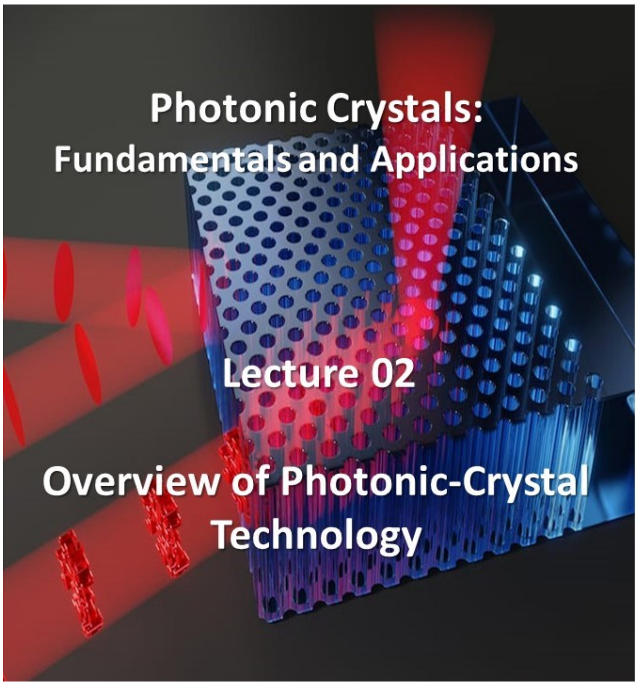

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Lec 2: Overview of Photonic Crystal technology

Hello students, welcome to lecture 2 of the online courses on Photonic Crystals Fundamentals and Applications. Today's lecture will be on the overview of Photonic Crystal Technology.

Lecture Outline

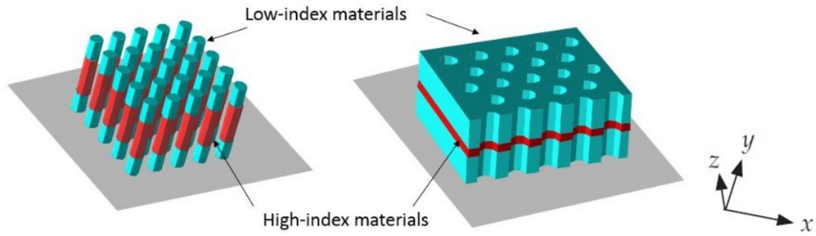
- **Photonic Crystal Slabs**
  - **Solar cells**
  - **Sensors**
  - **Lasers**
  - **Logic Gates**
  - **Polarizers, Beam Splitters**
  - **Filters**
- **Photonic Crystal Fibers**
  - **Fiber Optic Sensors**
  - **Mode splitter**
  - **Fiber Lasers**

Source: J. D. Joannopoulos *et al.*, Photonic crystals. Molding the flow of light, Princeton University Press, 2008.

So here is the lecture outline. When we talk about photonic crystal technology, photonic crystal slabs and photonic crystal fibers, they take the center stage. So, we'll discuss different applications of photonic crystal slabs today, such as solar cells, sensors, lasers, logic gates, polarizers and beam splitters, and also filters. On the other hand, for photonic crystal fibers, we'll discuss about their applications as fiber optic sensors, mode splitter, fiber lasers, and so on.

Photonic-Crystal Slabs

- Simple structures with only **one-dimensional periodicity** can be used to confine light in three dimensions by a combination of **band gaps and index guiding**.
- **Photonic-crystal slabs** or **planar photonic crystals** with *two*-dimensional periodicity but a finite thickness. They are *not* "two-dimensional" photonic crystals, despite the resemblance: the finite thickness in the vertical (z) direction introduces qualitatively new behavior, just as the periodic dielectric waveguides differed from photonic crystals in one dimension.



IIT Guwahati | NPTEL swayam Source: J. D. Joannopoulos *et al.*, Photonic crystals. Molding the flow of light, Princeton University Press, 2008.

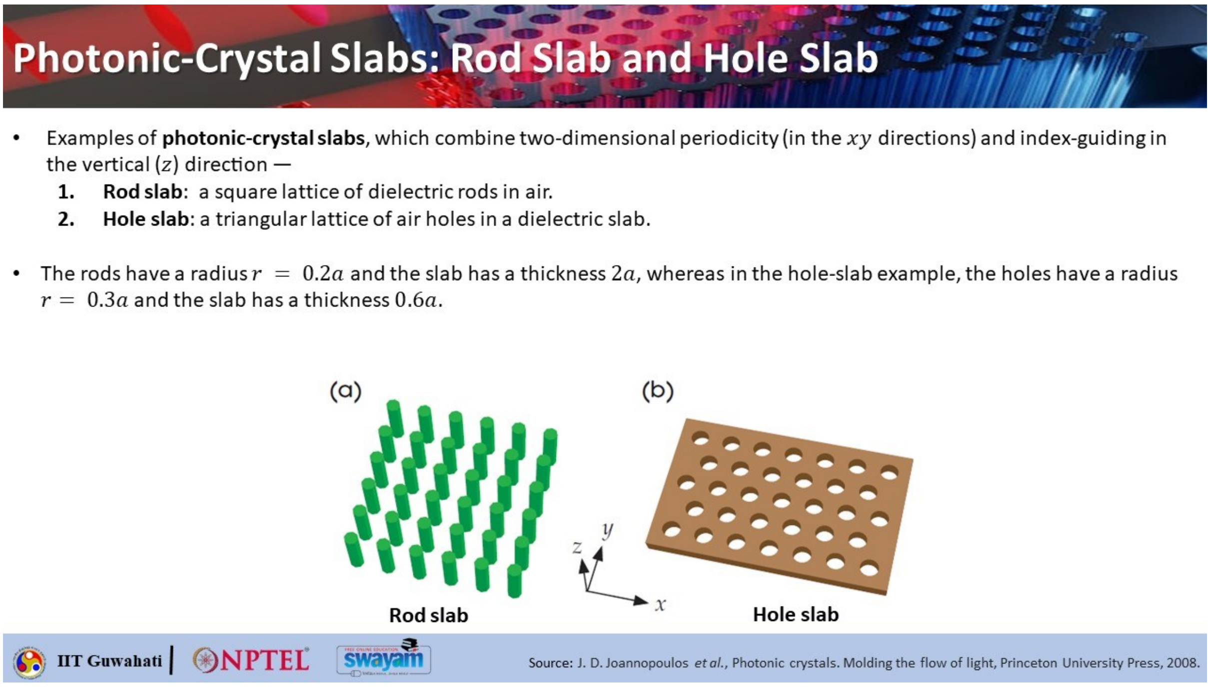
So what are photonic crystal slabs? So, photonic crystal slabs or you can say planar photonic crystals with two-dimensional periodicity, but there is a difference. They have finite thickness. So, they are not typically two-dimensional photonic crystals despite the resemblance. So, the finite thickness in the vertical or Z direction introduces a qualitatively new behavior just as for example, you can take the periodic dielectric waveguides differed from the photon crystals in one dimension.

So whether it is a one-dimensional periodicity or two-dimensional periodicity, you require a new concept to confine light in three dimensions. So that has to be coming from the combination of bandgap and index guiding. So laterally, you can actually restrict the light flow using photonic bandgaps. And in the vertical dimension, where you have finite thickness, you have to rely on index guiding. So, this is an example of a two-dimensional photonic crystal slab.

We are not calling them two-dimensional photonic crystals because they have finite thickness. So the vertical dimension is basically restricted. So here you can see the red region shows high index material and the light color region shows low index material. And the high index material is surrounded by low index material. And that is how index guiding takes place.

So this is very similar to the total internal reflection effect, which allows the light to be confined within the high index region. So, if you take the inverse of this structure of array of columns, you can actually also think of a slab with a periodic array of holes. So, here the hole thickness is basically limited. So, here also you can think of the red region to have high index material and the surrounding medium are basically low index medium that gives you that index guiding. And in the lateral dimension in x and y dimension, it is a 2D periodic photonic crystal kind of arrangement.

So, you get photonic band gap to confine light along the lateral dimensions. So, there are some examples of photonic crystal slabs. would be that they are able to combine two-dimensional periodicity in the x-y dimension and index guiding in the vertical or z direction. So, one example could be rod slab. As you can see here, it is basically a square lattice of dielectric rods in air.



Or you can actually have the inverse structure kind of, okay? So here you're basically looking for, this is not exact inverse structure because here you can see these are basically square array, square lattice. but here it is triangular or hexagonal lattice. But the concept is that here you take a slab and then you drill this periodic hole, okay, in this finite thickness slab, and you get a whole slab. So, what are the dimensions typically? So you can see that these rods have radius r which is 0.

2a. a is basically the periodicity or you can say lattice period and the slab thickness will be 2a. Okay, in this case, whereas for the whole slab example, the holes which are drilled, they will have radius of 0.3a and the overall thickness of the slab can be just 0.6a. Okay, so that way you can actually make much thinner device based on whole slab.

Applications of Photonic Crystal Slabs

Solar Cells

- Photonic crystals have been widely used in solar cells in recent years because of their unique optical properties such as **photonic band gap** and "**slow photon**" effect.
  - The introduction of photonic crystals can adjust the propagation and distribution of photons in solar cells.
  - The phenomenon of slow-photon effect is shown in the figure.
  - Photonic band gap and slow photon effect of photonic crystals can effectively enhance the efficiency of optical enrichment.
  - The introduction of photonic crystals can improve the performance of solar cells in five aspects:

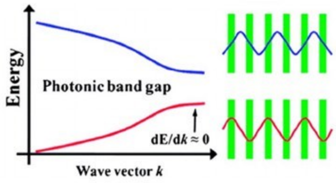


Figure: A schematic diagram of a photonic crystal "slow pho-ton" Effect

Source: Collins, Gillian, et al. "2D and 3D photonic crystal materials for photocatalysis and electrochemical energy storage and conversion." *Science and Technology of advanced MaTerialS* 17.1 (2016): 563-582.

