Integrated Photonic Devices and Circuits
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Lecture – 30
Integrated Optical Components: Distributed Bragg Reflector (DBR): Device Design - Part 2

Hello everyone, in this lecture today we continue this integrated optical components we have been discussing for several lectures important component like a distributed Bragg reflector and based on that basically this is a distributed perturbation in single mode or multimode waveguides typically and using that type of structure normally several important device could be designed and can be achieved a lot of important functionalities.

So, first we will try to discuss today how to estimate penetration depth. So, you know it there it can be a DBR structure like these very long restructure you can make you can make maybe 10 micron you can make maybe this one maybe 10 micron this one can be 25 can be 100 can be 500 microns or so on. But important question is how long this grating can be normally typically if you consider integrated photonics for large scale integration, so, footprint should be as small as possible.

So, smaller the length it is always good for compact photonic integrated circuits. So, we should know we should have a knowledge that how much maximum grating length we need to get so, that at least we can get reflectivity in the order of say 100% nearly 100% I would so I would get. So, that is how it is our understanding with this understanding will be just trying to learn how to estimate that penetration depth inside the grading that means a particular lambda say lambda B for example.

Bragg wavelength I know that that any electromagnetic signal propagating the waveguide because of the periodicity, and it is phase max to lambda b. So, that it will be reflected back but this reflection cannot happen exact at the beginning it is distributed reflected reflection is distributed. So, that is why it is very important to know how to delight the penetration depth of penetration length.

And then based on this principle, penetration length etcetera and stopband concept of a periodic structure. I will try to give a overview on how a photonic crystal waveguide works specifically concept of photonic crystal waveguide that is also an important component for photonic integrated circuit. I will show some examples, how this photonic crystal waveguides can be useful for short and active and passive device design.

And then third topic is the how one can use this DBR distributed Bragg reflector to design an integrated optical Fabry-Perot cavity. Perhaps some of you might be knowing what Fabry-Perot cavity is, but in spite of that, I will just give you some overview, the working principle its under common Fabry-Perot cavity and then how that Fabry-Perot cavity can be designed with a DBR structure which can be actually integrated in a photonic integrated circuit.

So, that will be discussed and finally, I will be discussed how to design add-drop multiplexer that is a very important device component used in fiber optic communications. So, sometimes it is also useful to have certain such a device at the multiplexer on chip for optical interconnect purpose. So, I will be discussing that one.

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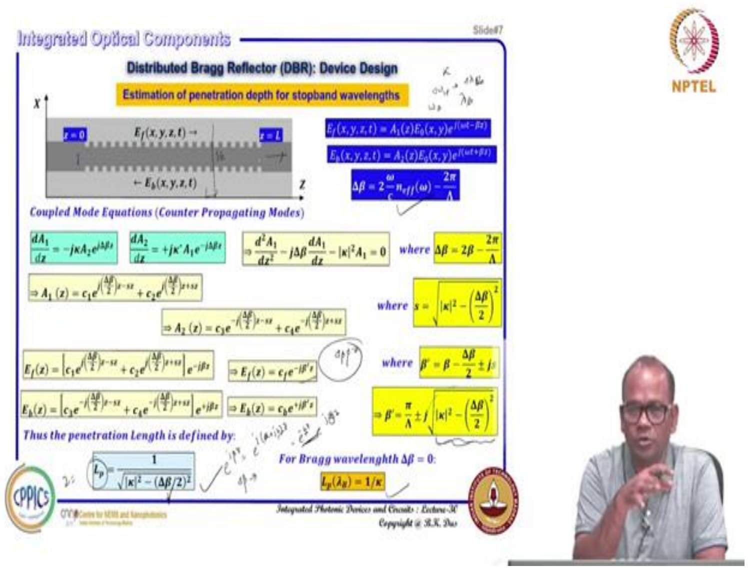

Integrated Optical Components

Slide#7

Distributed Bragg Reflector (DBR): Device Design

Estimation of penetration depth for stopband wavelengths

$E_f(x,y,z,t) = A_1(z)E_0(x,y)e^{j(\omega t-\beta z)}$

$E_b(x,y,z,t) = A_2(z)E_0(x,y)e^{j(\omega t+\beta z)}$

$\Delta\beta = 2\frac{\omega}{c}n_{eff}(\omega) - \frac{2\pi}{\Lambda}$

Coupled Mode Equations (Counter Propagating Modes)

$\frac{dA_1}{dz} = -j\kappa A_2 e^{j\Delta\beta z}$ $\frac{dA_2}{dz} = +j\kappa^* A_1 e^{-j\Delta\beta z}$ $\Rightarrow \frac{d^2A_1}{dz^2} - j\Delta\beta\frac{dA_1}{dz} - |\kappa|^2 A_1 = 0$ where $\Delta\beta = 2\beta - \frac{2\pi}{\Lambda}$

$\Rightarrow A_1(z) = c_1 e^{j\left(\frac{\Delta\beta}{2}\right)z - sz} + c_2 e^{j\left(\frac{\Delta\beta}{2}\right)z + sz}$

where $s = \sqrt{|\kappa|^2 - \left(\frac{\Delta\beta}{2}\right)^2}$

$\Rightarrow A_2(z) = c_3 e^{-j\left(\frac{\Delta\beta}{2}\right)z - sz} + c_4 e^{-j\left(\frac{\Delta\beta}{2}\right)z + sz}$

$E_f(z) = \left[c_1 e^{j\left(\frac{\Delta\beta}{2}\right)z - sz} + c_2 e^{j\left(\frac{\Delta\beta}{2}\right)z + sz}\right]e^{-j\beta z}$ $\Rightarrow E_f(z) = c_f e^{-j\beta' z}$ where $\beta' = \beta - \frac{\Delta\beta}{2} \pm js$

$E_b(z) = \left[c_3 e^{-j\left(\frac{\Delta\beta}{2}\right)z - sz} + c_4 e^{-j\left(\frac{\Delta\beta}{2}\right)z + sz}\right]e^{+j\beta z}$ $\Rightarrow E_b(z) = c_b e^{+j\beta' z}$

$\Rightarrow \beta' = \frac{\pi}{\Lambda} \pm j\sqrt{|\kappa|^2 - \left(\frac{\Delta\beta}{2}\right)^2}$

Thus the penetration Length is defined by:

$L_p = \frac{1}{\sqrt{|\kappa|^2 - (\Delta\beta/2)^2}}$

For Bragg wavelenghth $\Delta\beta = 0$:

$L_p(\lambda_B) = 1/\kappa$

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So, I again I reproduce this DBR structure input waveguide single mode guide output also single mode waveguide in between you have a DBR structure of length L Z = 0 to starting to Z = L and also in this DBR structure we know that that there will be powered propagating wave associated electric field is E f x, y, z, t and backward propagating wave E b x y z t. So, if it is a single mode, both power propagating mode profile field profile and backward propagating mode field profile will be identical.

