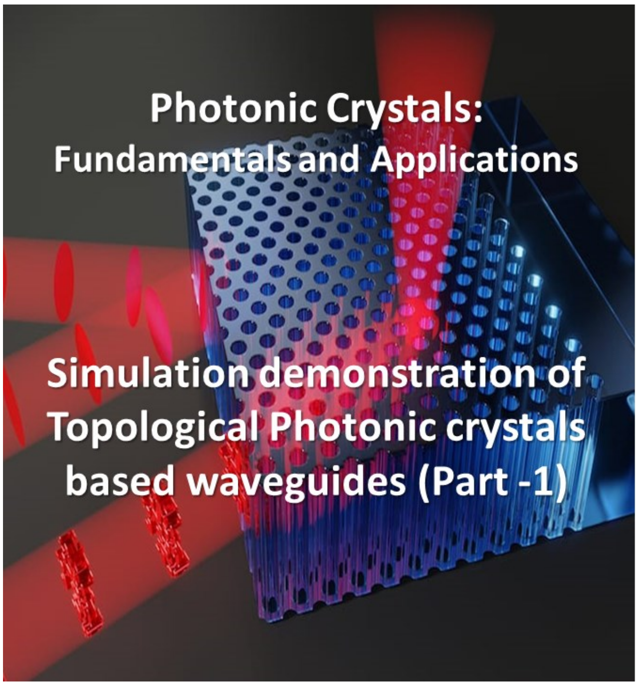

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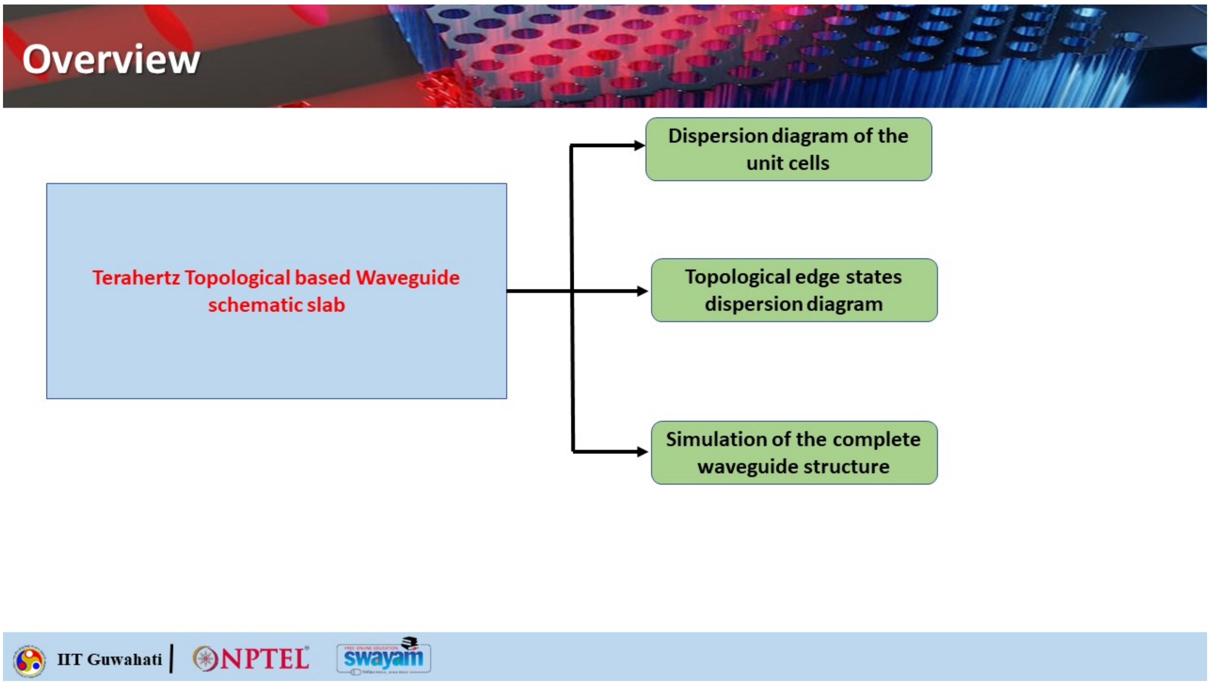
Lec 37: Simulation Demonstration of Topological Photonic Crystals Based Waveguides (Part -1)

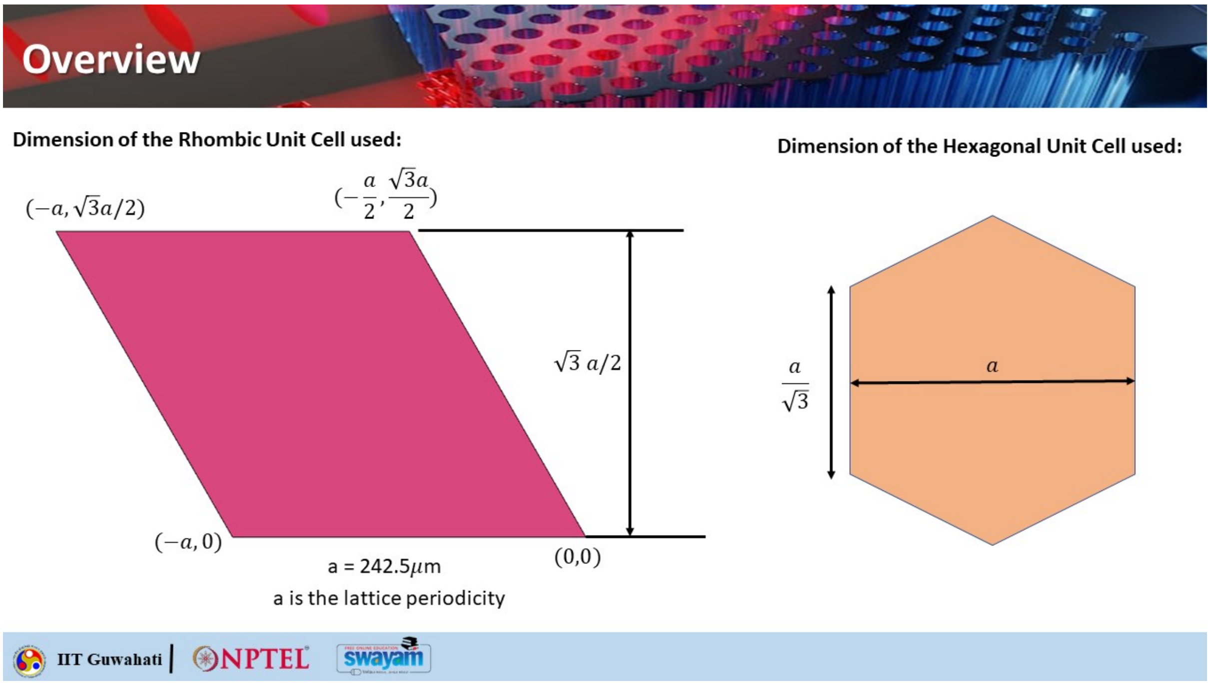
Hello students, welcome to the online course on Photonic Crystals Fundamentals and Applications. So, today's lecture we will have a simulation demonstration of topological photonic crystals based waveguide. So, the entire simulation demonstration will be shown in two different software. So, today in the first part that is why we are calling it as part one. We will be actually showing you the demonstration using a popular software which is COMSOL Multiphysics. And in the next one we will show you using another popularly used software which is CST Microwave Studio Suite.