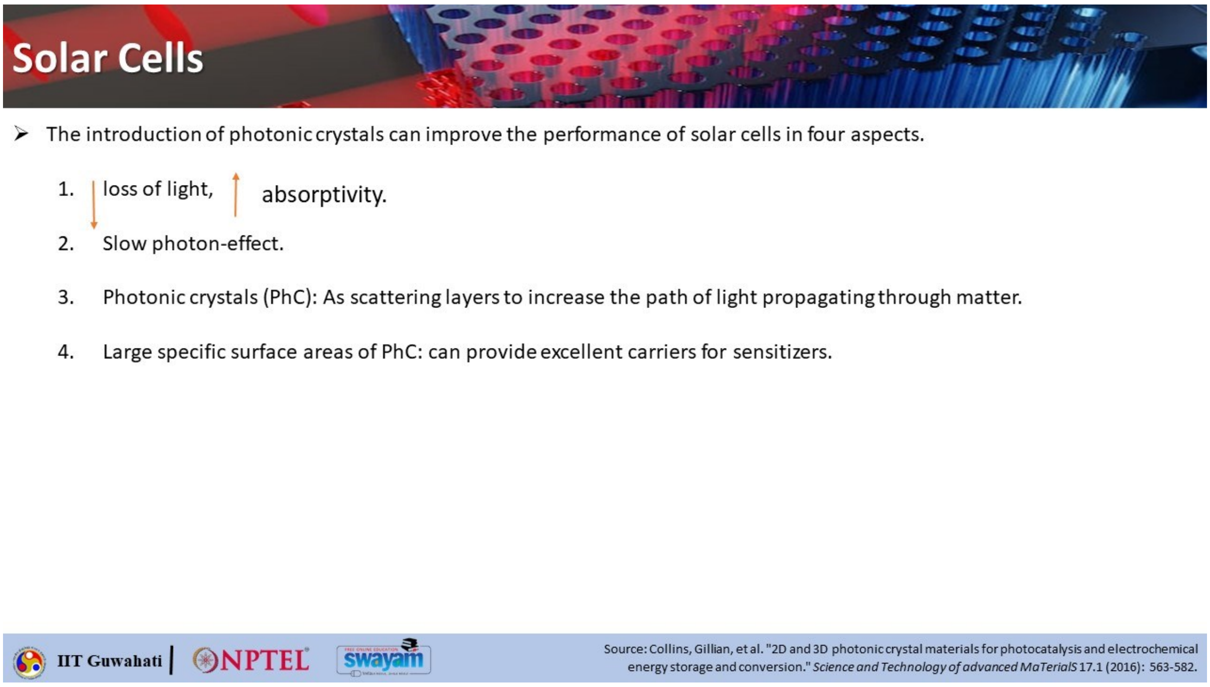
Now let us look into different applications of photonic crystal slabs. So, I believe the difference between photonic crystal slabs and 2D photonic crystal is clear. Photonic crystal slabs have a finite Z dimension or thickness and index guiding helps you confine light along the Z direction. So the first example we'll be discussing today basically solar cells. So, photonic crystal slabs have a lot of applications in solar cells in recent years because of two unique properties such as photonic bandgap and slow photon effect.

Now, the introduction of photonic crystals can adjust the propagation and distribution of photons in solar cells. And the phenomena of slow photon effect are shown in this particular figure. So here you can see it is basically the E-K diagram and this shows you the photonic band gap over here. Now, according to the Fermi's golden rule, photons whose energy is consistent within this photonic bandgap will be inhabited in their propagation and emission in the photonic bandgap, right. So, when the defect state is introduced into the photonic crystal, the photon state density at the defect state increases significantly and spontaneous emission can be enhanced at the defects state position.

In addition, the photonic crystals with defect states, protons, photons are localized at the defect location that is the optical location characterization of the photonic crystals. So, using these characteristics of photonic crystals, optical micro cavities with high enhancement factor and optical waveguides without any loss can be fabricated. Now what happens at the edge of the band gap of the photonic crystal, you can see the group velocity of the photons approaches zero. Because you can see the graph here, the dE by dK is becoming zero. It flattens out, okay? Which can form a standing wave and then it can produce a slow photon effect.

Using this effect, the interaction between photons and matter can be enhanced. So, from this figure, you can see that the photons at the red band edge of the photonic crystal are mainly concentrated in the high refractive index material, okay. So, all the dips, they are basically in this yellow region, which is the high refractive index material. Now, when you look into the photons of the blue bandage, they are mainly concentrated in the air gap in between this. So, they are basically at the low refractive index material.

So, by regulating the distribution of the functional material in the photonic crystal, photons can be effectively utilized. So, this slow photon effect generally occurs when the wavelength of blue and or red edge of the photonic band gap match with the electronic band gap of a semiconductor. So, when there is a match between the two band gaps, the slow photon effect takes place. So, this slow photon effect basically slows light propagation in photonic materials at certain wavelengths. So, what will happen because of that? It can enhance light absorption in semiconductor photocatalysts which can be used in solar cell and other optical or electro-optic devices.



So, photonic bandgap and the slow photon effect of photonic crystals can effectively enhance the efficiency of optical enrichment. Right. So, when you introduce photonic crystals in solar cells, it can improve the performance of solar cells in four aspects. The first is loss of light.

Okay. So, you can actually employ photonic crystals as back mirrors. So, it can reduce the loss of light and can increase the absorptivity. Secondly, we have discussed the slow photon effect. This can improve the interaction between the photons and the sensitizers and enhance the excitation efficiency. Third, the photonic crystals can be used as scattering layers to increase the path of light propagating through matter.

Solar Cells

- From top to bottom, anti-reflection layer, refractive index gradient medium layer, active layer and back reflection layer are sequentially arranged.
  - The anti-reflection layer is a photonic crystal with a dielectric cylinder as a light cone structure, and Si_3N_4 is filled on SiO_2 as a substrate.
  - The gradient refractive index dielectric layers are ITO and TiO2, respectively, which can effectively reduce the reflection of incident light.
  - The active layer is the light absorbing layer, the material is a Silicon.
  - The back reflection layer is composed of a ZnO quadrangular pyramid subwavelength grating and an Ag substrate.

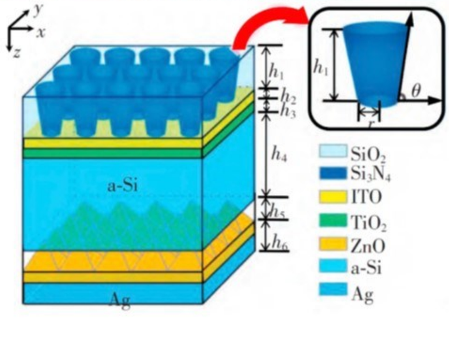


Figure: Structural model of thin-film solar cells.

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Source: Liu, Wei, Hailing Ma, and Annika Walsh. "Advance in photonic crystal solar cells." *Renewable and Sustainable Energy Reviews* 116 (2019): 109436.

At the same time, resonance enhancement mode was formed in the absorption layer to improve the absorption efficiency. And fourth, the photonic crystals have large specific surface areas, especially if you think of three-dimensional photonic crystals, they have really large surface areas which can provide excellent carriers for sensitizers. So, it can effectively increase the amount and activity of the sensitized molecules and improve the photoelectric conversion efficiency of the solar cell. So, this particular figure here represents a thin film solar cell which has got photonic crystal okay. So, from top to bottom, if you see there is an anti-reflection layer, then refractive index gradient medium, then you have active layer and then you have the back-reflection layer, which are sequentially arranged.

So if you think of the anti-reflection layer, it is basically a photonic crystal with a dielectric cylinder as light cone structure. OK, and these are basically made of silicon nitride. which is filled on SiO2 as substrate. Then you have the gradient refractive index dielectric layer, such as ITO and TiO2 respectively, and they can effectively reduce the reflection of the incident light. The active layer here, which is basically involved in absorbing light, is basically amorphous silicon.

Then you have this back-reflection layer, which is composed of zinc oxide, quadrangular period, sorry, quadrangular pyramid, sub-wavelength grating, and it is based on a, placed on a silver substrate. So, this actually is the back-reflection layer. So, that is typically how solar cells are involved sorry photonic crystals are involved in solar cells ok, where you can actually make the solar cells much more efficient.

Sensors

- Photonic Crystals (PCs) are highly dispersive and very sensitive to the material index changes so that such materials could be implemented for physical, chemical and biological sensing applications.

- Various types of sensors where photonic crystals are used are give by:

  - **Chemical sensor**:

    Photonic crystals can be used as chemical sensors for sensing the pH and ionic strength of solutions.

  - **Humidity sensor**:

    Hydrogel photonic crystals are also used for sensing humidity variations in the environment by directly exposing to the ambient atmosphere.

    From the changes in the optical properties of these hydrogel photonic crystals, the amount of humidity can be estimated.

Next is sensors. So, photonic crystals are highly dispersive and very sensitive to material index change.

