Indian Institute of Science

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Photonic Integrated Circuits

Lecture – 13
Photonic Band Gap Devices

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NPTEL Online Certification Course

So this topic is called the photonic band gap structures.

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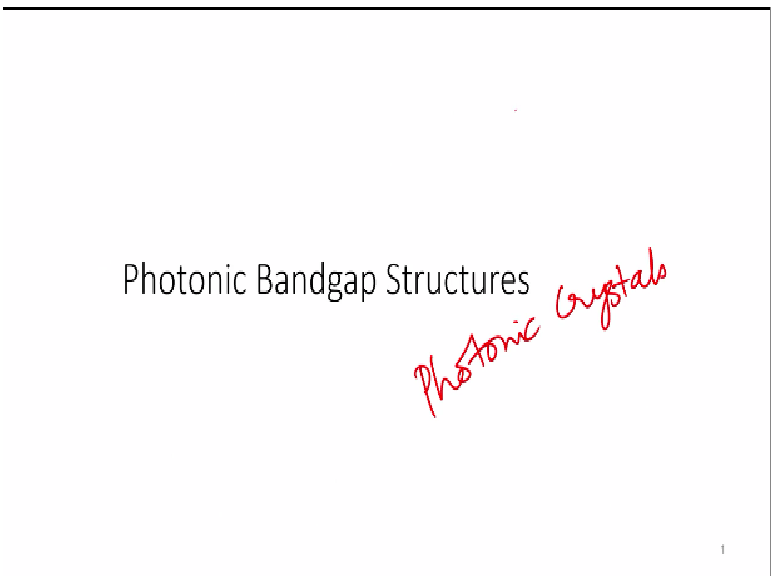

Sometimes it is also called the photonic crystals, we will talk about photonic band gap structures as integrated optical elements. There is another important field of this photonic crystals called photonic crystals fibers. So we will not worry much about the photonic crystals fibers at this moment.

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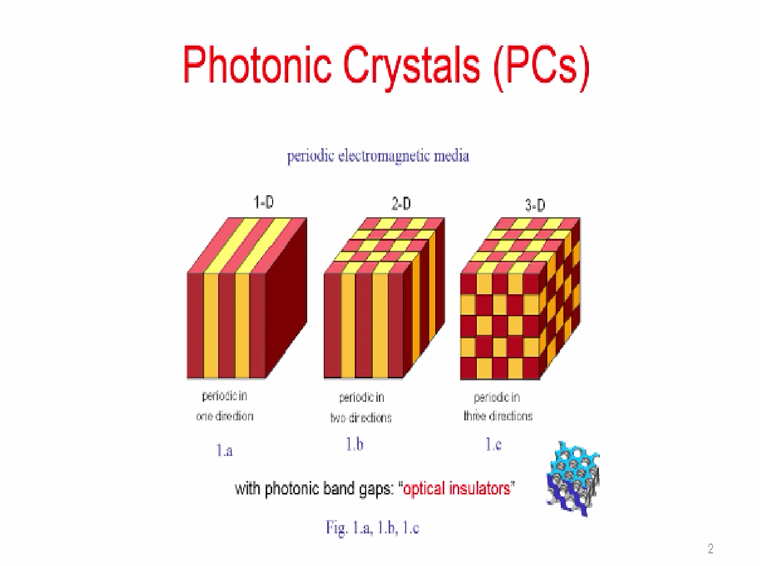

So photonic crystal is a periodic arrangement of the structures, periodic variation of refractive index various directions. So there are very peculiar properties as we will see soon. So I am showing the three different arrangements you have periodicity in one dimension, periodicity in both X and Y directions and there is a periodicity of refractive index variation in all the three dimensions.

So this can be called as 1D, 2D and 3D photonic band gap structures. So one of the important feature of this photonic band gap structures is all frequencies cannot be propagated through this, based on the periodicity and the structural and refractive, optical refractive index properties, certain frequencies are not propagated. And this could be exploited in making many, many devices like devices or communication, applications for sensor applications and so on and so forth.

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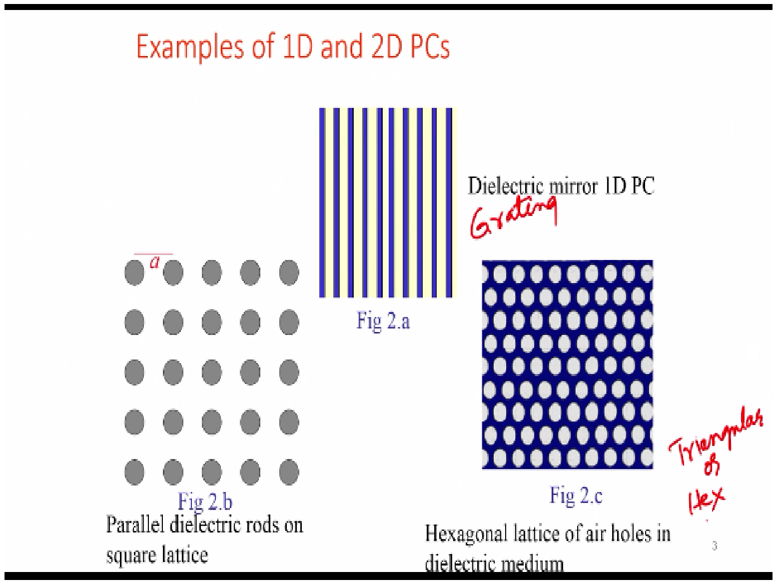

So I will show you a few cross-sections of this 1D and 2D photonic crystal structures this is photonic crystal or photonic band gap structures, you can also identify this with the grating and we have 2D photonic crystal structures this is called a hexagonal lattice of, square lattice of photonic band gap structure, this is hexagonal lattice of photonic band gap structure or it is sometimes called also the triangular lattice.

