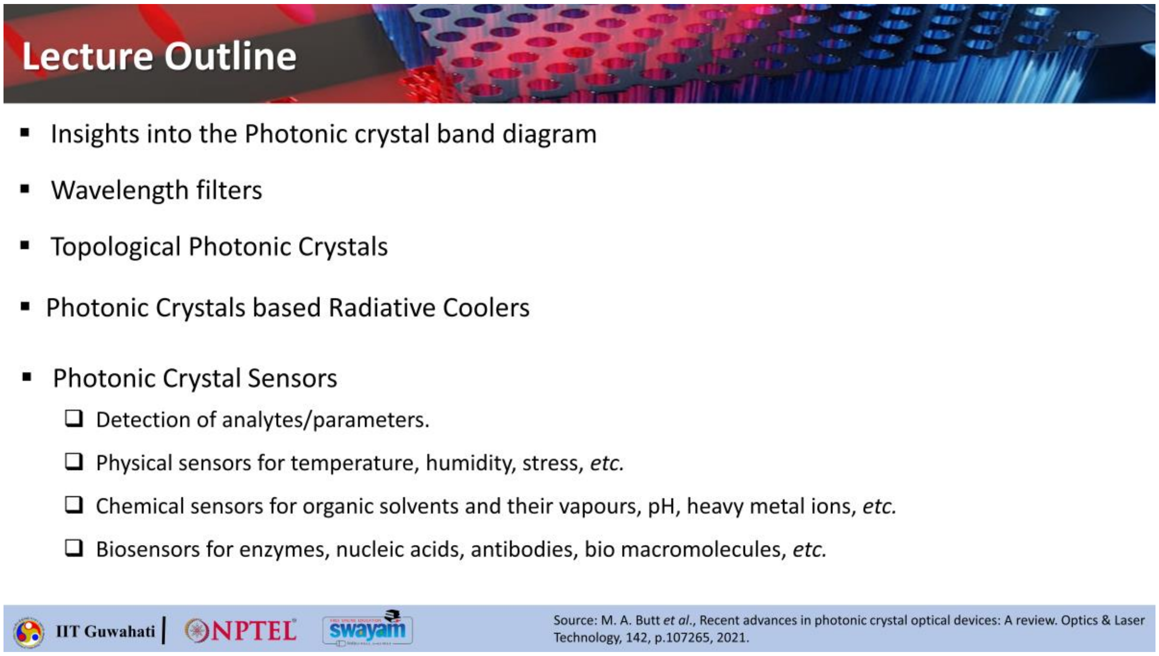
Lec 18: Applications of 2D and 3D photonic crystals

Hello everyone, welcome to lecture 18 of the online course on Photonic Crystals, Fundamentals and Applications.



Today's lecture will be on some extended applications of 2D photonic crystals and we will also cover some applications of 3D photonic crystals. So here is the lecture outline. We will first have some insight into photonic crystal band diagram. We will discuss about the dispersion relations in details. We will discuss about isofrequency contours and how those contours can be used now for engineering devices.

So that can be also termed as dispersion engineering. And then we will try to design wavelength filters and we will see some photonic crystal sensors okay in this particular lecture. So, first we will look into as I mentioned we will go into details of photonic band diagram mainly to understand how dispersion engineering can help us design different kind of devices, photonic devices. So, when you talk about dispersion, dispersion is a general term for any situation where the electromagnetic property of a medium change.

Insights into the Photonic crystal band diagram

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Isofrequency Contours

➢ Dispersion is a general term for any situation where the electromagnetic properties of a medium change.

- **Chromatic Dispersion:** Occurs when material properties change with frequency, leading to different refractive indices for each wavelength of light, as seen in prisms separating colors and phenomena like rainbows and sunsets.
- **Polarization Dispersion:** Happens in anisotropic materials where waves experience different material properties based on their polarization, commonly discussed in waveguide theory.
- **Spatial Dispersion:** Arises when material properties vary with the direction of wave propagation, causing waves to travel at different speeds in different directions, affecting the timing and wavelength of arriving pulses.

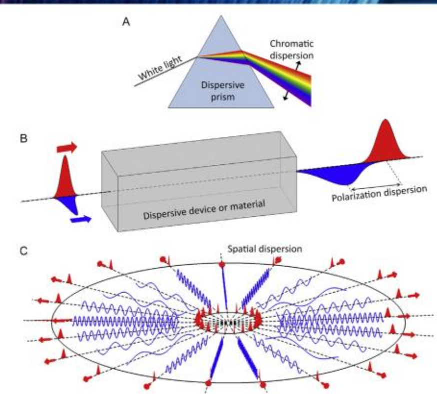

Figure: Illustration of different types of dispersion: (a) chromatic dispersion, (b) polarization dispersion, and (c) spatial dispersion.

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Source: Rumpf, Raymond C. "Engineering the dispersion and anisotropy of periodic electromagnetic structures." Solid State Physics. Vol. 66. Academic Press, 2015. 213-300.

So, you can see the first figure shows chromatic dispersion. So, this occurs when material properties change with frequency. OK, so it leads to different refractive indices for each wavelength of light. And as you can see, that is the reason why, you know, different wavelengths of light band differently. And that is how you get this, you know.

spectral separation when light comes out from a prism and you can call this as chromatic dispersion right. So this happens in prism you can also think of natural phenomena like you know rainbows okay where you see this kind of chromatic dispersion. You can also have polarization dispersion and that happens in anisotropic medium where electromagnetic wave experiences different material properties based on the polarization direction okay.

Say you have these two different orthogonal polarization going in, but the refractive index along say this is x and this is y. So, along x and y are different.

So, they will be affected differently and this is what is called you know polarization dispersion and it is commonly discussed in web guide. theory. Then other type of dispersion is also called spatial dispersion. So it is related to space. So as you can understand this arises when material properties vary with the direction of a propagation.

so that means you know the wave traveling at different direction will have different speed and that is what is shown here schematically okay so it basically affects the timing and the wavelength of arriving pulses so these are the three basic types of dispersion

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- **Dispersion Relation Explanation:** The dispersion relation links the wave vector $\mathbf{k}$ to frequency ω , quantifying the magnitude of the wave vector as a function of direction and the refractive index experienced by a wave based on its propagation direction.
- **Refractive Index Insights:** For a known frequency, the dispersion relation provides a measure of the refractive index, illustrating how it varies with the wave's direction through the material.
- **LHI Material Characteristics:** In ordinary Linear Homogeneous Isotropic (LHI) materials, the refractive index is consistent in all directions, leading to a dispersion relation that describes a spherical shape in k-space, represented by $k_x^2 + k_y^2 + k_z^2 = (k_0 n)^2$.
- **Dispersion and Optical Surfaces:** The spherical dispersion surface in LHI materials is analogous to index ellipsoids in conventional crystalline optics, describing the spatial dispersion characteristics of the material.

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Source: Rumpf, Raymond C. "Engineering the dispersion and anisotropy of periodic electromagnetic structures." Solid State Physics. Vol. 66. Academic Press, 2015. 213-300.

so when we talk about dispersion relation dispersion relation basically links the wave factor k to the frequency ω right and it quantifies the magnitude of the wave vector as a function of direction. okay and the refractive index that is experienced by the wave based on its propagation direction. When we talk about refractive index for a known frequency the dispersion relation provides a measure of the refractive index. So, that basically illustrates that you know how you know how the refractive index varies with the direction of the wave inside a material. You can also consider you know in case of linear homogeneous and isotropic material which are generally the ordinary materials we discuss okay.

The refractive index is basically consistent in all directions. So, along x, y, and z axis you can see that the refractive index is same. In that case the dispersion relation that describes this particular material takes the form of a sphere in the k space and you can write it as $k_x^2 + k_y^2 + k_z^2$ to be equal to $+ (k_0 n)^2$. So, the spherical dispersion surface in this linear homogeneous and isotropic materials is basically analogous to the index ellipsoid that we discussed in conventional crystalline optics ok. So, this basically describes the spatial dispersion characteristics of the material.

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- **Complex Dispersion in Anisotropic Materials:** In anisotropic media, dispersion relations are complex, allowing multiple dispersion surfaces corresponding to different polarizations, meaning waves traveling in the same direction can experience varying refractive indices based on their polarization.
- **Biaxial Material Properties:** Biaxial materials, characterized by two optic axes, exhibit unique dispersion surfaces that intersect at four points symmetrically around the origin. Waves propagating along these optic axes experience uniform refractive indices across all polarizations, mimicking isotropic material behavior.
- **Dispersion Relation for Biaxial Materials:** The general dispersion relation for biaxial media involves complex relationships between wave vectors and refractive indices along three principal axes, $\hat{a}$, $\hat{b}$, and $\hat{c}$, encapsulating the anisotropic nature of the medium in the equation provided.

$$|k|^2\left[\left(\frac{k_a}{n_b n_c}\right)^2+\left(\frac{k_b}{n_a n_c}\right)^2+\left(\frac{k_c}{n_a n_b}\right)^2\right]-k_0^2\left[\frac{k_b^2+k_c^2}{n_a^2}+\frac{k_c^2+k_a^2}{n_b^2}+\frac{k_a^2+k_b^2}{n_c^2}\right]+k_0^4=0$$

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Source: Rumpf, Raymond C. "Engineering the dispersion and anisotropy of periodic electromagnetic structures." Solid State Physics. Vol. 66. Academic Press, 2015. 213-300.

In anisotropic media however the dispersion takes a bit of complex form because the dispersion relations become complex which allows multiple dispersion surfaces corresponding to different polarization. That means wave traveling in the same direction may experience you know different kind of refractive indices based on their polarization. So that makes things complicated isn't it. can also have biaxial material which actually have two optic axis okay i believe you know the basics of this you know isotropic uniaxial and biaxial materials we will cover them briefly in this lecture as well so if you think of biaxial materials they basically have a different refractive index in all direction okay. So, they can be characterized by two optic axis.

So, what that means I will come to that okay in next few slides. So, they also exhibit unique dispersion surfaces and that interact intersect at four points symmetrically around the origin okay and that is what makes it biaxial and you will get two optic axis over there. okay. So, wave propagating along this optic axis experience uniform refractive index across all polarization. So, they could mimic the behavior of isotropic material only for those optic axis case okay.

Now if you think of the dispersion relation for biaxial material which are characterized by two optic axis. So, you can think of the relation between wave vector and refractive index along the principal axis say $\hat{a}$, $\hat{b}$ and $\hat{c}$ okay which encapsulates the anisotropic nature of the medium like this okay. you can see that n_a, n_b, and, n_c are basically the refractive indices along the three principal axes okay and these are the corresponding wave vector okay or you can say wave number okay. So, this is how the relation is okay.

Isofrequency Contours

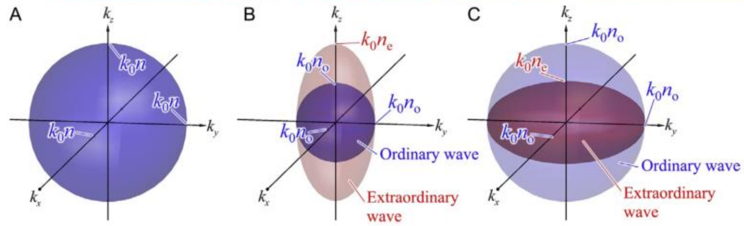


Figure: Dispersion surfaces: (a) isotropic, (b) positive uniaxial where $n_o < n_e$, and (c) negative uniaxial where $n_o > n_e$.

$$|k|^2\left[\left(\frac{k_a}{n_b n_c}\right)^2+\left(\frac{k_b}{n_a n_c}\right)^2+\left(\frac{k_c}{n_a n_b}\right)^2\right]-k_0^2\left[\frac{k_b^2+k_c^2}{n_a^2}+\frac{k_c^2+k_a^2}{n_b^2}+\frac{k_a^2+k_b^2}{n_c^2}\right]+k_0^4=0$$ ⟹ Biaxial **(Equation A)**

$$\left(\frac{k_a^2+k_b^2+k_c^2}{n_o^2}-k_0^2\right)\left(\frac{k_a^2+k_b^2}{n_e^2}+\frac{k_c^2}{n_o^2}-k_0^2\right)=0$$ ⟹ Uniaxial **(Equation B)**

Source: Rumpf, Raymond C. "Engineering the dispersion and anisotropy of periodic electromagnetic structures." Solid State Physics. Vol. 66. Academic Press, 2015. 213-300.

So, we can describe all these different dispersion surfaces with some example from by taking some examples of simple dispersion surfaces.

So, first let us consider the dispersion surface of an isotropic medium. So, that you have already discussed said that here and now along k_x, k_y and k_z you have the same refractive indices. So, in all direction you have the same refractive indices. So, the dispersion surface basically looks like a sphere. And we have seen that equation it is basically $k_x^2 + k_y^2 + k_z^2$ to be equal to $(k_0n)^2$ right simple that is the equation for sphere.