So, that is why we just consider that for our propagating wave can be can have some kind of slow amplitude modulation along Z direction slow means, because of the weaker perturbation I would say the we are structured it is designed with a perturbation with this perturbation periodic perturbation is not so, strong in that case we can say slowly varying and E naught x, y actually basically your mode filed distribution for the fundamental mode.

If it is a single mode waveguide and forward propagating wave, we can estimate our phase time dependent as well as position dependent e to the power j omega t – beta z. Similarly, backward propagating wave you have your amplitude modulation as a function of z variations that is also called slowly varying and since it is backward propagating and single mode waveguide the field distribution profile for the mode are same.

Consider only thing is that the phase part here that is actually since it is backward propagating we have just added plus and we know that page matching condition to satisfy page matching condition which is essential for sufficient coupling a significant coupling we find a parameter called delta beta that means, phase mismatch parameter we have derived earlier that should be angular frequency omega 2 times omega / c n effective omega, n effective omega is the guided mode effective index at operating at frequency omega -2 pi over lambda.

So, delta beta = 0 means it is your phase matched condition. So, coupling will be maximum, and we just reproduce again for understanding purpose that if your power propagating more amplitude that slowly varying j dependent amplitude and backward propagating amplitude if they are coupled, that we could derive coupled differential equation which can actually give us a idea about amplitude evolution along the grating length z.

So, 2 equation coupled equation, so, kappa we know kappa is the overlap integral. So, basically how grating is overlap with the field distributions are the propagating wave and backward propagate with that, using that one can estimate kappa and kappa star can be complex if it is complex then one will be - j kappa A 2 e to the power j delta beta z. This is the delta beta and in case of backward propagating wave it will be a plus j kappa star complex conjugate and of course, it is coupled with A 1.

So, that means, the evolution of A 2 mode is happened because of the A 1 here and here also in turn we can say that evolution of A 1 that means propagating mode that can also be associated with the backward propagating mode A 2 is there. So, these are coupled equations. So, to solve it, we could actually earlier also we have shown that we can eliminate from these 2 equations that A 2 and we can find a second order homogeneous differential equation only for A 1.

Similar equation we will be able to get from for A 2 that will be actually equal to dA 2 / d j 2 - j delta beta dA 2 / dz - kappa square A 2 that should be equal to 0 another equation we could write down I have just written one because it is obvious for the other. So, we can just get this equation and here we have considered of course, for all the equation delta beta equal to instead of this one we can write that 2 omega, omega / C this one basically equal to beta.

So, that is what we written 2 beta - 2 pi by lambda either you can write this in terms of beta or you can write delta beta in terms of omega by detuning omega from the phase matched frequency you can get significant variation in delta beta from 0 and if it is varying with delta beta is very large then we will be seeing that the coupling will be will not be that much significant. So, from here we know we have solved earlier I am just reproducing again that if you just follow standard second order differential equation homogeneous differential equation solutions.

The solutions will have basically 2 roads one first component will be e to the power j delta beta / 2 z – sz and this will be z + sz where s defined by this, so, that is straightforward. We have solved earlier reproduced here similarly; we can get for A 2 will be in this form. So, I can get another differential equation second order differential equation for A 2 and then A 2 can be solved also similar way only thing is that +j, -j that will be the difference here you will be getting.

But here you see this minus plus and minus plus because of the roots are plus minus coming it is a complex on real part another imaginary part based on that you will be getting. Now, next thing what we do we can say that this if this is A 1 z then we can write down this forward propagating wave E f z dependence you know z dependence is one factor is here another factor is here. So, we can club them together we have the A 1 z that is directly written here along with that e to the power j = beta z.

That we are writing as a z dependent evolution including phase in the forward direction. So, here also some certain kind of h is becoming because exponential and imaginary part is there this can be written as if you just do a little bit of math's here this E f z can be written as c f e to the power - beta prime z where beta prime can be written as this one, 2 values you be getting one for plus another one for minus.

So, instead of 2 different solutions linear combinations we are writing in a compact form with beta prime has 2 different values one corresponding to e to the power – j beta z to add to this one and another one with this one then you will get one will be plus value another will be one will be plus z and another will be minus z. So, beta prime can be expressed 2 different beta prime we can get and their linear combination will be the solution for forward propagating mode and it is just shown as a electric field.

So, magnetic field will be also identical similarly, we can think of backward propagating wave including the e to the power by j beta z. So, we have the backward propagating amplitude A 2 z is this one rating this one and you multiply this one then you get backward propagating wave also in this form again this beta prime will be same. So, it is something we can have this forward propagating wave with a modified propagation constant I would say and backward propagating wave also has a modified propagation constant same but in the backward direction.

So, with this 2 solutions, we could say that the perturbation earlier in analyzing normal DBR structures weak perturbation we consider and we have assumed that the forward propagating wave and backward propagating wave they are weakly disturbed and they are propagation constants are considered same, but we have the value of A 1 z and A 2 z that is coming as a complex z dependent and their z dependent part if you just include in the exponential term here.

Then I see that as if it is a kind of wave which is actually propagating with a modified propagation constant beta prime. This is some through our mathematical analysis we can say that beta prime sudden value is coming it is a modified propagation constant because of the perturbation I would say, and you see this has to be multiplied by e to the power j omega t and this has to be multiplied by e to the power j omega t.

And this has to be multiplied by e naught x y which is actually considered same e naught x y then you would be getting complete solution like this. So, now what now, we can slightly modify this beta prime. So, here beta prime is this one after modification of this one. Now, we can just do delta beta value here we know this one delta beta value is there. So, we can write beta prime equal to this beta value along with delta beta value I just put down here delta beta value and also s.

So, I can say that here for example, beta value equal to beta equal to delta beta / 2 pi / lambda minus. So, pi / lambda and I have pi / lambda delta beta. So, you have another delta beta 2 that will be canceled. So, beta prime can be written down like this form, if I just substitute s, s is given by this one. So, I am just putting s value here and beta - delta beta / 2 = pi / lambda. So, that is what beta - delta beta / 2 = pi / lambda from this equation you are getting that is by lambda capital lambda + - j what this one.

Now, you see this equation try to see this equation pi / lambda is the real value plus - j that is actually changed this part is the imaginary. Now, if delta beta / 2 or delta beta mode less than 2 kappa then what happens this one will become positive, and j will be there. So, in that case you will have a complex value with some beta prime will have a complex value with an imaginary part. So, normally when we consider a electromagnetic wave propagating along a homogeneous medium we consider alpha j beta that is actually propagation constant.

This real part contributes loss and imaginary part contributes your propagation constant here beta prime itself is again becoming complex it has beta considered a real normal waveguide mode the beta is a real value now, because of the perturbation we modified we have a modified propagation constant which can be imaginary when delta beta that means phase mismatch constant factor which is you lying within 2 kappa according to this expression.

So, when it is imaginary what does this mean this mean within stopband beta prime is a complex for wavelength within the stopband when this one this is the condition we found now, because of that, what do you have the penetration length is defined by L equal to that means, what we said that the electromagnetic wave forward propagating wave or backward propagating both actually it will be attenuated along DBR because of the imaginary part.