So that such materials could be implemented for physical, chemical and biological sensing applications. So various types of sensors where photonic crystals are used. So, one can be, you know, chemical sensor. So photonic crystals can be used as chemical sensors for sensing the pH and the ionic strength of solutions. They can be used as humidity sensor.

So, in humidity sensor, you require hydrogel photonic crystals, okay, which are used for sensing humidity variation in the environment by directly exposing those to ambient atmosphere. Now, what are these hydrogel photonic crystals? They basically refer to a class of photonic crystals that incorporate hydrogels. which are nothing but three-dimensional network of hydrophilic polymer chains capable of holding large amount of water into their structure. So, these materials exhibit responsiveness to external stimuli such as change in pH, temperature, or presence of specific chemicals, making them valuable for various applications in sensing, drug delivery, and tissue engineering. So, the combination of hydrogels with photonic crystals leads to materials that can respond to environmental changes by altering their optical properties such as reflectance, transmission and offering unique functionalities for different range of applications.

Okay, so in short, you can say from the changes in the optical properties of this hydrogel photonic crystals, the amount of humidity can be estimated.

Sensors

❖ **Biosensors:**

Certain photonic crystal biosensors utilize surface waves (SW) on the periodic structure for their sensing mechanism.

This approach offers a unique alternative to traditional sensors that rely on Bragg reflection or photonic stopbands.

Surface waves on photonic crystal sensors are advantageous for thin film characterization and other applications as they exhibit higher sensitivity in determining the structure of the material.

They offer potential advantages over sensors based on surface plasmon polariton waves on metallic surfaces.

❖ **Temperature sensor:**

The concept of the temperature sensor is based on the shift observed in the Bragg peak or the photonic stop band as the temperature of the material constituting the photonic crystal changes.

When the refractive index is varied, the optical properties of the photonic crystal get modified and if the refractive index is changed using temperature, it acts as a temperature sensor.

. Next comes biosensors. So certain photonic crystal biosensors utilize surface waves on the periodic structure for the sensing mechanism. So, this approach offers a unique alternative to the traditional sensors that typically rely on Bragg reflection or photonic stop bands. So, these are basically surface waves-based sensors.

So surface waves on photonic crystal sensors are advantageous for thin film characterization and other applications as they exhibit higher sensitivity in determining the structure of the material. They offer potential advantage over sensors based on surface plasmon-polariton waves on metallic surfaces. Next, they can be used as temperature sensors. So, the concept of temperature sensor is based on the shift in the Bragg peak wavelength or the photonic stop band as temperature of the material constituting the photonic crystal changes. Now, how it happens? Because of the temperature, the refractive index changes and that actually changes the optical property of the photonic crystal, right? So here, if the refractive index is basically changed due to external stimulus like temperature, it acts as a temperature sensor.

Lasers

- Figure shows a typical surface emitting laser using photonic crystal.
  - The central part is a two-dimensional photonic crystal structure, functioning as the lateral cavity.
  - Laser gain in photonic crystal structures is achieved by coupling the active layer beneath the photonic crystal layer to the evanescent waves of the modes.
  - Above and below that structure, there is an optically transparent and electrically conducting cladding layer made of doped semiconductor.
  - An electric current for pumping the active region is applied through metallic electrodes on the top and the bottom.
  - Important features of the Photonic Crystal Surface Emitting Lasers(PCSEL) include:
    1. Wavelength Tunability 2. High-Quality Beam 3. Compact Form Factor
  - Applications: Optical communication networks, optical sensing, 3D sensing, LIDAR systems, quantum cryptography and on-chip optical interconnects.

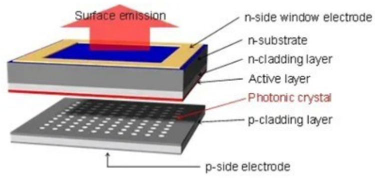


Figure: Schematic structure of a photonic crystal surface-emitting laser (PCSEL).

Source: https://www.rp-photonics.com/photonic_crystal_surface_emitting_lasers.html

Another important application of photonic crystals is towards these lasers, okay? So, figure, this particular figure shows the typical surface emitting laser based on photonic crystal. Now the central part here is basically a two-dimensional photonic crystal structure as you can see, okay. That functions as the laser cavity. It consists of a thin layer of semiconductor material such as gallium arsenide, gallium nitride or indium phosphate, okay. Containing some pattern, something like square or triangular patterns of air holes spanning over a certain area.

So here you are basically seeing a square pattern, right? The semiconductor material must be transparent, that is non-absorbing for the generated laser radiation. Now, the laser gain by stimulated emission is provided by coupling the photonic crystal structure to a thin active layer, which is here, okay? You can see this is the active layer, okay? beneath the photonic crystal layer within the evanescent waves of the modes. And that is how the coupling happens through the evanescent waves. The active region is separated from the photonic crystal structure by a thin electron blocking layer for keeping the electrical carriers confined in the active region. So, the active layer close to the photonic crystal layer excites bandage modes in the latter, okay.

It is pumped using N-type and P-type cladding layers and metallic electrodes at the bottom and the top, okay. Radiation is extracted through a hole. It is kind of a window electrode, okay, in the top electrode. So, this is where the radiation is extracted okay. So, above and below the structure there is optically transparent and electrically conducting cladding layer which are made of doped semiconductor.

So an electric current for pumping the active region is applied through the metallic electrodes on the top and bottom. On the laser emission side, that is the top side, the electrode covers only a small area, as you can see here. And usually, it leaves an opening or a window of, say, a rectangular region with dimensions of the order of 10 microns to 100 microns. So, there are some important features of this photonic crystal surface emitting lasers, which include wavelength tunability. So photonic crystal surface emitting lasers can be designed to emit light at specific wavelengths or tuned within a particular range, making them adaptable to various conditions, including telecom sensing and optical interconnects.

The other important feature is high quality beam. The use of photonic crystals enables precise control over the laser's optical mode, resulting in a high quality, low divergence beam with excellent spatial characteristics. And the third important feature is compact form factor. So, surface emitting lasers based on photonic crystals are typically smaller and more compact than the traditional edge emitting lasers. So, this makes them suitable for integration into various optical systems.

Logic Gates

- **Light localization** in a Nano-cavity as shown in figure 1.

- Cavities in photonic crystals can be used for creating optical logic gates, the building blocks of computing.
- Switching realised through optical cavities. (figure 2)

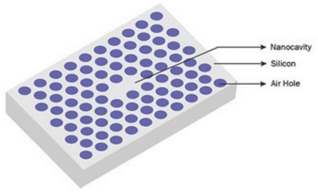


Figure 1. Cavity created in a photonic crystal slab. A cavity can be created in a photonic crystal by introducing the aperiodicity in the lattice

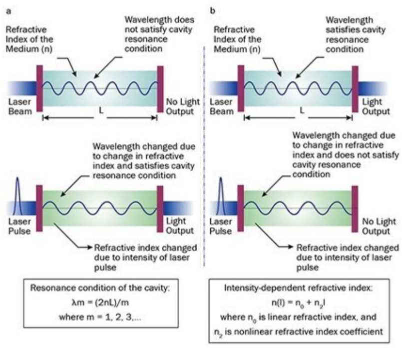


Figure 2. Optical switching process mediated by an optical cavity

IIT Guwahati | NPTEL swayam Source: https://www.photonics.com/Articles/All-Optical_Logic_Gates_Show_Promise_for_Optical/a63226

So here we have already discussed the important applications are optical communication networks, optical sensing, 3D sensing, LiDAR application, quantum cryptography and on-chip optical interconnects. The next application would be in logic gates. So here you can actually see that this is a photonic crystal slab where a cavity is formed. So how it works? Here you can see these blue dots are basically air holes. So, it is basically a triangular array of air holes in silicon substrate.

And then here one hole is missing and that is a point defect and that forms a cavity. Now, that cavity can help you achieve light localization in this particular cavity, right? And using this structure, you can also realize, you know, logic gates. How it works? These structures, which reflect light in forbidden frequency range, prohibit the light's passage through it. So that is the concept of photonic bandgap. Alternatively, if there is a defect, something like this, introduced in the periodic structure, so we have seen line defect that can produce a waveguide or we can think of a point defect that creates a cavity.

In such case, the forbidden frequencies can be confined within the structure with little propagation loss. So, this phenomenon is also known as light localization and it was first introduced in the year

1987. and has come to the fruition with now photonic crystals. So, a cavity that is created within a photonic crystal due to a point defect is shown here, right. Now, this cavities in photonic crystal can be used for creating optical gates.

Now, these are the building blocks of optical computing, right? So, all arithmetic and logic operations are carried out in a computer using the logic kits. So modern PC relies on them to perform tasks based on programs which are stored in memory. Now, once the technology for implementing logic gate is in place, it will be very straightforward towards realization of optical microprocessors. So, among different gates, if you consider, NAND and NOR are known to be the universal gates because they can be used for performing all kinds of logical operations. So, in other words, you can say a combination of NOT gate along with AND and OR can also be used for making all logical operations.

So, in optics, switching is very important phenomena and the switching can be realized using optical cavities. an optical cavity supports only certain wavelengths dependent on the length and the refractive index of the cavity. So more specifically, the length of the cavity must be an integral multiple of half the wavelength. So, this ensures that nodes are formed at both ends of the cavity. Once the length of the cavity is fixed, its transfer properties will depend only on the refractive index.

However, when the intensity of the light that enters the cavity becomes sufficiently high, the refractive index depends on the intensity of the light. So, this phenomenon as we will know is popularly known as optical cathet. care effect ok. So, and it can be harnessed by achieving optical switching within the cavity. So, this is the technique that has been used here in this particular figure ok.

