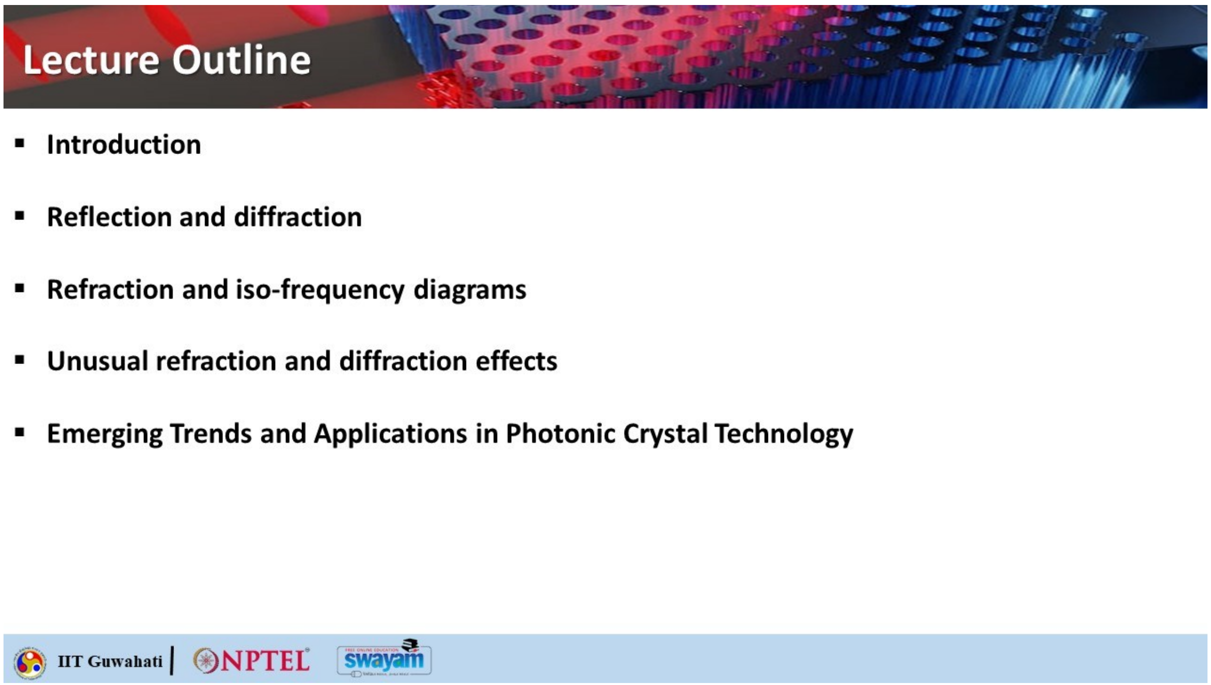
Lec 34: Unusual Refraction and Diffraction Effects

Hello students, welcome to lecture 34 of the online course on Photonic Crystals Fundamentals and Applications. Today's lecture we will be discussing unusual refraction and diffraction effects. So, here is the lecture outline. So, first we will have a brief introduction discuss about reflection and diffraction. Then we will go into this effect of refraction and then the isofrequency diagrams. We will also discuss about unusual refraction and diffraction effects.



And finally, we will look into some of the emerging trends and applications of the photoregressional technology. So, while this course primarily focuses on confining light within photonic structures, it is important also to know and explore the dynamics of light as it freely propagates in and around the photonic crystals. So, in this lecture, we will briefly review various interesting phenomena which are associated with the free propagation of waves through photonic crystal. And we will relate those phenomena to the fundamental principles which were discussed in the previous lectures, enhancing the understanding of both confined and free propagation wave behavior in this photonic environment.

Introduction

So let us focus on this slide and you can see the figure. This is basically a photonic crystal. So let us consider the case of an incident plane wave. okay. So, this is the incident plane wave and it strikes the interface of a photonic crystal okay.

Reflection, Refraction, and Diffraction

- **Interaction of Light with Photonic Crystal Interface:**
  - Incident light can be reflected at the same angle as the incident angle.
  - Outside the photonic band gap, light may be transmitted or refracted within the crystal at angles determined by the group velocity.
  - Depending on frequency, interface periodicity, and band structure, Bragg diffraction may occur, producing additional reflected and/or refracted waves.

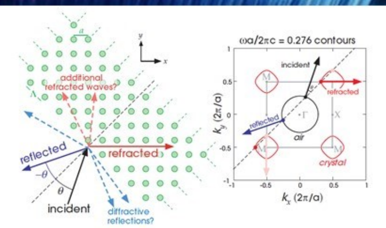


Figure 1: Left: Schematic of reflection (blue) and refraction (red) of a plane wave incident (black) on a square lattice of dielectric rods (green) in air, for an interface with period $\Lambda = a\sqrt{2}$ in the diagonal (110) direction. Right: Iso-frequency contours in k space at $\omega a/2\pi c = 0.276$ for air (black circle) and crystal (red contours), with the Brillouin zone in gray. The group velocity direction at various k points is shown as arrows (black/blue/red for incident/reflected/refracted waves).

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

So, this is a photonic crystal. Now, there is something interesting as you can see okay. So, this is the photonic crystal. So, it is basically a square lattice right, but this plane where the light is basically incidenting on, that is a diagonal plane, right? So, this is a 110 direction, okay? That is the interface. So, if you look into this what you are seeing, you are basically seeing the schematic of reflection which is shown in blue and then you have refraction that is shown in red ok of the plane wave which is incident at this interface ok. So, that is shown in black and this is basically a square lattice of dielectric rods in air ok and the lattice period you can see here that is *a* and the interface is this one the diagonal one that has got a periodicity of capital lambda. And the relation between capital lambda and A is capital lambda equals A root 2, okay? Because that is in the diagonal direction. Right. So what are the other things? This dashed arrows, they basically show diffracted reflections which can go higher order reflection in different direction.

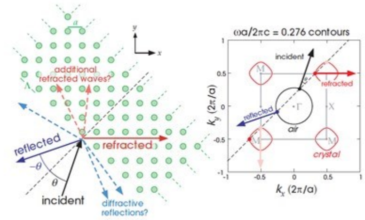
Similarly, you can also have some additional refracted waves. OK. On the right, what do you see? You actually see the isofrequency contour in k space. so if you remember what are those if you think of a 3D band diagram and then if you take slices along the frequency axis okay those those cross sections of the band diagram with that plane will give you isofrequency contours so this contours they represent the same frequency and here it is these ones are basically drawn for $\frac{\omega a}{2\pi c}$ equals 0.276 that is the control that you are seeing so you are basically having 1 2 3 4 4 almost like cycles that is how the contours look like here okay so we'll go into this description a little later because this is where we'll be representing air also so this is air okay circle which is shown in black and then for the crystal you have this red contours okay and this is the brilliant zone so it starts from -0.5 to 0.5 here also -0.5 to 0.5 okay so this is the brilliant zone which is shown in gray and then these points basically are the k points and the group velocity direction are shown for different k points. So, this is the direction of incident wave. So, this is the direction of incident wave.

You can see the reflected wave is here and this is the reflected wave. We will come into this discussion little late, okay. Let us first try to understand what is happening, okay. So, the first thing very simple the incident light can be reflected from the interface at the same angle as the incident angle. So, we all know this ok.

Now, outside the photonic band gap ok what may happen that there is possibility of light transmission. So, if it is if the frequency of the light falls within the band gap there will be no transmission or refraction at all like everything will get reflected. So, if we are considering the frequency outside the photonic band gap light may be transmitted or refracted within the crystals at some angles which are determined by the group velocity. So, this is where this particular diagram will come handy will come there. Now, depending on frequency interface periodicity and the band structure the Bragg diffraction may occur and that may produce this additional reflected and or this kind of refracted waves okay.

Reflection, Refraction, and Diffraction

- **Application of Bloch's Theorem:**
  - Bloch's theorem helps explain wave propagation in crystals with discrete translational symmetry.
  - Only the wave vector component $k_{\parallel}$ parallel to the interface is conserved due to translational symmetry along the interface.
  - Conserved wave vector parallel to the interface implies $k_{\parallel}$ changes by multiples of $2\pi/\Lambda$, where Λ is the periodicity parallel to the interface.