Introduction



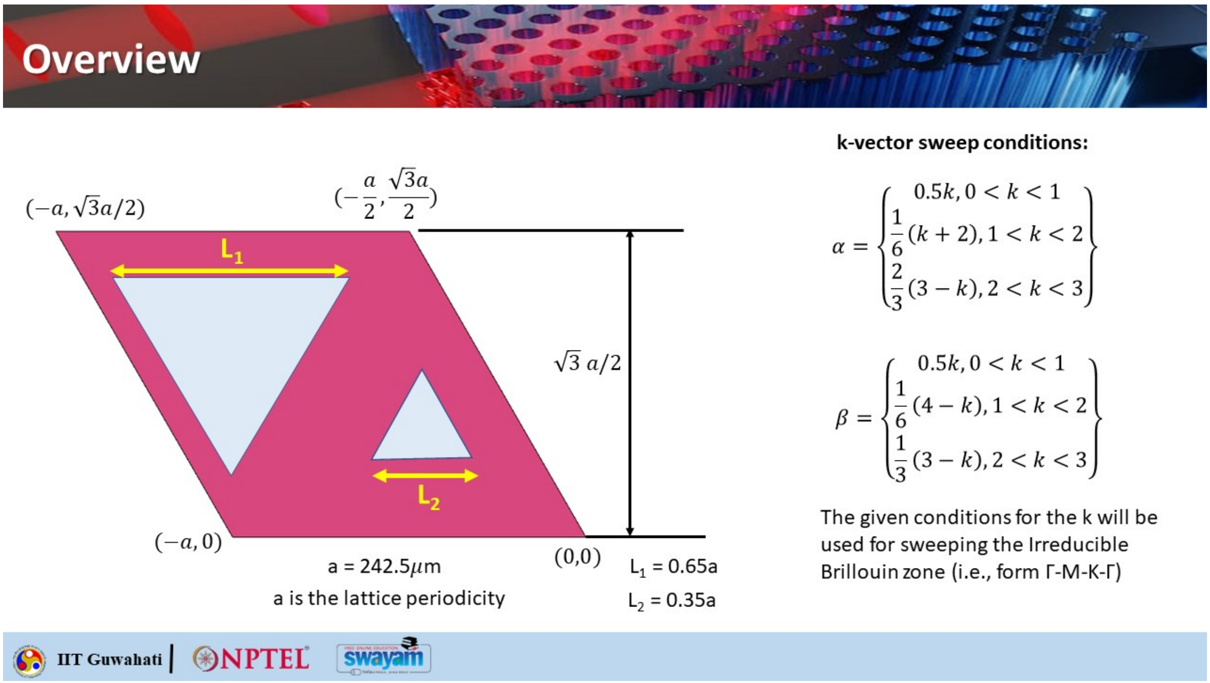
So here the main idea is to give you some hands-on experience. So we will be talking about terahertz topological based waveguide schematic slabs. So these are also photonic crystal slabs as we have discussed throughout our course. So here you will see that we'll be mainly focusing on the three major aspects.

The first one will be how to obtain the dispersion diagram for the unit cell, then how to obtain the topological edge states in the dispersion diagram and then finally, we will go for the simulation of the complete waveguide structure.



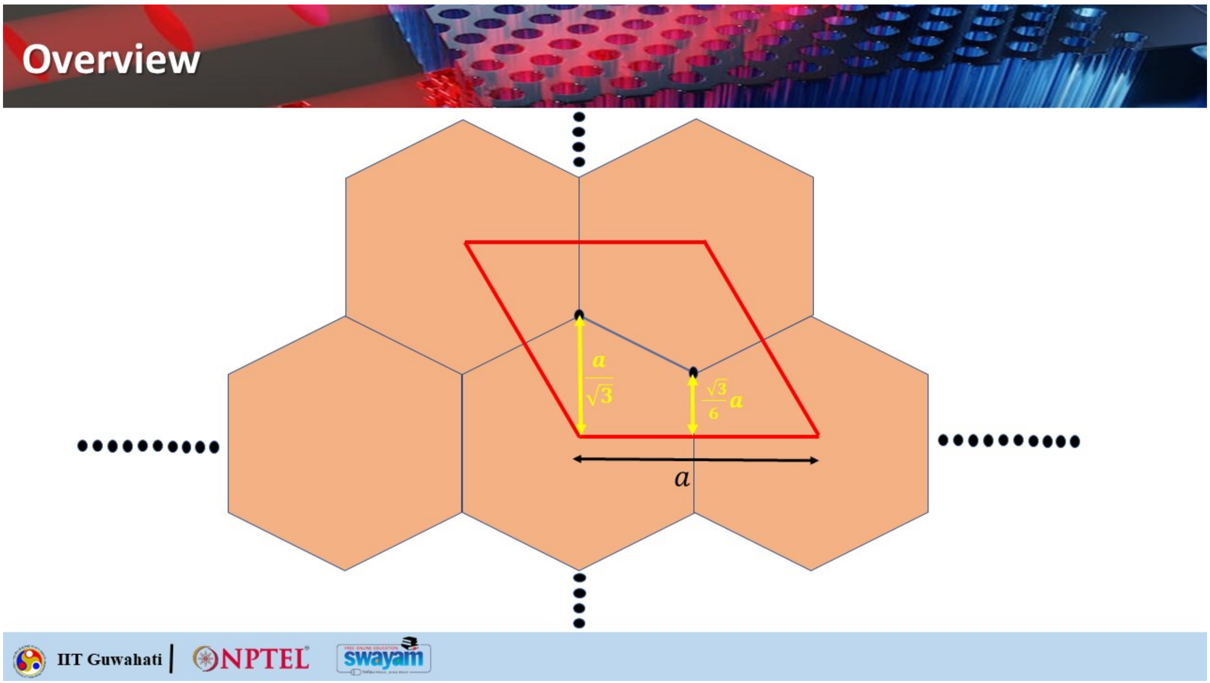
So for realizing a topological based waveguide will basically require all the simulation steps which are the basic requirements. So now if you consider any periodic system, it can have these two types of unit cell representation. So, you can think of a rhombic unit cell that is used. So, you can start with this point being the origin (0, 0) and this one will be minus (a, 0).