So, a laser pulse, so here you can see that it is a laser beam and there is a length of the cavity ok and there is a refractive index of this medium which is n ok and this cavity length at this refractive index does not support the cavity resonance condition, so you do not have any light output. But what happens when you put a laser pulse which has got a much larger intensity, it actually can change the refractive index of the medium. And now the wavelength changes due to the change in refractive index is such that it can satisfy the resonance condition of the cavity and in that case, you get a light output okay. So, that way you can actually tune the light output whether there is a light output or not from the cavity depending on the input laser pulse.

Logic Gates

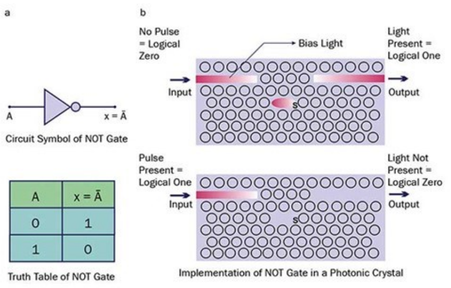


Figure 1. (a) Circuit symbol and truth table of a NOT gate. (b) Implementation of NOT logical operation using an optical micro-cavity in a photonic crystal slab.

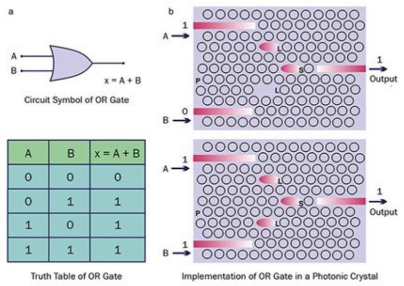


Figure 2. (a) Circuit symbol and truth table of a OR gate. (b) Implementation of OR logical operation using an optical micro-cavity in a photonic crystal slab.

okay. So, this is what we have seen for realizing logic gates based on these techniques two types of cavity configuration are used here. So, the in the first configuration the cavity length is set below the resonance wavelength okay and in the other configuration the cavity length is set to have resonance wavelength in this case, it is having the cavity length is same as the resonance wavelength. So, you are getting the light output in the very beginning when it is simply laser beam. But then when you put the laser pulse okay what happens the refractive index will change and that actually makes the wavelength change in such a way that it no longer satisfies the resonance cavity condition and the light output will stop. So, these are the two contrasting scenarios that you can obtain using an optical cavity, right.

So, these are basically switching applications which are very useful for realizing optical logic gates. So, we will actually see the very basic logic gate here. So, let us think of a NOT gate. So, this is the circuit symbol of a NOT gate.

So, you can see A becomes A bar or A prime. So, if you give a 0, you get a 1 and if you give a 1, you get a 0, okay. So how do you realize this? So, the implementation of a NOT gate using photonic crystal, okay, is shown here. So, for this purpose, what we are doing, okay, we need optical cavity that has a resonance wavelength same as that of the incident light. And the cavity is represented by S in this particular figure. So, the optical cavity serves as the coupling point between the input and the output waveguide.

So, this is the input waveguide and this is the output waveguide and this is your cavity. So, this is entirely the whole thing is inside a photonic crystal slab. And you can actually introduce line defect here means you miss those holes. You can actually create a waveguide.

Similarly, you miss some of the holes here. You can create another waveguide that you can use as output waveguide. And here you miss one hole and you can create a cavity. So, this is how you actually obtain this particular structure. It is very straightforward. Now, when you send a bias light through this input waveguide, it is basically coupled to the optical cavity and then it crosses over to reach the output waveguide as the resonance wavelength of the cavity is same as that of the input light.

That's pretty good. Now, when a laser pulse is also sent along with the biased light, because of the high intensity of the laser, the refractive index of the cavity medium is altered. Now what happens in that case? It actually prohibits the coupling of light to the output waveguide. It means whenever this laser pulse is present, you don't get any output. But when there is no laser pulse present, you actually get the output.

So, if you give a 0, you get a 1. If you have 1 here in the input, you get a 0. So that way, the presence of laser pulse denotes logical 1 state as we discussed. And because of the change in the refractive index of the cavity, this laser pulse detunes the resonance wavelength away from the resonance condition. And hence, your output becomes a logical 0. But in the absence of laser pulse, which is basically a zero state, the coupling of the cavity and the output is effective.

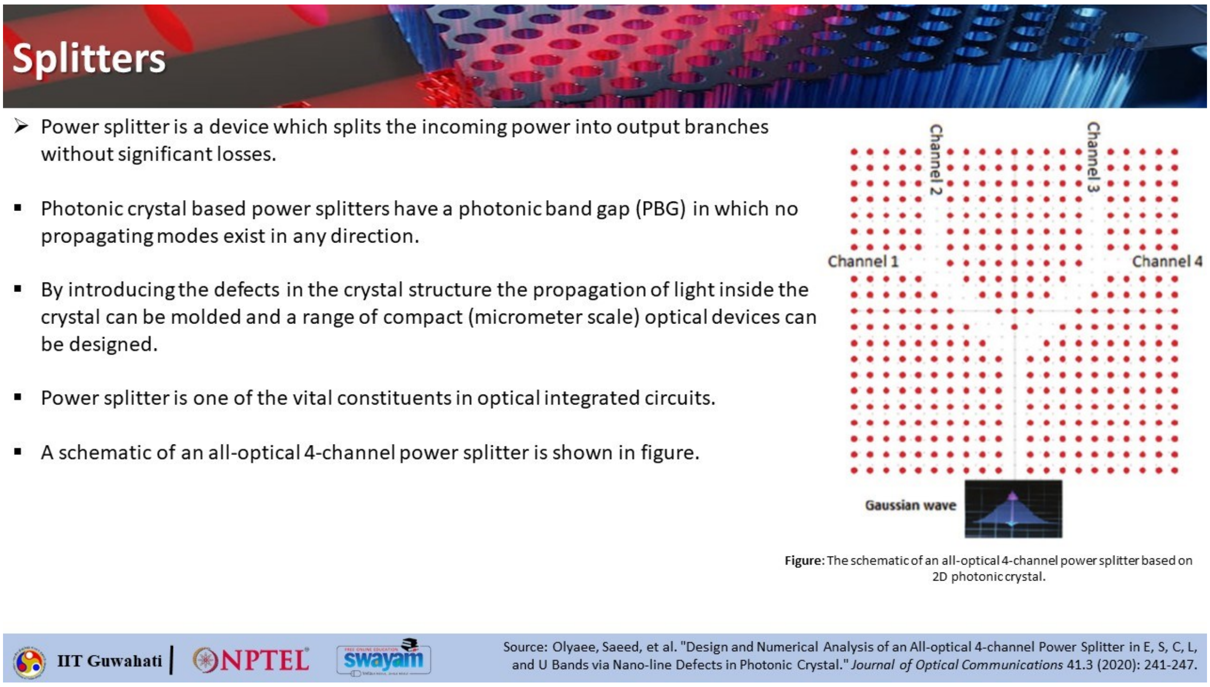
So the bias light can get coupled to the cavity and then get further coupled to the output waveguide and you can get some output here. So that is like logical one state. So, you can say that this particular device actually works as a optical NOT gate. Further, you can think of OR gate.

So, OR gate operation I believe everybody knows what OR gate is. So, OR gate has got two inputs and this is the output. So, if the both inputs 0 0, you get a 0 at the output. If any one of the inputs is 1, you get 1. If both the input is 1, then also you get 1, ok.

So, the only case NOT gate gives a 0 output is when both the inputs are 0. So here, this is how the structure of the odd gate in photonic crystals will look like. So you're basically having three optical cavities, two of them so this is this l l and s these are the three cavities so the two of them these two l ones are basically coupled to the input waveguide so this is one input waveguide this is another input waveguide and s is basically coupled to the output waveguide right So, this is basically the third cavity ok. So, what happens the bias light from the input waveguide cannot traverse the cavity since it wavelength does not match with the resonant wavelength of the cavity ok. So, this is done because the L cavities are coupled to the input waveguides, they basically have resonance wavelength lower than that of the bias light. And when you see S cavity, the third cavity, which is coupled to the output waveguide, it has got its resonance wavelength set to be same as that of the bias light.

So what happens? The bias light from the input waveguide cannot travel through this L cavity since its wavelength does not match with the resonance wavelength. So, this constraint can be sorted by sending out a high intensity pulse which will enable this cavity to achieve resonance with the wavelength of the bias light because of the change in the refractive index of the cavity medium. So, whenever there is a high intensity pulse coming with the bias light, this cavity will also resonate and then you will get a coupling to the output. So, in this situation, when you have 1, 0, you get an output 1.

In case of 1, 1, you get a output 1. you can also try for 0 1 you will get a output 1 ok. And in the case of 0 0 you will see that because this are not coupled tuned to this wave lengths you will not get any output. So, in that case you can say 0 0 will produce a 0.



Another important device that you can make out of this photonic crystal is splitters. So, power splitter is a device which splits the incoming power into output branches without any significant loss.

So photonic crystal-based power splitters have photonic bandgap in which no propagating modes exist in any direction. So, it's basically a photonic crystal where you have removed this particular row of this dielectric cylinders okay. And then you have created this row also. So, they are basically your waveguide. So, this is one incoming channel and then you have channel 1, channel 2, channel 3 and channel 4.

