Indian Institute of Science

Photonic Integrated Circuits

Lecture – 07
Passive Devices and Beam Propagation Method

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We shall look at some passive devices now.

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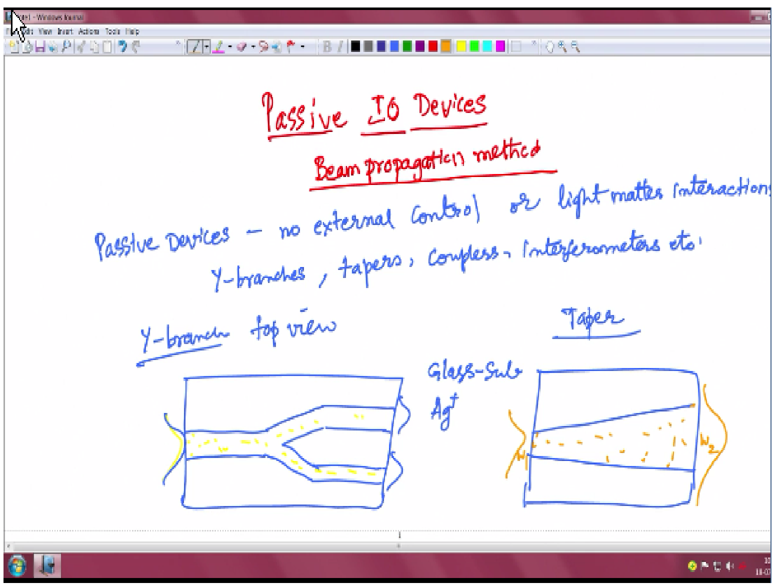

And I will introduce an important technique and a very popular technique called the beam propagation method. Passive devices are those where you do not have external control, and they could be made just by using the waveguides and their patterns or even the light matter interactions are not there. So typical examples of passive devices are Y branches, tapers, couplers, and interferometer etc, all using integrated optic waveguides.

So I will illustrate a couple of examples and their functionalities. They could be fabricated by standard fabrication process which we shall discuss later on. For example, let us take the functioning of Y branch, the top view, I am drawing the top view. We have a sub state and we make a pattern in this form. So this is the waveguide region, so its function is to divide the power injected at the input equally between the two output ports.

There are many, many other uses of this Y branch, for example Y branches are needed not only to divide the power across output ports, we can also use them to split the modes then you are talking about more than one mode propagated in the waveguide which we can think of splitting the modes and so on and so forth. So this could be fabricated very easily by using this standard fabrication process.

For example, we can code the entire vapor with aluminum and protein then make openings in the region where you want to diffuse and diffuse some impurities like silver into a glass. So typical is a glass, sub state and we can make them by diffusing silver ions into the, so let us look at one more example a tapered optical waveguide. So the top view of the taper looks like this. So the waveguide is patterned in the form of a taper like this.

These are all the waveguide region and the light injected into the input port, the mode of the light can have a variable size at the output port. The mode with can be different in the output port, so at the input port you have a W1 and at the output port you have with W2.

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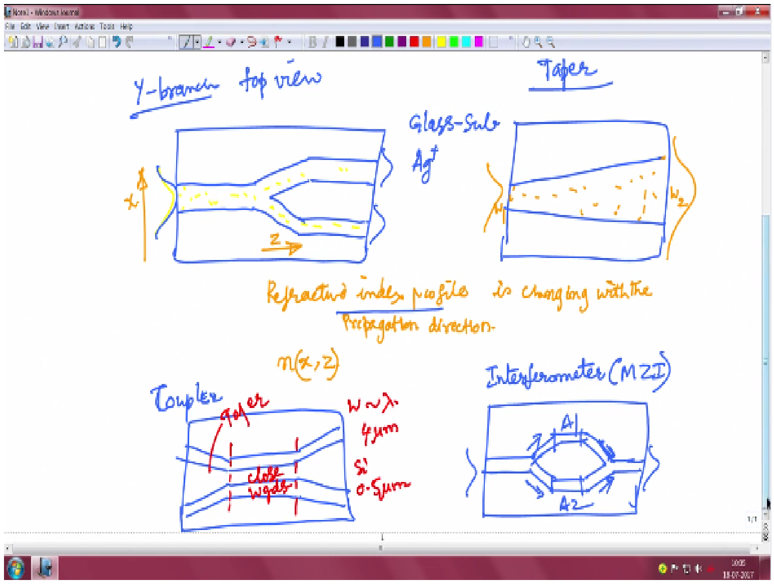

So one of the important feature in all these examples is the refractive index profile is changing with propagation direction. We say Z as the propagation direction and X is the direction in which the mode is confined, we can say that the refractive index profiles along the propagation direction n is the function of X as well as Z. so one more example is of very much used in integrated optics is a coupler, we have already talked about the coupler earlier.

