Lec 15: Applications of 2D photonic crystals

Hello students, welcome to lecture 15 of the online course on Photonic Crystals Fundamentals and Applications. Today's lecture will be covering applications of 2D photonic crystals.

Lecture Outline

- Introduction
- Light Emitters
- Optical Waveguides
- Optical Fibers
- Wavelength Filters
- Photonic Crystal Sensors
- Topological Photonic Crystals

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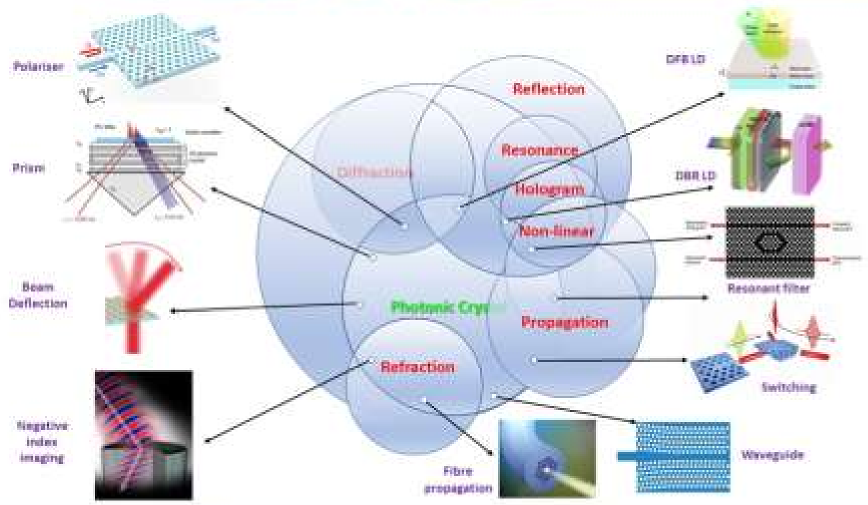
Introduction



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Here is the lecture outline, we will look into the introduction, some light emitters, we will discuss about optical waveguides and optical filters. So, as you can see in this particular figure The image provides a detailed overview of various applications and properties of photonic crystals in the context of optics and photonics. So if I try to provide a concise summary, you can see that photonic crystals, which is central to this diagram, So, these all are different types of photonic crystals which are basically structures with periodic optical properties that manipulate light at wavelengths comparable to the spacing within the crystal. So, the periodicity is basically of the order of the wavelength of the light that is interacting with the crystal.

If you look into various parts of this image, it shows beam deflection here, which is basically the art of redirecting light beams to achieve desired propagation paths. You can also think of negative index imaging that creates images using materials where the refractive index is less than zero. So, that allows for novel imaging techniques such as perfect lens. you can think of waveguides and fiber propagation which is basically directing light through specific paths efficiently which are crucial for you know optical communication.

This is for long haul and this is for short haul you know on the chip. So, there are some other associated optical properties as well which are something like you know reflection and refraction So, these are basically the fundamental principles of light interaction with materials which are used to guide and control light in devices something like lenses and mirrors. You can also see diffraction effect here which is basically nothing but bending of light around obstacles which are basically used in various optical devices to control light spread. You can also see resonance and holography which uses interference of light waves to create holograms and enhance light matter interaction through resonance. Here you can also look into another field which is nonlinear.

okay. It tells you about the non-linear optical effects which accounts for the phenomena occurring at high light intensities which are typically used in switches and signal processing devices. There are some advanced devices as well which are like DFB laser diode or distributed feedback laser diode or DBR-LD which is distributed Bragg reflector laser diode okay. So, these are basically sources of coherent light essential in systems requiring stable wavelength emission something like you know optical sensors and optical communication system. You can also think of resonance filter these are the devices that allow specific frequencies of light to pass through while blocking others okay and these are important for applications such as in communication and spectroscopy.

So, overall this diagram effectively captures the extensive and expansive role of photonic crystals in modern optical technologies by highlighting their importance in developing advanced optical systems and devices. So, we shall discuss some of these applications in this particular lecture and we will see how they are useful to us.

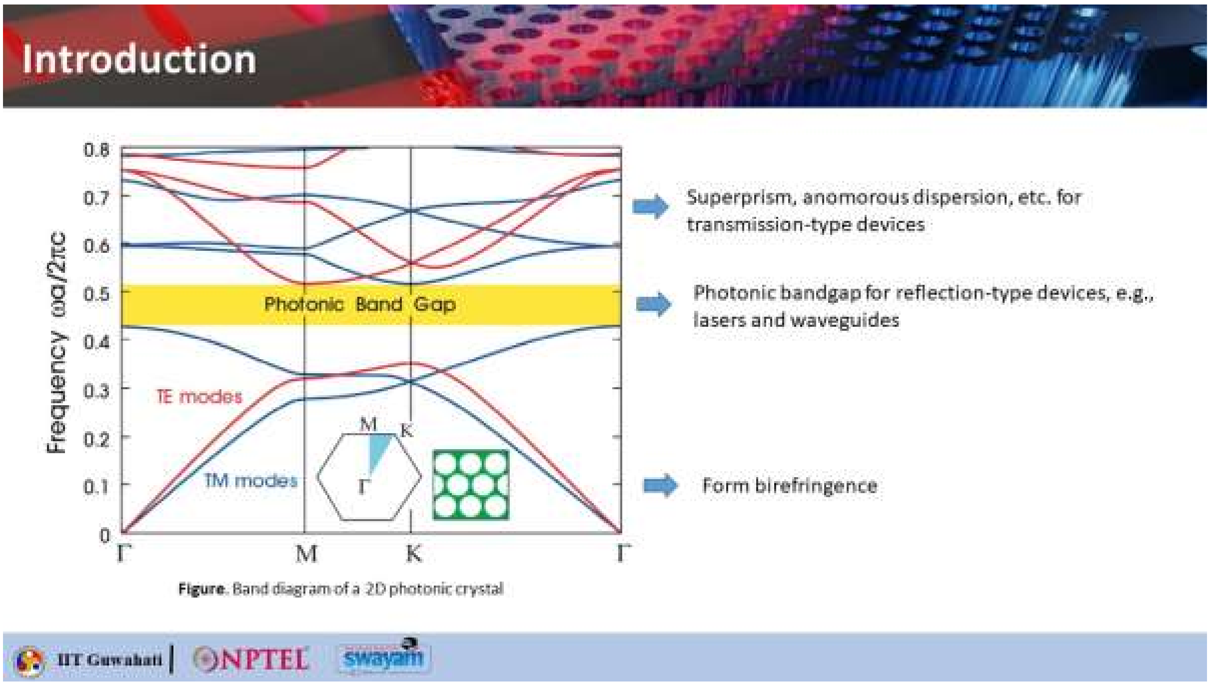

Figure. Band diagram of a 2D photonic crystal

So, when we are talking about photonic crystal the first thing that should come to our mind that these are the crystal that allows us you know engineering photonic band gap. So, here you can see the photonic band diagram which indicates that there are three different frequency ranges right for light that can be utilized for real application. So, this is one range, this is another and this is the third one.

So, you can start from the lowest frequency. So, this is the frequency axis and this is your you know k vector. you can start with the lowest frequency range which is below the first zone folding of the photonic band, okay. And the gradient of the lowest straight photonic band is determined by the effective index n of the photonic crystal, okay. And it is different for different polarization as you can see here.

So, classically this characteristics is called form birefringence because there are two different refractive index for two different polarization means in two different direction there are two different effective index okay. Since the photonic band calculation precisely predicts the effective index of each polarization the index is artificially controlled by the photonic crystal structure. So, you can actually engineer this by reference by designing the photonic band structure or photonic crystal structure. The second one is the highlight okay, as you can see it is already shown in yellow. So, the second one is basically showing you the photonic band gap, which means it is an omnidirectional stop band.

So, any frequency that lies within this particular yellow band will be blocked from entering that photonic crystal. So, it is one of the most unique properties of photonic crystals and actually it was the main topic at the early stage of photonic crystal research. The photonic bandgap can be used as a reflector for light that is to enter the photonic crystal from arbitrary directions. So, it is applied to reflection type of devices something like you know lasers and waveguides. And the third one as you can see here, the third one is the higher frequency range which is above the photonic band gap.

So, here complex photonic bands exist. And as you understand the slope of a photonic band is basically proportional to the group velocity which is Vg of light, right. So, if you see that the horizontal band at the band edge okay, means typically you are getting 0 group velocity, right and that will give you localization of light energy. So, in 2D and 3D photonic crystals such 0 Vg or very small Vg appears not only at the band edge but also in many other bands as you can see here, right. So, they will be effective for the enhancement of various interactions of light with materials in the photonic crystal.

In addition, the 2D or 3D distribution of bands and the so called dispersion surface provides unique light propagation in the photonic crystal. Thus, the frequency range can be used in transmission type functional devices. So the most devices that are presently studied use 2D photonic crystals because they are relatively easy to fabricate and it is compatible with LSI planar technology.

Light Emitters

- PC light emitters are categorized into four types.
- This is as shown in figure.
  - (a) Ultralow threshold micro laser having a point-defect active region in a uniform PC,
  - (b) High-power **distributed feed back** (DFB) laser utilizing the whole area of a uniform PC,
  - (c) High-power and stable single mode **vertical cavity surface emitting laser** (VCSEL) with an air-hole array, and
  - (d) **Light-emitting diode** (LED) with high extraction efficiency by PCs.

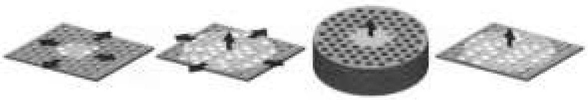

Figure. Four photonic crystal light emitters: (a) point-defect laser; (b) band-edge laser; (c) VCSEL; (d) light-emitting diode

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

So, now let us look into a few interesting light emitters based on photonic crystals. So, photonic crystal light emitters can be categorized into 4 types.

So, the first one is a point defect laser as you can see here, it is the ultra low threshold micro laser that has got a point defect active region within a uniform photonic crystal. The second one is a band edge laser. So it has got a high power distributed feedback DFB laser utilizing the whole area of a uniform photonic crystal. The third one shows VC cell. What is that? It is a high power and stable single mode vertical cavity surface emitting laser.

which has got air hole array okay and this is how this VC cell is made and the last one is a light emitting diode which has got higher extraction efficiency because of the photonic crystals. So, these are the four different types of light emitters which are based on photonic crystals

Light Emitters

- **Historical Context**:

  Point-defect Laser

  - The concept of using defects in photonic crystals, analogous to impurity doping in semiconductors, was first discussed in 1987 to localize electron waves near impurity atoms.
- **Defects in PCs**:
  - In photonic crystals, defects are used to localize light, akin to how impurities localize electrons in semiconductors.
  - These defects in a PC with a photonic band gap (PBG) act as ultrasmall laser cavities.