Now when you consider that your n_a and n_b are equal but it is not same as n_c okay that those kind of materials are called uniaxial okay. So here we are showing you two different types of uniaxial crystal right. Because here you can see that along x and y or you can say A and B okay primary axis You can also some papers or some books refer to them as you know n_x and y and n_z that is also fine you can also write them as n_a, n_b and n_c this is ok. So, what is important here is to note that n_a and n_b are equal, but that is not same as n_c. okay that is along the z direction.

So, this kind of material are called uniaxial and if you put that into this particular generic equation which is basically for the biaxial okay. If you put this n_a equals n_b okay and you take that as ordinary okay and you say n_c is different so that is extraordinary you denote it as n_e then this equation boils down to this particular equation. clear. So, in a particular uniaxial crystal you will have two directions or along which the refractive indices are same. So, you can call them as ordinary and the third direction can be called as you know extraordinary right.

So, you can actually see ordinary wave and extraordinary wave depending on the axis along which the waves are propagating inside this particular crystal right. Now, the dispersion relation that you see in this particular equation okay is basically capped in such a form that it is easy for you to interpret. So, you can see that it is basically a product of two dispersion surfaces. So, this one is a sphere which is shown here. right and then you have another one which is like a ellipsoid which is shown here right.

So, having two dispersion surfaces at the same time actually produces interesting effect something like you know double refraction which is best known for occurring in calcite crystals ok. So, the dispersion surfaces for an isotropic material And as you can see, this is for the case of one uniaxial where your n_o, the ordinary refractive index is smaller than n_e. It is called positive uniaxial crystal. And there is also possibility of the other one where n_o is larger than n_e. In that case, you know, you will have n_o is this one and n_e is this short one.

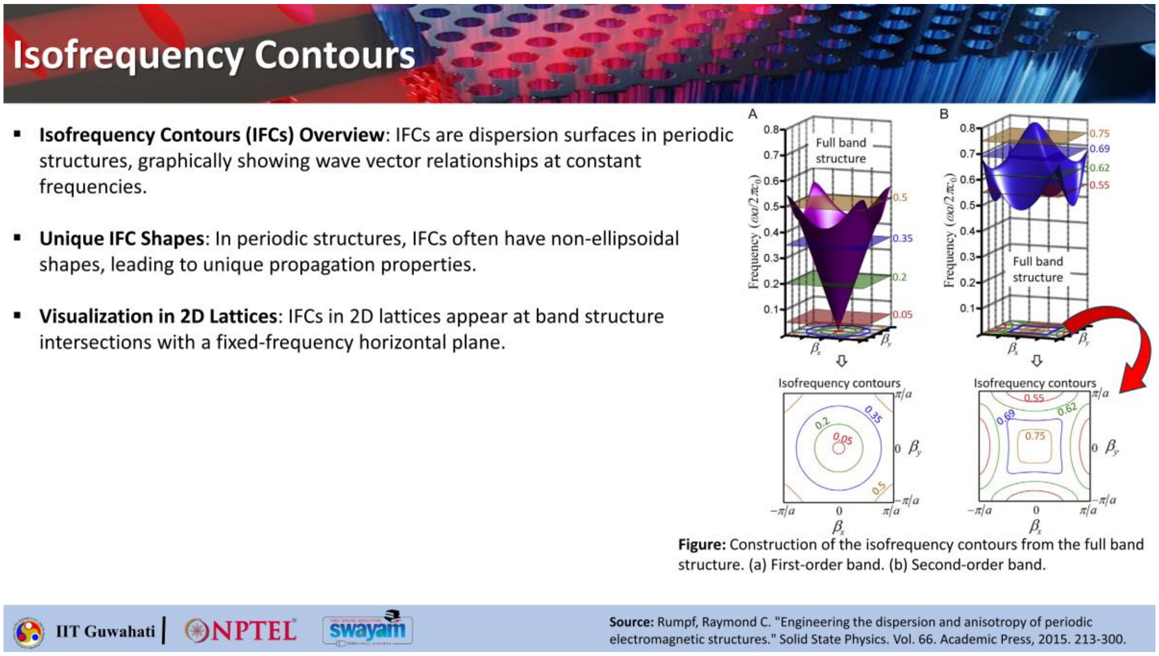
So, in that case n_o is greater than n_e, so that is called negative uniaxial crystal. So, these are the two different types of uniaxial materials shown in this figure. ok. So, here it is very simple that the dispersion surface for this isotropic media is nothing but a sphere. What is the radius of the sphere? It is basically k 0 n or you can say k 0 n o because it is ordinary in all three directions.

So, you can simply say k 0 n or k 0 n o that is fine ok. Now, how about this one the uniaxial media, here you can see that one dispersion surface is basically a sphere. What is the radius of this sphere? It is k naught n o and that actually describes the refractive index for the ordinary wave which is travelling in either this direction or this direction. the second dispersion surface which is basically the extraordinary wave is for the wave that is traveling along this that direction. So, in that case it is basically an ellipsoid where you will have you know the semi major axis and minor axis.

So, the semi major axis is k0 Ne and semi-minor axis is k0 No right. So, that is how you can actually see the different direction of the waves propagating through this particular uniaxial crystal will have different refractive index right. So, the refractive index of the external wave will fall somewhere in between NO and NE depending on the direction in which it is propagating right. So, for the case of positive uniaxial media The ordinary refractive index is basically smaller than the extraordinary one. So, that we have seen it means the ellipsoid is basically elongated along.

So, it is basically a prolate shape like a capsule ok you can think of. So, everything is in k space ok. So, that you have to keep in mind this in the momentum space right. So, it looks more like a egg or cucumber ok, whereas you know the negative uniaxial crystal is where you know you have the ordinary refractive index larger than the extraordinary refractive index. And that is the case when the ellipsoid is like compressed it is like a gems ok chocolate.

So, it is like a oblate shape ok. This is how it will look like. So again here also depending on the direction of propagation the wave may experience anything between n_o and n_e refractive index. right.



Now with that we will go to some interesting features from the band diagram okay that will also tell us. So this band diagram is nothing but you know telling us about direction okay and the frequency okay or ω.

So these are also like you know dispersion surfaces okay. So what you actually see here is that for any 2D photonic crystal if you think of the full band structure if you remember the normal band structure we have seen that we only try to plot it for the irreducible brilliant zone isn't it that actually reduces the load on our computation but actual band diagram looks like this it is basically a 3D because you have you know x and y these are the two different momentum vectors β_x and β_y okay and then the z axis is basically the normalized frequency okay which is nothing by but a by lambda isn't it you can write it as omega a by 2 pi c naught which boils down to a by lambda naught okay what is a is basically the period of the of the photonic crystal okay we assume that it is a 2d photonic crystal okay and then what is lambda naught that is the frequency in vacuum okay of the light at which you want your photonic crystal to perform or work So, let us first see that what are these isofrequency contours. Now, isofrequency contours are basically dispersion surfaces or in periodic structures. So, they are basically telling you that these are the wave vectors relations relationship at constant frequency. OK, so this is a this is the 3D diagram of the first order band.

Now, if you try to take the cross section for a particular same frequency, so say frequency 0.05, you take a slice, then 0.02, you take a slice. How the slice of 0.02 look like? If the band structure is conical, you will cut and you will see that you are basically getting a circle same at 0.05 you get a smaller circle right so what is same in this particular relation or in this particular circle is that the frequency is same because you have obtained it at the same frequency level so that this is why these are called isofrequency when same frequency contours Same at 0.35 you will get this blue circle and if you go high you actually you know come out of this cone. So, when you have 0.5 you are basically getting cross section of this 4 extended legs and this is what you see that is for 0.5. So this is corresponding to okay the first band structure. So what is important here to notice that this isofrequency contours are very much unique in shape. In periodic structures you know isofrequency contours often have non ellipsoidal shape and that leads to very unique propagation you know properties. So you can also you know try to think of you know what happens for higher order band something like second order band. So in 3D the second order band looks like this and same if you take you know slices at different fixed frequencies say this one the first one 0.75 it will look more or less like a square. If you go below slightly at 0.69 you will see this kind of a shape. Little curvy but then it is also having those say it is kind of a square pattern with little curves. Okay. Then if you go further you can actually get this kind of shape.

Isofrequency Contours

- **IFC Use in Predicting Phase and Power:** Isofrequency contours (IFCs) help predict the relationship and direction of phase vector ($\vec{\beta}$) and power vector ($\vec{\mathcal{P}}$) propagation.
- **Analysis Method:** Starting with a selected point on an IFC, the Bloch wave vector ($\vec{\beta}$) connects the Brillouin Zone origin to this point, indicating the direction of phase propagation.
- **Poynting Vector Direction:** Power, as indicated by the Poynting vector ($\vec{\mathcal{P}}$), propagates perpendicular to the IFC at the chosen point.
- **Shape Impact on Propagation:** Circular IFCs result in phase vector ($\vec{\beta}$) and power vector ($\vec{\mathcal{P}}$) propagating in the same direction, while non-circular shapes like a pincushion cause them to diverge, as demonstrated in various figure illustrations.

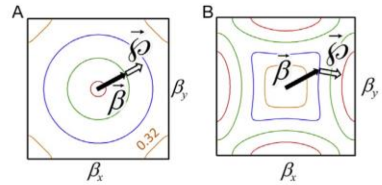


Figure: Determining the direction of phase and power using iso-frequency contours

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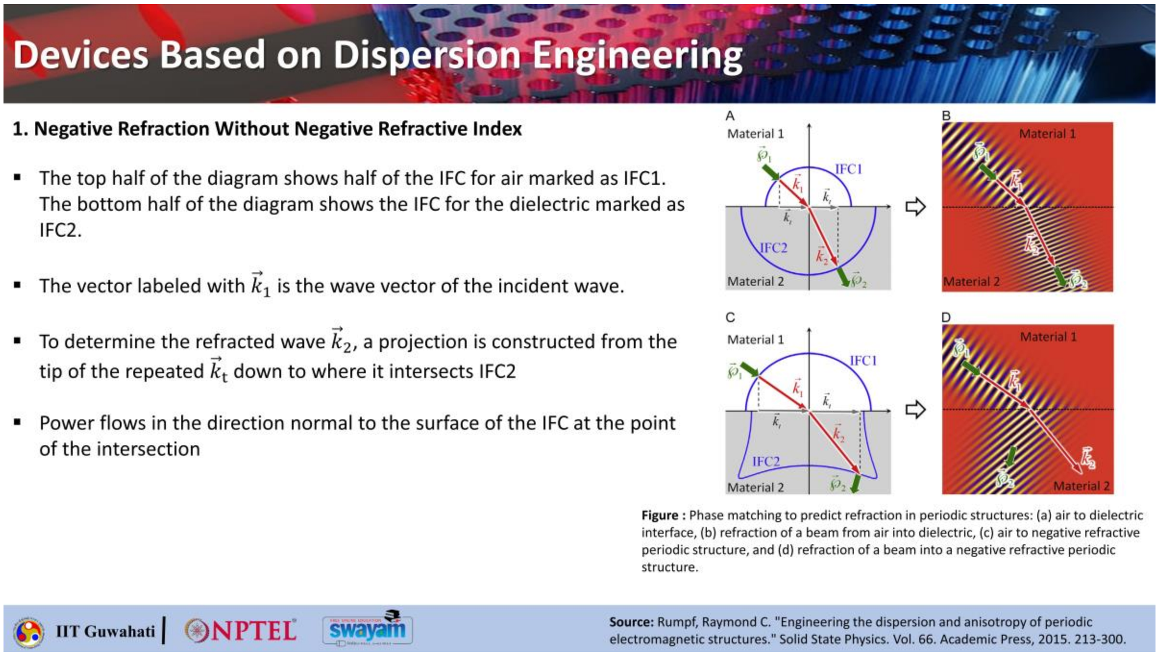
Source: Rumpf, Raymond C. "Engineering the dispersion and anisotropy of periodic electromagnetic structures." Solid State Physics. Vol. 66. Academic Press, 2015. 213-300.

Now why these things are important? Okay. that we will see that you can actually design a lot of devices when you explore this kind of features dispersion relation right. Isofrequency contours can be used in predicting phase and power. So, you can actually look into the direction of the phase vector and also the power vector propagation. So, if it is a circle it is very very simple because in that case the block wave vector will connect to the origin of the Brillouin zone that is the center and that direction actually marks the direction of you know phase propagation. for the power vector or you can say the power propagation direction or you can say the pointing vector, you need to actually draw a perpendicular to that particular chosen point at the isofrequency contour that is IFC.

Now, in the case of Now different types of isofrequency contour how this makes a lot of difference that if you are having a circular IFC that will result in your phase vector and propagation vector propagating in the same direction right. But if you have this kind of you know non circular shapes something like almost square shape or this kind of a pin cushion kind of shape okay. In that case so the wave vector or you know you can say the block wave vector can be simply say at this point you connect it to the center of the brillouin zone and this vector is your block wave vector. But however, the pointing vector it has to be normal at this particular point and that goes like this. So, it diverges from the direction of the beam propagation is not it.