So, by introducing defects in the crystal structure, the propagation of light inside the crystal can be molded and a range of compact optical devices can be designed. So, a schematic of an all optical four channel power splitter is shown in this figure. So, what happens here? When the light enters a defect, that is a specific row in our 2D photonic crystal, it encounters the lattice. And if the wavelength is within the photonic band gap, that is the 1550 nanometer wavelength say, then the only permitted path for its propagation is this particular row. So, in this condition, it can propagate easily without any loss and when light reaches the initial bending of the structure, it gets divided into equal two parts.

Splitters

- The polarization beam splitter (PBS) can split two different beams of mutually orthogonal polarizations along different directions.

- Traditional PBS uses birefringence in a natural crystal or polarization selectivity, but has drawbacks:

  (1) The natural crystal requires a high thickness,
  (2) The multilayer structure has a complex processing technology
  (3) Sensitive to the change of angle, and
  (4) The transmission light has a low extinction ratio.

- Figure 1 shows a schematic of the photonic crystal structure and illustrates the ability of the Photonic Band Gap to guide light.

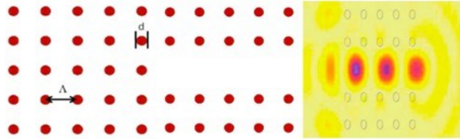


Figure 1: Photonic crystal structure. (Left) The diameter of the dielectric column is d and the spacing between the dielectric columns is the lattice constant Λ. (Middle) PBG structure. (Right) PBG light guiding

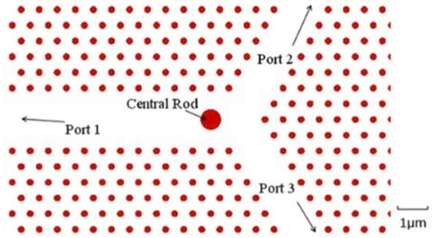


Figure 2: Structure of photonic crystal beam splitter.

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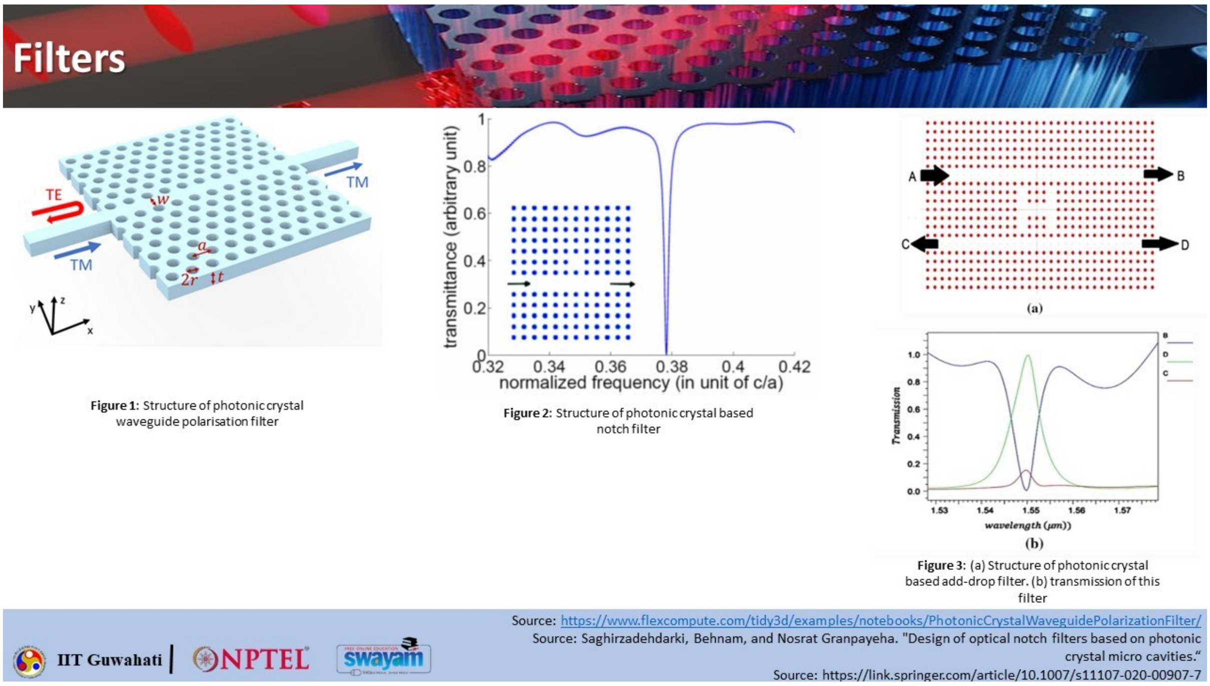
Source: Yang, Z., Chen, K., Wang, Cg. *et al.* A photonic crystal beam splitter used for light path multiplexing: synergy of TIR and PBG light guiding. *Opt Quant Electron* **52**, 84 (2020).

Subsequently, as you can see, the light passing through each of these 45-degree bands, it can reach the preceding bands on both sides of the photonic structure and like it can reach here and here and then equally can get divided in channel 1, channel 2 and channel 3 and channel 4, okay. So, that way you can get a 4-channel power splitter. So, another important device is polarization beam splitter, which can split two different beams of mutually orthogonal polarization along two different directions. So here again, you can see the photonic crystal structure. OK, so this tells you about the lattice constant and this is the diameter of the dielectric column and then you can have a row missing so that actually prepares the waveguide okay and this is a simulation result that shows photonic band gap light guided guiding through this particular structure.

So what you have to do here, because it's a polarization beam splitter, so it means in one polarization can go this way and another polarization has to go the other way. So traditional polarization beam splitter uses birefringence, means refractive index values are different in different direction. So, birefringence in a natural crystal and polarization selectivity. But then they have drawbacks something like you know the natural crystals require very high thickness and multi-layer structure has a complex processing technology with millimeter level size and that cannot be applied to the micro machining technology. And then they are also sensitive to the change of angle and the transmission of light has a low extinction ratio.



So, figure 1 as I mentioned here shows the schematic of how you can do this polarization beam splitting using photonic crystal structure and it shows the ability of photonic bandgap to guide light in a particular waveguide structure. So, this is the design of a photonic crystal beam splitter. So, what happens here you know in order to realize the light path multiplexing function in addition to the necessary channels for splitting and cycling the asymmetry of the photonic crystal microstructure must be considered. That is an asymmetry microstructure must be designed in the photonic crystal beam splitter to satisfy the asymmetry of the input and the output light path. So, as you can see in figure 2, a large circular dielectric column at the center of the Y-shaped branch.

So, this is a Y-shaped branch. So, this central rod is placed at that particular point. Now the existence of this circular dielectric column introduces asymmetry. So, the light path had a suitable splitting ratio at the input and output, thereby satisfying the splitting and cycling requirements. When the large dielectric column is positioned at the center of the branch, the beam gets strongly reflected back, something like 85%. and it causes very low beam intensity at the output at port 2 and port 3.

So the beam splitting is very poor. Now if you want to improve the beam splitting you can actually change the size, shape and the number of this central rod and that can give you the control on the power splitting ratio as well. Next, we will discuss about filters. Now filters are very important devices in photonic applications. So here is a structure of polarization filter.

It means this structure can actually block the TE polarization and only allow the TM polarization. Again, this is a two-dimensional photonic crystal where there is a missing row of holes and that actually forms the waveguide. So integrated photonics very often come across with the devices and systems that operate only on TM polarized light with their efficient functioning. So, TM polarized light is also very useful for level-free sensing as its evanescent field can penetrate deeper to the top and bottom cladding layer when you compare it with the T polarized light. Moreover, applications such as polarization multiplexing requires TM polarized light in order to make the most of the channel capacity. Hence, it would not be wide of the mark to say that TM polarization filters are indeed necessary for very efficient photonic integrated circuit design.

So from the design point of view, the design parameters need to be optimized such that you get first the bandgap for suppressed polarized light that is TE and the index guided mode for TM must be in the same wavelength range. It means you are supporting the TM waves to propagate but then for TE those should lie in the bandgap. Secondly, the bandgap guided mode of TE polarized light which are generated while creating a line defect waveguide must not overlap with the index guided mode of the TM polarized light in that overlapping operating region. So, in that case you can ensure that only TM waves are coming out and TE waves are reflected back.

So, this kind of filters, this uses periodic structure. So, photonic crystal polarization filters, photonic crystal polarization filters, as you can see, they utilize a periodic NAND structure to create a bandgap for specific polarization of light, which means they selectively transmit light of a certain polarization while they block others. They have other features like selective transmission. So, photon and crystal polarization filter allow light waves with specific polarization to pass through by matching the polarization direction with the periodicity of the crystal lattice. In contrast, the light waves with other polarizations are reflected or they're absorbed. They can also show tunable properties because these filters can be designed to operate in various spectral regimes.

