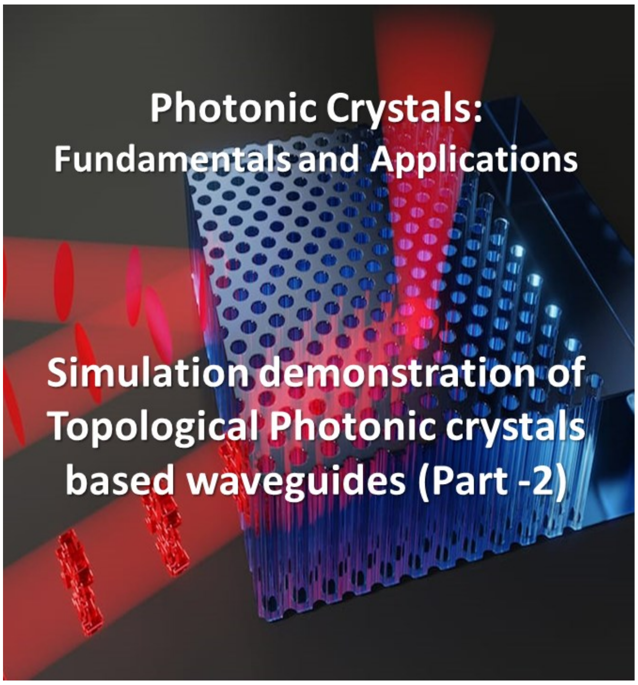



FREE ONLINE EDUCATION
swayam
शिक्षित भारत, उन्नत भारत

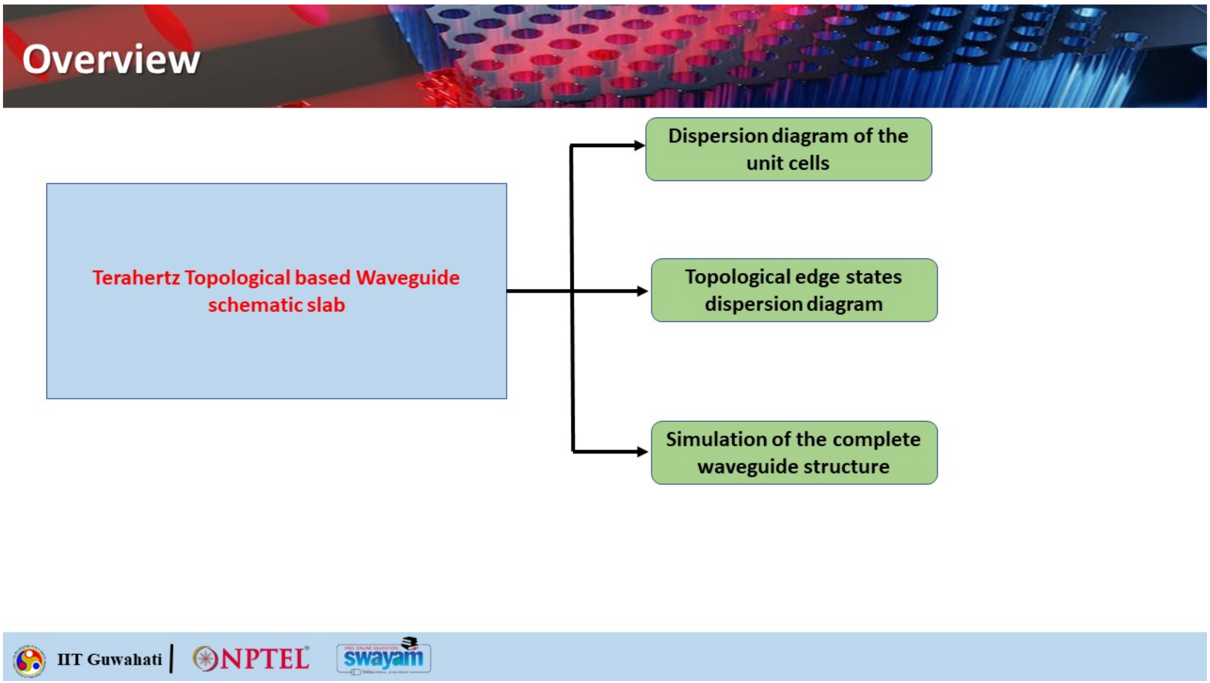
**Dr. Debabrata Sikdar**
Department of Electronics and Electrical Engineering
Indian Institute of Technology Guwahati
Web: https://www.iitg.ac.in/deb.sikdar
Email: deb.sikdar@iitg.ac.in

NPTEL
NPTEL ONLINE CERTIFICATION COURSE
AN INITIATIVE OF MoE, GOVT. OF INDIA

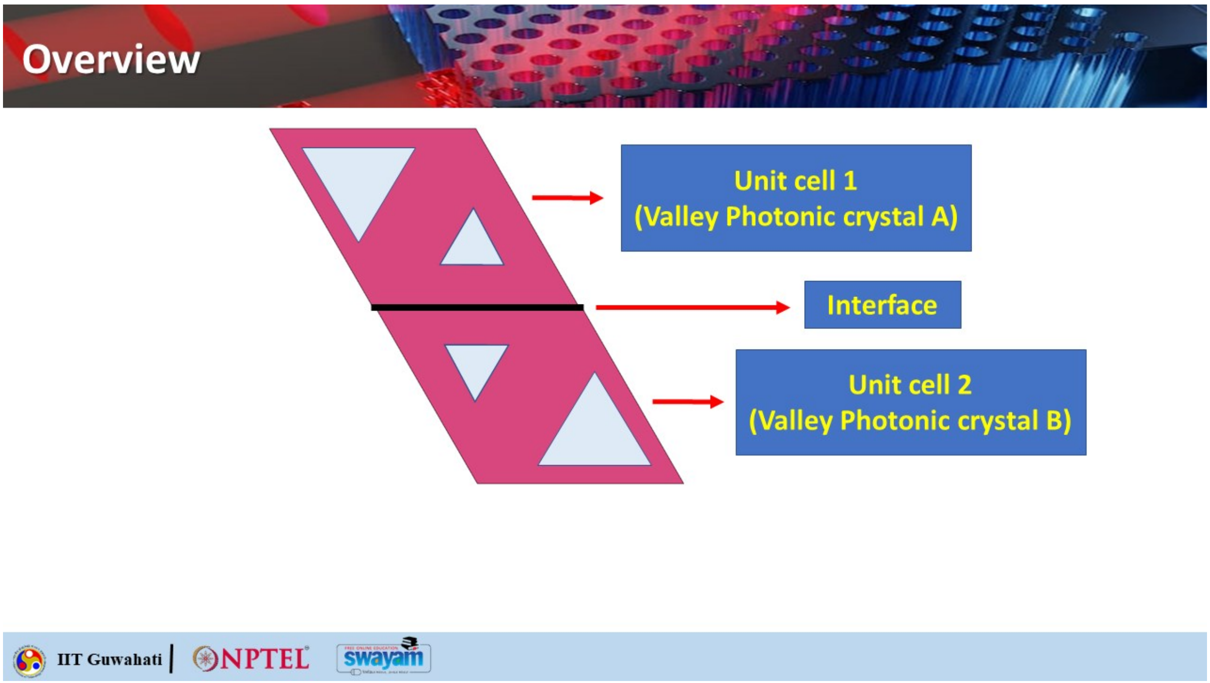
Lec 38: Simulation Demonstration of Topological Photonic Crystals Based Waveguides (Part -2)

Hello students, welcome to the online lecture on photonic crystals fundamentals and applications. In today's lecture, we will continue with the simulation demonstration of photonic crystal or topological photonic crystal based waveguides.