So you can compare this analogy with semiconductor crystals, so in semiconductors as you know the atoms arranged in various ways and some of them are square and triangular lattices. So we can describe the properties of photonic band gap structures and photonic crystals also, the analogous to electronic structures. But instead of having the electronic properties you have your optical properties of the structures and optical materials properties which are important here.

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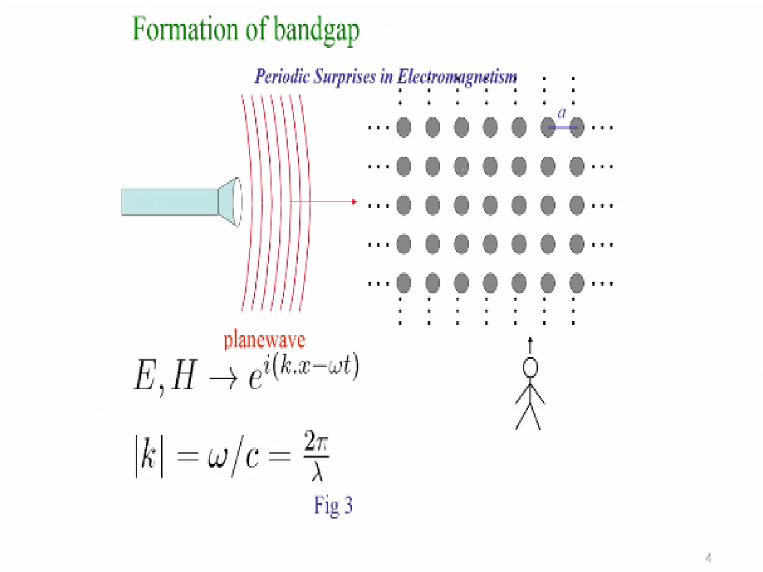

So in order to study the formation of the band gap you need to consider this scattering of light across all these periodic variations.

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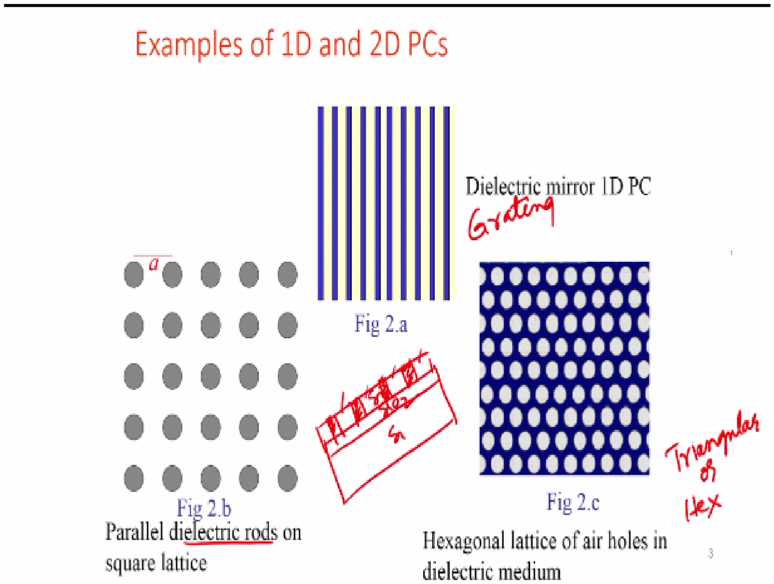

In the simplest case I need to mention that you can, these are all the top views that you are absorbing and you can form these structures by lithographic process, you can really holds, if you have a, just to mention that silicon vapor layer or so, and on top of it you can have one more silicon layer. And in this silicon layer you can either create holes or rods, so you remove the material in this region, it can be called as a whole configuration holes in silicon configuration.

If you remove the other material, for example this, if you remove these materials you come with the rods direct rods configuration. So this is a square lattice of rods, this is the hexagonal lattice of holes.