And we have seen how the coupler could be analyzed, so the coupler as we have seen earlier has got two waveguides placed close together. And of course we need tapers to take light in and light out. So these are the taper regions of the coupler, these are the close waveguides. Even though the waveguides are very close together to launch light in and take out the light we need these take out regions.

Recall that typically these designs are very small of the orders of wavelength of light, the widths of the orders of wavelength of light, typically on a glass about 4 micrometers glass only thing but there were 4 micrometers on silicon waveguides here of the fraction of micron 0.5 micron typically. So here also we have refractive index varying along the propagation direction and one more example of an important integrate optical device is the interferometer called the MZI equivalent of MZI on a wave guide so the structure looks like this has got two arm an input section and an output section and two arms this see arm one and ram two is a input sections slight launched into this.

And output is taken across the sport and the light is divide equally at this branch and it is recombined at the output combiner and the lengths of the arms could be different or depending on the requirement as the function we can manipulate the light propagation each of these braches to make very good integrated optical devices for example later on we will see that we can make a margin lateral out of this interferometer by coating an electro optical material on top of this waveguide or it could be made in a electro optical material and we can use some electrodes to control the light propagation characteristics even here we have light propagation around z direction and the refractive index profile being variable.

So in all these examples, it is not possible to solve the wave equation directly and in general we need numerical methods to handle such problems so TDS through apply the general techniques analogical techniques which we have seen earlier like in the slab waveguide or the channel waveguide so we cannot talk about the normal mode also.

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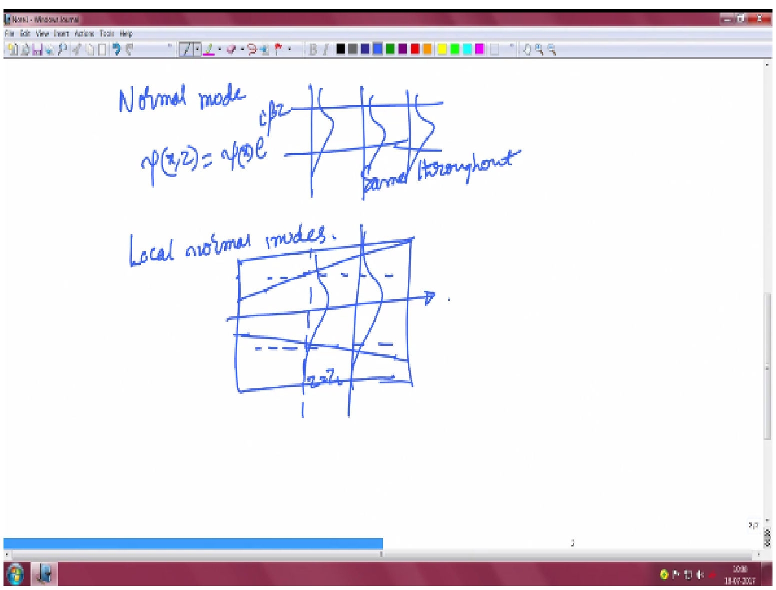

We have seen that in the case of a straight waveguide we can talk about the normal mode at any even point the mode can be optioned by solving the wave equation subject about the conditions and that remains same throughout, the profile is remaining same throughout the propagation direction and we have defined the normal modes using the fields like ψ(x, z) ψ(x) alone multiplied by $e^{i\beta z}$ where β is the propagation constant so in the case of waveguides with z varying refractive index we cannot defined the normal mode as we did earlier but we need to use what are call the local normal modes.

Local normal modes are modes of the I will taken an example to illustrate this case the width of wave guides is different at each of these points and I will describe how a local normal modes could be defined as at any given point along the propagation direction could be defined as the e the mode normal mode of the equivalent straight waveguide so at this points at z = some z_L we can define an equivalent waveguide equivalent straight waveguide and defined the local normal and defined the normal mode at that point.

