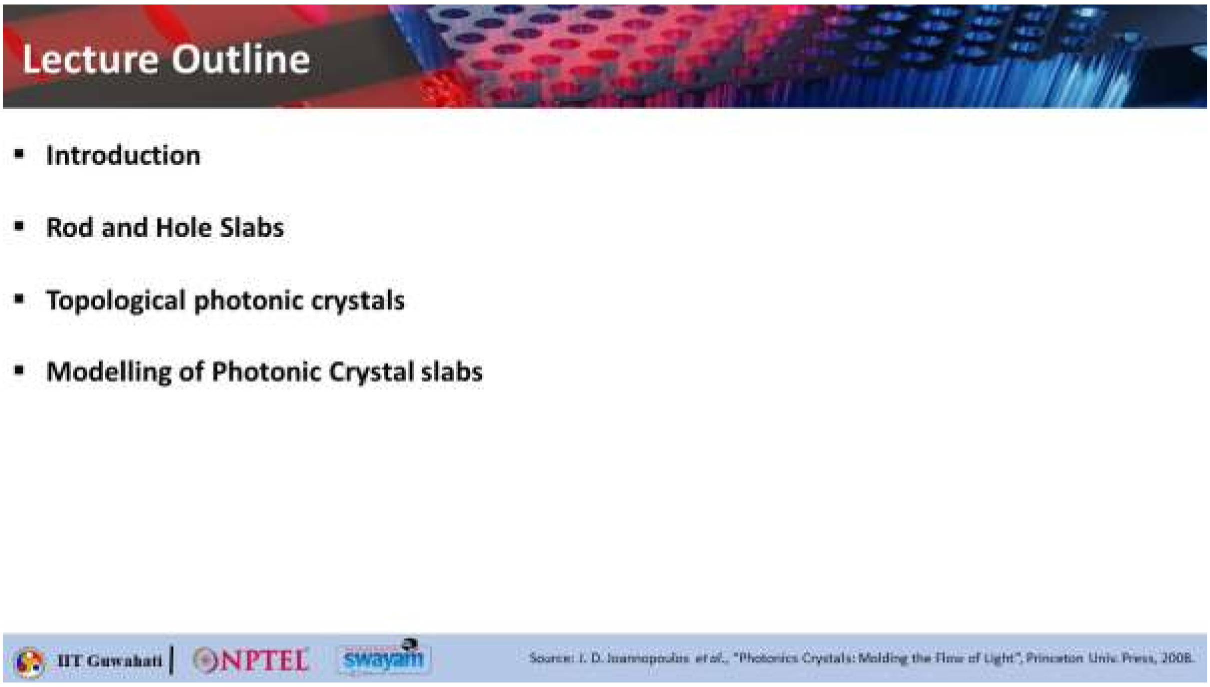
Lec 22: Overview of Photonic Crystal Slabs

Hello students, welcome to lecture 22 of the online course on Photonic Crystals Fundamentals and Applications. This lecture will be on overview of photonic crystal slabs.



So, here is the lecture outline. We will have a brief introduction, discuss about the rod and hole slabs and then we will introduce you to a new topic which is topological photonic crystals and how do you do modeling of this photonic crystal slabs. So, simple structures we have seen already with one-dimensional periodicity that can be used to confine light in three dimensions and that uses both photonic bandgap feature as well as index guiding in the other two orthogonal direction.

Introduction

- Simple structures with only one-dimensional periodicity can be used to confine light in three dimensions by a combination of band gaps and index guiding.

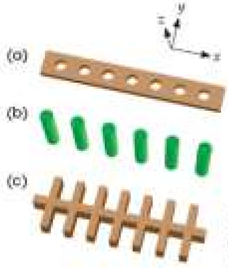


Figure: Examples of periodic dielectric waveguides, which combine one-dimensional periodicity (in x) and index-guiding in two transverse directions.

- Now, carry that idea one step further, by investigating structures with *two*-dimensional periodicity but a finite thickness.
- Such hybrid structures are known as **photonic-crystal slabs** or **planar photonic crystals**.

So, if you remember as we discussed earlier also that this is an example of three different examples of periodic dielectric waveguides.

So, these are the x, y and the z dimensions marked here. So, you can see that each of these structure has one dimensional periodicity in x and they are basically supported by index guiding in the other two transverse direction. Now, let us carry that idea one step further by investigating structures with two dimensional periodicity, but with a finite thickness. So, this kind of hybrid structures are known as photonic crystal slabs or you can also call them planar photonic crystals.

Rod and Hole Slabs

Photonic-crystal slabs or **planar photonic crystals**:

- They are ***not*** "two-dimensional" photonic crystals, despite the resemblance.
- The finite thickness in the vertical (z) direction introduces qualitatively new behavior, just as the periodic dielectric waveguides of the previous chapter differed from photonic crystals in one dimension.
- As in the three-dimensionally periodic crystals, defects in photonic-crystal slabs can be used to form waveguides and cavities.

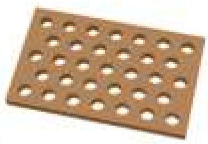
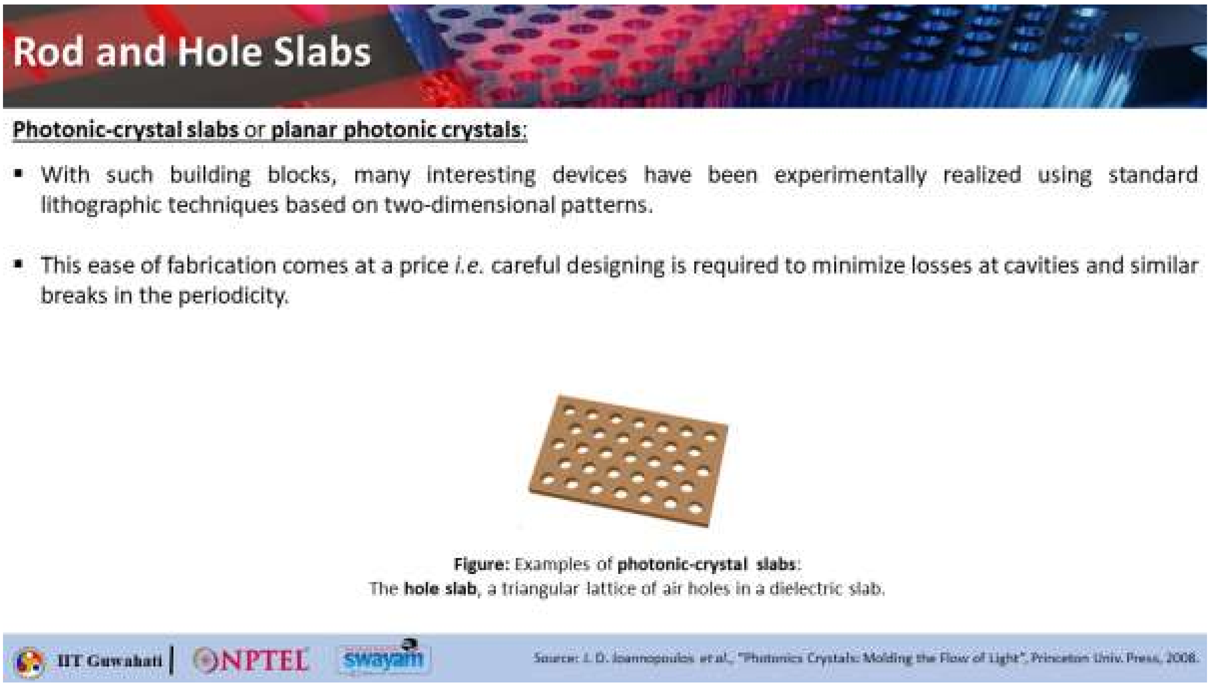


Figure: Examples of **photonic-crystal slabs**:
The **hole slab**, a triangular lattice of air holes in a dielectric slab.

So, that is where our discussion on rod and hole slabs begin ok. So, these are not know perfectly two-dimensional periodic crystals despite their resemblance. If you remember from the definition of the two-dimensional photonic crystals, the third dimension should be continuous. But here it is not because they have a finite width. So, this finite thickness that you can see in the vertical or z dimension if you consider the lateral dimensions to be x and y.

So, this finiteness in z dimension introduces qualitatively new behavior right. Just as the periodic dielectric waveguides which you have seen in the previous section okay or previous lecture you can see they basically differed from photonic crystals in one dimension. So, let us begin our discussion with rod and hole slabs. So, they are also called photonic crystal slabs or planar photonic crystals. And as we discussed before that they are not two-dimensional photonic crystals despite their resemblance.



In the case of a two-dimensional photonic crystal, this whole cylindrical holes would have been infinitely long, but that is not the case right. So, these are basically a this shows a basically hole slab which is actually a triangular lattice of air holes in a dielectric slab, but it has got the finite thickness. Now, because of this finite thickness in the vertical or z direction, so if you consider the thickness exist to be z ok, that introduces a qualitatively new behavior ok. And this is very similar to the case where we have discussed the periodic dielectric waveguides ok. And they also differ from one-dimensional photonic crystals because of their finite height or thickness.