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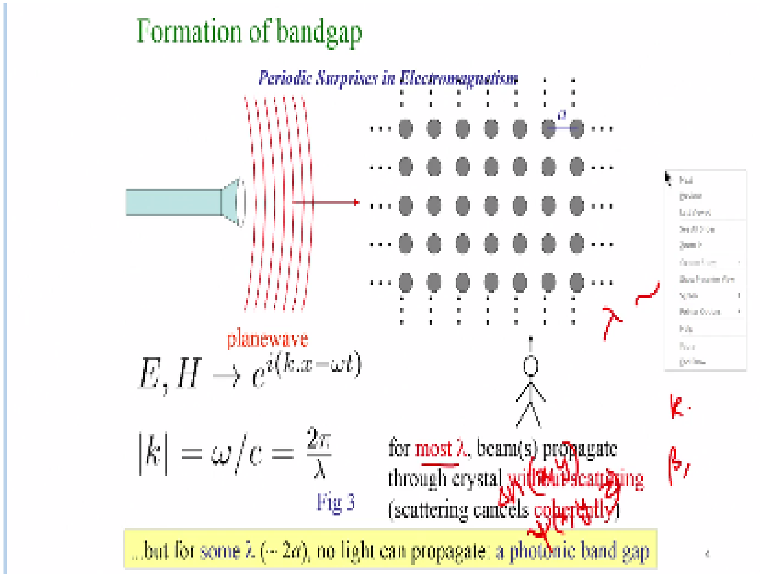

So we study of this lecture structures is complicated, now straightforward compare to the other optical geometries, we need to the broad technique to analyze such problems is to attack directly from the wave equation, we can write the refractive index as a periodic function of x,y and the field also has a periodic function of x,y of course the propagation direction also could have some variations.

And manipulate the wave equation to obtain the values of the fields, the propagation characteristics like β's and the spectral properties K as function of the structural parameters and so on and so forth. But at this moment we can say that this study of such a mathematical stay of such photonic band gap structures is still not well developed. And there are scope for new mathematical techniques for analyzing these structures.

So we can say that for most of the wavelengths compared to the dimensions optical wavelength compared to the dimensions along with the dimensions of the structures. So if we say d is the dimensional parameter, so the properties depending on how close or away this operating wavelength is with respect to this structural parameters. So for most of the wavelengths you can say that, the light propagates through and when there is a phase matching sort of conditions then you can say that those wavelengths light of those wavelengths is scatted more and form some gabs in the band structure.

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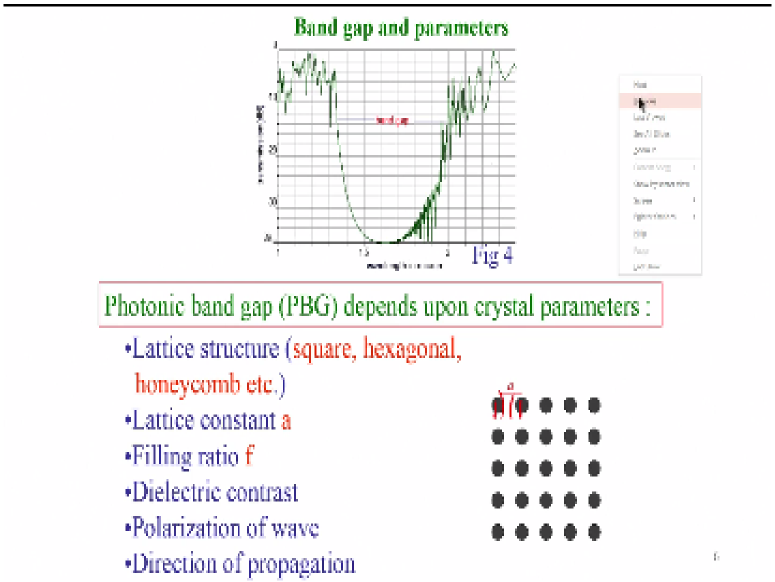

So this is a typical band structure of a photonic band gab structures you have a wave length in micron on the axis and transmission coefficient on the y axis so you can see that there is a band of frequency which are not allow to propagate typically in the communication band this is designed operate in the communication band between 1.4 to 1.7 micros you see large band gab so the photonic bad gab depends on many permanents of the crystal structure in particular they of course it depends on whether it is a square lattice or hexagonal lattice etc.

And you have the lattice constant that spacing the cell unit cell dimensions the film factor how close these no not touching but how close these are weather they are very close by or far away how this let us one that the electric constant contrast between the whole and the outside medium or the odd and outside medium polarization of wave that direction of the propagation and so on so forth.

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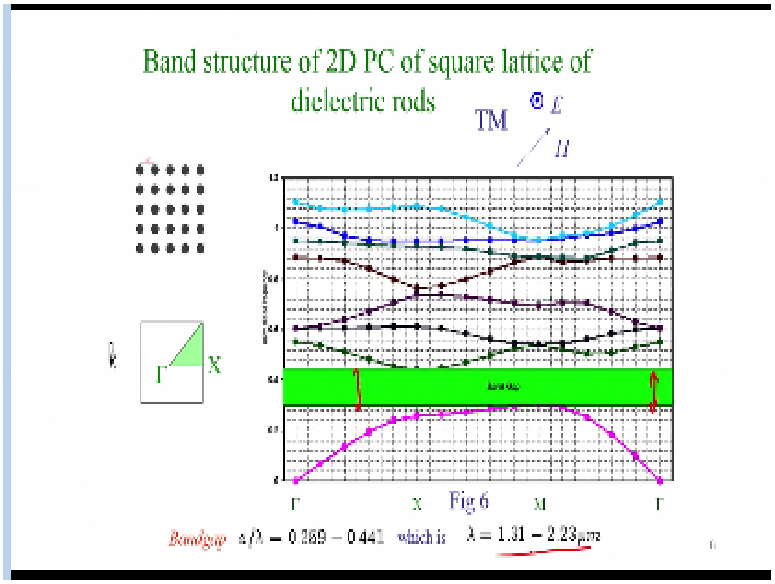

So this is an example of a of course as you know in like in the electronic crystals the directions matrices most and it is expressed in terms of the EK diagrams and in the different direction you have you express in terms of the unit cells so you choose a unit cell and look at the frequency of frequency at it is allowed to propagate along the different directions and you cam plot the curves disposition curves presenting the variation of normalized frequency along the different directions along the say S.