So, you can actually utilize this particular feature to understand couple of interesting features and devices ok. The first one. could be to achieve negative refraction without negative refractive index. So, the dispersion offered by photonic structures can be used in other ways ok. So, now let us look into the devices that can be designed based on dispersion engineering.

So, the first example would be to think of you know negative refraction without negative refractive index. How is that possible? So, the figure over here actually help us understand how dispersion engineering can be done ok. So, the dispersion offered by periodic structure can be used in different other ways ok and many of this use cases can be understood through the simple concept of phase matching. So let us take a very simple example, which is the routine refraction, right? So let us try to understand the refraction using the concept of you know phase matching. So, look into the first figure here which shows the phase matching between air and some kind of medium okay.

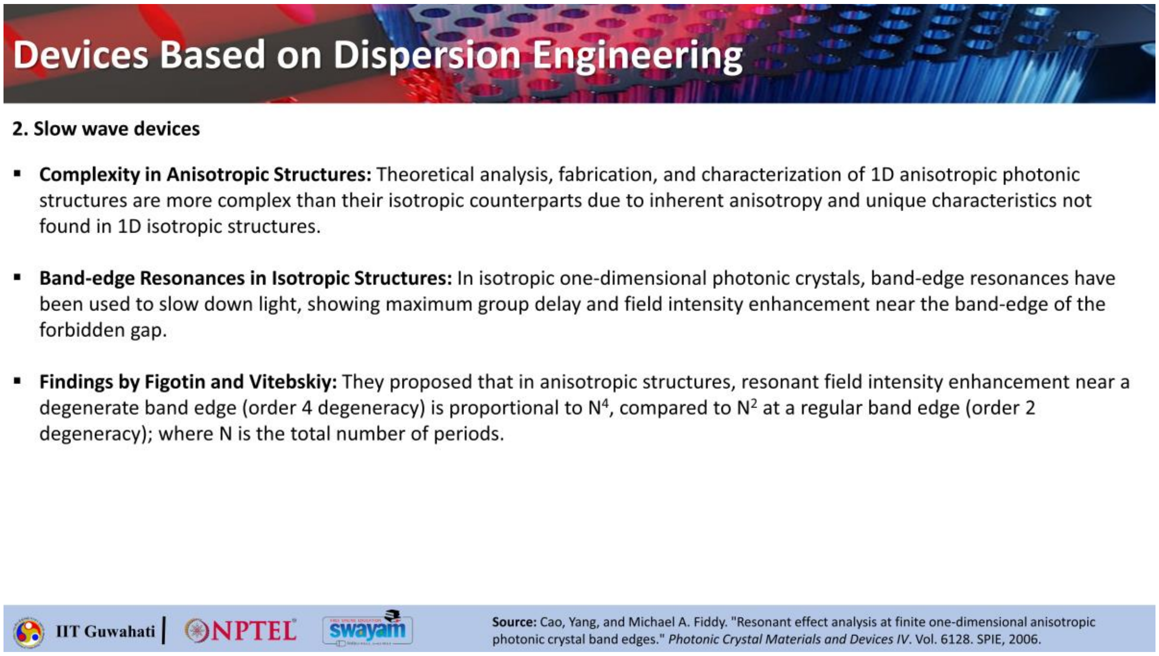
So, both medium are isotropic and they have isofrequency contours which look like circles. Now, here you can see that the material 2 has a larger circle it means it has got a larger refractive index as compared to the first medium. So, we can take this as air and this can be any dielectric. Now, what happens this is the direction of the wave factor So, if you draw a normal you can also see what is the direction of the power flow. You try to get the component of this wave vector which is along the surface.

So, you can take it as k_t that is the tangential component of the wave vector k and the same will be continuous across the interface. So, you put it over here. And then if you try to find out the intersection of this one with this isofrequency contour you see you actually come to this point.

Now, you join this point and this point and you see that the wave vector actually has bent ideally it was going this like this in this particular direction it has now bent this way. from here if you try to plot a normal that will give you the pointing vector direction.

So, it tells you about the power flow direction in the case of refraction clear. So, imagine if you go for denser to rarer medium you will have the opposite scenario. Say this is now the isofrequency contour and in that case you will have a smaller isofrequency contour here ok. And you will see that This component will then heat at much higher position in the isofrequency contour 2 and you will see that this is basically deviating much further away from the normal and that is what happens when the light incident from a denser to a rarer medium. So, using this concept you can very well explain the concept of refraction.

Isn't it amazing? So here also you can see that, you know, the power flow and the wave flow, wave vector, they are in the same direction, right? So that is the case of refraction of a beam from air into directory. Now, okay, these are the things mentioned here. So now look at the case over here. Now, imagine that you have the first material is same you have air ok, but the second medium is now not a normal dielectric. You replace this by a photonic crystal ok, which has isofrequency contour of this at that particular area.



wavelength okay so how do you choose that you can go and you know look for this kind of a you know pattern okay so you know what frequency or what normalized frequency this will be achieved normalized frequency is nothing but a over λ_0 you know the operating frequency or the wave number that is incident on your system. From that you can find out what is the A that is the lattice period required. that can give you this kind of a isofrequency contour. So, if you have something like this as your material tube. So, this part remains same again you try to you know match this tangential component of the wave factor k_t.

Devices Based on Dispersion Engineering

- **Dispersion Curves and Inflection Points:** Dispersion curves show zero group velocities at inflection points, causing strong, varied resonant effects.
- **Regular Band Edge (R.B.E) Studies:** Extensive research on 1D isotropic and anisotropic photonic crystals' resonance, slow-down, and nonlinear effects.
- **Stationary Inflection Point (S.I.P) Research:** Published studies on axially frozen modes associated with S.I.P.
- **Degenerate Band Edge (D.B.E) Findings:** Figotin and Vitebskiy noted that near D.B.E, resonant field intensity enhancement scales with N^4, contrasting with N^2 at R.B.E.

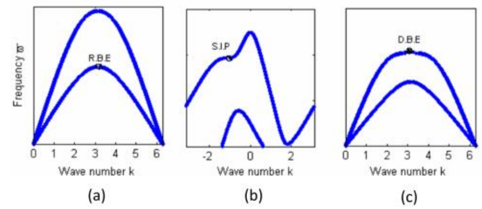


Figure: (a) Regular band edge (R.B.E): corresponds to two equal real K (b) Stationary inflection point (S.I.P): corresponds to three equal real K (c) Degenerate band edge (D.B.E): corresponds to four equal real K

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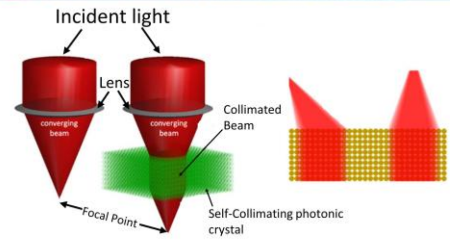
Source: Cao, Yang, and Michael A. Fiddy. "Resonant effect analysis at finite one-dimensional anisotropic photonic crystal band edges." *Photonic Crystal Materials and Devices IV*. Vol. 6128. SPIE, 2006.

here you come over here but then if you try to find out the power flow direction you will see that the power flows along the normal so the wave goes in this direction but the power will be along this direction so this is how you know the overall thing will look like okay so you are basically having um you know the refraction of a beam into a negative refractive periodic structure. So, this looks like you know negative refraction is not it. So, you can actually achieve negative refraction without negative refractive index fine. So, these are some interesting features that can be obtained by using you know.

photonic crystal of particular dimensions. And that is why those band diagrams and isofrequency contours are so important because all the frequencies in the isofrequency contour are normalized ones. So, they are basically a/λ_0. So, if you fix that you are you want to work for the telecom wavelength that is λ_0 is 1.55 micrometer, you can immediately find out what should be a the lattice spacing to design that particular photonic crystal.

Self Collimation

- Self-collimation is a property of some periodic structures where a beam appears to remain collimated indefinitely almost independently of the source beam
- **IFC Analysis for Self-Collimation:** Lattices designed for self-collimation are analyzed using their isofrequency contours (IFCs), which guide both phase and power propagation directions.
- **Directional Propagation in LHI Materials:** In linear homogeneous isotropic (LHI) materials, IFCs are spherical, resulting in phase and power propagating in the same direction.



Source: https://empossible.net/wp-content/uploads/2020/01/Lecture-Photonic-Crystals.pdf

The next important feature is called self-collimation. So, self-collimation is a property of some periodic structures where the beam appears to remain collimated that is parallel. ok indefinitely almost independently of the source beam. So, normally with the lens a beam will become convergent, but if you you know put a collimated beam like this ok. So, this is the self collimated photonic crystal you can see the convergent beam can actually you know propagate parallelly in that particular crystal. So, how do you do that? Okay again IFC isofrequency contour analysis can help you.

Lattices designed for self-collimation are analyzed using their isofrequency contours which guide both phase and power propagation directions. So, in case of linear homogeneous and isotropic materials we have seen IFCs are spherical okay that means your phase and power propagates in the same direction. But what you want you want self-collimation that means you want somewhere you know your direction of power should be parallel independent of the direction of the wave propagation like this. It means you actually want a periodic structure which gives you a isofrequency contour which is flat.

Self Collimation

- **Flat IFC Sections and Self-Collimation:** In periodic structures, flat sections of IFCs allow selfcollimation, where a cone of wave vectors ensures power propagates uniformly in a single direction, preventing beam divergence.
- **Practical Implementation:** A specific lattice spacing ($a = 0.73\lambda_0$) is set to achieve self-collimation at the free-space wavelength (λ_0), demonstrated by a beam staying collimated as it travels along the lattice axis in simulations.

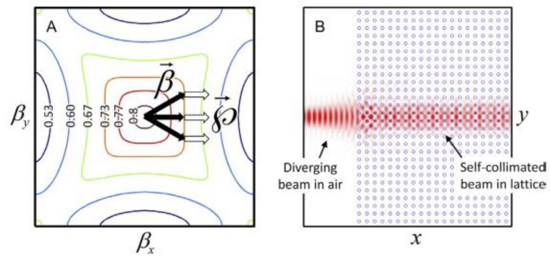


Figure: Physics of self-collimation: (a) flat portion of the IFC produces selfcollimation, and (b) diverging beam incident on a self-collimating lattice no longer diverges and propagates along an axis of the lattice.

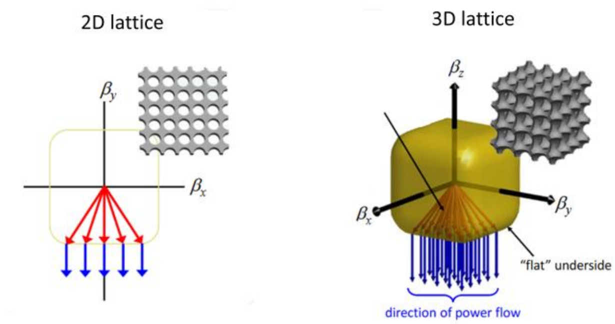
Source: Rumpf, Raymond C. "Engineering the dispersion and anisotropy of periodic electromagnetic structures." Solid State Physics. Vol. 66. Academic Press, 2015. 213-300.

So, that allows self collimation. So, here you can think of you know a cone of wave vectors something like that, but then when the power actually you can find out the pointing vector in each case you will see that that is parallel. So, that way you can prevent the beam from divergence and it has got many applications ok. So, this is how a diverging beam in air can become self collimated beam inside the lattice ok. So, if you take this particular example, so the isofrequency contour is 0.73. So, if you choose a LED spacing which is a/λ_0 equals 0.73 or you can say a = 0.73 $\lambda_0$you can actually achieve self collimation at the free space wavelength of lambda naught right. It means you can actually see the beam staying collimated as long as it travels along the axis okay like this. So, this is what the simulation shows. So what kind of lattices give us? So you can think of typical 2D lattices like this which is basically a whole array okay or you can think of the 3D lattice which will have a 3D isofrequency contour okay.

