Indian Institute of Science

Photonic Integrated Circuits

Lecture – 05
Channel Waveguide

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NPTEL Online Certification Course

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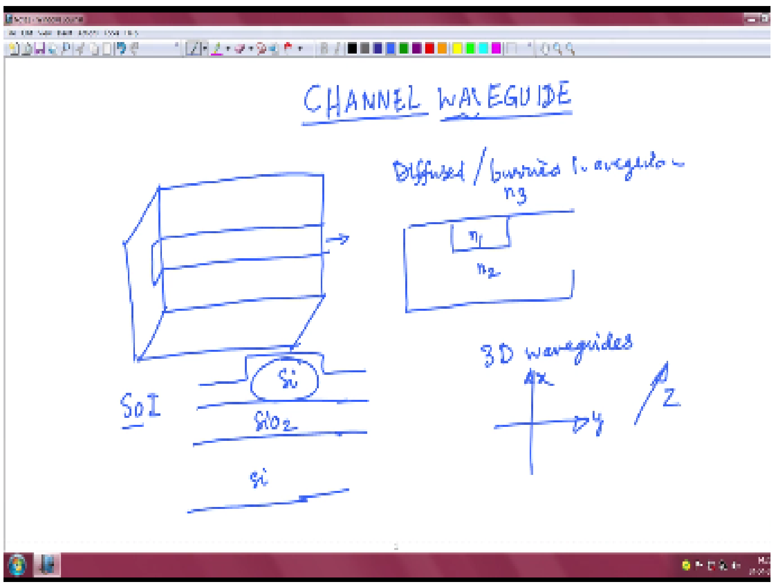

So channel waveguides are the main elements of integrated optical circuits which can be used to connect different components and also they can be used make many, many devices. So typical configuration of a channel waveguide is as follows, we have a substrate I am drawing the top view and also be all these projections. So we shall worry about how to fabricate these later on but you have a information that this can be formed by diffusing some material into the waveguide region the cross section will look like this.

So in this region the refractive index is higher than in the substrate social on slides into the input of the favorite you can expect the right to propagate in this waveguide and exit at the other end so there are many other important configurations depending on the technology that we used to fabricate these devices for example the most popular being the silicon technology where you have SOI waveguides this one for example can be called as a diffused or buried wave guide.

The silicon technologies have a silicon substrate is an oxide and on top of that you form what can be called as a ridge waveguide made of silicon. So these are cross section so the right propagates in this region, so all these of channel waveguides are three-dimensional they can be called as 3d waveguides because the right is confined in both X as well as Y directions maybe let us call this as Y and this is X will disserve X for the depth direction and Y for the width direction and the propagation direction is Z.

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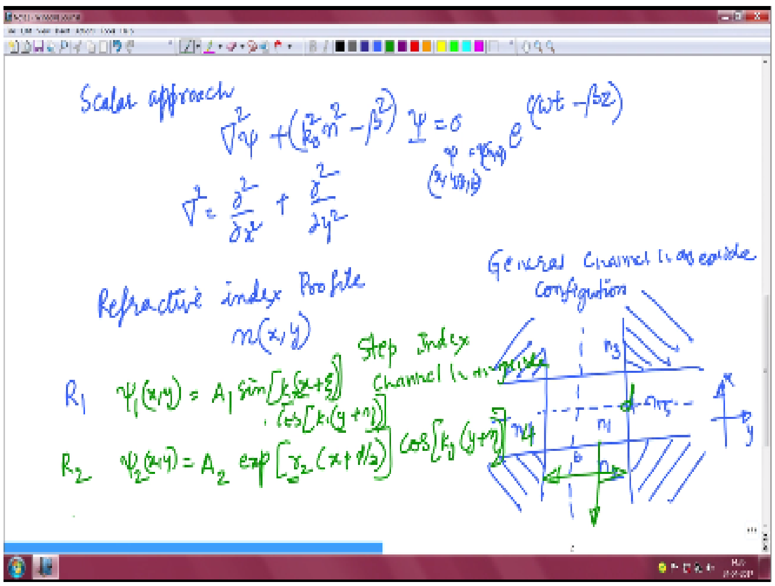