And you observe that there are several more that it can allow to propagate in particular we would like to notice that band of frequencies which is allow to propagate so you have band gab in this region, this particular example as a function of the distance or the crystal parameter just try to it us designed to operate for a values of a here ranging from 0.259 to 0.441 micron times the wave length of λ you have this stop band in a range of 1.312, 2.23 micros this is a typical band structure.

And this how it is expressed and of course for T rods and TM rods and other configurations we have different variation of this band structure.

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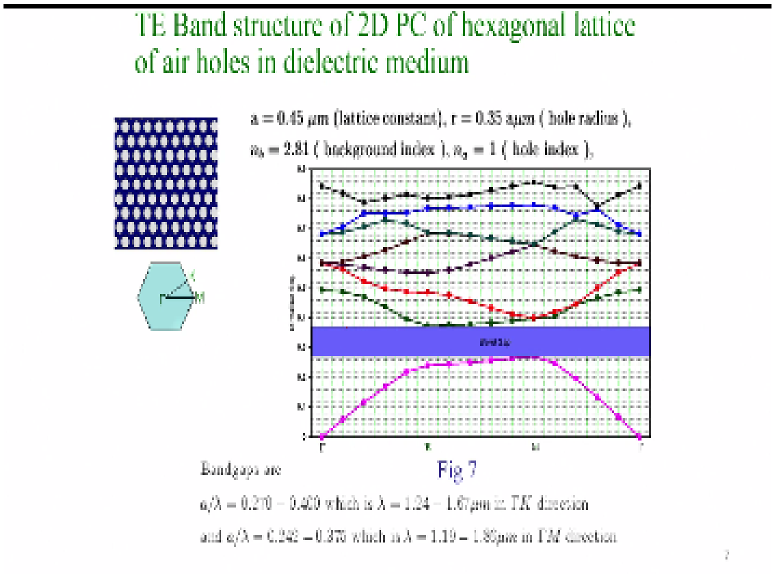

Fig 7

So this is a T band structure for 2D photonic crystal of hexagonal lattice of air holes in the link medium and this is the direction k direction this is the main m direction and so on so here you have for a of 0.44 micron of the lattice constant of you have a radius of 0.35 micron of the whole radius you have and the refractive ness constant of 2.81and whole index of 1 you have these band gab properties the TK direction you have 1.24 to , carnation 1.24 to 1.67 and in , come in this direction we have 1.12.

So you observe that different direction it has got different properties and we have choose the crystal parameters probably in any given design.

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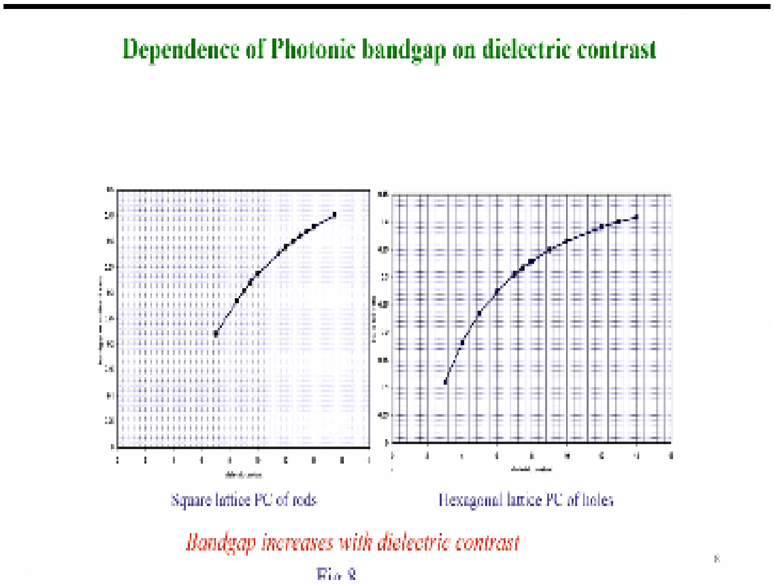

So this is this picture show the depends of photonic band gab on delivery constant or refractive index of the medium you have square for square lattice of rods we have band gab varying the directory constant like this almost somewhat parabolic and similarly for band gab to mid band ration on this for hexagonal lattice, so we observe that band gab is increasing with refractive index. So as increase the refractive index of the whole square rods you have more band gab.