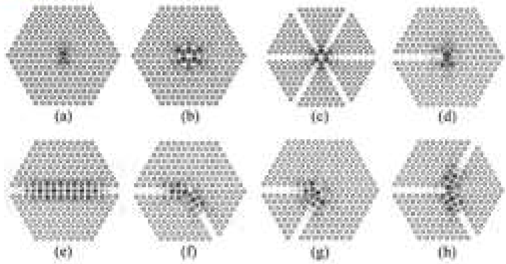

Figure. Localised modes at various defects of 2D Photonic crystal of triangular lattice holes.

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

. let us look into point defect laser. So, the concept of using defects in photonic crystals which are basically analogous to impurity doping in semiconductors was first discussed in 1987 okay. So, in photonic crystal defects are used to localize light which is very similar to what impurities does in semiconductor to localize electrons.

So, these defects in photonic crystal in a photonic band gap can act as an ultra small laser cavity. So, as you can see here different localized modes at various defect sites in a 2D photonic crystal are shown here okay. So, different types of modes can be localized based on the defect in a 2D photonic crystal which is basically made of triangular lattice holes. So, you can also see cavity quantum electrodynamic effects there, okay. So, the defect induced cavities in photonic crystals can control spontaneous emission which offers potential application in the field of cavity quantum electrodynamics.

Light Emitters

Point-defect Laser

- **Cavity Quantum Electrodynamic Effects:**
  - Defect-induced cavities in PCs can control spontaneous emission, offering potential applications in cavity quantum electrodynamics.
- **Applications in Photonics and Quantum Technologies:**
  - Development of ultralow threshold lasers or "threshold less" lasers.
  - Use as internal light sources in densely packed photonic integrated circuits.
  - Utility in quantum communication and computation systems that operate with single photons.
- **Types of Defects:**
  - Simplest Defect: Involves the deformation or removal of a single unit cell in the crystal structure.
  - Complex Defects: Includes larger defects, line and point composite defects, and modified line defects. These also strongly localize light.

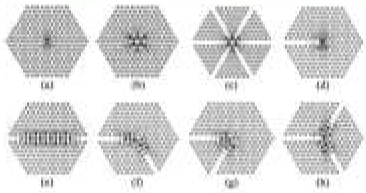

Figure. Localised modes at various defects of 2D Photonic crystal of triangular lattice holes.

There are different applications of this in photonics and quantum technologies such as development of ultra low threshold lasers or you can say threshold less lasers okay. You can make them use as internal light sources in densely packed photonic integrated circuits and they can also be used in quantum communication and computation systems which operate with single photons okay. So there are different types of defects you can think of simplest defects that is basically involves deformation or you know removal of a single unit cell in a crystal structure. And you can also think of complex defects which will involve larger defects something like you know line or point composite defects or modified line defects. So these are basically you know line defects or modified line defects as you can see.

Light Emitters

Point-defect Laser

- **Field Profiles and Localization Modes:**
  - Analysis using finite-difference time-domain (FDTD) simulation demonstrates that both small point defects and larger structural modifications can localize light effectively.
  - Light localization in composite and modified line defects is governed by the cutoff conditions of the waveguide mode.
- **Waveguide Modes and Expanded Modes:**
  - Simple line defects can lead to expanded modes which are influenced by the PB edge of a waveguide mode.

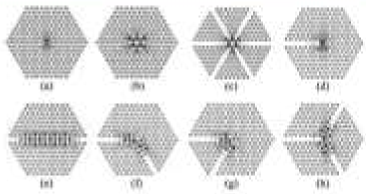

Figure. Localised modes at various defects of 2D Photonic crystal of triangular lattice holes.

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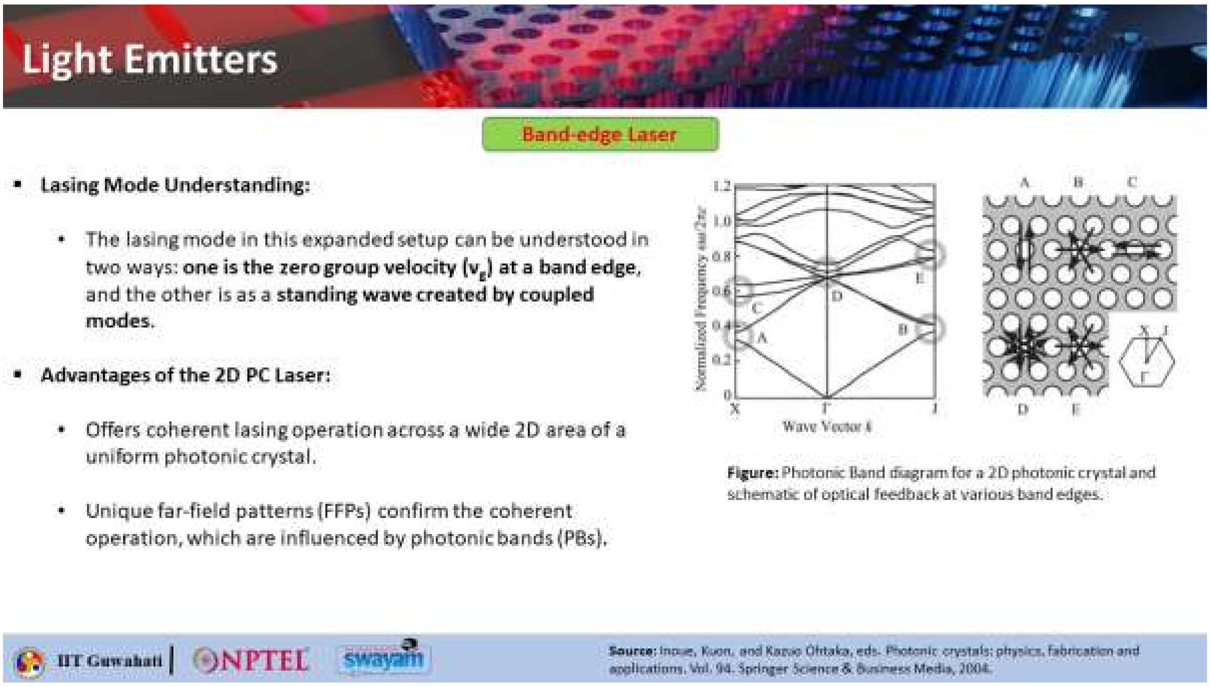
Source: Inoue, Kuon, and Kazuo Ohtaka, eds. Photonic crystals: physics, fabrication and applications. Vol. 94. Springer Science & Business Media, 2004.

So they can strongly localize light and these are basically know defect made of single unit cell. You can study this field profiles and localization modes using you know finite difference time domain kind of simulation. So, these are FDT dissimulations which demonstrate that both small point defects and larger structural modifications are able to you know localize light effectively. So, these simulations are the only way to visualize how the localization will look like in a real crystal before you can actually fabricate them. Light localization in composite and modified line defect is governed by the cut-off conditions of the waveguide mode.



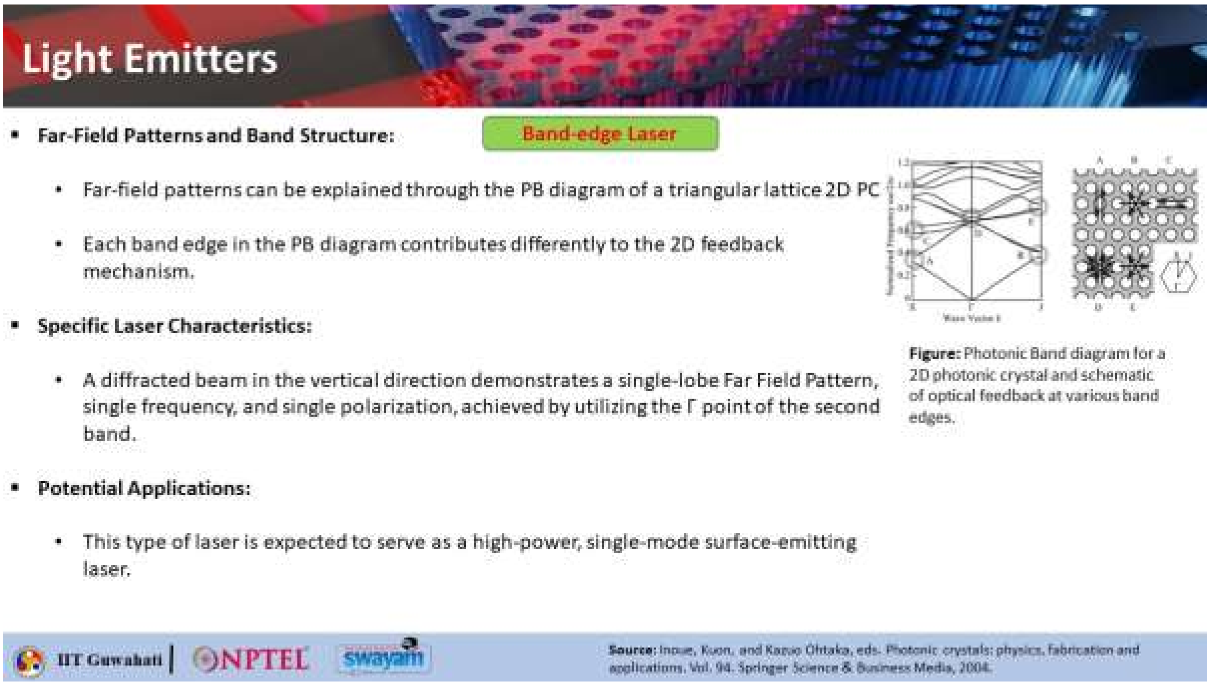
So, simple line defect can lead to expanded modes which are basically influenced by the photonic band edge of a waveguide mode. So, now we will look into you know band edge lasers. So, this is a photonic band diagram for a 2D photonic crystal right and we will see the schematic of optical feedback at different band edge okay. So this band edge are marked as A, B, C, D, E. And we will actually see that how the optical feedback works at different band edge.