- **Wave Vector and Frequency Conservation:**
  - Any reflected or refracted wave at the interface must retain the same frequency ω as the incident wave.
  - The wave vector of these waves is modified to $(k_{\parallel} + 2\pi\ell/\Lambda, k_{\perp})$ for any integer ℓ, with $k_{\perp}$ possibly varying.

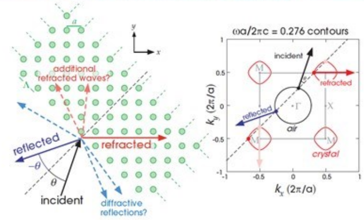
Source: J. D. Joannopoulos *et al.*, "Photonics Crystals: Molding the Flow of Light", Princeton Univ. Press, 2008.

So, let us apply bloch theorem here. So, bloch theorem will help explaining the wave propagation in crystals with discrete translational symmetry and this is what this crystal has got right. So, only the wave vector component k parallel which is basically the parallel to this interface will be conserved due to the translational symmetry along the interface. Okay, so the conserved wave vector parallel to the interface will imply that k parallel changes by multiples of $2\pi/\Lambda$, right and where Λ is basically the periodicity that is parallel to this interface. So, that plays an important role, not a.

But then lambda and a are related because $\Lambda = a\sqrt{2}$. Now, let us look into the wave vector and the frequency conservation. so any reflected or refracted wave at the interface must retain the same frequency omega as that of the incident wave right so the wave vector of this waves is modified by this factor so the parallel one can have this form $k_{\parallel} + 2\pi\ell/\Lambda, k_{\perp}$where ℓ can be an integer and then you have also the normal component which is k normal or $k_{\perp}$ okay So, with k perpendicular possibly varying, right? So, all these possibilities are there. Now, let us look into this diagram which is the isofrequency diagram. Now, why you need this? This is useful for analyzing how the refracted wave propagate within the crystal based on the frequency and the direction, okay? The interface has got a periodicity Λ that we understood and that is different from the lattice periodicity, which is a.

Reflection, Refraction, and Diffraction

- **Isofrequency Diagrams:**
  - Useful for analyzing how refracted waves propagate within the crystal based on their frequency and direction.
- **Interface Periodicity:**
  - The periodicity Λ of the interface might differ from the crystal's lattice constant; for example, for a square lattice with constant a, a diagonal (110) interface could have $\Lambda = a\sqrt{2}$.
  - Analysis primarily focuses on periodic interfaces to simplify predictions of wave behavior.



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

And this is the reason why because the interface is basically a diagonal interface and the plane is 110. So analysis primarily will focus on periodic interfaces to simplify the predictions of wave behavior.

Reflection and diffraction

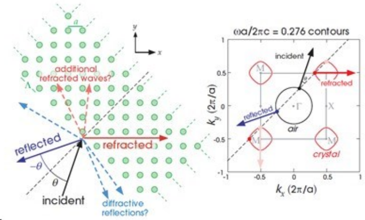
So now let us go into reflection and diffraction and try to figure out what is happening here. The first thing is specular reflection or the normal reflection. So here you can see you get this bold blue line that shows the specular reflection which is basically the reflected wave corresponding to ℓ equals 0 and that represents the plane wave with k vector which has got $k_{\|}, k'_{\perp}$. So k parallel remains same but then the conservation of frequency and wave vector component will imply that the normal component is basically negative of the incident one. So you get $k'_\perp$ will be $-k_\perp$ okay. So that basically adheres to the law of equal incident and reflected angles okay as you can also see here. So, if the incident angle is theta reflected angle will be minus theta right.

Reflection

- **Specular Reflection Overview:**
  - The reflected wave corresponds to $\ell = 0$, representing a plane wave with $\mathbf{k} = (k_\parallel, k'_\perp)$
  - Conservation of frequency and wave vector components implies that $k'_\perp = -k_\perp$, adhering to the law of equal incident and reflected angles, as illustrated in figure (left).
- **Refractive Index and Wave Vector Relationship:**
  - Given the incident medium's refractive index n_i, the relationship $n_i^2\omega^2/c^2 = k_\parallel^2 + k_\perp^2 = k_\parallel^2 + (k'_\perp)^2$ holds.
  - It results in $k'_\perp = \pm k_\perp$, and the negative sign is selected to ensure the wave propagates away from the interface.
- **Diffractive Reflections and Frequency Conditions:**
  - Diffractive reflections for $\ell \neq 0$ depend on the frequency, where $k'_\perp$ is derived from:

$$k'_\perp = -\sqrt{n_i^2\omega^2/c^2 - (k_\parallel + 2\pi\ell/\Lambda)^2}$$

If ω is too small or ℓ is too large, $k'_\perp$ becomes imaginary, indicating an evanescent field that decays exponentially from the interface.



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

With that you can establish the relationship of a refractive index and the wave factors, ok. So, given the incident medium has got a refractive index say n_i, you can write the relationship that $n_i^2\omega^2/c^2 = k_\parallel^2 + k_\perp^2$ ok. So, if you write for reflected that will be same $k_\parallel^2 + (k'_\perp)^2$ that will also hold true. So, as a result what we can get we can see that $k'_\perp$ can be $\pm k_\perp$ and the negative sign is basically selected to ensure that the wave basically propagates away from the interface. So, then you have this diffractive reflections and frequency conditions and that will happen when $\ell \neq 0$.

So, you have those higher order terms. So, ℓ is integer. So, you can put 1, 2, 3 and so on. So, the diffractive relations for non-zero ℓ will depend on frequency where you can derive this $k'_\perp$ from this particular equation. So, $k'_\perp$ will be $-\sqrt{n_i^2\omega^2/c^2 - \left(k_\parallel + 2\pi\ell/\Lambda\right)^2}$.

So, Now looking at this equation if omega is too small or your ℓ is too large in that case this quantity becomes imaginary. So that indicates an evanescent field and that will decay exponentially from the interface. So, what are now for the reflection case, what are the conditions for non-evanescent diffractive reflections? So, you want higher order reflections, but then they should not be evanescent. So, the non-evanescent reflections will occur only if you have this particular condition satisfied, where ω should be larger than see $\omega > \frac{c|k_\parallel + 2\pi\ell/\Lambda|}{n_i}$, okay.

So, for an incident angle of theta which is greater than equal to 0, the critical condition for the first diffractive reflection that is ℓ equals minus 1 will be this.

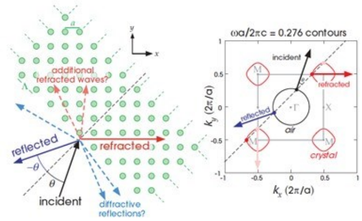
Reflection

- **Conditions for Non-Evanescent Diffractive Reflections:**
  - Non-evanescent reflections occur only if:

$$\omega > \frac{c\left|k_{\parallel} + 2\pi\ell/\Lambda\right|}{n_i}$$

  - For an incident angle $\theta \geq 0$, the critical condition for the first diffractive reflection ($\ell = -1$) is:

$$\frac{\omega\Lambda}{2\pi c} = \frac{\Lambda}{\lambda} > \frac{1}{n_i(1+\sin(\theta))} \qquad k_{\parallel} = \omega \sin(\theta)\, n_i/c$$



- **Practical Implications for Air ($\mathbf{n_i} = \mathbf{1}$) :**
  - Diffractive reflections are absent if $\omega\Lambda/2\pi c = \Lambda/\lambda \leq 0.5$, covering frequencies near most band gaps if $\Lambda = a$.
  - When diffractive reflections occur, each diffracted order (ℓ) starts at glancing angles(parallel to the interface) ($k'_{\perp} = 0$) and moves toward the specular reflection angle $-\theta$ as ω increases.