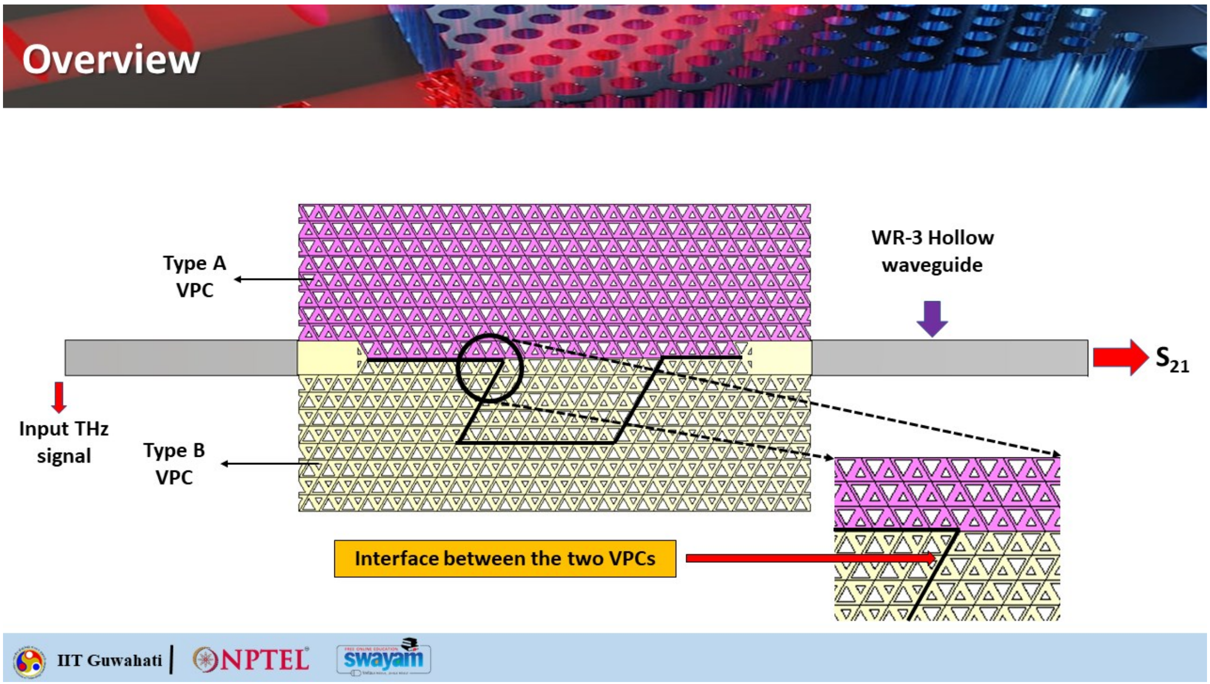
## Introduction




So, this lecture is basically part two. Here we will be mainly looking into the video demonstration of an actual waveguide kind of structure. and then we will be using CST Microwave Studio Suite for doing the simulation. So that will actually give you an idea of how things work in console which you have seen in the previous lecture  and also in CST Microwave Studio Suite which you will be seeing today.



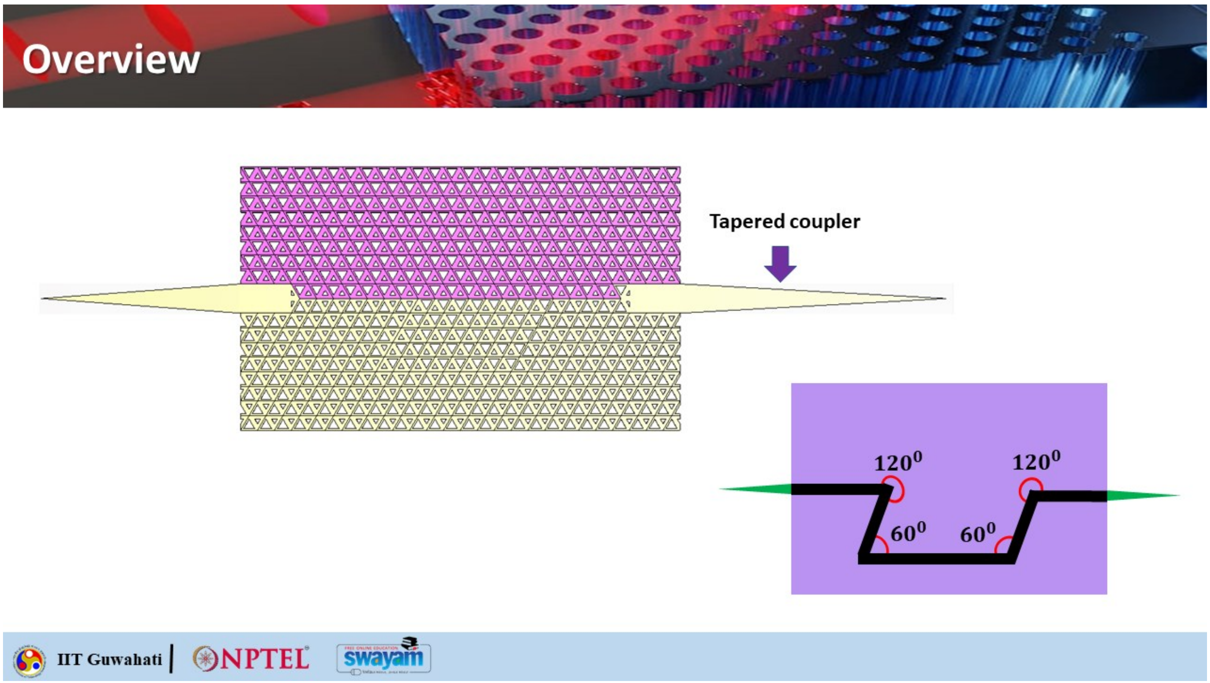

Now why we have been stressing so much on this topological photonic crystal based web guides and other structure simulation because this is a very very popular  topic  of research worldwide and lot of researchers have been actively working on this and this is why we have been focusing on this particular area. So, as we have already seen in the previous lecture about the simulation demonstration of the band diagram of topological value photonic crystal unit cell and the edge state dispersion diagram. We will now see in this lecture how with all this information that is whether the design is going to exhibit topological behavior or not, all these things we understood from the dispersion diagram and the calculation of the topological edge states. Now, we should go ahead and try to design the web guide, okay.




So, as I mentioned in this particular tutorial video, we will be showing you with comsol, not comsol, CHT microwave studio suite software, okay. So, this is a quick recap of the two types of unit cell. So, this was VPCA and this is VPCB. okay so this is unit cell 1 this is unit cell 2 and this is the actual structure so as you can see i'll go into the details of the entire waveguide  so this is the connector so this is basically the input terahertz signal okay and this is s21 that shows transmission so this is the waveguide port, okay. So what are these two? These are basically WR3 hollow waveguide.

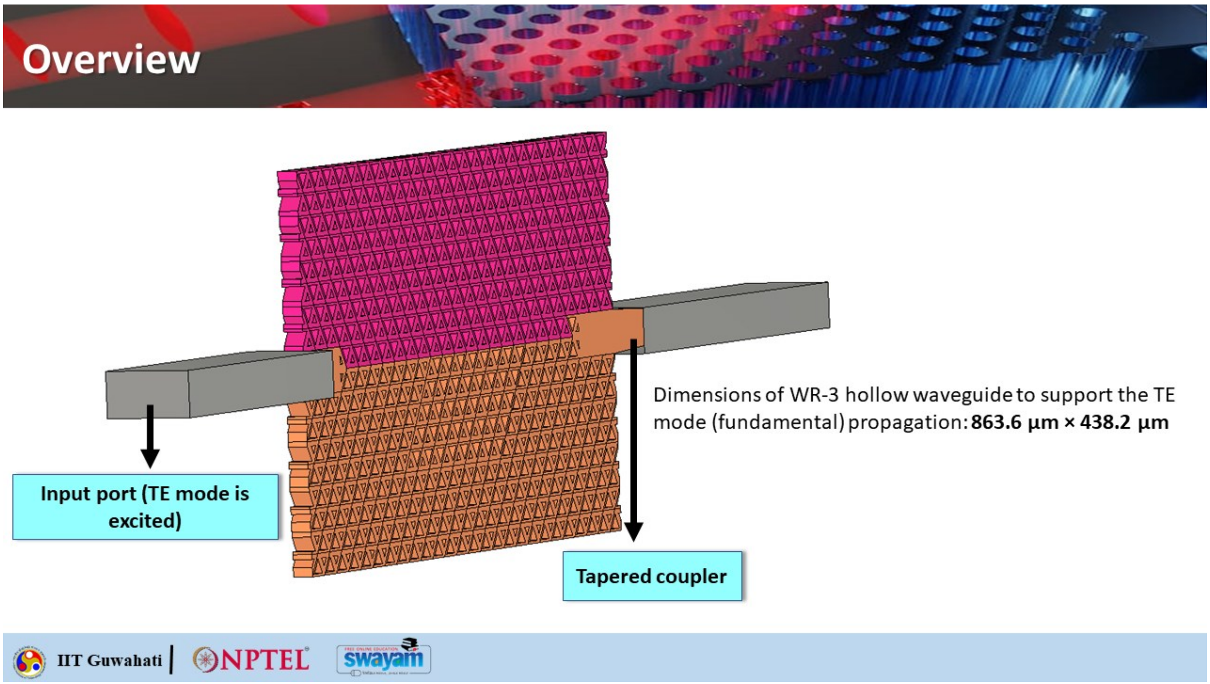
Okay. And this is your terahertz topological photonic based passive device. So this is basically a waveguide. Okay. That I have designed.