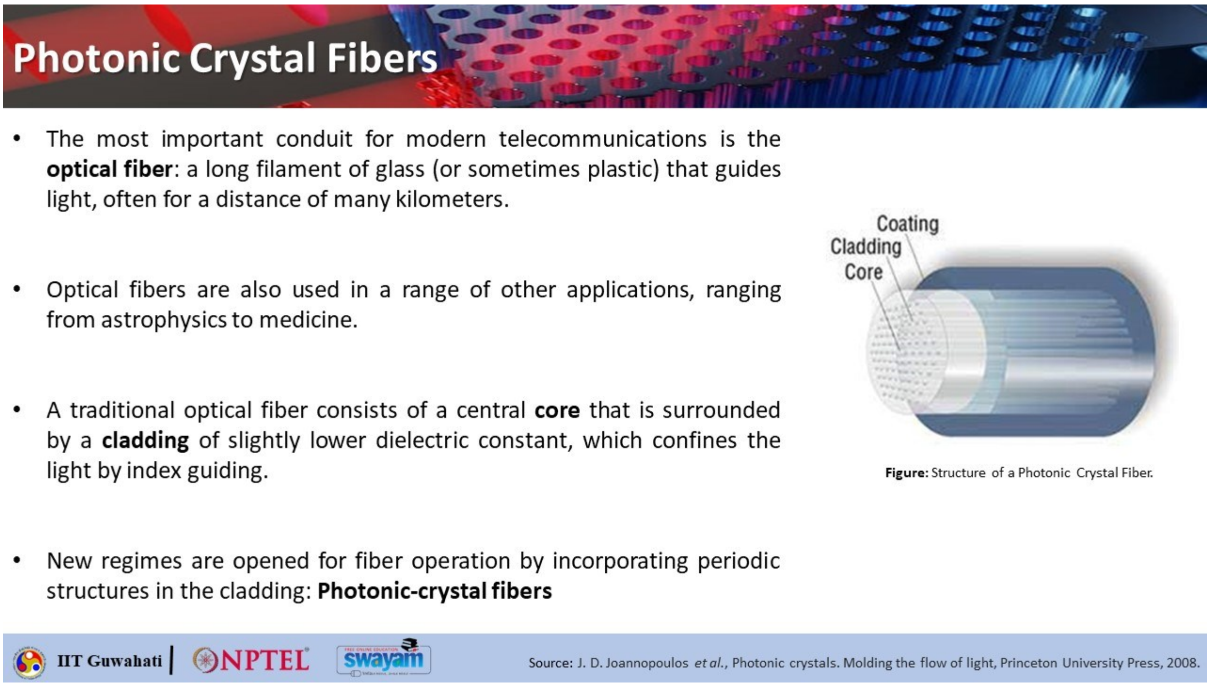
by adjusting the photonic crystal's geometry and periodicity. So, you can actually change the pattern of the holes or size of the holes, the period of the holes, diameter of the holes, and you can actually shift the entire operating wavelength to a different window. So, this allows you to use this kind of design for optical communication and imaging. The other important application is notch filter. As you can see here, you can actually create a waveguide and a small cavity and this cavity can trap a particular wavelength and that is not allowed to transmit and that gives you the notch.

So notch filter, you are basically getting bandgap formation, okay. So, you have photonic crystal notch filters which are designed to create a bandgap in their optical transmission spectrum. So, this bandgap basically prohibits the propagation of a specific range of wavelengths which forms the notch region. You can also use this resonant cavities or defects. So, the notch in the transmission region is basically created by introducing localized resonant cavities or defects in the photonic crystal as you can see here.

And these defects interact with the incoming light causing destructive interference for certain wavelengths. So those wavelengths are not allowed to pass and you get a very sharp notch filter. Not filters selectively reject or attenuate slight at the resonance wavelength associated with the cavities or defects effectively creating a notch in the transmission spectrum while allowing other wavelengths to simply pass through. So, this makes them valuable for applications such as optical signal filtering and spectral analysis and by adding a point defect to the photonic crystal structure a micro cavity can be made to trap electromagnetic energy with wavelength inside the photonic band gap. And by increasing the radius of the defect, higher order modes can be activated, which may have quality factors greater than the lower order modes.

So different type of flexibility is there when you design notch filters using photonic crystal slabs. The other one is an air drop filter. So, air drop filter is a key component in optical integrated circuits that can be used in all optical communication network and wavelength division multiplexing WDM systems. quality factor coupling efficiency transmission efficiency and coupling length are important parameters in this add drop filter so here you can see a drop filter which includes a square lattice okay and then you have a h shaped filter that is placed between the two wave guides which are created by this missing row okay and this particular figure shows that all of the wavelengths pass from port B okay except for 1550 okay. In 1550 you have a drop all other wavelengths are allowed to pass through and you can see that the dropped wavelength is basically coming out from this particular drop port which is D port.

So, that typically tells us about different applications of photon crystal fiber sorry photonic crystal slabs. So those tells us about the applications of photonic crystal slabs.



So now let us look into different applications of photonic crystal fiber. The most important conduct for modern telecommunication is basically optical fiber, which are nothing but long filament of glass or sometimes plastic that guides light and typically over distance of several kilometers. Optical fibers are also used in range of applications starting from astrophysics to medicine while doing surgery and all, okay. A traditional optical fiber consists of a central core which is surrounded by cladding of slightly lower dielectric constant which basically confines light in the core by index guiding.

Photonic Crystal Fibers

- **Photonic-crystal fibers**, also called **microstructured optical fibers**, can be divided into a few broad classes, according to whether they use **index guiding or band gaps** for optical confinement, and whether the periodicity of the structure is one-dimensional or two-dimensional.
- **Photonic-bandgap fibers** confine light **using a band gap rather than index guiding**.
- *Band-gap confinement is attractive because it allows light to be guided within a hollow core*.
- This minimizes **the effects of losses, undesired nonlinearities, and any other unwanted properties of the bulk materials** that are available.

Source: J. D. Joannopoulos *et al.*, Photonic crystals. Molding the flow of light, Princeton University Press, 2008.

So new regimes are opened for fiber operations by incorporating periodic structure in the cladding and that gives you photonic crystal fibers just like this. So, this is a structure of a photonic crystal fiber where you have a photonic crystal in the cladding region. when you say photonic crystal fibers they are basically microstructured optical fibers and they can be divided into few broad classes according to you know whether they are using index guiding or photonic band gap for optical confinement okay and whether the periodicity of the structure is one dimensional or two dimensional So when you say photonic bandgap fibers, they basically confine light using bandgap mechanism rather than index guiding. So, bandgap confinement is attractive because it allows light to be guided within a hollow core.

So when there is no material, so there is no loss. So, it can actually, you know, you can really transmit without any loss of signal. And then there is no undesired nonlinear effects coming into.

And all those things are possible with a hollow core fiber. Okay. So, index guiding. is basically the mechanism if you remember it is it relies on the manipulation of the refractive index profile within the fibers cross section to confine and guide light? Whether in contrast to that conventional optical fibers okay when you talk about photonic crystal fibers they utilize an engineered periodic arrangement of air holes. of high and low index material to achieve the guiding properties. This structure creates a photonic bandgap that can confine and guide light within the fiber score enabling various applications something like super continuum generation, high power pulse delivery and also nonlinear optics.

Photonic Crystal Fibers

- Three examples of **photonic-crystal fibers**:
  - **a) Bragg fiber**: a one-dimensionally periodic cladding of concentric layers.
  - **b) Two-dimensionally periodic structure** (a triangular lattice of air holes), confining light in a hollow core by a band gap.
  - **c) Holey fiber** that confines light in a solid core by index guiding.

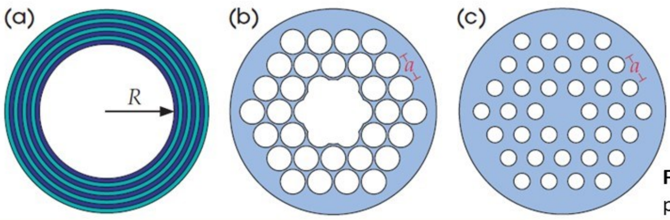


Figure: Three examples of photonic-crystal fibers.

Source: J. D. Joannopoulos *et al.*, Photonic crystals. Molding the flow of light, Princeton University Press, 2008.

So, these are the three different examples of photonic crystal fibres we have discussed. One is Bragg fibre where you have one-dimensionally periodic cladding of concentric layers. You can have two-dimensionally periodic structure which are basically triangular lattice of air holes where you can confine light in a hollow core by using the concept of photonic bandgap and then you have holy fiber where the cladding is basically made of you know holes and then you have a solid core where you are basically confining light in the solid core by index guiding mechanism. Because of the holes, the refractive index of this region is lower than that of the core and that is how core becomes a high permittivity or high index material and light is confined within the core. So, you can see the photonic crystal fibers, especially the holey core fibers have enormous practical advantage over the periodic structures, okay, that have been discussed in the previous lecture

Photonic Crystal Fibers

- **Photonic-crystal fibers** have **an enormous practical advantage** over the periodic structures that discussed in previous lectures.
- Fibers can be created through a **drawing** process. In the first step of this process, a scale model of the fiber (or **preform**) is created, typically centimeters in size.
- Next, the preform is heated and pulled (*drawn*), stretching it like bubble gum into a thin strand whose cross section is a scaled-down version of the preform's.
- *In this way, hundreds of meters or even kilometers of fiber can be drawn from a single preform, with near-perfect uniformity.*

(a) (b)

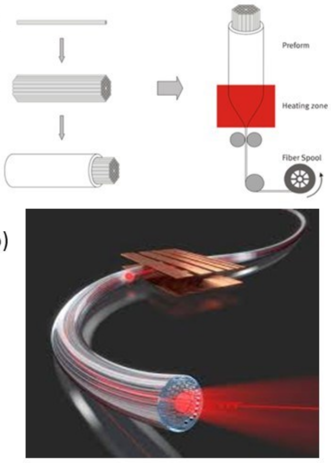


Figure: Illustration & fabrication of Photonic-crystal fibers.