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

So, you can put here ℓ equals minus 1 you can simplify and find out what is that condition. So, you know that with this condition where $\frac{\omega\Lambda}{2\pi c} = \frac{\Lambda}{\lambda} > \frac{1}{n_i(1+\sin(\theta))}\, k_{\parallel} = \omega \sin(\theta) n_i/c$ and this is the parallel component of the wave vector. So, this is the condition for getting the first diffractive reflection corresponding to ℓ equals minus 1. Now, let us consider some practical implications for air. So, if you take n_i equals 1, so you can find out that the diffractive reflections are absent if this is the condition that if $\omega\Lambda/2\pi c$ or you say $\Lambda/\lambda \leq 0.5$ okay. In that case the diffractivity reflections will be absent okay. So, that is basically covering the frequencies near most bandgap if Λ is taken as a also. So when diffractive reflections occur, each diffracted order, that is ℓ, starts at glancing angles which are basically parallel to the interface. That means you can take k normal prime, so $k'_{\perp}$ to be equal to 0 and then it moves towards the specular reflection angle which is minus theta as omega increases. So, as I mentioned the specular reflection angle is basically the angle of reflection where it equals to the incidence angle, but on the opposite side of the normal that means for minus theta.

Refraction and iso-frequency diagrams

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So, now let us that is what we understood for reflection. So, now let us look into refraction and the isofrequency diagrams. Okay, so first thing we have to investigate the propagating waves in the crystal with a modified surface parallel wave vector. So instead of k parallel, now you have $\mathbf{k}_{\parallel} + 2\pi\ell/\Lambda$ Okay, and then we have to ensure that the group velocity points away from the interface.

Refraction and iso-frequency diagrams

- **Analysis of Refracted Waves:**
  - Investigate propagating waves in the crystal with a modified surface-parallel wave vector $\mathbf{k}_{\parallel} + 2\pi\ell/\Lambda$ and ensure that the group velocity points away from the interface.
  - The set of available states, $\omega(\mathbf{k})$, is dictated by the band structure of the crystal, complicating the analysis beyond simple reflection scenarios.
- **Utilizing Band Diagrams and Isofrequency Diagrams:**
  - Traditional band diagrams, usually limited to showing states around the Brillouin zone boundaries, are not sufficient for detailed analysis here.
  - Employ contour plots of $\omega(k_x, k_y)$ in the (k_x, k_y) plane, known as isofrequency or wavevector diagrams, to depict curves of constant ω.

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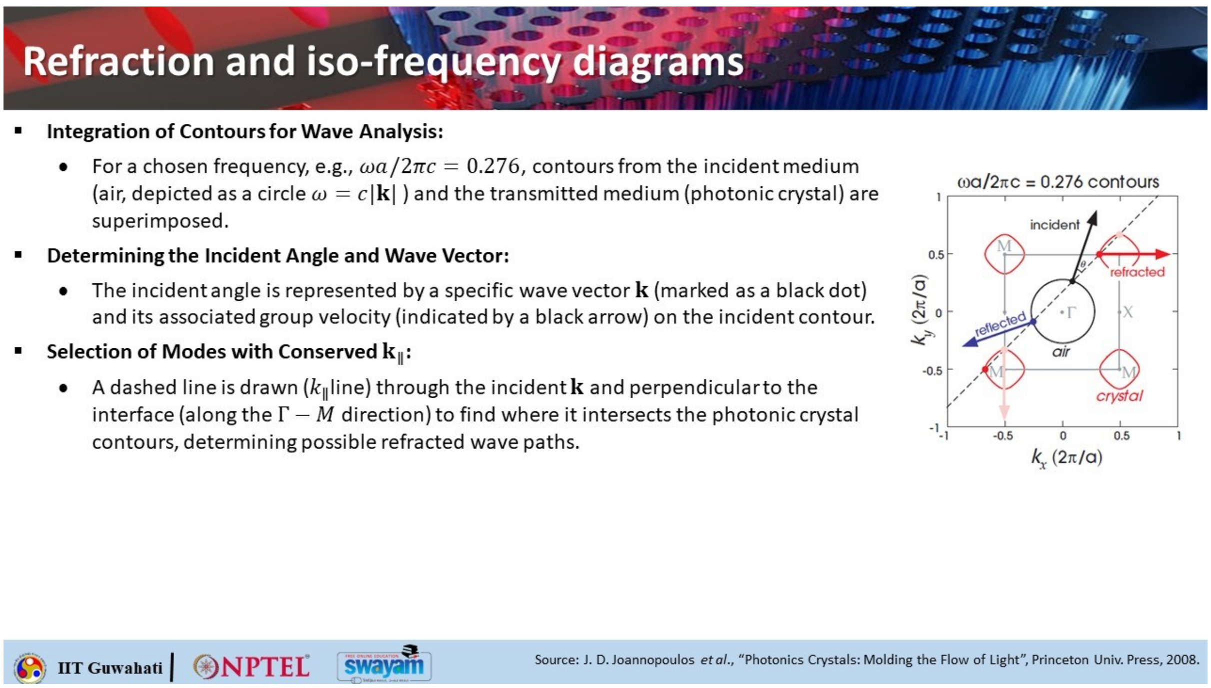
Source: J. D. Joannopoulos *et al.*, "Photonics Crystals: Molding the Flow of Light", Princeton Univ. Press, 2008.

So, the set of available states that is if you find omega as a function of k. So, that is basically dictated by the band structure of the crystal. So, there will be nothing within the band gap. So, that is why it is crystal dependent. So, if you change the crystal you can actually change the band gap and those are the frequencies for which you will never get a refracted wave.

So you've got to have the idea of how the band gap looks like for a typical photonic crystal that you are dealing with. Now, how do you utilize the band diagrams and the isorequency diagrams? So traditional band diagrams, they are usually limited to showing states around the Brillouin zone boundaries. But they are not sufficient for detailed analysis here. So here we have to employ contour plots of omega as a function of kx and ky in the kx, ky plane. So these are basically known as isofrequency or wave vector diagrams to predict curves of constant omega Okay, so if you consider the frequency here, which is normalized frequency 0.276, that represents the value of $\omega a/2\pi c$.



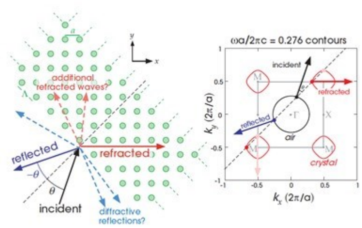
So this contour from the incident medium, so here the incident medium is air. OK, that is depicted as a circle. OK, so this is basically that omega equals c-k relationship OK, and the transmitted medium is basically the photonic crystal, right? So here in this diagram, both are superimposed. So how do you analyze this? So you have to first determine the incident angle and the wave vector. So the incident angle is represented by a specific wave vector k. OK, that is marked as a black dot as you can see here and its associated group velocity is indicated by a black arrow on the incident contour okay so this is how the incident angle is marked Now, how do you select modes with conserved K parallel? So, first thing is that you have to draw a dashed line. As you see here, they have drawn this dashed line, which is basically the k parallel line, okay? So, which is the parallel wave vector, okay? So, that goes through this incident wave vector k and it is also perpendicular to the interface.

So, if you remember the interface is this way. So, the interface goes this way. So, this line is basically perpendicular to that interface and wherever it intersects. So, this is where it intersects. this particular line and this determines possible refracted wave paths as well.

So, this is air and this is where it intersects with the crystal contour. So, this is the way you can determine the refracted wave direction. So what is interesting here to note that how do you identify the valid refracted waves? So not all intersections of this K parallel line with the photonic crystal contours. Okay, so you can see there is an intersection here also. okay but will that produce a viable refracted wave okay that we have to see.

Refraction and iso-frequency diagrams

- **Identifying Valid Refracted Waves:**
  - Not all intersections of the $k_{||}$ line with the photonic crystal contours correspond to viable refracted waves; intersections where the group velocity points towards the interface are discarded.
- **Handling Equivalent Points in Periodic k-space:**
  - Intersections differing by a reciprocal lattice vector (i.e. equivalent points in the periodic k-space) represent the same eigenstate, so redundant points are not considered distinct.
- **Outcome of the Refraction Analysis:**
  - In the depicted scenario, only one refracted wave is valid (red dot/arrow), which interestingly is on the same side of the normal as the incident wave, contrary to typical Snell's law refraction.



