Lec 1: Motivation and Introduction to Photonic Crystals

Hello students, welcome to lecture one of the online courses on Photonic Crystals, Fundamentals and Applications. So, in this course, we'll provide a detailed introduction to this new technology, Photonic Crystals, covering their fundamentals and discussing their latest advancements. Now, if you look into Photonic Crystals, this is inspired by the concept of electronic bandgaps in semiconductors and it was proposed first in late 1980s as periodic structures that can control the flow of light. Now these nanostructured materials have shown immense potential towards controlling and manipulating the propagation of electromagnetic waves. In the future, photonic crystal also holds the promise to revolutionize various technologies. They can enable ultra-compact optical circuits, leading to faster and more efficient data communication.

Additionally, they may open door to new advances in quantum computing and imaging technologies, paving the way for a brighter and more interconnected future. They also have a lot of application in 6G technology. So that is why photonic crystal becomes very relevant in today's world. This course will first cover the overview and applications of photonic crystals.

Then we'll go into the fundamentals of electromagnetic wave theory of light. We'll talk about photonic band structures. Later on, the course will also focus on the analysis and discussions of 1D, 2D, and 3D photonic crystals. This course will also introduce discussions regarding photonic periodic dielectric waveguides, photonic crystal slabs, and photonic crystal fibres. So finally, the course will end up discussing photonic crystals for different applications.

Course Plan

Module	Module Name	Week	Lecture No	Title of the Lecture	Assignments
1	Introduction	1	1-3	• Motivation & introduction to Photonic Crystals • Overview of Photonic-Crystal technology • Fundamentals of EM theory of light	Online
2	Fundamentals of electromagnetism in dielectric media	2	4-6	• Electromagnetic properties of material • Electromagnetism as an Eigenvalue problem • Scaling properties of Maxwell's equations	Online
3	Symmetries and Electromagnetic modes of a dielectric structure	3	7-9	• Symmetries for classification of EM modes • Real and reciprocal Lattice • Photonic Band structure: Computation and Analysis	Online
4	1D Photonic Crystals	4	10-12	• Fundamentals of 1D Photonic crystals • Analysis and engineering of 1D photonic band structures • Applications of 1D Photonic crystals	Online

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So we have actually designed this course for undergraduate and postgraduate students with some basic knowledge of physics and electromagnetics. So we hope that UG and PG students with background in electronics, electrical instrumentation, physics, chemistry, chemical, material science and engineering and any researcher and or industry people working in the areas of photonics and related areas will be benefited from the course content. So we believe that this will surely motivate you to study further and explore this exciting interdisciplinary area of research, which has got endless opportunities. So here is the course plan. So we'll cover 10 modules over the span of 36 lectures.

The introduction week will cover the motivation and interaction to photonic crystals. We'll give a brief overview of the photonic crystal technology and discuss the fundamentals of electromagnetic theory of light. In week two, we'll cover more or less all the fundamentals of electromagnetism in dielectric media needed for this particular course. So we'll discuss about electromagnetic properties of material, electromagnetism as an eigenvalue problem, and scaling properties of Maxwell's equation. In week 3 and module 3 we'll look into the symmetries and electromagnetic modes of a dielectric structure.

Course Plan

Module	Module Name	Week	Lecture No	Title of the Lecture	Assignments
5	2D Photonic Crystals	5	13-15	• Fundamentals of 2D Photonic crystals • Analysis and engineering of 2D photonic band structures • Applications of 2D Photonic crystals	Online
6	3D Photonic Crystals	6	16-18	• Overview of different 3D Photonic crystals • Crystals with complete bandgap • Applications of 3D Photonic crystals	Online
7	Periodic Dielectric Waveguides	7	19-21	• Overview and modelling of periodic dielectric waveguides • Point Defects in Periodic Dielectric Waveguides & Quality Factors of lossy cavities • Applications: Fiber Bragg grating example	Online
8	Photonic Crystal Slabs	8	22-24	• Overview of photonic crystal slabs • Different types of defects in photonic crystal slabs • Engineering High-Q resonant cavity	Online

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So we'll be discussing about the symmetries for the classification of electromagnetic modes. We'll discuss about real and reciprocal lattice with photonic band structure and how do you compute them and analyze them. In week 4, we'll be discussing about 1D photonic crystals where we'll cover the fundamentals and we'll look into how we can analyze and engineer the 1D photonic band structure and we'll look into different applications of 1D photonic crystals. In week five, we'll be discussing more about 2D photonic crystals. We'll discuss about their fundamentals.

We'll analyze and engineer the 2D photonic band structures and discuss some important applications of 2D photonic crystals. Week six, we'll go into the 3D photonic crystals and we'll look into different structures or designs of 3D photonic crystals. How do we get crystals with complete band gap and some applications of the 3D photonic crystals? Week seven will cover periodic dielectric waveguides. So, there we'll be discussing about the overview and modeling of periodic dielectric waveguides.

Course Plan

Module	Module Name	Week	Lecture No	Title of the Lecture	Assignments
9	Photonic Crystal Fibres	9	25-27	• Overview of photonic crystal fibers • Index-guiding photonic crystal fibers • Band-gap guidance in Holey Fibers	Online
		10	28-30	• Overview of Bragg Fibers • Losses in Hollow-core Fibers • Applications of photonic crystal fibers	Online
10	Designing Photonic Crystals for Applications	11	31-33	• Designing a mirror, waveguide and cavity • Temporal Coupled-mode Theory Fundamentals • Analysis using Temporal Coupled-mode Theory: Filter transmission & Waveguide Bend	Online
		12	34-36	• Analysis using Temporal Coupled-mode Theory: Waveguide splitters and 3D filters • Nonlinear Filters and Bistability • Unusual refraction and diffraction effects	Online

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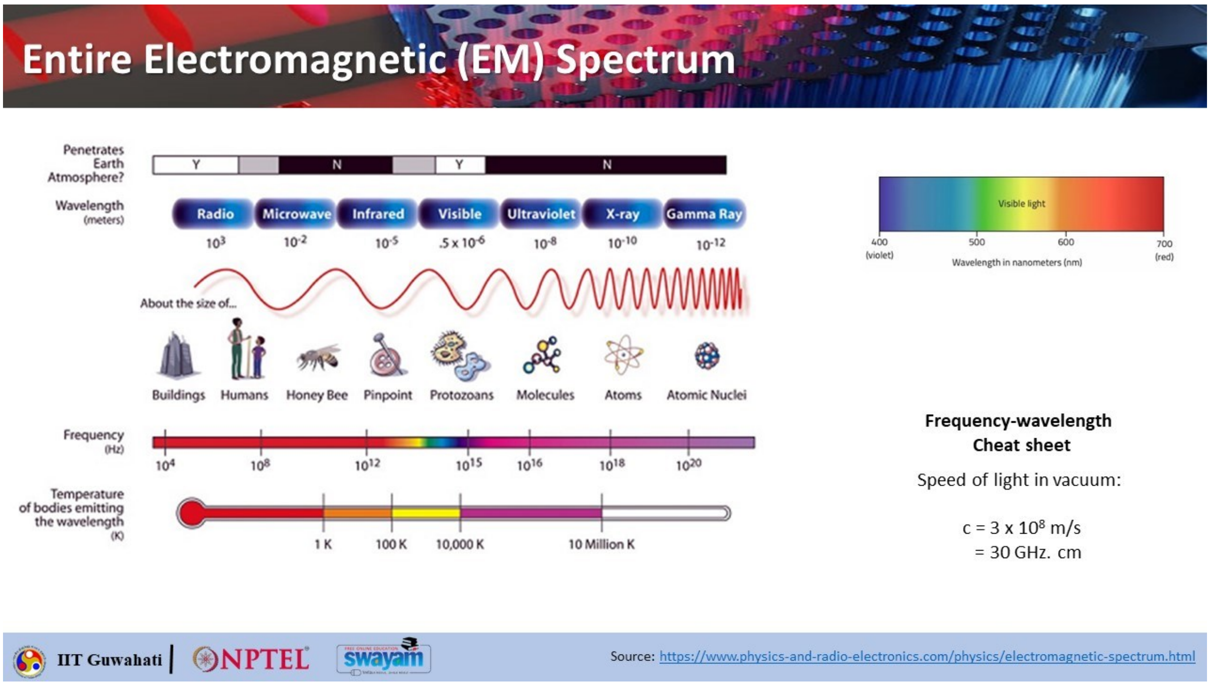
We'll discuss about point effects in those waveguides and the quality factor of lossy cavities. And we'll take some examples like fiber break rating and discuss their applications. Week eight or module eight will be focusing on photonic crystal slabs where we'll give a brief overview of how it is designed and then different types of defects that you can introduce in photonic crystal slabs. And also, how do you engineer high Q resonant cavity. Module nine will be placed across two weeks, week nine and 10.

So there we'll mainly focus on photonic crystal fibers. So that's a lot of different application areas we'll be covering. So, we'll first start with the overview and then index guiding photonic crystal fiber. We'll discuss about band gap guidance in holy fiber. We'll also go and discuss about Bragg fibers, the losses in hollow core fibers and different applications of photonic crystal fibers.