Rod and Hole Slabs

Rod and Hole Slabs

- *Two examples of photonic-crystal slabs are shown:*
- Let us study two basic topologies:
  - **(a) Rod Slab:** A square lattice of dielectric rods in air
  - **(b) Hole Slab:** A triangular lattice of air holes in dielectric
- In the rod-slab example, the rods have a radius $r = 0.2a$ and the slab has a thickness $2a$.
- In the hole-slab example, the holes have a radius $r = 0.45a$ and the slab has a thickness $0.6a$.

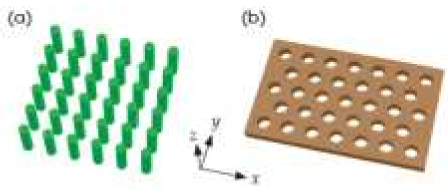


Figure: Examples of **photonic-crystal slabs**, which combine two-dimensional periodicity (in the *xy* directions) and index-guiding in the vertical (*z*) direction. (a) The **rod slab**. (b) The **hole slab**.

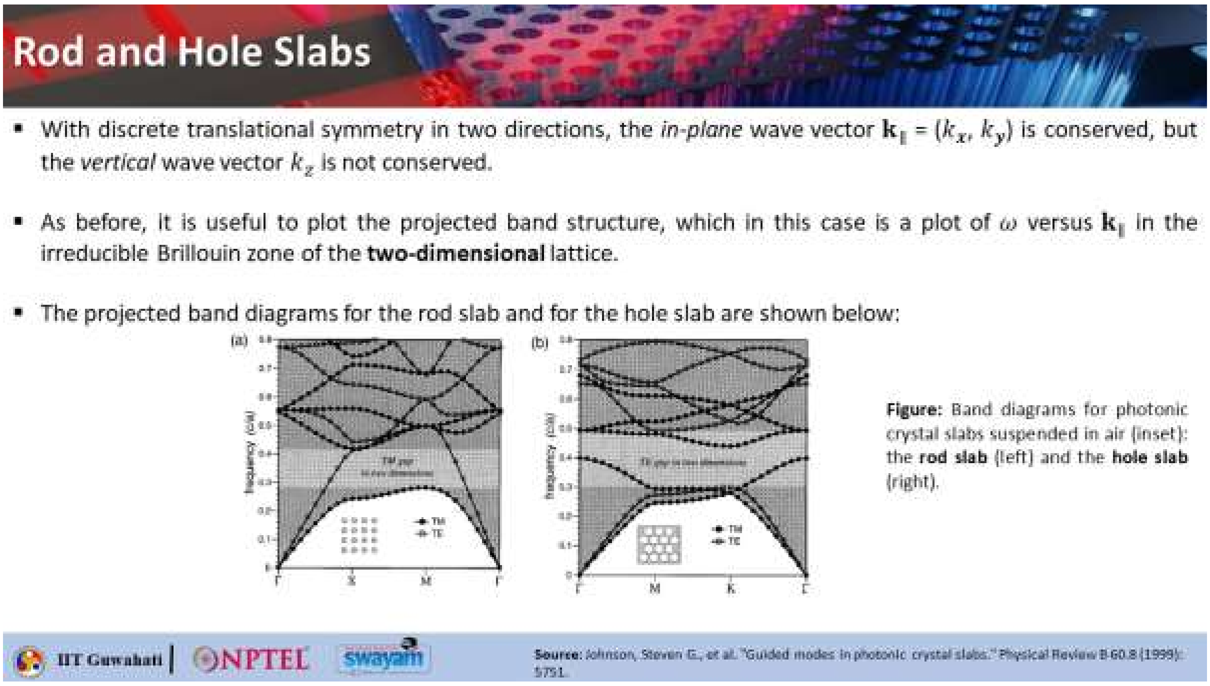
 Source: J. D. Joannopoulos et al., "Photonics Crystals: Molding the Flow of Light", Princeton Univ. Press, 2008.

Now as in the 3-dimensionally periodic crystals defects in periodic crystal slabs can be used to form waveguides and cavities. So, that we will discuss later maybe in the next lecture, but here we will be mainly analyzing about some new features ok. So, with such building blocks many interesting devices have already been experimentally realized by using standard lithographic techniques based on two dimensional patterns. This ease of fabrication comes at a price that is careful designing is required to minimize the loss at the cavities and similar breaks in the periodicity. So, let us take up this hole and slab arrays in more details.

So, here are the 2 examples of photonic crystal slabs ok. So, once again like they have 2 dimensional periodicity. So, there is 2D band gap along x and y and in the vertical or z dimension there is a finite thickness and there index guiding is helping you to keep the light confined within the slab itself. So, this is basically a rod slab which is nothing but you know you can think of an array of dielectric cylinders and this is the inverted array not exactly inverted array because this is a square lattice and this is a triangular lattice. So, this is you can just think of in whole slab or whole array.

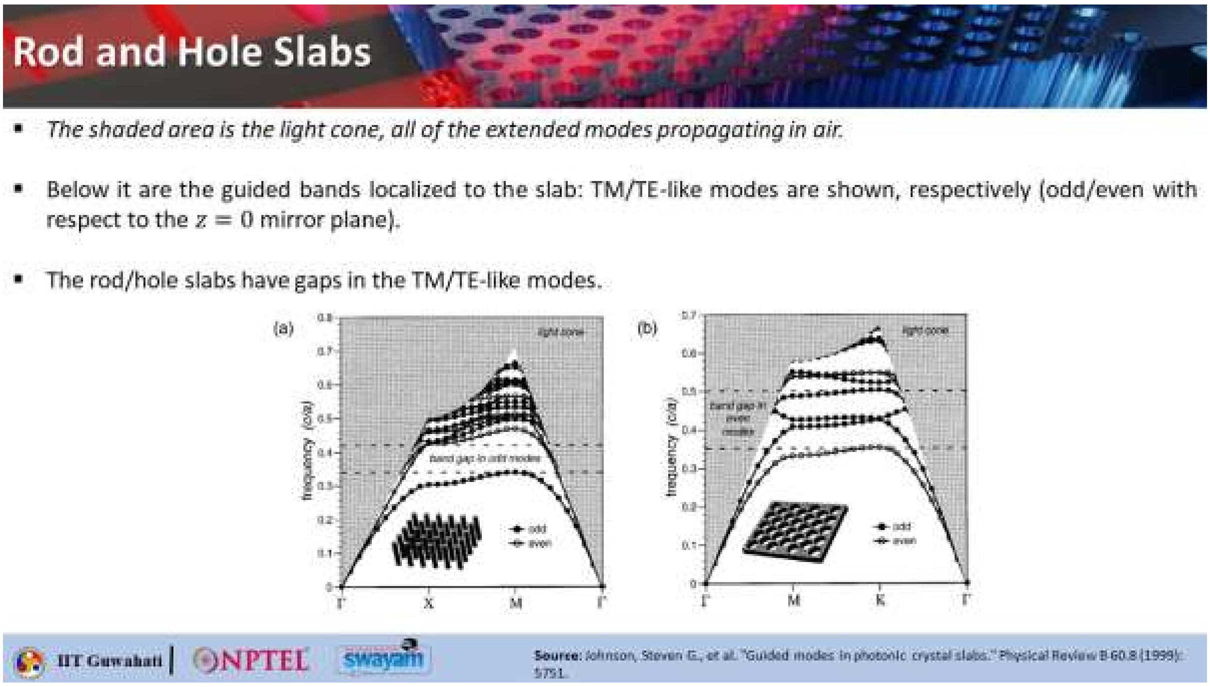
So, here the holes air holes are making triangular lattice ok. So, as mentioned here. So, what are the dimensions typically taken? So, in this case the case of rod slab you consider the rods to have radius r equals 0.2a and for the case of slab the thickness is 2a what is a is the lattice period. So, in this particular example the thickness is 2a that is good.

So, what about the radius of the holes? The radius of the holes taken to be r equals 0.45a and in the case of the slab the radius was 0.2a as I mentioned ok. in in the so we need to record this again. So, in the in the whole slab example or no sorry in the rod slab example for this one ok the rods are having radius r equals 0.2 a and the overall slab has a thickness of 2 a. And if you go to this hole slab example, here the holes have a radius r equals 0.45a and the slab has got a thickness of 0.6a. In this slide, we are basically showing you the band diagrams of this 2D photonic crystal slabs which are suspended in air.



So, these are basically the 2D one. So, we have not considered the Z at all in this case. So, these are just 2D structures or 2D simulations. So, this is the rod slab, and this is the hole slab. So, z is not considered here, okay? With discrete translational symmetry in two dimensions, you can say that the in-plane wave vector.

The sentence can be corrected to: "The quantity given by k parallel, which can also be written as kx and ky, is basically conserved in these two components." But the vertical wave vector k_z is not conserved, okay? So, that is the case when you have a finite thickness of the slabs. Now, before you go into that kind of structure regarding the actual scenario, we can start our discussion with a very simplified version. Where you consider them as simple 2D lattices, the z dimension does not exist. So, it will be useful to plot the projected band diagram, which in this case is the plot of omega versus k parallel in the irreducible Brillouin zone of the two-dimensional lattice, as shown here.