Now, because of the imaginary part this imaginary part you know normally you have the imaginary part it will be a j beta and beta will have z and then e to the power j beta z and you have supposed alpha suppose a + jb is there z then what will happen e to the power - b z and e to the power j a z. So, now a will become your propagation constant, and this be the imaginary part that contribute the exponential decay.

So, according to this expression both forward and backward propagating waves exhibit decaying along plus Z axis so, if I forward propagating wave if it is initially it is a one then it will be decaying along z direction along z direction it will keep calling and then from here up to hear it will go and backward propagating wave also it will be building in backward direction but along positive direction if you say this is also decaying and this is also decaying in nature if you just see along positive direction.

You will just match the amplitude of the electric field associated electric field then you will see both are reducing along positive direction. So, that is what it is mentioned that decaying part if it is decaying exponentially according to this thing seems like that is decaying exponentially. So, anything decaying exponentially, so, that we can consider as some kind of after a certain length that field amplitude will be significantly reduced.

So, in that case we can consider this B in this case is this one and we know if z equal to something like this I can consider z = L p equal to this one z = L p equal to this one then what happens that field amplitude will be attenuated to 1 / E. So, you know 1 / E penetration rate that means, in the surface if it is 1, so, after L p distance suppose L p distance here. So, z = L p there, the amplitude will reduce to 1 / E because of the nature of the attenuation we have discussed beta prime becoming propagation constant becoming complex having imaginary part.

So, that is actually called penetration depth. So, that penetration depth can be calculated 1 over this one. So, if this is your B so called imaginary part of the beta, that imaginary part you know that the inverse of that one can be considered as a length at which the field will be attenuating to 1 / E. So, if you consider if it is your Bragg wavelength then delta must be equal to 0 page matching condition. So, when delta beta = 0 whatever lambda you can find out from here or omega you can find out that is the Bragg wavelength.

So, in that case delta beta 0 then what we will be getting L p lambda B = 1 over kappa. So, that means, if you know coupling strength of a DBR structure which you can calculate then you can find that 1 over kappa length will be the Bragg wavelength any electromagnetic wave operating at Bragg wavelength that will be reduced to 1 / E. So, now I know depending on the knowledge of penetration depth.

So, accordingly I can say that my DBR structure can be a little bit higher than the penetration depth then we can see that significant amount of reflectivity I can expect if this delta beta is deviated from 0 delta beta not equal to 0 suppose delta beta not equal to 0. So, in that case what will happen you can get certain value is less than kappa that means L p will be longer. So, Bragg wavelength will be the electromagnetic wave operating at Bragg wavelength that will penetrate less.

As it is going away from the Bragg wavelength both side if delta beta is having some value, then it will penetrate longer. So, if delta beta tends to very large value. So, in that case you can consider that is far away from lambda B and that will be penetrating up to infinity and that will be passing through that. So, this is a very nice way of representation how much to estimate how much DBR length you supposed to have for your photonic integrated circuit. So, this is a good example.

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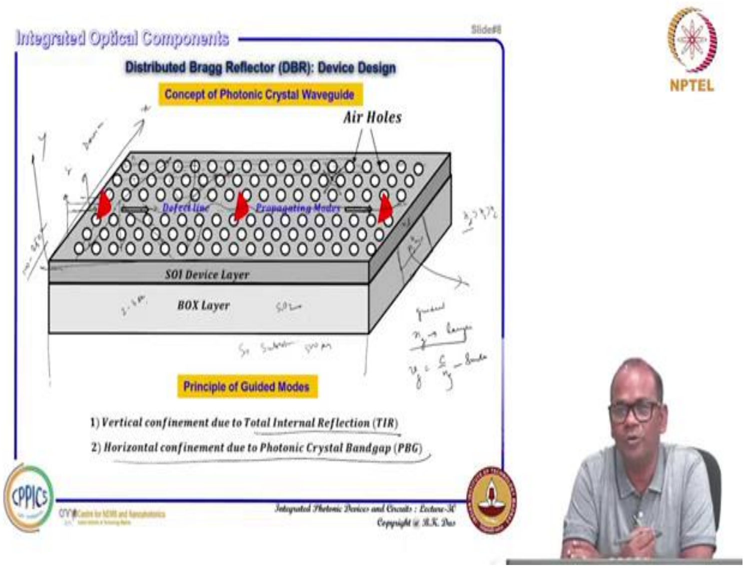

Integrated Optical Components

Slide#8

Distributed Bragg Reflector (DBR): Device Design

Concept of Photonic Crystal Waveguide

Principle of Guided Modes

1) Vertical confinement due to Total Internal Reflection (TIR)
2) Horizontal confinement due to Photonic Crystal Bandgap (PBG)

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Now, let us try to see how this DBR structure the concept of DBR structure what we understand from the concept of DBR structure. So, we have learned that there is a stopband you can express in omega, or you can express in lambda is sb stopband I mean to say stopband around the lambda B or around omega B you will see that this is decaying almost like a evanescent field meaning that particular within that particular band it is not allowed to the DBR structure because of the periodic structure and phase matched wavelength.

So, called Bragg wavelength lambda B around that you have a shortened band we have already shown earlier how to calculate that, that particular band will not be allowed it is evanescently decaying means everything is getting reflected in that backward direction significantly it is reflected in the backward direction the same concept it is a kind of periodic structure it is like a we can call that as a one-dimensional photonic bandgap structure.

If it is a DBR, I can say that normally you know semiconductor you have a conduction band valence band, and we have a band gap where electron energy is not allowed. So, here also that is happening in crystal because you have a periodic structure periodic atomic structure is there that periodic potential that actually created by the nucleus of the atoms actually is reproduce analogously in case of a waveguide structure, we did periodic perturbation here periodic perturbation means periodic dielectric constant.

So, periodic dielectric constant, dielectric constant is a part of periodically as a similar to electron it is a potentially perturb because of the presence of atomic nucleus. So, atomic presence of atomic nucleus produces stopband for electron that is how you get conduct our semiconductor dielectric we are bandgap actually defines if it is there is no bandgap the conduction band valance went almost overlapping.

That is a metal and then if there is some gap is there between 2 bands then it is called semiconductor and if it is this band is bands are widely apart there is a large band gap then that is called dielectric material. So, similarly here also if I make some periodic perturbation periodic perturbation in terms of dielectric constant or refractive index, then you can say that certain band of energy around Bragg wavelength will not be allowed. So, it is a band gap.

So, here also we have a periodicity that is why it is called kind of crystal, but it is a photonic crystal it is not the crystal like a real crystal we know that is a crystallographic structure we learned but here also we are getting a crystal-like structure but in one dimension and even one dimension a guided mode with a certain band of frequencies will not be allowed to stopband. So, this particular concept actually you can use for developing a special type of waveguide called photonic crystal waveguide that there are various types of photonic crystal structure.