Now what you can clearly see that we are basically using two different colors for VPC type A and this is VPC type B. So here pay attention to this. when the small triangle and the small triangle, inverted small triangle are coming close to each other, they are basically forming this interface. And this continues till here. So, this is where VPC type A and VPC type B are forming  the interface okay  now then there is a sharp band of 120 degrees here okay  so what happens in this sharp edge so we are basically zooming in here and you can see that  now the interface is between two different types in VPC type B itself so in VPC type B you can actually have the smaller triangle on the top So the neighbor should be should have such an orientation that the smaller triangle is next to this okay.




So that is how you form the domain wall and this is how you can extend it further. So this is the way you can actually make this interface. Take the sharp bands 120 degrees here and 60 degrees here and then it can  go like this. That shows you the capacity and capability of making any sharp band waveguide using valley photonic crystals or topological photonic insulators. Now, you must be remembering why we are doing this because this waveguides will be robust to any kind of defect and imperfection.

So, there will be no loss at all while propagating through this particular waveguides. So this is how the actual device will look like. So you will basically have tapered couplers at both ends. So this is also another model that shows that you have put the tapered couplers and this is the area of the chip. So this is 120 degrees, 60 degrees and so on.



And this is how the 3D view of the  photonic crystal slab looks like you see this is the finite thickness. And then these are the tapers which go into the tapered couplers that goes into this hollow waveguide WR3. So you can have input port here and then you can have output port over here. So the dimensions of this WR3 Holo Waveguide are chosen so that they can support the TE mode, the fundamental one,  because that is the one that you are exciting here. So the dimension of the Holo Waveguide, the width and length are basically given here.

So this is typically the system that you are going to see how it works. So now we will look into the video demonstration  of the same using CST microwave studio suite. So, our TA for the course, Dibaskar Visas, will take you through this particular video demonstration. And that will give you a complete idea of how you can go ahead from scratch to design topological photonics-based web guides.

## Video Demonstration

IIT Guwahati | NPTEL swayam

Hello, students.

So, welcome to part two of the series on the simulation of topological photonics-based waveguides. So, here we will actually be analyzing based on the previous part of this series, where we discussed the unit cell. Also, regarding the unit cell band diagram and the topological edge state dispersion diagram. This is commercially available.  (The sentence is already grammatically correct.

) After clicking on this software, what you need to do is go to "New Template" and create a new template here. After clicking this, you will see that there are many options for project templates, such as if you want to work in low frequency. That is the megahertz or hertz domain, or if you prefer, the microwaves, RF, and optical domain. So, this is the working area. Then, if you want to work in electronics, consider EMC or particle dynamics.

So these are basically the typical interfaces that CST is providing us. So this is actually very similar to the physics interface of COMSOL that you have already seen. So, we'll actually be working in the microwave and RF or optical domain. After selecting this, it will provide a list of options. That is your antennas, the circuit and components, the radar cross-section, and the biomedical exposure—all these things.

So, we'll just go down. And we'll select the periodic structures, and after clicking this, you click "Next" here. Then it will ask you to select a workflow. So this workflow is essentially asking whether you are designing a unit cell for FSS metamaterial or if it is a full structure. It is either a metamaterial FSS full structure or a metamaterial full structure.

So, FSS stands for frequency selective surface. So we are not actually concerned with our analysis of the FSS. It is mainly about the actual full structure of the metamaterial. So we'll be selecting the third option, which is the metamaterial full structure. After selecting this, you go to the next step, and now you can see that there are actually two important solvers.

So it is asking which solver you need to use. Okay, so there are actually other solvers, such as the eigenmode solvers and other stationary solvers, as well. But here in CST, if you work in the RF domain or optical domain, two types of solvers are actually recommended. So, that is the time domain. And the frequency domain solver—actually, you can see here that it is already written that in the frequency domain, it is for smaller models.

So, our slab structure model is actually pretty big because, as I design the structure, You can see how the structure actually appears at the micrometer level; the entire dimension of the slab extends to a millimeter. So that's why, for bigger models, a time domain solver is preferred. So you click that, and it actually comes in the time domain by default. So you just click here and then go to the next step. Now it actually asks you to select the units.

So, whatever units it uses by default will be in micrometers for the wavelength of frequencies. In millimeters or gigahertz, time is measured in femtoseconds, temperature is measured in Kelvin, and the rest of the parameters are by default. You can only change the first four things, but you don't need to change anything here because our dimensions are in micrometers. You can if you can recall that the lattice periodicity is 242.

5 micrometers. So we don't need to change anything here, and also the frequencies in gigahertz, actually. So whatever default units the CST provides, you don't have to change them. So just click on "Next," actually. And then you can see here that you need to provide either the wavelength or the frequency. So, we are actually concerned with the frequency here.

You need to provide the range for which the simulation will be performed. So, you have to provide the minimum frequency and the maximum frequency. So, if you can remember the band diagram that we created in COMSOL. So, that band diagram actually shows that the band opening, upon breaking the symmetry, changed from around 310 to more or less 335 or 337.

So that was the opening band. So we just take it slightly higher, making the bandgap margin slightly larger. Now, after substituting these frequency values... What you need to do is monitor the situation.

In what field will you be working, and what type of analysis do you prefer? We will also be asking about this in CST. So, we are actually concerned with the distribution of the magnetic field here. So, we will be analyzing the magnetic field. So, you just click here. So take this box, and then below, you simply take the reflectance and transmittance.

And absorbance, because we will mainly be dealing with transmittance, actually. The sentence is already grammatically correct. However, if you would like a slight variation, you could say: "We will check the S21 parameters." After filling everything out, they just need to click "Next" here and then click "Finish," so their working environment will be ready. So, you can see that this is basically the typical working interface of the CS team.

This is the box here. So this is actually inside that box where your model will be designed, and this is it. A small square sheet is actually there, so it is known as the working plane. If you want to deselect this working plane, you just need to go to the view. And then you can click here and check it off, okay? But I generally keep it like this, and you can too.

As for the bounding box... You can disable it for the time being; right now, it is actually the... The view, as you can see in the simulation box, is actually slightly tilted. So, if you want to take the 2D view, what you need to do is click on the keypad option; you just press the number five.

So, if you press number five, it will display its 2D angular projection or 2D view. If you press Control, left-click the mouse, and move it like this, you can move your structure, okay? Simply clicking and dragging the mouse left, right, up, or down will suffice. You can move your structure like this, but this is in your 2D projection, okay? But if you want a slanted projection, you need to click Control, then left-click, and then press 5 to return it to its original position. So this was about the interface of the CST, and now we will go directly to modeling our design.

Let me quickly show you. You see, this was the model. Actually, here you can see that this is unit cell 1, the VPC A, and this is the VPC B. The unit cell 2 is assembled, and this interface will serve as the waveguide that we will typically design. This is the structure here; this is the brown part.

If you can see it, let me show you. Yes, this is the PEC box. The tapered coupler is located inside. (The sentence is already grammatically correct.) This box is where we will apply the material called PC, which mimics the properties of metal in real-life situations. While testing this slab structure, the evaluation of the circuit was conducted.

The hollow rectangular block box will be replaced by the metal waveguide. (Note: The original sentence is already grammatically correct.) Okay, we will primarily design this interface in this way. And this interface, this zigzag path, will act as the waveguide here.