This point is (-a , $\frac{\sqrt{3}a}{2}$) and this point being (-a/2, $\frac{\sqrt{3}a}{2}$). So this particular distance is basically $\frac{\sqrt{3}a}{2}$. What is a here? a is basically the lattice periodicity. You can also consider this another representation that is the hexagonal unit cell. So hexagonal unit cell you can draw like a rectangle which has got the length of a and the width of $\frac{a}{\sqrt{3}}$ and then you take this rectangle and rotate it by plus 120 degree.

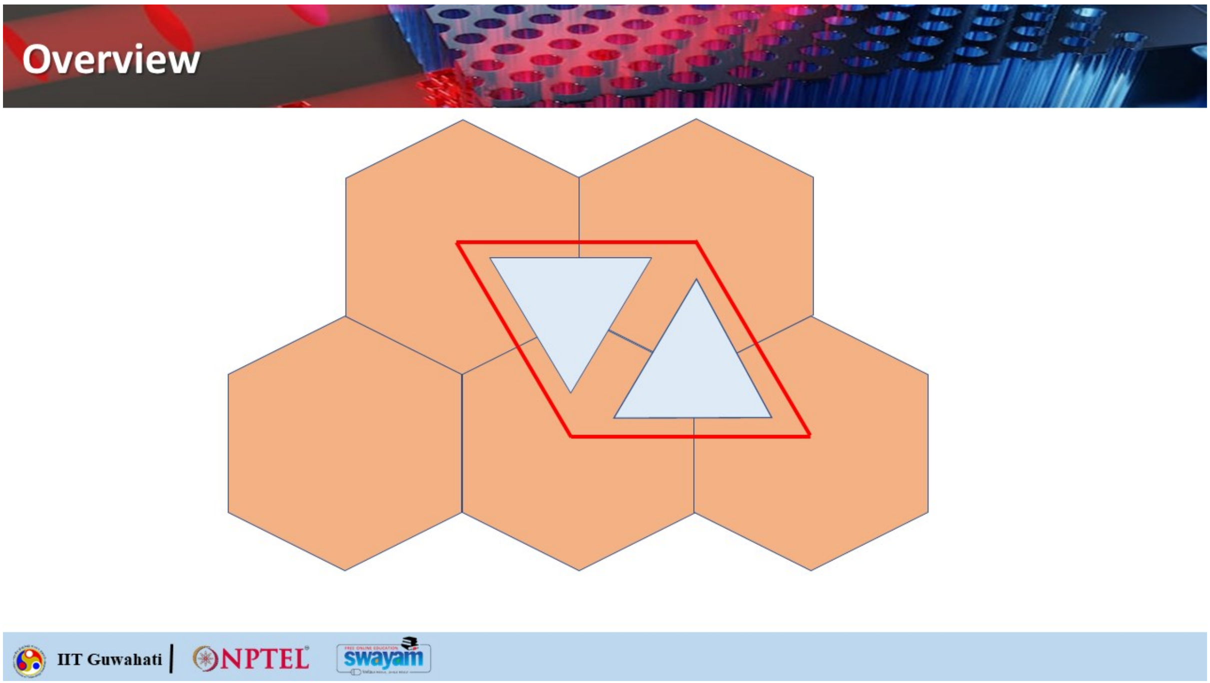


You will get this rectangle and then you rotate this horizontal lying rectangle. By minus 120 degree you will get this particular rectangle. So when you add up all these three rectangles you basically get this hexagonal unit cell. Right. So here we'll first consider the unit cell, which has got two inverted asymmetric triangles. As you can see, the triangles, these are like equilateral triangles. So every side is of equal length. But this guy, the length is L1 and this one, the length is L2. Okay. So, L1 was taken to be 0.65A and L2 was taken to be 0.35A. What is A? A is the lattice periodicity. It is taken to be 242.5 micrometer in this particular example.

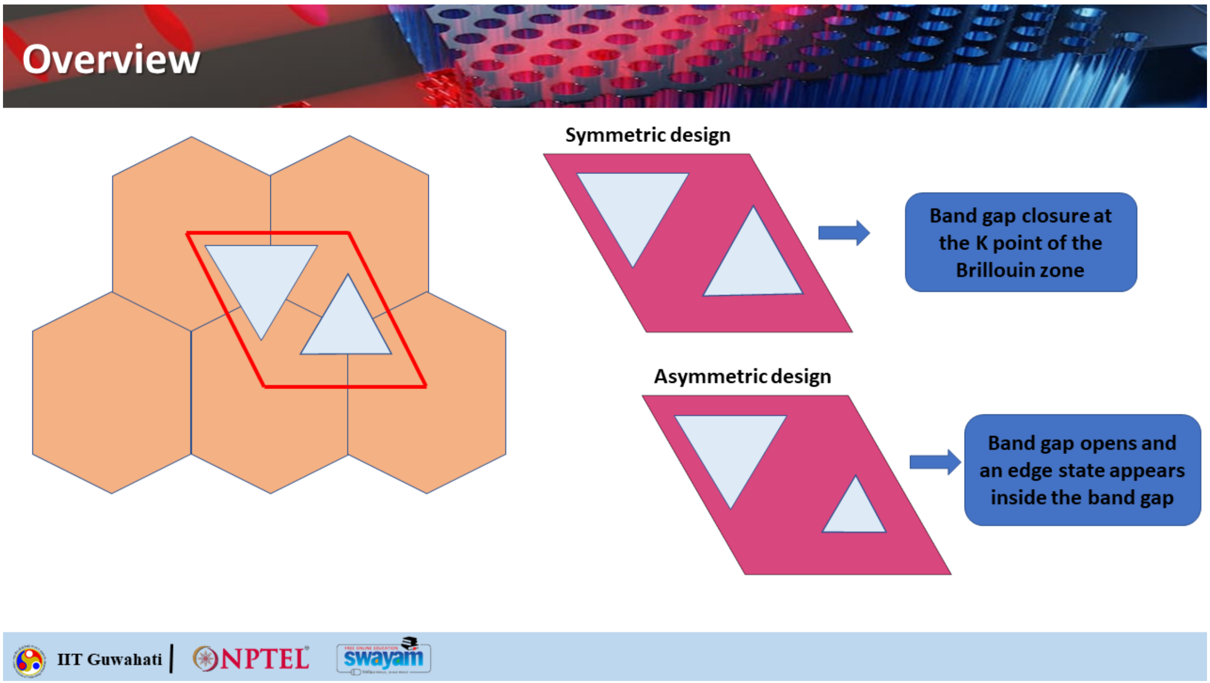
Now, we have kindly gone through the earlier simulation of the topological photonic insulators, you will see that for the k vector sweep, we require these two conditions, okay, alpha and beta for different ranges of k, okay. So, these basically are the conditions given for the wave vector k that will be used for sweeping the irreducible Brillouin zone. That means we have to go from This has to be corrected from gamma to M to K to gamma and so on.



