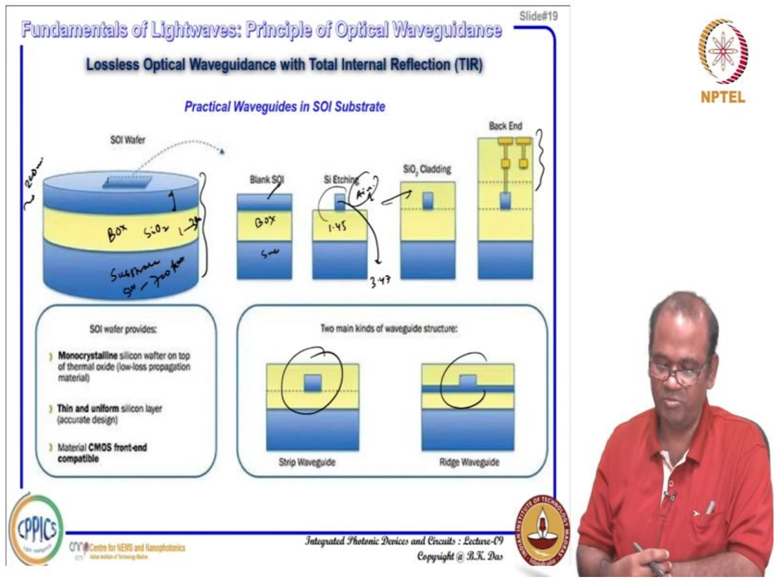

This is the silicon on insulator commercially available 300 millimeter it is a 3 layer system this is called substrate 700 micro meter thickness 500 to 500 to 700 micro meter normal typical thickness substrate for handling purpose. Then you have a box basically silicon dioxide it can happen 1 to 3 micrometer thickness. And then top layer in the order of say 200 nanometer or more layers also more or less it can happen these type of waves are available.

If you take a particular squares shape of the wave for then you can just particle you can see box layer substrate silicon and SOI this is basically actually silicon thin layer of silicon will be there and if you edge like this then your silicon dioxide here, refractive index is around 1.45 and outside is here, it is refractive index is 1 and silicon refractive index is 3.47. So, you can actually design a waveguide photonic layer waveguide.

And here can be replaced by another silicon dioxide cladding and you can have all the CMOS technology different types of metal layers for reconfigurable structures etcetera, but biasing purpose etcetera, all this type of thing 2 different types of waveguide structures. Normally we will be using for optical interconnects. So, now next our objective is to understand how to design this single mode waveguide or multimode waveguide or certain waveguide property for special applications. That will be in the next lecture I will be discussing. Thank you very much.