The original sentence is indeed correct. No grammatical corrections are needed. So, we'll be going to the CST again. So now, in the modeling part, what we'll do is click on the curves. Then, we'll click on the polygon here, which will display a dialog box similar to the one that appears when double-clicking polygon points in the working plane.

So, press the Escape key to display the dialog box. Okay, just press the Escape key, and this coordinate pop-up box will appear. So, you just need to enter the coordinates of the rhombus that you have already created in your console. The first point is the origin point (0, 0); the second is -a. After clicking "minus," it will prompt you for the value of a, so you might want to remember it.

That is 242.5, so you don't need to present it this way; it is not valid. In the console, we also need to provide the unit. But we in CST have already mentioned the unit, if you can recall, at the beginning of our discussion about the CST software. It asked for the unit of measurement, so we provided micrometers.

You just need to click on 242.5 and then click OK, and we'll proceed quickly. Putting the values here. Corrected: I am putting the values here. So now you can see in the console that what we did was directly write "square root of 3.

" So, this command is actually not valid here in CST. So, the square root of 3 should be written as 3 raised to the power of 0.5. Okay, so this is the square root of 3 multiplied by a over 2. Okay, so now the third point is \(3\) to the power of \(0.5\) multiplied by \(a\) divided by \(2\), and then the final initial point.

By simply scrolling the mouse, you can zoom in and out like this. So, our rhombus is ready now. So, it is a 2D structure.

We will turn it into 3D. We will see it later. So now, next, we need to design the big triangle and the small triangle. The sentence "Okay." is grammatically correct. However, if you would like a more formal alternative, you could use "Alright.

" or "That is acceptable." So that is your kind. The sentence "Yes." is already grammatically correct. This is the big triangle, and this is the small triangle. So, we need to design this. So what we need to do is refer to the list of parameters below. So, you click on "New Parameter" and then double-click on "New Parameter.

" You need to define all those parameters here. So, like what we did in Comsol, we defined all those variables.

So you define it one by one. So it is 0.65 times A. Then your L2 is 0.35 times A. Then, m is equal to 3 raised to the power of 0.5. That is your input L1 by 2.

I think we are at \( \frac{\sqrt{3}}{2} \) in L1. Then n is your root 3 times L2 divided by 2. Then your p is given by a divided by 3 to the power of 0.5, which is your a divided by the square root of 3, and q is your square root of 3 times a divided by 6. So this is your square root of 3 times a divided by 6. Okay, so after defining all those variables here, we will now go back to the curves and click on the polygon, just like in COMSOL.

Also in CST, whatever difficulties we face in COMSOL are similar to those faced here in CST, so there are not actually any direct comparisons. A better way to design the equilateral triangle here is to use the coordinate method, so we don't have those other shapes. Then press escape. Now, give the name whatever you like, such as "Big Triangle.

" One by one, you place the coordinates of the big triangle here. So, subtract a, and it will be p minus two-thirds of m, two-thirds of m. Then it is minus, okay, minus a minus l1 by 2. Then you give your P plus one-third of M. Now it is minus of A plus L1 by 2, minus of A plus L1 by 2, and it gives you here P plus one-third. Here is the corrected sentence: "If we take m and subtract p from it, then your result will be two-thirds of m.

Let's go back to the original position." Here, your big triangle is ready. We designed this big triangle, and now we click on curves, and then you click on the polygon. Then click "Escape," and we will design the small triangle, so we need to enter the coordinates here. So it is actually your minus a divided by 2 minus l squared divided by 2, and this is your q minus one third times n. And this is minus a divided by 2, minus a divided by 2; sorry, minus a divided by 2, then plus your L2 divided by 2.

And then it is your turn again; I think it's minus one-third into N. Now you go to minus a by 2, then you go again to q plus, and then your two-thirds of n. And then you go back to your minus a, by 2 minus l, 2 by 2, and you go q minus one third times n. Okay, so I think this is your smaller triangle. Click "OK" here, and our unit cell is ready.

You can see that this is the 2D structure. To create a 3D object, go to the curve option in the left panel, where you can find it under the navigation tree. You will see the curves there. You just expand the curve; when you expand the curve, you can see this polygon. This is a big rhombus, a big triangle, and a small triangle.

So, what do you do? Use the extrude feature. What extrude does is project your 2D structure into 3D. Please do all three structures together; don't select them separately. Because this will create some errors here, please do it one by one.

Click on the polygon here. Then you click this option, "Extrude Curve." Click this, and it will appear red. After that, press Enter. So this will be placed here so you can see the thickness. Now, one thing you just don't give directly is thickness.

You need to see the direction of the projection. OK, so you press Control here, and then with the mouse, you just rotate it so you can see that the direction of the arrow is going downward. OK, so we want this thickness to extend downward. OK, so that's why you only have to give 200 here. So the thickness is actually 200.

We are taking the thickness to be 200 micrometers, and we'll add 200. You will see how a minus 200 will also come into play, okay? So, after clicking this, you don't directly click "OK"; you just see the preview. Okay, so it is actually a correct way of projection. In the material section, you go down to the material library, where you can select a load; here, you click on silicon. It is loss-free.

You select this loss-free silicon and then click "Load," then "Preview," and finally "OK." So, this is the rectangular rhombus 3D box. Now, click on the big triangle, then extrude again, and then press enter. You will see that the direction is downward, so just click on 200. Silicon is the material preview, and then you click "OK.

" Now, it will show a pop-up box because this triangle has become a 3D model. And also inside the 3D model of the rhombus, these two shapes are now intersecting. So it is asking whether I should keep it like this or if I should add both shapes, intersect them, or cut them away. What we do is that we just keep it as is; we don't want to perform any operations here. So, we just leave it as "none" and then press "OK," similarly for the small triangle.

Also, extrude. Now you can see that its direction is upward. Okay, so we need a downward projection. That's why we have to click here and enter minus 200. Click here to preview.

See? Now it is going downward. That's why I told you not to select all the geometries. And do the extrusion simultaneously; do it one by one, and click "OK" here. Then, again, none here. Okay, so our unit cell is ready. Now you need to make a triangular hole because this model has a triangular shape; you need to create it as a hole here.

So, to do this, you go to the component now. So, expand it. (The sentence is already grammatically correct.) You will see that all those solids have arrived. So, what you need to do is subtract the larger triangle and the smaller triangle from the rhombus. So, how do you do that? You just click the solid one that is a rhombus, and then on your keyboard, you click minus.

Okay, then you click to select both triangles, which is your solid two, and press Control. And then click on the items you selected, and then press enter. See? Now you can see that it is a hole. Actually, we created a triangular hole, and this is our VPCA. You can also change the material color by clicking on Solid One.

Right-click, then go down to see "Assign Material and Color." This color actually matches. With the background, you need to change the color to red. Click OK, and then you can proceed. Press 5 so it will go down. Now we have created our first unit cell, and we need to create this part, which is now done. Now we need to create the bottom part so that the interface is made, and we know that we can do this just by taking the mirror projection.

In this unit cell, what you need to do is double-click on this structure, and this transform will be enabled, okay? So, this is the transform feature similar to your Boolean operation or the transform operation of your console. So, by expanding this, you can see the mirror option here. So, you click on the mirror. So, you click "copy" because we want a copy of this model.

So, it will show one thing: it will ask for the normal of the mirror plane. Okay, so the mirror plane normal means this is the mirror plane. Okay, this is the mirror plane, and it will indicate the normal. So, in which direction is the mirror plane normal? So, this is the x-axis, and this is the y-axis, the particle axis.

So, your mirror plane normal is the y-axis. So, that is why you just give the value of 1 for y. Okay, so if I preview it, you can see that it has already arrived here. So you can see, this is actually the interface. Okay, this is the origin of the mirror plane. So your origin is actually the mirror plane origin, which is the 00.

That's why you shouldn't change the values here. Okay, so you just click "Preview" and then click "OK." See, this structure is actually completed, so you might be wondering about this figure. Um, this idea is that this rhombus is actually oriented like this, and in CST, it is oriented like this. So that doesn't matter, actually, because we just want the mirror version.

Okay, we could have. We can also do it like this by translating it there and then rotating it again. So, because it will actually mean the same operation here. We are just creating the interface that we wanted, which is right next to the existing interface. This is if there is a smaller triangle in the upper portion of the unit cell; there should also be a smaller triangle in the bottom part of the unit cell. The second unit cell actually creates the interface, or we can say the domain wall.