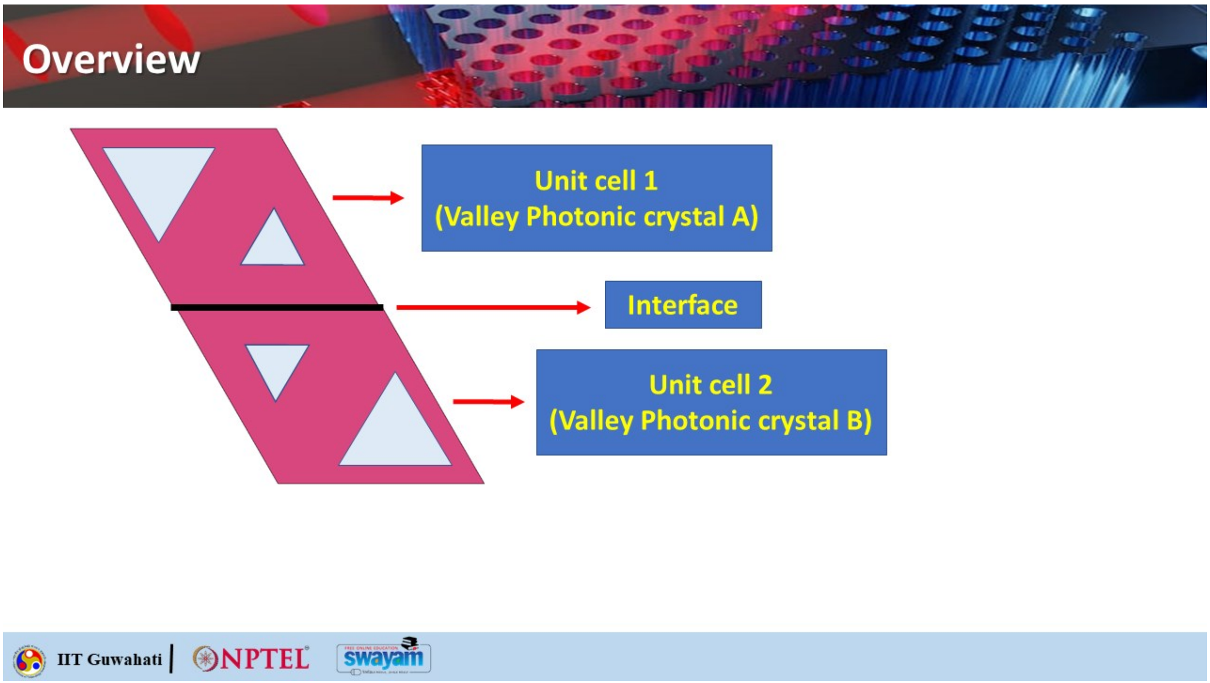
So, this is the rhombus geometry unit cell that you have seen. This is basically taken by connecting the centers of the four hexagons as you can see here, okay.



if you can put the triangular shapes okay as geometric holes which are basically etched from the rhombus shape silicon structure you basically get one type of unit cell okay.

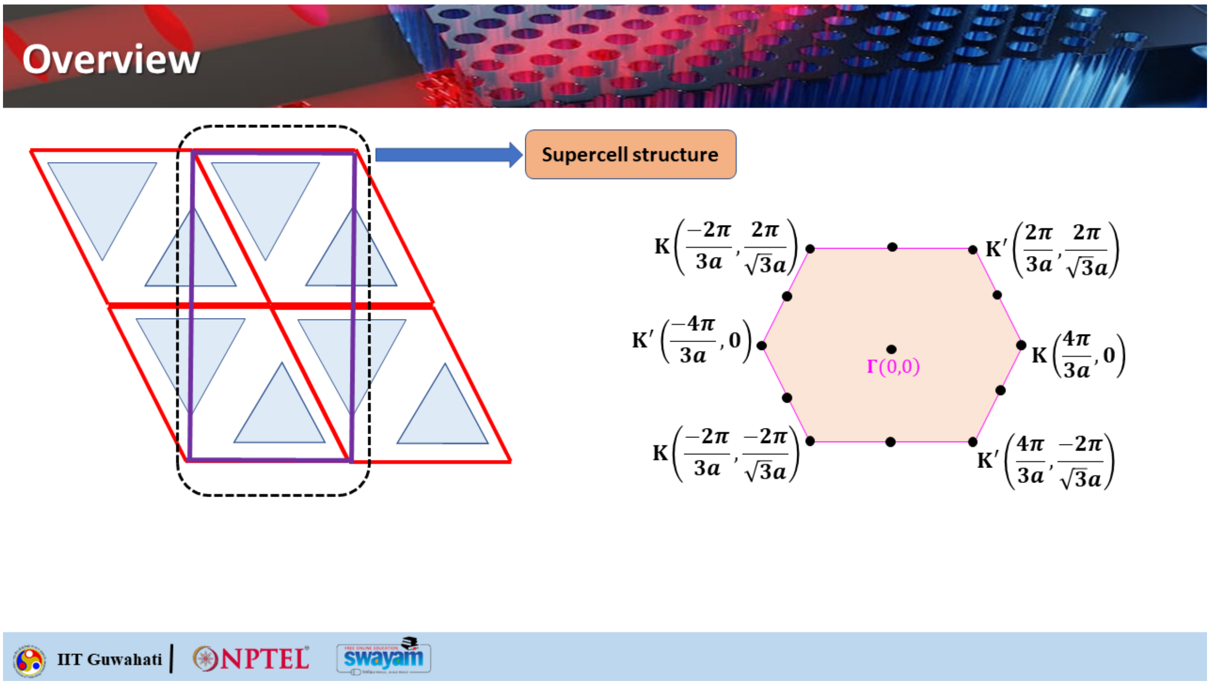


So this is the symmetric design where you have the two triangular holes to be of equal size. So in that case there will be no band gap. So the band gap will close at the K point of the Brillouin zone. But in case if you introduce asymmetry means one you keep as it is, but one hole, triangular hole, you shrink in size.



In that case, the bandgap opens up and an edge state will appear inside the bandgap and that will allow the propagation. So, we will call this type where the larger triangular hole is on the top. And the smaller one at the bottom, we can call this as unit cell 1. Or you can say this is VPC type A. VPC is basically valley photonic crystal.

And if you flip this design, if you take a mirror of this design, that is where the smaller triangle will come closer to the smaller triangle, okay. This particular unit cell can be named as unit cell 2 that is valley photonic crystal B, okay. So, why are you going to do this? When you have these two types of unit cells making a boundary, you are getting an interface and this is where the topological edge states can propagate through.