There are 2D photonic crystal 3S photonic crystal for various application theoretically lot of thing is analyzed a lot of interesting phenomena could be achieved using a periodic dielectric perturbation that can be 1D that can be 2D that can be 3D in this case it is a 1D photonic crystal DBR structure can be considered as 1 D photonic crystal structure. So, the photonic crystal structure can be if it is the periodicity is in 2 dimensions 2 directions equally periodic or maybe not equal also that is also called a 2 dimensional photonic crystal.

If the periodicity dielectric constant periodicity you can manufacture also such material in all 3 dimensions and there is a periodicity exists. So, in that case that will be called as a 3D photonic crystal, but we will be discussing the very important waveguide structure one of the important waveguide structures working principle is completely different. So, far we have learned how the waveguide theory and the guiding modes we have evaluated it is based on we know that that is based on total internal reflections.

So, in this case we will be just coming up with a new type of waveguide structure based on the stop band that means a certain band will not be allowed because of the periodicity that is actually well known at and a lot of interesting device components integrated optical components have been demonstrated for certain advantages, I will just explain qualitatively how those type of photonic crystals are realized for planner integrated circuit photonic integrated circuit.

You see this is a 3-dimensional structure this is your box layer maybe silicon dioxide and then here in the bottom you have a silicon substrate that can be 500 micrometer thickness and this can be about 2 to 3 micrometer thickness and device layer in the order of 100 to 250 or 350 nanometer device layer thickness. So, this is actual silicon dioxide. This is again silicon. So, now what you can do you can have a periodic structure you can make periodical hole in the device layer. This is device layer periodic hole.

Here it is shown that one this is the hole and then another hole you can consider this one is the period here. So, that along this line if you see it is a periodic structure periodic holes are there. So, along this direction you can see that if you are just forgetting all other direction you can say that it is identical like a DBR structure. So, if you consider also these direction it is also identical like a DBR structure any other direction you consider this direction it is identical like a periodic DBR structure.

But in this case what we see that this DBR structure is there, but in a planner way 2 dimensional periodicity is there hope 2 dimensional periodic holes. But in our conventional DBR structure what we have, we have a waveguide and along the waveguide periodicity is there. So, that is why DBR is 1D in this case 2D. So, what does it mean? If you see that any light try to escape this direction. Suppose you have a source somewhere here somewhere we have a source here.

If it tries to escape this side this side or this side, this side everywhere because of the periodicity it can see that that particular frequency if it is falling within the stopband that will not be allowed to go in this direction in this direction in this direction in this direction and no where it will be trapped if all the boundary condition is actually satisfied. However, if you make a defect line this is a defect line if you see this is one line and one-line next line little bit shifted and it is a hexagonal lattice structure if you say this one, this is something like a hexagonal structure.

Anything you consider in the center will be one thing is there. So, hexagonal structure if you see one defect line is created here, just broken the periodicity there along this defect line. So, in this defect line if you have a guided mode if you are launching here if you are having second light you are entering you are just coupling here then what happened this light cannot be escaped in this direction in this direction in this direction in this direction because all direction you will see stopband. It is not allowed it is like a DBR structure.

However, if it is possible if it has a wave vector only in this direction it is possible that it will be guiding other direction it will be restricted. So, in this way you can see a guided mode along the defect line. So, light can be coupled here and can be confined along this defect line lateral direction it cannot escape because of the photonic crystal bandgap. So, photonic crystal bandgap actually not; allowing your electric field or electromagnetic wave propagating in that direction.

It is like you evanescent field we have seen that in total internal reflection also when the evanescent field is there, it is a decaying field will be there and here also because of photonic crystal it is like a DBR structure you have seen that stopband it is decaying exponentially. So, it will be decaying this direction decaying this direction, but it will be oscillating propagating in this direction as a mode.

So, this is how one can think of confinement along this direction if this is X and this is your Y and this is your Z. So, along X direction you have a confinement because of the 2-dimensional photonic crystal and a defect line but what about vertical direction, vertical direction still it is 220 nanometer or 250 nanometer thickness and it is a lower refractive index. This is your so-called substrate, and this is called device and this is called cover.

So, all these n d greater than n s greater than n c. So, vertical direction can satisfy total internal reflection because n d greater than n s and n c. So, vertical direction you can have a mode confinement because of the TIR total internal reflection. If possible, you can also make a trench here you can remove this oxide in the defect along the defect line this oxide if you remove then it will be just MIR.

So, along this line; so, you can say that vertical direction light will be confined because of the total internal reflection and horizontal confinement due to photonic crystal bandgap. So, you can have a guided mode. So, one advantage here is that in the photonic crystal will show later that any more guided through this defect line or even in the DBR structure in transmission that guided mode will have a n g very large group index is very large, guided mode group index becomes very large much much higher than the normal strip or photonic waveguide structure.

That means the group velocity C / n g is lower smaller. So, light can be traveling very very slow. If you can design a suitable photonic crystal structure, the light velocity group velocity can be reduced 30 times can be reduced 100 times slower that means, a guided mode will travel very slowly. So, when the guided lights travel slowly along the photonic crystal waveguide it will interact more it and it will take more time to interact with the material. So, that interaction enhancement is helpful for certain device applications.

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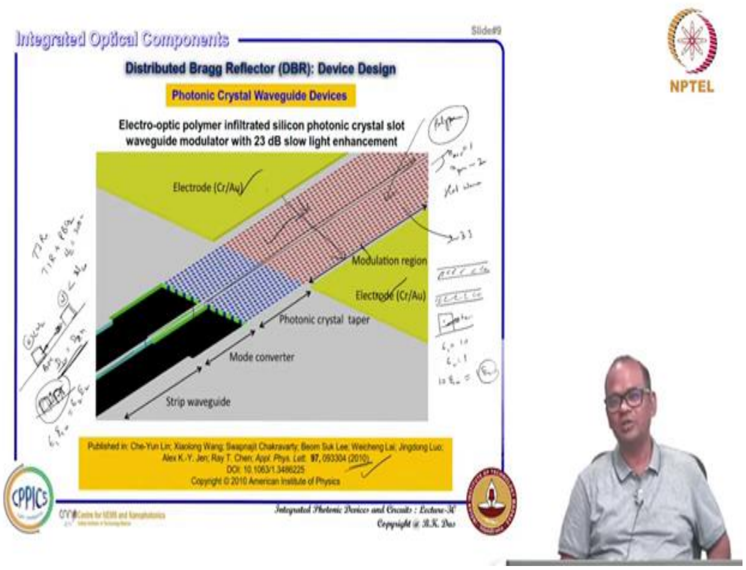

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Slide#9

Distributed Bragg Reflector (DBR): Device Design

Photonic Crystal Waveguide Devices

Electro-optic polymer infiltrated silicon photonic crystal slot waveguide modulator with 23 dB slow light enhancement

Published in: Che-Yun Lin; Xiaolong Wang; Swapnajit Chakravarty; Beom Suk Lee; Weicheng Lai; Jingdong Luo; Alex K.-Y. Jen; Ray T. Chen; Appl. Phys. Lett. 97, 093304 (2010).
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I will show one example here recently I think not recently in 2010 demonstrated by Che-Yum Lin et al and published in journal Applied Physics later American Institute of Physics journal where they have used to you see this is a structure this is the waveguide and a special type of spar size converter. So, that you can couple light into the photonic crystal waveguide along the; defect light. So, light will be guided through this one here.