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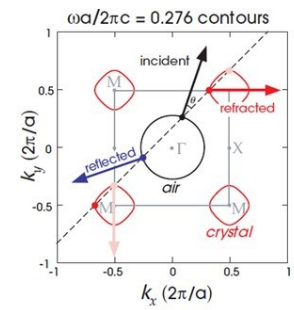
Source: J. D. Joannopoulos *et al.*, "Photonics Crystals: Molding the Flow of Light", Princeton Univ. Press, 2008.

So the intersections where the group velocity points towards the interface okay will be discarded. So this is the interface okay so if the group velocity points towards the interface that is discarded. So you have to see that the group velocity has to move away from the interface. This is the interface, so you have to move away from the interface. Next, how to handle the equivalent points in periodic case space.

So intersections differing by a reciprocal lattice factor that is equivalent points in the periodic case space will basically represent the same eigenstate. So redundant points are not considered as distinct. Okay. So in this depicted scenario what you can see that only one reflected wave is valid that is basically this red dot and the arrow. And it is interestingly on the same side of the incident wave that means this is not typically the Snell's law of refraction. If it is a Snell's law, it would have gone this side of the normal. But it is basically on this side and that is only possible.

Refraction and iso-frequency diagrams

- **Potential for Multiple Refracted Waves:**
  - Multiple refracted waves can occur if the fixed $k_{\parallel}$ line intersects multiple bands in the band structure, necessitating the superimposition of several contours on the isofrequency diagram.
- **Single Band Operation and Intersection Conditions:**
  - The example provided operates below the band gap, where only one band is present, thus typically limiting the occurrence of multiple refracted waves.
- **Geometrical and Angular Considerations:**
  - If the interface were angled differently, the fixed $k_{\parallel}$ line might intersect the same contour at multiple, inequivalent points in different periodic unit cells, potentially leading to multiple refracted waves.



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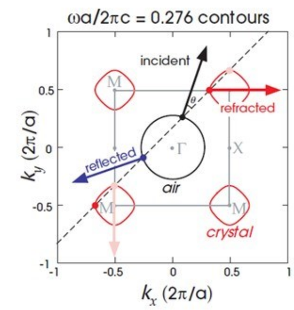
So this particular crystal basically gives you kind of negative refractive index OK, so another important point that you can see that you can eliminate any intersections which are basically marked as the pink points OK, here are the pink dots. OK, they are basically corresponding to a group velocity that is this pink arrow. OK, towards the interface of the crystal OK, as this would basically violate the condition that you know boundary condition because the only incoming power is basically coming from the incident medium right so only this can go like this so in the figure we happen to only have a single refracted wave that is basically this red dot and arrow okay which in this case lies on the same side as we have seen that it is basically opposite to that of the Snell's law. Now multiple reflected wave can occur if the fixed k parallel line basically intersects multiple bands in the band structure right. So, that will necessitate the superposition of several contours on this isofrequency diagram.

So, how about single band operation and intersection condition? So, the example provided here operates below the band gap where only one band is present and thus typically that limits the occurrence of multiple refracted waves. So what are the geometrical and angular consideration? Now, if the interface is tilted differently, OK, in that case, this fixed k parallel line would have also been different because this line is basically perpendicular to the interface. So that would have intersected the same contour at multiple points like here. ok. Here also it is there you see the pink dot is there ok, but then if you move it like this it would have done in other place as well ok.

Refraction and iso-frequency diagrams

- **Single Refracted Wave and Cutoff Frequency:**
  - At frequencies below a certain cutoff, typically only one refracted wave is possible, aligning more with traditional Snell's law as the wavelength becomes large ($\lambda \to \infty$).
- **Approach to Ordinary Snell's Law:**
  - In the limit of large λ, the behavior mimics Snell's law, suggesting the medium acts like an effective medium with an "average" refractive index.
- **Isofrequency Diagram Characteristics:**
  - At small $\omega \ll \pi c/a$, the isofrequency diagram features nearly circular contours, indicative of a constant group velocity.



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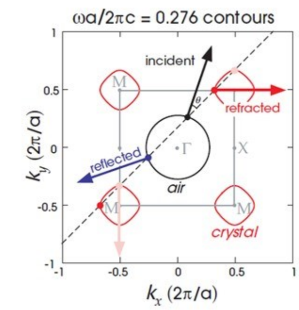
And if there are in this case these are equivalent points, but then you could have got non-equivalent or in equivalent points also in different periodic unit cells ok and that would have definitely led to multiple refracted waves. Now at the frequencies below certain cut-off typically only one refracted wave is possible and that aligns more with the traditional Snell's law as the wavelength will become large so that you know when lambda becomes very large okay. in that particular limit, the behaviour will basically mimic the Snell's law that will suggest that the medium will start acting like an effective medium with some average refractive index. So, in that case, that large wavelength will not see the periodic crystal, it will rather see a homogeneous equivalent medium, effective medium something. So, that is the approach to ordinary Snell's law in large wavelength limit.

Now, if you consider small frequency(ω) which are much smaller than $\pi c/a$,. In that case, you will see that the isofrequency diagram, they will feature nearly circular contours, okay. And when you have circular contours, they basically are indicative of constant group velocity. Now, certain conditions may also lead to no refracted waves similar to the phenomena of total internal reflection which are basically observed in traditional optics.

Refraction and iso-frequency diagrams

- **Conditions with No Refracted Waves:**
  - Certain configurations lead to no refracted waves, similar to the phenomenon of total internal reflection observed in traditional optics.
- **Influence of Photonic Band Gaps:**
  - Photonic band gaps provide additional scenarios where reflection can occur, even if the conditions do not traditionally favor total internal reflection.
- **Geometric Impact on Refraction and Reflection:**
  - Larger incident angles may prevent the intersection of the $k_{\parallel}$ line with photonic-crystal contours, resulting in total reflection, as depicted in figure, even for frequencies outside the photonic band gaps at other angles.



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So, that is also possible. And how the photonic bandgaps are influencing this. So, photonic bandgaps will provide additional scenarios where reflection can occur even if the condition is typically not favouring the total internal reflection. That is where you know this is something extra in the photonic crystal case. So, though the incident angle is not satisfying, but if it is you know if the frequency is falling within the bandgap in that case it will get totally reflected.

The geometric impact on refraction and reflection. So, larger incident angle may prevent the intersection of the k parallel line with the photonic crystal contours, okay. So, you can see if it goes like this, okay, it will not reflect, it will not actually intersect these contours. In that case, there is no refracted wave at all, that means there is total reflection, right. So, that could happen even for frequencies which are outside the photonic band gap at some other angle ok. So, all these possibilities are there.

Unusual refraction and diffraction effects

Now, let us look into some unusual refraction and diffraction effects. So, the first one is having sharp corners in the isofrequency contours that you can see here ok. So, the sharp sharp corners in the isofrequency contours such as those around the M points ok. in the first band would allow for a dramatic change in the direction of the group velocity as the incident angle or the frequency is slightly altered. So, this will basically lead to rapid transition from one side of the contour to the other okay and you can also that see the super prism effect.

Unusual refraction and diffraction effects

- **Sharp Corners in Isofrequency Contours:**
  - Sharp corners in the isofrequency contours, such as those around the M point in the first band, allow for a dramatic change in the direction of the group velocity as the incident angle or frequency is slightly altered.
  - This leads to rapid transitions from one side of the contour to the other.
- **Superprism Effect:**
  - The significant change in refracted angle for minimal adjustments in incident angle or frequency is known as the superprism effect.
  - This is similar to how a traditional prism disperses different wavelengths into various angles, but with a much narrower wavelength range affecting a broader angle spectrum.
- **Applications and Related Phenomena:**
  - This effect opens up potential applications in frequency demultiplexing and other areas where precise control over the direction of light is crucial.
  - Similarly, flat contours in the band structure facilitate large changes in phase velocity, further enhancing control over light propagation.

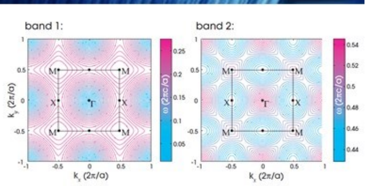


Figure 2: Isofrequency diagrams: contour plots of ω(kx, ky) for the first two TM bands of a square lattice of radius 0.2a dielectric rods (ε=11.4) in air. The first Brillouin zone is shown as black squares.