Self Collimation

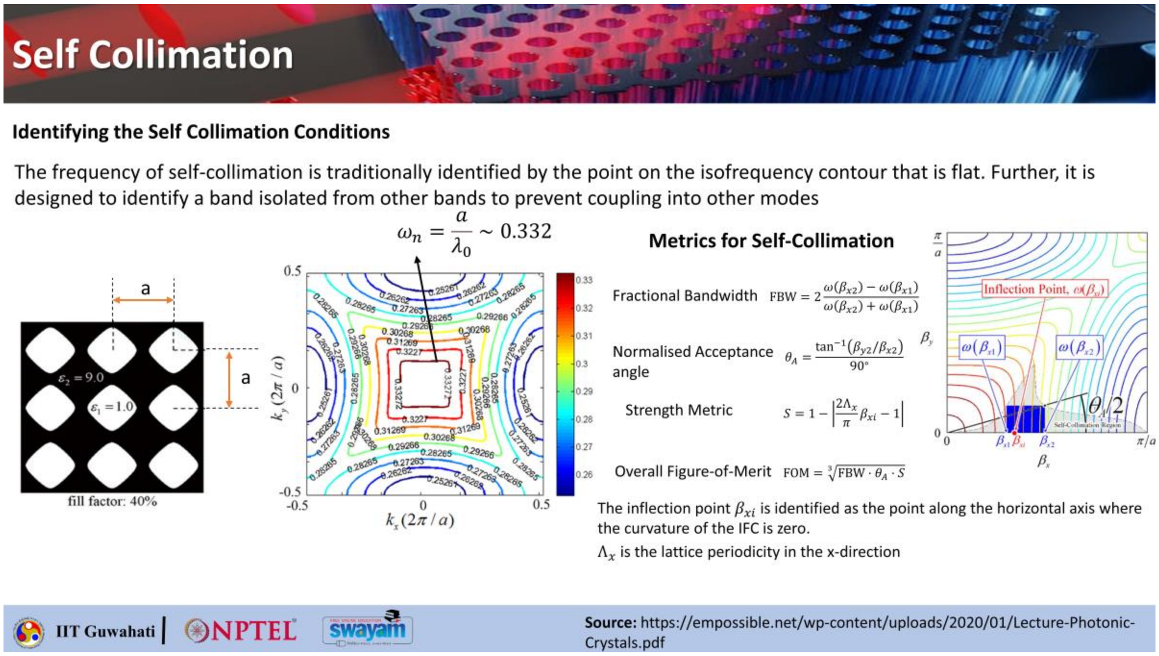
Conditions for Self-Collimation

Self-Collimation occurs whenever the index ellipsoids have flat surfaces.



Source: https://empossible.net/wp-content/uploads/2020/01/Lecture-Photonic-Crystals.pdf

So here you can see it has got a flat isofrequency contour. So irrespective of the direction so any diverging beam you can say can become kind of you know collimated something similar happens in 3D as well right.



So, as you understand that for identifying the condition for self collimation what is important you have to look for a isofrequency contour which is basically flat ok. And further it has to be designed to identify a band isolated from other bands. So, that there is no coupling to other modes ok. So, if you take this kind of a air hole array here the substrate is basically epsilon 2 equals 9 and this is epsilon 1 equals 1.
So, that this is air hole and the fill factor is 40 percent. So, for that case this is how the you know isofrequency contours look like. What are these numbers? These numbers are basically A by lambda naught. So, we could find the almost flat response here when it is A by lambda naught is equal to 0.332 that is also your normalized frequency.

So, with that you can actually find out what is the fractional bandwidth. So, you can identify the two points like this. So, this is called β_{x1} and this is β_{x2}. So, you know these two values ω at β_{x1} and ω at β_{x2} with that you can find out what is the fractional bandwidth of this self collimation ok. So, between this band it will remain you know self collimated you can also find out what is the inflection point that is this particular point one specific point okay.

You can also find out what is the normalized acceptance angle using this formula. You can find out the strength matrix overall figure of merit okay. So, these are the points okay for self-collimation which are the figure of merits. Now as I mentioned what is this inflection point? So, it is called β_{xi}. So, it is identified as a point along the horizontal axis where the curvature of this isofrequency contour surface is 0 ok and yeah and what is this Λ_x it is basically the lattice periodicity along x direction. So, that actually tells us how you can define or design self collimator, lens and different kind of other effects.

Wavelength filters

Wavelength filters

- A high-performance wavelength filter is crucial in wavelength division multiplexing (WDM) systems.
- Photonic crystals (PCs) are expected to provide a compact solution for such filters.
- There are three fundamental types of wavelength filters:
  - **Resonant type**
  - **Directional coupler type**
  - **Diffraction type**
- These filter types are illustrated in Figure.

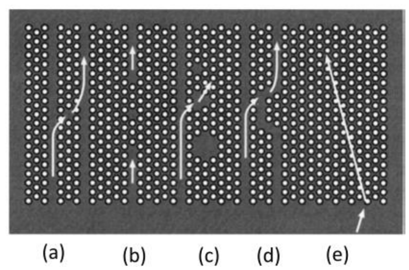
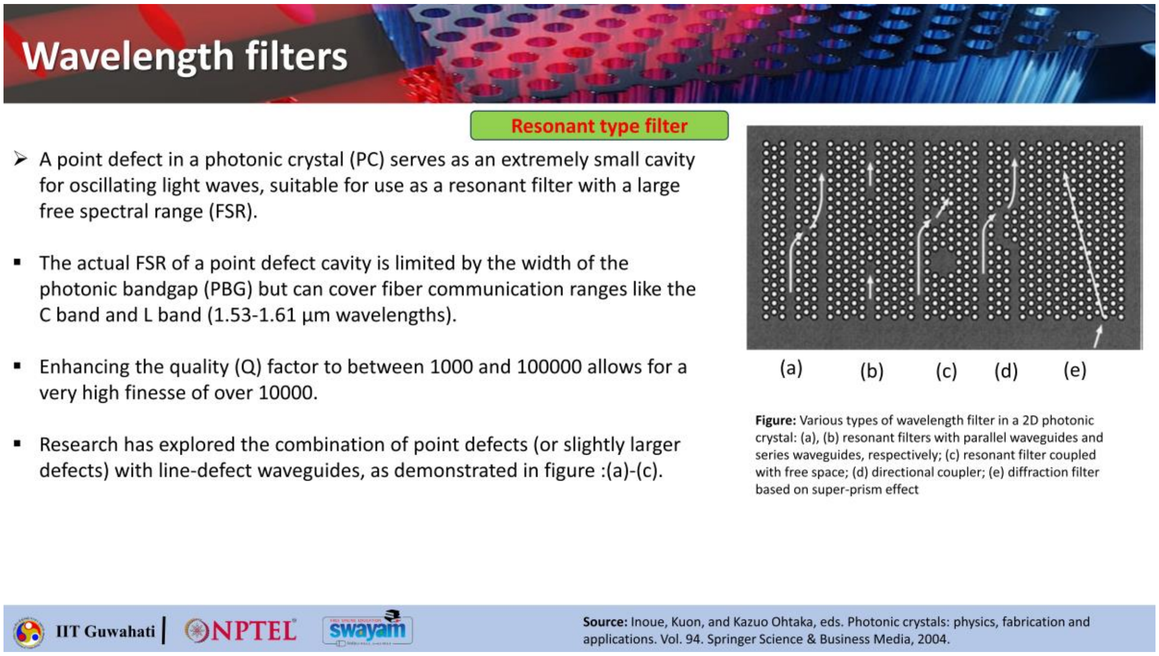


Figure: Various types of wavelength filter in a 2D photonic crystal: (a), (b) resonant filters with parallel waveguides and series waveguides, respectively; (c) resonant filter coupled with free space; (d) directional coupler; (e) diffraction filter based on super-prism effect

Source: Inoue, Kuon, and Kazuo Ohtaka, eds. Photonic crystals: physics, fabrication and applications. Vol. 94. Springer Science & Business Media, 2004.

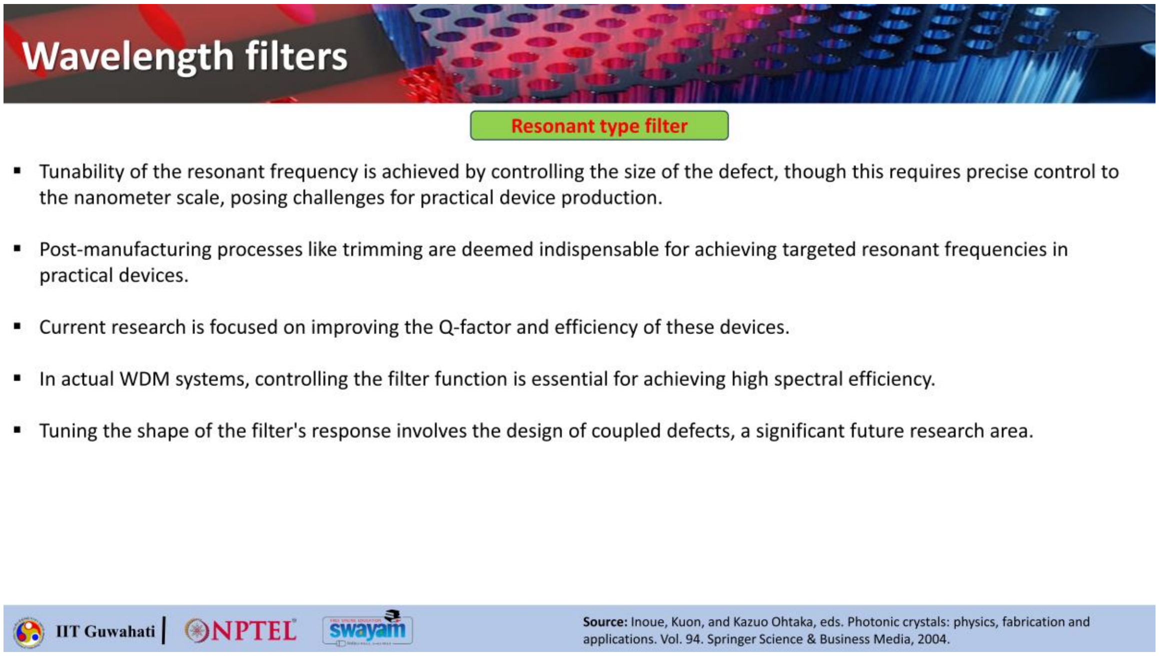
The next important application would be wavelength filtering. So, a high performance wavelength filter is very important in wavelength division multiplexing or you can say the high speed optical dense optical networks. So, photonic crystals are expected to provide a compact solution for such filters. So there are three fundamental types of filters, one is resonant type, one is directional coupler type and the third one is diffraction type okay. So these figures are actually shown here. So a and b are basically showing you resonant filters with this one with parallel waveguides and this one with series waveguides okay.

The third one is basically a resonant filter as you can see here, it is coupled with a resonant filter coupled with free space and this one is a directional coupler based and this one is a diffraction filter based on super prism effect.



So, a point effect inside a photonic crystal can serve as a cavity. It's an extremely small cavity for oscillating light waves. And it is important as resonant filter with large free spectral range. So the actual free spectral range of a point defect cavity is limited by the width of the photonic bandgap.

But it can cover the optical fiber communication ranges something like C band and L band ok. So, L band is from this. So, enhancing the quality factor to you know somewhere between 1000 to 100000 allows a very high finness of over 10000. These are some you know characteristic qualities of the resonant filters that can be achieved using photonic crystals. So research has explored the combination of point defects or slightly larger defects than points with line defects as you can see here in this A, B and C.



Now what is important? The tunability is important. Tunability of the filter or the resonance frequency is important and it can be achieved by controlling the size of the defect. And although this will require you know precise control up to nanometer scale and that poses an important challenge towards fabrication of this kind of devices. And post manufacturing processes something like trimming are deemed indispensable for achieving targeted resonance frequencies in practical devices. So, current research is basically focused on improving the quality factor and the efficiency of this kind of devices. In actual WDM system controlling the filter function is essential for achieving high spectral efficiency.

Wavelength filters

Resonant type filter

- The peculiar dispersion characteristics above the photonic bandgap, shown in figure-a, are utilized as a diffraction type filter, known as a super-prism filter.

- In standard 1D diffraction gratings, wavelength-dependent diffraction is achieved through simple zone folding of dispersion characteristics.
- Higher dimensional PCs exhibit more complex zone folding, enhancing wavelength sensitivity (angular dispersion) and altering beam propagation.
- This behavior is analyzed through dispersion surface analysis, specifically by drawing contour plots of band curves over the Brillouin zone (BZ), as in figure-b.