And the last module, that will be on designing photonic crystals for different applications. That will be spread across two weeks, 11 and 12. So there we'll be looking into how do you design a mirror, waveguide, and cavity. Then we'll discuss about temporal couple mode theory fundamentals. We'll analyze the different structures like filter transmission and waveguide bands using temporal couple mode theory.

We'll also take this theory further to discuss and analyze waveguide splitters and 3D filters. We'll discuss about nonlinear filters and bi-stability and also unusual refraction and diffraction effects. So we'll actually cover different application aspects of photonic crystals to end this course. So as you can see, every week will come with an online assignment and at the end of the course, you will have an exam if you register to do so. Now, before we begin the study of a photonic crystal, we need to pay some attention on the electromagnetic spectrum



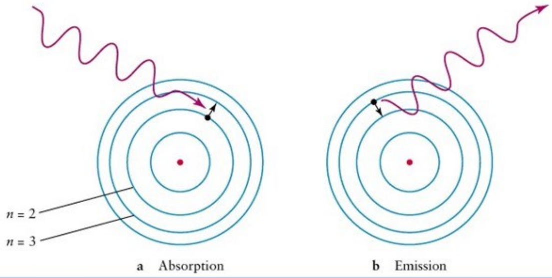
So here you can see, the entire electromagnetic spectrum that ranges from radio waves to gamma waves. And this is the wavelength that has been mentioned in meters. So, radio waves like 10 to the power 3 meters is the typical wavelength, whereas gamma rays are very, very tiny wavelength. So, 10 to the power minus 12 meters. And these are the corresponding frequency scale and the corresponding black body temperature of the black bodies that can emit this particular radiation.

So what is interesting is that in this entire spectrum, there is only a very small portion that you can actually see. So, 400 nanometer to 700 nanometer is typically the wavelength that is visible to human eyes. Now, I believe all of you know this particular frequency wavelength cheat sheet that helps you convert the frequency to corresponding wavelength. So, you can express the speed of light c as 3 into 8 meter per second, or you can say it's 30 gigahertz centimeter. So, it means a wave of 30 gigahertz will have one centimeter wavelength.

If it is 15 gigahertz, it will have 2 centimeter wavelength and so on. So now let's go into the discussion of photonic crystals. So, when you first say photonic crystal, you first need to understand what is photonic. Okay, so photonics is basically a subcategory of optics that focuses on the science and technology of photons. Now photon is often interchangeably used.

Photonics: a subcategory of optics that focuses on the science and technology of photons

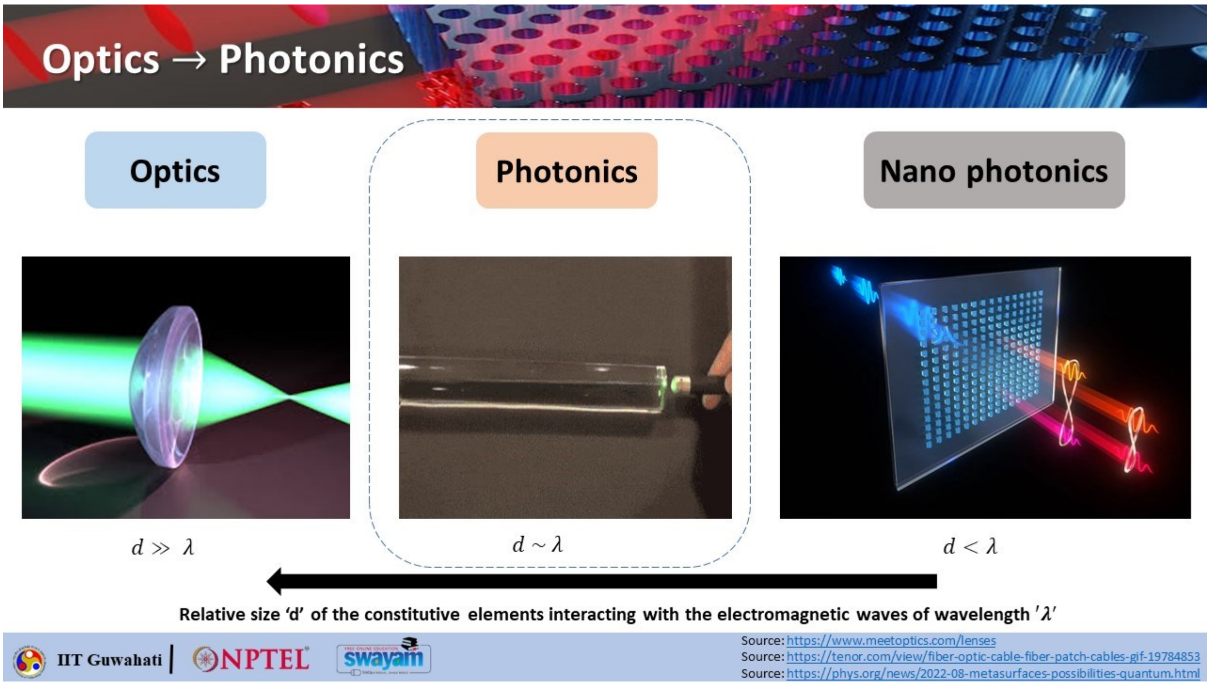
- Photonics is often used interchangeably with optics, but they have distinct meanings
  - Optics is a broad branch of physics: studies the general behaviour and properties of light, as well as vision and perception
  - Photonics involves in generation, detection, and manipulation of light in form of photons
  - Photonics is concerned with **absorption** & **emission** of light - besides its **transmission**, **modulation**, **signal processing**, **switching**, and **amplification**



Source: https://www.sketchbubble.com/en/presentation-applications-of-photonics.html

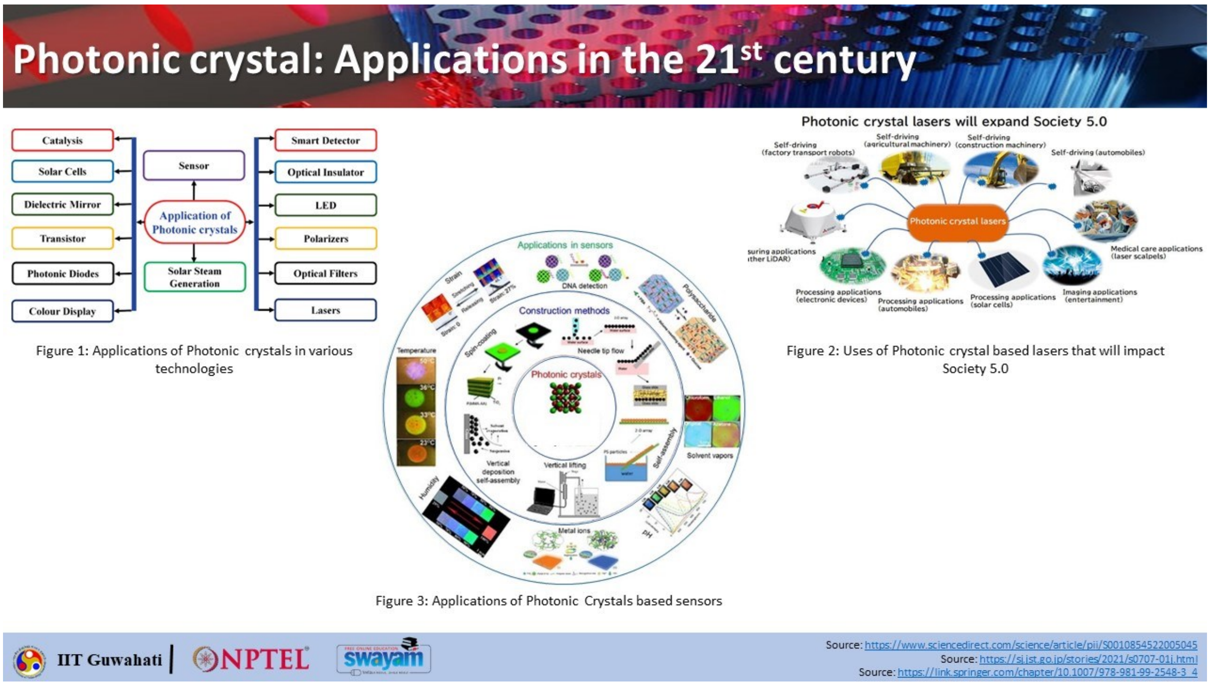
Now photonics Photonics is often interchangeably used with optics but they do have distinct meanings. So optics is basically a broad branch of physics which studies the general behavior and properties of light as well as vision and perception. Whereas photonics mainly involves in generation, detection and manipulation of light in the form of photons and that is where the name photonics come from. Now, photonics is concerned with absorption and emission of light besides its transmission, modulation, signal processing, switching, and amplification. So here, this is what happens in absorption, as we all know, when it energy is accepted or absorbed by an electron, it will jump to the higher energy state.

And on the other side, the reverse phenomena is also possible when there is emission. So when the electron jumps from a higher energy level to a lower energy level, it can emit the difference of this energy in form of a radiation and that is the emission. So these are two different properties.