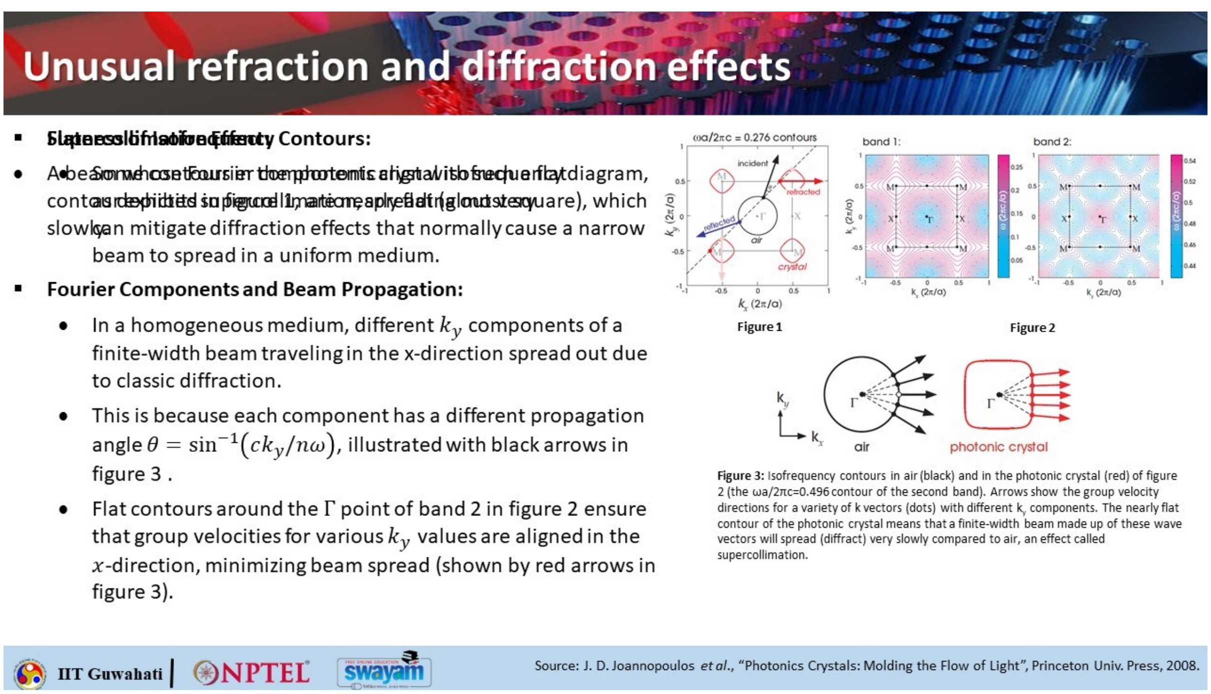
Source: J. D. Joannopoulos *et al.*, "Photonics Crystals: Molding the Flow of Light", Princeton Univ. Press, 2008.

So, this is basically nothing but the significant change in the refractive angle. for minimal adjustment in the incident angle or frequency right. So, it is like you know what a prism does, but here with very little change in the incident angle there will be a significant change in the refractive angle and that can give rise to super prism effect. So as I mentioned this is similar but to the traditional prism which disperses different wavelengths into various angles but with a much narrower wavelength range that affects a broader angle spectrum.

So, here you can see this is for band 1 and band 2. So, these are the contour plots that means these are basically frequency as a function of kx, ky for the first two TM bands of a square lattice of radius 0.2a. So, these are basically dielectric rods where the permittivity is 11.4 and they are kept in air. Now, this super prism effect basically opens up some potential applications in frequency demultiplexing and some other areas where process control over the direction of light becomes very crucial.

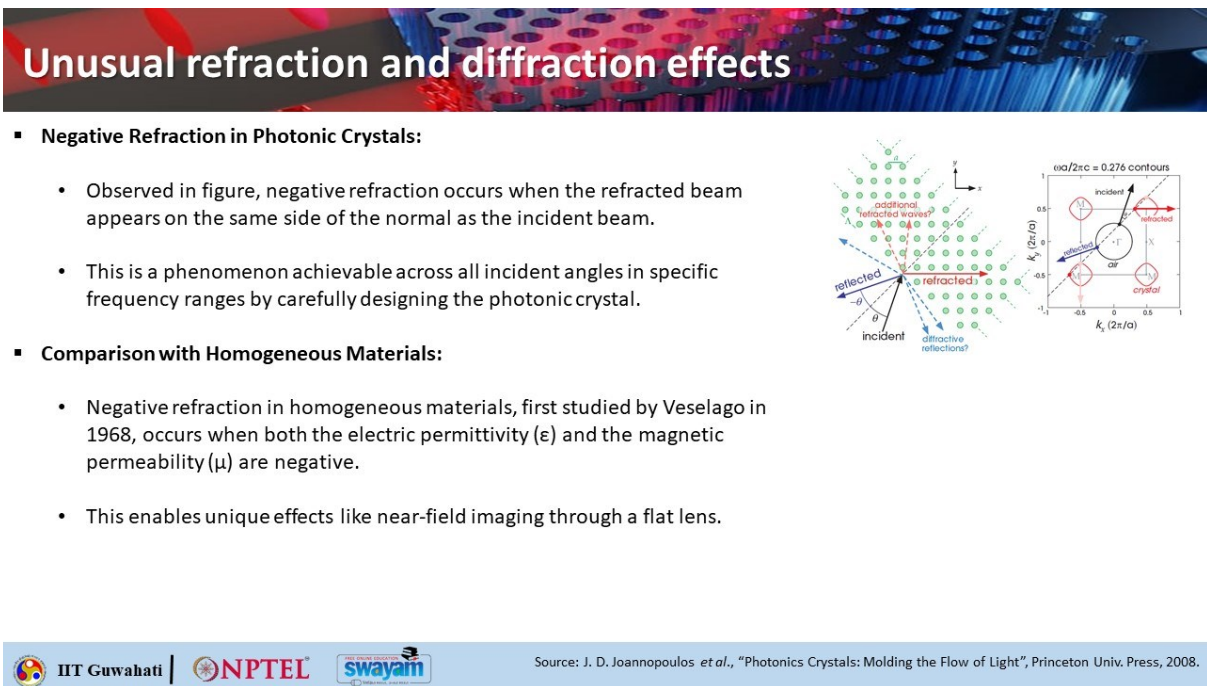
So, similarly if you have flat contours in the band diagram that would facilitate large changes in the phase velocity and that can further enhance the control over the light propagation. We will look into these effects here. So, first one we can discuss about the flatness of isofrequency contours ok. So, some contours in the photonic crystal isofrequency diagram as you can see here ok are nearly flat they are almost like square.

So, you can see like this ok. So you can also see here, right, this part. So this part is shown here, okay? So when the light comes out of this one, so the velocity direction is almost, they're normal to this particular contour. So you'll see that almost parallel waves are coming out, okay? So that is how you can make collimated beams using photonic crystals. So, in a homogeneous medium different kx component of the finite width beam that is travelling in the x direction can spread out okay like this is in the case of normal medium. So, the finite width beam will basically spread out as you can see and that is basically due to the classical diffraction.



So, if you consider the angle that different propagation angle theta(θ) can be calculated as $\theta = \sin^{-1}\left(\frac{ck_y}{n\omega}\right)$ ok as you see in this case ok. But if you have the flat condors around the gamma point as you can see here in band 2 okay. So, here you can see that these are basically almost square or flat kind of contours okay. This will ensure that the group velocities for various kx values are basically aligned in the x direction and that basically minimizes the beam spreading okay.