Now, To check the presence of the edge states, we will perform simulations of the supercell array structure of the unit cell design. So, you take the unit cell like this and then repeat four of this.

So, you can mark this box. that is basically the supercell that can be extended infinitely and you can get the characteristics of the first one any one type of the photonic. crystal cells like this one. So we are just considering this case say you have VPCA you have taken four cells of VPCA and then you can actually arrange this supercell structure in the form of an array of strip okay. Why we do that? If you do that, you can use the eigenvalue simulation for the wave vector k in COMSOL multiphysics software and that will give you the edge states.

So you'll be basically calculating for all these different points. So this is the gamma point, then this is the k, k prime, k, k prime, k and k prime and so on. So these are basically coming from those different points. adjacent cells, okay? So, these are the important points for which you have to calculate, you have to do the eigenvalue simulation to obtain the H state. So, all these things we will be seeing in the video demonstration that I will be showing you right now.

So, I will show you the video demonstration using COMSOL multiphysics and that will cover all those different aspects that we have discussed. So, it will show you how the dispersion diagram of the unit cells are obtained, how the topological edge states are calculated and then we will go for the simulation of complete waveguide structure. So our TA for the course Dibaskar Visas will take you through this particular video demonstration and that will give you a complete idea how you can go ahead from the scratch to design topological photonics based web guides.

Video Demonstration

Hello students, so this will be a demonstration video the part one for the simulation of topological photonics-based waveguides, basically, in the actually terahertz frequency region. So basically, in this demonstration, actually, this simulation demonstration is of actually two parts.

So in the first part, actually, we'll be watching, we'll be actually doing the analysis of the band diagram of the unit cell and also the edge state analysis or the edge state dispersion diagram of the same design, whatever unit cell design we'll be discussing here. So we shall be discussing, we'll be analyzing two main things here in the first part. In the second part, so here in the first part the software that will be using it is commercially available COMSOL software and in the second part actually we will be designing the waveguide structure based on the topological valley photonic crystals and based on that we shall be analyzing the transmission analysis. We shall be doing the transmission analysis of that crystal slab structure and that will be that will be doing it on the CST studio suit so. So actually so in in this video so as you can see that I have opened the console software and you can see that after clicking on the console software it will show you this interface.

This is the kind of interface, the opening interface of the console. So you can see that in the top left corner you can see that This model wizard and blank model two options are there. So blank model is generally it's not required. Actually it is for more advanced applications. Advanced designing for building applications.

Actually application oriented actually design so we don't require this for our purpose. Only model wizard actually is required. so we'll be clicking on this model wizard now you can see that there are many interfaces of console so you need to select the space dimensions so that is in what uh what will be the space dimension that will be working whether it is 3d or 2d or 1d or even the zero dimension also that is the point so you have the 3d option first option then your you have the 2D axis symmetric that is along the across the Z axis. Then you have the conventional 2D space dimension. Then you have the 1D axis symmetric.

Then you have the conventional 1D and the 0D. So for our purpose, so we actually do the pan diagram analysis of the unit cell for the 2D actually structure. So for the 2D unit cell, we will be doing all the analysis that is the dispersion diagram of the unit cell or the band diagram and also the dispersion diagram of the edge states. So both will be done on the 2D platform. So we'll be clicking here on this 2D option here.

after clicking here uh so after selecting the space dimension so now console will be asking for selecting the physics so physics is an important tool uh because uh whatever uh analysis whatever simulation you will be doing on a particular space dimension or on a particular uh after selecting the space dimension you will be requiring the physics that is that is every um simulation that you perform so on the background actually what happens is that the source the software performs some mathematical calculations or mathematical analysis so this is particularly based on the particular physics that you choose So that's why here you can see in the console, there are a list of physics that are actually there. So right starting from the AC to DC, then acoustics, then the chemical species, transport, electrochemistry, fluid flow, heat transfer, a lot of physics interfaces are there. So for our purpose, we actually select this radio frequency. We expand this option and then on the third option you can see that is the electromagnetic waves frequency that is the EMW. So we require this physics interface.

So we click here. And then in the add button we click the add button. to add our physics interface on this blank window. So after, as you can see that now in the, after clicking, after adding this, it will show the electric field components, that is the Ex, Ui, Ez. So we are working on the So that is the possible electric field components that will be doing the analysis here for this particular physics. So after adding the physics, we shall be quickly moving to the next part that is the study.

So we'll be clicking on the study button and then you can see that there are many sort of analysis options are there. So in our case, actually we need to do the eigen frequencies analysis. It is because we are actually required to find the dispersion diagram and dispersion diagram is nothing but the plot between the eigen frequencies that eigen frequencies is nothing but the allowed modes inside that particular structure. Okay, so whatever industry we will be designing, there will be certain allowed the modes or the frequencies that will be allowed by the structure. these are known as the eigen frequencies uh so this dispersion diagram is the actually the plot between the eigen frequencies versus the uh the wave vector that is the k vector or the wave vector inside the structure okay so this uh study will be the eigen frequency so we'll be selecting this study here and after selecting this we go to the bottom part and then this done option click the time option here and It will take few seconds here so you can see that this is the typical interface of the console.

So this graphics is the working area where you can visualize your design and then this is the model builder where you can see some specific interfaces actually have been set up by default. So you can see that in the global definition you have the parameter where you will be defining all the parameters which are necessary for your design. and then in the geometry option under the component section so you will be defining all the blocks or the polygon or whatever it is so you will be basically we will be designing our model here then after designing the model we will be moving to the material part where we will be adding the material okay for the structure and then in the physics under the physics will be doing we'll be making all the changes we'll be actually inserting the boundary conditions here that we'll see it later on and then after filling after doing all these we go step by step so we go down and we can see this mesh so meshing is actually a very important aspect for particular for all these actually simulations why because what actually machine is machine does actually in the simulation so probably you all have studied about the Maxwell's equation in the electromagnetic field theory. So what Maxwell equation does is that It gives us the core, it correlates the time varying electric field with the time varying magnetic field actually.

That is the last two equations. So these Maxwell equations that we read in our textbook, these are all for the infinite cases. That is we are considering an infinite simile that is infinitely big or we can see that for a continuous body. OK, for continuous structures we are actually using those equations. That's why you can see that these are the integral. The Maxwell's are equations are in the integral form or the or the or in the Dell form.

But when whenever we are dealing with practical structures. Like the discrete actually structures which have finite size, so they are actually the Maxwell equations take the discrete form. So in the discrete form what the software does is that it actually breaks down. What machine actually does here that it breaks down that particular structure, whatever it is, be it your 2D structure or the 3D structure. So it breaks down your structure into a very small finite component.