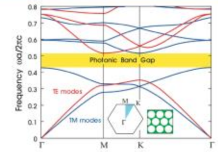


Figure-a. Band diagram of a 2D photonic crystal

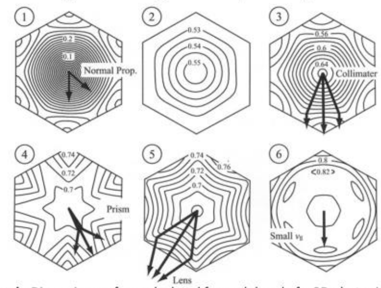
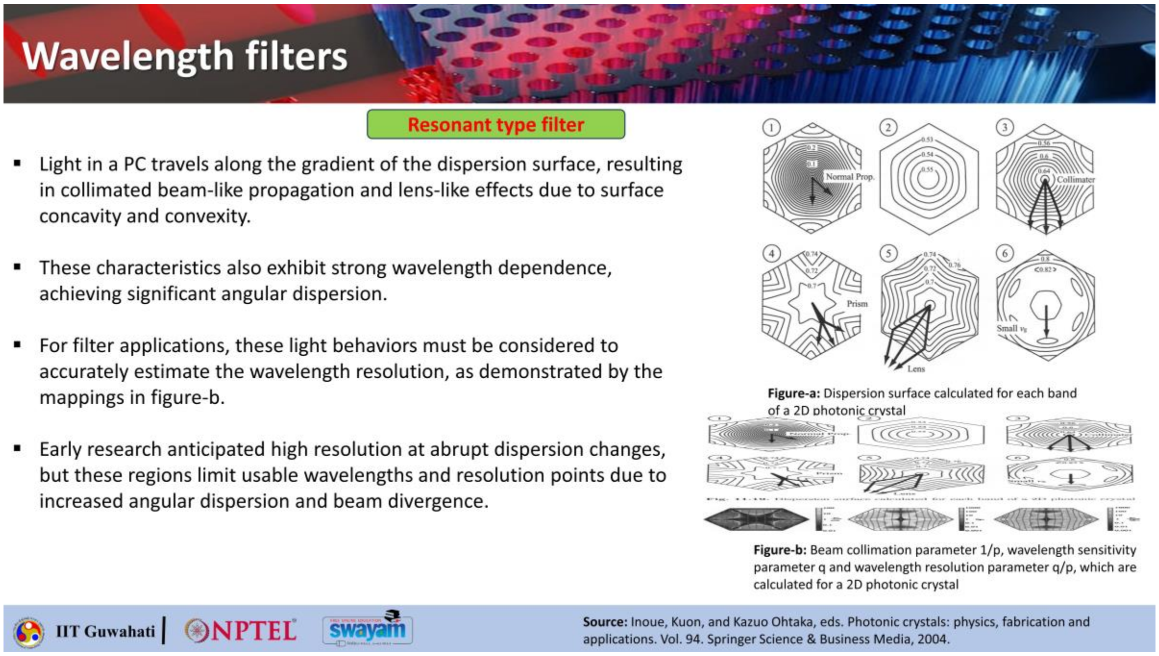


Figure-b: Dispersion surface calculated for each band of a 2D photonic crystal

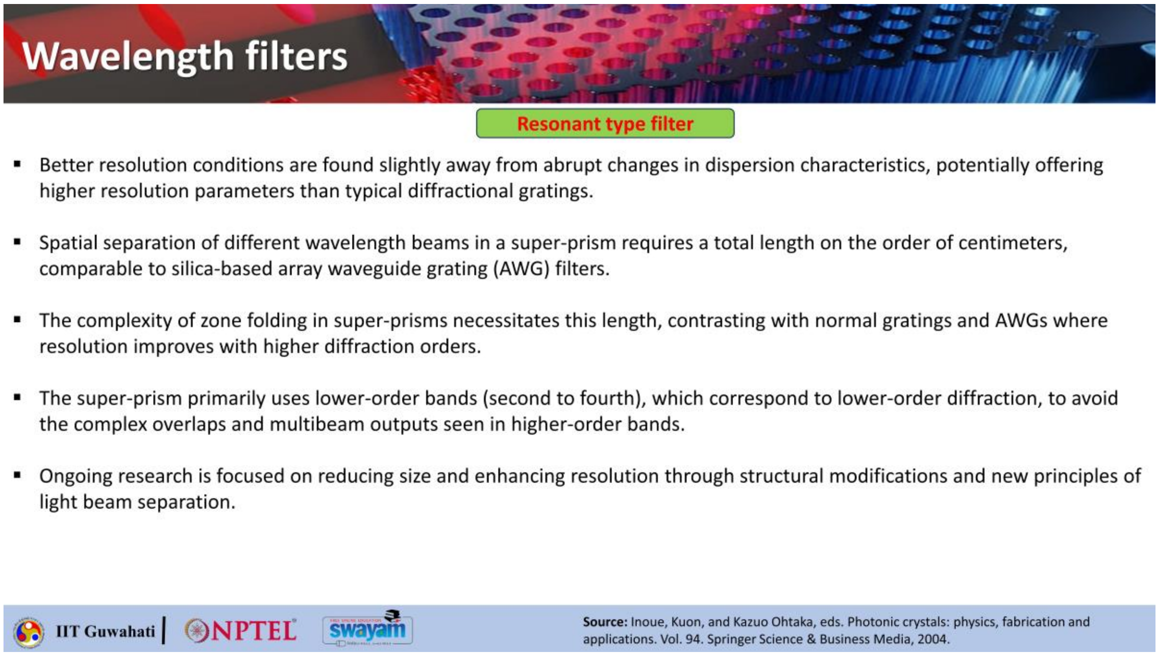
Source: Inoue, Kuon, and Kazuo Ohtaka, eds. Photonic crystals: physics, fabrication and applications. Vol. 94. Springer Science & Business Media, 2004.

And tuning the shape of filters response would involve the design of coupled defects which is a new significant future research area ok. So, the peculiar dispersion characteristics which is seen above a photonic band gap ok as you can see in this particular figure is used for the diffraction type of filter which is also called the super prism filter ok. So, in standard 1D diffraction grating wavelength different dependent diffraction is achieved through simple zone folding of the dispersion characteristics. If you go for higher dimensional photonic crystals, they will exhibit more complex zone folding which we discussed briefly in the 2D and 3D case, right. And that enhances the wavelength sensitivity and also the angular dispersion and altering the beam propagation, right.

So, the behavior is analyzed through the dispersion surface analysis again. And you can draw you know contour plots of the band curves over the brillouin zone which are shown here right. So, for normal propagation you can see this kind of spherical you know dispersion surfaces. You can have collimators like from dispersion surfaces like this okay. You can have prism kind of effect from dispersion surface like this okay.



where suddenly the normal will you know deviate in different direction. You can also have you know lengths which gives you converging beams ok from this dispersion surfaces. So, all these possibilities are there. So, light in a photonic crystal will travel along the gradient of the dispersion surface resulting in a collimated you know beam like propagation and also you know lens like effect due to the surface convexity or you know concavity. So, depending on how your surfaces are you can actually make collimator, you can make you know prism effect or you can get lens effect right. So, what is important to understand that these characteristics also exhibit strong wavelength dependence.



So, they are significant for achieving strong angular dispersion. Now, if you think of filter application, this slide behaviors must be considered to accurately estimate the wavelength resolution, which is determined by the mappings in figure B. In the case of how to characterize this kind of filters, you can see that the early research anticipated high resolution at abrupt dispersion changes, but this regions limit usable wavelengths and resolution points due to increased angular dispersion and beam divergence. So, what you see here this this first one shows beam collimation parameter 1 by p. The second one shows the wavelength sensitivity parameter that is Q.

And the last this graph shows you the wavelength resolution parameter which is Q by P. So, these are all calculated for 2D photonic crystal. This one also for 2D photonic crystal. So, as you can see the 2D photonic crystal is basically the most popularly used one because it is easy to fabricate.

3D ones are very complicated. 1D ones also have application but they are limited. Now the better resolution conditions can be found slightly away from the abrupt change in the dispersion characteristics. Potentially now they offer higher resolution parameters than the typical diffraction gratings.

Wavelength filters

Polarization filter

- Photonic crystals (PCs) feature numerous boundaries with high refractive index (n) contrast, leading to strong polarization dependence.

- In 2D PC band diagrams, band curves vary significantly between two orthogonal polarizations, enabling the use of PCs as polarization selective filters.
- The simplest method for creating such a filter involves utilizing the photonic band gap for one specific polarization to achieve a reflection-type filter.
- A 2D PC built with multilayers on a corrugated substrate has been developed as a vertical input type filter.
- Demonstrated performance includes less than 0.5 dB transmission loss and a -50 dB extinction ratio, both of which meet practical application standards.
- Discussions are currently focused on production costs due to the filter's readiness for practical use.

Source: Y. Ohtera, T. Sato, T. Kawashima, T. Tamamura, and S. Kawakami, Electron. Lett. 35, 1271 (1999)

So spatial separation of different wavelength beams in a super prism would require a total length of the order of centimeters comparable to silica based array waveguide grating filters AWG filters if you have studied about you know integrated photonics or silicon photonics you will come across this kind of filters. which are used for you know different wavelength can be diffracted into different direction and routed into different direction those kind of filters. So, the complexity of zone folding in super prism necessitates this length which is of the order of centimeter and this is in contrast to the normal grating ok and AWG is where resolution improves with higher diffraction orders.

Topological Photonic Crystals

Topological Photonic Crystals

- **Origins in Condensed Matter Physics:** Topological order began with the integer quantum Hall effect, surged with topological phases in graphene, and was realized experimentally in 2D topological insulators in 2007.

- **Photonic Analogs of Quantum Hall States:** In 2008, Haldane and Raghu proposed the concept of unidirectional electromagnetic states in nonreciprocal magnetic photonic crystals, akin to quantum Hall states.

  This idea was experimentally demonstrated in the microwave frequency regime by 2009.

- **Development of Photonic Topological Insulators:** Following the initial discovery, proposals emerged for photonic analogs of quantum spin Hall states, leading to the concept of photonic topological insulators.

- **Extension to Continuous Media:** Research expanded beyond structured materials to continuous media, where topological electromagnetic states were theorized and numerically demonstrated, such as topological Langmuir-cyclotron waves in magnetized plasmas.

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

Topological Photonic Crystals

Topology

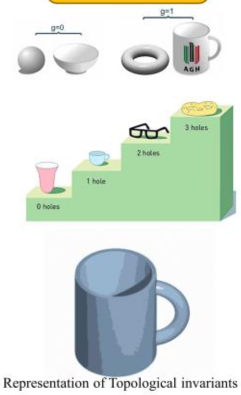


Figure: Representation of Topological invariants and the donut-cup topology

- Formation of conducting one-dimensional channels, develop at the edges of the sample.
  - Each of these edge channels exhibits a quantized conductance that is characteristic of one-dimensional transport.
  - The charge carriers in these channels are very resistant to scattering.
  - Within the channels, charge carriers can be transported without energy dissipation.

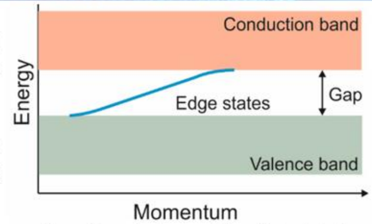


Figure: Energy band representation of a topological material

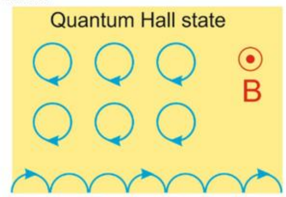


Figure: Representation of electron movement

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

So, the super prism effect primarily uses lower order bands something like second to fourth order which corresponds to lower order diffraction to avoid the complex overlaps and multi beam output which are typically seen for the higher order bands. So, you will see that you know the photonic crystal band based super prism filters or diffraction filters they basically are based on this lower order diffractions. So, ongoing research is focused on reducing the size because right now it is of the order of centimeters. What is the other objective to enhance the resolution through structural modification and look for new principles of light beam separation.

Topological Photonic Crystals

- **Electron Motion in Bulk Material**
  - When electrons in a material are subjected to a magnetic field perpendicular to their motion, they experience the Lorentz force.
  - This 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.
  - This is known as cyclotron motion.
  - The radius of this circular motion, the cyclotron radius, depends on the electron's speed, the strength of the magnetic field, and the electron's effective mass.