Source: J. D. Joannopoulos *et al.*, Photonic crystals. Molding the flow of light, Princeton University Press, 2008.
Source: https://www.nanowerk.com/nanotechnology-news/newsid=40674.php

So, fibers that can be created through drawing process. So, in that process you know the first step is to make a scale model of the fiber which is also known as preform which typically centimeter in size like this ok and then the preform is heated okay and then it is pulled through this kind of rollers. So, that makes them into very thin strands and the cross section can scale down to you know micrometers. So, that way you know several meters or even kilometers of fibers can be drawn from a single preform with near perfect uniformity. So, this is the you know method of fabrication of photonic crystal fibers.

Electron Microscope Images of Photonic Crystal Fibers

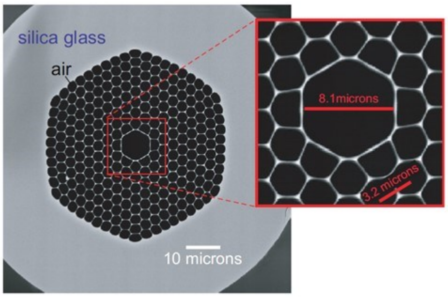


Figure: Electron-microscope image of hollow-core holey-fiber cross section.

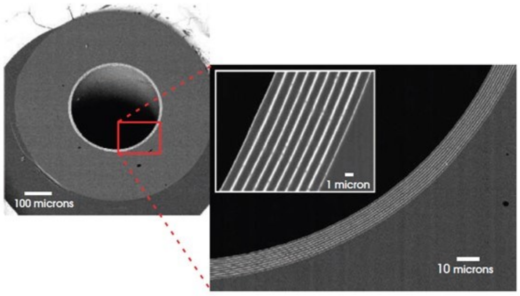


Figure: Electron-microscope image of a hollow-core omnidirectional-mirror Bragg-fiber cross section.

Source: J. D. Joannopoulos *et al.*, Photonic crystals. Molding the flow of light, Princeton University Press, 2008.

These are some electron microscope image of photonic crystal fibers. So, here you can see this is basically the dark region is the hollow region ok. You can see this is how a hollow core fiber looks like ok. And this is the electron microscope image of the black fiber cross section, which is basically an omnidirectional mirror. It's also a hollow core, but it has got this mirror at the boundaries. Now, what are the applications of photonic crystal fibers? The photonic crystal fibers based sensors are very advantageous over the standard optical fiber sensors.

in many aspects they not only have great design flexibility but because of the holey internal structure that can be filled with analyte so that you know a controlled interaction can take place between the propagating light and the analyte sample this greatly enhances the sensitivity of the fiber optic sensors as well as opens up new direction for making advanced portable sensors

Applications of Photonic Crystal Fibers

Fiber Optic Sensors

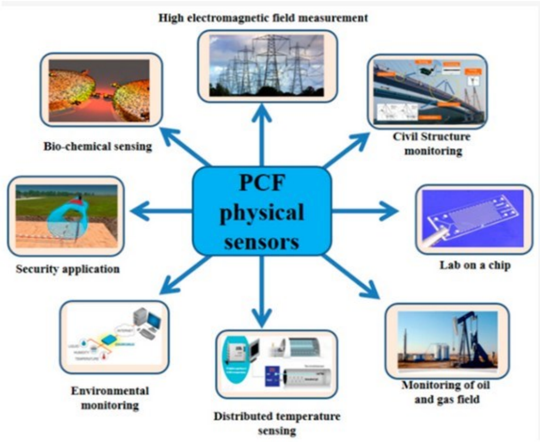


Figure 1: Applications of Photonic crystal fiber based physical sensors.

Figure 2: Applications of Photonic crystal fiber based surface plasmon resonance sensors..

Source: https://www.mdpi.com/1424-8220/19/3/464
Source: https://www.sciencedirect.com/science/article/pii/S0925400516319116

So, photonic crystal fiber sensors have a wide range of applications such as measurement of different physical parameters like temperature, pressure, strain, twist, torsion, curvature, band and electromagnetic field etc. Okay. So, observation as well as control of these applications including civil structural health monitoring.

Okay. Then you can use PCF based physical sensors for remote sensing capabilities. They can be they can have immunity from hazardous environment of high electromagnetic field. So, you can actually use them for high electromagnetic field measurement and high voltage measurement. They can be used for biomedical sensing capabilities and so on. So, these are the different applications areas which are mentioned here. Something like distributed temperature sensing, monitoring of oil and gas field, lab on chip, biochemical sensing, security applications, environmental monitoring and so on.

Photonic crystal fiber surface plasmon resonance has also allowed the emergence of plasmonic sensors. So, these are basically high sensitivity portable sensing technology for testing chemical and biological analytes. So, if you think of photonic crystal fiber surface plasmon resonance sensing, it combines the advantages of photonic crystal fiber technology with plasmonics to accurately control the evanescent field and light propagation in single or multimode configuration. So, you can actually use them for medical diagnostic, biomedical imaging, glucose monitoring, environmental monitoring, telemedicine, chemical sensing, and so on. Another application of this kind of photon crystal fiber is in mode splitter.

So, this particular figure shows the cross section of a photon crystal fiber based polarization beam splitter ok. So, a polarization beam splitter as you know is an extremely common optical device in optical fiber communication. optical fiber sensing and measurement system that can split an incident light into two orthogonally polarized beams that constitute a fundamental mode.

Mode Splitter

- Figure-a displays the cross-section of the designed PCF-PBS.
  - All air holes are arranged in a hexagonal lattice fashion.
  - The lattice pitch is expressed by Λ, and there were only two sizes of air holes, d_1 and d_2 as shown in figure.
  - The conventional coupling characteristics of a direction coupler based on a dual-core fiber can be employed to calculate coupling length given by:

$$L_c = \frac{\pi}{\left(\beta_i^{\text{even}} - \beta_i^{\text{odd}}\right)} = \frac{0.5\lambda}{\left(n_i^{\text{even}} - n_i^{\text{odd}}\right)}$$

where i=x, y and β_i^{even} and β_i^{odd} represent the propagating constants of the odd and even modes for the x- and y-polarization modes, respectively.

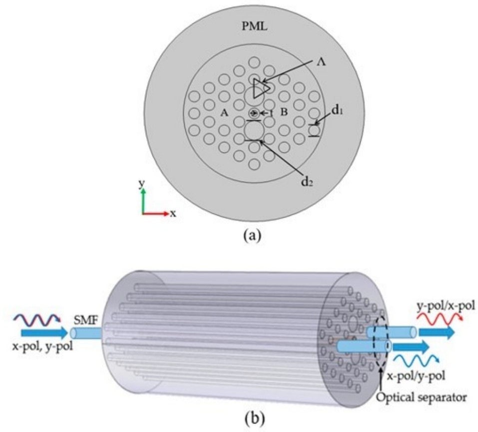


Figure . (**a**) Cross-section of the proposed photonic crystal fiber-polarization beam splitter (PCF-PBS). (**b**) Schematic diagram of the PBS operation, where an incident light with the x- and y-pol modes enters the input port, and the x- and y-pol modes can be split out at the output port.

Source: https://www.mdpi.com/2072-666X/11/7/706

So, PCFs are widely popular because they have special transmission mechanism and their optical properties can be enriched by tailoring the arrangement of internal capillary rods. So, these are those internal capillary rods, okay. And you can see that the as compared to conventional fibers photonic crystal fibers have unique properties like endless single mode transmission high birefringence large mode area and tunable dispersion so photonic crystal fibers can be utilized as excellent carriers for in fiber polarization beam splitters so this is an example here you can see that the all the air holes are arranged in hexagonal lattice fashion So this is the diameter of one hole.

And this is, you can see the periodicity. These are the two larger holes which are having diameter of d2. And A and B are the two cores. So, the lattice pitch is given by Λ. And there are only two size of air holes as you can see here, d1 and d2. So, the conventional coupling characteristics of directional coupler based on dual core fiber can be employed here to calculate the coupling length. So, you have one fiber straight away coming like this and then you have another one where the coupling can take place ok.

So, the coupling length $L_c = \frac{\pi}{\left(\beta_i^{\text{even}} - \beta_i^{\text{odd}}\right)} = \frac{0.5\lambda}{\left(n_i^{\text{even}} - n_i^{\text{odd}}\right)}$ So, you can actually write it in terms of λ. So, 0.5 times λ divided by the difference in their refractive indices, okay. So, here you can see the schematic diagram of the polarization beam splitting operation. So, the periodic normalized power that comes out of core A and B can be calculated as this. These are basically formulas very common for directional couplers.

Mode Splitter

- Figure-b displays schematic diagram of the PBS operation.

- The periodic normalized powers at the output side of cores A and B can be calculated by:

$$P_{out}^{A} = P_{in}\cos^2\left(\frac{\pi}{2}\frac{z}{L_i^c}\right) \qquad P_{out}^{B} = P_{in}\sin^2\left(\frac{\pi}{2}\frac{z}{L_i^c}\right)$$

  where P_{in} denotes the input light power, z denotes the propagation length, and $L_i{}^c$ denotes the coupling length for the x- and y-pol modes.

- The Coupling Length ratio (CLR) can be defined by:

$$CLR = m/n = L_x/L_y$$

  where m/n is equal to $even/odd$ or $odd/even$.

- After propagating a length of mL_x or nL_y in a PBS, two lights with different wavelengths will exit through the A and B out ports.