Now, if you compare optics and photonics, the difference basically comes in the form of the relative size d of the constitutive elements which are interacting with the electromagnetic waves of wavelength lambda. So, when we talk about optics, we are typically talking about elements which are much, much larger in size as compared to the wavelength of but when you go to photonics domain, we are basically discussing about elements which are of dimension typically comparable to the wavelength of light.

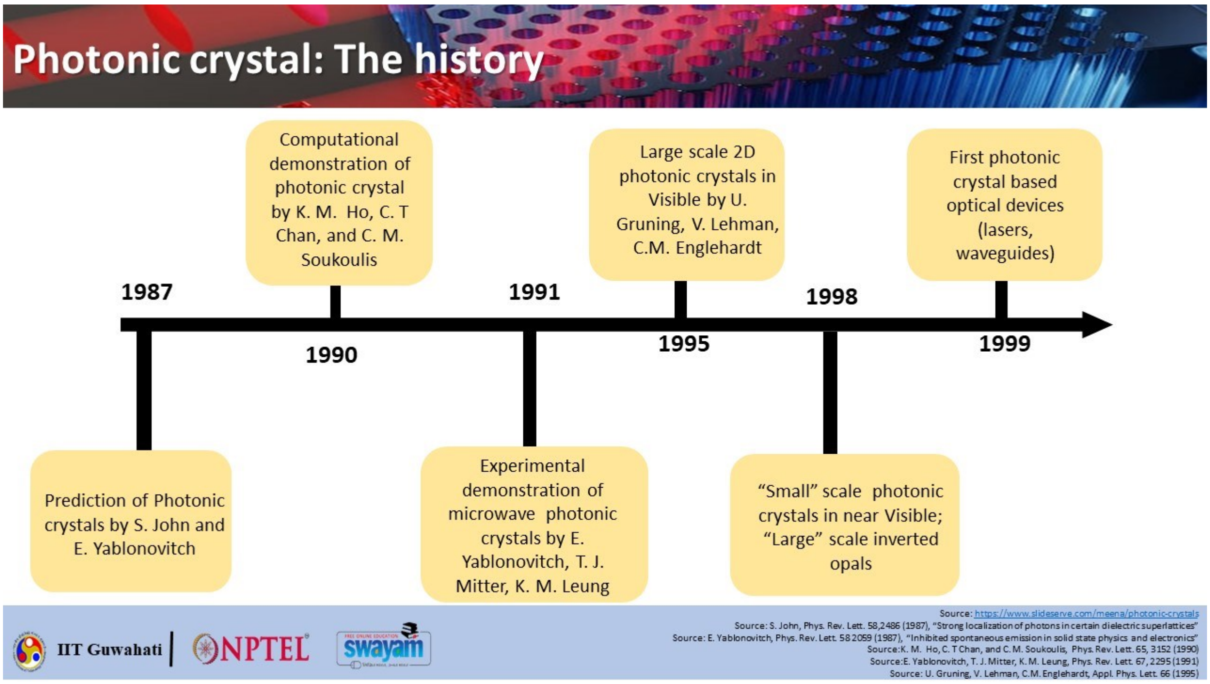
So, d is comparable to λ. This is the domain of photonics. And there is another one also possible where the elements are much, much smaller than the wavelength of light and that makes it go to nanophotonics domain. So nanophotonics or nano optics is again, it's the study of the behavior of light on nanometer scale, or actually it is basically the interaction of nanometer scale object with light. So, when we talk about photonic crystal, that basically falls in this particular category where the relative size D of the constitutive elements are basically comparable to the wavelength of the electromagnetic wave. So, what are the applications of photonic crystal in 21st century? So, if you see that even though the discovery of photonic crystal dates back to centuries ago, it is still relevant in today's modern world.



And we will see the historical timeline and the progress of research in photonic crystal technology very shortly. So here we'll show some major areas of photonic crystal-based application. So, figure one shows the overall application of photonic crystal where it actually covers a wide range of technologies. And some of these technologies are still progressing in today's time. Photonic crystals can be used as sensors for solar stream generation.

They can be used for catalysis, solar cell. They can be used as dielectric mirrors, transistor, photonic diodes, color display, smart detector, optical insulator, light emitting diode, polarizers, optical filters, lasers, and so on. So, you can see there are a lot of relevant applications of photonic crystals in today's world. If you see this figure too, it tells you how photonic crystal-based laser will revolutionize the market in the future. So, they can be used for self-driving robots, self-driving cars.

They can be used for construction machinery, automobiles, healthcare, imaging applications, processing applications like solar cells, electronic devices, LiDAR, light-based detection and ranging, and all this. So here, this particular figure shows you the applications of photonic crystal-based sensors. So, if you look carefully, it can actually tell you that you can make humidity sensor, temperature sensor, strain sensor, and different type of other sensors based on photonic crystal. So, all in all, you can actually have a very big market of sensors based on photonic crystals. You can have a lot of, you know, automation done through photonic crystal lasers and all those different applications are also possible.



So, if you want to briefly look into the history of photonic crystal, here it is. So photonic crystals have been studied in one form or the other since 1887, but no one used this term photonic crystal until over 100 years later after Sajeev John and E. Yablonovitch, they actually published two milestone papers on photonic crystals in 1987. Sajeev John actually was formulating and answer to the question whether Anderson localization of electrons in disordered solid can be extended to photons in a strongly scattering medium and he predicted that localized states of the electromagnetic field can be created in a periodic dielectric medium. and at the same time Yablonovitch was also trying to address the possibility of suppressing the unwanted spontaneous emission affecting the semiconductor lasers and he then predicted a 3D periodic dielectric that can produce a forbidden gap in electromagnetic spectrum So as a consequences of the unique properties of the periodic photonic crystals, they attracted worldwide attention of the physicists, chemists, and engineers in the field where photonic crystal is now seeing continuous expansion.

So the computational demonstration of photonic crystal was shown in 1990 by Chan and Soukoulis. In 1991, experimental demonstration of microwave photonic crystals was done by Yablonovitch group. In 1995, large-scale 2D photonic crystal in visible range was done by Gruning and Lehman. 1998 saw small-scale photonic crystals near visible and large-scale inverted opals. And in 1999, the first photonic crystal based optical device such as lasers, waveguides were realized.

Motivation

➢ *Photonic crystal market: Expected to grow exponentially.*

- Growing use of image sensors and LED applications have fostered demand for photonic crystals.
- Low power consumption, high reflectivity, and a high resolution of pixels per inch: To drive photonic crystal demand during the forecast period.

Figure: Photonic Crystals Market Size USD 99.26 Bn by **2027**

So that's a brief history of photonic crystals. And what is the motivation of working on photonic crystal currently? is that the photonic crystal market is expected to grow exponentially. You can see it is expecting a growth rate of 8.2 percent CAGR. Growing use of image sensors and LED applications have fostered demand for photonic crystals.

Lower power consumption low power consumption, high reflectivity and high resolution of pixels per inch. These are basically driving the demand for photonic crystal during this forecast period. You can also see the number of papers being published on photonic crystal over the years. So, this is typically the data during the COVID break. So, there is this bit of decline here, but overall the trend shows you that there is a lot of people still interested in the research of photonic crystals.

Motivation

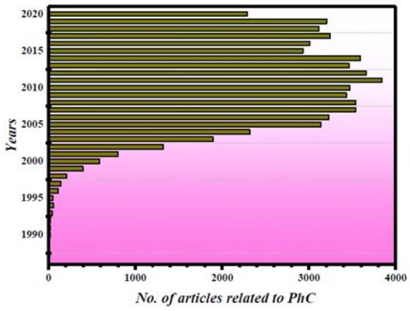


Figure 1 : The annual trend of Photonic Crystal (PhC)-related publications between 1990 and 2020.

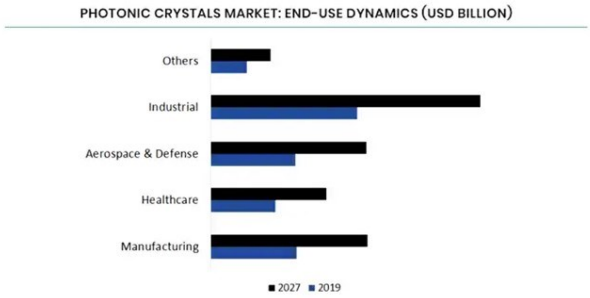


Figure 2 : Photonic crystal market analysis in different sectors.

Source: Butt, M. A., Svetlana Nikolaevna Khonina, and N. L. Kazanskiy. "Recent advances in photonic crystal optical devices: A review." *Optics & Laser Technology* 142 (2021): 107265.
Source: https://www.emergenresearch.com/industry-report/photonic-crystals-market

Figure two here shows the photonic crystal market analysis in different sectors like manufacturing, healthcare, aerospace and defense, industrial and others. And you can see that there is a rapid growth towards, you know, 2027 as well. So, with that we understood the application brief application area and motivation behind studying photonic crystal technology. And right now, let us go into bit of technical details of each of these terms. So, when you say crystals, so what comes to your mind? So, people usually visualize beautiful mineral objects with smooth faces in regular dielectric patterns.