So now let us start with the scalar approach, we have been following scalar approach for the slab waveguide symmetric slab waveguide and asymmetric slab waveguide and we have seen that you can relate the scalar watch with the vector approach when we need to deal with the polarization in other issues in other discussion we will talk about the vectors approach for the time being let us start with the scalar wave equation and see what are the modes of a channel waveguide how to find out the β and how we can use the theory study earlier of the slab waveguides to design and analyze channel waveguides.

So this is scalar equation reveries scalar equation, so we have reduced it by assuming the type and propagation direction variation factor as $E^{i\omega t - \beta z,}$ so all the fields I have been assumed to be a function of only X, Y, X come by measure come at, so here the transfer slaplacian is given by ∇^2

with respect to X^2 and ∇^2 with respect to y^2 and the most important input parameters is the refractive index profile N is a function of X , Y compared to the slab waveguide where we have refractive index profile depending only on either X or Y we have refract next profile dependent on both X as well as Y here.

So let us look at a very generic channel wavelength which can be present almost all types of channel waveguide of course we will assume the refractive index profile to be constant in each of these regions. So let me draw a typical a general channel waveguide consideration, so it will look like this. So the refract X is n1 this region n 2 in the substrate using and 3 in the covered region and for side and n5 and you can also consider the refractive index in this corner regions but good approximation we can ignore the fields indeed corner regions.

It not make a lot of difference except one when we are copying the wavelets this is N4 and let us call the depth as D and width as d and the coordinate axis in the middle and as described earlier let us say why it is width direction and X to be the depth direction. So our object is to find the wave function ω of X , Y or the mode field profile you can call it and the propagation constant β, so taking clue from the earlier discussion about the symmetric slab waveguides and a symmetric slab waveguides.

We can express the field to be oscillating the guiding region and exponentially or exponentially decaying in the substrate and cladding regions but then you have a complication that is a function of two variables, so by in each of the regions by considering the field to be a product of fields the varying in the x direction in the field that varying in the y direction we can express the mode fields in each of the regions separately and then use the boundary conditions to find out what are the expressions relating the mode field the propagation constant and so on and so forth.

So that is the Z one, I use another cross you can express as ω 1 X , by let I am assuming the field the refractive next to be constant in each of these regions even though it is different across the regions it is a step index channel waveguide. When we separate the field in terms of x and y variations depending on the oscillatory nature or decaying nature of the field we can choose an trigonometry function or an exponential function for each of these X and y variations.

And also we are seeing a symmetric channel waveguide that is a combination of sine and cos for trigonometric functions and exponential decaying exponential rising for the dicing portions, so consider the field variations are as follows instead of considering A sine + B cos notation we can put the other arbitrary constant in terms of phase like this. So in the region 1 a 1 sine of KX I will define all these constants as we go along it will X + some arbitrary constant ω x one more oscillating field KY x Y + η.

So we can express the field in the guiding region as a combination of the product of sine and cos where KX and KY are constants representing the variation of a field along x and y directions oscillating. Similarly the region 2 we can express the field ω 2 this is region 2 where we have oscillating nature in the X direction and exponentially decaying nature divided erection. So for that we can express the field as follows.

K 2 is an arbitrary constant we can say exponential or checkmate sin of K X x X + ω same as at earlier but the X direction you know in the x-direction it is exponential I will call decay constant as comma 2 x-d/2- or + occurs because that caused arbitrary constant it will absorb other arbitary of the constants and along the Y variation I will call it as K/xy plus so I am using the decay constant γ - I will call this positive y-direction and d/2d is the depth.