Okay, so this is for the rod slab, and this is for the pole slab. Now, as in two dimensions, one is able to decompose the guided modes into two non-interacting classes. The lack of translational symmetry in the vertical dimension, however, means that these states are not purely TE and TM. So in the previous case, you could see that you are able to obtain a TM band gap in two dimensions for this kind of rod slab. You are able to obtain the TE band gap in two dimensions when you have this kind of hole slab.

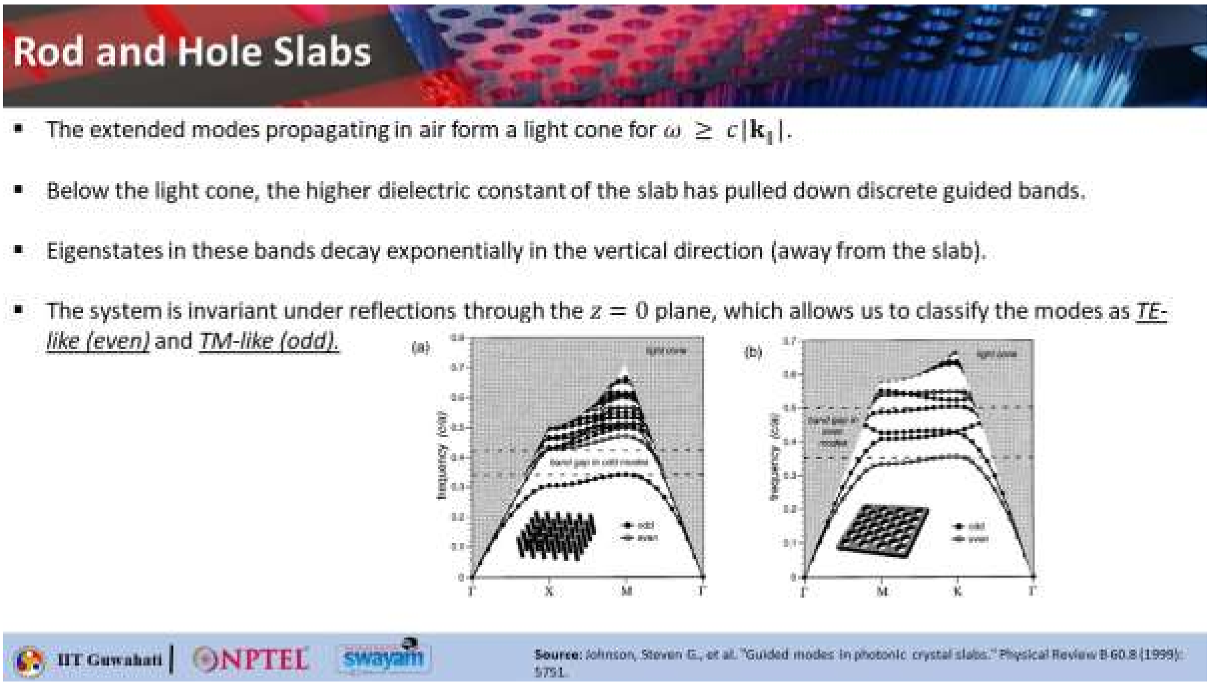
But, you know, when you consider the third dimension—that is, the finite thickness of the rods or the whole slab—that is where things become critical. The sentence "Okay." is grammatically correct as it is. If you would like it to be more formal, you might consider saying "Alright.

" or "That is acceptable." However, "Okay." is perfectly fine in casual contexts. Here, the lack of translational symmetry in the vertical direction means that the states will not be purely TE or TM-polarized. Okay, due to the presence of a horizontal symmetry plane bisecting the slabs, the guided modes can be classified according to.

.. Whether they are even or odd with respect to reflections through this plane. They can actually be indicated by, you know, odd or even modes. Okay, and you can see here that the field circles are showing odd modes. The open circles represent even modes, and this has been done for both cases, right? So here you can see the band diagrams, which are actually for the three-dimensional structure. So these are 2D photonic crystals that have some finite thickness, right? So there you can also clearly see that these band diagrams are different from those that you saw in the previous slide.

But here you can observe that the band gap is visible in odd modes. The sentence "Okay." is already grammatically correct. However, here you can also see the band gap for even modes in this case.

The sentence "Okay." is grammatically correct as it stands. So, what are these shaded areas? This shaded area is essentially the light cone. So, all of the extended modes propagating in the air actually reside here. So, below this, these are all guided bands, okay, localized to the slab. So, they are TTM-like modes, okay? But here, you are actually calling them odd or even.



So, that is with respect to the z equals 0 mirror plane. So, with that, if you look at the field distribution, you have to decide whether it is an even mode or an odd mode. So, more or less, you can understand that these odd and even modes also behave like TE and TM modes, you know. But these are more accurate in this particular perspective of a 2D slab because they are three-dimensional structures, which means they are 2D slabs with some practical or finite thickness. So, the extended modes propagating in air essentially form a light cone for omega greater than or equal to Ck, or you can say Ck parallel.

So, this particular slope corresponds to Ck. This equal sign, and then there are some regions that are also extended. So, these are the extended modes, okay? Below this light cone, you can actually see that the higher dielectric constant of the slab has pulled down the discrete guided bands. So, eigenstates in these bands will decay exponentially in the vertical direction, which is away from the slab. And you will get to see how the modes decay in the actual simulation, which we will discuss toward the end of this lecture.

So, the system here is essentially invariant. Under reflections through the z equals 0 plane. Thus, it allows us to classify the modes as TE-like, which we can also refer to as even, or you can think of TM-like modes, which are basically referred to as odd modes in this case. So, we will actually discuss the optimization of these parameters later on.

Topological Photonic Crystals

Topological Photonic Crystals

- Another exciting research area which has been in the news of scientific community since past few years is the Topological Photonics.
- Topological photonics is an intriguing research area that emerged from the rich interplay between condensed matter physics and optics.
- This field investigates the properties of light in specially designed photonic materials that mimic the topological characteristics of electronic materials, such as topological insulators.
- The fundamental interest in topological photonics lies in its ability to guide light in robust ways that are immune to defects and disorder, akin to the edge states in topological insulators that conduct electrons without dissipation.
- This robust propagation is governed by the photonic band structure's topological properties, often characterized by nontrivial topological invariants.

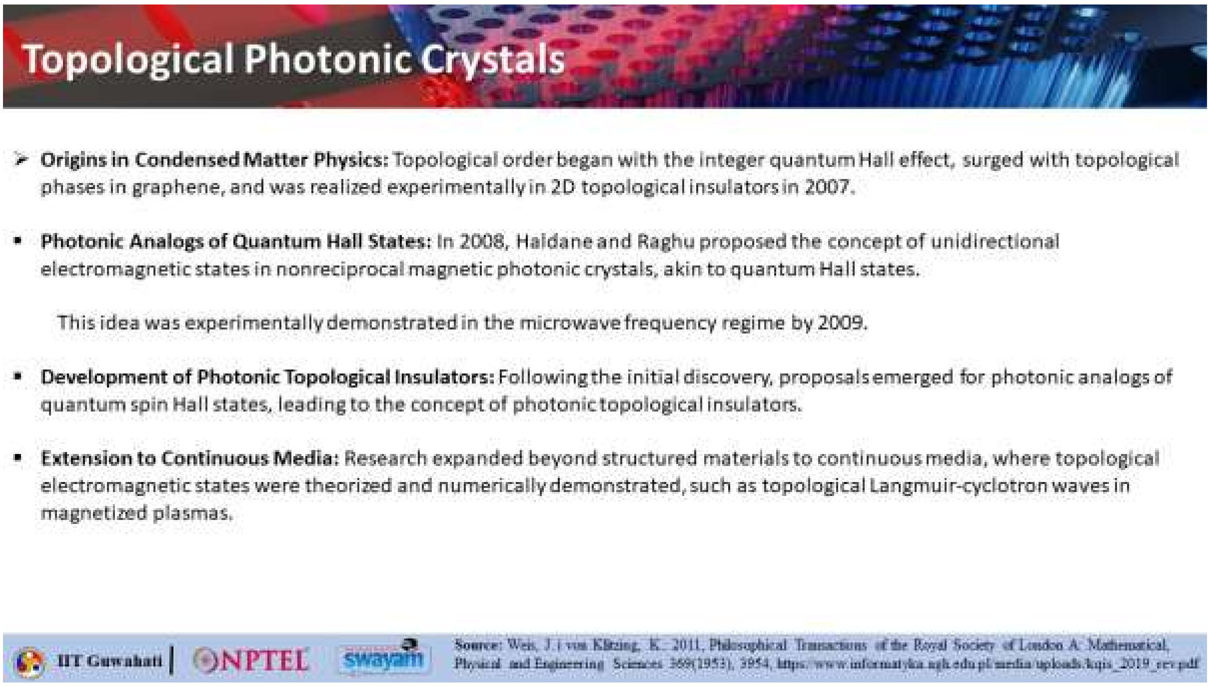
Source: Weis, J. i von Klitzing, K. 2011, Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences 369(1953), 3954, https://www.informatyka.agh.edu.pl/media/uploads/kqis_2019_rev.pdf

So, now we will move on to the next interesting topic, which is topological photonic crystals.