This could be called as local normal modes and we will be very useful to analysis the devices with z varying refractive index profile so at each point you can define in normal mode because the β is different the mode field is different so on so forth, and we can analysis or study these local normal modes like what we have been doing with the normal modes so the way that these normal modes local normal modes could be used is as follows we divide the given device along the propagation direction into small, small segments. So let me ease once again and then get back I will draw a fresh. So I will taken an example but the method is quite general and we can generalize easily.

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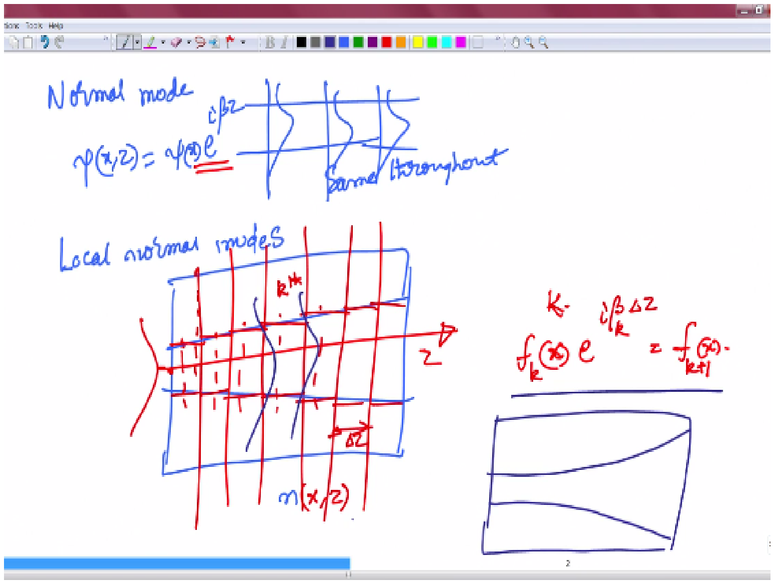

Suppose we have structure like this and at every point along the propagation direction we have the refractive index profile here and at every point along the propagation axis we can define a local normal mode, so the use of this techniques is we can divide the given structure into several segments like this and define a normal mode in each of these of these segments let us say of the length Δz each of these segments are of the size Δz and define a local normal mode at each point and then assuming that the wave guide is straight in each of these sections.

And knowing the propagation is defined as $e^{i\beta z}$ we can obtain the field propagation characteristic at every segment and then obtain the full propagation characteristics so let me say the mode field at any section k the input is f(k) the input beam shape and multiply it with $e^{i\beta k}$ (Δz) you get the field at the output of the section so the output of the k^{th} let me say this is a k section at input at this point wait a second and the output at this point or related as follows.

And successively by repeating the process we can get the field in each of the sections and we can say that the mode field profile changes according to the propagation direction and we can easily observe that it depends on the profile that we take for example I have chosen in this example a linear tapper where the refractive index are the width of the waveguide varies uniformly.

We can also think of refractive index profiles which need not vary uniformly for example we can have a tapper which is like this non-uniform tapper so all these can be very useful to change the mode shape in integrated optic circuit application.

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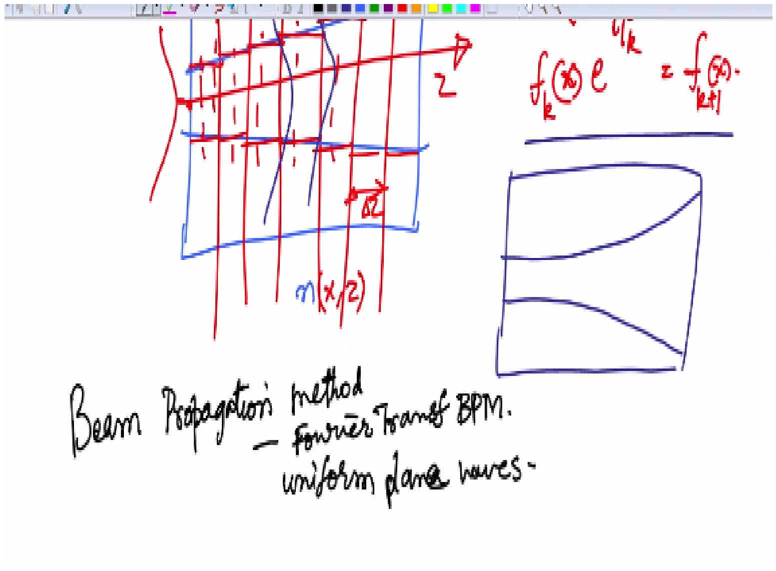