Now, it might happen that there is one. A smaller triangle is here, and if we keep the bigger triangle here along with the smaller triangle, it will not create the domain. You might be physically seeing the interface, but it will not create the topological domain that is required. So, for the topological domain, if there is a small triangle in the upper part, there should be another small triangle in the lower part.

The bottom part is the same for the vice versa for the big triangles. Okay, so... So, we just change the color here; otherwise, it will look the same. So, we click "OK" to make it green.

So what you need to do is, after doing this, first save your project, because sometimes it happens that... Whenever the model becomes very large, your software might encounter an error, and it will automatically shut down. So, your work will not get saved either.

That's why you click Control + S and then save it. The sentence "Okay." is grammatically correct as it is. If you need any further assistance or a different context, feel free to ask! So this is like your new demo. We need to save our project to work; otherwise, it might suddenly stop. Actually, during your process, if the model becomes very large, we can proceed with this now. You can see in this diagram that this is repeated, so if you can visualize it, you will understand better.

So, this unit cell is actually repeated in this direction. This unit cell is repeated in this direction, and you can see that the domain wall is formed here. And then it is repeated again; here, the domain wall is created.

The sentence "OK." is already grammatically correct. So you can see, we will examine how this domain wall is made. So, there is actually a repetition of unit cells occurring. The sentence "OK.

" is already grammatically correct. However, if you would like to expand it for clarity, you could say, "Okay." or "All right." The top portion, too. And in the left and right portions as well. So what is it that we will also be doing? So, here we will use the translate option. So again, you just select those two unit cells like this.

Yeah, use this control and then click on "Transform" to select "Translate." So, in Translate, you click on "Copy." And then, what is the translation vector? It is actually the lattice periodicity because we want the adjacent rhombus. The distance of a lattice periodicity will be determined, so we click here and then set the repetition factor. What is the number of repetitions? We want to take it as 10 here, so you see, you just need to zoom out to see that this is the structure that is actually being created here. So after that, you just click "Preview" and then click "OK.

" You can see that our unit cell has been designed like this, so you can see this smaller triangle. And this smaller triangle of the two unit cells, this is the interface here. Okay, so this will create the domino topological domain. Okay, so now what we need to do is focus on this unit cell. Here, this will go down, and there, another rhombus will appear like this.

This will be just the opposite of what we have, and we will learn how this is done. Such that the domain wall now actually goes downward. Okay, now here it is actually going in the right direction, from left to right. So, we need another rhombus where the smaller triangle will face the smaller triangle here.

So, what we need to do is this: the upper unit cell will actually repeat as it is. There are no changes. So, what we need to do is to double-click on this, okay? And then what you need to do is go to "Transform." First, you translate it. Okay, take the copy option and keep one.

That will give us a preview. So you click on "OK," and now you can see that the smaller triangle is facing the bigger triangle. The domain wall has not been created here, so please double-click again. Then go to "Transform," and then select "Rotate." Okay, now don't take a copy because we are making changes to this design.

Only okay, so you don't create a copy of this design. Okay, for the rotation axis, we need to rotate it 180 degrees. Okay, and then we can repeat this as well. So, first, what we need to do is double-click this and then press control.

You select all these unit cells. (The sentence is already grammatically correct.) And then you click on "Transform," then "Translate." Now, click copy here. Now, here the translation vector is a bit tricky.

The sentence "Okay." is already grammatically correct. The sentence "So, why?" is grammatically correct. However, if you're looking for a more formal version, you could say, "So, why is that?" or simply "Why?" depending on the context.

Because let me go to a blank space. Yeah, blank slide. So, if I take the pointer, your rhombus is like this. Okay, so in order to... this is your a by 2 option. So now you let me do the row like this. So this rhombus will be shifted to this part.

The sentence is already grammatically correct. However, if you want to change its form, you could say: "A copy will be created." What it means is that your rhombus will actually come downward. So it will shift vertically by an amount that is nothing but your $\frac{\sqrt{3}a}{2}$, if you can remember. The sentence is grammatically correct. However, if you want a slightly more formal version, you could say: "It will also shift laterally.

" The sentence "How much?" is already grammatically correct. If you would like it to be more specific or formal, you could say "How much does it cost?" or "How much is it?" The corrected sentence is: "At this distance." And this is nothing but your A by 2.

So, your lateral shifting is minus a by 2, and downward shifting is minus root 3 by 2. This is the translation vector. (The sentence is already correct.) We will just keep this in mind. So, this is your minus a divided by 2, and this is your minus 3 raised to the power of 0.

5 multiplied by a divided by 2. So, click on preview. See, now it is coming. (The sentence is already grammatically correct.) So, we will take a copy of what I think will be fine, which is 8. Yes, it will be fine.

So, preview and then click OK. The array has been created; you can see this is the array now. The domain will not extend entirely to the end of the slab. It might go up to here or it might be here, but not way down, okay? Otherwise, the field will actually penetrate, and it will come out. Radiate from outside the slab structure. So, we will not make the interface too deep within the slab.

So, now we will be double-clicking and then translating like this: minus a divided by 2 minus 3 to the power of 0.5 into a divided by 2. So, I think we will be doing 5 instead. No, four is better.

Yes, four is better. Yeah, so you can see the domain; it is coming from left to right and then moving downward. Okay, so this is the zigzag path. Okay, so this is the zigzag path, and we are now here. We have designed this 120-degree slanting bend position. And now we need to design this straight portion, then a slant, and then another straight section.

We'll also be designing a coupler. Now, after this, this portion, this unit cell portion, will be repeated again. Okay, so what we need to do is double-click the control. Translate OP here, and then give this A and this as 8. "8 is fine here; 8 is fine in the preview.

" So, yeah, now here’s what you need to do: just copy it. You will see this domain will come here, and then again, this domain. It will continue like this: just double-click this point, then select the translate option here. Copy it, then click on "A," and then click on "9" and "9." Preview, and then, okay, so you can see this.

If you can visualize this, the domain is coming from left to right. And then it is going in a slanting, oblique position downward, and now it is going straight. Okay, now you can see here. Here, the domain will also be created. So the bigger triangle is facing this domain. So we need to fit the rhombus like this so that a bigger triangle will fit here.

So again, we will select all those rhombuses by double-clicking on them, then we will click on "Translate," copy, and then click "A." 8 is fine here; 8 is also fine in the preview. So, yeah, now here’s what you need to do: just copy it. You see, this domain will appear here. And then again, this domain will continue to illustrate like this, so you just need to double it.

Click this point, then select the translate option, copy it, and then click on nine and nine. Preview, and then, okay, so you can see this. If you can visualize it, the domain is coming from left to right. And then it is slanting obliquely downward, and now it is going straight.

Okay, now you can see it here. Here, the domain will also be created. A larger triangle is facing this area. We need to fit the rhombus like this so that a larger triangle will fit here. So again, we will select all those rhombuses by double-clicking on them, then click on "Translate," copy it, and finally click "A.

" Okay, so you click on "Preview." Then, click OK. Now you can highlight them because you need to rotate it. So, rotate it. And now, you need to copy it here. 180-degree preview.

(Note: The original sentence is grammatically correct as it is.) Yeah, that's fine. (The sentence is already grammatically correct.) The domain has now been created. Yeah, okay, so this will come like this, and this will go like that. Okay, so now this part will actually continue. Okay, so there are no changes here, so we'll just select this and then translate it here.

If you click on 8, it might be less; if you click on 10, it will be more. (Note: The original sentence is already grammatically correct. No changes are needed.) Because some unit cells will be merged for the coupler, your domain path will become shorter. That's why you should try to keep a sufficient number of unit cells; keep 10, and then click OK. You can see now how big the model is getting. Okay, so here, you just double-click to translate this; it will be 12—no, sorry, 11.

So here you can see that there is no domain, and in this large triangle, it is evident that it is not creating a topological domain. Because the smaller triangle is facing the larger triangle, a topological domain is not being created here.

It is being created here; see this. It will go like this. Now, actually, the smaller triangle should be placed here. We simply double-click on this, and then we translate it. The sentence is indeed grammatically correct as it stands: "So, our design is almost ready." We just need to repeat our upper unit cells in the upward direction. So now you see that after coming here, the domain appears and then moves from left to right in a straight line.