And what it does is that it for that particular small component for each component it will solve the Maxwell equations using all the necessary boundary conditions and whatever result it will get, it will store it in a particular matrix and then the further analysis actually the software does. So that is how actually a machine becomes an important aspect because if you do coarse mesh, coarse means the machine is not of high quality. So if the machine quality is not high, then it will produce error in your results. And if the machine quality is very high, so obviously we'll get very good result, but the simulation time will, computation time actually will increase drastically. So that actually sums up the importance of the meshing in the simulation.

So after doing the meshing part, we'll be moving to the study part here where we'll be doing the parametric analysis of the wave vector k. So I already actually in the previous lectures I already showed one demonstration of photonic crystal slab where actually creating the defect line defect we showed the we designed a waveguide and we showed the band diagram there where actually I showed there the how the K vector is actually swept across the irreducible Brillouin zone. So here also, the concept is actually basically the same. So the same concept actually applies here, but there are some new things to be learned here.

So I shall be discussing all of that. So after so we'll be in the study part we'll be doing the parametric simulation of the wave vector here and then after that we'll be going to the eigen frequency option and in the eigen frequency option we'll be choosing the desired number of eigen frequencies. So we'll be just keeping it we'll be restricting ourselves to only two eigen frequencies So, that is only the first band and the second band because we just need to see whether for the symmetric case, whether it is meeting at k equals to 2, that is the k-symmetry point. And after breaking the symmetry, whether it is creating the band gap or not. And then search for eigenfrequencies will be typically keeping it at 1 GHz only. So, 1 is the actually default value for the comsolver, actually for the eigenmode solver.

And gigahertz is the unit because we'll be basically it's actually the terahertz range, but it is either of the range of 250 to 350 gigahertz. So that's why we are taking the unit as gigahertz actually. This will be the eigenfrequency search method will keep it as larger real part because if we take other values options here so the complex eigenvalues actually will appear and that will give error in our analysis. So that is pretty much about the basic interface of the console here. So now we shall be defining all the parameters for designing the unit cell here.

So first, we shall be starting with the lattice periodicity. So that is the lattice periodicity is your A actually. So we'll be defining here that is 242.5. then you give third bracket, then you in place of micro, so micro symbol is actually replaced by U, is denoted by U here in console, then micrometer M and close the third bracket and then you click tab on your keyboard, then it will take the value.

Description you might enter it as latest periodicity or it is not required, it is not that much important. So after that you need to define alpha and beta here. So alpha is basically the if else condition here. So if k less than 1, so the value will be your 0.5 into k else if then positive record starts k less than 2, then the value will be 1 by 6, 1 by 6 into k plus 2.

closed for that K plus 2 else the final value is 2 by 3 into 3 minus K. So bracket close for 3 minus K bracket close for the second if and then bracket close for the final if. So you need to ensure that all the brackets are getting closed. Otherwise you will be getting a red symbol just like this. So the your entire if else condition will appear red because of some error.

So if it appears like this, you just what you need to do is that you just put the cursor on that if else condition and it will show what is the error. So here you see the error is unknown model parameter parameter K. So this is because we have not defined K. So that is why console is actually showing the error.

So we'll be defining K here. But first of all, let me define alpha and beta and then we'll be defining the K accordingly. So, for k less than 1, so it is actually pretty much same. Let's see if k less than 2, then it is, I think, 1 by 6. 1 by 6 into 4 minus k.

Or else the final value will be this, 1 by 3 into 3 minus k. OK, now we shall be defining K here. You just give any arbitrary value 0.1. So it will take now see the red color on the statement. The red statement has actually turned black, so it means that our the error has actually we removed that error.

OK, then you need to define cannot here. So it is your 4 into pi divided by. A striket. square root of t into a okay fine then you will define a x here so it will be alpha into k naught into square root of 3 divided by 2 okay and then accordingly ky ky will be your k naught into beta minus then again bracket 0.

5 into alpha. Then you define your L1 and your L2 here. So what is your L1 and L2 that will be just let me define all those points here. M is square root of 3 into L1 by 2. Then N is your square root of L2 by 2.

And then P. P is your A divided by square root of 3. And then Q is defined by square root of 3 into A by 6. So you might wonder, you might be wondering that why I have defined all these things. So L1 and L2, you can see it from the presentation, the PPT file itself. So you can see that this is the rhombus unit cell.

These are all the coordinates here of the rhombus. That will be inserting all all will be defining the numbers in the console and L1 is the. Length or the side of the big triangle equilateral triangle and L2 is the side of the smaller equilateral triangle. So this rhombus will be filled with silicon and these two triangles will be the triangular holes.

So we'll be filling those triangles with air. OK. And these are the alpha conditions actually. So how we are actually getting this alpha equations that I've explained it in detail in the photonic crystal Slab I think in the photonic crystal dielectric photonic waveguide actually. So in that lecture series I actually also showed the demonstration of how the line defect using line defect we can create a waveguide. So there I've explained in details regarding how from where this alpha and beta are coming and also the regarding the complete Brillouin zone and also the irreducible Brillouin So all these things are there. So after this, after defining here, so we will be moving to the geometry section.

 So in the geometry section, an important thing to note here is that the length unit, so you change it to micrometer, otherwise some error might be there. Okay, so you expand the geometry here and then you go to the geometry on the top. Then you click polygon here.

 OK, so you name it as rhombus. So put the coordinates here accordingly. Minus A0 and minus 1.5 into A. Square root of g into f right 2 minus 0.

5 into A. And you hit build all objects. Now you can see in the top there is called zoom extent. So if you click it, it will zoom out your figure so you can see this is the rhombus structure. This is not a. This is just a closed curve structure. This is not a solid one, so for solid one you can see that the sketch option is on here.

 So you just click it and off it so you will be coming out of the sketch mode. And see now you will be getting solid structure rhombus structure. So I have only all all I have inserted all the coordinates of the rhombus. So these are coordinates are already there actually and A is the lattice periodicity so. After designing the rhombus you click now you have to design the two triangular holes.

 So so basically the two triangles. So you need again polygon and you write here big triangle. I need to enter the coordinates of the triangle, so it's a bit tricky one because we don't have directly don't have all the triangle option here in the console and we simply cannot draw a line and then rotate it twice to get an equilateral triangle that is also a difficult process and it will not give proper equilateral triangle also. Also you need to keep in mind that that this you can see two there are two midpoints. So one midpoint actually its distance from the base of the rhombus is a by root 3 and another midpoint its distance from the base of the rhombus is root 3 by 6. So we need to ensure that triangle you are designing here so its midpoint uh should be one of those two midpoints okay so for big one so this will be big triangle this is this this is the midpoint and for small triangle this will be the midpoint and vice versa for uh the vpc uh itself b uh okay uh so So to get such kind of accurate geometry, so it's a bit difficult, so there are not so there are not so easy process that you can directly get the little triangle.