So to understand the lasing mode, the lasing mode in this expanded setup can be understood in two ways. one is the zero group velocity that is Vg at the band edge. So, this is more or less you know flat line. So, you can take the slope which comes out to be 0 and the second thing is it is as a standing wave created by coupled modes ok. So, you can think of two ways okay for understanding the lasing mode.

One is the mode with zero group velocity so it is not moving anywhere it is kind of a trapped one and the second one is a standing wave again it is not moving anywhere and that is created by coupled mode. So, if you take the 2D photonic crystal laser they offer advantages such as you know coherent lasing operation wide across 2D area of uniform photonic crystal and they also have unique far-field patterns that confirm the coherent operation which are influenced by the photonic bands. So, here you can see that how different you know optical feedback is giving rise to this particular edges. So, more or less you can see at A, C, B and E okay you actually see that you know here only two bands are there. So, you can see there are two modes which are opposite direction.

So, they are basically forming a standing wave kind of pattern okay. At C also the same thing happens okay. For D there are many many bands. So, all these are taken care over here and that is how you can interpret this particular tag. So, the fault field patterns that can be explained from the photonic band diagram.

So, if you consider this triangular lattice of a 2D photonic crystal, you can see here that you know each band edge like A, B, C and E contribute differently to the 2D feedback mechanism. So, you can actually see that the contributions are quite different. And, you can also think of specific laser characteristics like you know a diffracted beam in the vertical direction demonstrates a single lobe furfield pattern. which will have single frequency and single polarization and it can be achieved by utilizing the gamma point of the second band. So, you can actually go for this one and you can obtain single lobe furfield pattern with single frequency and single polarization.



So, that is a special characteristic for this particular band edge laser. So, what are the potential application? This type of laser is expected to serve as a high-power single mode surface emitting laser

Light Emitters

- **Overview of VCSEL:**

VCSEL

  - The VCSEL is a type of microcavity laser that utilizes optical feedback from a 1D photonic crystal, specifically a semiconductor multilayer stack.
  - It is commercially available and commonly used as a cost-effective light source in local area networks.

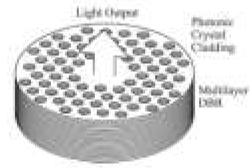


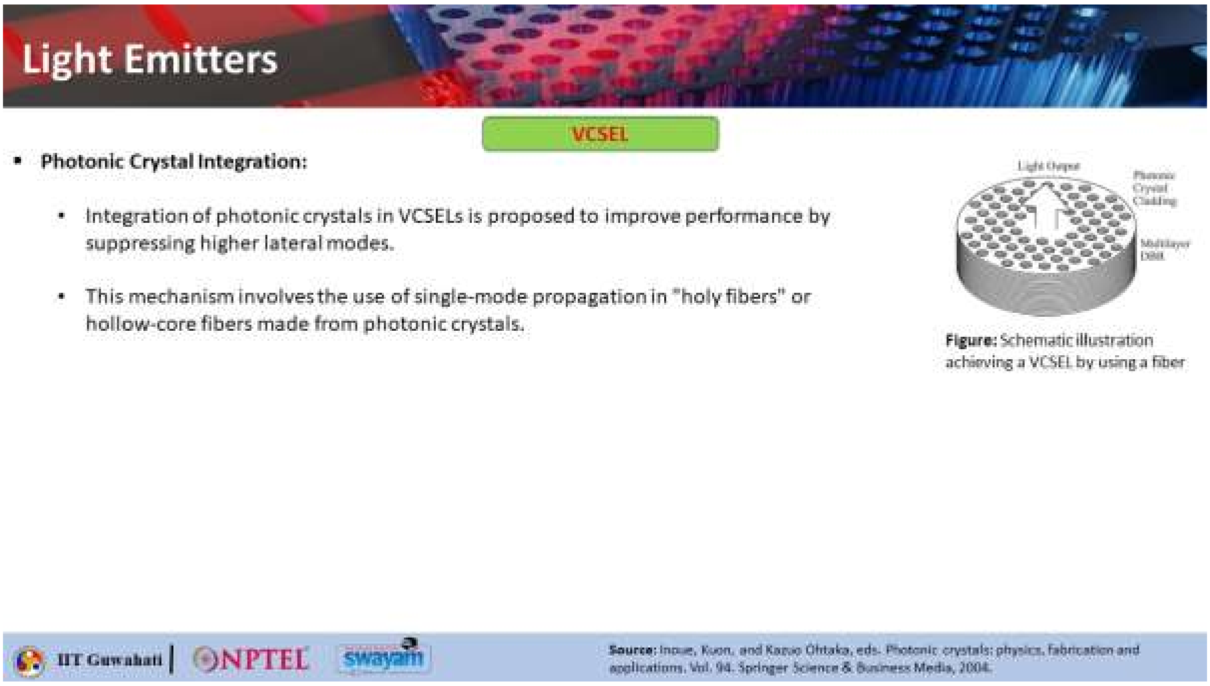
Figure: Schematic illustration achieving a VCSEL by using a fiber

- **Limitations of Current VCSELs:**
  - Current models are limited to a light output of less than 8 mW, primarily due to unstable lateral modes caused by the large aperture of the devices.

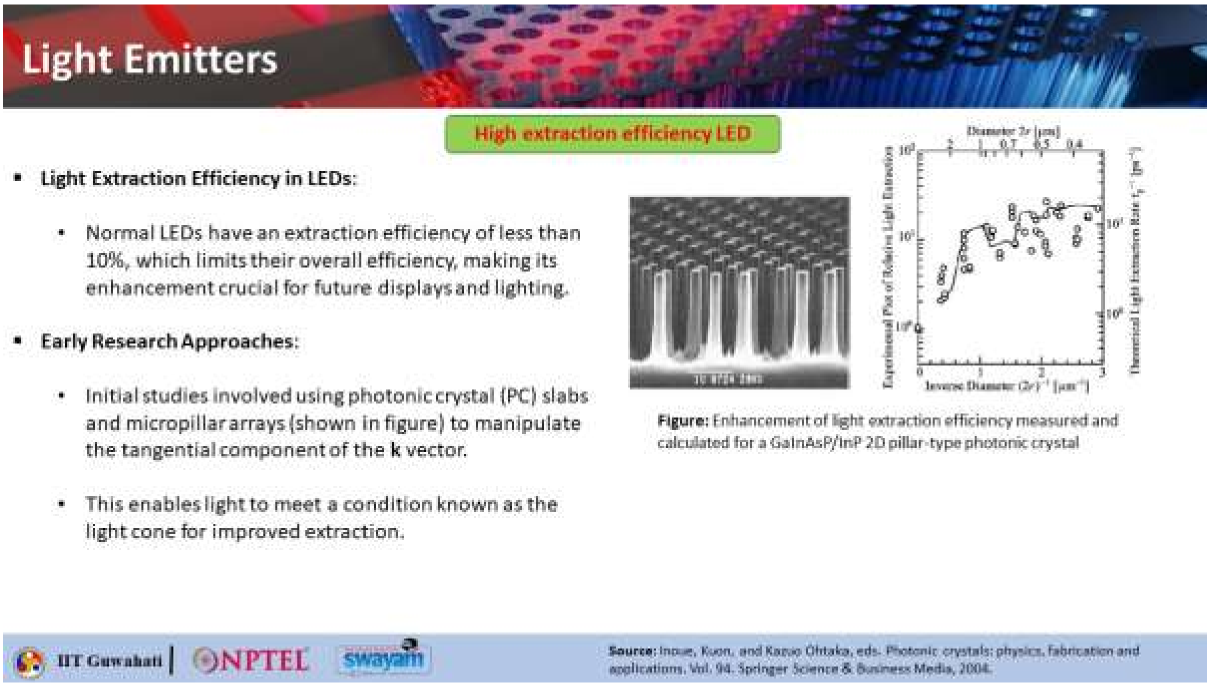
Source: Inoue, Kuon, and Kazuo Ohtaka, eds. Photonic crystals: physics, fabrication and applications. Vol. 94. Springer Science & Business Media, 2004.

Next, we will go into the discussion of VCACL which is basically vertical cavity surface emitting laser. So, here you can see the construction of this particular laser. So, it is a stack of multilayer distributed Bragg reflectors and then you have a photonic crystal cladding and from here you will get the light output.

So, this VCACL is a type of micro cavity laser that utilizes optical feedback from a 1D photonic crystal that is this distributed Bragg reflector which is a semiconductor multilayer stack. This kind of laser is commercially available and commonly it is used as a cost effective light source in local area networks or LAN. okay and this mechanism involves use of a single mode propagation in holy fiber okay or hollow core fibers which are made of photonic crystals which will be discussed to some extent in this particular lecture. So, what are the limitations of the current VCACL? You can see that the current models are limited to light output of less than 8 milliwatt. This is particularly due to the unstable lateral modes which are caused by the large aperture of the device.

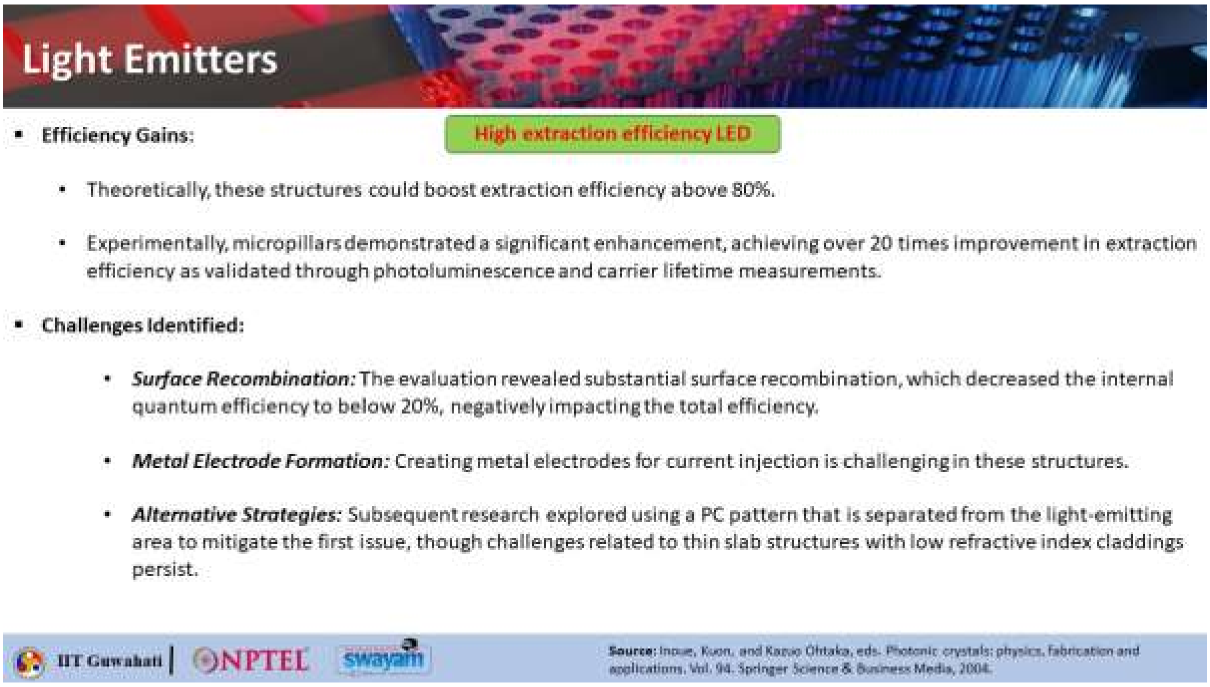


Now, integration of photonic crystals in VCACL is proposed to improve the performance of the VCSEL by suppressing the higher lateral modes.