The domain is now ready. So now we just need to select all those red unit cells. Yeah, so after selecting this, you click on "Transform," then "Translate," and then you copy it. Now it will be shifted backward. Now, that's why it is minus $\frac{a}{2}$; however, it is in the upward direction—vertically upward. That's why it is positive $\frac{\sqrt{3}a}{2}$. We don't give negative points here, so if it's 8, that's fine, or we can keep it at 10.

Previews, and okay, now click Control + S because the model has become bigger, so just save it; otherwise, it might get closed as well. Okay, so this is the type of slab structure. Now you can see that it has taken on an arrow-like design due to these slanting positions. And this is similar to the arrowhead position.

We need to cut down this portion so that our structure looks like this. Yeah, it becomes a rectangular box. To cut this one, we need to select those points and then create a polygon here. Okay, so you go to Curves, then Polygon, and instead of clicking the escape point, it will ask for the coordinates. We don't know the coordinates because using the coordinate method can be quite time-consuming. Just click the "P" button on the keyboard, and it will prompt you to select which point you want as the initial point of the polygon.

So, you double-click this, and then you start going downward, and this line will appear. And this is the edge of the polygon. Actually, it will start to go downward slowly. Yeah, so you click on P again, and then you double-click to join. Click P to join at this point, and then you move upward or downward.

Sorry, then you click 'P', double-click, and then you go up. Then you click "P" and double-click. Now your polygon is ready. Okay, just click "OK." This is the 2D structure. Here, we will be extruding it again. Now, you should do the same thing for this, um, here as well, okay? So, we just need to check.

Whether this straight line will meet at this point. So, you just go to the curves polygon, then press P. You double-click here, and then carefully align it vertically. It makes a straight line. Yes, it will come here, so you just click on P. So, unclick on P here, then go upward, and then go to P here, and go upward again.

Then you click on "P," double-click, and then click on your "P" again, followed by double-clicking. Yes, this polygon is now ready; click "OK." So, now we need to extrude these two polygons. (The original sentence is already grammatically correct.) So, you do it one by one, but first you need to save; otherwise, the model has become very big. So, you just click on the polygon, then select the extrude option, and finally click enter.

So, the direction is actually outward from this simulation area. So, we want a downward projection; that is why we have minus 200. So you click "Preview," check that the material is silicon, and then click "OK." So it will ask what to do with this model, whether we need to intersect it or combine it.

So we don't do anything to the model. (This sentence is already grammatically correct.) You just click "none" for all. If you click none, it will take everything one by one. So, just none to all, finish. Click on this polygon again, then extrude it by pressing enter.

Its direction will be downward, so we will only click 200 for the preview. Okay, then, none to all, yeah, fine. Now, what we need to do is subtract this entire structure. We need to select this structure and subtract this entire structure from it. Sorry, we need to subtract this polygon.

You can see this polygon and that polygon from the entire slab structure. How we do it is by clicking this, then holding Shift and going downward. The sentence "Okay." is already grammatically correct. Click here because this is solid; these are the two polygons to be removed. If you click up to here, your entire slab will be selected.

You click the minus sign, then select those two solids. After selecting, you just press ENTER. It will take some time to perform this operation, maybe two to three minutes, and then press ENTER. Just wait for a few minutes because what it does is actually subtract those unit cells. Because there are a lot of unit cells inside this polygon.

So when it tries to subtract this from here, it is not finding any structure to subtract. So that's why this kind of error occurs. So, just click on "OK." It will come again and again, so what you need to do is press the Enter button. Press the enter button on the keyboard for a long time, and it will work like this.

Okay, this arrow will appear because it will come back again. And again, it becomes quite irritating to click repeatedly. Okay, so just hold down the entire Enter button, actually. So this is basically how a topological slab structure is actually simulated. You create the interface so that it is not like a casual type interface, and you need to ensure that if a smaller triangle is facing the interface. For the first unit cell, the bottom unit cell should also have the smaller triangle facing the interface.

And then only the topological domain will actually be created; using this interface, we have designed this zigzag waveguide. Uh, we can also design a straight waveguide that I will show you. After we design this slab structure, we'll move on to designing the next one. The tapered coupler will be designed, and then we will also design the PEC box.

After that, we will apply the mesh and then the input ports. So, you can see that the operation has been completed. You just need to remove your hand from the enter button.

So, it will just take a few seconds to refresh all the designs. Yeah, I think that's fine. So, we click on "Press Five" and then quickly save it; otherwise, it might... Here’s the corrected version of the sentence:  "Actually, we are showing an error.

Now, what we need to do is ensure that our model is ready. This is your domain, which goes from left to right." And then, here it goes downward; you can see it follows along the straight line. Here it comes. And then it goes at an oblique angle, upward, and then it goes straight. So now we will design the tapered coupler. So, you can remember that I showed the magnetic field distribution in the topological edge state, which was actually symmetric across the domain wall. So, we need to place our tapered coupler so that the field integral or field overlap is maximized.

So, if you see, we will be placing a tapered coupler like this, okay? Like this, so that it is symmetrical around the interface. So, what we need to do is click on the polygon here, then click on the "P" option, and select this point.

Okay, so what we need to do is go a bit deeper into the domain. So, we just take 1, 2, and 3. So, three will be fine. Three units will be fine. So, you just start from here. The sentence "Okay." is already grammatically correct. However, if you would like a variation, you could also say "Alright.

" So, now you just go and check if this dx is actually increasing. So, typically, it should be around 3000 micrometers. Okay, so you just—yeah, fine, this will be fine. Yeah, this will be—yeah, double-click, and then go again here.

Then you click "P," and then click "P" again. Yeah, so your tapered coupler polygon is ready. Similarly, you should press save here, as the model is now very large. Again, you go here. Okay, so double-click here, and then you click on this.

Yeah, so this teplot coupler is ready, as you can see. Now, click "Save" again. Click on the polygon here, extrude it, and then enter the value, so that the arrow direction points upward. You need to click on minus 200. Then preview it and click OK.

So here you don't click any of the options. You click both shapes because we need to combine them. We need to create a union of the tapered coupler with the entire slab structure. So, you add both shapes and then click "OK.

" So it will do this for each of those unit cells. The sentence "Yeah." is grammatically correct as is. However, if you want a more formal alternative, you could say "Yes." So now you click "Save" again. Now, again for polygon 2, click enter so it goes downward to 200.

Then, click preview, followed by okay. After that, add both shapes, and then click. Here's the corrected sentence: "Again, save. This is how the typical structure will look.

Okay, we have designed more or less this kind of structure here. Now we will be..." Designing this PEC box, we will be applying the input signal here, and the dimensions are as follows: this is the dimension of the PEC box.

To accomplish this, we will... Go to the model; you can see this is the brick or the box. It's a 3D box, so just click here and keep it as close as possible to the structure. Click, then zoom out, and make sure that the box is slightly away from the last endpoint.

The tapered cobbler should take this much distance, or maybe this much distance. Yeah, then double-click. And then you do it like this: this is a vertical projection along the z-axis, so don't... Do too much just slightly; it will do like this.

Now, press Ctrl and then zoom out, and now you will see. This is the projection of the box, so you need to change it. Okay, this is what you need to change: it should be minus 863.6 divided by 2. Why are we dividing by 2? Because it will place it exactly. In the middle, okay, so you will just get to know that it has shifted slightly to the left.

Therefore, you need to click on minus 100 here, okay? So that's why it will shift slightly. Yes. Now you can see that it is exactly in the center position.

The tapered coupler is located exactly at the center position of the box. Similarly, you do this for minus 438.2, subtracting 2 and then 120. Then, this is 438.2 divided by 2 minus 120. Okay, I don't think 120 is required. The sentence "Yeah." is grammatically correct as it stands. However, if you would like a more formal affirmation, you could say "Yes.

" I think it is uncertain whether it is cutting or not, because if it does cut, then it will create an error. That is not cutting. (Note: The sentence is already grammatically correct. If you meant something else, please provide more context.) How do you click on a PC using the material instead of silicon? Then preview, then click "OK.