Now, this is an exciting area of research that has been in the news within the scientific community for the past few years. So, the area is called topological photonics. Now, this topological photonics, as I mentioned, is an integrating research area that has emerged from the rich interplay between condensed matter physics and optics. So what happens in this particular field is that it investigates the properties of light in a very specially designed photonic material. That basically mimics the topological characteristics of electronic materials, mainly the topological insulators.

The fundamental interest in topological photonics lies in its ability to guide light in robust ways that are immune to defects and disorders. So, just like the edge modes that you can see in topological insulators, which conduct electrons without dissipation. It means without scattering losses. Here, you will also be able to use topological photonic insulators to create different waveguiding structures where light can be guided without any loss. So that is something very, very interesting.

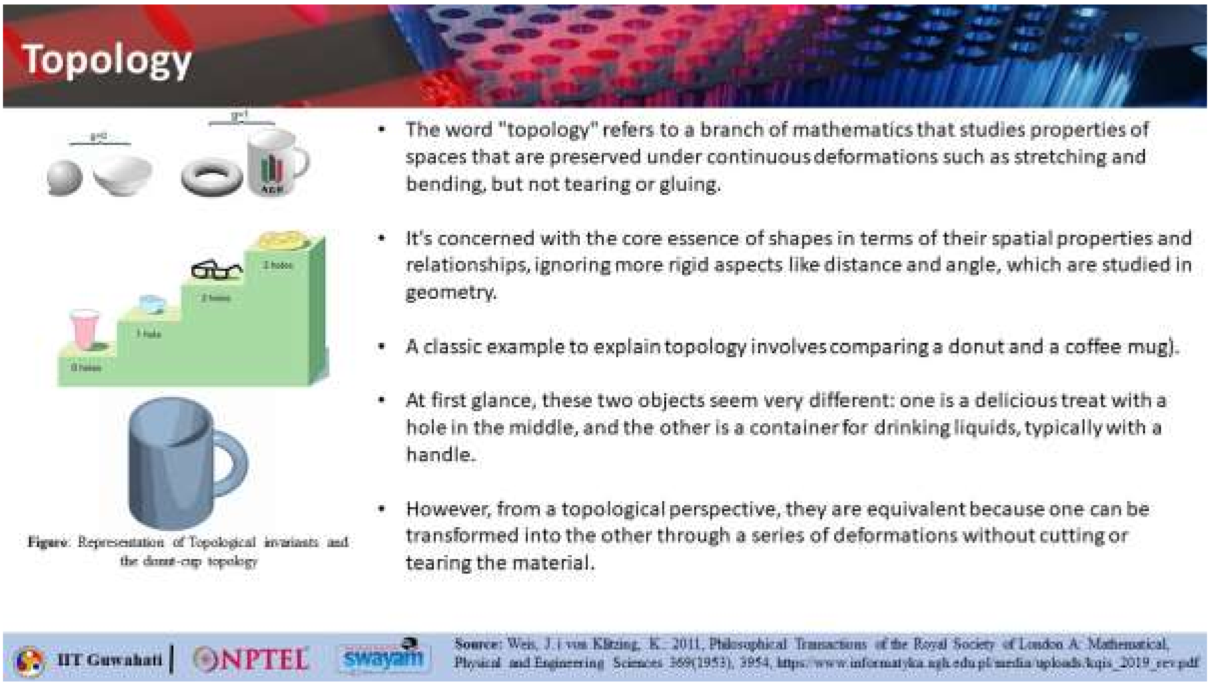
This robust propagation is governed by the photonic band structures and topological properties, often characterized by non-trivial topological invariants. We will go into detail.



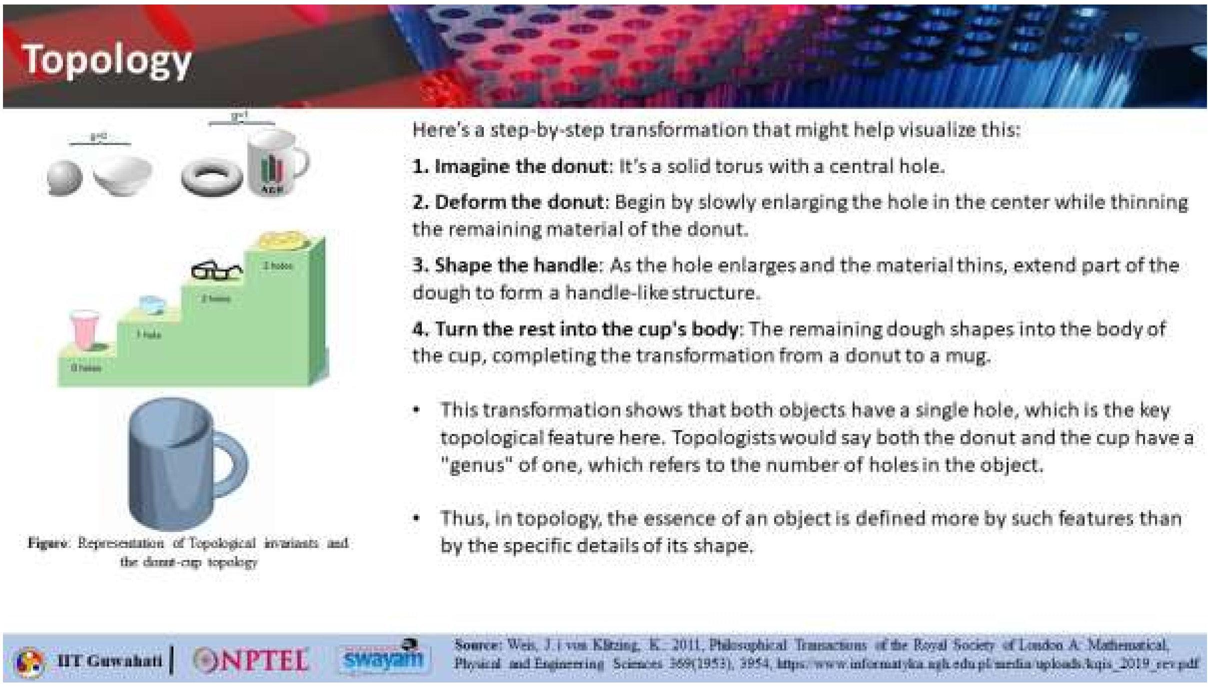
So, we learned a new term here: topological insulator and topological photonic crystals. Now, they all originated in condensed matter physics a long time ago. So, the topological order began with the integer quantum Hall effect that surged with topological phases in graphene, and finally, They were experimentally realized in 2D topological insulators in 2007.

So it is not as very old as you might think. The concept of photonic crystals is very old, but not this, you know, topological photonic crystals. They are a very new and hot topic of research. So, photonic analogues of quantum Hall states can be understood by considering what people have done. In 2008, Halden and Raghu proposed the concept of unidirectional electromagnetic states in non-reciprocal magnetic photonic crystals, which are similar to quantum Hall states. So, this idea was experimentally demonstrated in the microwave frequency range in 2009.

What followed was the development of photonic topological insulators. So, proposals emerged for a photonic analogy of the quantum spin Hall states, which has led to the concept of photonic topological insulators. So, research has expanded beyond structured materials to continuous media where topology.



.. Electromagnetic states are theorized and numerically demonstrated, such as topological Langmuir cyclotron waves in magnetized plasmas. So, these are all difficult concepts to understand, but let me introduce the first notion of topology in this lecture. So, what do you mean by "topological insulators," and what is "topological invariance"? So, when you think of the word "topology," it basically refers to a branch of mathematics that studies the properties of spaces. That are preserved under continuous deformations, such as stretching and bending, but not tearing or gluing, is important, okay? So, it is concerned with the core essence of shapes in terms of their spatial properties and relationships, ignoring more rigid aspects like distance and angle, which are studied in geometry. So, one classic example involving topology is comparing a doughnut with a coffee mug, as you can see here.