So, when you put the photonic crystal you know cladding what happens this mechanism will involve the use of single mode propagation in holy fibres that we will be discussing in details okay or hollow core fibre made from photonic crystal. So, that way you will be able to suppress the higher lateral modes. The next one would be how do you use photonic crystals to improve the extraction efficiency from light emitting diodes. So, if you look into normal LEDs they have very little light extraction efficiency which is typically less than 10 percent ok.

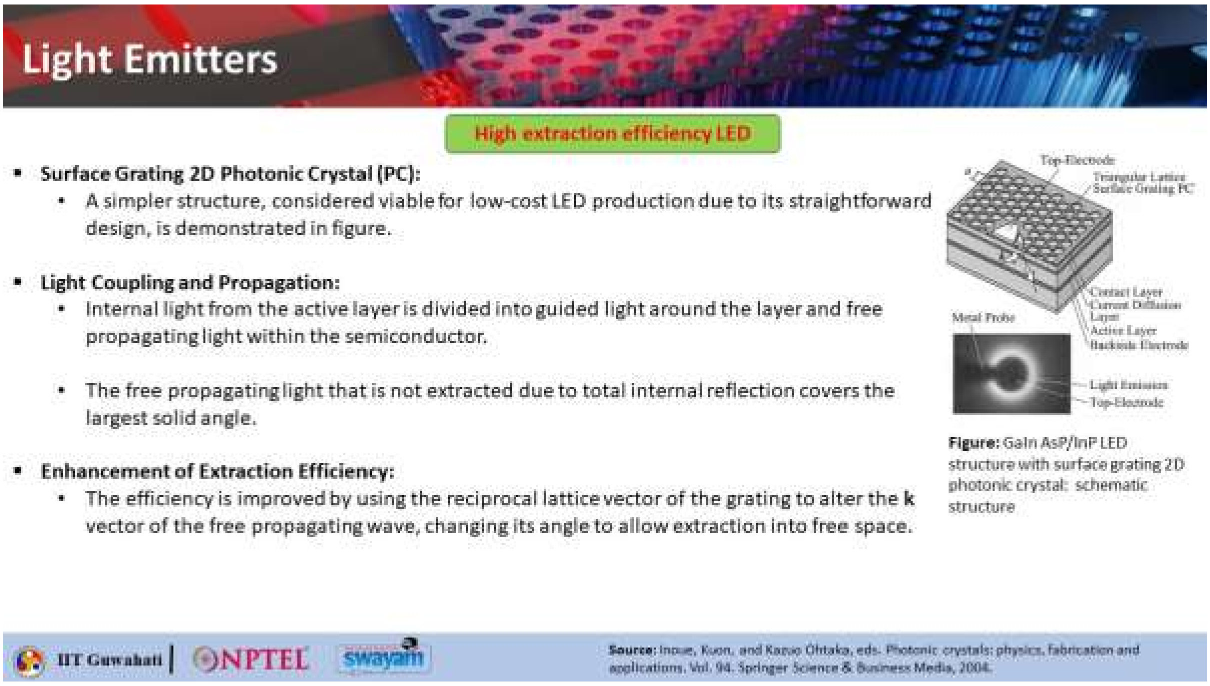
And that basically limits their overall efficiency and making this enhancement very critical for future displays and lighting. So, by using you know photonic crystals 2D photonic crystal you can actually enhance the light extraction from LEDs multiple times and here you can see how it is done. So, this is for light enhancement of light extraction efficiency which is measured and calculated. So, the solid one is the measured calculated one and the dots are the measured values for gallium indium arsenide phosphate and indium phosphate.



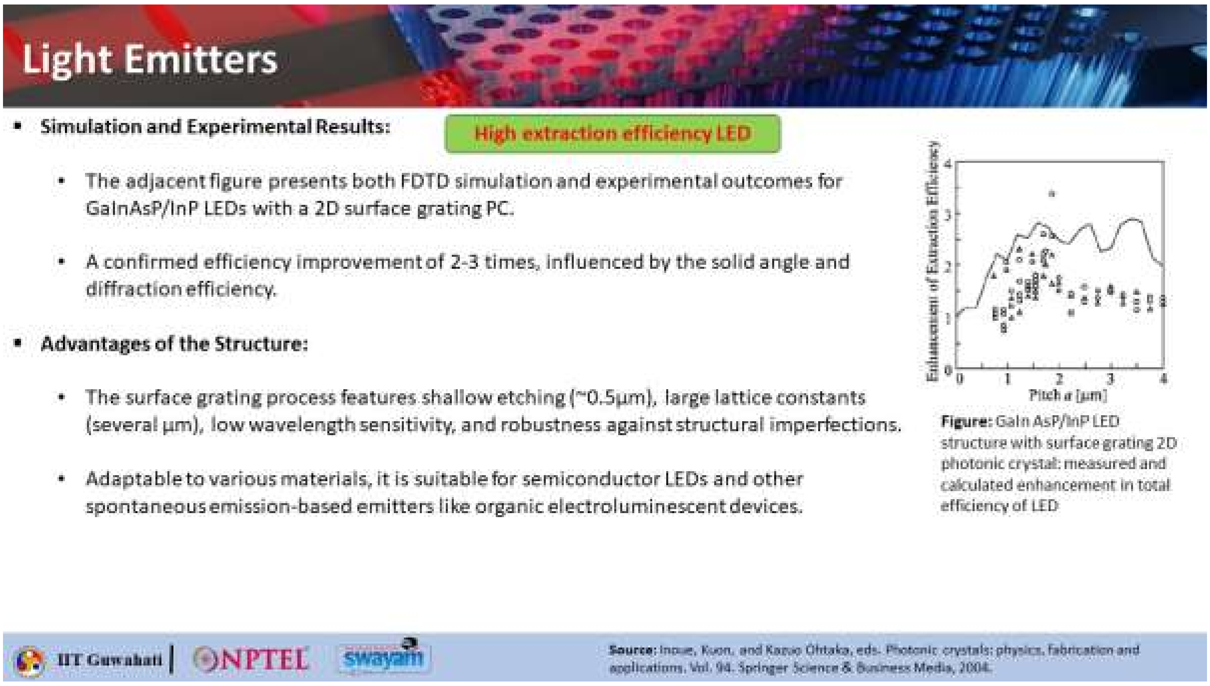
So, these are the 2D photonic crystal type. So, what happens you know we have seen that when you use you know photonic crystal slabs and micropillar array something like this that can be used to manipulate the tangential component of the k vector and that way you will be able to extract more light you know through the light cone and that actually improves the efficiency. So, that is what is mentioned here that this enables light to meet a condition which is known as the light cone for improved extraction. So, theoretically this kind of devices could boost the extraction efficiency above 80 percent which is otherwise only 10 percent right. So, experimentally it was seen that the micro pillars demonstrated a significant enhancement achieving over 20 percent improvement in extraction efficiency which was validated through photoluminescence and carrier lifetime measurements. So, that was a significant enhancement or step towards making high efficient or highly efficient LEDs.

Now, what are the challenges there? Surface recombination that is a challenge. The evaluation revealed that you know substantial surface recombination which decrease the internal quantum efficiency to below 20 percent are negatively impacting the total efficiency. than the formation of metal electrode that is like creating metal electrodes for current injection okay. So, you can I will go to the structure later is also challenging in these structures and what are the alternative strategies. So, subsequent state research explored that using a in a photolytic crystal pattern that is separated from the light emitting area to mitigate the first issue though the challenges.

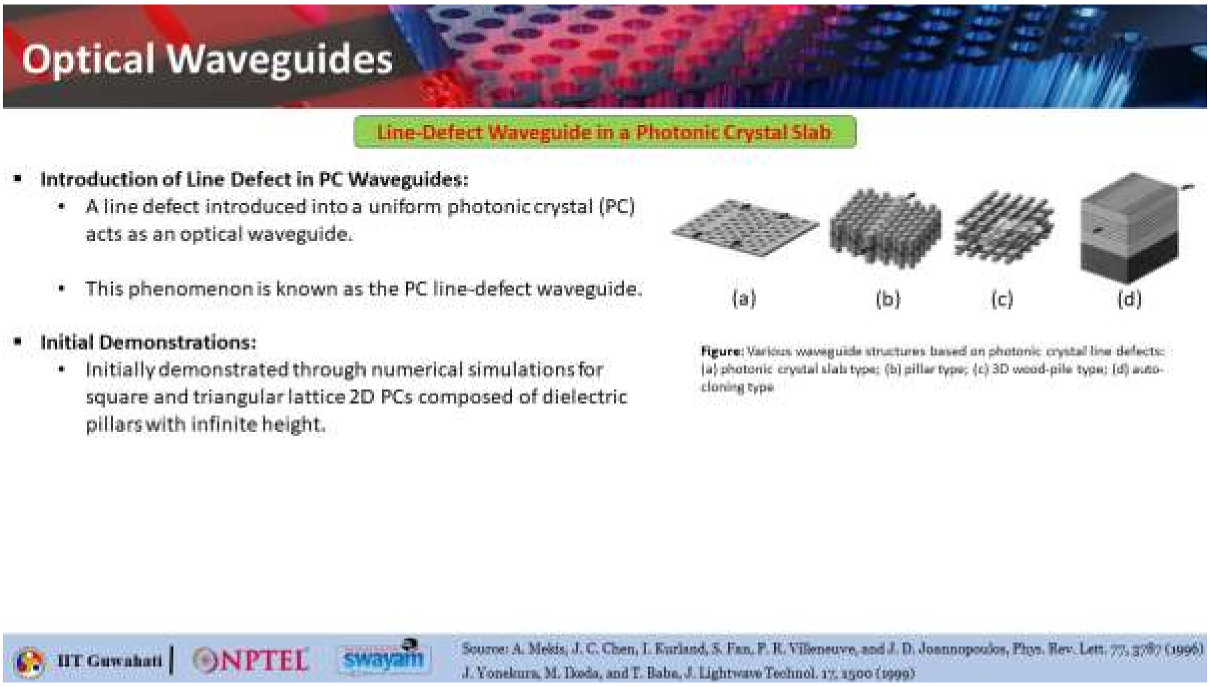
related to thin slab structures with low refractive index claddings will still persist. So, here you can see you know surface grating 2D photonic crystal. So, it is a simpler structure considered viable for low cost LED production due to its straightforward design. So, you can see it's a triangular lattice surface creating photonic crystal. So the period is A, and this is where the top electrode will be placed, okay? So light coupling and propagation, you can see that the internal light from the active layer is divided into guided light around the layer and free propagating light within the semiconductor, right? Now the free propagating light that is not extracted due to total internal reflection covers the largest solid angle.