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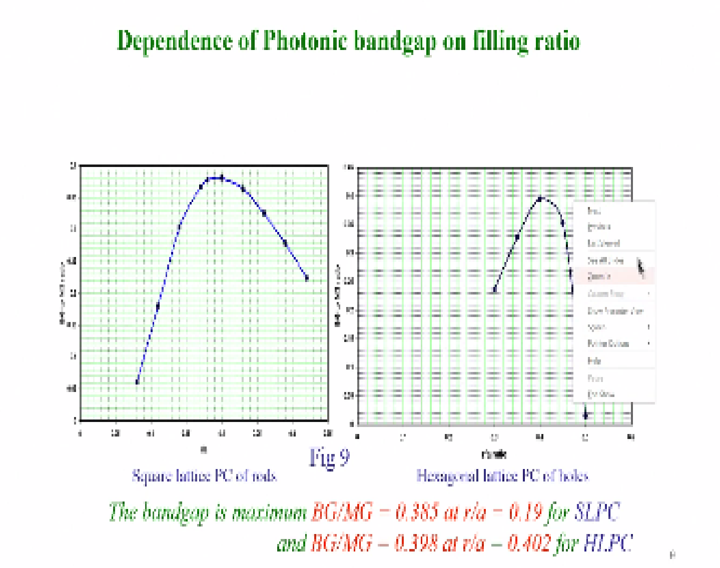

So this example which shows the depends of photonic band gab on the filling factor so you have a square lattice and for both hexagonal lattice there is a peak at a particular value of the with respective radius of the order of point 2 hours so we have the maximum value of band gab similarly for hexagonal so both are behaving similarly but there is some finer differences for example this is more symmetric than this and this has got a lesser band gab and as the one for the similar parameters.

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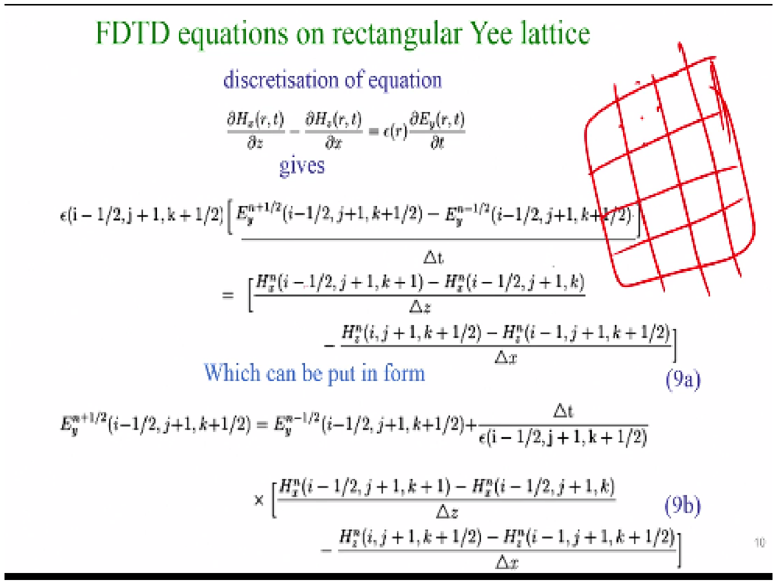

So one of the most common techniques to solve this photonic band gab problems are the design is the FDTD which we have seen earlier. We have not gone into much detail about the FDTD method in the when we discussing about the bream provocation method and the passive devices but I have include some expressions we directly used we can also find this in some books and later current literature.

So basically what you can this FDTD method discriticizes the filed in both phase as well as time coordinate using different finite different techniques like central difference or the and so on and we need to divide the entire area of operation the grid in terms of very, very fine grid points and at each point you define the field in the middle of the point or at the end of some particular point and express it in terms of the neighboring points. So you can finally reduce this wave equation using all these approximations.

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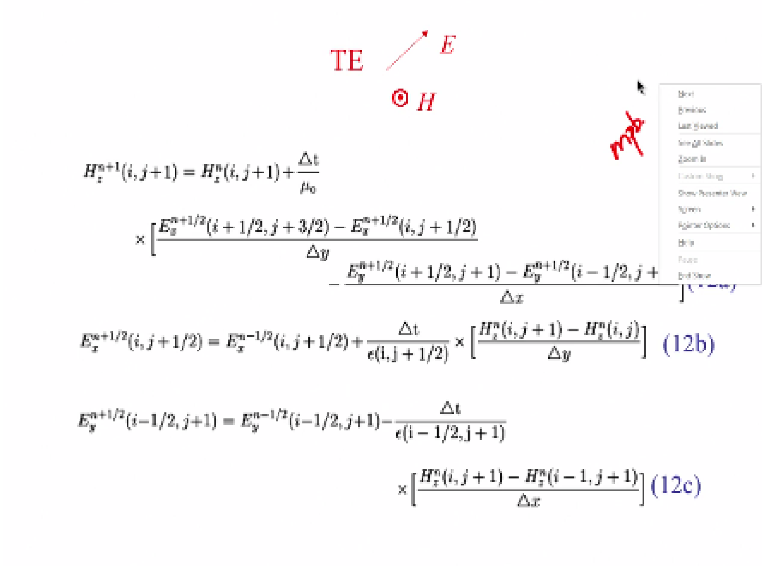

Into a set of equations matrix equations which when solved would give you the field profiles with respect to this structure. So in the case of factorial approach you can you have more complicated sectors with all the fields taking different values. I would like to mention that there are several freeware developed by different universities one of most popular ones called midi photonic band gap tool which is freely available on the web you can install it and do all these finite different time domain method on easily. So you can also improve it depending on the requirement of your problem.