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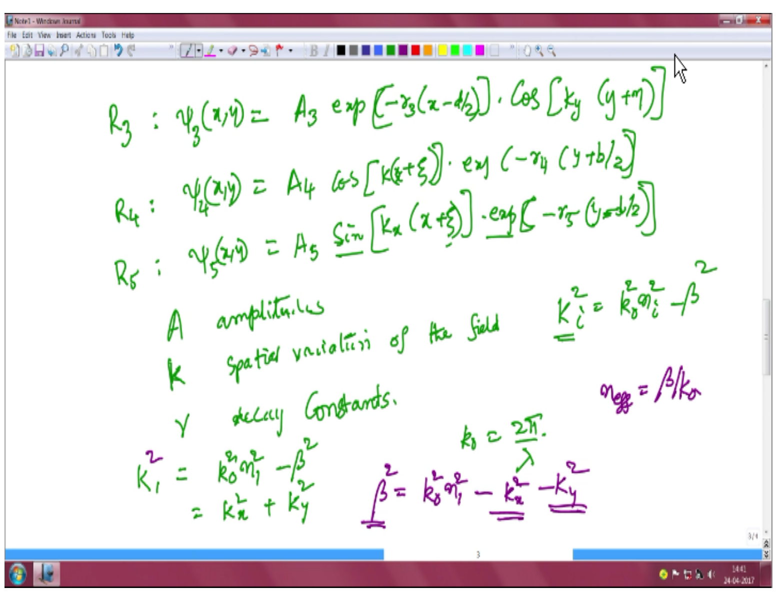

Similarly I will write for other regions Rz recently where we have ψ_3 of x,y given by A_3 into exponential - γ_3 x-d/2 multiplied by cos Ky(y+β the reason for the side force of x,y as a four multiplied by exponential of so region 4, region 4 is here.

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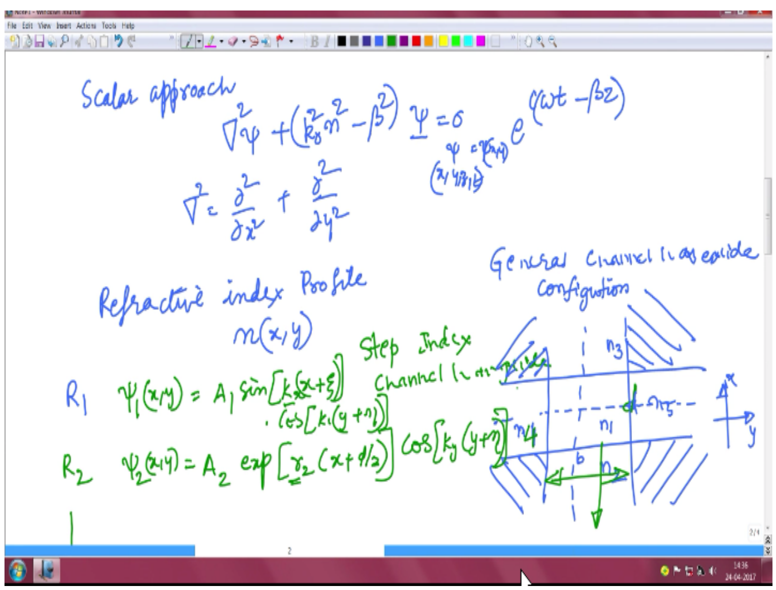

It is oscillatory with respect to X and exponentially decaying with respect to Y finally region 5 is similar region fourth and you can express our five in terms of and positive field sin our cos K_X into X +I and exponential of minus γ 5 y-v/2 I would suggest you to focus on the nature of the field and please take care of the arbitrary constants in a involved like sightly and whether we make the - key or + B will depend on the coordinate axis chosen and so on.

So now we need to define a bit about the constants involved you know that they are amplitude constant presenting amplitudes then K are constants representing spatial variation of the fields that is the constant K because they are useful presently oscillatory fields consider spatial frequencies and γ can be called as a decay constant but once again look more carefully at this constant K which are used for different regions.