So, what how do you can enhance the extraction efficiency? You can actually enhance the efficiency by using reciprocal lattice vectors of the grating okay to alter the k vector of the free propagating waves which are otherwise trapped okay and once you do that that changes its angle okay. So, you can extract that light that guided light into free space. So, people have done simulation and experiments and this particular figure as I mentioned it shows a result of FDDD simulation the solid line and the experimental outcome which are measured for gallium indium arsenide phosphate okay, indium phosphate LEDs with a 2D surface grating photonic crystal. okay. And they have seen a confirmed efficiency improvement of 2 to 3 times which is influenced by the solid angle and the diffraction efficiency.

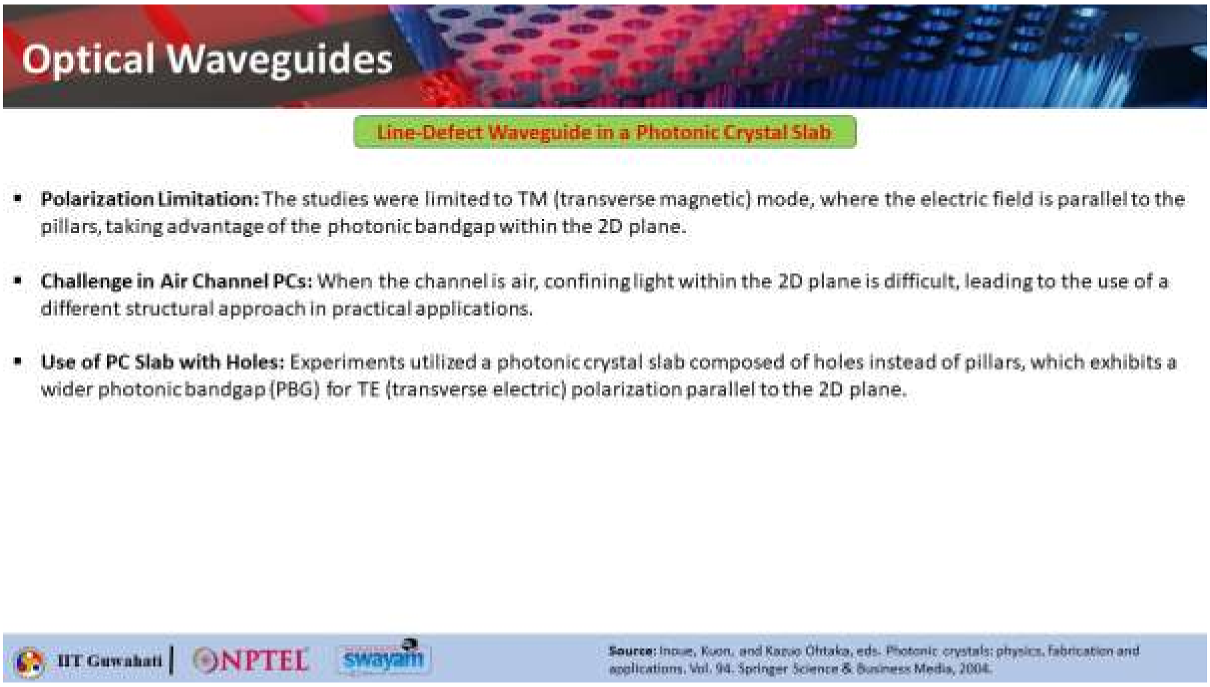


So, what are the advantages of the structure? So, the surface grating would allow you know the process This surface grating process features shallow etching okay, so you do not need to make those difficult structures you can you know make shallow etching like 0.5 micrometer and then you can use large lattice constants of the order of several micrometers, low wavelength sensitivity and it is also robust against structural imperfection. It means making those structural grating or surface grating is not that challenging. Now, it is also adaptable to various materials and thus it is suitable for semiconductor LEDs and other spontaneous emission based emitters something like organic electroluminescent devices.



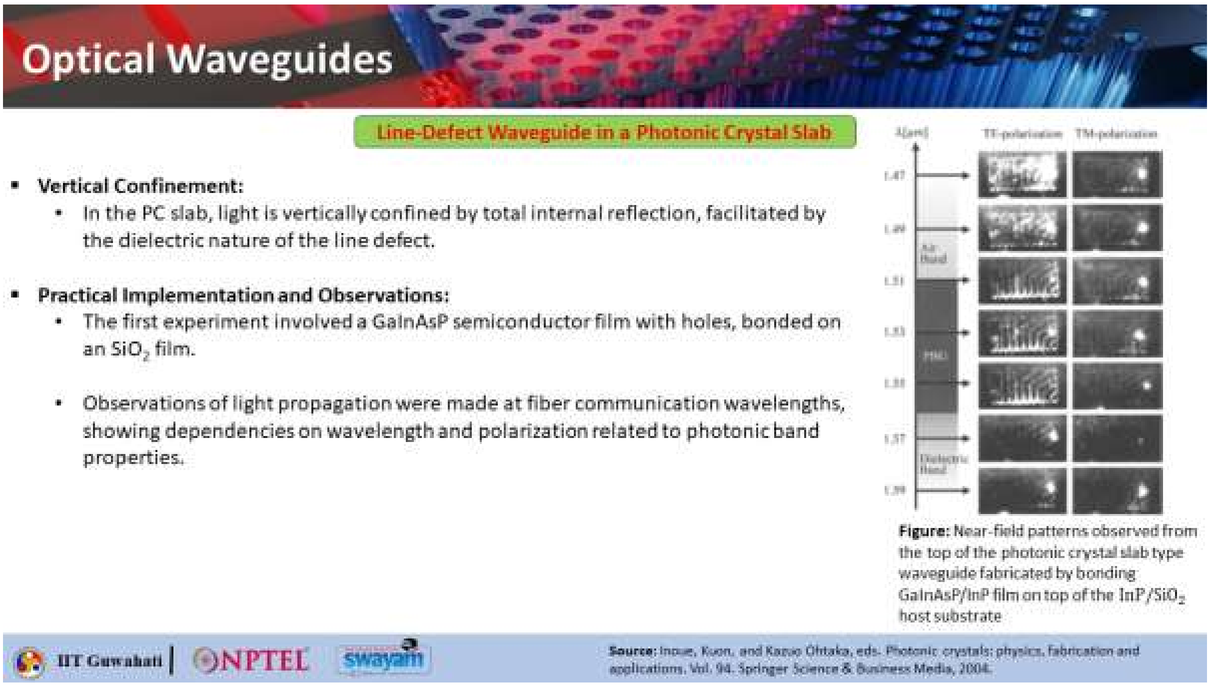
So, these are something very very encouraging. Now, we move on to optical waveguides another application of 2D photonic crystals. So with introduction of line defect in a photonic crystal, you can actually form waveguides. So we can actually see various type of waveguide structures over here, which are basically in the form of line defects. so here you can see what has happened this is like a missing row of holes that can create a line defect here the holes can be of slightly a larger diameter that can create a line defect so this is in a photonic crystal slab okay so it's a 2d photonic structure with a finite height You can see this as a pillar type photonic crystal 2D photonic crystal where the pillar diameters are larger along this particular line. You can think of you know 3D structure, wood pile structure and also auto cloning structure.

There also you can introduce line defects right. So introducing this kind of line defect will give you photonic crystal line defect waveguides. So, initially they were basically demonstrated through numerical simulations for square and triangular 2D photonic crystals composed of dielectric pillars with infinite height because that is what is easy to simulate ok. So, you can only do a 2D simulation and see the characteristics ok.