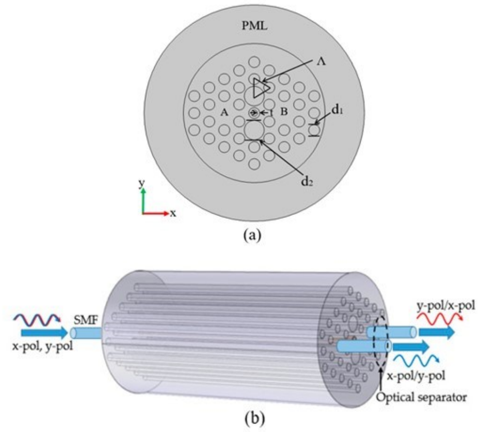


Figure . (**a**) Cross-section of the proposed photonic crystal fiber-polarization beam splitter (PCF-PBS). (**b**) Schematic diagram of the PBS operation, where an incident light with the x- and y-pol modes enters the input port, and the x- and y-pol modes can be split out at the output port.

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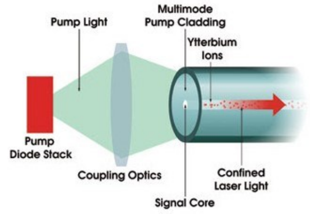
Source: https://www.mdpi.com/2072-666X/11/7/706

So, you can write P out at A port is nothing, but $P_{\text{out}}^{A} = P_{\text{in}}\cos^2\left(\frac{\pi}{2}\frac{z}{L_i^C}\right)$ $P_{\text{out}}^{B} = P_{\text{in}}\sin^2\left(\frac{\pi}{2}\frac{z}{L_i^C}\right)$ ok and this is. So, the one will be cos square the other one will follow sin square ok. the coupling length ratio can be calculated as m by n which is basically Lx by Ly. So, m by n is equal to the odd even by odd or odd by even depending on the you know the length ok. After propagation After propagating a length of MLx or MLy, so M can be even or odd in a polarization beam splitter, the two lights of different wavelength will exit through A and B port. So here you can see that in the single mode fiber, basically you are having x pole and y pole together and then finally you can get either x pole here and y pole here or vice versa you can have y pole here and x pole here so this is how you are able to split the beams okay you can also use for making excellent lasers.

Lasers

- **Photonic crystal fiber**: Most promising technology to significantly lift the current power levels.
  - Gain medium: Rare-earth-doped fiber.
  - Optical pump source: Multimode laser diodes
  - The active fiber converts the low-beam-quality pump light into signal light with high beam quality (Figure).
  - The pump light can be coupled by free-space optics such as lenses and mirrors or can be delivered in one or more multimode fibers that are fused onto the active fiber.
  - The preferred gain medium for high-power lasers is ytterbium, a result of its high efficiency



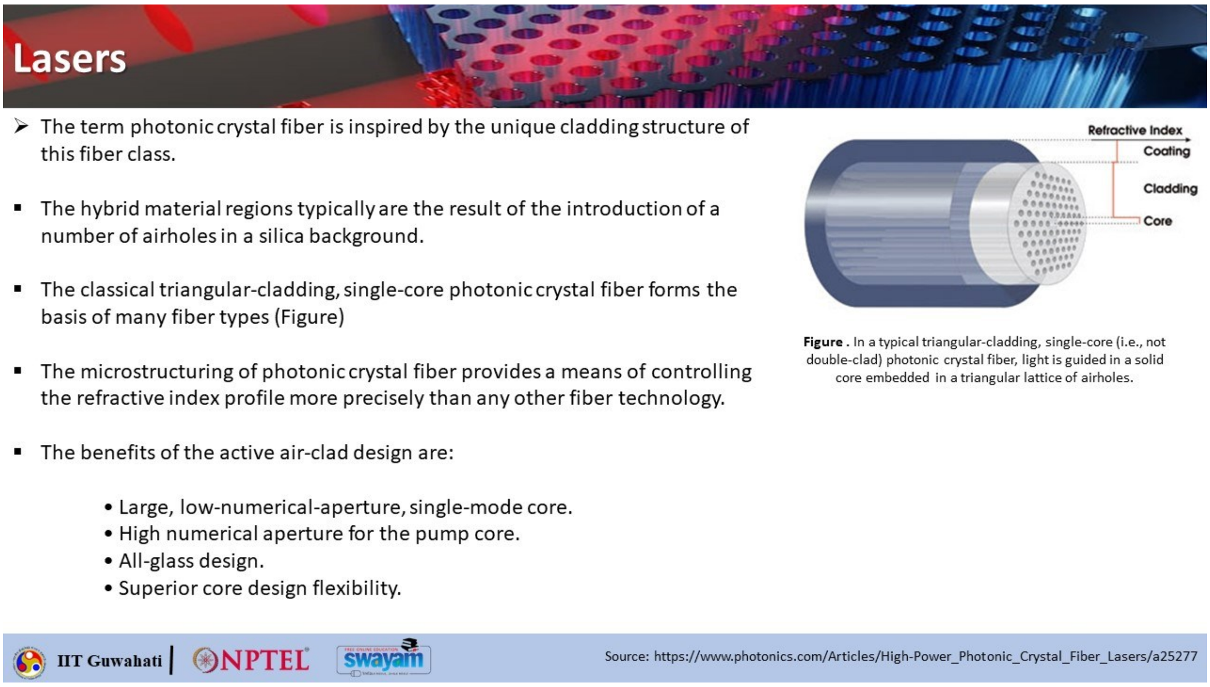
Source: https://www.photonics.com/Articles/High-Power_Photonic_Crystal_Fiber_Lasers/a25277

So, one of the fastest growing and most promising application of the optical fiber is high power fiber lasers. So, in the past few years fiber lasers have evolved from low power systems for niche applications into challenges to the traditional high-power industrial lasers for material processing. So fiber lasers are gaining market share at a strong pace and are projected to be the industry standard within a few years for marking, painting, cutting, and welding. So, their advantages are low cost. operation, high beam quality and high efficiency in a maintenance free format with a low footprint and low weight.

So, you are actually getting the benefit of small footprint and lesser weight. In particular, they offer a superior beam quality compared to other laser systems for power range in kilowatts. So, this improves the precision and processing speeds for industrial material processing systems and introduces the possibility for achieving extreme power levels like in kilowatts by combining or even more by combining multiple lasers. So, here you can see that you know the There is a rare earth doped fiber over here. The optical pump source is basically multimode laser diodes.

The active fiber here, it converts the low beam quality pump light into a signal light with high beam quality. and the pump light can be coupled by this kind of free space optics arrangement something like lenses or mirrors that can be delivered in one or more multimode kind of fiber that are fused onto the active fiber okay. So, here the preferred gain medium for high powered laser is ytterbium and as a result of its high efficiency right. So, the highest reported power level for a single mode fiber laser is approximately 3 kilowatt which is demonstrated by IPG Photonics Corporation of Oxford. It is noting that the record power level has increased dramatically over very short time and further increase is also expected in near future.

So, photonic crystal fibers is perhaps the most promising technology to significantly lift the current power levels. And this is because of their increased flexibility in the single mode core size, as you can see here. The increased numerical aperture of the pump cores in double clad fiber configuration and also high thermal stability of low loss all glass structure. So, these are couple of the features which enables this particular photon crystal fiber to deliver good quality lasers.



The term photonic crystal fibers is also inspired by unique cladding structure of this particular fiber. So, you can see the cladding material over here. So, this is a typical triangular cladding. So you have got a single core photonic crystal and light is guided in this solid core which is embedded in this triangular lattice of air holes. So, the hybrid material region is typically the result of interaction of the number of air holes in this silica background. So, the classical triangular cladding, a single core photonic crystal fiber can form the basis of many different types of fibers. The microstructuring of the photonic crystal fiber provides a means of controlling the refractive index profile more precisely than any other fiber technology.

Right here you can actually change the periodicity or the pattern of the holes or the dimension of the holes and that can give you different type of you know index profile. So, what are the benefits of this active air clad design? So, you can actually have large low numerical aperture single mode core. You can also go for high numerical aperture for the pump core, all glass design and then you can have superior core design flexibility. So, all these things are possible in this particular case.

Photonic Crystal Fibers Market Overview

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So, there are many other applications of photon crystal slabs and fibers which are beyond the scope of the discussion due to the time constraint. But we have tried to cover what is important and give you a basic of all the different aspects of photon crystal technology. Okay. So, we will discuss this little more in the future lectures when you go into the technical details of designing.

Market Overview

Figure1: Photonic Crystal Fiber Market Size And Forecast

Figure 2: Global Photonic Crystal Fiber Market Segmentation Analysis

Source: https://www.verifiedmarketresearch.com/product/photonic-crystal-fiber-market/

So, let us have a brief look at the market overview of photonic crystal fibers. As you can see here that from 2020 to 2028, okay, a growth rate of 7.86 percent is estimated, okay. And if you look into the segmentation analysis of global photonic crystal fiber market. You can see that there are end users, something like industrial aerospace and defense licenses and healthcare and R&D. And then, you know, mainly it's been used in North America, Europe, Asia specific and rest of world.

And by application, it is mainly towards fiber, LEDs, image sensors, and then solar and photovoltaic cells. And these are the key players, okay, in this technology, like Agilent technologies, ICX Photonics, Luminesce Devices, and NEC Corporation. Okay? So, this is typically the overview of the market of these photonic crystal fibers. And with that, we will stop here.

In case of any doubt regarding this lecture of overview of the photonic crystal technology, you can drop an email to me at dev.sigdar at itg.ac.in and I will try to reply that. Make sure you mention MOOC and photonic crystal on the subject line. Thank you. Thank you.

Thank You