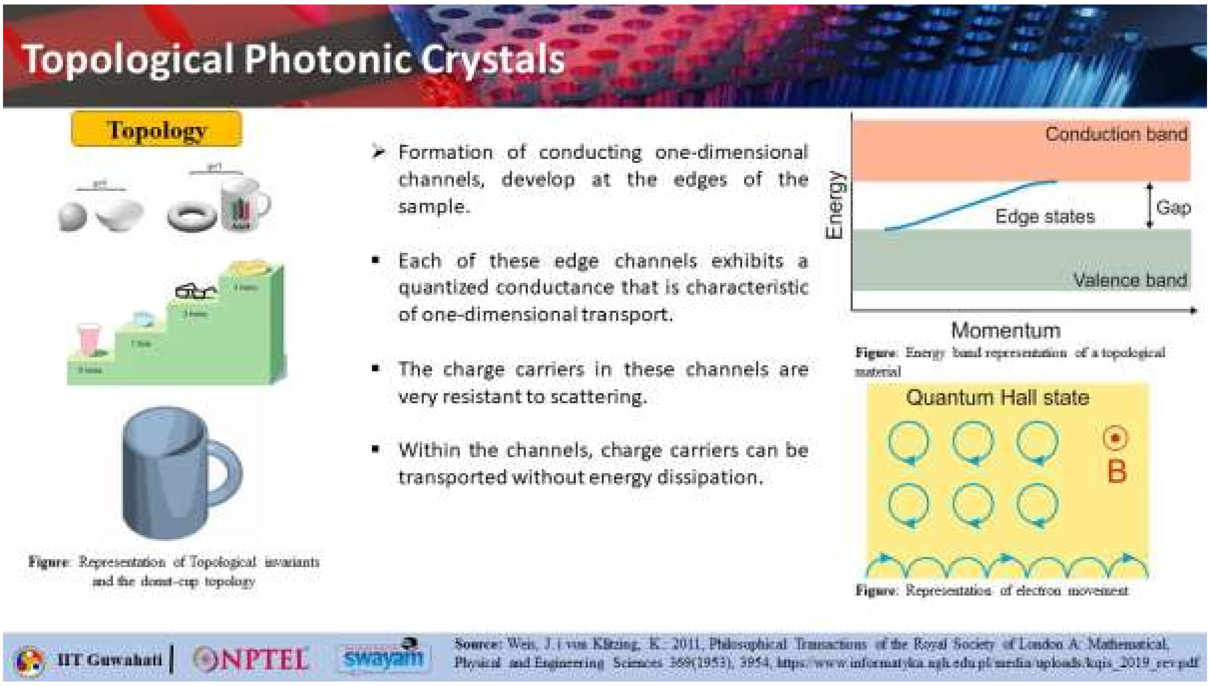
At first glance, the two objects may appear very different. So, one is a very delicious treat with a hole in the middle. That's a donut. The other one is a container for liquid, typically coffee.

And it has a handle. Now, if you consider it from a topological perspective, you can see that they are basically equivalent. The sentence "How?" is already grammatically correct. It is a complete sentence as it stands, often used to inquire about the method or manner of something. If you need a different construction or context, please provide more details! Because one can be transformed into another shape through a series of deformations without cutting or tearing the material, as shown here in the animation.

You can think of these two as the same type. G equals 0 and G equals 1 tell you about the number of holes present. So, 0 holes, 1 hole, 2 holes, 3 holes, and so on. So this is how it is: If you want to visualize what is happening here, these are the step-by-step transformations that might help you visualize it. So, imagine the doughnut, which is basically this structure.

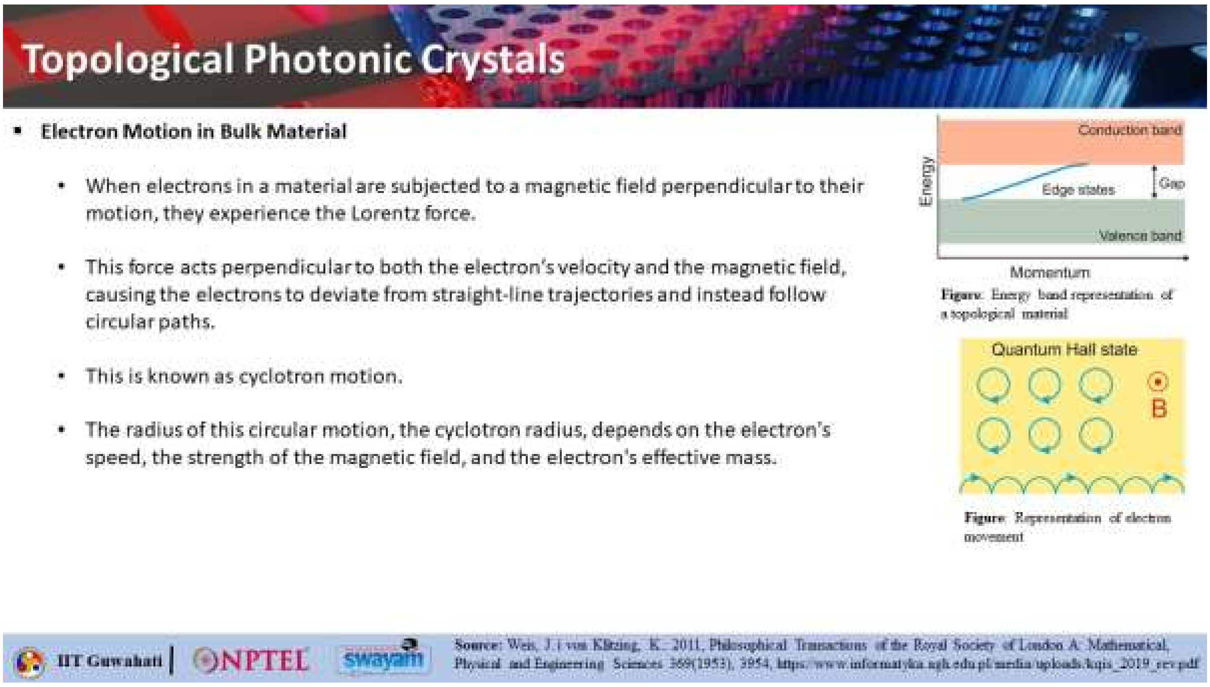
It is a solid torus with a central hole. (The original sentence is already grammatically correct.) Now, deform the doughnut. (The original sentence is already grammatically correct.) So, you begin by slowly enlarging the hole in the center while thinning the remaining material of the doughnut.

And then you shape the handle. As the hole enlarges and the material becomes thin, extend part of the dough to form a handle-like structure and turn the rest into the cup's body. So the remaining dough can then be shaped into a cup, and that is how you can actually complete the transformation from a doughnut to a mug. So what is important here is that the transformation shows that both objects have a single hole, which is the key topological feature. A topologist would say that both a donut and a cup have a genus of 1, which refers to the number of holes in the object. Therefore, in topology, the essence of an object is defined more by its features than by the specific details of its shape.



So, that is what topology is. Now let us discuss how you get the idea of topological insulators. The sentence is already grammatically correct. So the first thing to consider is the motion of electrons in a material in response to a magnetic field. For example, imagine you have a magnetic field coming out of the screen. So, the response of the electrons in a material to this kind of magnetic field is basically a fundamental aspect of condensed matter physics.

It plays a critical role in various topological phenomena. Such as the quantum Hall effect. So, we have all understood the fundamentals of the quantum Hall effect during our B.Tech or school days. So, here is how the motion occurs and leads to this uniquely boundary-dependent behavior.



So, this is what we will discuss here. So, when the electrons in a material are subjected to a magnetic field that is perpendicular to their motion, they essentially experience the Lorentz force. So, this is how they are compelled to follow this circular path. So, what happens? (The sentence is already correct.) The force acts perpendicular to both the electron's velocity and the magnetic field, causing the electrons to deviate from straight-line trajectories and instead follow circular paths.

Now, this is referred to as cyclotron motion. Now, the radius of the circular motion, which is also known as the cyclotron radius, depends on the electron's speed, the strength of the magnetic field, and the electron's effective mass.

Topological Photonic Crystals

- **Electron Motion at Boundaries**
  - At the boundaries of the material, the behavior of electrons changes significantly due to the confinement of their paths.
  - When electrons moving in cyclotron orbits reach a boundary, they cannot continue their motion outside the material and are thus reflected back into the material.
  - This reflection alters their path into a helical trajectory along the edge of the material.
  - The helical paths at the boundaries lead to what are known as edge states. These states are crucial for understanding topological phenomena in materials.