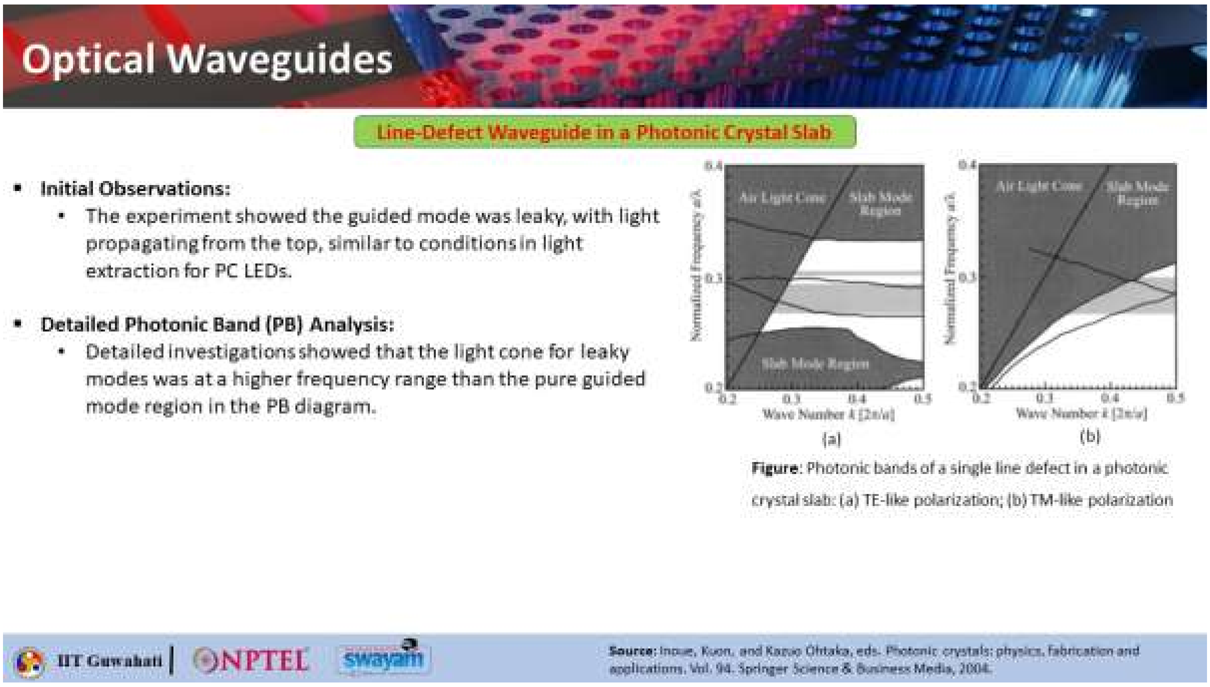


And then you know when you go into the details of line defect waveguide for the first example that is the photonic crystal slab you can say that you know this studies show polarization limitation. It means the studies were limited to TM transverse magnetic mode where the electric field is parallel to the you know pillars taking advantage of the photonic band gap within the 2D plane.

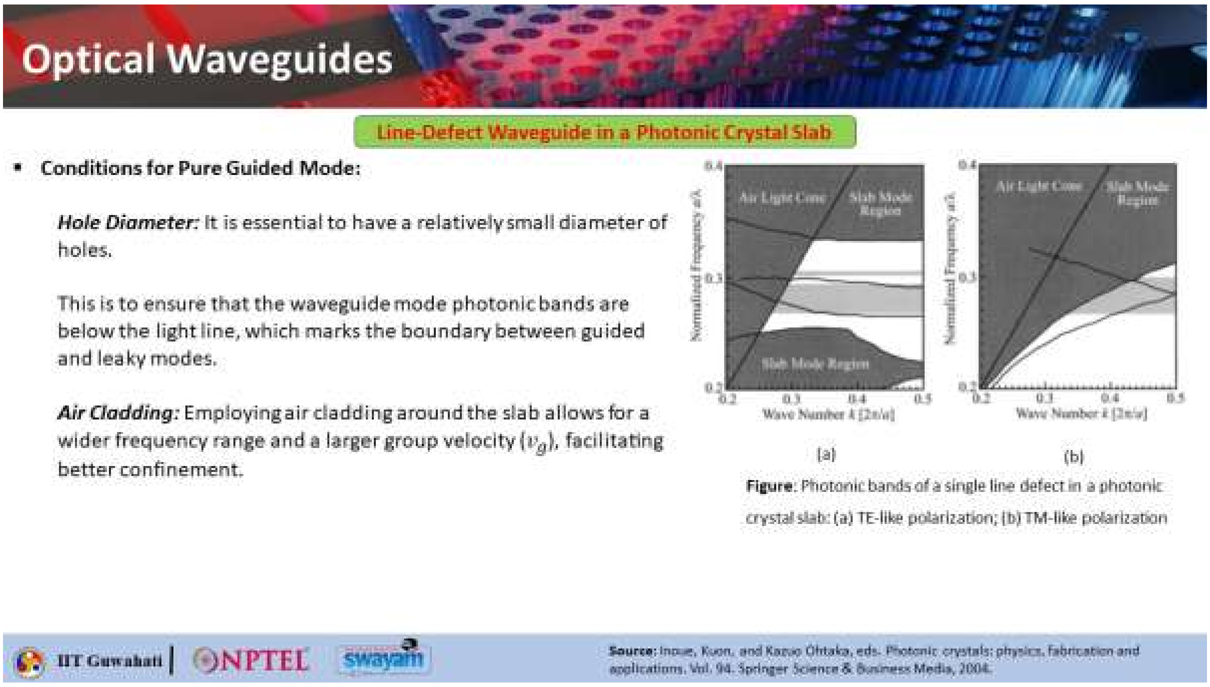
There is challenge in air channel photonic crystal. So, when the channel is air confining light within the 2D plane becomes difficult that leads to the use of different structural application or approach in case of practical usage. Now, use of photonic crystal with holes okay, so when experiments utilized a photonic crystal which has used holes instead of pillars in that case the it exhibits wider photonic band gap for TE polarization parallel to the 2D plane. So, these are some of the near field patterns which are observed from the top of the photonic crystal slab type waveguide which are fabricated by bonding this film on top of a indium phosphide silica host substrate. So, here you can see a different wavelength this near field patterns are captured. So, these are basically dielectric bands, these are within the photonic band photonic band gap okay and these are in the air band okay.



So, you can see the vertical, so this column is for TE polarization, this one is for TM polarization. So what you can see here the vertical confinement that is in the photonic crystal slab light is vertically confined and that confinement comes from total internal refraction which is basically facilitated by the dielectric nature of the line defect. And so this was the first experiment that involved a gallium indium arsenic phosphate okay, indium phosphate semiconductor film okay with holes which was actually bonded on a silica film, okay. And what you see here that light propagation was studied at different fiber communication wavelengths and it showed that the propagation characteristic depends on both wavelength and the polarization, okay. So, that is how it differs



So, here you can see the photonic bands of a single line defect in photonic crystal slab for TE polarization and TM polarization. So, the experiment showed that the guided mode was leaky with light propagating from top which is similar to the conditions in light extraction from photonic crystal LEDs. And if you look into the details of the photonic bands it shows that the light cone for the leaky modes at higher frequency range lies at you can say that the light cone for leaky modes was at a higher frequency range than the purely guided modes region in the photonic band diagram. So, these are basically, so this is the band gap as you can see here and this is called the dielectric mode or dielectric band and this is called the air band and here also you can see that the band below the photonic band gap is the dielectric band.



So, usually dielectric band will have lower frequency. So, it has got the higher wavelength or larger wavelength and air band has got a higher frequency than the photonic band gap. So, they will have shorter wavelengths. So, what are the conditions for pure guided modes? First thing is the hole diameter. So, it is essential to have a relatively small diameter of the holes. So, this will basically ensure that the waveguide mode photonic bands are below the light line.

So, that will mark the boundary between the guided mode and the leaky modes. and then air cladding. So, if you employ air cladding around the slab that will allow wider frequency range and larger group velocity which will basically ensure you have got better confinement. So, what are the fabrication challenges or how do you improve the fabrication? So, use silicon on insulator wafers and gallium arsenide or indium gallium arsenide films as high quality transparent substrate for fibre communication wavelengths. you can fabricate the waveguides by simply drilling holes and forming air bridge structure to meet these predefined conditions.

Optical Waveguides

Line-Defect Waveguide in a Photonic Crystal Slab

- **Fabrication Improvements:**
  - Use SOI wafers and GaAs/AlGaAs films as high-quality, transparent substrates for fiber communication wavelengths.
  - Waveguides were fabricated by simply drilling holes and forming an air-bridge structure to meet these refined conditions.
- **Observation of Pure Guided Modes:**
  - With these improvements, a pure guided mode showing no light leakage was observed.

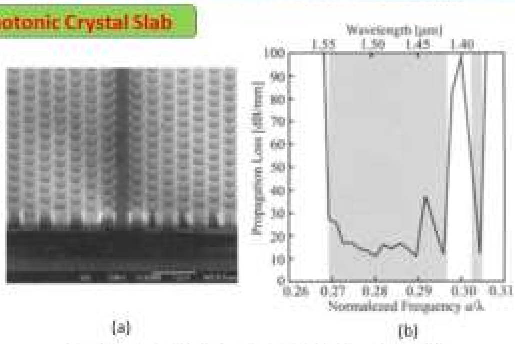


Figure: Fabricated single line defect waveguide and propagation loss: (a) picture of waveguide fabricated on an SOI wafer; (b) measured propagation loss spectrum

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

And this is how the picture of a waveguide looks like when it is fabricated on a silicon on insulator substrate or wafer ok. And with this kind of improvement you will see that there is a pure guided mode which shows no light leakage ok

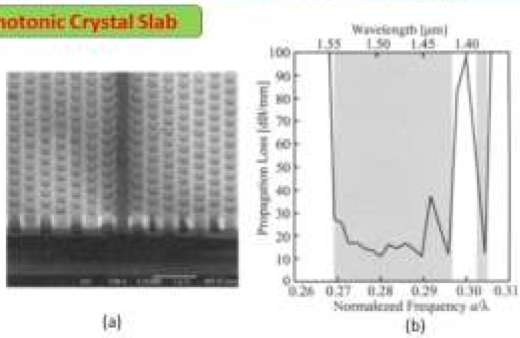
Optical Waveguides

Line-Defect Waveguide in a Photonic Crystal Slab

- **Current Challenges and Future Potential:**
  - ***Propagation Loss:*** The propagation loss in the waveguide is currently evaluated between 1 to 10 dB/mm.

    This is mainly due to light scattering caused by structural imperfections.
  - ***Potential Reduction in Loss:*** Improved fabrication techniques could reduce scattering loss significantly, as the PB restricts radiation modes.

    This indicates lower potential loss than high-index-contrast waveguides.