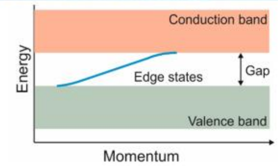


Figure: Energy band representation of a topological material

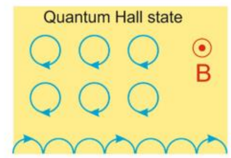
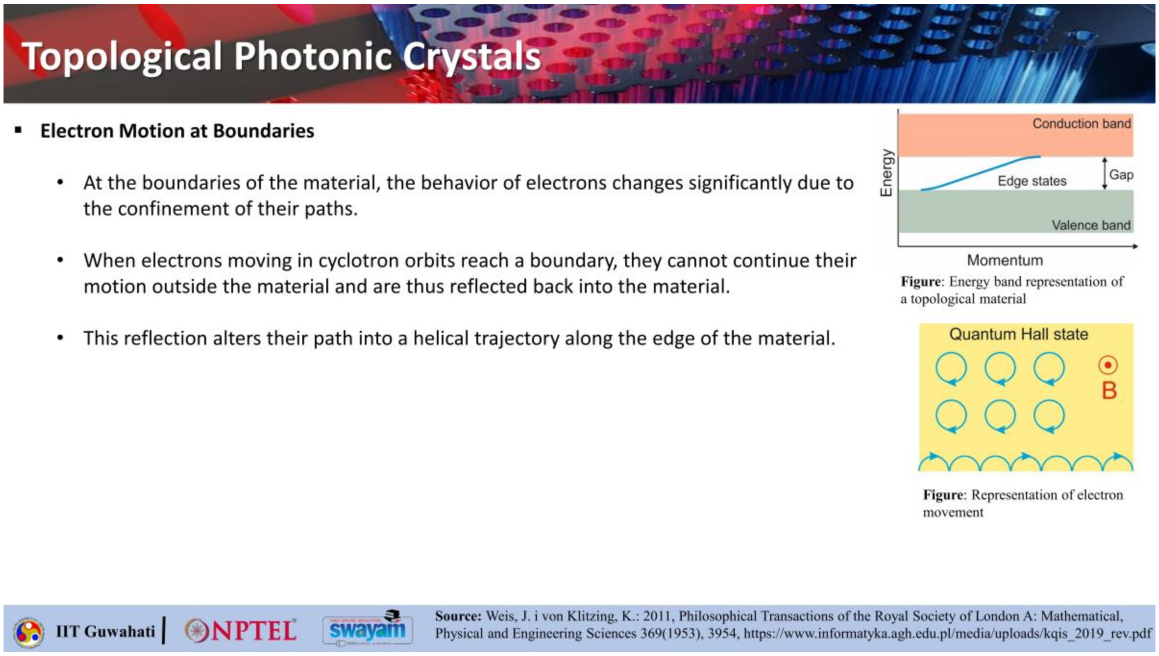
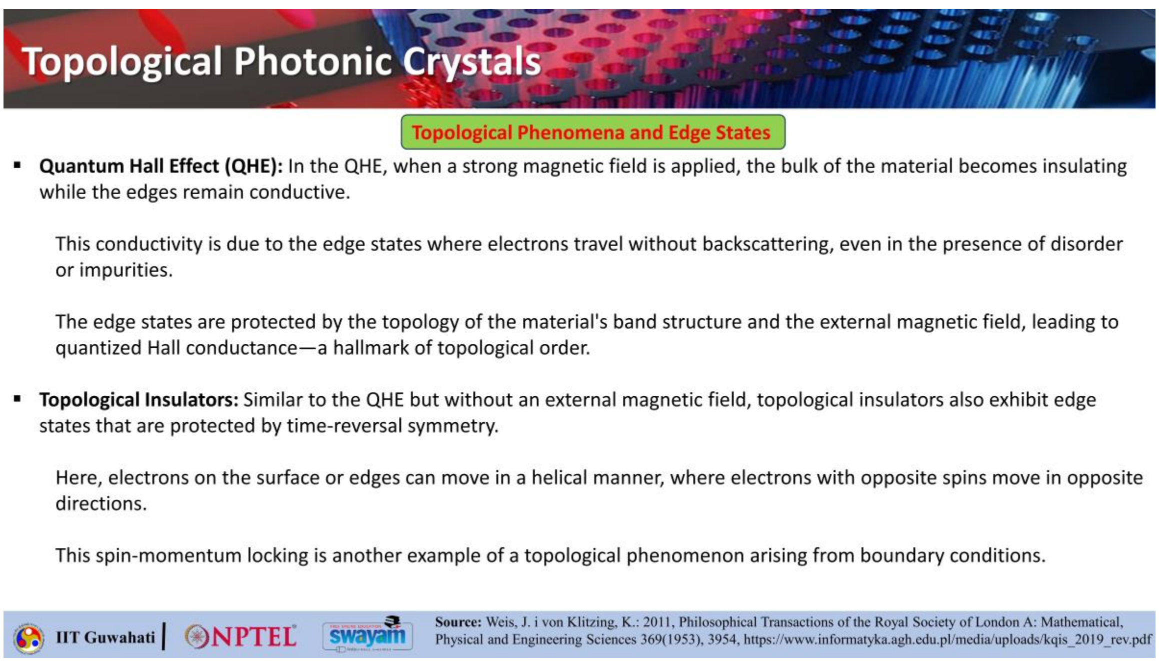


Figure: Representation of electron movement

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

So, these are all active areas of research and this is why I am discussing all these things here. The other type of filter is the polarization filter you can think of photonic crystals which feature numerous boundaries with high refractive index contrast that can lead to strong polarization dependence right. So, in the case of 2D photonic crystal band diagram we have seen that you know for different polarization the bands look different. So, the band curves basically vary significantly for the both polar orthogonal polarizations. So, you can actually use photonic crystal as polarization sensitive filters. The simplest method for creating such a filter involves utilizing the photonic band gap of one particular polarization to achieve a reflection type.

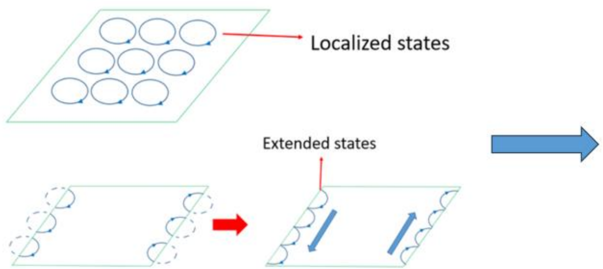


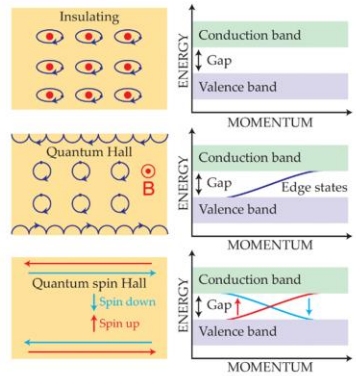


So, if it is having a band gap for one particular polarization, so for the same wavelength if the polarization is along say Te and you have a Te band gap at that particular wavelength, Te will not be able to enter the crystal it will be simply reflected. So, you can actually make reflection type filter. A 2D photonic crystal built with multi layers on a corrugated substrate has been developed as a vertical input type filter. And they have demonstrated the performance typically, you know, less than 0.5 dB transmission loss and minus 50 dB extinction ratio, which are very good, meeting the practical application standards.

Topological Photonic Crystals

Topological Phenomena and Edge States





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

Topological Photonic Crystals

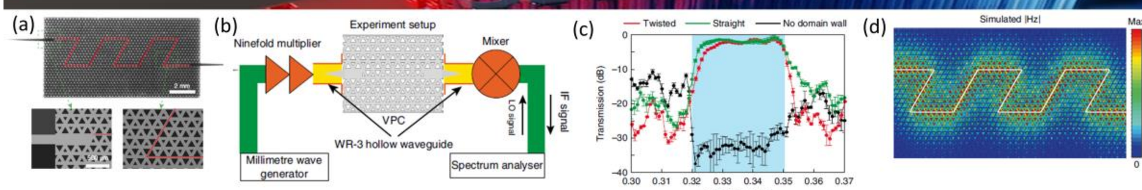


Figure 1: Experimental observation of robust topological valley kink states along a twisted domain wall in a large-scale THz photonic chip. a, An optical image of the fabricated twisted domain wall. The red lines represent the position of the domain walls. b, The experimental setup for measuring transmission. c, Measured transmission curves for a VPC with a straight domain wall, a twisted domain wall with ten corners and no domain wall. The error bars are derived from the standard deviation. The blue region represents the bulk bandgap. d, Simulated |Hz| field distribution (colour scale) in the onchip VPC at 0.335 THz. The white line denotes the position of the domain wall. IF, intermediate frequency; LO, local oscillator.

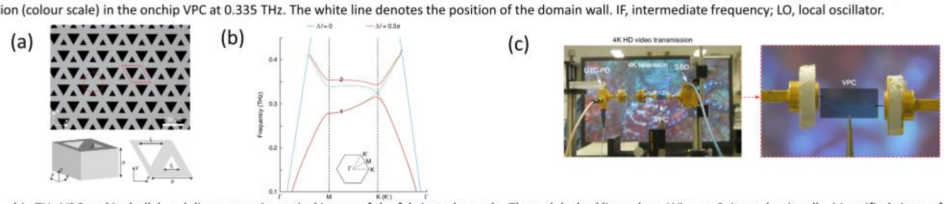


Figure 2: On-chip THz VPC and its bulk band diagram. a, An optical image of the fabricated sample. The red dashed lines show Wigner–Seitz and unit cells. Magnified views of the unit cell are presented below the optical image. b, Band diagrams with and without inversion symmetry. c, An experimental demonstration of uncompressed 4K high-definition video transmission.

Source: Yang, Yihao, et al. "Terahertz topological photonics for on-chip communication." Nature Photonics 14.7 (2020): 446-451.

Topological Photonic Crystals

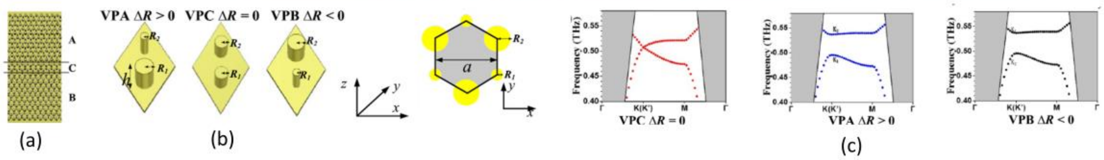


Figure 1. Designer surface plasmon crystal configuration, band diagram, and eigenmodes. (a) 3D structure of the DSPCs. (b) The 2D unit cell. R1 and R2 are the radii of cylindrical metallic pillars. (c) The band diagrams for unperturbed PhCs when ΔR = 0 and perturbed PhCs when ΔR = ± 20 μm.

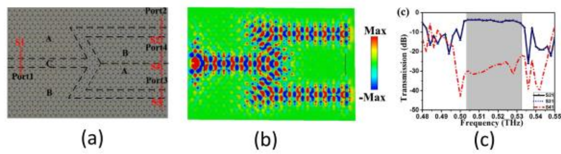


Figure 2. A harpoon-like beam splitter based on A|C|B heterostructure. (a) Configuration. (b) The E_z field distributions of ETVSs at the frequency of 0.51 THz at the plane 20 μm above the metallic pillars. (c) Transmissions of topological SSPP waves from Port1 to other three ports. The grey regions represent the bandgaps.

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Source: Zhao, Yulin, et al. "Extended terahertz valley-locked surface waves in designer surface plasmon crystals." Journal of Physics D: Applied Physics 56.18 (2023): 185101.

So you can actually visit this particular reference for further details of polarization filter device that has been designed using photonic crystals. So, the discussions are kindly focused on you know production cost due to the filters readiness for practical usage. Next we move on to some discussion about you know sensing applications of 2D and 3D photonic crystals. So, we have seen that this particular band diagram couple of times and we understood that this region is mainly used for you know super prism and then amorous dispersion something like transmission type devices.

Topological Photonic Crystals

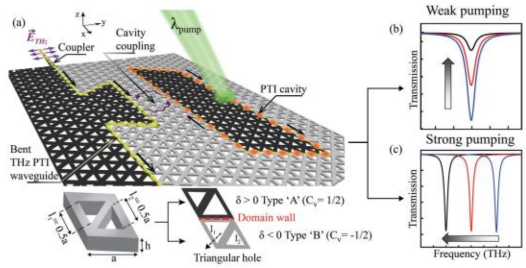

Figure 1. All-optical control of a THz topological cavity-waveguide chip. a) Artistic illustration of a VPC cavity-waveguide chip on an all-silicon (Si) platform. A continuous laser with wavelength 532 nm (energy 2.33 eV) photoexcites the Si above the bandgap (1.1 eV). b) Schematic illustration of THz intensity modulation caused by photoexciting the domain wall of VPC cavity. c) Schematic representation of frequency agility of the topological cavity resonance upon high-power photoexcitation.

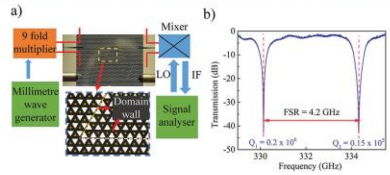

Figure 2. Experimental characterization of the topological cavity-waveguide chip. a) Schematic of experimental setup to measure transmission spectrum. b) Measured transmission spectrum between the input and at the output port of the topological waveguide-cavity chip.

Source: Kumar, Abhishek, et al. "Active Ultrahigh-Q (0.2× 106) THz Topological Cavities on a Chip." Advanced Materials 34.27 (2022): 2202370.

Topological Photonic Crystals: Roadway to 6G

- Topological photonics can revolutionize 6G by enhancing data speed, efficiency, and reliability, ensuring error-free signal propagation, and reducing signal loss and latency.
- Topological photonic devices handle high data rates with minimal energy, aligning with 6G goals for data-intensive applications like 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 due to their localized and protected nature, crucial for future wireless technologies involving critical data and personal information.
- Topological photonics addresses key challenges of upcoming 6G networks, making it a transformative technology for future wireless communication.

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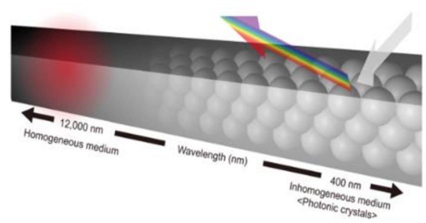
The band gap can be used for you know reflection type devices something like lasers and waveguides and this can actually give some birefringence kind of effect because different polarization has got different properties so using all these things you can always think of photonic crystal based sensors okay which are useful for detection of analytes and parameters Physical sensors for temperature, humidity, stress, chemical sensors for organic solvents and their vapors, pH, heavy metal ions and you can also make biosensors for enzymes like nucleic acid, antibodies and other things.