It is a special type of waveguide that horizontally, it can be confined because of the photonic crystal bandgap and particularly it can be confined because of the because of the fact of total internal reflection as explained here. But here instead of simple defect line there is a slot created here that is called slot waveguide. What about that slot I have got? I will be just explaining very quickly qualitatively they are also a guided mode will be there.

And that guided mode also can travel very slow and so that it can actually get more interaction with the material more time for the interaction. So, what it is done when they have created holes on the top of it, they have just power certain kind of polymer this polymer actually very much good in electro optic effect that means, if you apply a voltage across a certain distance with a 2 electrode maybe this is one electrode this is electrode this is electrode.

And if we apply a voltage across that that means, you can create electric field since this polymer is a electro optic material, because of the electric field you can actually modulate refractive index if you can modulate refractive index you can modulate the phase velocity of the guided light. So, you can create a modulator high speed modulator electro optic modulator you know silicon is not a good electro optic material that is a different type of modulator normally people demonstrated.

And that is actually called your; that is why you need to have a photonic crystal structure and wherever you have holes there you power polymer which is actually electro-optic material not only electro-optic material this polymer has a lower refractive index than silicon but higher than air. So, normally hole will be creating air will be 1 but if it is a polymer that polymer will be in the order of 2 and refractive index per silicon is 3.5 around 3.5.

So, in that case you can periodic whole structure actually that will create periodic modulation of dielectric constant and in this way, you can expect stopband along permanent band along horizontal direction, but it can be guided in this direction. So, that is how the high-speed electro-optic modulator with a very low figure of merit you do not need very high voltage or to create a required phase shift maybe pi phase shift you need for Mach gender interferometer type of modulator.

But as I mentioned here, they have used a special type of waveguide. So, we have discussed the waveguide so far that is based on total internal reflection and then based on hybrid total internal reflection plus photonic bandgap type one direction it is confined because we put any bandgap either direction is confined because of the total internal reflection but another type of waveguide called a slot waveguide. So, that slot I get what it is you know suppose you have a device layer you are creating a waveguide.

It is your oxide box layer and this your device layer you have a waveguide and waveguide to confine to support fundamental mode you need a particular width below which it may not confine a guided mode. Similarly, if you want to have another waveguide far apart, single mode certain waveguide mode single mode, it can be coupled it can be guided and if they are far apart, they will not be coupled.

Now, if you bring them closer, if they are guiding individually one mode, then what happens as they come closer and closer they interact each other and we know using that interaction when they are coming closer and closer because of the interaction their modes are getting overlapped to each other and you can actually design directional coupler and directional coupler is a important component even know we have learned earlier.

But if you consider this W are not sufficient to guide a guide even a single mode. Suppose a single mode can be guided cut off maybe W cutoff maybe say around 300 Nanometer and if you create the structure, which is less than 300 or less than W C, this is also less than W C so independently, they would not be able to confine the light. However, if you bring them closer, then what happens combined thing.

They can confine your light together guided mode can expect you can expect a guided mode but in that case what will happen you know the electric field inside the so called rib region will be lower and it will be enhanced just to follow the boundary condition you know that normally we know that normal component of displacement vector in 2 media according to the boundary condition they are equal if there is no charge and displacement vector you know epsilon 1 E 1 n should be equal to epsilon 2 E 2 n.

Suppose your electric field is oscillating in this direction you have let me see here suppose you have a structure suppose you have field in the boundary we are considering this is silicon epsilon 1 around 10 for example, and this air here that is actually epsilon 2 = 1 for example, now, if you see if you are seeing an electric field in the boundary and it will satisfy this condition then you can say 10 times E 1 n in this case it is a tangential in this direction we are considering equal to 1 E 2n.

So, that means E 2 n is 10 times of E 1 n that means outside the electric field will be 10 times higher strength than the inside. So, similarly here whenever you are just considering a guided mode type of things here to get that joint is giving a guided mode because of the boundary condition you will see in the gap region in the in between the gap region where air lower refractive index region their field strength will be high.

So, normally we can say that in a standard single mode waveguide your core region refractive index are high where electrical strength is higher as you go towards the cladding electric field strength will be reducing and exponentially decaying towards the cladding. But in this case, you see individually these ribs they cannot supporting mode, but when you bring them together closure and closure in the gap region big to satisfy the boundary condition the field strength will be enhanced, and you can get it mode like solutions.

If you solve Maxwell's equation you will see that some eigen modes will be there some eigen propagation constant will be there eigenvalue propagation constant will be there and as a mode it can guide so, but that mode specificity is that electric field strength is higher in the lower effective index region. So, here also they have used that said that type of slot in the center region so, in that slot again they have polymer electro optic polymer.

So, lower effective index region field strength is higher and electro optic is more electro optic effect is more so, you can get more effect on the propagation of the guided mode. So, you can get very efficient electro optic modulator. So, that is what they have demonstrated in 2010 later on actually in this direction it is a very amazing theoretically it is very good, you can get very good results and if you have a very good fabrication technology high technology then you can get a very good periodic structure with smooth sidewalls.

Then you can get a very low loss device which can be useful, but typically you know so, many periodic holes are there and holes in the sidewall there will be roughness will be there and that is the reason normally photonic crystal waveguides are lossy in practice theoretically it is very good you can actually bend very sharply for your guided mode even 90 degree bend it is possible some people demonstrated theoretically but experimentally normally these type of waveguides are highly lossy.

Because of the roughness because of the non-homogeneity sometimes fabrication related yield is required that period so, many holes if they are periodicity somewhere it is broken that point will be leaky. So, that will not be very good. So, unless and until the waveguide loss is reduced this type of device will not find much application. So, you know this is actually demonstrated in 2010 but nowadays people are demonstrating modulator with different technology but not with this technology.

It is in today in the market available of course, but this type of device could not be commercialized because loss insertion loss light from here to here whatever you will get loss is very high. So, this is one application both technology with the advancement of technology this technology may come back again. So, one need to work hard to develop improves the technology process technology, fabrication technology. So, we have discussed so now we learned that in the course of DBR understanding, we have learned 3 different type of waveguides.

One is actually standard waveguide based on total internal reflection light is confined because of the total internal reflection inside the core and another type of thing is that light can be confined in one direction, because of the 2D photonic crystal bandgap structure and another direction it can be total internal reflection. So, hybrid type of photonic crystal waveguide I would say planner waveguide structure planner photonic waveguide structure and another type of waveguide as I mentioned that the slot waveguides your waveguide will have a 2 rail.