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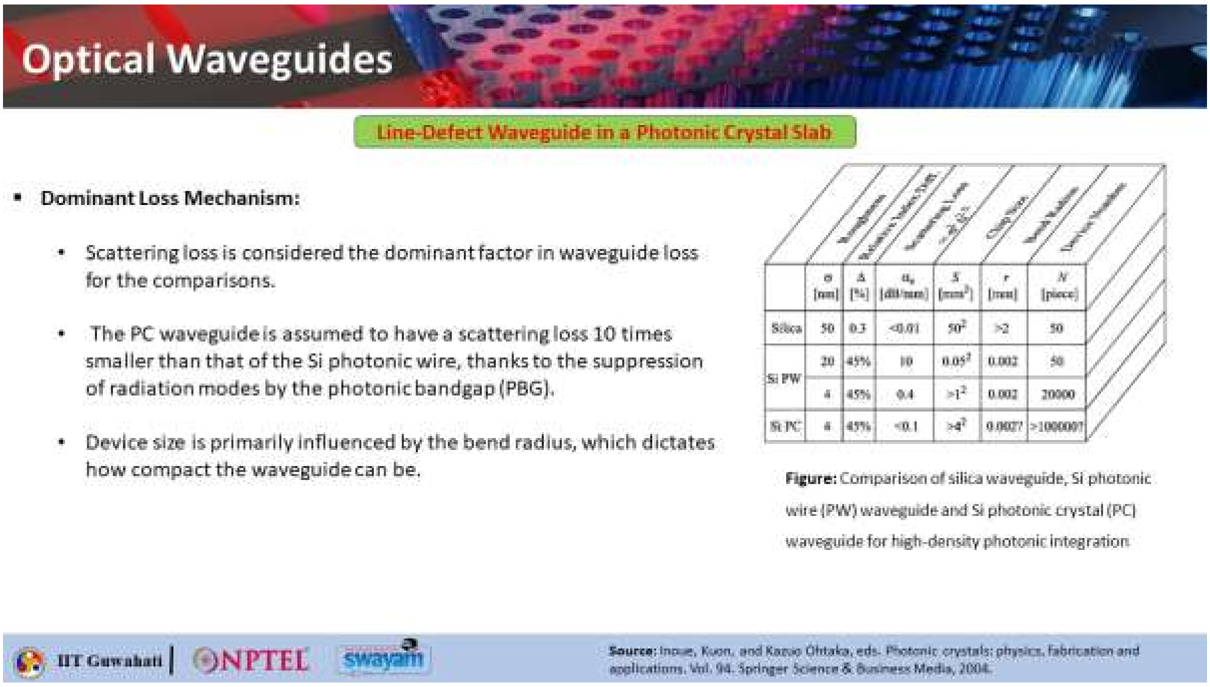
. So, What are the current challenges and future potential? So, you can see the main challenge in a waveguide will come from the propagation loss. So, the right now the propagation loss is evaluated somewhere between 1 to 10 dB per millimeter and this is mainly because of the light scattering due to structural imperfections, otherwise there is no reason why light there will be so much of loss, okay. You can also see for normalized frequency A by lambda and then you know this is the wavelength scale and this is where the propagation loss is.

So, you can actually keep the propagation loss minimal if you operate in this particular wavelength range. Now, with improved fabrication techniques you can reduce the scattering loss significantly and that will happen when the photonic band restricts the radiation modes right and this indicates lower potential loss than high index contrast waveguides. So, let us now in this particular section let us compare you know different type of waveguides. So, they are basically the conventional silica waveguide, high contrast waveguide which are basically silicon photonic wear and you can also think of silicon photonic crystal waveguides okay. So scattering loss is considered to be the dominant factor in waveguide loss for comparison as you can see this particular one tells you about the scattering loss which is pretty high in case of silicon photonic wear okay and very less for silica and also less for silicon photonic crystal okay.



	σ [nm]	Δ [%]	α_s [dB/mm]	S [mm^2]	r [mm]	N [piece]
Silica	50	0.3	<0.01	50^2	>2	50
Si PW	20	45%	10	0.05^2	0.002	50
	4	45%	0.4	$>1^2$	0.002	20000
Si PC	4	45%	<0.1	$>4^2$	0.002?	>1000000?

Figure: Comparison of silica waveguide, Si photonic wire (PW) waveguide and Si photonic crystal (PC) waveguide for high-density photonic integration

This one tells you about the roughness. So, this has got you know 50 nanometer roughness typically okay. So, what you can see that the photonic crystal waveguide is assumed to have a scattering loss which is 10 times smaller than the silicon photonic wire right. this is mainly because of the separation of the radiation modes by the photonic band gap.

and device size ok. So, this is the chip size. So, you can actually compare the chip size and this is significantly smaller as compared to the conventional silica waveguide ok. So, device size also typically depends on the band radius. So, if you look into the band radius you can actually go very very sharp or small band radius using photonic crystal. So, that way you will be able to get high density photonic integration if you use silicon photonic crystal web guides. So, what are the advantages associated with silicon photonic wear? You can see that it can achieve a significant reduction in the device size okay and it also enables ultra high density integration which is beneficial for compact and densely packed optical systems.

Optical Waveguides

Line-Defect Waveguide in a Photonic Crystal Slab

- **Si Photonic Wire Advantages:**
  - Achieves a significant reduction in device size.
  - Enables ultra-high density integration, beneficial for compact and densely packed optical systems.
- **PC Waveguide Potential:**
  - Could allow for larger-scale integration if process roughness is reduced to less than 10 nm and scattering loss is decreased to approximately 1 dB/cm.
  - This would improve both performance and integration capacity.

	σ [nm]	Δ [%]	α_s [dB/mm]	S [mm²]	r [mm]	N [piece]
Silica	50	0.3	<0.01	50^2	>2	50
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Figure: Comparison of silica waveguide, Si photonic wire (PW) waveguide and Si photonic crystal (PC) waveguide for high-density photonic integration

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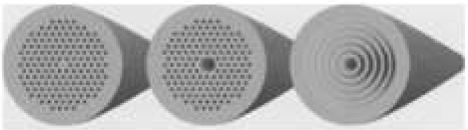
When you look into the photonic crystal waveguides they could allow for large scale integration if the process roughness can be reduced to less than 10 nanometer and if scattering loss can be reduced to approximately 1 dB per centimeter and this will improve both the performance and the integration capacity

Optical Fibers

- **Overview of PC Fibers:**
  - Three kinds of PC fibers are discussed as shown in the figure.
- **Common Manufacturing Process:**
  - These fibers are made by drawing a silica glass preform with air holes, forming periodic cross-sections and uniform optical axis structures.



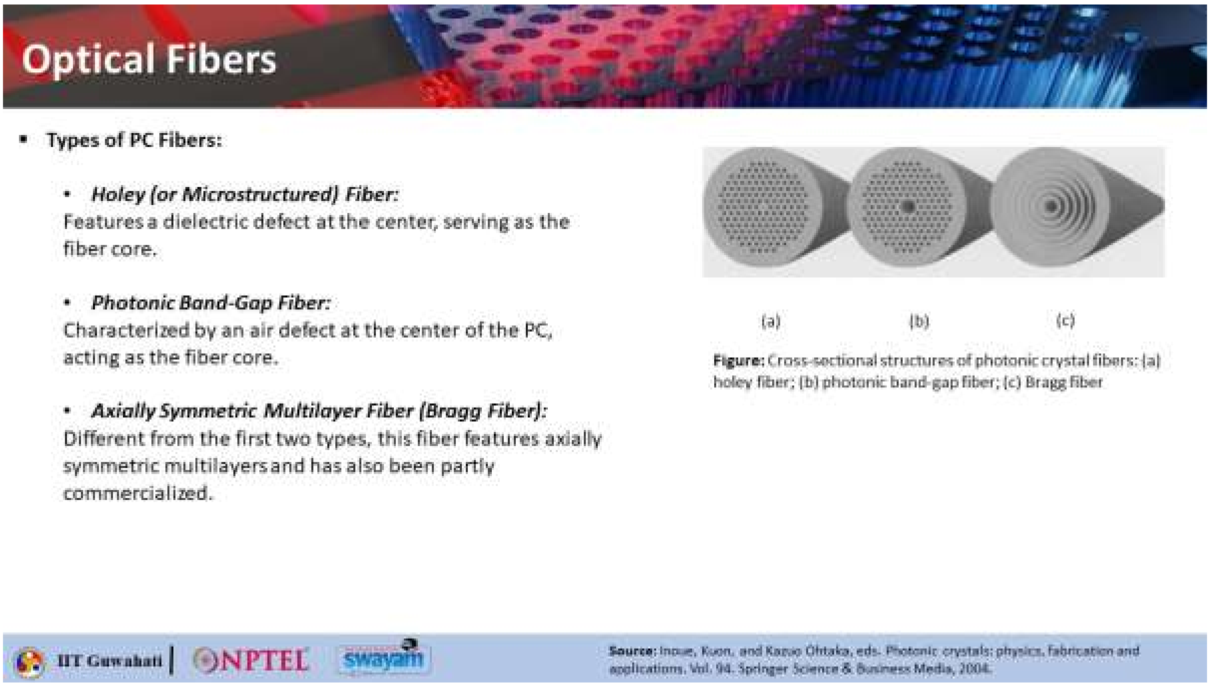
(a) (b) (c)

Figure: Cross-sectional structures of photonic crystal fibers: (a) holey fiber; (b) photonic band-gap fiber; (c) Bragg fiber

Source: J. C. Knight, T. A. Birks, P. St. J. Russell, and J. P. de Sandro, J. Opt. Soc. Am. A 15, 748 (1998)
R. F. Cregan, B. J. Mangan, J. C. Knight, T. A. Birks, P. S. Russell, P. J. Roberts, and D. C. Allan, Science 285, 1537 (1999)

. With that we move on to the last application that we will be discussing today that is optical fibres and here you can see the cross section of the photonic crystal fibres which are basically the holy fibre, photonic bandgap fibre and the Bragg fibre. So, these are the basically three types of photonic crystal fibres which are popularly used. Their common manufacturing process is basically you know these fibers are made by drilling, these fibers are made by drawing a silica glass preform with air holes which forms periodic cross section and uniform optical axis structures. So, if you pay attention to this particular cross sections you will see this wholly or microstructured fiber basically has a dielectric defect at the center.

and this is otherwise a you know triangular array of air holes but at the center there is a defect where the hole is missing you have a solid core okay and that basically serves as the fiber core. If you look into the second one which is photonic bandgap fiber it is characterized by an air defect at the center of the photonic crystal. So, you see a large air hole at the center and this basically acts as a fiber core. For the last one, the Bragg fiber which is also called axially symmetric multilayer fiber.



So, this is basically slightly different from the first two types. This fiber features axially symmetric multilayers and it has been also partially commercialized. So, let us first look into the holy fiber. So, this is the cross-sectional structure which you have already seen. So, what is the light propagation principle in case of holy structure or microstructured fiber? So, light propagation is basically governed by total internal reflection here not by photonic band gap. So, the light is confined around the center silica core due to the difference between the refractive indices of the core and the cladding.