" You save it. So this is the box here, but we need to create a hollow box inside it that should be filled with air. So this is what we will do. We'll do it later, but first we need to design the left cup coupler. We will also do the same thing for the left coupler. Minus eight sixty-three point six by two minus one hundred two minus one hundred; this is your minus four thirty-eight point two by two, and this is four thirty-eight.

Point two by two, yeah, okay. Then click five; it will return to its original position. So now we can see that our design is more or less ready. Just a few changes have to be made here. So now we need to make this hollow. OK, so this hollow box is for doing this: you press F, and this will appear.

Then, when you double-click, it will select this face. OK, and then? So, you press Control and then click here to rotate. Again, press F to do this for all those faces, but not for all faces—just leave the entry.

Just leave the face as it is. You can go to this option, which is for faces. And the apertures you click here are shaped from the faces you select. Click this. And then you simply click "OK.

" The sentence "OK." is already grammatically correct. The sentence "Do it." is grammatically correct as it is. No changes are needed. What I'm doing is creating a 2D sheet structure for this box.

And then I will simply delete this solid rectangular box. The sentence "OK." is already grammatically correct. That will create a hollow box here.

So, you click "OK." Then this: Press F, and do it again here. So, click OK here. Now, you should go to the components. I think you are searching for the, yeah.

So, this box is solid. Press control and scroll down. I think it will be at the bottom. Yeah, that's a solid 2. So, select those solids, and then press delete. The sentence "Yes." is grammatically correct as it is. There are no errors to correct.

The sentence is already grammatically correct. However, if you want to add more context, you could say, "Now, do you see?" or "Now you can see." You can see this. (The sentence is already grammatically correct.) The sentence is already grammatically correct.

However, if you're looking for a more formal expression, you could say: "Yes, indeed." So, you can see how this hollow was made. So, this is a sheet-like structure of the box. So, we just deleted the 3D solid box. (The sentence is already grammatically correct.

) So you can see that the tapered coupler goes inside the PEC box. So while doing the experimental analysis. So, this box will be replaced by a hollow metallic waveguide. The sentence "Okay." is grammatically correct as it is. And then, from here, the input signal will be placed here. The input signal will pass through, and it will be coupled to the tapered coupler here, and this will come here.

This will come here, and this will find this domain. And then this input signal will actually excite the edge mode here inside the band gap. Then the signal propagation will occur. OK, so you save it. (The sentence is already grammatically correct.) So, our design is actually ready. So now what we need to do is go to the simulation.

Now you need to apply the port for both the input signal and the transmission. So you press Control, then move it, click F, double-click, select this space, and then click on the waveguide port. Okay, so this is port number one. You just click "OK." You don't need to make any changes here; whatever is there, you can keep it as the default.

Click "OK." Then, go to this screen again, click "F," and then double-click. We will get the port, and then click "OK." Our input ports are ready, and you can go to the boundaries here. Okay, the boundary is important. Here, what we do is use open space, so we don't impose any kind of periodic boundary or any other boundaries. Because there are many boundaries, such as periodic conducting wall unit cells and electric and magnetic fields, we are considering this as a slab structure.

So, while conducting the experiment, this entire slab will be placed in the air, and then this hollow metallic waveguide will be connected to the VNA. So, it will be connected.  (The original sentence is already grammatically correct.

) So, this tapered coupler will go inside this hollow waveguide structure, and these two tapered couplers... And those hollow waveguides will be connected through some mechanisms, and they will be connected to the VNA. Okay, so this chip will actually be placed in the air. That's why the boundary condition is open in space; we provide some space, so you can check this.

Apply in all directions and then click "OK." If you want to check the box, go to "View." And then click on the bounding box. Okay, so in the simulation, just check the frequency from 300 to 350. Yeah, that's fine. Okay, so after all this, you need to add a field monitor. So, what is a field monitor? The field monitor is nothing but a specific frequency, as you will be receiving the S-parameter plot. And then you need to check the field distribution to see how the field is actually propagating along the waveguide path. So, it actually shows specific frequency points; it does not display results for every frequency point.

Therefore, in CST, you need to click on "Monitor." The monitor will display the field propagation for that particular frequency, so we are actually concerned with the magnetic field. Here is the corrected sentence: "To distribute, click on the 'h' field, and then you need to provide some frequency values here." So, if you can remember, I think the band gap ranges from 312 to 339. You can enter any frequency within that range; for example, we are taking 325, but it can also be 310.

Also, whether it is 320 or whatever, just take 320 and then click OK. The CST actually takes all these values as default: 350, so 325, 300, okay? So you can see that 350 is outside the range of the band gap. When the simulation is over, if you want to check the field distribution of your system, you can do so. Outside the band gap, you will see that the field will get scattered; it will not be guided along the waveguide.

Okay, we shall see it. I have already done the analysis, so you just need to save your model. OK, so after setting up all the field monitors, you need to go to the global properties machine. Here, the machine is actually a bit different from what we did in COMSOL. So you can see in the machine that it displays the cells per wavelength.

OK, so. (This sentence is already correct but can be expanded for clarity. For example: "OK, so let's continue.") The CST actually takes the value of 15 by default here, and you can see the statistics in the bottom dialog box. This is the smallest cell. This is the largest cell, and here is the number of cells, so you can see how large the number is. It represents the one curve in total. What it will do is that the software will actually break down your entire structure into small mesh cells.

Known as this number of cells, the rotor number of cells is one curl, so you can understand. Here's a corrected version of your sentence: "That is how big the simulation will be, and how much computation time it will take." So, if you increase this number, let's say you make it 20, and then you update it, You can see how drastically the number of cells is increasing from 1 crore to 2 crores.

So, you just keep it as 15 here. It actually depends on your CPU, as well as your laptop or PC configurations. If you have a very strong CPU and your RAM is at least 16 GB or even greater, then you are well-equipped.

So you can go ahead and increase this number from 15 to about 20. So, let me show you how it will affect you and how it is affecting you. Mesh, yes. Mesh view. Okay, so in the mesh view, instead of X, you just click Z.

You can see how dense the mesh is. It is not even visible. So, you just zoom out. Actually, zoom in. The sentence is already grammatically correct. Now you can see how densely it is cutting into the silicon part. Now, if you make it 30, you will see what changes will happen. The density of the mesh has increased significantly, going from 2 crores to 7 crores exponentially.

That is a huge number of mesh cells, and it will exponentially increase your meshing computation time. So you just keep it up to 15 here. We don't need to increase it. Okay, this is the cells per max model box edge. We just need to check this box, and then you can increase it to about 50.

The fraction of maximum cells is close to the model. So, what is the fraction of maximum cells near the model? If you increase this, it will also.

.. It can increase your mesh accuracy, but it will not significantly increase your memory requirements. As you can see, it has not increased much. But it actually enhances the meshing accuracy. So, you click "OK" here. So, our mesh is actually ready. So you click "Close Mesh View." You save it again.  (The original sentence is already grammatically correct.) So after that, as you can see, our model is actually pretty much ready. Now, go to the simulation box and select "Setup Solver." In this dialog box, you can see that the simulation settings will ask for the source type, which will be displayed by default.

All ports are not needed; we don't want to use the source in all the ports because this port will act as the input port and this is the output port, so we will only mention the relevant port. One is the source, and we take only mode one because this will unnecessarily increase our computational time. If you click here like all ports, it will first check the simulation for this port, then it will show the transmission, and after completing this, it will proceed to the next step. The second port will act as the input, while this port will function as the output.

Therefore, they will actually change the port. Nature is okay, and then it will again perform the simulation, which will unnecessarily increase the meshing. The computational time, and then you click only mode 1, which is the adaptive mesh refinement. If you click it, then it will go to the adaptive mesh properties. So, what it does is break down your simulation into a number of passes, and after each pass, you can see the number of passes.

What it will do is, if you mention, say, 4, then 4 is the maximum number of passes. So after four passes, your simulation will be complete. For the first pass, it will take one crore mesh cells, as you can see, and it will perform the simulation. And then it will automatically increase the mesh cells. It will make it more likely that the quality of the mesh will increase, and it will again attempt to run the simulations. Here is the corrected sentence: "So, why does it do that in order to reduce the error?" So it might happen that in the first pass of the simulation, there could be some errors in the results.