Individually they cannot support a guided mode but if you bring them together then you can get a solution of a guided mode and eigen value also propagation constant and field strength will be somewhere something higher in that middle low refractive index region that is called slot waveguide there are many research many application many devices demonstrated especially for sensing applications this type of slot waveguide people are using the region.

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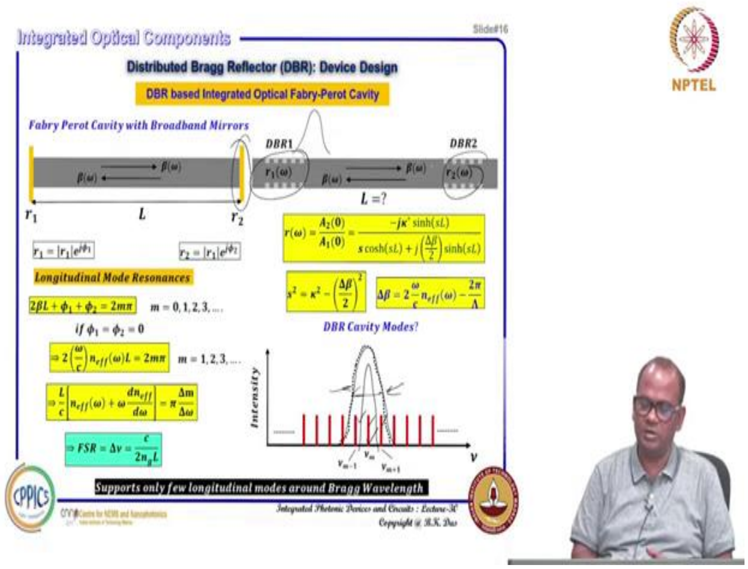

Distributed Bragg Reflector (DBR): Device Design

DBR based Integrated Optical Fabry-Perot Cavity

Fabry Perot Cavity with Broadband Mirrors

$r_1 = |r_1|e^{j\phi_1}$

$r_2 = |r_1|e^{j\phi_2}$

Longitudinal Mode Resonances

$2\beta L + \phi_1 + \phi_2 = 2m\pi \quad m = 0, 1, 2, 3, \ldots$

$if\ \phi_1 = \phi_2 = 0$

$\Rightarrow 2\left(\frac{\omega}{c}\right) n_{eff}(\omega) L = 2m\pi \quad m = 1, 2, 3, \ldots$

$\Rightarrow \frac{L}{c}\left[n_{eff}(\omega) + \omega \frac{dn_{eff}}{d\omega}\right] = \pi \frac{\Delta m}{\Delta\omega}$

$\Rightarrow FSR = \Delta\nu = \frac{c}{2n_g L}$

$r(\omega) = \frac{A_2(0)}{A_1(0)} = \frac{-j\kappa^* \sinh(sL)}{s\cosh(sL) + j\left(\frac{\Delta\beta}{2}\right)\sinh(sL)}$

$s^2 = \kappa^2 - \left(\frac{\Delta\beta}{2}\right)^2$

$\Delta\beta = 2\frac{\omega}{c} n_{eff}(\omega) - \frac{2\pi}{\Lambda}$

DBR Cavity Modes?

Supports only few longitudinal modes around Bragg Wavelength

Now, another application I would like to discuss that is DBR based integrated optical Fabry-Perot cavity. So, perhaps you many of you know, what is Fabry-Perot cavity Fabry-Perot 2 scientists basically Fabry and Perot and 2 scientists, they have passed a demonstrated a cavity like this and both sides it will be mirror and mirror reflectivity will be r 1 and r 2 and then there will be some kind of we will just this r 1 and r 2 if it is not equal to 1 not equal to 1 partial mirror, then some light will enter and because of the multiple reflection back and forth.

Certain wavelength will be stored because of the resonance and some waveguides will be out of resonance that will be passed through. So, in the output you will be seeing something characteristics like this periodic transmission, it is something like air dropping resonator type things you will be getting. So, in that if you just say new frequency and this is the transmission, then it will be getting something like that. That is actually Fabry-Perot cavity and that Fabry-Perot cavity.

First time it was used to by Miemann, you know, who demonstrated the DBR who demonstrated first laser around 1960 Yeah, so, laser demonstration they have used to this type of cavity. So, this type of cavity it was a bulk at that time and so, medium, active medium, and you have mirror both sides partial mirror, and that is how the laser was demonstrated not only the cavity used for laser demonstration, sometimes a special filter special particular wavelength you want to filter certain wavelengths you want to filter, that purpose also Fabry-Perot cavity used.

So, we will be just discussing now, how this DBR structure can be used to demonstrate a Fabry-Perot cavity and not only Fabry-Perot cavity, there are many more applications are there I will be just discussing very important. So, what is the fundamental requirement to understand those types of devices I will be discussing now. So, just start with Fabry-Perot cavity bit with a broadband mirror suppose this is your waveguide single mode waveguide.

And it has a fundamental mode with a propagation constant beta and beta you know beta is always omega / c n effective that is why we have written beta is a function of omega n effective also can be a function of omega and you can have a forward propagating wave, backward propagating wave if you have a mirror both side and the mirror is having amplitude reflection coefficient r 1 and r 2 respectively.

Amplitude reflection coefficient normally if amplitude reflection coefficient is R and if you see the rr star that would be actually power reflection reflectivity. So amplitude refection coefficient r 1 and r 2 and they are separated by L. Suppose, this mirror is giving the reflection because it can be complex it can have some kind of amplitude and it can introduce some kind of phase so, that if it is introducing upon the reflection if electromagnetic wave undergo some kind of phase change, then the reflection coefficient is complex.

And that complex reflection coefficient can be expressed like this as a mod r 1 e to the power j pi 1 similarly r 2 so it should be r 2, r 2 equal to the mod of r 2 e to the power j / 2. Now L they are separated by L and this is a waveguide for understanding purpose we are just considering waveguide and separated by mirror, now longitudinal mode resonance. So, to have resonance any signal travel this and reflect back coming back again reflect if it is 1 round trip occurring phase of 2 pi times integer value.

Then that particular wave is resonant it can happen for a certain wavelength. So, for that certain wavelength it satisfies that ground phase shift is 2 pi then that particular wavelength can be stored it is resonant it can go it can reproduce again this wave again comes back it will produce it is a building constructive interference it is creating. So, this original condition it is same like a ring resonator round trip phase accumulation is 2 pi times integer then it is a resonant wave length.

So, here also it is a ring like thing, but you see it is just forward direction it is going to trip for example the ring waveguide wave goes comes back here one round trip, but here again coming back, but in between you have a mirror type things this is like a ring resonator, we have discussed you have a loss waveguide. So, something goes here and goes here and comes back here. So, this type of air-drop multiplexer ring resonator we have discussed earlier similar type of model can be considered like a simple Fabry-Perot cavity.