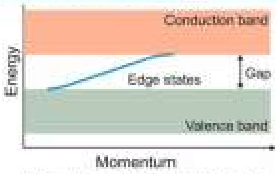


Figure: Energy band representation of a topological material

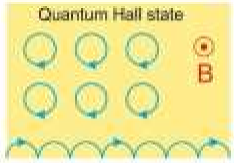


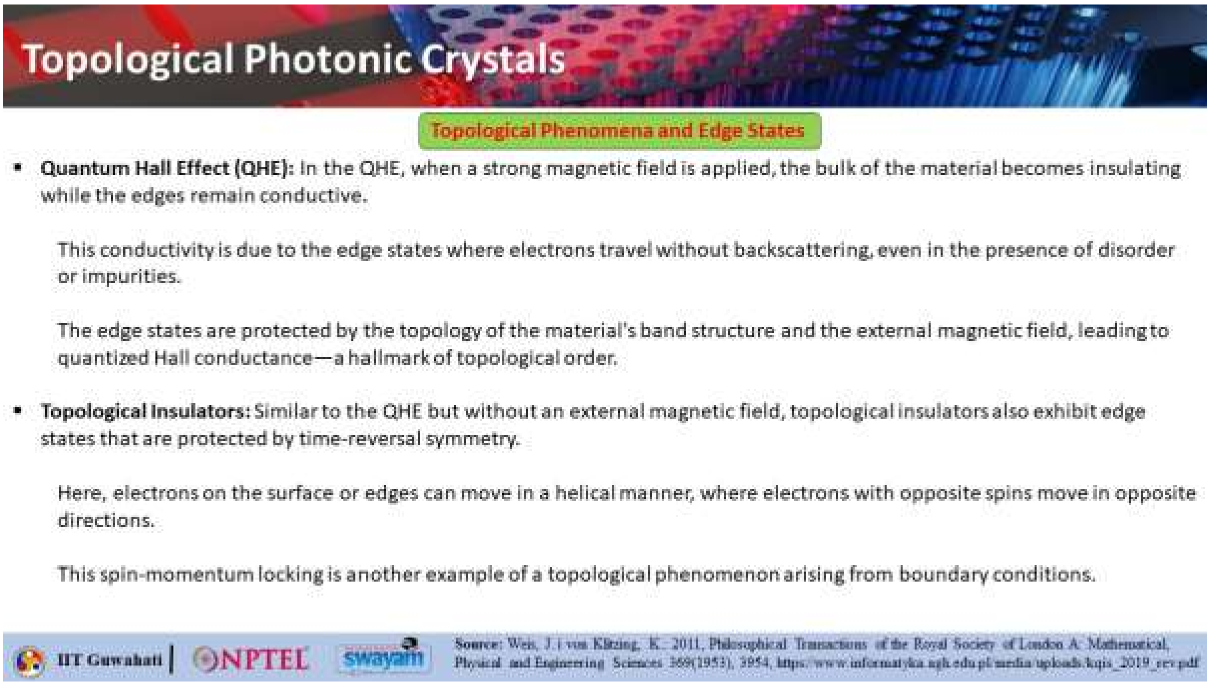
Figure: Representation of electron movement

Source: Weis, J. i von Klitzing, K. 2011, Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences 369(1953), 3954, https://www.informatyka.agh.edu.pl/media/uploads/kqis_2019_rev.pdf

Now, what happens to the electrons at the boundaries? At the boundary of the material, the behavior of the electrons changes significantly because their path is confined. Okay, so when the electron moving in the cyclotron orbit reaches a boundary, it cannot continue its motion outside the material. Because there is no material here, it reflects back instead, and it continues like this. So, that is how this reflection basically alters their path from a circular trajectory to a helical trajectory along the edge of the material.

Now, these helical paths at the boundary lead to what are known as the edge states. And these edge states are crucial for the understanding of topological phenomena in materials. So, this is what the energy band representation of a topological material looks like. So, this is the conduction band, this is the valence band, the minimum of the conduction band, and the maximum of the valence band. The difference between these two gives you a gap; that is the band gap, and this is where the edge state will lie.

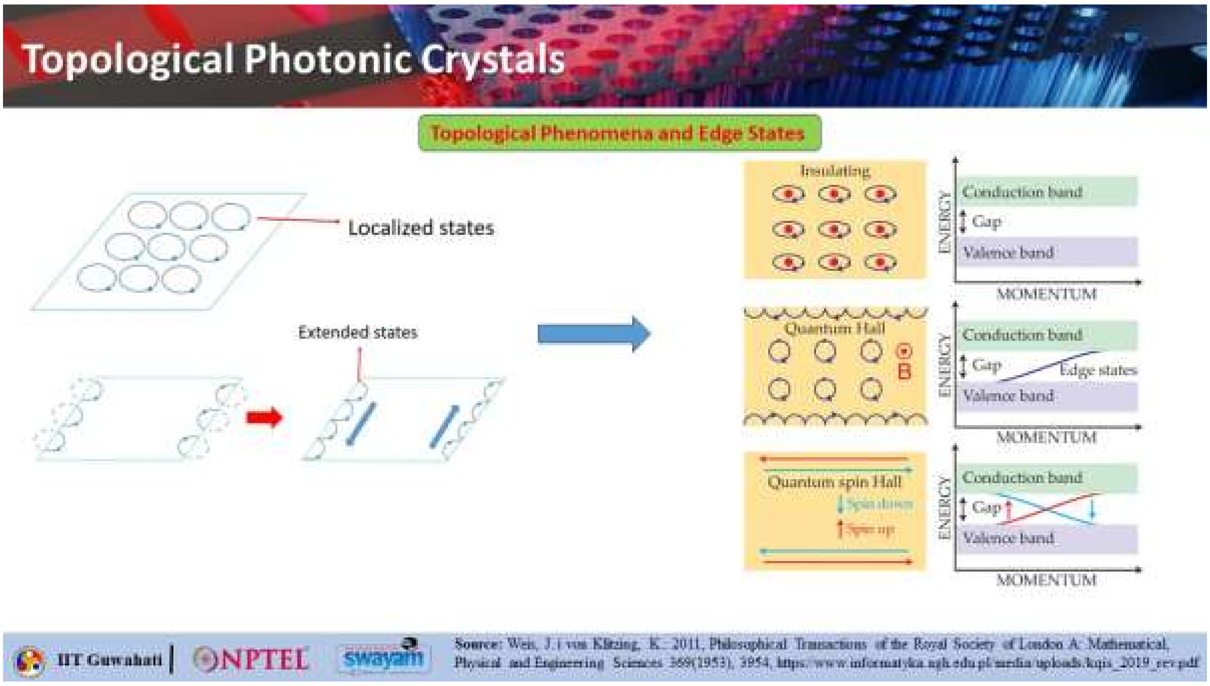
The sentence is already grammatically correct. However, if you want a slight variation, you could say: "We will get to that." In more detail.



So, what did we understand? We understood the topological phenomena and the edge states. Let us go into further detail about this interesting concept. So, in the quantum Hall effect, when a strong magnetic field is applied, the bulk of the material, including the insulating parts, becomes insulating, while the edges remain conductive.

So, what happens when the bulk of the material is an insulator, but the edges are conducting? So, this conductivity is due to the edge states. Where the electrons travel without backscattering, there is no reflection, even in the presence of disorder or impurity. Now, this is the beauty of this: even if there is a disorder or impurity, the electrons are allowed to move forward only. How do you know that the edge states are protected by the topology of the material's band structure and the external magnetic field? And they lead to the quantized Hall conductance, which is a hallmark of topological order.

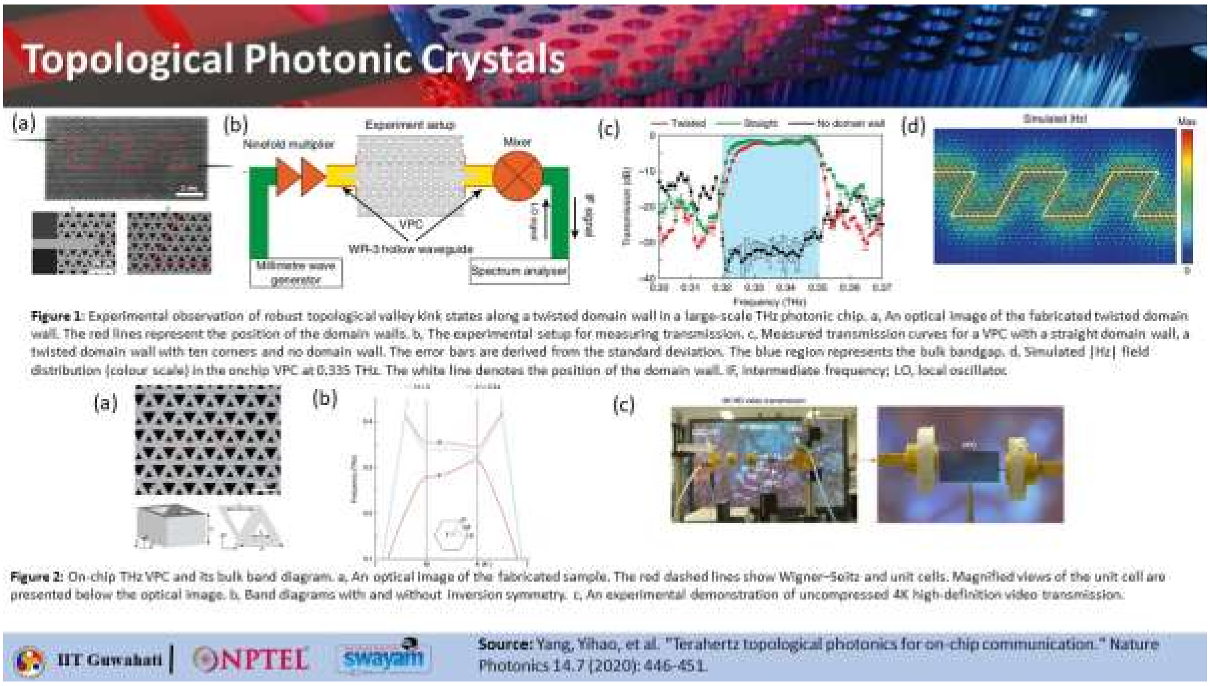
So, using these concepts, you can think of a topological insulator. So, similar to the quantum Hall effect, but without an external magnetic field, you can see that topological insulators can exhibit edge states that are protected by time-reversal symmetry. So here, electrons on the surface or edges can move in a helical manner, where electrons with opposite spins will move in opposite directions. So, this spin-momentum locking is another example of a topological phenomenon arising from the boundary conditions. So when a particle moves under the influence of a perpendicular magnetic field, it moves in orbits or circles. So, in a material with a lot of particles moving, we have something like the following.