So we will go by the coordinate method here. So we know that. In the equilateral, the midpoint actually, so the midpoint behaves as the centroid of the equilateral triangle and it divides the perpendicular bisector. So if I go into the this presentation mode. And if I use a pen. So this is typically your.

Equilateral triangle here and this will be the perpendicular line. so there this this is the centroid so this is 2 by 3 of this l and this is your one third of l okay and this is the entire l is this and you know this entire l this is nothing but your root 3 a by 2 where A is your side length of the equilateral triangle. OK, so. This is the centroid point here and this is the. OK, so this is this will be the base of the rhombus base length and from this center to this distance.

Yeah, so this is the distance and this is given by A by actually root 3 here. So. We require three coordinates for the equilateral triangle. So this coordinate, then this coordinate and this coordinate. Okay. So for this coordinate, what you need to do is you just simply subtract this a by root 3 minus this two-third of L.

Isn't it? So from there, actually, we'll be getting the y coordinate for this point. This distance at this distance is nothing but the Y coordinate of this point. X coordinate actually is pretty much easy because it is just not nothing but the minus of A. OK, so that is how you get and for these two points. Actually, these two points are very know what will be this.

So minus A is the point here, X coordinate and you move. further in the positive direction by an amount a by 2. Okay, so it is nothing but your minus a plus a by 2. This is the x coordinate and y coordinate will be you just add.

So your a by root 3 plus okay, a by root 3 then plus this distance. 1 third of L. OK, and then this will this will give the Y coordinate of this of this point. Similarly, the Y coordinate of this point will also be same. Only the X coordinate will change.

Now you have to in place of plus a by 2 you need to go minus a by 2. OK, so I think. The the coordinate how to get the coordinate it is clear. So I'll be discarding this. I'll be going again. So you need to now enter all the coordinates here.

So I have actually already designed that particular thing structure. So here in the big triangle part, also the geometry part actually.

OK. Yeah. So in the geometry part, big triangle. So what I'll do is that. So you can see that minus a p minus two by three m. So whatever I have defined here, actually p, q I have defined here. So that's why to make our analysis easier because if I go on writing a by root three minus two third of root three l by two, so this will make it very lengthy process and it will be time taking. So I already assigned those a by root three, root three by l as variables here and then I have done this analysis.

So I'll be copying all those points here and then I'll be taking directly here. List so this will be build all objects now see. So this is the big triangle here. So similarly for small triangle will again clicks polygon here and then. And the displacement vector is actually A because it is shifted by a distance of A actually. So the same rhombus will come here and then again move to and select this and then you click build selected.

Now what you do is that displacement you specify positions. So your old vertex will be this. This is the old vertex, so this should move here. So that is That is what you are doing is you are shifting this rhombus to the upper portion. OK, so your vertex final vertex will be this.

And then you click build selected so you will get the third of the rhombus here. The unit cell here. And then you click on again move and then you do the same thing so you will get this whole kind of structure. So which is similar to this thing. OK, so now you need to. make this rectangular box by removing all the unwanted thing uh so what you need to do is is that you take line segment in the more primitives option you take click line segment and then you uh join take the vertex here so this and this and starting vertex and vertex and then you click build selected and then again line segment OK, now what you need to do is that these are all domains.

So these are called domains actually. So you need to divide those domains into you need to separate them so that you can delete those unwanted parts. So you go to booleans and partitions and then you click partition domain. So you will arrive at this.

You select entire structure on except these two lines, two straight lines, vertical lines. OK, so. This is the domain to partition so and what what will be the particular object that will be doing the partition with so partition with will be the edges that is the two vertical lines. So here you select edges and then you select all those two vertical lines and then you click build selected. And then here delete option is there you click delete. So the delete by default object will come.

So you click on bound you click on domain domain and then you select this. Can now see so these domains are have been separated. So you select those all those domains and then you click build selected. OK, so now you will getting this initial structure. So this is similar to this purple box.

Now what you need to do is that this red line boundary and this red line boundary you need to remove this. So what we do is that? You first even do the Union so. In the Boolean partition again you go to Union and then you click Union here and we just select only those parts, not the triangles and you just keep it. Keep them off. Give them unchecked.

Actually keep input objects and keep input boundaries unchecked and then you click build selected. So you will be removing that particular boundaries and then again on Union 2 you select all those triangles to merge with that particular rectangular box. Here you keep the interior boundary set checked, otherwise the entire C and that structure will go. So just keep it as like this.

OK, now you make the array. So this you select and then you repeat it in the particle direction. Typically we take it as 15 times and the displacement vector will be your. In the y direction it will be square root of 3. Why? Because this is the rhombus.

OK, so the rhombus height is square root of 3 into a by 2. This is another rhombus, so it will be twice of. square root of 3 into a by 2 so this 2 2 gets cancelled that is why the displacement is root 3 into a so after clicking this you will get the strip okay in the upward direction now what you need to do is that so this is actually for the entire ab part this entire strip is of the uh your vpca repetition of vpca if you can see this so this is the big triangle this is a small triangle this is the big triangle this is a small triangle so this actually gets repeated in the upper direction so this is because this all four unit cells are vpca so in so this is if i take um you highlight So this is your interface. So beneath that, you have to take the VPCB portion. So similarly, a similar thing, you will do it for VPCB like this, making four options and then you remove this, take the line and then you remove the unwanted part.

So this will be a time taking process. What shortcut is you just make this supercell and then you flip it. This will give you the VPCB configuration. And that's why after that you do the union. So you take all the union of the area and then you take the mirror.

So you click, select this entire area and the mirror, the line of reflection. So this is important. You choose this edge. So along this edge, mirror analysis will be done. See, now this upper portion is actually the A type. And from there this is the interface. So this is the interface and from from the from this interface to the bottom the B portion comes.

So this is basically the AB type AB type acetate configuration. OK, similarly. You fill all those triangular holes with air and then this with silicon. Then you go to electromagnetic waves.

And. And the periodic option. So in the periodic option actually you select all those edges. Don't miss them. Select all those edges and then you here you define as Flockett periodicity kx and ky and you take scattering boundary condition here and and in the top part. So in the top part and also in the bottom part. to give it as a scattering boundary condition because your periodic condition won't be able to because you have already hit the hit the boundary of your slab structure. So this is only a single strip. Okay, and if you now to get the final slab structure, what is the basic thing you need to repeat this strip in the right direction in the right hand direction and also the left hand direction.