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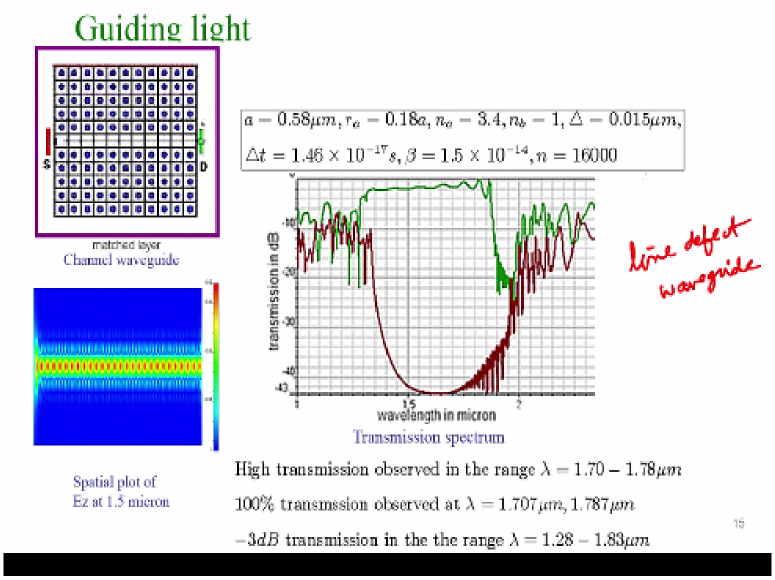

So I will describe some now some devices which we can make using the photonic band gap structures, so one of this implies since that you can think of in analogous with electronic crystals is to create line defect you call this as a line defect where these dots or rods are removed in the form of a line, so you do not have holes in this region of course there is removal form of a, so this acts as a waveguide.

So a line defect acts as a waveguide for light as we have seen earlier that if it is a uniform crystal it will block certain waveguides whereas you have a if you remove line defect as you can see in this particular picture like we propagate in the photonic band gap structure, so this is simulations which shows the spatial plot of electric field active 1.5 micron wavelength generated from one of the commercial yeah I would like to mention there are several commercial tools also along with their are several freeware and in the FDTD code also is available in the mat lab program sets one which can be used for such simulations.

So these are some of the parameters which are given here is a large number of points are taken to at a very good accuracy, in general we can say that there are there is a requirement for numerical methods are computational methods for this photonic applications. So in this particular case we have a high transmission in the range of 1.7 to 1.78 for this line defect so 3D transmission range of 1.28 to 1.3 that means 0 point I think is equal to waveguide. So you can also think of creating a.

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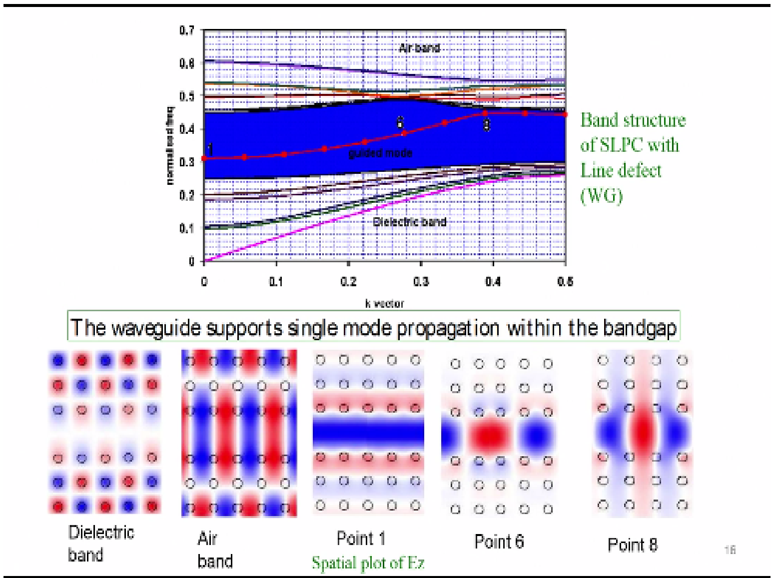

So these are band structure so this red line in the band structure shows that the lightly this particular frequencies being propagated you can call them as a guided modes, so the line defect creates a one line in the dispersion spectrum so the waveguides for single mode propagation within the band gap as shown in this example, this simulation plot showing various bands the dielectric band, air band at different points along the K vector are spatial plots.