So a more accurate way of dealing with certain problem is a beam propagation method. First let me describe the algorithm then we will go back to the actual method. So we have tapper like structure or a z varying refractive index profile structure like this we can divide this into several segments as we did earlier but now will divide the input profile into several components. So we use light propagation across each of a sections in terms of uniform plane waves.

I am taking a typical simple example of the variations of this wave propagation method called the four year. Transform BPM so let us consider the light propagation such as structure divided into several segments by propagating the beam in each of these regions. In each of these regions as if this propagating in a uniform space, okay.

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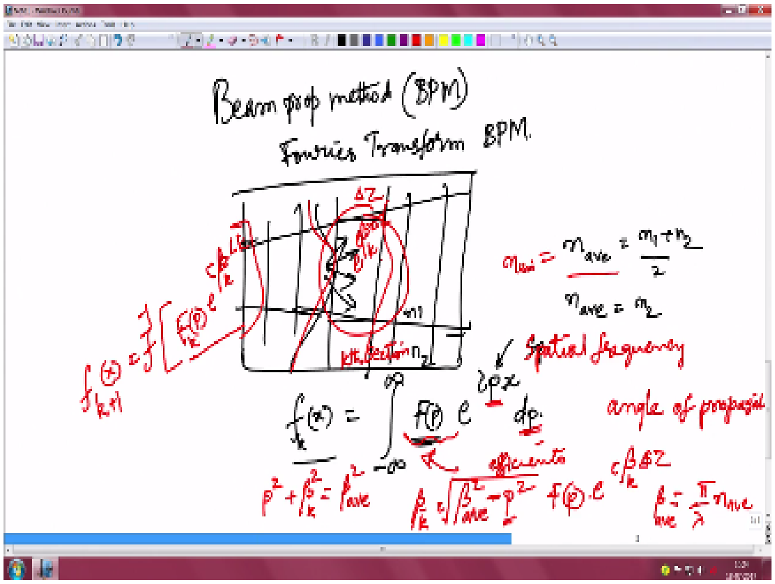

There are several variations how these propagation method one of the popular ones easy to understand explain is a Fourier transform BPM, where we divide the one of the important features of the Fourier transform BPM is, that use light propagation between segments as if we are propagating a uniform medium of some refractive index for example if refractive index is NI and the waveguide region and N2 is the substrate region we can assume that within this region you can assume that light is propagating in a refractive index which is average of N1 and N2.

Just as an example we can even take the N average or N uniform be equal to m2 and noting that Δn1 and m2 are very close by there are lot of approximation that we can do and we can study the propagation so the process goes like this, so there is an input beam to each of the sections we I mean think of a K^{th} section I am describing everything for a k^{th} section then we can repeat it for all the sections this is k, Δz.

K^{th} section of size Δz, K^{th} section so let me divide into many, many parts. So the process goes like this we divide the input beam into its various spatial frequency components so we know that a beam I am just using only one dimensional but this could be equally varied for two dimensional by simple exchange. So you are given a input beam f(x) let me say for k(x) it could be expressed as a super position of several components f(k) or I shall use some other symbol e^i because I have been using k.

Let me use I will use some other i^{th} element or I will use P for the, I think I should change the symbols okay. So what I have done here is I have expand at the given mode field or the input beam in terms of its Fourier components these are spatial Fourier components where p could be called as a spatial frequency. P can called as a spatial frequency so we are dividing the input beam into several components.

These are the Fourier components, coefficients called them as a Fourier coefficients or Fourier components and we are expanding in the whole set of all the frequency components possible. So I have intuitively put the integration range as a whole space where we can take the values. So we can also interpret this spatial frequency or the components of the input each of this component has having a different angle of propagation. Is having a different angle of propagation because the total field propagation could be expressed in terms of the Fourier components multiplied by e^{i}

Tahe corresponding propagation constant $\beta_k x \Delta z$ there β_k could be expressed using the average refractive index or uniform refractive index so we are considering this as a uniform medium not thoroughly waveguide and so on, to take care of the waveguide related variations we will apply corrections actually it form.