OK, you don't need to repeat this trip in the upward and downward direction because already you have hit the extreme of your slab structures. That's why we're using the scattering boundary condition here, OK? then after scattering boundary condition all those have been applied uh you just make sure that this is in plane vector because sometimes three component vector it it stays there by default and then your simulation will not run it will give erroneous results okay so make sure that this is in plane vector is selected and then you go to mesh so in the mesh actually you take physics control and then normal because if you by any chance if you increase it to like finer or extra fine your simulation time will increase drastically. So it might take even two days also. And also it's not only about the simulation time, it is also about how powerful your PC or laptop is.

So like my operating system is running on i5 12th Gen with 16 GB RAM. That's why it is able to handle attachment that much amount of mesh here so and even even with that configuration it is taking at around 20-22 hours time so if you have configurations lesser than that so just make sure that you don't you just keep physics control mesh here and you do the analysis in the normal mode okay so after clicking selecting the normal mesh you click build all And in the study option, you select this parametric sweep and then you sweep it from minus one to one and the step size is at 0.01. Sweep the character. And in the eigenfrequency analysis, you search frequency, you keep it as by default larger real part.

And then in the number of eigenfrequencies, you take it as 110. Yeah, fine. Let me show it here. So eigen analysis will be coming like this. So these are the lower bands. So a lot of bands will come.

OK, so lot of bands will come and these are the upper bands. A lot of bands will come and this will be the band gap. So inside the band gap, such kind of edge state will appear, a single line. OK, a single line will appear and this you can see this will actually confirm that your structure is a logical behavior. Okay, so for AB type design, this might be the edge state. So for BA type, BA type will get such kind of opposite characteristics curve. Okay, so why we are getting this opposite here and some interesting phenomenon happens here at this point, intersecting point and at this intersecting point, this will be discussing it.

So a lot of eigen bands will come, so that's why the simulation time takes so much time. So that's why you keep the number of eigen frequencies as much higher as you can, so that way by default you take it greater than 100. OK, and then you click on you go to home and then you click on build all and then build mesh and then you click compute. So I have already.

Done the simulation analyzer of the edge state and you can see This is for the AB type. There is the red one and for the BA type. So as I have already told here, you can see at this intercepting point. So this intersecting point are nothing but if you take the exact analysis. So this is the plot that I have done. So I have extracted the data and I have plotted in origin.

So if you take a single straight line in the origin and you can check the x coordinate, you will get it as minus, that is 0.67 and here it is minus 0.67. So you can see that the graphs are actually contrasting in nature. how it can be visualized if you take the tangent at this point, the slopes will have opposite values, okay, equal and opposite values.

So, this means that for your AB type and for your BA type designs, the slope of the curve is given by the group velocity. So, for your this uh slope the group velocities actually they are for these two modes okay so for this two type of designs okay for the two type of uh configuration the group velocity will be will have actually uh will uh these two configurations will have uh opposite group velocities and that's why uh they will not uh couple with each other so that uh inter valley mixing Interval mixing is actually absent here. Why we are calling it as a valley here? That is because at this point actually it looks like a valley actually. And this point corresponds to, if you can remember, this point actually corresponds to K dash.

And this point corresponds to K point. So if you go to this, see, so this is K dash is nothing but 2 pi by 3, that is 0.675 by 8. That's why this point corresponds to K' and this point corresponds to K. So that's why they are known as K' valleys, K' valleys.

That's why they are known as the valley points. Okay. Or you can say it as, and that's why that is, and that's why we call it as intervalley mixing. Intervalley mixing is absent. That's why the propagation losses is also less. And that is the beauty of topological photonics. So And actually I have extracted the data and I have plotted it in origin because that data extraction becomes a huge headache actually for this simulation, for this topological edge state simulation.

Because after finishing, if you try to export the data also, the data, the file size will be typically of the order of 20 to 25 GB. So it's a humongous file and that will not be opened even that is your default software that is in notepad. It will not be able to open this kind of huge file size. So for that you will be requiring the notepad plus plus. So notepad plus plus actually can open this kind of huge file size and and that also actually it will take a lot of time.

It takes around 15 to 20 minutes depending upon your how powerful your CPU is. So, in a nutshell, actually, this topological edge state analysis is one of the most important also, and it is also one of the most difficult analysis in the entire topological photonics simulation part. So, I think our simulation has got over. Okay. So, for the symmetric case, we'll be checking the band diagram here. So we covered the band diagram analysis and also we covered the topological edge state in this first part and in the next part demonstration we'll be seeing how so based on these simulations we'll be designing the entire um the waveguide structure so this the in the interface so the interface will behave as the waveguide and we will see how the terror signal actually uh passes so you can see that for the symmetric case now see the two bands actually are meeting at k equals to two and this k goes to two corresponds to the uh k symmetry point okay in the britain zone so that's why uh this uh point actually uh It is the band is actually meeting now.

What we'll be doing is that if you take it as 65 and if you take it as 35, so now you are actually breaking it. OK, so now you are breaking the symmetry. So now the band will open. So I think we need to wait for another. I think 76 to 7 minutes. so this is the kind of edge state analysis you can see that how dense is the mesh although you might it might appear that the mesh quality is dense but you if you zoom it you can see that this is the smaller triangle and you can see the mesh actually has divided the smaller triangle into only one two three and four parts so this is not that much kind of dense mesh okay but still The machine quality.

If you improve, you will try from here. If you try to improve the machine quality, the computation and time will increase exponentially, so we don't want that kind of complex computations. OK, and I think. And this is more or less.

About your OK. So one thing after the simulation of topological edge tape, you go to this electric field and click on the surface here. I need to show you one thing. So this is the kind of. The your.

The electric field distribution will look like you change it to the magnetic field. It is the HZ component because TE mode we are analyzing the TE mode. So you just click it on HZ Then click it like this. Hey. typically we keep it as finer option uh mesh quality uh because this is a single rhombus so if you uh if you ever try to increase the the mesh quality also here so that will not hamper your simulation time that will not drastically increase but for topological ad state simulation just make sure that you don't increase the mesh quality to a much higher value so our simulation has gone over see here in this emw also at k equals to two you can see there are two values see these two are this uh this uh the this two are dissimilar values actually okay so you can from there you can calculate the bandwidth also so now you click on the one diploid group so just wait for one minute so you can see here so the now you can see the band gap actually has opened and inside that band gap an edge state will appear as we have seen in the topological edge state analysis.

So this is called the zoom box. If you zoom it here, so you will be able to see the band gap range also, exact band gap range, what is that exact. So this is pretty much all about the band diagram analysis and the edge state analysis also. OK, so in the second part we shall be discussing about the entire photonic crystal, topological photonic crystal slab simulation where we shall be discussing how the interface will behave as a waveguide and then we can see the input signal will excite the edge state and then the transmission will happen.

OK, so we shall be discussing it in details in the second part. OK. So thank you, that is all for this lecture. If you have got any query or doubt regarding this lecture, you mention simulation demonstration part 1 and photonic crystal MOOC on the subject line and you can drop an email to me. Thank you.