Photonic Crystals based Radiative Coolers

Photonic Crystals based Radiative Coolers

- The 3D photonic crystal with an opal structure also has good cooling properties.
- It should be emphasized that opals are easy to produce and cheap.
- Besides cooling effects, applying opals with different sphere sizes caused the desired colorization.
- In the visible region, opals can be viewed as an inhomogeneous medium as the length scale of their unit cell is comparable to the wavelength of visible light.
- Therefore, Bragg diffractive colorization can occur via the inhomogeneous medium effect (i.e., photonic crystal effect).
- In contrast, such a structural length scale becomes negligible in the mid-IR region, where opals can be considered to be a homogeneous medium.

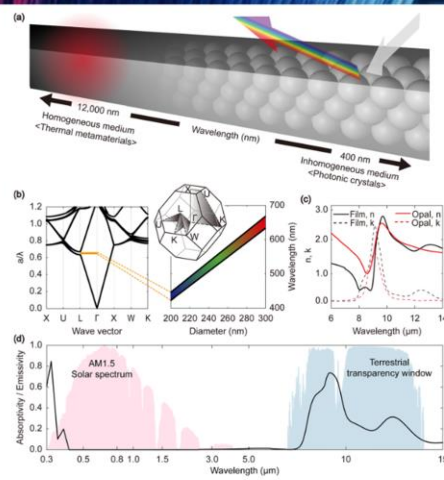


Source: H. Kim *et al.*, Colloidal photonic assemblies for colorful radiative cooling, Langmuir, 36(23), pp.6589-6596, 2020.

So this is the whole spectrum starting from humidity, temperature, strain, different kind of solvents, pH, metal ions, all these things can be designed based on photonic crystal filters. So at the core you can see it is a 2D photonic crystal or 3D photonic crystal that helps you in the sensing application and these are the construction methods or fabrication steps mentioned here. So, what is important the sensitivity in 2D photonic crystal sensors is important because it is calculated based on the interaction between the light and the surrounding matter. So, specifically measuring the smallest change in the resonant wavelength relative to the changes in the environment know or you can say ambient refractive index.

Photonic Crystals based Radiative Coolers

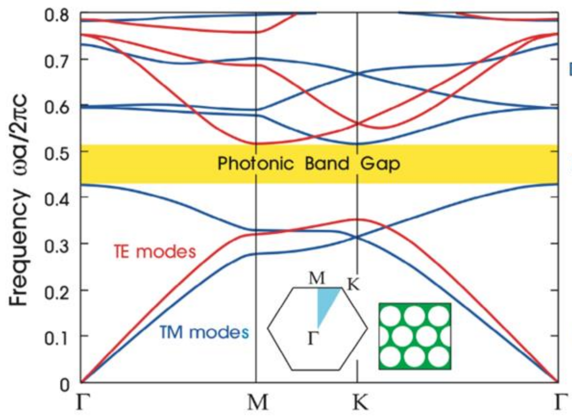
- (b) Photonic band gap diagram of opals.
- According to the diameter of the silica nanospheres to be assembled into opals, the photonic band gap along the Γ to L points [i.e., (111) diffraction] can be widely tuned from reddish to bluish colors.
- (c) Effective refractive indices of silica opals (e.g., assembled by 300 nm silica nanospheres) in the mid-IR region. Herein, the legend "film" corresponds to the 100% fused silica film.
- Absorptivity/emissivity of 150 µm thick silica opals from the UV to mid-IR regions.



Source: H. Kim *et al.*, Colloidal photonic assemblies for colorful radiative cooling, Langmuir, 36(23), pp.6589-6596, 2020.

2D & 3D Photonic Crystal Sensors

Introduction



Superprism, anomorous dispersion, etc. for transmission-type devices

Photonic bandgap for reflection-type devices, e.g., lasers and waveguides

Form birefringence

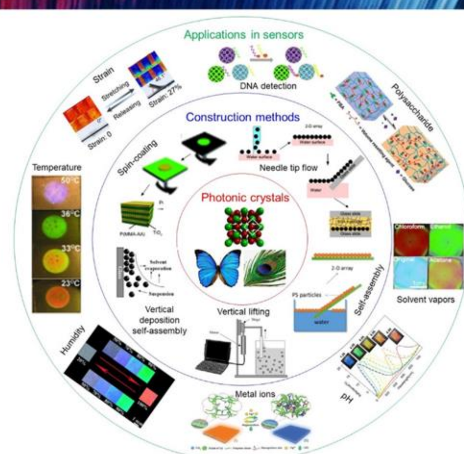
Figure. Band diagram of a 2D photonic crystal

So, what is changing your resonance wavelength because of a change in the refractive index. So, the change has a unit of you know nanometer per RIU which is refractive index unit. So, selectivity is the sensors ability to accurately identify target analytes within a simple. ah that contain a variety of other substances as well ok. So, that way your sensor will only react to the particular ah specific sample that it is supposed to work and that is how it will become a effective biosensor.

Photonic Crystals based Sensors

Photonic crystals based sensors:

- for the detection of analytes/parameters.
- Physical sensors for temperature, humidity, stress, *etc.*
- Chemical sensors for organic solvents and their vapors, pH, heavy metal ions,etc.
- Biosensors for enzymes, nucleic acids, antibodies, bio macromolecules, *etc.*



Source: T. Li *et al.*, Recent advances in photonic crystal-based sensors, Coordination Chemistry Reviews, 475, p.214909, 2023.

Photonic Crystals based Sensors

- Sensitivity in 2D PhC sensors is calculated based on the interaction between light and the surrounding matter.
- Specifically measuring the smallest change in resonance wavelength (λ_o) relative to changes in ambient refractive index (RI), expressed in nm/RIU.
- Selectivity is the sensor's ability to accurately identify target analytes within samples that contain a variety of other substances, a critical factor for biosensor effectiveness.
- Stability refers to the sensor's performance consistency in the presence of environmental interference, impacting the accuracy of measurements.

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Source: S. Zlatanovic, L.W. Mirkarimi, M.M. Sigalas, M.A. Bynum, E. Chow, K.M. Robotti, G.W. Burr, S. Esener, A. Grot, Photonic crystal microcavity sensor for ultracompact monitoring of reaction kinetics and protein detection, Sensors and Actuators B: Chemical 141 (1) (2009) 13–19.

It should not give you false reading by interacting with other similar kind of species. And stability is the consistency on the performance ok in the presence of environmental interference on and stability will affect the accuracy of the measurements. So, you want a stable sensor right. You do not want the you know the sensor to give you different readings based on the you quick change in the environment. So, that is how you think of a stable sensor. Then other parameter is limit of detection it is a crucial metric used to compare different you know optical biosensors defined as the smallest refractive index change needed to produce a detectable change in the sensors output signal.

Photonic Crystals based Sensors

- Limit of Detection (LoD) is a crucial metric used to compare different optical biosensors, defined as the smallest RI change needed to produce a detectable change in the sensor's output signal.

- The sensitivity formula for optical biosensors is represented as:

$$S = \frac{\Delta\lambda}{\Delta n}$$

where: $\Delta\lambda$ is the change in resonance wavelength

Δn is the change in ambient medium RI

Source: S. Zlatanovic, L.W. Mirkarimi, M.M. Sigalas, M.A. Bynum, E. Chow, K.M. Robotti, G.W. Burr, S. Esener, A. Grot, Photonic crystal microcavity sensor for ultracompact monitoring of reaction kinetics and protein detection, Sensors and Actuators B: Chemical 141 (1) (2009) 13–19.

So, that is the limit of detection. So, sensitivity formula for optical biosensors can be presented as S equals by $\Delta\lambda/\Delta n$. So, Δn is basically the change in the ambient refractive index and Δn will be the corresponding change in the resonance wavelength. So, photonic crystal sensors and you know metal insulator metal based plasmonic waveguide sensors these are extensively used for refractive index sensing.

Photonic Crystals based Sensors

- **PhC and MIM RI sensors:** Photonic crystal (PhC) sensors and metal-insulator-metal (MIM) plasmonic waveguide (WG) sensors are extensively researched for refractive index (RI) sensing.

  PhCs offer minimal preparation and high sensitivity, while MIM sensors are compact and highly sensitive due to surface plasmon polaritons.

  Challenges and advantages in fabrication: PhC sensors are easier to fabricate on SOI platforms with CMOS-compatible processes, while MIM sensors face challenges due to their complex thin metal layers.

- **Diverse PhC-based gas sensors:** PhC gas sensors detect mid-IR gases like CO_2, CH_4, and CO, with sensitivities from 510 nm/RIU in air-slot cavities to 3200 nm/RIU in SPR nanocavity arrays.

- **Innovative designs and high sensitivities:** Additional designs include sensors with sensitivities of 748 nm/RIU (guided-mode resonance), 1550 nm/RIU (fiber-optic Fabry-Perot), and 1178.6 nm/RIU (PC/Ag/graphene Tamm state).

Source: S. Zlatanovic, L.W. Mirkarimi, M.M. Sigalas, M.A. Bynum, E. Chow, K.M. Robotti, G.W. Burr, S. Esener, A. Grot, Photonic crystal microcavity sensor for ultracompact monitoring of reaction kinetics and protein detection, Sensors and Actuators B: Chemical 141 (1) (2009) 13–19.

Photonic Crystals based Sensors

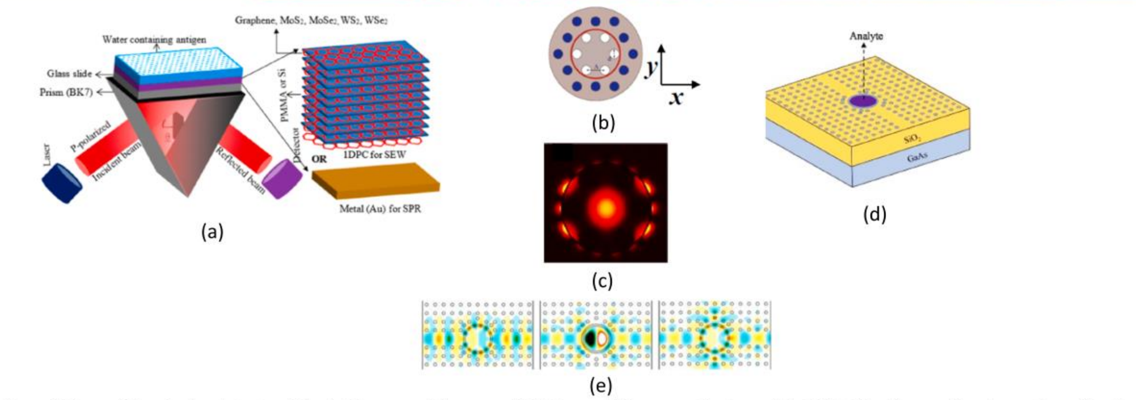

Figure: a) Diagram of the prism-based structure of the Au-SPR sensor and the proposed 1D PhC sensor, b) The cross-sectional area of the SPR-PhC fiber biosensor. The outermost layer of the air hole is filled with the aqueous of biological factor, c) E-field distribution of the SPR mode of 7th SPP mode and fundamental mode, d) PhC biosensor based on two WGs and a ring, e) the vertical component of the E-field for different resonance peaks.