So β could be $2\pi/\lambda$ n average, so we can relate p at β as follows, we know that the total wave propagation, the total wave vector could be expressed in terms of p and β as follows equals expressed in the form of k average β average I will call it as, so the β for the propagation could be obtained as I will call it as β average that is better I will use integration β average or uniform. So for every component spectral component, spatial spectral component with p you can obtain a propagation constant β_k.

So the propagation is in terms of we can say as $e^{i\beta k \Delta Z}$, obviously only for values of p less than β average β_k is real and so those are the components which propagate and sustain others can be thought of as getting estimated because this imaginary quantity β_k is imaginary and all the other components die out. So the better is until now what we have observed is we have an input beam we divide into various spectral components and propagate each of this spectral component and finally you recompose back the field at this point.

So the field propagated field $f_k(x)$ can be expressed as inverse Fourier transform of the propagated field let me put it as f_{k+1} f_k f of propagated field $e^{i\Delta\beta\Delta k}$ so this is the propagated field all the components and the inverse Fourier we get the fielders part. Now the cuts of all these beam propagation method is how do we account for the propagation in the waveguide, we have seen that the elite propagation in the uniform medium like in previous example.

So in order to account for that we need to go back to the wave equation and derive what is extra factor that we can co-operate into this propagation so that it represents still light propagation in the actually device structure, let us address that problem right now later on I will once again re-describe the algorithm.

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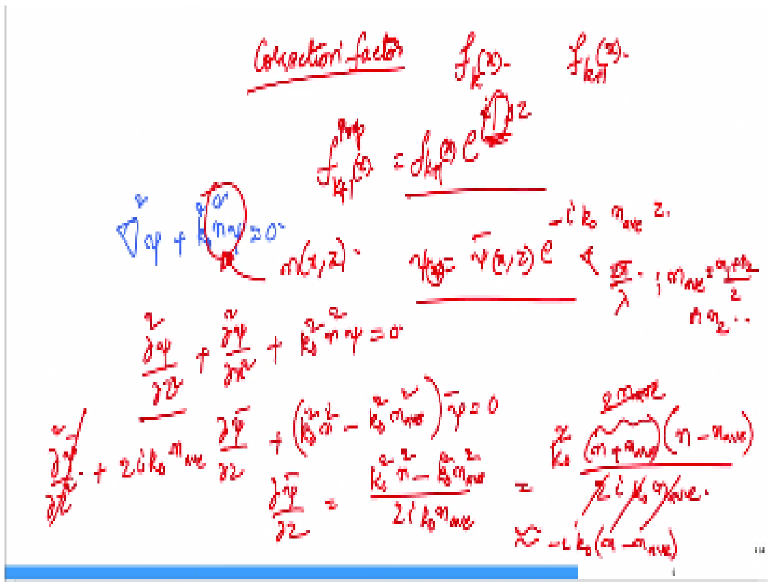

So let us once again start with the wave equation to derive the, we can call it as a correction factor so once again let me write f_k is the given profile and f_{k+1} is the propagated field and we need to apply correction factor let me in the simplest case I will show that we will use $e^{i\Gamma\Delta z}$ as a correction factor by multiplying the propagated field $f_{k+1}(x)$ into the correction factor we can obtain the propagated field $f_p(x)$ or because we have being using p values some other.

The propagated field I will put it here, so in order to obtain a express for Γ let us consider this scalar wave equation and expand it and substitute with the expression for the propagation factor and derive what is this Γ. So we will start with the scalar wave equation, so $\nabla^2\psi+k_0^2n^2\psi=0$ where is the wave equation we are trying to solve where this n is the important factor which is a function of z now x,z let me put it x,z.

So we will assume a field of the form $\psi=\psi'$ x,z $e^{-ik0navg}$ let us put or z, so where k_0 is $2\pi/\lambda$. N_{ave} or N uniform as we describe earlier could be $N_1 + N^2 / 2$ or simply N^2 whatever, so substituting this in to the equation we can obtain $\partial^2 \varphi / \partial z^2 + \partial^2 \varphi / \partial x^2 + k_0^2 N^2 \varphi = 0$, and differentiating this with respect to z within replace the z variation retain the x variation as it is and since it is propagating in uniforms space with the replace with the wave equation for the uniform space and we can obtain as follows.