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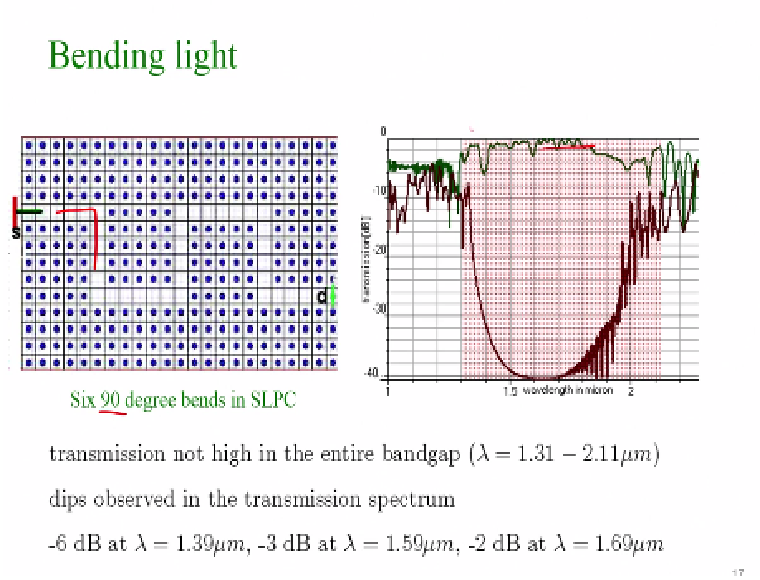

So this an example of another device may made using photonic band gap structures there bent waveguides, in this particular place a line defect is created by removing the holes in this region so Six 90^0 bands these are all 90^0 bands are formed by using this configuration, so recall me that it is almost impossible the band the light 90^0 integrate of a structure because it would radiate out the light in does it function as a band.

So with photonic band gap structures it is possible to create 90^0 bands in square lateral in this particular case the square lateral of photonic slice used here, so in most all the cases we observe this spectrum and correlate with the properties of the device we are looking at for example a good properties in characteristics is what is being observed at this point, these are some of the parameters of computation and the computational results.

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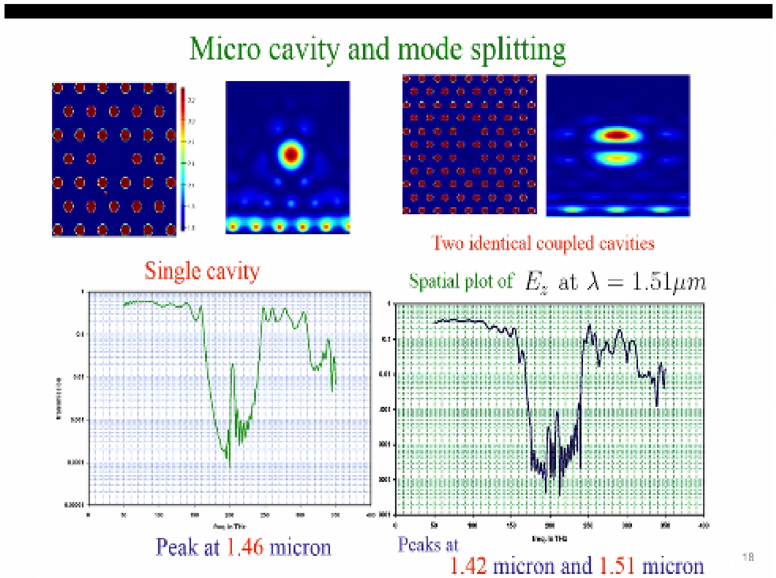

So this an example of another case of what is called a micro cavity, so in a uniform photonic crystal if you create a defect only one hole is removed is called a point defect and you can use it as a very good micro cavity a point defect in photonic crystal acts as a micro cavity whose properties are being studies here.

So at this particular case you see that the light is concentrated in the pointed effect and here it is possible to create a structure where you can have modes so you can use this, if you launch slide through this photonic crystal second mode if you launch it is possible where you to split the mode you can use it, you can use micro cavities to design acts at in it horizontaors or more splitters.

This particular case we see a peak at 1.46 micron is in the single cavity using a double cavity you can create mode splitter so there are two peaks here because 0.3 of these things and of course they are coupled. So that the field propagation across this two identical cavities has a coupled structure and it is interesting features for many applications.

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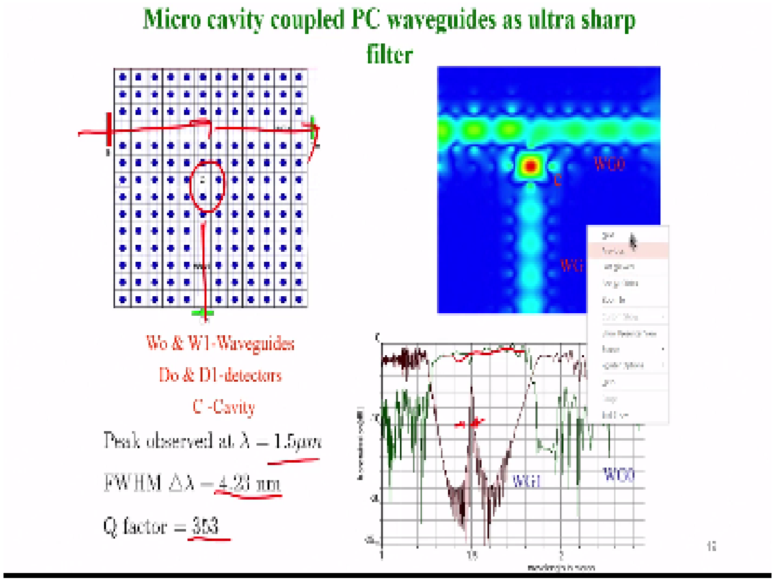

So this example of using the micro cavity coupled photonic crystal waveguide to create an ultra sharp filter, so you have bus waveguide here, line defect acting as a bus and this is the C the point C is the micro cavity point defect is created which will act as a micro cavity and there is one more waveguide tapped the light out, so light is launched into this and can be tagged at this point, so these are the properties which are shown here the AC stimulator of this photonic crystal waveguide sharp filter.