So, mode resonances longitudinal direction mode resonances because we are considering longitudinal direction phase round trip phase beta is the propagation constant round trip length is 2L 2 times beta L that is the path dependent phase and then mirror introduces pi 1 phase mirror 1 and mirror 2 introduce pi 2. So, in a round trip it undergoes 2 times path forward direction backward direction 2L and because of the propagation constant is beta multiply that you get a propagation constant phase total phase accumulation round trip.

And 2 times reflections starting from here you go here one reflection with pi 2 and comes back another reflection pi 1. So, that is why total phase round trip phase if you estimate that will be 2 beta L pi 1 + pi 2 = 2 m pi, m equal to can be 0 1 2 3 4 depending on the pi 1 and pi 2 value. So, it will just proceed a bit just assumption we just consider that this is something a standard mirror metal mirror and most of the time it does not give any phase shift.

So, if pi 1 and pi 2 equal to 0 then what we get 2 times beta, beta means omega / c n effective this is beta times L that should be equal 2 m pi and, in that case, m starts from 1, 2, 3 not equal to 0. If it is 0 then everything is 0 that means omega = 0 has to be A not equal to 0 omega has to be 0 that is that is why we are awaiting but, in this case, it can be 0 consider a pi 1 and pi 2 are negative values phase shift can be negative.

So, now 2 times omega / c n effective omega L what do we do here this you just differentiate with respect to omega you see L / c we have kept here. Now, if you have omega times n effective omega, if you just differentiate with respect to this with respect to omega d d omega, for example, if you do then what you get n effective you just differentiate with respect to omega that is 1 plus you keep omega you differentiate n effective d n effective by d omega.

So, that is what we have written and right hand side what would be the variable 2 pi is constant variable could be m, m varies from 1, 2, 3 discrete variations is there that is why for differentiation instead of dn effective by d omega, what we write delta m / delta omega because delta m is discretized discrete values and then you know these value this value is nothing but group index we have described earlier discussed earlier. So, in that case what we do, we can write this one l maybe we can write a little bit L / c n g equal to pi delta m / delta omega.

Now, if delta m = 1 that means, successive phase resonant I am considering this can be written as omega m = 1 whatever the result for omega you are getting that is a resonance frequency for omega 1, m = 2 omega 2, m = 3 that way you can get the resonance frequencies. Now, if I simplify this one, I get L / c this one equal to n g and right hand side pi delta m / delta omega suppose, I want to get delta omega that is the separation between angular frequency because of these successive resonance.

So, that successive resonance means one if it is m next resonance is m + 1 so, if you subtract this one delta m will be 1. So, if we put 1 then this delta omega will be called delta omega that means, called as a free spectral range in terms of angular frequency and if this is delta omega equal to linear frequency be considered 2 pi delta nu. So, that means, we can write this one equal to pi delta m equal to 1, 2 pi delta nu and that will be this delta nu it will be called as a FSR free spectral range.

So, pi, pi cancel 1 over 2 delta nu. So, this delta nu if I call as a FSR so, FSR can be written as delta nu equal to c / L 2 n g, n g is there. So, free spectral range you remember that we have considered FSR we have derived FSR microring resonators c / n g L, L that case is a ring resonator perimeter with a total perimeter and in this case, total round trip is 2 L that is why same expression is coming.

So, free spectral range you are getting that means, you can get a resonance wave length like nu n, nu n + 1, nu n + 2, and nu n - 1 different order of resonance frequency I can consider and if I just subtract nu n + 1 - nu m that will be your delta nu that will be called as a FSR. So, this FSR is actually C / n g L if you have n g frequency independent then the separation between resonance frequencies that they are they will be constant as long as the n g is constant L constant C constant everything constant.

So, they are FSR will be only L dependent or n g dependent, but they must be constant. So, we can see there a Fabry-Perot cavity modes through this path if I just see that nu m satisfying from this equation for a certain m, if it is resonance, then you can get neighbouring nu m + 1 and nu m - 1 nu m + 2 3 ports are one and this side also order will be m - 1 starting from all the frequency and you can see these are the actually resonance frequency these are the point they are resonance frequency their separation is a FSR and FSR exactly equal to C / 2 n g L.

And if you see this is a cavity intensity or in the transmission you can see this much it will be transmitting depending on the cavity here you will be getting this type of transmission and depending on the loss inside you can see that instead of single line it can be a little bit broad and also that you can see. So, the problem here is if you want to this very nice device, it is the replacement of ring resonator, but one problem is that you have a mirror you have to use a mirror.

If you want to use a mirror at the edge it is very difficult to integrate mirror at the edge of the waveguide and you want to integrate it in a photonic integrated circuit because mirror mostly it is a metal mirror or dielectric different type of technology required it is very complicated to fabricate in a microelectronics technology, but you can demonstrate maybe if it is a single individual waveguide and mirror you can deposit at the polish the nail phase and then you can actually get a mirror deposited mirror you can get.

However, this type of device that is one technological problem and another problem is that this type of mirror when you fabricate most of the time, metal mirror or anything else you fabricate they are actually almost same reflectivity for all wavelength it is a broad wavelength. That is why we are considering broad mirrors. So that is the reason all the resonance intensity they will be at equal height.

Their intensity will be at a equal height their regular their intensity will be equal height. So periodic filtering can consider a periodic filter. So, if you are bandwidth or new range is only this much, then you can see that only this much we will be storing and other wavelengths will be just transmitting or reflecting that way it will happen. So, sometimes it is not very good for many applications because of multiple resonance frequencies.

Sometimes you may need multiple frequencies, but many times it is most of the times they are not very good there are certain applications. So, what should what to do if we can use your DBR cavity modes you know DBR cavity r equal to reflectivity we have derived using coupled mode theory this is the expression amplitude reflection coefficient where s is defined like this and delta beta in terms of omega that is why r is frequency dependent.

So, we can say that this is complex. So, we can have this reflectivity is frequency dependent highest reflectivity around Bragg wavelength and you can have a stopband we have derived this is something like this. So, you have this type of stopband you can get it this is a stopband that will be reflected and outside transmission not stopband they will be transmitting. So, that is why you can get a frequency dependent reflectivity around the narrow bandwidth and since it is a complex amplitude is a complex.

So, you can write a + j b like that r omega = a + j omega thing. So, you can have also amplitude as well as phase. So, that phase also becomes independent we can write like that and if we just derived this one here, you just expressed like this then we can get r omega like square root of a square + b square and angle phase pi will be tan inverse b/a. So, you can express this one and find the phase right this phase it will be because - j that is why - pi / 2 is there and rest of the thing if you do it will be tan inverse delta beta / 2s tan hyperbolic sL.

And when delta beta = 0 that means exactly are the Bragg wavelength then pi lambda b will be delta beta 0 means this will go. So, this will be just – pi/2. So, exactly Bragg wavelength the phase changes in a mirror – pi / 2. I have put a question mark here normal standard Fabry-Perot what is the length I know. So, mirror to mirror distance, but here you have distributed Bragg reflector 1 distributed Bragg reflector 2 it can have a r 1 omega it can have r 2 omega they can be Bragg wavelength can be matched but they are bandwidth can be different.