So in general you can say that k_i are the constants of the form K_0^2 and $I^2 - \beta^2$ there k_i could be the oscillatory constants Ky γ which are the opposite β^2-k_0^2 i for so in particular the constants K the oscillatory constant K is important the region one and we would like to call it as K_0^2 N_1^2 - β^2 where K0 is 2ρ/λ and which can be expressed in terms of KX and KY as KX^2 and KY^2 in other words β can be written as β^2 is K_0^2 $N1^2$ – Kx2 –Ky^2 this was about a special significance that if we can if we are able to solve for Kx and Ky separately we can find out the propagation constant β and of course once you get the β we can find out the effective refractive index of the waveguide as β/K_0.

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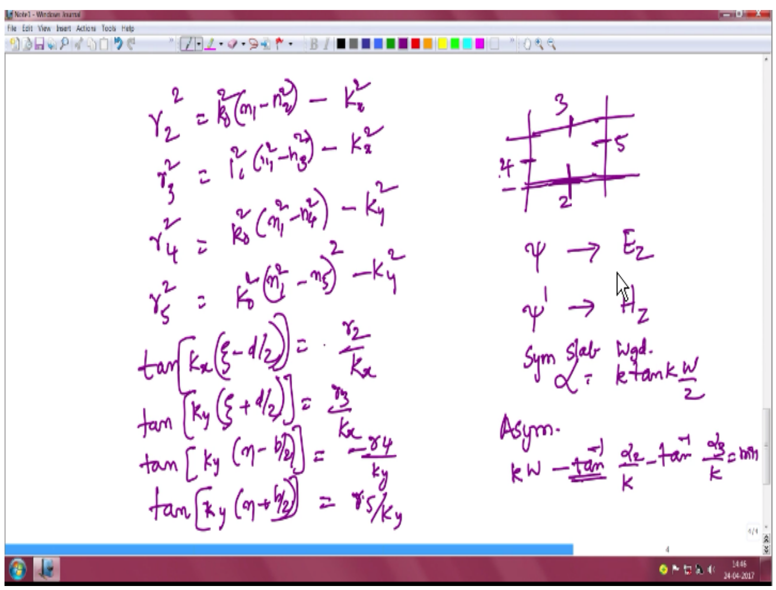

So let me quickly put down the definitions for the decay constants γ2 is $N1^2$-$N2^2$ k_0^2 –Kx^2 and γ 3 decay constants that we recently k_0^2 and 1^2 –$n3^2$-kx^2 because of second and third regions so both contains cakes and γ4 and γ 5 will contain $N1^2$ times in four squares minus K y^2 and come off 5,4^2 so 4^2 and 5^2 and y^2 we can take k_0^2 $N1^2$-$N5^2$ point ky^2.

We have Kx for γ 3 and γ 2 and K/4 so effectively we need to worry about solid for Kx and Ky which in turn would give us β so in order to find these all these constants we need to have the boundary conditions that the fields at the interfaces we can say that the fields are continuous as we do for the slab there waits within force the fields to be continuous across the boundaries and also the derivative of the fields.

To the continuous across the boundary just recall that the derivatives of fields could be related to the magnetic fields if the fields are related to the electric fields the so I represents the electric field variation the derivative sorrowfully could represent magnetic field variation or any of the components of this field depending on the way that you formulate the scalar wave equation you can choose appropriate form of the Ez and xz and relate them to the wave functions.

So finally we can say that will obtain like in the case of us symmetric slab they would recall that we have got the equations of the form α equals K times- kw/2 symmetric slab favorite and in the case of a symmetric slab we would also we have a combination of this like k the x w- an inverse α/K and α 2/ K and α3/K so effectively it is in terms of transcendental functions of 10.

So similarly we can apply the boundary conditions and obtain the, the characteristic equation for the dispersion equations to obtain the values of Kx and Ky so I will just right down and summarize later on I will put I am using a tan only a scale of approximation Kx into Z minus T by 2 is related to γ2/Kx and tan of KYξ+D/ 2 come a3/x and tan Ky β-d/2 –γ4/2 and at the arbitrariness of the sign used maybe finally with a combined is to get.