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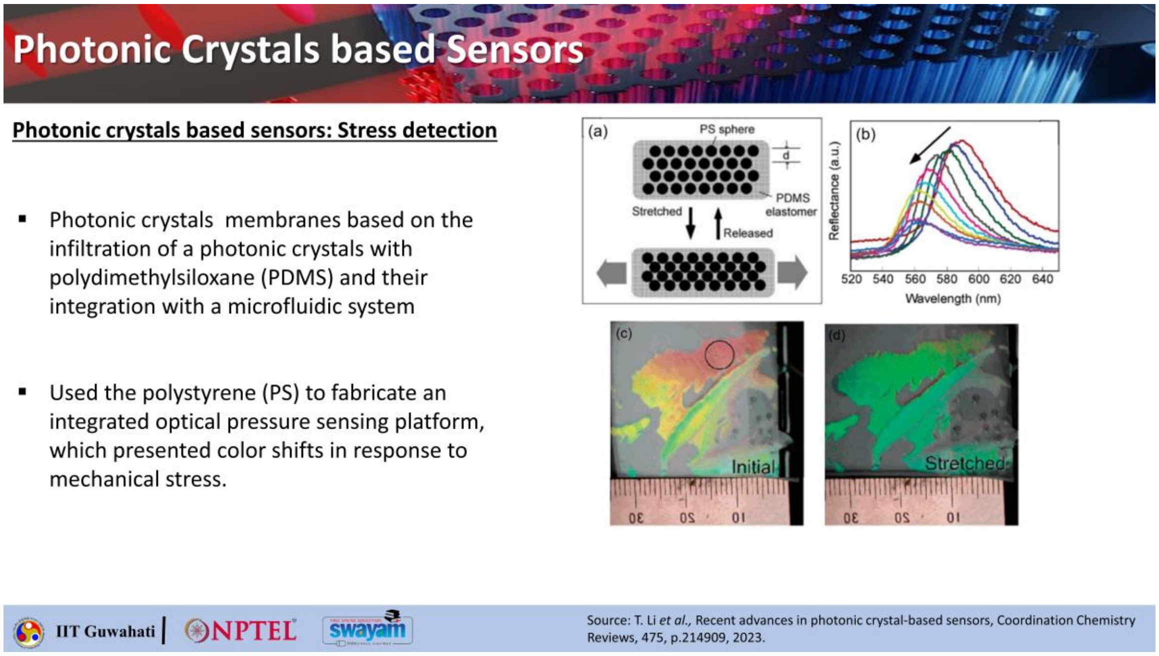
Source: S. Zlatanovic, L.W. Mirkarimi, M.M. Sigalas, M.A. Bynum, E. Chow, K.M. Robotti, G.W. Burr, S. Esener, A. Grot, Photonic crystal microcavity sensor for ultracompact monitoring of reaction kinetics and protein detection, Sensors and Actuators B: Chemical 141 (1) (2009) 13–19.

Photonic crystal offers you know minimal preparation and high sensitivity while metal insulator metal based sensors are compact and they also have you know high sensitivity due to surface plus bond polyatoms ok that is a different effect and I have got a course on this NPTEL MOOC that is nanophotonics plus phonics and metamaterials there all this surface plasmon polyatoms have been discussed. Now, what are the challenges and advances in fabrication? This photonic crystal sensors are easier to fabricate on silicon on insulator platform with CMOS convert compatible processes whereas, if you think of metal insulator metal kind of sensors they have steep challenges because of their complex thin metal layer you can also think of different gas sensors based on photonic crystals to detect you know mid infrared gases something like co2 methane carbon monoxide with sensitivities of the order of 510 nanometer per RIU in air slot cavities okay to 13 um you know 1300 nanometer per RIU in SPR nano cavity arrays ok, surface plasmon resonance nano cavity arrays.

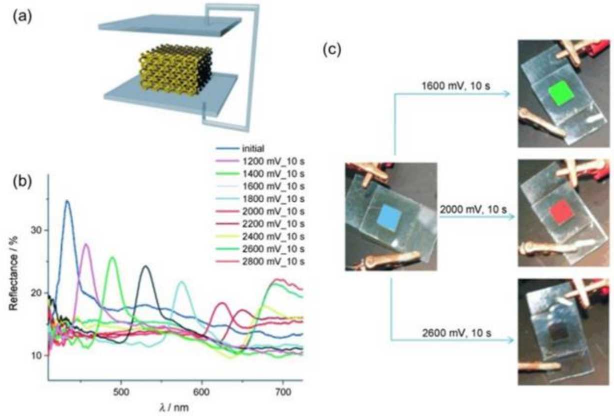


So, what is clearly seen here is that it is more sensitive, the surface plasmon ones are more sensitive, but then fabricating this kind of sensors photocrystals sensors are much easier because they can use you can use silicon or you can say CMOS compatible processes. So, additional designs include sensors with sensitivities of the order of you know 748 nanometer per Riu using guided mode resonance or 1550 nanometer per Riu for Fabry-Perot you know fiber optic Fabry-Perot cavity resonance and different other resonance features people are also exploring. So I will show you briefly how a photonic crystal based sensor would look like. So here the figure shows you you know the details of few refractive index sensors based on photonic crystals which have been reported in recent years ok. And here you can see it is a prism based structure ok and it is having this is a laser incident light and this is the reflected light you have some kind of water containing antigen okay there is a glass side and then you have this prism which is basically bk7 okay and in between you have this metal which is gold for a sphere okay or you can actually use this one which is a 1D photonic crystal for similar kind of effect okay.

Photonic Crystals based Sensors

Photonic crystals based sensors: Detection of electric field

- Electrically responsive PC sensors showed observable optical characteristics of PCs under the stimulation of applied electric field
- The corresponding PC materials include the PCs based on liquid crystal molecules and metallic polymers.

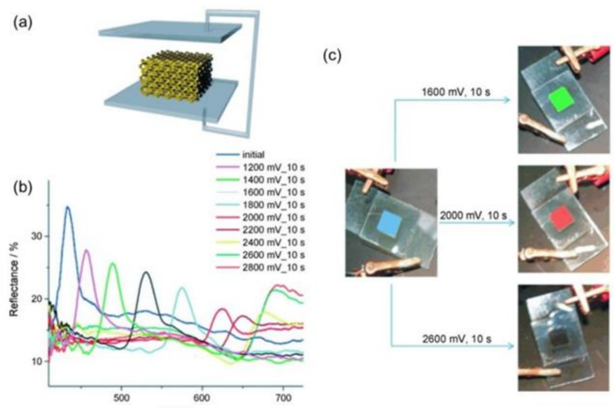


Source: T. Li *et al.*, Recent advances in photonic crystal-based sensors, Coordination Chemistry Reviews, 475, p.214909, 2023.

Photonic Crystals based Sensors

Photonic crystals based sensors: Detection of electric field

- Electro-responsive photonic crystals with an inverse polymer-gel opal structure prepared by injecting the metal polymer, polyferrocenylsilane (PFS), into the SiO_2 opal structure.
- The electrical tuning was achieved by preparing an electrochemical cell consisting of photonic crystals on ITO as the working electrode.



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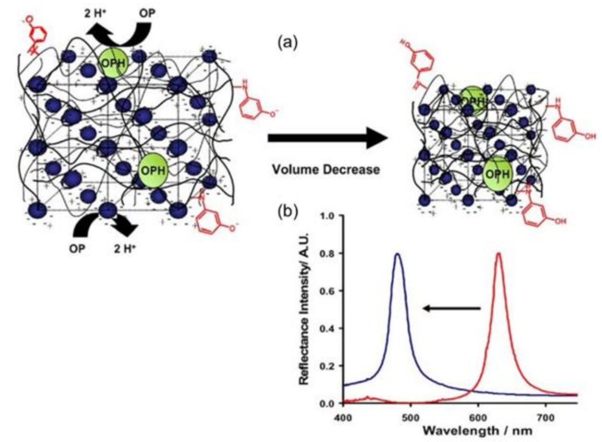
Source: T. Li *et al.*, Recent advances in photonic crystal-based sensors, Coordination Chemistry Reviews, 475, p.214909, 2023.

So, it is made of graphene MOS_2 and other things okay. So, the base is basically PMMA or silicon on top of which you can have this 2D kind of materials sandwiched or alternating layers. So, you can think of PMMA MOS_2 PMMA graphene something like that and a periodic array. So, this kind of sensors ok. So, this is basically another sensor which is surface plasmon resonance and photonic crystal fiber based biosensor ok. here the outermost layer of the air hole is basically filled with this blue blue circles that you are seeing these are basically filled with the aqueous form of the biological factor that is that you are going to sense the inside ones are basically air holes okay.

Photonic Crystals based Sensors

Photonic crystals based sensors: Detection of Organic Pollutants

- By combining poly-2-hydroxyethylacrylate hydrogel with PCs, the organophosphorus hydrolase (OPH) enzyme catalysed the hydrolysis of methyl paraoxon insolution with basic pH, creating pnitrophenol, dimethyl phosphate, and two H+.
- *Inducing blue-shift on the diffraction wavelength.*



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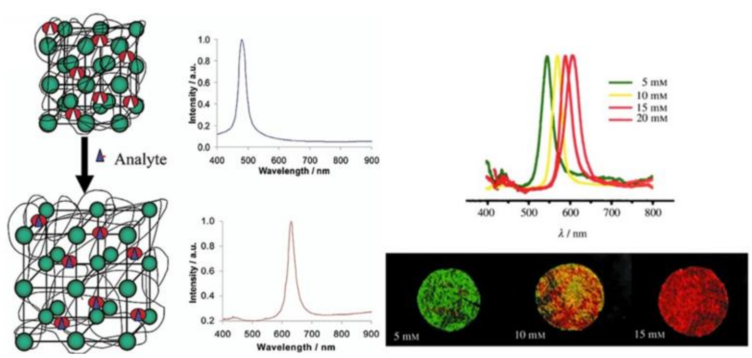
Source: T. Li *et al.*, Recent advances in photonic crystal-based sensors, Coordination Chemistry Reviews, 475, p.214909, 2023.

So, this one shows the electric field distribution of the 7th order SPP mode and also the fundamental So, this shows another example of photonic crystal biosensor ah based on two waveguides and one ring ok. this figure shows the vertical component of the electric field for different kind of resonant peaks in this particular structure right. So you can also use photonic crystal based sensors for stress detection. So in that case you need to have this photonic crystal you know membranes based on the infiltration of photonic crystals with PDMS which is a flexible substrate and you integrate them in a microfluidic system.

Photonic Crystals based Sensors

Photonic crystals based sensors: Detection of Glucose

- The recognition of photonic crystals with glucose molecule induced the increasing of the lattice spacing and the red-shift of the diffractive wavelength of photonic crystals.



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Source: T. Li *et al.*, Recent advances in photonic crystal-based sensors, Coordination Chemistry Reviews, 475, p.214909, 2023.

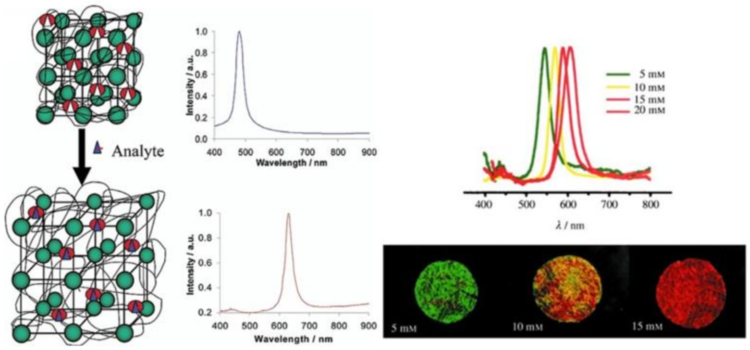
So, the polystyrene can be used to fabricate an integrated optical pressure sensor sensing platform. So, that way when you are basically stretching, so the periodicity changes. So, the reflectance curve changes and when you release it, it actually goes back to the original state. So, depending on the you know amount of stress being applied the periodicity changes and that will change the reflection pattern right. So, based on this feature you can actually see that the colours reflected colours are changing from the initial to the stretched state.

You can also have photonic crystal based sensors for detection of electric field. So you can think of electrically responsive photonic crystal sensors which showed observable optical characteristics of photonic crystals under the application of electric field something like you know if you have 1600 millivolt for 10 seconds you can see this is the color it keeps okay if you apply 2000 millivolt you get this color 26000 2600 millivolt you get a different color. So, how it is working it is basically you know you have corresponding photon crystal material which include photon crystals based on liquid crystal molecules and metallic polymers right. So, with the different electric voltage that is being applied the response of the photonic crystal will slightly change and that is how the color that is getting reflected is also changing. So, you can actually see that the electrical tuning was achieved by preparing some sort of electrochemical cell which consists of this photonic crystals on ITO which works as the in this one working electrode on both sides.

Photonic Crystals based Sensors

Photonic crystals based sensors: Detection of Glucose

- When the photonic crystals appear green, the blood glucose concentration is in the normal range; when the color is yellow, the blood glucose reaches the pathological critical value, and red indicates that the test subject has severe diabetes



Source: T. Li *et al.*, Recent advances in photonic crystal-based sensors, Coordination Chemistry Reviews, 475, p.214909, 2023.

You can also use photonic crystal based sensors for detection of glucose. So, the recognition of photonic crystals with glucose molecules induced the increase of light spacing and that actually gives you red shift in the diffraction wavelength from the photonic crystals. So, you can see here that from 5 nanometer when it change millimolar sorry this is the glucose concentration. So, the diffraction peaks actually moves when you have larger concentration. So, all it does is that you know with higher concentration it adjusted it adjust the lattice spacing and that is why you see a different diffraction color ok.

So, when the photonic crystal appears green that is here the glucose concentration is basically in the normal range. Okay, but whenever it comes here that is it is showing you yellow color that means your glucose level has reached a pathologically critical value. Okay, and red means that you will have severe diabetes. Okay, so three different colors you know green, yellow, red can be used for you know identifying you know basic diabetes level in a person.

So these are different examples of photonic crystal based sensors. There are a lot of more applications. I will try to cover some of the new applications also in one of the lectures which is topological photonic insulator based devices.

So, till then we will stop here any questions regarding this lecture you can email to this particular email address mentioning MOOC and photonic crystal on the subject line. music music