But I know that distributed Bragg grating structure what would be the length can we consider from here to here because I know that any field goes it exponentially decays at Bragg wavelength for example or any other wavelength within the stop band and deflect back. So, it penetrates into the DBR the field then reflect back partially similarly, it will be penetrating inside and reflected back partially.

So, that means can we use L exactly this one obviously will be saying no, but you can use this value as long as you can consider that inside the phase DBR you have a phase this phase actually is takes care of how much path length you must be considering that information is involved here. So, you can consider L and this pi you can consider and same principle we use here. Then you can find a resonance wavelength.

So, in turn, you can get suppose it typically I consider this is for example, your DBR response and you know how Fabry-Perot cavity they are regular resonances are there but your mirror this broadband mirror replaced by a mirror like this. So, that means you only this mode this mode this mode will be surviving in this particular example, other mode since the mirror is not giving any positive feedback deflection.

So, they will not be resonant they are like a simple waveguide type thing you will be getting. If you have a relatively narrower bandwidth such that you are getting something like this, then you can really filter only a particular mode particular longitudinal mode. So that is beautiful. So, you can control the bandwidth, we know how to control the bandwidth of a DBR structure, we have discussed in detail. So, design parameters, you can just optimize, and you can actually design a length so that you can get a single frequency oscillation.

Moreover, since DBR just a periodic perturbation within the waveguide anywhere you can fabricate on the photonics chip, so, this type of cavity if you want for certain applications, it is very easy to integrate on chip using CMOS technology. So, this is one of the important parameters just a DBR Fabry-Perot cavity.

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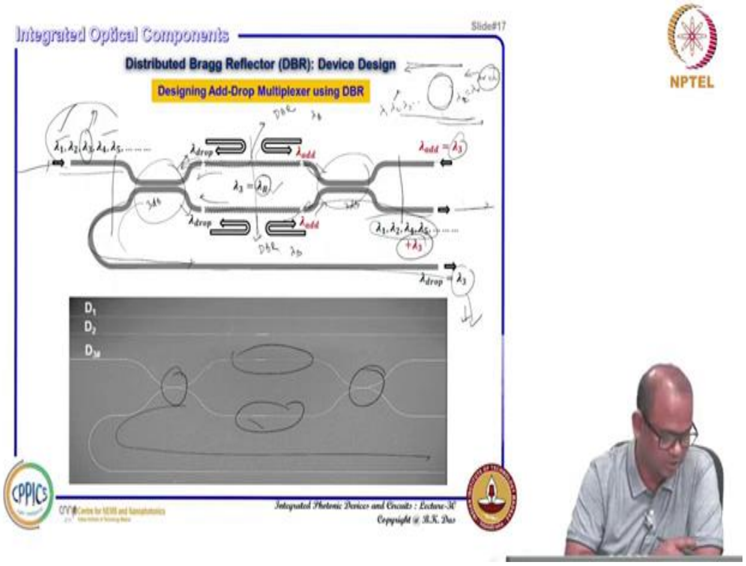

Integrated Optical Components

Slide#17

Distributed Bragg Reflector (DBR): Device Design

Designing Add-Drop Multiplexer using DBR

Integrated Photonic Devices and Circuits : Lecture-30
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Next, I am going to discuss about very interesting application using DBR structure that is actually Add-Drop multiplexer we have seen this Add-Drop multiplexer you can demonstrate using ring resonator, you can have a ring resonator, you can have one loss waveguide and other loss waveguide you can have lambda 1 lambda 2 lambda 3 and so on and certain lambda 2 for example, lambda 2 = lambda r that will be stored, but it can be coupled back here.

So, that particular event can be dropped same way if you just launch here lambda r resonance equal to lambda 2 that will be uncoupled and that will be coming here. So, lambda 2 that particular information will be dropped additional information at with same channel carrier wavelength you can add here. So, add-drop multiplexer I have discussed earlier using micro regenerator we can use also DBR structure for Add-Drop multiplexer.

But how that has to be integrated in a Mach gender interferometer you know Mach gender interferometer if you consider here and here this is a 3dB power splitter with a simple Mach gender, let us forget about what is DBR here this is for example, DBR structure. This is also a DBR structure in both the arm is integrated and that DBR structure actually has some certain kinds of Bragg wavelength that is same we have designed if you forget about this DBR structure any series of channels.

For example, your channel carrier lambda 1 lambda 2 lambda 3 lambda 4 lambda 5 maybe multiple channels are coming each of them are having information and they are distinct for different locations you want a particular location particular channel for example lambda 3 we want to drop you want to take without disturbing other channels. How to do that, if you use it simple Mach gender what do you do?

Normally all the channels will come if you have this 3dB directional coupler is wavelength independent then all the channels will be splitted into both arms comes back here comes back here again interfere and because this is 3 dB, this is 3 DB identical balanced arm. So, all the channels supposed to come here all this supposed to come here, but what we did we have a DBR structure exactly reflecting lambda B Bragg wavelength these this one also reflecting Bragg wavelength.

So, what will happen that lambda 3 that match to the Bragg wavelength that will reflect back here this will be played back here and they will interfere they will actually reproduce here it is like a for lambda 3 it is like a folded Mach gender interferometer. So, that means normal Mach gender interferometer 2 3dB directional coupler is there in between arm is there, but here this lambda 3 maybe up to here it is going and then reflecting back.

That means it is like a folded and then again saying the same the directional coupler and in the cross port it will be appearing here. So, this lambda 3 if it is exactly match to lambda B that particular channel I can drop here and I can send to our particular recipient where you need that information and here what you will see lambda 3 will be missing. So, I could drop the interesting point is that in ring resonator you have multiple resonances, but in DBR you can select particular channel particular narrow bandwidth.

That particular narrow bandwidth channel, you can actually drop without disturbing the rest of the channels. What else you can do I know that my exact path the channel that can carry one more channel, lambda 3 is missing that information is already sent to certain destination. What you could do, I can have same lambda 3 with additional information may be from that port I can collect from any other sender, transmitter, that lambda 3 along with that information.

I can just launch here. It can split again here and the same principle it will reflect back and come back here lambda 3 will be added. So, I can drop a channel and I can add channel with same wavelength but with different carrier different information. So, these types of devices; actually very useful when it is called add-drop multiplexer and widely use to this type of device in optical networks. But as I mentioned, this is very important also for on chip applications, if you want to drop a certain wavelength without disturbing other wavelengths.

Then it is very important device when we actually have fabricated such a device you see this is a similar type of identical structure you see 3dB power splitter wave length independent power splitter here one type of DBR structure you can integrate and integrate that will be reflected back we could achieve I am not shown here results but if you want some of our published paper you can find the details how it can be fabricated and how it can be demonstrated. With this I stop here and let us see in the next lecture. Thank you very much.