2i k_0 and average into $d\varphi/dz + k_0^2 N^2 - k_0^2$ and average 2 of φ bar = 0, and of course I have ignored the second derivative with respect to the φ, so we can ignore the secondary way to factor considering that the propagation is very slow, so that we get a first order differential equation ∂φ bar / ∂z = $k_0^2 N^2 - k_0^2$ in average 2 / 2 / k_0 and average which could be approximated to $k_0^2 N^2$ + N_{ave} 2 R^2 x N – N_{ave} / $2ik_0$ N average.

One could be related with this and looking at this factor very close to and where it is replace with 2 N_{ave} and we can kill that factor, so you could be approximately this has $-ik_0$ N – N average.

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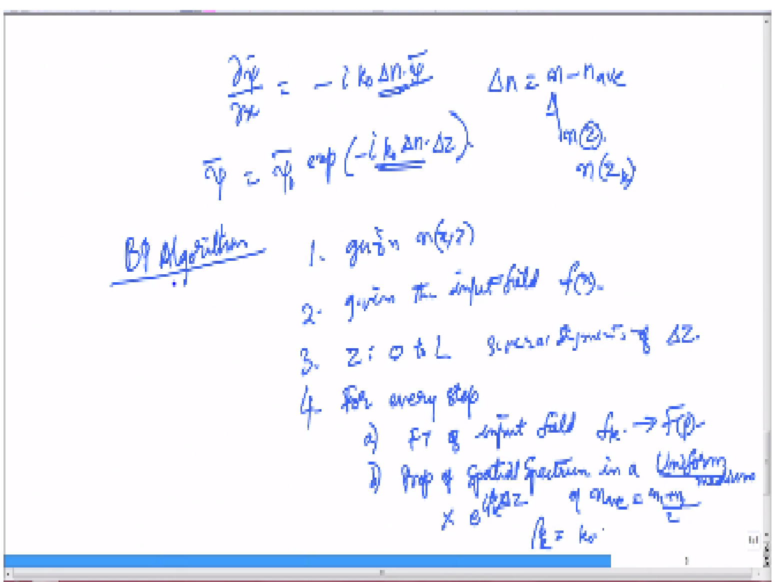

So the solution of this differential equation dφ/ dx, where this ΔN is N – N_{ave} remember that N is a function of z and we are taking its value in the middle of the zk in the region. So the solution of this can be expressed as φ_0 exponential $-ik_0$ Δn x Δz, so we can that the correction factor is k_0

Δn comparing the previous formulation that we did we can say that this correction factor is k_0 x Δn.

It is a very simple derivation use to describe or illustrate how we can obtain the correction factor; we can take more regress approach to obtain better values of coma resulting in more accurate description of the phenomena and more accurate results. So the beam propagation algorithm as follows, so first of all we are given N(x, z) the structural parameter we are also given the input field profile f (x).

So we need to divide the structure along propagation direction 0 to l x several segments of with Δz, more the number of points more accurate propagation but more competition, for every step so we do the following operation for the transform of the input field of the resulting in spectrum of the propagation of the spectrum of the special spectrum in the uniform medium of and average this is achieve by using multiplication with E^{I} βK^{Z} Δ Z where the β k is given by is K 0.

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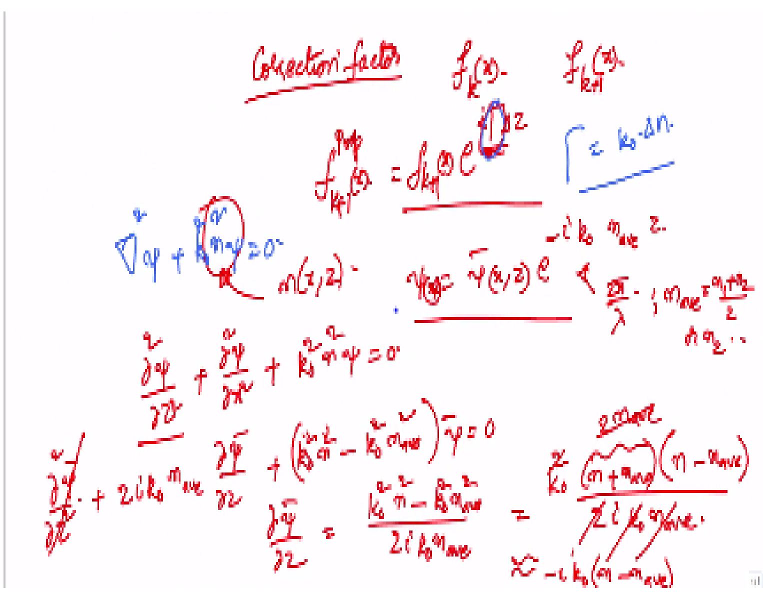