What it does is try to minimize those errors. That's why it actually breaks down the simulation into a number of passes. If you click four, your simulation will be over after four passes. Do this because if your laptop or PC configuration is very good, you will benefit from it. You can go for it because what sometimes happens is that after reaching 1 crore, it will directly jump to the second pass, and then it might go to 3-4 crores. It may happen that your system could lag, so we are not going for adaptive mesh refinement here; I just wanted to show you.

So, this is pretty much all about the simulation. Then you click "Apply," and then you click "Start." So if I click "Start" here, the simulation will begin, as indicated in the dialog box and the message box. OK, so I'm not starting here because I've already done it, and it takes around four to five hours. So, yeah, I think this is the straight one.

So, I made two types of waveguide paths: the straight path and the zigzag path. Okay, so yeah, this is more or less the same design, actually. In this design, you can see how the domain is actually moving. So you can see it starts from here and goes from left to right in a straight line. So, this is the straight domain. You can see the 1D result in the left panel under the navigation tree after your simulation is over.

You can see both 1D results and 2D results. So in the 1D results, if you expand it, you will see the S parameter. You click it so you can see how your transmission is performing, allowing you to analyze your transmission results for your particular range. From 310 to, I think, 339 or 335, you can see that the transmission is happening, and just after, outside the band gap, you can see it. See, the transmission falls drastically, so there is actually no transmission here. So, this is actually due to the edge state.

So, as you have seen in the topological edge state diagram and the dispersion diagram, You can see that an edge state appears within the band gap, and because of that edge state, this kind of transmission occurs. If you want to see the magnetic field distribution, you can expand the 2D results.

Then, click on the edge field and select one frequency inside the band gap. I will calculate the arrow plot so that you can go upward. At the top, you will see the arrows, and it is written there. Click here, and then you can change it to a contour. And this is the absolute value. Okay, so you can see that the propagation is happening, so you just need to increase it.

So, this is the strength bar chart. You click here with the mouse, and then you scroll up, which will actually increase the normalized strength. Strength, actually, so you can see how this is propagating. If you want to check the propagation, and if you want to animate the propagation, you go again to... At the top, you can see the animated field; just click it to observe how this field is actually propagating in the animation. Okay, so it is actually going along the domain wall, and as for the others, these are also domains.

However, here, the propagation is not happening. Outside the band gap, you can see that the field is actually getting scattered; it is not being guided along. The domain wall exists only because this frequency lies outside the band gap range. That's why you can see this kind of scattering; the field is actually being scattered all over the slab structure and is not being guided. So this was actually for the straight waveguide, and if we go for the zigzag or the band waveguide, you can see that this is the same domain we have created.

This kind of domain is coming here, and then it goes like this, and then actually it goes like this, and from there it goes there. So, you click on the 1D results, and then you click on the S parameter. You can see that the results are actually pretty much the same. It pretty much coincides with your straight wave path, which actually confirms how robust the topological structures are. Because of the sharp corners, you can see here that this is the 120-degree bend and this is the 160-degree bend.

There are many angular sharp bends present. Even after this, it can still retain its transmission so well, and that is primarily due to the opposite group velocities, if you can remember that. I showed you the dispersion in the F state diagram at the k dash point and at the k point, which is at approximately 0.

675a, and k equals minus 0.675a. So, at those two points, if you take the tangent to the curves, it will give the group velocities. So, the group velocities were actually opposite. So that's why interval mixing was not present. That's why we don't see any of that kind of loss.

Whatever losses you are actually seeing here, this is equivalent to minus 10 dB. This is solely due to the coupling loss. As you can see here, this is the structure. From the input port, the signal is coupled to this adiabatic coupler. So, the signal needs to be coupled from this coupler to this waveguide. So, the coupling losses actually happen there.

So, this loss indicates that further optimization is actually required to reduce this kind of loss. So, yeah, this is outside the bandgap; you can see that transmission doesn't occur again for the field.

You can observe the 2D and 3D results. Expand this, and then click on the frequency inside the bandgap. After that, click on "contour." So, you just click like this, and then click on "animate." So, yes, fine. But maybe you can take 205 as well. So you can see in 305 that it is not going; it is actually scattering. So in 345, you can also see how the field actually gets scattered.

In 325, you can see here that the reflection is actually dominant as well. So that's why you can actually see such a field. This is actually because the red is due to the reflection that is occurring. If you take another frequency range, let's say 330, you will see a very well-defined transmission.

I have not actually placed... The field monitor here is for 330 now. If I place it and then run the simulation, it will take three to four hours. So, I don't want to do that, but you can. Anyway, you can do it by yourself. I just want to show you where you can see how the field is actually propagating. Just check it out; you can see how it gets from the input waveguide port.

Couples to the tapered coupler, and it will gradually come together like this. It will gradually get coupled to this domain wall. There are actually coupling losses present. But some of the majority of the field will get coupled, and then it will move and propagate across the domain wall.

Let’s see. After the field, it actually comes here, and then it propagates downward. So, there are actually some reflections here. Then it will go like this. Then, it will follow the path and move to the output tapered coupler. See here. So, that was pretty much about the simulation based on topological photonics. So, as you saw in the first part, you learned how the band diagram analysis is performed and how the topological edge state analysis is conducted. Then, in this second part, you will see how you can design the entire slab structure using the CST software.

You can see how the S parameter is visualized, and by using the field monitor, you can observe the transmission. Actually, how does it happen, and how is it affected outside the band gap? Okay. So, in this frequency, the name of the hollow waveguide actually it is named as WR3.

Okay. So, if we go up also in the frequency, so it will be like WR4 maybe or maybe WR2.8 something. I just cannot recall it properly. So, its dimensions are different from that of WR3. Okay, so because these are some standard dimensions for which the input T mode that is the fundamental mode here. So we are actually discussing about the fundamental mode. So the fundamental mode will get excited from this port to inside the structure.

Okay, so if you take different dimension, your field will not get excited. Okay, so that's why this is the typical dimensions that has been taken from the literature. So or from the company from various websites you can get like those who manufacture all these WR3 waveguides. They actually mentioned these kind of dimensions. So it depends on the frequency. That's why for specific frequency ranges, these dimensions are present. So here we are using this kind of dimension. and for the excitation of fundamental T mode and in practical actually this PEC box is replaced with a metal so metallic waveguide will be present and this will actually yeah if I take it is that yeah so so if i take yeah so from there actually uh they are actually a frequency extender will be there which will uh so uh so this is the vna setup will be typically the vna will be like this okay and there actually the signal will come and vna actually has a range of around like in the below 100 gigahertz so and your wave propagation actually supports in the range of like 250 to 300 gigahertz so we need to up convert the frequency so this is done by frequency extenders okay so these extenders will be multiplying the frequency like this by number of times and this will pass through this hollow waveguide this signal will cross there and whatever transmission will happen so it will again demultiply so it will shift it to the compatible range of VNA this extenders and then it will connect it will get connected to this VNA here and this output signal will go there and then you can see the transmission here okay the measured transmission like this so this is how the experimental analysis actually is done okay And from the fabrication perspective point of view, so this is basically the, this is actually the slab, silicon slab only.

So you take one silicon wafer and then you lay down all those geometrical designs using the lithography process. and then you do the etching part and because because this your the unit cell is a rhombus okay and the triangles actually are basically the hole so it's a see-through directly it's a see-through if you check this discard this yeah if you check this see it's a directly it's a hole So, your etching process should be very accurate such that whatever chemical or whatever process you are employing, the etching should be very accurate such that the shape does not get disoriented. and you get a clean hole actually see through kind of structure in your silicon wafer and then for the coupler it is basically the silicon part itself at the extension of silicon so you using the lithography process also you design the coupler here and then the slab is actually placed in air and then it is the couplers are inserted into the hollow metallic waveguide and then the experimental analysis is done.


IIT Guwahati | NPTEL swayam Send your queries at deb.sikdar@iitg.ac.in

So, that is all for the demonstration. I hope it is clear to everyone how these band diagram simulation, the topological edge state dispersion diagrams and the Final waveguide simulation is done. So that is all for this lecture. Thank you. So if you have got any queries regarding this video tutorial, you can always drop an email to me at this particular email address mentioning MOOC, Photonic Crystal and this tutorial 2 on the subject line. Thank you. Thank you.