You can see this spectrum that there is a very sharp peak in the stop band such of course this inch was the like propagation the waveguide, so the peak is designed at 1.5micro meters with 4.23 nanometer where lens spread, it is also possible to create much shaper filters. But of course as you note there is a important limitation that the Q factors of the resonance are quite small, so in most of engineering applications including optical applications you need Q factors of the observable thousands. So that is an important channel for the designer of photonic band gap structure based devices.

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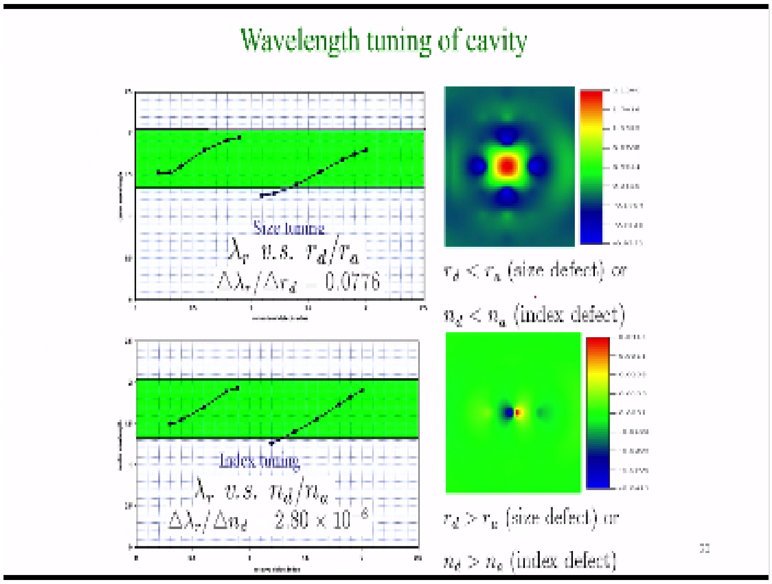

So this is the chart which shows how you can decide what wavelength can resonant you can tune them of operating wave length with various parameters how the cavity, in this particular case there are two methods of tuning are shown here you can change the size of the photonic crystal and tune it and get a different wavelength resonant wavelength. Similarly you can change the defect refractive index where is very small values this is of the orders of 2.8 you can obtain a very good tuning with refractive index.

So refractive index is varying here from 0.5 to 1.5 of the relative value and you can get a very good variation in between the wavelength, so these are the plots which show the amplitude or the field variation.

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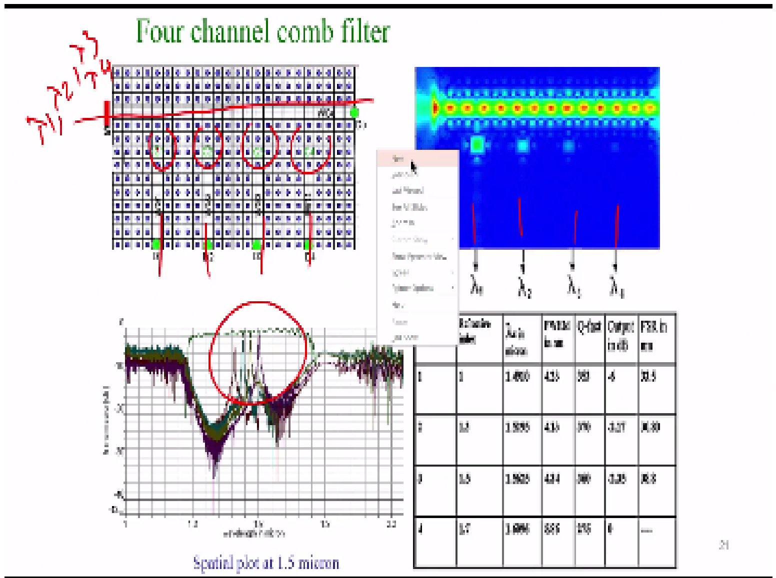

So finally one more example you can create a comb filter by using photonic band gap structures I am showing you four coupled, four cavity C1, C2, C3 and C4 so there is a common bus which brings in the light of all the wavelengths λ1 to λ4 these are the channels optical communication channels each are independently modulated and pass through this bus waveguide and there are four output waveguides for tapping the power and C1, C2m, C3, C4 are designed such that the resonant different frequencies.

Either the refractive index contrast or this size can be varied so that they resonated different wavelengths. And here is the similar of that much of the light is going straight whereas the some refracts small fraction of the light is strapped at each of the output ports, this picture shows the peaks which are resonant so we observe that there are quite uniformly placed and this chart shows the channels the refractive index, operating wavelengths and other features.

So this is an example of photonic band gap structures to comb filter. So this concludes the special topics three topics that we have considered or the optical memos that in resonators and the photonic band gap structures, thank you very much.