Crystals

- **Definition:** A solid material whose constituents (such as atoms, molecules, or ions) are arranged in a highly ordered microscopic structure.
- **Crystal Types:**
  - **Crystalline**: A solid material in which the atoms, ions, or molecules are arranged in an ordered and repeating patterns.
  - **Polycrystalline**: Consist of multiple crystalline regions, known as grains.
  - **Amorphous**: Non-crystalline materials which lack a regular and repeating atomic structure, resulting in a disordered arrangement.
- Not all solids are crystals.

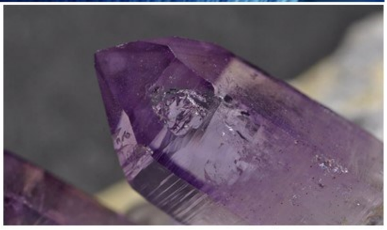


Figure 1: Crystals of amethyst quartz

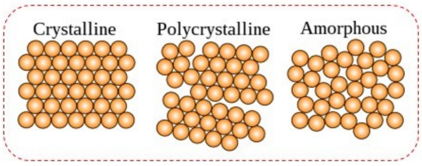


Figure 2: Types of crystals according to their periodic arrangements

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Source: https://en.wikipedia.org/wiki/Crystal
Source: https://www.gemsociety.org/article/crystal/

Others might imagine elegant glassware. For gemologists, the scientific definition of a crystal goes right to the atomic level. So, it is something like a solid material. whose constituents such as atoms, molecules or ions are arranged in a highly ordered microscopic structure, okay. So, this is typically a crystal of quartz So there are different crystal types. So, we can say a solid material is crystalline, where the atoms, ions, or molecules are arranged in an ordered and repeating manner, something like a flawless diamond.

This is how crystalline arrangement looks like. It's a perfect orderly pattern. And then you have polycrystalline, which consists of multiple crystalline regions, which are known as grains. As you can see, here are different crystalline regions. So common examples are like most metals and ceramics. And then there is amorphous materials, which are basically non-crystalline materials, which lack a regular or repeating atomic structure.

So it results in a disordered arrangement. So typical example is glass. Now remember that not all solids are crystals. So, for example, when liquid water starts freezing, the phase change begins with small ice crystals that grow until they fuse, forming a polycrystalline structure. In the final block of ice, each of the small crystals, which are called crystallites or grains, is a true crystal with a periodic arrangement of atoms but the whole polycrystal does not have a periodic arrangement of atoms because the periodic pattern is basically broken at the grain boundaries so from that those are like natural crystals from that people have engineered photonic crystals

Photonic Crystals

- Photonic crystals are composed of periodic dielectric or metallo-dielectric nanostructures that affect the propagation of electromagnetic waves (EM).
  - Photonic crystals contain regularly repeating internal regions of high and low dielectric constant as shown in figure 1.
  - By shaping the incident waves, one steers the waves deep into the crystal, thereby enabling the focusing of light at any desirable depth.(see figure 2)

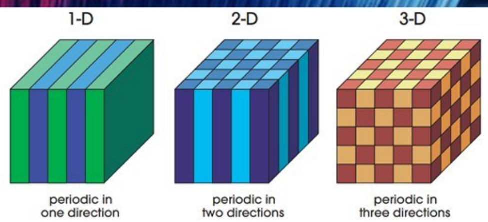

Figure 1: Simple examples of one-, two-, and three-dimensional photonic crystals.

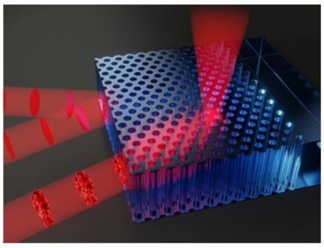

Figure 2: Interaction of light with a Photonic Crystal

Source: https://www.opli.net/opli_magazine/eo/2021/steering-waves-deep-into-a-forbidden-gap-april-news/

Now, what is photonic crystals? Photonic crystals are basically composed of periodic dielectric or metallo-dielectric nanostructures that affect the propagation of electromagnetic light. Now, they are basically containing regularly repeating internal regions of high and low dielectric content.

So here you can see different colors. They represent different dielectric constants. So, this is where high, low, high, low being repeated in 1D, one direction. So, it's called a 1D periodic crystal or 1D photonic crystal. This one shows the periodicity in basically two dimensions. So here high, low, high, low patterning is changing in two directions.

So, this is basically two-dimensional photonic crystal and this is a three-dimensional photonic crystal. So, the different colors here they represent different materials with different dielectric constants and What is important? So 1D, 2D and 3D basically are the periodicity of the dielectric material along one axis or more. So that will tell you what photonic crystal it is, whether it's a 1D photonic crystal or 2D or 3D photonic crystal. Now, by shaping the incident waves, one can steer the waves deep into the crystal, thus enabling the focusing of light at any desirable depth as shown in this particular figure. So, here we will also see in the next slide that how basically designer can control the propagation of light in this crystal.

How do Photonic Crystals work

- Photonic crystals work by exploiting the principles of interference and periodicity to control the propagation of light within a material.

- The Bragg's equation is a fundamental component of understanding how photonic crystals function.

$$2d\sin(\theta) = m\lambda$$

d: Represents the spacing between the layers or periodic elements in the crystal lattice.
θ: Is the angle of incidence of the incoming light.
m: Denotes an integer (1, 2, 3, ...) representing the order of the diffraction peak.
λ: Represents the wavelength of the incident light.

- **Bandgap Formation**: According to Bragg's law, if the condition of constructive interference is met for a specific wavelength and angle of incidence, then that wavelength is prohibited (falls within a photonic bandgap).

- This means that light of that wavelength cannot propagate through the crystal, creating a bandgap similar to the electronic bandgap in semiconductors.

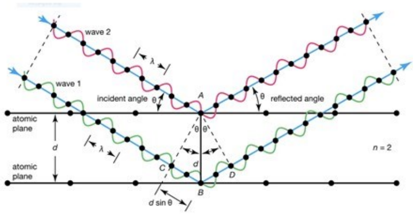

Figure 1 : Bragg Diffraction in 1D photonic crystal

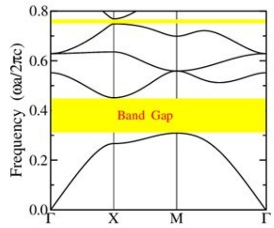

Figure 2 : Photonic band structure of a 2D photonic crystal

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Source: : https://www.researchgate.net/figure/The-band-gap-structure-of-the-photonic-crystal-consisting-of-a-square-lattice-of_fig1_2166347
Source: https://www.britannica.com/science/Bragg-law

So photonic crystals work by exploiting the principles of interference and periodicity to control the propagation of light within the material. So here is the Bragg diffraction seen in a 1D photonic crystal. So, this is like one layer and then this is another layer.

The difference between the two atomic plane is d. So, here is wave 1 that has been reflected from the second layer and this is wave 2 that is reflected from the top layer. So, what is the difference the part difference between the two is this is the dsin(θ) this angle is theta this distance is d that is the distance between the two planes and dsin(θ) is basically the length. in one arm, so the overall difference in path length will be 2sin(θ). So, when this 2sin(θ), the path length is integral multiple of λ, that is where you can say that these two waves will interfere constructively. So that is the case where you will see that you are getting reflection.

So in those case, according to Bragg's law, where the constructive interference condition is met, you can say it is for a particular λ and a particular angle. And that particular light is reflected by the crystal. It means that particular wavelength cannot enter the crystal and it is within the photonic band gap. So, this is how typically a photonic band gap structure looks like for a 2D photonic crystal. So, these are the different crystal orientation and these are the allowed frequency bands and you can see this yellow painted region shows you the band gap where no frequencies are allowed to enter the crystal or propagate into the crystal.

Photonic Crystals

- The principle of propagation of light is in the same way as the periodic potential in a crystal affects the electron motion by defining allowed and forbidden electronic energy bands.
- Photons (as waves) propagate through this structure - or not - depending on their wavelength.
- Wavelengths of light that are allowed to travel are known as modes, and groups of allowed modes form bands.
- Disallowed bands of wavelengths are called photonic band gaps.
- This gives rise to distinct optical phenomena such as inhibition of spontaneous emission, high-reflecting omni-directional mirrors and low-loss-waveguides, amongst others.