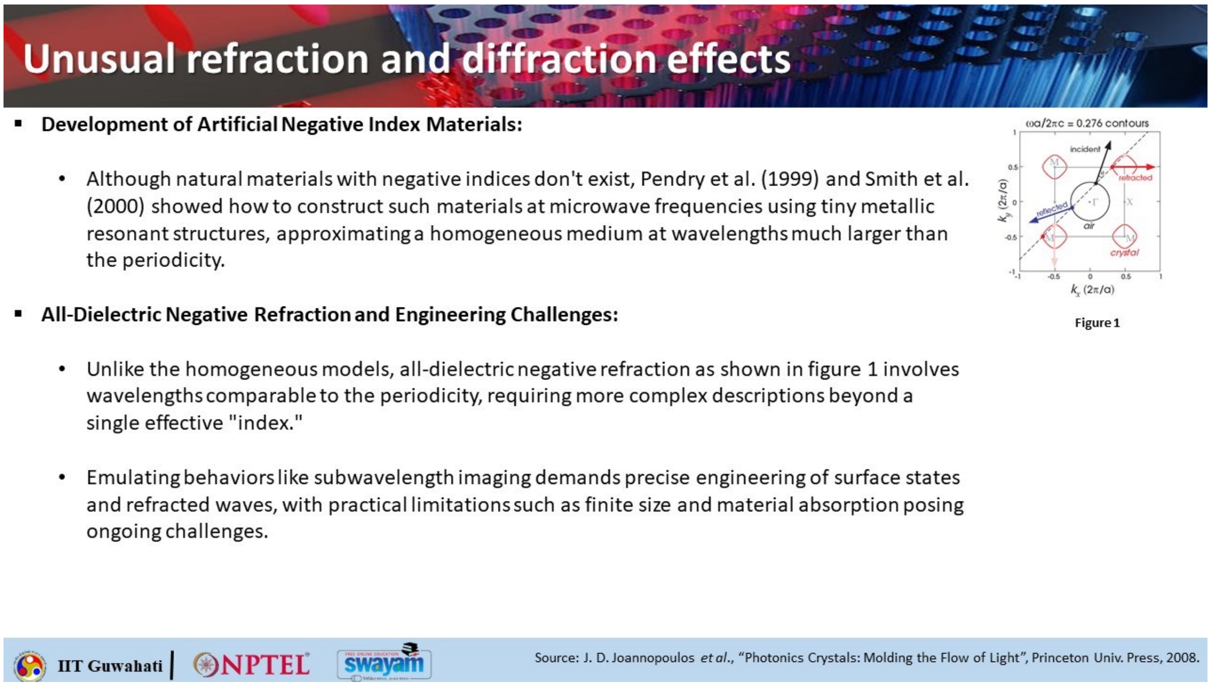
So, this is what is shown as red arrows in figure 3. as I mentioned these are also known as super collimation effect. So, here a beam whose Fourier components align with such a flat contour that will exhibit super collimation that means they will the beam will spread out very slowly. okay and I have already indicated this earlier that you can actually see negative refraction in photonic crystals and this is what is happening okay. So, ideally the refracted beam should have gone this side, but here you are getting this way okay. So, this negative refraction occurs when the refracted beam is basically appearing on the same side of the normal.



So, this is the normal. So, it is appearing on the same side of the normal as the incident beam. And this phenomenon is basically achievable across all incident angles in specific frequency range by carefully designing the photonic crystal. So, this is something very unique and interesting. And if you compare with homogeneous materials okay, the negative refraction in homogeneous materials was first studied by Vasilago in 1968 which I believe I have mentioned in the initial lectures okay. And that occurs when both electric permittivity epsilon and the magnetic permeability mu are negative.

So this enables, you know, unique features, something like near field image imaging through flat lenses and all these things. So regarding development of artificial negative index materials. So although, you know, natural materials with negative index does not exist. Professor Pendry, Sir

John Pendry and Smith in 2000, they were able to construct such materials at microwave frequencies using some tiny metallic resonators which approximates a homogeneous medium at wavelengths much larger than the periodicity. Right? So, next important thing would be like to find out all dielectric negative refraction and the engineering challenges therein.



So, unlike the homogeneous models, if you think of all dielectric negative refraction that is basically shown here, isn't it? Because this entire structure is made of dielectric material, but here you had those metal involved, right? They were giving you that negative permittivity. Okay? So, here they are basically using wavelengths which are comparable to the periodicity and it requires more complex description beyond a single effective index ok. So, emulating the behaviours like sub wavelength imaging demands precise engineering of the surface states and the refracted waves with some practical limitations such as finite size and the material absorption that could pose some ongoing challenges to this area. But a lot of people are working on this because this requires a lot of attention to make a viable solution in this particular imaging applications. So, let us now quickly briefly look at some other emerging trends and applications in the photonic crystal technology okay.

Emerging Trends and Applications in Photonic Crystal Technology

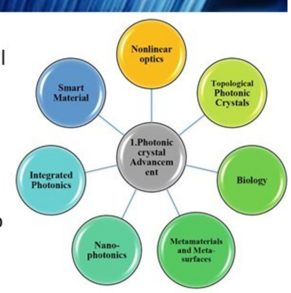
So, we can see that there are non-linear optics, then you have topological photonic crystals, you have applications in biology, then you have metamaterials, nanophotonics and so on. So, non-linear optics how how photon crystals are used. So, photonic crystals are used to manipulate non-linear optical processes such as second harmonic generation, four-wave mixing enabling applications such as optical parametric amplifiers and frequency converters.

The future of Photonic Crystal technology

- **Nonlinear optics:** Photonic crystals are being used to manipulate nonlinear optical processes such as second-harmonic generation and four-wave mixing, enabling applications such as optical parametric amplifiers and frequency conversion.
- **Topological Photonic Crystals:** These structures exhibit protected light propagation along the edges or surfaces, making them robust against defects and imperfections.

  Topological photonic crystals hold promise for applications in low-loss waveguides and on-chip optical circuits
- **Biology:** Photonic crystals serve as carriers in drug delivery systems, designed to release drugs in response to specific stimuli like pH or temperature changes, enhancing targeting accuracy and reducing side effects.

  Researchers are exploring the use of photonic crystals to improve photosynthesis efficiency in plants by more effectively channeling light into plant cells, potentially increasing food production with lower energy requirements.



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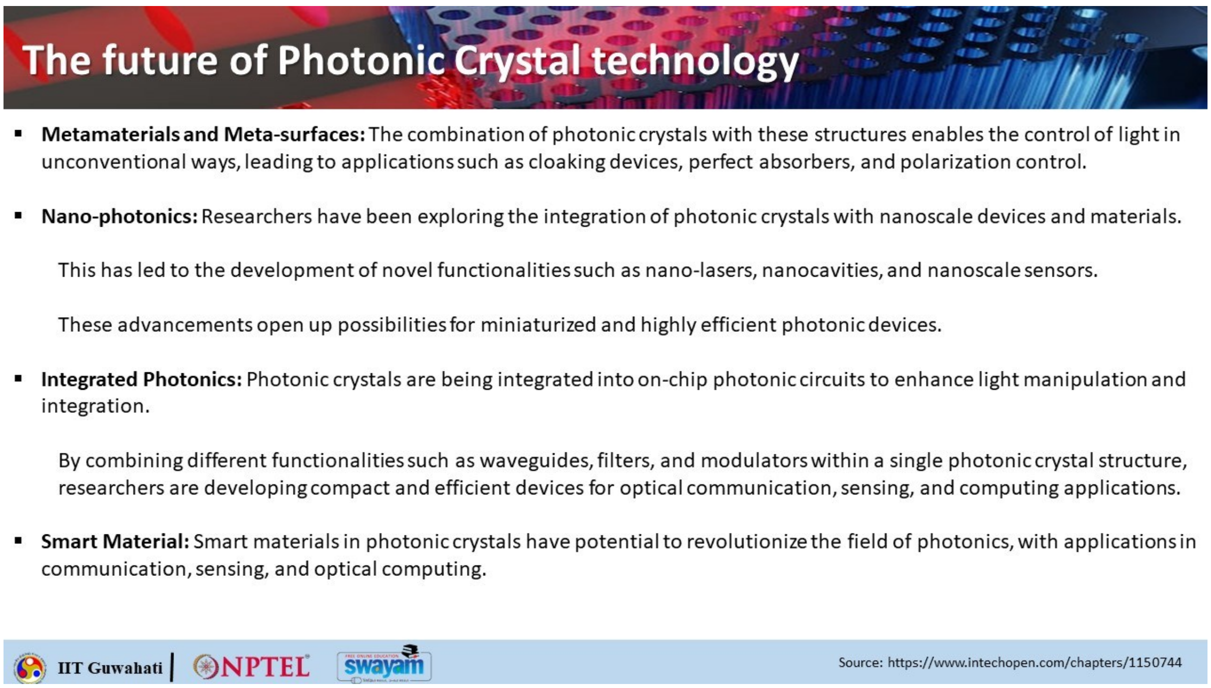
Topological photonic crystals, they basically exhibit protected light propagation along the edges or surfaces with the topological states making that robust against defects and imperfections. So there are a lot of work going on in the 6G technology using topological photonic insulators to prepare devices which are robust and eligible for this high frequency operations. So they hold promise for low-loss waveguides and on-chip optical circuits. For biology, you know, photogenic crystals can serve as carriers in drug delivery systems, which are designed to release drugs in response to some specific stimuli, something like pH or temperature change. And that will actually enhance the drug delivery accuracy, and that will reduce the side effects. So researchers are also working towards using photonic crystal for improving photosynthesis efficiency in plants so that they can channel light more effectively into the plant cells potentially increasing the food production with lower energy requirements.