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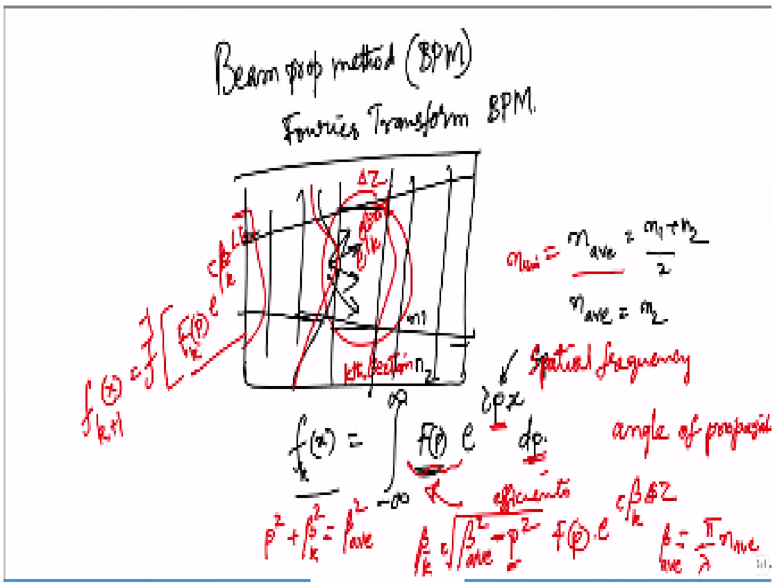

It is the average.

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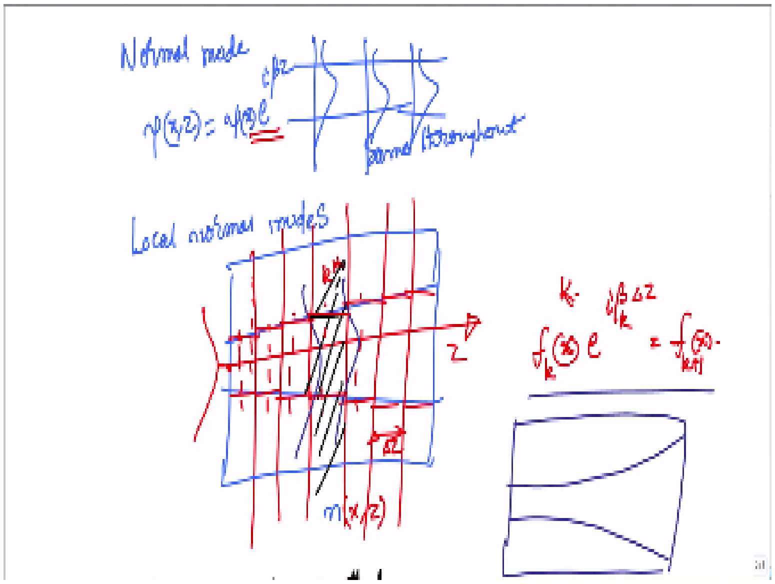

And it was transformed for the transform to get the proper gated feed from F these letter says the result in F of P and that is proper gated enough the K and F proper grated F inverse of the F proper grated and it is the function of the K or P or it has the p then finally then application of the correction fare term are by multiplying E^{I} γΔ Z .so the is the specific 2 that specific interval so in the simplest way obtain the γ K to be K 0 Δ K and off course the Δ is the already required here.

So each of these steps we can store the necessary field components are extract some important information like propagation constant in the so on and so for.