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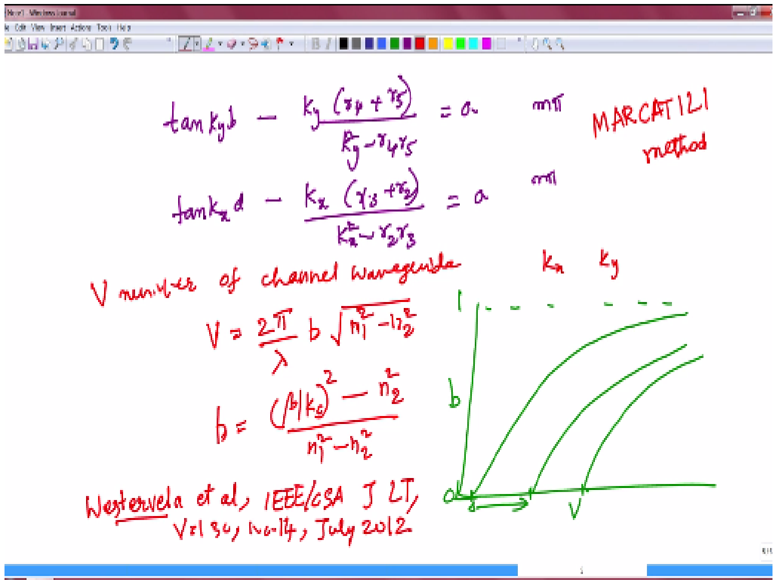

Here this $\tan K_{yb}$ – K_y x γ_4 + γ_5 divided by K_y^2 - γ_4 γ_5 = 0 and also tan K_xd - K_X x 2 γ 3+ γ 2 divided by K_x^2 - γ 2 γ 3 = 0 or mπ depending on when you invert it you can introduce the constants m and n as the mode numbers. So like the way we did for the slab waveguide, we can define the V numbers of the channel wavelength and express it in terms of the width and depth parameter, V number of channel waveguide, so can be defined in several ways but the most common way of using the V number is in terms of the width as earlier as for the asymmetric slab waveguide it is in terms of the width parameters.

We call it as b in this discussion can be expressed as n_1^2 - n_2^2 and also the normalized propagation constant b in terms of propagation β constant β normalized constant ei ta x ^{2} divided by n_1^2 - n_2^2. So this one of the most useful ways even though it does not exactly match with the definition for the asymmetric slab waveguide and finally, we can solve for K_x and KY and we can express β in terms of K_x and K_y and plot the Vb characteristics this is the definition front. So like incase further waveguide problems you end up plotting the Vb characteristics.

V on the x axis and B on the y axis for the channel wavelength and typically you can expect the design curves, as follows but we would like to make the point that tip that there is a cut-off for each of these modes including the fundamental mode and that depends on the geometry and a symmetry and so on and so forth, and also there are very certain about the cut-offs successive cut-offs and the distance between them. It depends on the geometry and so on but we can be sure that the V according to the definition is within a 0 and 1 and this is a generally curve and can be compared with other the raid configurations.

And we can draw some conclusions based on the structures and the nature of variation of the propagation constant, so what details of these mathematical expressions of this channel wave weight can be found in the text books and also I specifically, there are several papers so one of them I am just quoting here, this is by Westervel et al IEEE/CSA a channel of light wave technology in 2012 volume number 30, number 14 and way 2012. So I really mentioned that there is a very popular technique on similar lines, vertically devised by markedly.

So these are variation of the markedly a limited, the most popular marketed is method, there are many improvements of multi release method, now and there are also mathematical programs you can look , by these authors we have a open way of mathematical mat cal program, which can be used to solve and compute the properties of the channel waveguide. We shall look at one more popular method to analyze, the properties of the channel waveguide called the effective index method.