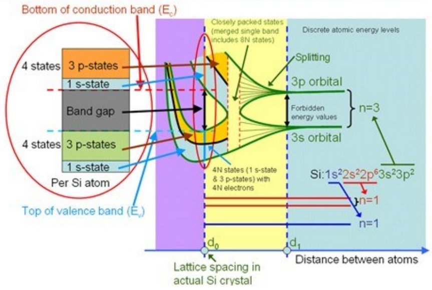

Figure 1 : Electronic band structure in a crystal

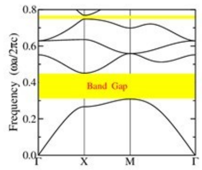

Figure 2 : Photonic band structure of a 2D photonic crystal

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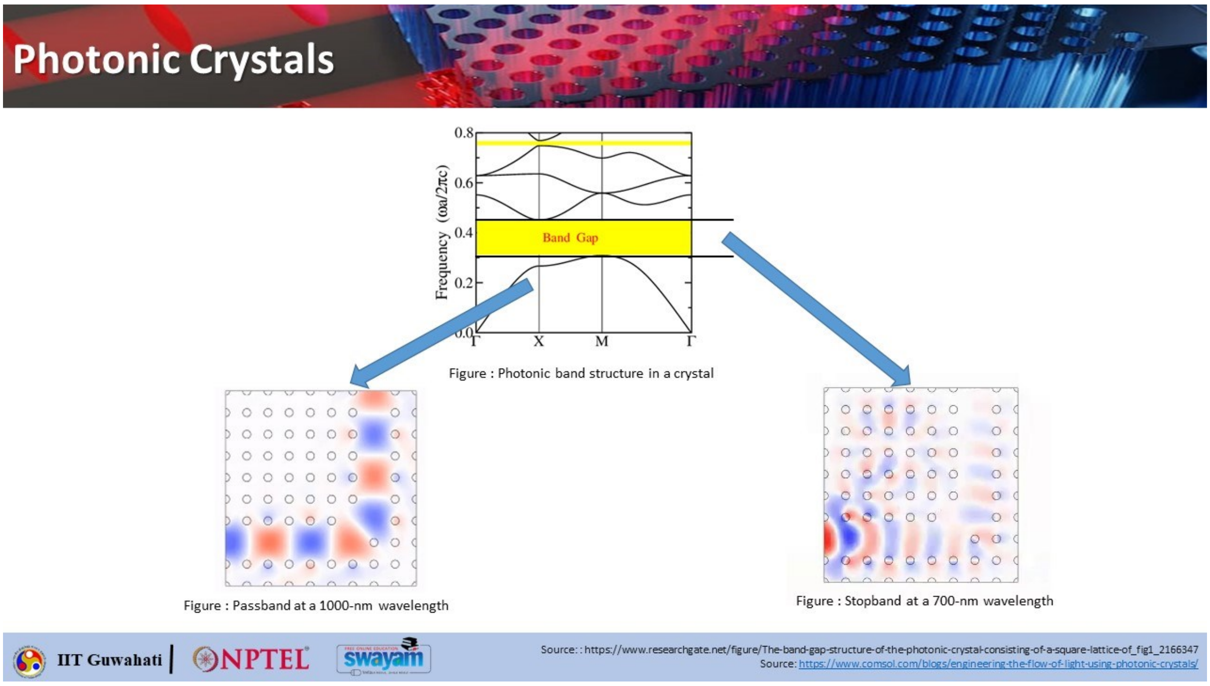
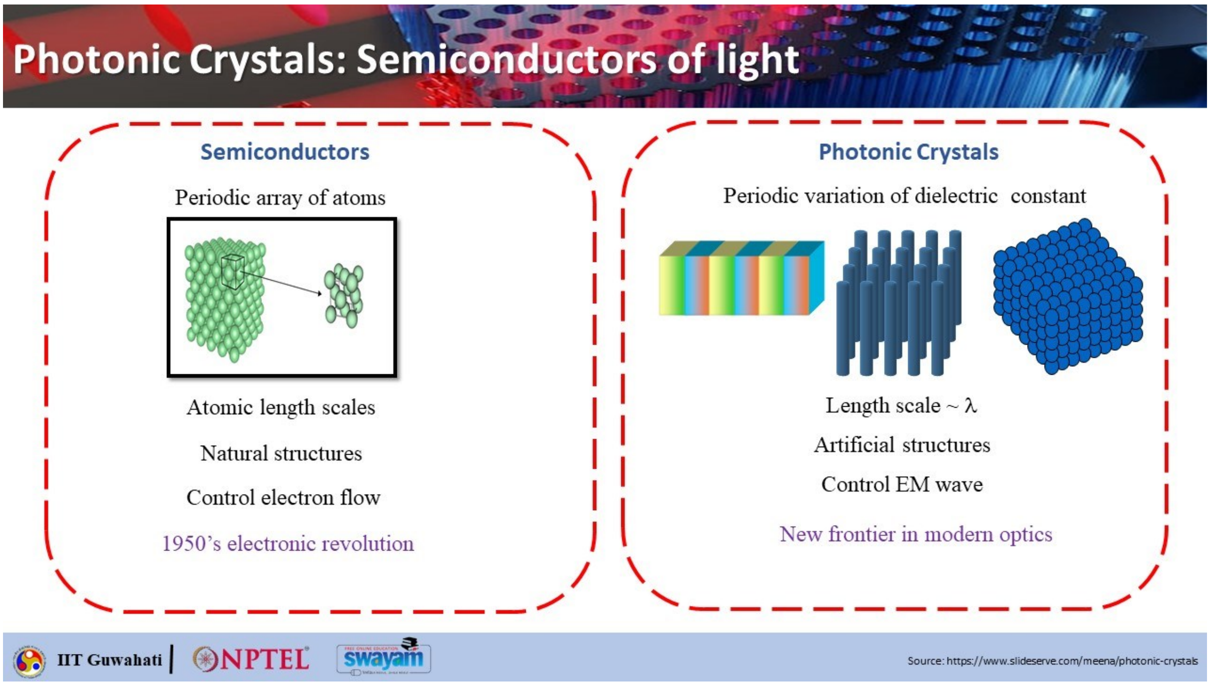
Source: https://www.globalsino.com/EM/page2632.html
Source: https://www.researchgate.net/figure/The-band-gap-structure-of-the-photonic-crystal-consisting-of-a-square-lattice-of_fig1_2166347

So, this is very similar in concept to the electronic band gap in semiconductors. So, the principle of propagation of light is in the same way as the periodic potential in a crystal effects the electron motion in semiconductors. And you can actually do that by defining allowed and forbidden electronic energy bands. just like this shown here so photons as waves they can propagate through the structure or not depends on their wavelength so this frequency also can now it also carry the information of the wavelength right so the wavelengths of light that are not allowed that that are allowed to travel those are known as modes and a group groups of allowed modes form bands okay So, the disallowed bands of wavelengths are called photonic bandgaps ok. So, this gives rise to distinct optical phenomena such as inhibition of spontaneous emission, high reflecting omnidirectional mirrors and also low loss waveguides etcetera.



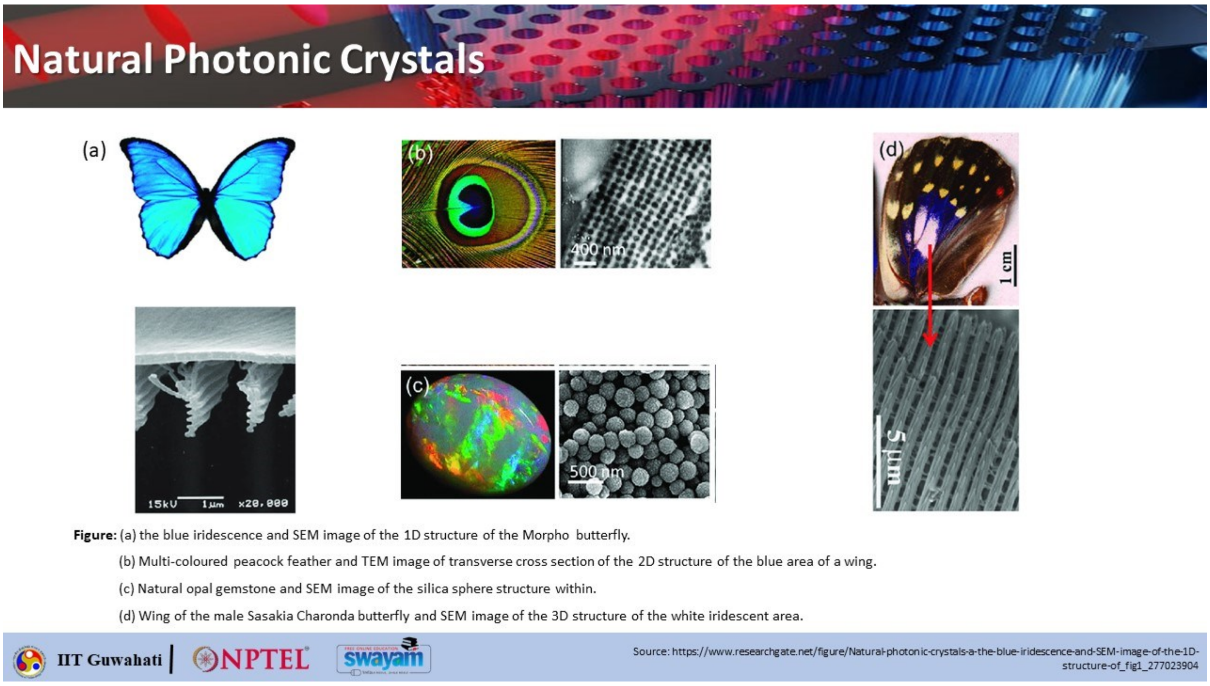
So, if you carefully look into the band diagram and create a waveguide, which is a band waveguide, 90-degree band waveguide. And you can see if, so this is a 2D arrangement of, say, holes or cylinders. Okay, we'll go into the details of the structure later on. What you can see, one particular row is missing here.