So, classically, the particles moving in orbit correspond to what are called localized states. If you use the language of quantum mechanics, it is because they are localized around certain points. Now, at the edges of the material, you can see that the particles try to deform the closed orbits, but they are stopped at the boundary where they collide and are essentially sent back to the next orbit. So, these incomplete orbits at the edges look like this. So, as you can see, hitting the edge and moving on to the next orbit causes the particles to move forward along the edge of the orbit.

So, quantum mechanically, this corresponds to extended states, meaning that they are not localized ones. Hence, these particles move along the edges, but at each edge, they move in different directions: on one edge, they move in one direction, while on the other edge, they actually move in the opposite direction. So this is how you know what the band diagram will look like. So, this is for the normal case of insulating material.

So here you can see that there is a band gap. And this is where these are the central points of the axis. You can also see the quantum Hall effect giving rise to the edge states, which are marked here. You can also see that for spin-up, this can be considered the direction of propagation for which this is the edge state, okay? The red color indicates that if you go for the spin down, then this is the direction of propagation, and this will be your edge state in the energy pentagram, right? So, with that basic understanding, we can look for different applications of topological photonic crystals. So, as I discussed, these crystals are also immune to backscattering or any scattering losses due to impurities and defects. So, you can actually guide light through this kind of topological photonic crystal using any sharp geometries or bends.



So, there are some applications here. So, let us quickly discuss them. So here, one application that you can see is basically a waveguide channel that has been designed, and this is the simulation. So you can see the zigzag path that has been taken. The path has very sharp bends, but because of these edge states, they are able to propagate without any loss. So, how do you actually get this? You can actually create this kind of topological photonic crystal where the two different sets of unit cells can give you the domain wall. And this is how you create the red mark: one shows you the domain wall, which is actually shown here.

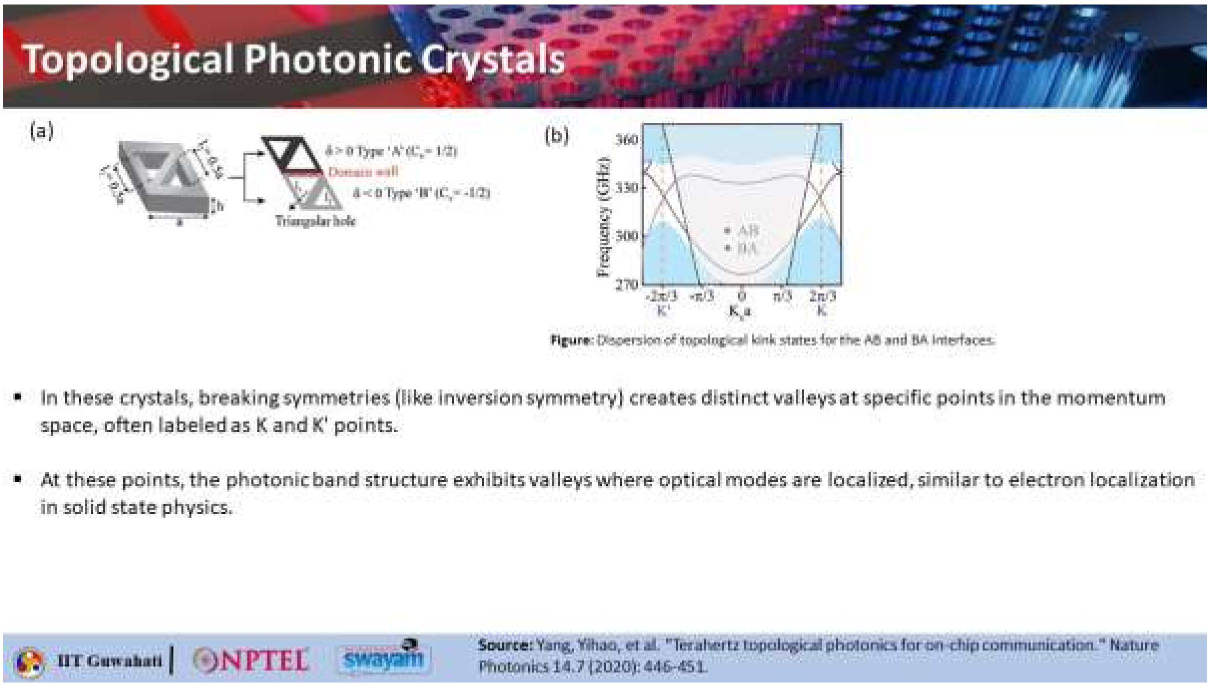
So, this tells you the experimental results of the measured experimental setup for measuring the transmission. So, you have a millimeter wave generator, and then a multiplier to provide that signal to you. These are the hollow waveguides. And this is your valley photonic crystal, or the topological photonic crystal that you have made.

Okay, and then this is the final transmission graph that you see. So what is important to note here is that if there is no domain wall, the transmission drops significantly because of the scattering losses in this very sharp case. But in the case of straight and twisted structures, both show a similar kind of performance, which is where photonic crystals, particularly topological photonic crystals, are very useful. They are very useful for making these high-channel waveguides, so this is the basic unit cell. Okay, and this is how the edge state will look; this is the band diagram opening. So, what you can actually see here is that if you take them symmetrically, you will have these dotted lines that are kind of, you know, closing in.

So, there is no band gap, but as you make one triangle different from the other in size, you will be able to introduce asymmetry, which will open up the band gap. So, this is an experimental demonstration of transmitting uncompressed 4K high-definition data. Using this waveguide channel, a transmission rate of 11 Gbps was achieved. What is the frequency range for this kind of waveguide channel that people are designing? For 320 to 350 gigahertz, a 30 gigahertz channel is essentially created.

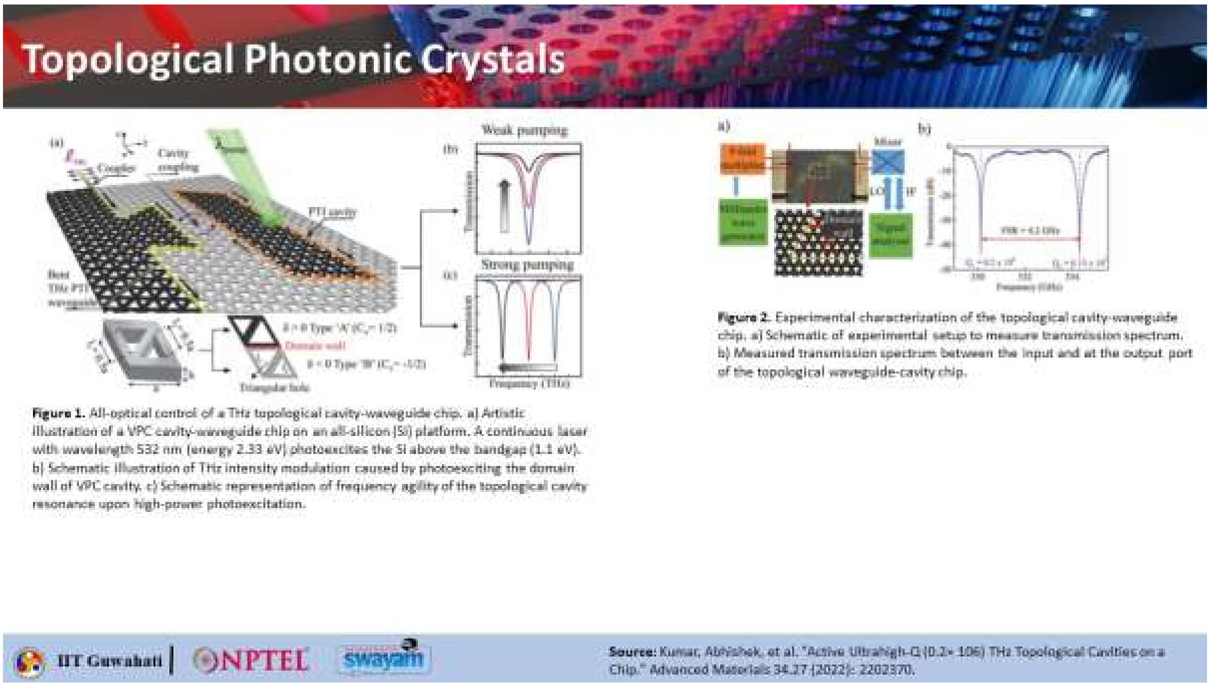
Here are some details about it. Valley photonic crystals. So, valley photonic crystals in topological photonics essentially employ the concept of valleys from solid-state physics. These are the regions in momentum space characterized by local energy minima. So, that is why they are called valleys. So, these are basically like this, you know, and they are akin to the electronic valleys in materials like graphene. So, these structures manipulate light using the valley degree of freedom, resulting in a distinctive photonic band diagram like this.