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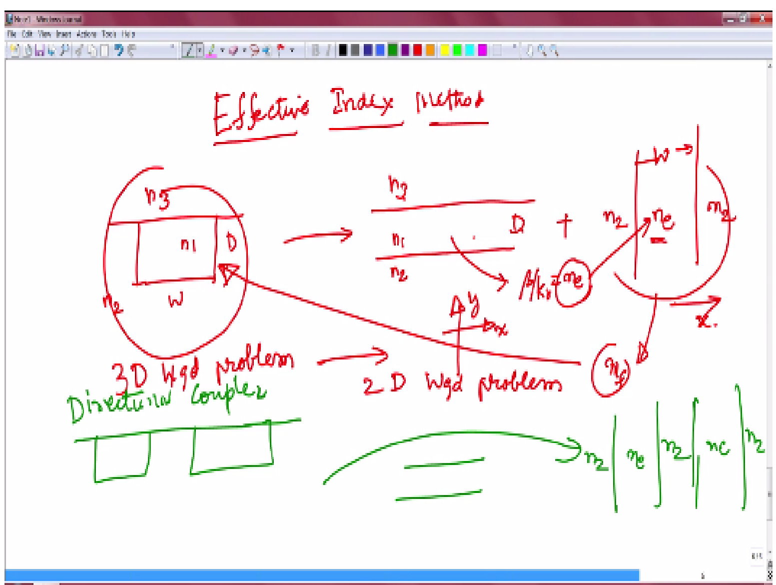

Effective index method a simpler method to analyze and design channel waveguides, here the analysis of the given channel waveguide splits into two successive slab waveguide as follows I will take a typical example rather than genetic example, the cross section of a buried channel wave weight, with width W and depth D, reflected index x n1 in the course region refractive index n 2 and the substrate in D, can be devised in two parts. In the first part we consider the horizontal slab of depth D and the diffraction n_1 and n_2 in the front from the same two for the substrate and for the slide and we know how to solve this problem as an isometric slab the effect.

So in the effective index method you find out the properties of this pessimistic slab wave weight find out the β on β by K_0 which here is called the effective index waveguide and use it to device another so called vertical slab waveguide, it is only a symmetric slab wave weight rotate 90^0 but of width W and refractive index n_2 in the cladding region and n effective in the guiding vision, so that n effective obtained in the previous section is substituted for an effective of the vertical slab this will be called as a depth wise a symmetric slab waveguide this is width wise slab this bit.

So in the particular case of example that we have considered this is symmetric slab rotate around width direction and a symmetric slab waveguide in depth direction and we have known all the expressions to calculate the effective refractive index of the select the slab wave, as well as symmetric slab wave guide. The crux of the problem is to find the refract index of the first region and substitute for the slab region and a final refractive index that we obtain, let us call this n_f is the final refractive index of the original channel we will get.

So we can prove this by substituting T operations in a scalar wave equation 2d scalar wave equation and then reducing, the mode field expression the wave equation for the expression for the mode field in terms of only a 1-dimensional, suppose you call it as xy, we can say that we have only a equation for x. We are reducing at 3-dimensional problem into a 2 dimensional problem; 3D waveguide problem is converted, into a 2D divided problem. In other words you can say that this weight is equal to the given channel rate and it is quite easy to handle compared to the 3D example.

So this has got many advantages in many applications, we can use it for many other devices for example is when two waves are close together, it is much more complicated to analyze suppose you have a problem like this to a vessel close together this is called a directional coupler problem. We can reduce this into a 2-dimensional problem by using the effective index method by finding out the effective refractive index of the first slab.

A symmetric slab will get and using that refractive index the effective refractive index of the first region and substitute in for the refractive index of the guiding regions of the individual channel wave it n_1 and n_2. So a 3D the word problem is reduced where to revisit problems there are several ways to solve this multi-layer slab, we have good proper so we will summarize all the things in the next few slides thank you very much.