So that is how you create a line defect. And in this particular case, you are seeing that you are having a pass band at 100 at 1000 nanometer wavelength. And you can see the light is actually able to propagate because it is within the allowed band. But if you choose the frequency that is within the band gap for the same structure, you can see this cannot propagate through this particular channel. So, you are actually having a stop band at 700 nanometer wavelength which basically falls within the band gap.



So here the main idea is to show you that within the band, the frequencies outside the band gap can propagate, but which lies within the band gap cannot propagate through this crystal. So, if you compare photonic crystal with the semiconductors, you can say that photonic crystals are basically semiconductors of light. In semiconductors, you have periodic arrangement of atoms. Here in photonic crystal, you have periodic variation of dielectric constant.

This is how you do it in 1D. This is how you do it in 2D. And this is how you do it in 3D. So here it is atomic length scale, but here the length scale is of the order of wavelength. Here you are mainly talking about the natural structures, but here these are mainly artificial structures which are manmade designed. So, they can control electron flow whereas, photonic crystals can control electromagnetic wave or light flow ok. So, semiconductor as we know have revolutionized electronics industry and then photonic crystals now have the potential to revolutionize photonic circuits photonic integrated circuits as well as towards 6G communication where different devices can be actually made using topological photonic insulators.



If you look into the natural photonic crystals, nature also gives us a lot of applications or application scenarios where photonic crystals are found. So, over the years, scientists have discovered that the iridescence of various colorful creatures, something from beetles to birds to butterflies, they're not mainly because of the pigmentation, rather they are because of the microscopic structures which are there on the particular creature. So here is the SEM image of a Morpho butterfly wing. So, you can see these are basically periodic structures which are able to reflect these bright, beautiful colors. Similarly for all this you know peacock feather and this crystal you can see that all of them are basically periodic crystal which are found naturally so this is for for peacock feather and this is for a opal gemstone and this shows the SEM image of silica sphere structure within this which is basically a 3D photonic crystal kind of arrangement which gives that bright color So, this is for again from another butterfly and you can see the SEM image of the 3D structure for this particular white area.

So, what is happening? The bright color that you see that are not coming from the pigmentation rather they are basically the color reflected because of the photonic band gap. which exist naturally because of the structure of these natural objects. So, photonic crystal is being engineered by God for all these particular creatures. Now, as engineers, when we discuss and think about photonic crystal engineering, we need to think why we need photonic crystals. The invention of photonic crystals actually addressed several long-standing challenges in the field of optics and photonics.

Why Photonic Crystals

- The invention of photonic crystals addressed several longstanding challenges in the field of optics and photonics.

- Some of the key challenges that photonic crystals have helped overcome include:
  - **Light Confinement and Guiding**:
    - Before photonic crystals, achieving effective light confinement and guidance in small-scale optical devices was challenging.
    - Photonic crystals allowed for the creation of miniature waveguides and cavities that could confine and manipulate light at the nanoscale, enabling the development of compact optical components.
  - **Optical Bandgap Creation**:
    - Controlling the flow of light and creating optical bandgaps (forbidden regions of certain wavelengths) was difficult with conventional optical materials.
    - Photonic crystals introduced a way to engineer these bandgaps, enabling the development of photonic devices with precise spectral control.

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Some of the key challenges that photonic crystals have helped overcome, they include light confinement and guiding. So, before photonic crystals achieving effective light confinement and guidance in small scale optical devices was very challenging. So, photonic crystals allowed for the creation of miniature web guides, sharp bands, cavities that can confine and manipulate light at the nanometer scale, macrometer scale, enabling the development of compact optical components. Second one is optical bandgap creation.

So controlling the flow of light and creating optical bandgaps. Bandgaps is basically a forbidden region for certain wavelengths. Was difficult with conventional optical materials, but photonic crystal allowed us to achieve those. So photonic crystals actually engineered a way introduced a way to engineer these bandgaps enabling the development of photonic devices with precise spectral control.

Why Photonic Crystals

- **High-Resolution Imaging**:
  - Overcoming the diffraction limit in optical imaging was a long-standing challenge.
  - Photonic crystals paved the way for superlenses and high-resolution imaging techniques, allowing researchers to image nanoscale structures with greater detail and accuracy.
- **Efficient Lasers**:
  - Achieving efficient and high-performance lasers with narrow linewidths and low threshold powers was a challenge.
  - Photonic crystals provided a platform for designing and fabricating advanced lasers, which find applications in telecommunications and scientific research.
- **Optical Signal Processing**:
  - Traditional optical signal processing faced limitations in terms of speed and efficiency.
  - Photonic crystals have been used to create photonic circuits and switches, enabling faster and more efficient optical data processing.

Further, it has also helped in high resolution imaging. So, when you want to do high resolution imaging, overcoming the diffraction limit in optical imaging becomes a long-standing challenge.

So using photonic crystals, you can actually make superlenses and high-resolution imaging techniques, which we'll discuss in the subsequent lectures that has allowed researchers to image nanoscale features with great details and accuracy. Achieve efficient lasers. Achieving efficient and high-performance lasers with narrow line widths and low threshold power was always a challenge. So, photonic crystals provided a platform for designing and fabricating advanced lasers which find applications in telecommunications and other scientific research.

Why Photonic Crystals

- **Quantum Technologies**:
  - Developing components for quantum technologies, such as quantum computers and quantum communication systems, required precise control over the generation and manipulation of quantum states of light.
  - Photonic crystals have been instrumental in advancing these technologies.

- **Advanced Sensors**:
  - Achieving high sensitivity and selectivity in optical sensors and detectors was a challenge.
  - Photonic crystals have been employed to develop highly sensitive and specific sensors for various applications, including biosensing and environmental monitoring.

It has also helped towards optical signal processing. So traditional optical signal processing faced limitation in terms of speed and efficiency. Photonic crystals have been used to create photonic circuits and switches, which enabled faster and more efficient optical data processing. They have also been very useful in quantum technologies. It's like developing components for quantum technologies such as quantum computers and quantum communication systems required precise control over the generation and manipulation of the quantum states of light. So photonic crystals have been very instrumental very useful in advancing this technology.

So you can actually look into lot of new research papers which are basically looking forward to this kind of applications of photonic crystals. Advanced sensors, achieving high sensitivity and selectivity in optical sensors and detectors was a challenge. So photonic crystals have been employed to develop highly sensitive and specific sensors for various applications, including biosensing and environmental monitoring. control light manipulation.

Why Photonic Crystals

- **Controlled Light Manipulation**:
  - Photonic crystals can control the flow of light in specific ways, allowing for the creation of optical bandgaps, which act as "forbidden" regions for certain wavelengths of light.
  - This property is essential for designing optical devices with precise control over light propagation.
  - Light propagation inside a photonic crystal is forbidden by a propagation gap. (see figure)
  - By shaping the incident waves, one steers the waves deep into the crystal, thereby enabling the focusing of light at any desirable depth inside the otherwise forbidden gap.(see figure)

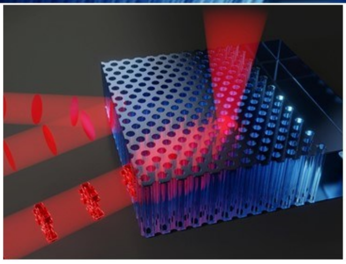

Figure : Interaction of light with a Photonic Crystal

Source: https://www.opli.net/opli_magazine/eo/2021/steering-waves-deep-into-a-forbidden-gap-april-news/

So, photonic crystal can control the flow of light in specific ways allowing for creation of certain you know specific optical band gaps.

So, these band gaps are nothing but the forbidden region of certain wavelength of light inside that particular crystal. So, this property is essential for designing optical devices with precise control over light propagation. So light propagation inside the photon crystal is forbidden by a propagation gap. So, you can see here, this one, this particular wavelength is reflected, okay, but this particular wavelength is propagating. So, by shaping the incident waves, one can steer the wave deep into the crystal, enabling focusing of light at a desirable depth inside the otherwise forbidden gap, okay.

Why Photonic Crystals

- **Miniaturization**: Photonic crystals enable the miniaturization of optical components and circuits, making it possible to create smaller and more efficient photonic devices, such as waveguides, lasers, and sensors.

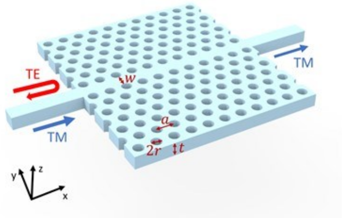

Figure 1 : Photonic Crystal waveguide polarisation filter

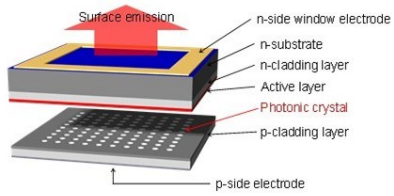

Figure 2 : Photonic Crystal based surface emitting laser

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Source: https://www.flexcompute.com/tidy3d/examples/notebooks/PhotonicCrystalWaveguidePolarizationFilter/
Source: https://www.sciencedirect.com/science/article/pii/S0925400516319116
Source: https://www.rp-photonics.com/photonic_crystal_surface_emitting_lasers.html

So, one particular wavelength will simply reflect the other can actually be focused at a particular point. Photonic crystal also helped us towards the miniaturization. Miniaturization means making the devices small. So photonic crystals have enabled miniaturization of optical components and circuits, making it possible to create smaller and more energy efficient photonic devices such as web guides, lasers and sensors.