The sentence "Okay." is already grammatically correct. So, you can see that this is a symmetrical structure with symmetrical holes. So, you can actually make delta greater than or equal to 0. This is a type 8 where the bottom triangle is larger than the top one, or you can make the other one. When these two different unit cells are placed side by side, they can create this domain wall. You will see that if you know the line defect, you can actually create any kind of domain wall in any shape, and that will be the waveguide you are forming.

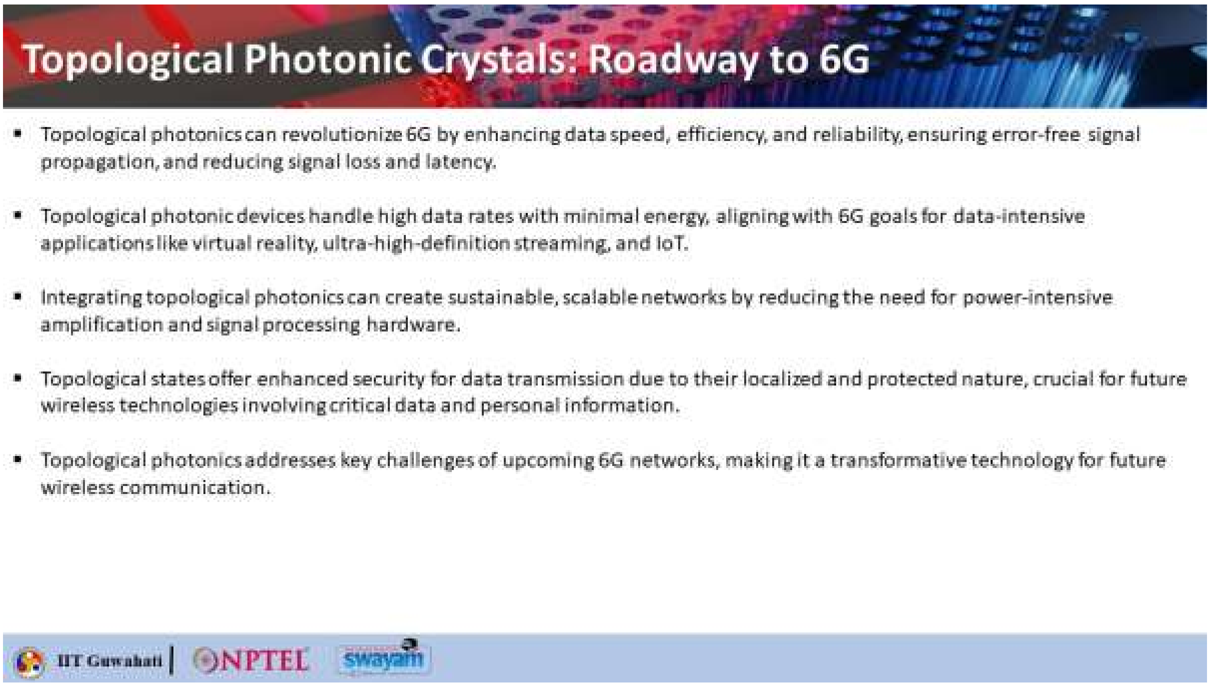


Okay, so what is important in these crystals? The sentence is already grammatically correct. However, if you're looking for a more elaborate version, you could say: "Symmetry breaking is an important concept." That will actually break the inversion symmetry and create distinct valleys at specific points in momentum space, which are marked as k and k prime. At this point, the photonic band structure exhibits valleys where optical modes are localized, similar to electron localization in solid-state physics. So, the blue region highlights the projected bulk dispersion, and in the black region, you can see the blue area. The black dashed lines also show the light lines, while the blue and black dotted lines represent the dispersion of the kink states at the AB and BA interfaces.

Okay, so these are the two interfaces. Kx denotes the wave vector along the domain wall. What is A? The periodicity is okay. So, what is important here is that the valley's topological nature ensures that robust edge states can be formed along the boundaries of the crystal. So, when light travels through these edge states, it is highly resistant to backscattering and defects. Mirroring the unidirectional robust flow seen in electronic topological insulators. So, this configuration makes topological valley topological crystals or photonic crystals, known as VPC valley photonic crystals, valuable.

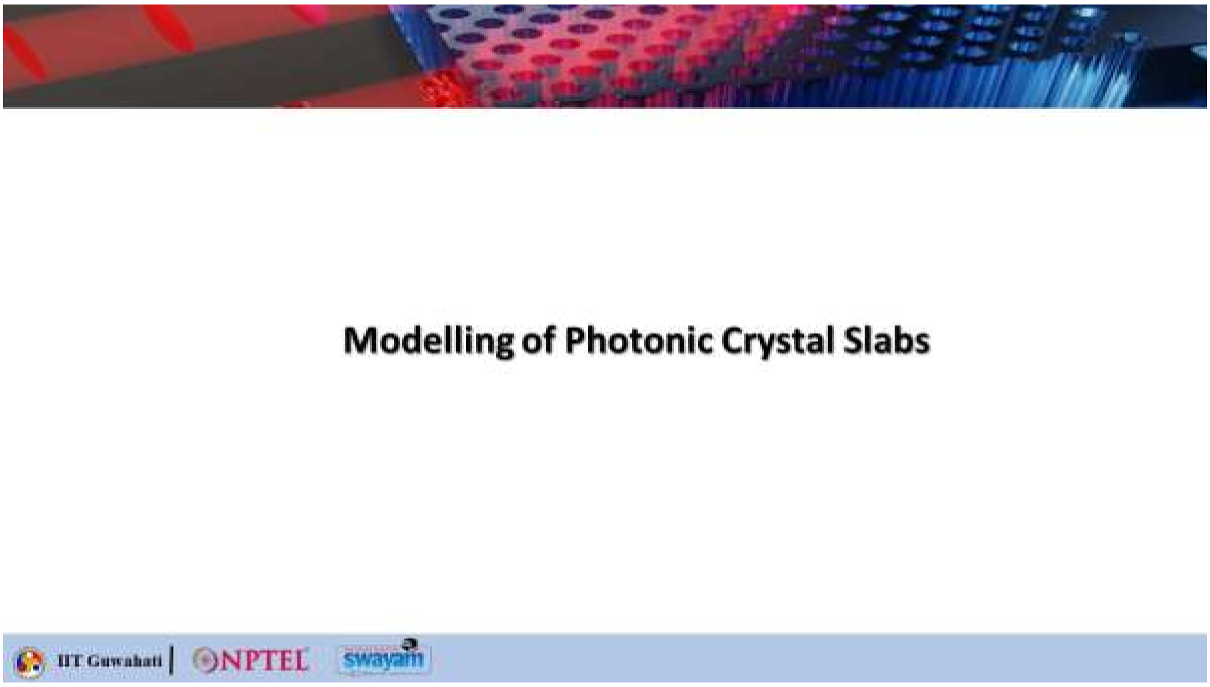


For creating resilient photonic devices that guide light with minimal loss and interference. You can also make other kinds of structures. I will not go into the details of it. I'll just show you that you can make couplers, optical cavities, waveguides, and filters. So, these are different applications possible through the use of topological photonic crystals. So what we understood is that these topological photonic crystals support very high frequencies, on the order of 300 gigahertz.



Okay, so you can actually use topological photonic crystals to revolutionize 6G technology. By enhancing data speed, efficiency, and reliability, and by ensuring error-free signal propagation through the reduction of signal loss and latency. So, topological photonic devices can handle high data rates with minimal energy consumption. Aligning with 60 goals for data-intensive applications, such as virtual reality, ultra-high-definition streaming, and IoT. Integrating topological photonics can create sustainable, scalable networks by reducing the need for power-intensive amplification and signal processing hardware. Topological states offer enhanced security for data transmission because of their localized and protected nature.

Which are also critical for future wireless technologies that involve critical data and personal information, right? So, topological photonics addresses the key challenges of the upcoming 6G networks, and that is why it is going to be a transformative technology for future wireless communication.



. So, with that, we will now go into the modeling of these photonic crystal slabs. Right now, I will show you a video that has been recorded by the TA for the course, Dibaskar. So, he will take you through the console simulation of the photonic crystal slab. So, we will discuss in detail the two examples of rod and slab photonic crystals, and we will see how introducing a line defect will change the band diagram.

So, all of this simulation will be shown here.

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So, that is all for this lecture. We will start the discussion of different types of defects in photonic crystal slabs in the next lecture. If you have any queries regarding this lecture, you can send an email to this address, mentioning "MOOC," "photonic crystals," and the lecture number in the subject line. The sentence is already correct as it is. The sentence "Thank you." is already grammatically correct.