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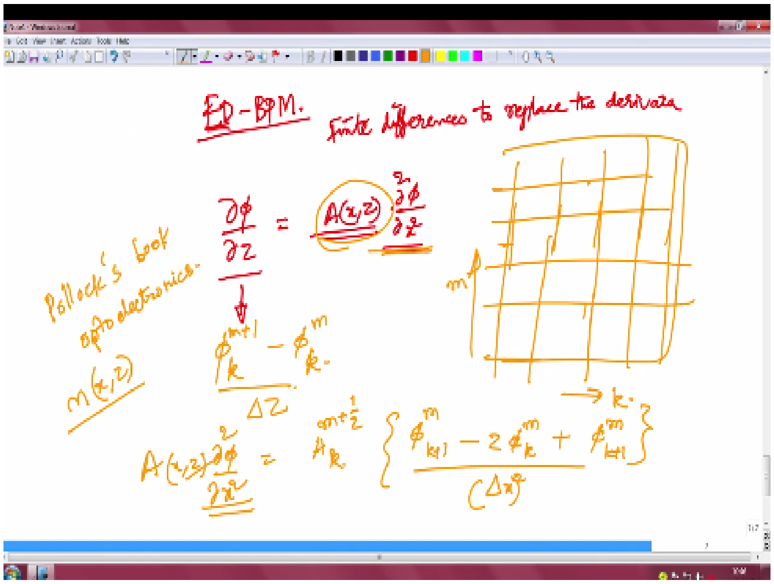

So extension there are several extension that are possible extension and the variations so first of all we should consider what are the various factors involve in using this B P M, the most involve in the grid size .so most of a these algorithm are used in the digital way that is the proper transfer from taken it is the discreet for a continuous for a transform which requires dividing the given input beam or the structure in to several X component.

So that you can take that the D F T for example in the end point D F T it is typically used similarly we have the propagation grid along the proper ration in the direction ,so we are discussing along the population direction in the Δ Z also matrix, so these define the accuracy and utility of the method the extension along the B P M how come practice or the various some are there rest follows they have the vector B P M their instead of the considering in the field as the scalar field we can consider all the components of the feel and get the system of the differential equation and convert them in to the green propagation method similarly we have ignored the second derivative component.

Variation of the field is consider we have reduced to mud can be consider as the paraxial form so we have consider only the first derivative aspersing something so this can be Called as we can cooperate more are higher ink the terms of the non paraxial B P M there we can retain some higher and the components do more mathematics and the get the improved value of the propagation or the factor similarly when we are ignoring the second derivative we are ignoring another aspect and called that propagation back ward waves may consider the light to the proper gating only along when the particular direction so many devices there could be reflections which can be accounted by using what can be called as a π directional SPM.

Another important variation of the BPM which is very briefly described. This called the finest difference BPM. We have consider the four transform as the way for the propagating the light cross uniform medium. Can extend it by using it called final difference between. In which the derivative or replaced by the differences by used the finite differences to replace the derivates. I represent the small suppose we have a differential equation as followed.

I have take in the earlier example were we have first with respect to said, and the propagation is not replace for a transform were it can as it is. They could be a profession containing these structural parameter in the reflect in the file in the six. So we can replace this propagation factor to dividing into several small signals once again is earlier by using ϕ^{mth} I intersection I rk by Δz. So I replaced mth iteration kth element and then I will also replace the derivative with the respected x^2.

Of course with respective we can replace the corresponding value of A obtain the that corresponding separate value. Let me right in toughly grid, the other thing is the single on the grid. So we can replace the second derivative A right side component as x, z. the whole square ϕ by δx^2 as I will retain A off. Let me see I will take it as m +1 because we are m is in this direction and k is in this direction dissertation.

So let me called the middle of the segment like m+ ½ for the I^{th} component. And then the second derivative will be replaced by of x with replace by m k+1let it called k - $2\phi^m_k + \phi^m_{k+1}$ divided by $\Delta x^{2.}$ So there are many ways, otherwise to do the describe the resistant of the second derivative with respect to x. so we have a left side factor and right side as one factor.

We can put the form of matrix and get a matrix equation to solve for the field profiles i. so not it is several commercial pre propagation methods and more or depending on the new problems and the encounter integrate propagates. Now I hope this description will given in side into how things work and I hope the readers can go to the standard literature and to more accurate description of these tip, one of the typical differences in the side Pollock book on up to electronics.

Where descriptions I would have mention at the end of the course. There is a malted program to do this inform the transform BPM in the book. So it could directly you should typing and executed just by changing in the increment profile we can apply to any problem like a tapered or away branch or interferometer so on thank you very much.