So here you can see a photonic crystal web guide-based polarization filter. So TE and TM both polarizations may incident, but then TE is basically reflected back and only TM is allowed to propagate. Okay. So only the TM mode. So, what happens? TE is basically having a band gap and TM is allowed to propagate.

Now, the second application is about photonic crystal-based surface emitting laser. So, if you remember while many semiconductor lasers are edge emitting lasers and some of them are surface emitting that is the output beam is basically perpendicular to the wafer surface. Now, originally such lasers have been realized as vertical cavity surface emitting laser or VC cells, okay, where the laser resonator contains at least one external mirror. However, it is possible to obtain vertical emission in combination with a horizontal cavity as well. That is the device where the intracavity laser radiation propagates essentially in directions along the wafer surface. Okay, one of the ways to realize this kind of thing is to utilize a 2D photonic crystal structure.

Okay, like this. Okay, and such devices are called photonic crystal surface emitting laser. Okay, so for VC cells, one needs to strongly restrict the diameter of the active region when single mode operation is required. That usually limits the possible output power to a couple of milliwatts. higher much higher output power is possible with larger active areas and this is where photonIC crystal comes into the picture as it provides much larger active area while maintaining single mode operation. So, that is where photonic crystal-based surface emitting lasers are also gaining popularity.

Why Photonic Crystals

- **Optical Computing**:
  - The development of photonic crystals has the potential to revolutionize optical computing.
  - By controlling the flow of light at the nanoscale, they can be used to build high-speed optical logic gates and interconnects, paving the way for faster and more energy-efficient computing.

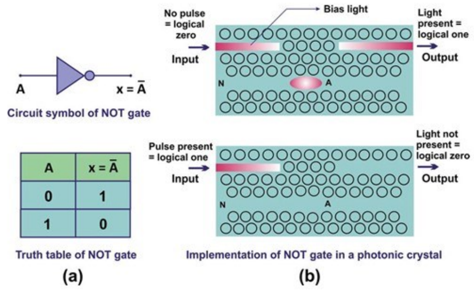


Figure : (a) Circuit symbol and truth table of a NOT gate and (b) implementation of NOT operation using a photonic crystal slab.

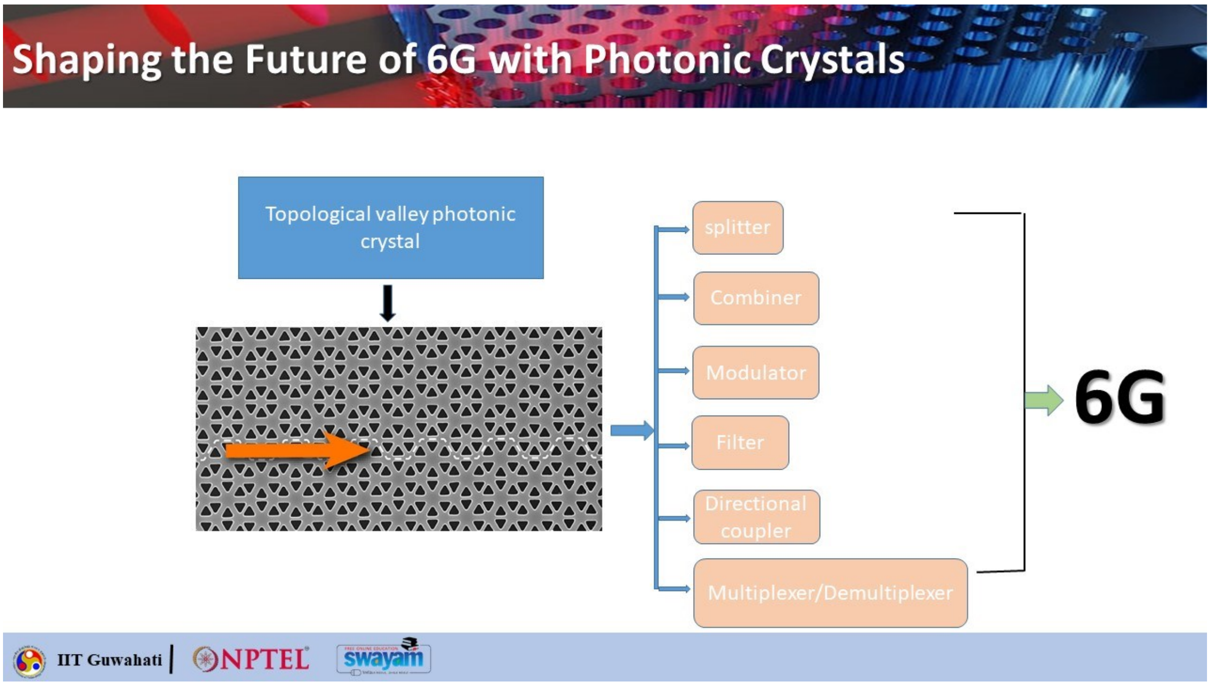
Source: https://www.intechopen.com/chapters/57266

Important aspect is optical computing. The development of photonic crystal has actually got the potential to revolutionize optical computing and by controlling the flow of light at nanoscale, they can be used to build high speed optical gates and interconnects. So, these two, you know, optical gates and interconnects can help you get faster and more energy efficient computing. So, here is an example of how you know you can realize a NOT gate using a photonic crystal slab ok. So, what is done a non-linear medium with negative value of N2 can be used for achieving this goal as you can see here.

Okay, here coupling between the waveguide. So, this is the waveguide and the nano cavity. Okay, is such that when there is no optical pulse at the input the bias light would emerge at the output. Okay, but on the other hand when the optical pulse is passed through the input refractive index of the medium gets reduced due to the negative nonlinearity of the medium. As a result, the resonant wavelength of the resonator differs considerably from the input wavelength of the bias light, resulting in decoupling of the bias light from the nano cavity and the output.

So, in this case, light is not present. So, it behaves like a logical zero. when there was a pulse present. But in this case, when there was no pulse, because of the coupling of this tube, there was some light present. So, it's like when there is a zero, you get a one.

When there is one, you get a zero. So, it basically works like a NOT gate. So, in this way, the requirement of a NOT gate can be satisfied using this design, wherein the presence of an optical pulse at the input and gives no light at the output and the absence of the optical pulse at the input give an optical pulse at the output. So, this is how you can actually differentiate logic 1 and logic 0. So, if one gate, not gate can be realized, you can also think of the other fundamental gates like NAND gates and NOR gates, and then you can actually do optical computing



Now, photonic crystals are also shaping the future of 6G technologies with photonic crystal. So topological valley photonic crystal is a different type of photonic crystal where we'll go into the details later on where you can actually make domain boundaries and make light propagate without any backscattering or any other losses.

So they can be used for fabricating splitter combiner modulator filters directional couplers multiplexer demultiplexer and so on so all this technology all these devices will be very useful for enabling 6g at high frequency something like say 270 to 80 gigahertz range okay So these are all based on topological photonic crystals that can revolutionize the communication technology. So, with the advent of 6G, topological photonic crystals, which are basically a special class of photonic crystals, which can manipulate the flow of light and they are more robust to wave propagation through defects and bands. So, this is a very dynamic area of research and it's a very hot topic people are currently working on it and in future they can come up with many exciting innovations. So, many passive and active devices can be modeled using this particular technology which can contribute towards setting up the entire 6G technology in the future.

Topological Photonic Crystals: A Revolution

- **Topological photonics** is a cutting-edge field of research that combines principles from topology, a branch of mathematics, with photonics, the study of light.
  - Topological photonics emerged in the early 2000s, drawing inspiration from the ground-breaking discovery of topological insulators in condensed matter physics.
  - These insulators exhibit unique properties at their surfaces, where certain electronic states are topologically protected, leading to remarkable robustness against disorder and defects.
  - 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.

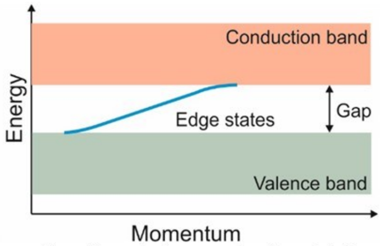


Figure: Energy band representation of a topological material

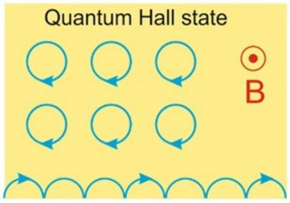


Figure: Representation of electron movement

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
Source: https://www.informatyka.agh.edu.pl/media/uploads/kqis_2019_rev.pdf

So, how it works? So, topological photonics is basically a cutting-edge field of research that combines the principle from topology which is a branch of mathematics with photonics which is basically study of light.