Optical Fibers

Holey Fiber

- **Light Propagation Principle:**
  - Light propagation in the holey fiber is governed by total internal reflection, not by a photonic band-gap (PBG).
  - Light is confined around the center silica core due to the difference between the refractive index of the core and the effective index of the photonic crystal (PC) cladding.
- **Reduction of Propagation Loss:**
  - Propagation loss was significantly reduced to approximately 0.5 dB/km by enhancing the uniformity of the holes and minimizing additional losses from absorption and contamination.

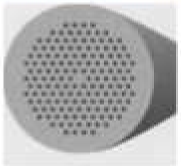


Figure: Cross-sectional structures of photonic crystal fibers: holey fiber

So, this photonic crystal cladding will have a effective index which is slightly lesser than the core and that is way it is typically very similar to how the conventional fiber operates. okay. So, propagation loss was significantly reduced to approximately 0.5 dB per kilometer by enhancing the uniformity of the holes and minimizing additional losses from adsorption and contamination. So, when you make the structure uniform you can get rid of the scattering losses and that way the overall propagation loss also decreases.

Optical Fibers

Holey Fiber

- **Optical Confinement:**
  - Enhanced for longer wavelength light as it penetrates into the air holes of the PC cladding, reducing the effective index and strengthening confinement in the core.
  - Moderately weakened for shorter wavelength light, which remains well confined within the silica of the PC cladding, bringing its effective index closer to that of the core.

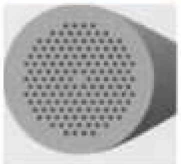
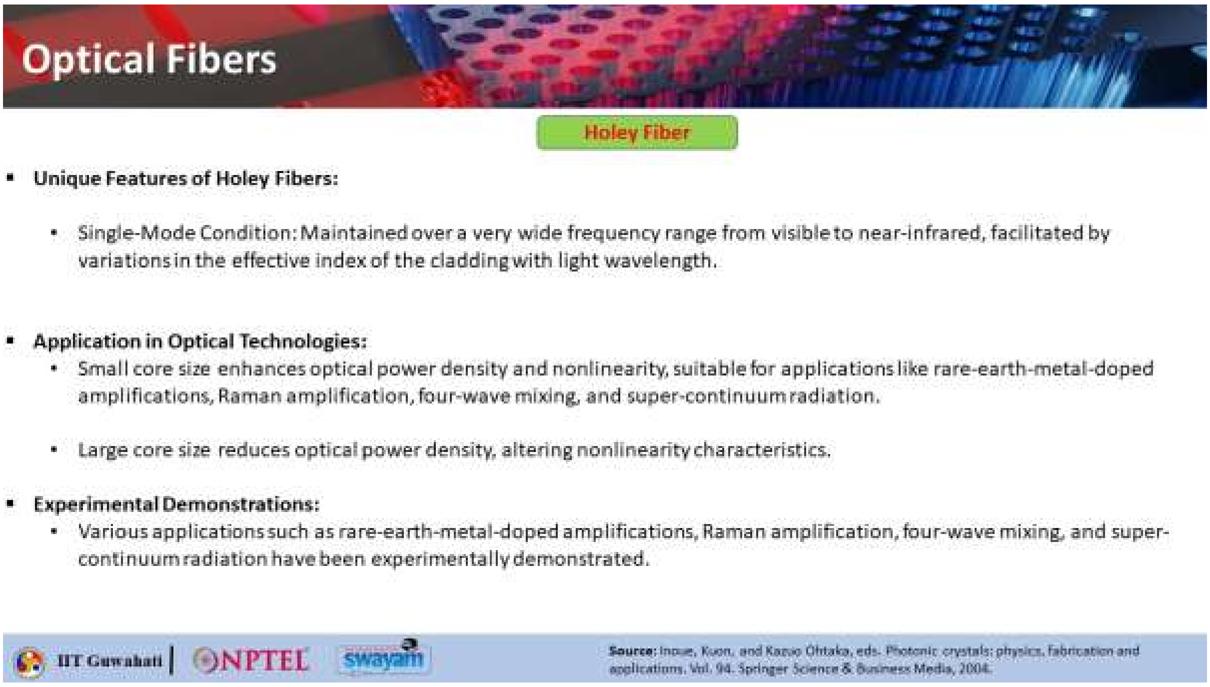


Figure: Cross-sectional structures of photonic crystal fibers: holey fiber

You can also see that The optical confinement can be enhanced for longer wavelength light as it could penetrate into air holes of the photonic crystal cladding which reduces the effective index and strengthening the confinement to the core. moderately weakened for you know shorter wavelength light okay. Because if you consider shorter wavelength light your confinement will get weaker which remains well confined within the silica of the photonic crystal cladding bringing its effective index closer to that of the core. Now if you consider the holy fiber okay. The unique feature for this holy fiber is that it gives you single mode condition that is maintained over a very wide range from visible to near infrared and that is facilitated by the variation in the effective index of the cladding with light wavelength.



So what are the applications of this kind of fiber in optical technologies? The small core size enhances the optical power density and nonlinearity. So it is suitable for applications like you know rare earth, metal doped amplification, Raman amplification, 4 wave mixing and super continuum radiation and so on. And the large core size could reduce the optical power density altering the nonlinear characteristics. So, you have different applications depending on the size of the core. So, there are experimental demonstrations people have shown various applications such as rare earth, metal doped amplification, Raman amplification, 4 wave mixing and all these things okay experimentally already.

Optical Fibers

Photonic Band-gap fiber

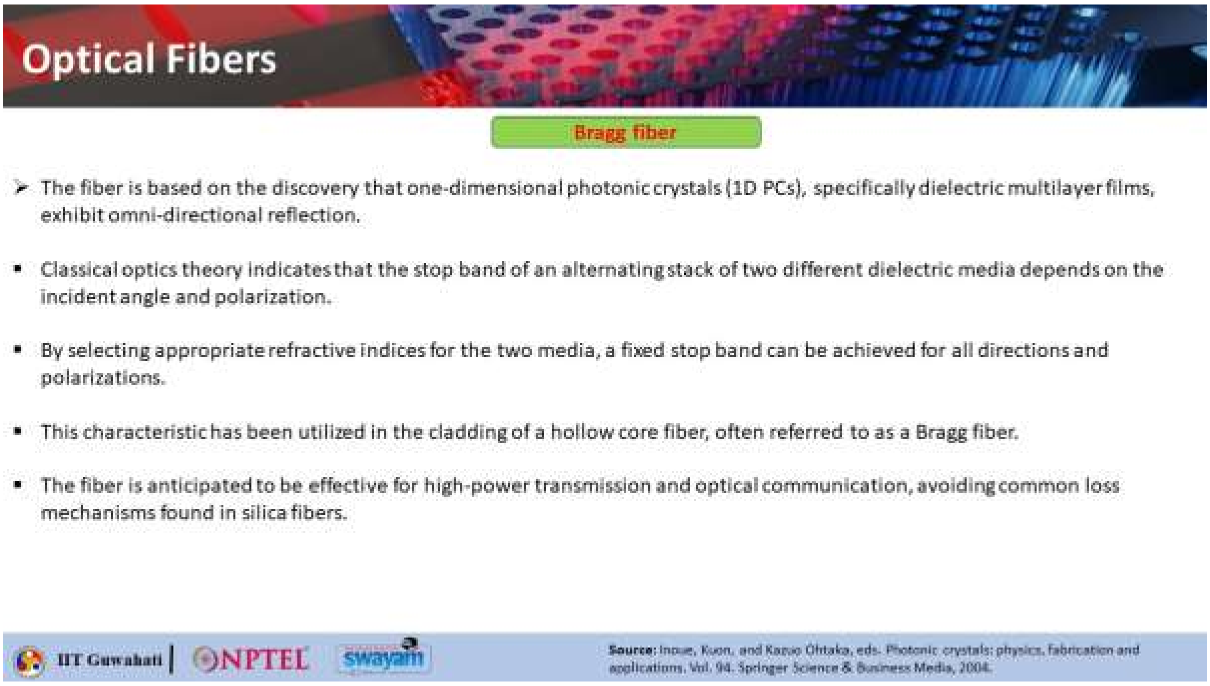
- This fiber relies on reflection governed by the photonic bandgap (PBG), controllable through lattice design and hole shapes.
  - It facilitates single-mode propagation in a large core and supports tight bending radii, unattainable in traditional holey fibers.
  - The fiber characteristics are ideal for high power transmission with minimal nonlinearity.
  - Recent improvements have significantly reduced propagation loss to the order of dB/km.
  - A key challenge remains: the transmission range is relatively narrow, limited by the PBG's range.

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

Now, moving on to the second type which is the photonic band gap fiber. This fiber basically relies on the reflection governed by the photonic band gap. So, that is controllable through the lattice design and the hole shapes. So, it facilitates single mode operation in a large core and it also supports tight bending radii which is typically unattainable by that traditional holy fiber. Because the cladding is a photonic band gap light cannot escape into that material.

So, you can actually afford much shorter or tighter bending radii using band gap fiber. The fiber characteristics are ideal for high power transmission with minimal nonlinearity because the core is made of air. So, recent improvements have significantly reduced the propagation loss to the order of several you know dB per kilometer okay. So, it has it has reduced the propagation loss okay. And a key challenge remains that the transmission range is relatively narrow because it is limited by the photonic bandgap range.

So, that is a drawback of this photonic bandgap fiber



Now, coming to the last type which is the Bragg fiber, this fiber is based on the discovery that one-dimensional photonic crystals which is basically dielectric multilayer films, they can exhibit omnidirectional reflection. So classical optics theory would indicate that you know the stop band of an alternating stack of two different dielectric media depends on incident angle and polarization. But when you select appropriate refractive indices of the two media, you can find a fixed stop band that can be achieved for all direction and both polarization. So it becomes an omnidirectional reflector. So, this characteristic can be utilized as a cladding of a hollow core fiber and this fiber is known as a Bragg fiber fine.

So, this fiber is anticipated to be more effective for high power transmission and optical communication avoiding common loss mechanisms found in the silica fibres.

So, this is all for the lecture on applications of 2D photonic crystals. We will cover some other interesting applications of 2D photonic crystal. in you know I think lecture number 18 when we will be discussing applications of 3D photonic crystals as well we will have some of the latest applications of 2D photonic crystals there. So, regarding this lecture if you have got any queries you can drop an email to this particular email address mentioning MOOC and photonic crystal on the subject line. Thank you

Thank You

Send your queries at deb.sikdar@iitg.ac.in