The other areas as I mentioned like metamaterials and metasurfaces where the combination of photonic crystals with these structures will enable the control of light in unconventional ways leading to the applications such as cloaking devices, perfect absorbers and polarization controllers and so on. In nanophotonics, researchers have been exploring the integration of photonic crystals with nanoscale devices and materials. And this has led to development of novel functionalities, something like nano lasers, nano cavities, nanoscale sensors, and so on. So these advancements open up possibilities for miniaturized and highly efficient photonic devices of the future. Other areas would be like integrated photonics where photonic crystals can be integrated into on-chip photonic circuits to enhance light manipulation and integration and by combining different functionalities such as waveguides, filters, modulators within a single photonic crystal structure, researchers are basically developing compact and efficient devices for optical communication, sensing and computing applications.

Other applications include smart materials, okay. So, smart materials in photonic crystals have potential to revolutionize the field of photonics where the application will be typically in communication, sensing and optical computing. So I will not go into much details of this, I will just give you an overview that these are the potential applications of 3D non-linear photonic crystals okay. So they can provide enhanced non-linear effects, non-linear dispersion engineering where by engineering the band structure of the photonic crystal it will be possible to modify the dispersion relation of light. enabling control over the phase matching conditions for non-linear processes. You can also develop non-linear optical devices something like photon crystal waveguides will be then used to guide and confine non-linear optical signals following allowing for efficient energy transfer and enhanced non-linear effects.

Non-linear Optics

Overview of the role of Non-linear photonic crystals

Enhanced Nonlinear Effects	By adjusting the photonic crystal's lattice constant, refractive index contrast, and defect structures, specific nonlinear optical interactions can be optimized.
Nonlinear Dispersion Engineering	By engineering the band structure of photonic crystals, it is possible to modify the dispersion relation of light, enabling control over phase-matching conditions for nonlinear processes.
Nonlinear Optical Devices	Photonic crystal waveguides can be used to guide and confine nonlinear optical signals, allowing for efficient energy transfer and enhanced nonlinear effects
Nonlinear Optics for All-Optical Switching	Photonic crystal structures can be designed to exhibit large nonlinear responses, allowing for the modulation and control of light signals using other light signals
Quantum Information Processing	Photonic crystal waveguides and cavities can confine and guide photons, enabling efficient photon generation, manipulation, and detection, crucial for quantum communication, quantum cryptography, and quantum computing

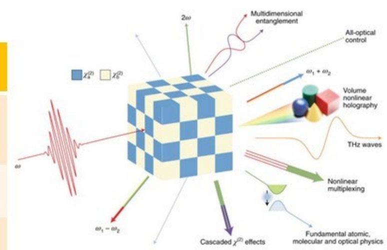


Figure 4: Illustration of potential applications of 3D nonlinear photonic crystals

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The non-linear effects can also be used for all optical switching. So photonic crystal structures can be designed to exhibit large nonlinear responses, which allows for modulation and control of signal of light using other light signals. So that becomes all optical. You can also use them for quantum information processing. So, that is an another very interesting area currently going on. So, photonic crystal waveguides and cavities can confine and guide photons enabling efficient photon generation, manipulation and detection which are crucial for quantum communication, quantum cryptography and also quantum computing.

So, this is I think we have already seen this in the topological photonic crystal kind of discussion we had earlier. So, here it shows the routing photons with the topological photonic structure. So, how it helps this topological photonic crystals? It helps in integrated optics. So, topological photonic crystals can be used to design compact and efficient photonic devices such as waveguide splitters and couplers for on-chip optical communication and computation. They allow robust light propagation because they are basically lossless and they are prone They are not prone.

Topological photonic crystals

Applications of topological photonic crystals

Integrated Optics	Topological photonic crystals can be used to design compact and efficient photonic devices, such as waveguides, splitters, and couplers, for on-chip optical communication and computation
Robust Light Propagation	The protected edge states in topological photonic crystals enable robust and lossless light propagation, making them promising for applications in telecommunications, optical interconnects, and quantum information processing
Optical Sensors	The unique properties of topological photonic crystals can be leveraged for highly sensitive and robust optical sensors, capable of detecting changes in the environment or analytes with high precision
Nonlinear Optics	The presence of topological edge states in these crystals can enhance nonlinear optical effects, enabling the development of efficient all-optical signal processing devices, frequency converters, and optical switches

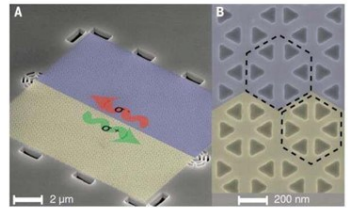

Figure 5: The fabricated topological photonic crystal structure. The routing photons with a topological photonic structure is shown

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They are robust against any kind of manufacturing defects. So you can safely use them for telecommunication, optical interconnect, quantum information processing and so on. You can use them for optical sensors. So the unique properties of this topological photonic crystals can be leveraged by using them in highly sensitive and robust optical sensing which are capable of detecting changes in the environment or analyte with high precision, okay. Then you can also use them in non-linear optics. So, the presence of topological edge states in these crystals can enhance the non-linear optical effects which enables the development of efficient all optical signal processing devices like frequency converters, Okay and also optical switches. You can use them in biophotonics. Okay. So you can use them for biosensing, drug delivery and therapy, cell imaging, analysis, photonic crystal fibers. Okay. So one just one important application you can you can go through this table here and find out more details about it. So photonic crystal fibers are those currently used in various biophotonics application including endoscopy, fluorescence imaging and light delivery of photodynamic therapy.

Bio-photonics

Applications of Bio-photonic crystals

Bio-sensing	By functionalizing the surface of the photonic crystal with biological molecules such as antibodies or DNA probes, they can selectively capture and detect target analytes such as proteins, viruses, or DNA strands
Drug Delivery and Therapy	By engineering the properties of the photonic crystal, such as the size, porosity, and surface chemistry, drugs or therapeutic agents can be encapsulated within the crystal structure
Cell Imaging and Analysis	By incorporating photonic crystals into microfluidic devices or biochips, researchers can achieve enhanced light-matter interaction and optical contrast. This enables the visualization of cellular structures, tracking of cellular processes, and analysis of cell morphology and dynamics
Photonic Crystal Fibers (PCFs)	PCFs have been used in various bio-photonics applications, including endoscopy, fluorescence imaging, and light delivery for photodynamic therapy

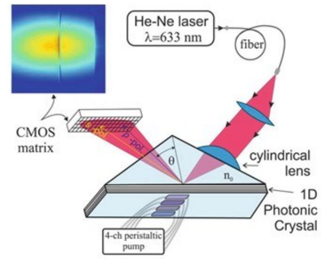

Figure 6: Schematic of label-free biosensing via photonic crystal

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So this is something very very useful okay. So this is a schematic that shows level free biosensing via photonic crystal. These are the applications in metamaterial and metasurface front ok. So, you can actually see the binding process of biotin and streptavidin. These are basically some kind of biomolecules. So, the liquid wall that is shown in red circle it shows the receptible for liquid solution confinement.