So, topologic means where they will keep the main feature same, but then the shape can go some kind of transformation, but that will keep overall feature similar. OK, so we'll go into details right now. It's the first lecture, so we'll not tell you about more details right now. OK, we'll see what are these topological photonics states.

They basically depend on this particular edge states. And also, this is a diagram of a topological photonic insulator where When a magnetic field is applied, you can see circulating currents in the bulk. But then at the boundaries, you can see helical loops through which electrons can propagate. So, these are basically robust against any kind of disorder or defects. That is why there is no backscattering loss when you create structure based on topological photonic insulators.

They are helpful in forming 1D channels that are basically developed at the edges of the sample. And that is why I was telling that we need to do it at the domain boundary. So, each of these edge channels, they exhibit the quantized conductance that is the characteristic of a 1D transport. And these charge carriers in these channels are very resistant to scattering. So, you can actually transport energy without any kind of dissipation.

Topological Photonic Crystals: A Revolution

Electrical interconnect bottleneck: THz Si interconnects

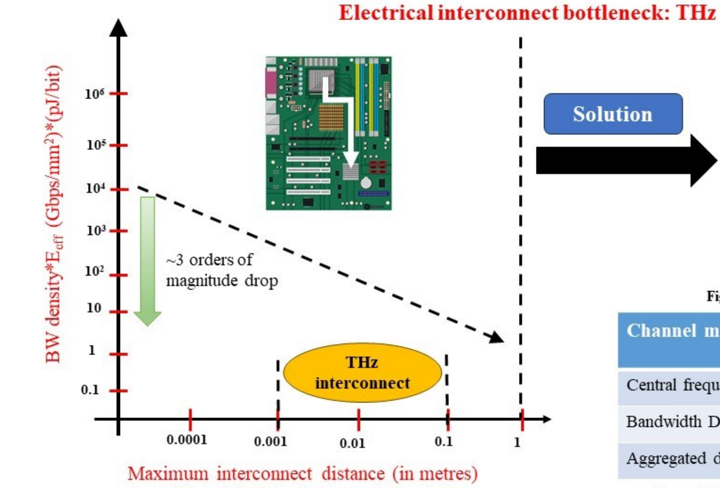


Figure: Electronics interconnect bottleneck

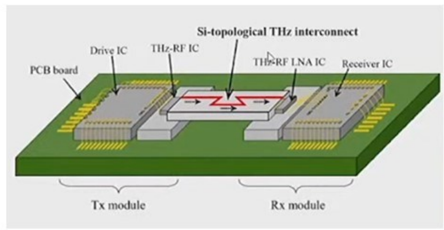


Figure: Schematic representation of a Silicon topological THz interconnect

Channel media	Copper interconnect	Silicon interconnect
Central frequency(GHz)	3 to 6	335
Bandwidth Density (GHz/mm^2)	~5	100
Aggregated data rate per channel	10 Gbit/s	300 Gbit/s

Figure: Table showing the comparison between copper and silicon interconnects

Source: https://spectrum.ieee.org/silicon-photonics-stumbles-at-the-last-meter
Source: Gu, Qun Jane. "Sub-THz/THz interconnect, complement to electrical and optical interconnects: Addressing fundamental challenges related to communication distances." IEEE Solid-State Circuits Magazine 12.4 (2020): 20-32.

So why they're very important? They're very important towards the interconnect. So when there is chip to chip interconnect, which are typically made of copper, but when you go for high frequency, something like 280 or 300 gigahertz, which will be required for 60 technology you can also see that the bandwidth density and the energy efficiency with the length of the Interconnect it drops dramatically so and copper is also very lossy at those high frequencies So we act basically need to use the silicon topological photonic insulator based interconnects for connecting one IC to another IC, okay. So, there will be very good interconnects. So, you can see that the copper interconnect will be typically works at 3 to 6 gigahertz, whereas silicon interconnect works around 335 gigahertz. and they support much larger bandwidth density and also much larger aggregated data rate per channel.

So, this is the future, okay. We have to look for topological photonic crystal-based solution towards developing this interconnect. So, this is a typical example of a straight domain boundary. So, this is like one-unit cell and a different type of unit cell where there is a boundary.

This is like a straight boundary. You can also arrange them in a twisted pattern. Simulation has shown that the twisted and the straight typically have the similar transmission characteristics. As mentioned, these topological states, they do not have any backscattering loss and they're very robust to defects and bends. So, you can actually make them go in any shape without any loss.

Okay. So, they are robust against imperfections and disorders. And this robustness is critical for maintaining the signal integrity in high speed communication system, making them less susceptible to signal loss and interference. They're also backward compatible. So topological photonics can be integrated into existing photonics systems, making it a viable option for upgrading the current 5G networks to meet the demands of the 6G communication.

Topological Photonic Crystals: A Revolution

- Scientists saw the potential to apply the topological insulator principles to control and manipulate light.

- This emerging field offers exciting prospects for revolutionizing 6G communication networks which would require THz interconnects.

- It comes with several advantages over existing photonic crystal structures:-

  - **Robustness to Defects**:

    - Topological photonic structures are inherently robust against imperfections and disorder.

    - This robustness is crucial for maintaining signal integrity in high-speed communication systems, making them less susceptible to signal loss and interference.

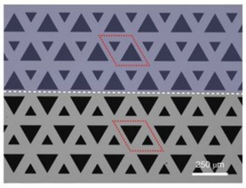


Figure: An optical image of the fabricated domain wall(shown by white dashed lines)

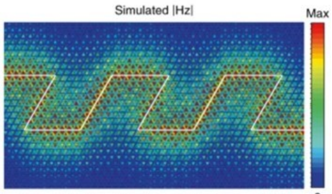


Figure: Simulated |Hz| field distribution (colour scale) in the on-chip VPC at 0.335 THz

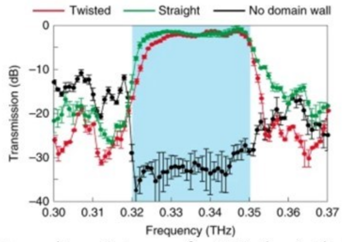


Figure: Measured transmission curves for a VPC with a straight domain wall, a twisted domain wall with ten corners and no domain wall.

Source: Kumar, Abhishek, et al. "Phototunable chip-scale topological photonics: 160 Gbps waveguide and demultiplexer for THz 6G communication." *Nature communications* 13.1 (2022): 5404.

So, all of you must be knowing that 6G communication demands terahertz of tbps data rate where current 5G typically can deliver up to say 10 gbps data rate.

So, 6G along with topological photonic crystals is going to build the future technology. Efficient signal processing is also possible using this kind of structures because they enable efficient manipulation of photonic states, allowing for faster and more energy efficient signal processing. This is particularly relevant for 6G networks that will require massive data throughput and ultra-low latency, which is typically less than a few microseconds. And also, this supports advanced optical switching. So topological photonic devices can offer advanced optical switching capabilities, facilitating dynamic network configuration and adaptive routing, which is crucial for managing the complexity of a 6G network, where it is estimated that 10 million devices IoT devices will be connected over one square kilometer of land, okay, as compared to one million that is connected in 5G technology.

Topological Photonic Crystals: A Revolution

- **Backward Compatibility**: Topological photonics can be integrated into existing photonic systems, making it a viable option for upgrading current 5G networks to meet the demands of 6G communication.
- **Efficient Signal Processing**: These structures enable efficient manipulation of photonic states, allowing for faster and more energy-efficient signal processing. This is particularly relevant for 6G networks that will require massive data throughput and lower latency.
- **Advanced Optical Switching**: Topological photonic devices can offer advanced optical switching capabilities, facilitating dynamic network reconfiguration and adaptive routing, crucial for managing the complexity of 6G networks.
- **High-Dimensional Data Transfer**: Topological photonics allows for the exploration of higher-dimensional optical states, which can significantly increase data transfer rates and capacity, addressing the burgeoning data demands of 6G.
- **Security**: The topological protection of certain photonic states can enhance the security of optical communication, making it more resistant to eavesdropping and tampering.

High dimensional data transfer rate, okay. So, topological photonic will allow for exploration of higher dimensional optical states, which can significantly increase data transfer rates and capabilities addressing the ever-increasing demands of 6G technology. And finally, the security aspect. The topological protection of certain photonic states can enhance the security of optical communication, making it more resistant to eavesdropping and tampering. So, all in all, you can see that photonic crystal, although the technology was started several decades back still has got a lot of potential to become one of the promising technologies in the current context when 6G research is going on. So topological photonic crystals are one of those important areas of research where researchers and industry people will be very much interested in.

Apart from that, the conventional photonic crystal-based devices are also particularly interesting for photonic integrated circuits where you can actually make waveguides, splitter, coupler, filter, modulator, demodulator, all different devices based on photonic crystals

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So, photonic crystal-based device engineering or bandgap engineering is very very important and this is what is the main goal of this particular course to cover all these different areas and application and show you how to do it okay so with that we'll stop here and This is all for this introductory lecture or the first lecture on photonic crystals and if you have got any doubt you can drop an email to this particular email address deb.shikdar at iitg.ac.in mentioning MOOC photonic crystal on the subject line. Thank you. Thank you.