Metamaterial and meta-surface

Applications of Metamaterial and meta-surface

Optical switches	By incorporating metamaterials into a photonic crystal waveguide, the waveguide can be made to exhibit nonlinear optical phenomena, which can be used to create ultra-fast optical switches
Superlensing	Metamaterials with negative refractive index, also known as negative index materials (NIMs), can be combined with photonic crystals to achieve superlensing. This involves focusing light beyond the diffraction limit, allowing for the imaging of subwavelength details
Cloaking Devices	By controlling the refractive index distribution in the photonic crystal, combined with the unique properties of metamaterials, researchers have developed designs for cloaking devices operating in various frequency ranges, including visible light
Energy Harvesting and Solar Cell	By manipulating the dispersion properties of the photonic crystal and incorporating plasmonic structures within the metamaterial, the absorption of specific wavelengths can be optimized, leading to improved energy conversion efficiency

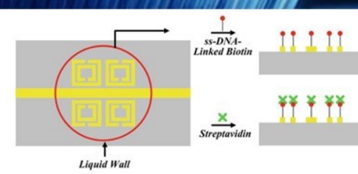

Figure 7: Binding bioprocess of biotin and streptavidin: The liquid wall (red circle) shows the receptacle for liquid solution confinement

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So, how does it help ok? This kind of These are some applications where metamaterials are basically used in conjunction with photonic crystals right. So, these are basically surface plasmon resonance based biosensor which consisted of sensitive biological elements like transducers or detector elements that you can see okay. So, when biotin is introduced the resonance frequency gets shifted and this shift in resonant frequency changes the capacitance. This basically shift comes from the change in capacitance of this linkers ok, because bonding of this biotin and streptavidin basically changes the capacitance and that will reflect in the resonance frequency shift. You can also think of other devices like optical switches, super lenses, cloaking devices, energy harvesting and solar cell.

So, cloaking devices like by controlling the refractive index distribution in the photonic crystal combined with the unique properties of the metamaterials, researchers can develop designs for cloaking devices in various frequency ranges including the visible light. There are applications in nanophotonics as well. So, here is a diagram of an ultra-broadband multi-mode interference coupler. So, it incorporates a central multimode region that is basically divided at a subweb scale and it can manipulate the waveguides and isotropy and dispersion ok. So, you can also think of making other optical communication devices optical filters based on photonic crystals.

Nanophotonics

Applications of Nanophotonics

Optical communication devices	Photonic crystals can be used to create ultra-compact waveguides, which can guide light with very low losses and high efficiency, enabling faster and more reliable communication in optical networks
Optical filters	Photonic crystals also have been widely explored for their application in tunable optical filters. Tunable optical filters are devices that can selectively control the transmission or reflection of specific wavelengths of light, and they are essential components in various optical communication systems, spectroscopy, and sensing applications

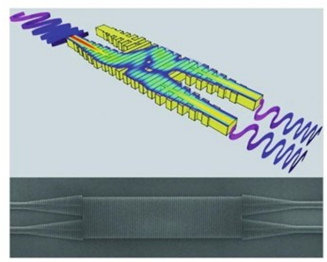

Figure 8: An ultra-broadband multimode interference coupler. It incorporates a central multimode region that is divided at a sub-wavelength scale to manipulate the waveguide's anisotropy and dispersion

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So, photonic crystals I will just highlight on this application. Photonic crystals we have seen this that they have lot of application towards making tunable optical filters. So, tunable optical filters are basically those devices that can selectively control the transmission or reflection of specific wavelength of light. And they are particularly very important for optical communication or optical sensing application. These are some applications in integrated photonics.

Integrated Photonics

Applications of Integrated photonics

Photonic crystal cavities	Integrated photonics facilitates the integration of photonic crystal cavities with other optical components on a chip, enabling the creation of highly efficient and compact optical resonators. These cavities are used in applications such as lasers, filters, and sensors
Optical modulators	Integrated photonics can be used to fabricate photonic crystal-based modulators that control the intensity, phase, or polarization of light. By incorporating active materials, such as electro-optic polymers or semiconductor materials, within the photonic crystal structure, efficient modulation of light signals can be achieved.

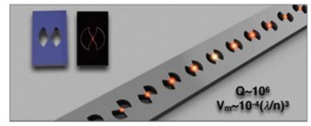

Figure 9: Design of photonic crystal cavities for extreme light concentration

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So here a design of photon crystal cavity for extreme light concentration is shown. OK, so you can have photon crystal cavities and optical modulators. OK, so integrated photon crystal photonics facilitates the integration of photon crystal cavities with other optical components on the chip. that enables the creation of highly efficient and compact optical resonators. And these cavities are used in applications such as lasers, filters and sensors ok. And for optical modulators integrated photonics can also be used to fabricate those modulators that can control the intensity phase or polarization of light.

And if you incorporate some active materials such as electro optic polymer or semiconductor materials within the photonic crystal structure, you can achieve efficient modulation. There are different smart materials something like you can incorporate liquid crystals, okay. So, by incorporating liquid crystals into the structure of photonic crystals, you can change the refractive index of the crystal within the crystal dynamically by applying some voltage and that will allow tuning of the band gap or the spectral response of the crystal, right. So, liquid crystal based photonic crystals will find applications in tunable applications like filters, switches, displays and so on. You can also have some electroactive polymers, which are basically materials that can change shape or volume in the response of some electrical stimuli.

Smart material

Overview of Smart material

Liquid crystals	By incorporating liquid crystals into the structure of photonic crystals, the refractive index distribution within the crystal can be dynamically controlled which allows for the tuning of the photonic bandgap, spectral response, or polarization properties of the crystal. Liquid crystal-based photonic crystals find applications in tunable filters, switches, and displays
Electroactive polymers	Electroactive polymers (EAPs) are materials that can change their shape or volume in response to electrical stimuli. They offer the ability to actively deform or modulate the structure of a photonic crystal. By integrating EAPs into the photonic crystal structure, the lattice parameters, refractive index, or photonic bandgap can be modified. This enables tunable optical devices such as deformable mirrors, waveguides, or modulators
Phase change materials (PCMs)	By incorporating PCMs into photonic crystals, the crystal's optical properties can be switched between different states, enabling reconfigurable and programmable optical devices. PCMs find applications in optical memories, modulators, and reconfigurable photonic circuits
Optically active materials	Optically active materials, such as chiral molecules or nanostructures, have the ability to selectively interact with circularly polarized light. By incorporating these materials into the structure of photonic crystals, the crystal's polarization properties or chiroptical response can be controlled and manipulated.

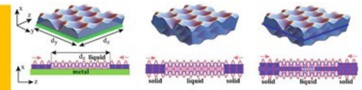

Figure 10: Schematic presentation of thin liquid dielectric film deformation forming optical liquid lattices (blue) due to surface tension effects triggered by interference of surface optical modes (red)

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So they also offer ability to actively deform or modulate the structure of the photonic crystal. So if you integrate this kind of electroactive materials in the photonic crystal structure, the lattice parameter refractive index of the photonic band gap can be adjusted. And that allows you to again achieve tunable optical devices, something like deformable mirrors, waveguides, modulators, etc. You can also incorporate phase change materials into photonic crystals. So there the crystals optical property can be switched between different states that enables reconfigurable and programmable optical devices. What are the applications? You can think of optical memories, modulators, reconfigurable photonic circuits and so on.

You can also think of some optically active materials something like chiral molecules and nanostructures. They basically have the ability to selectively interact with circular polarized light. So, the chirality depends the decides the way it will interact with circular polarized light ok. You can use them for enantiomer separation in drug molecules and so on. So, by incorporating this kind of molecules in the structure of photonic crystal, the crystals polarization properties or the chiro-optical response can be manipulated or controlled.

So, with that we will come to a conclusion of this lecture. So, if you have any query or doubt regarding this lecture, you can drop an email to this email address mentioning MOOC and the lecture number on the subject line.