Lec 25: Overview of photonic crystal fibers

Photonic Crystals: Fundamentals and Applications

Lecture 25

Overview of Photonic Crystal Fibers

Dr. Debabrata Sikdar

Department of Electronics and Electrical Engineering
Indian Institute of Technology Guwahati

Web: https://www.iitg.ac.in/deb.sikdar
Email: deb.sikdar@iitg.ac.in

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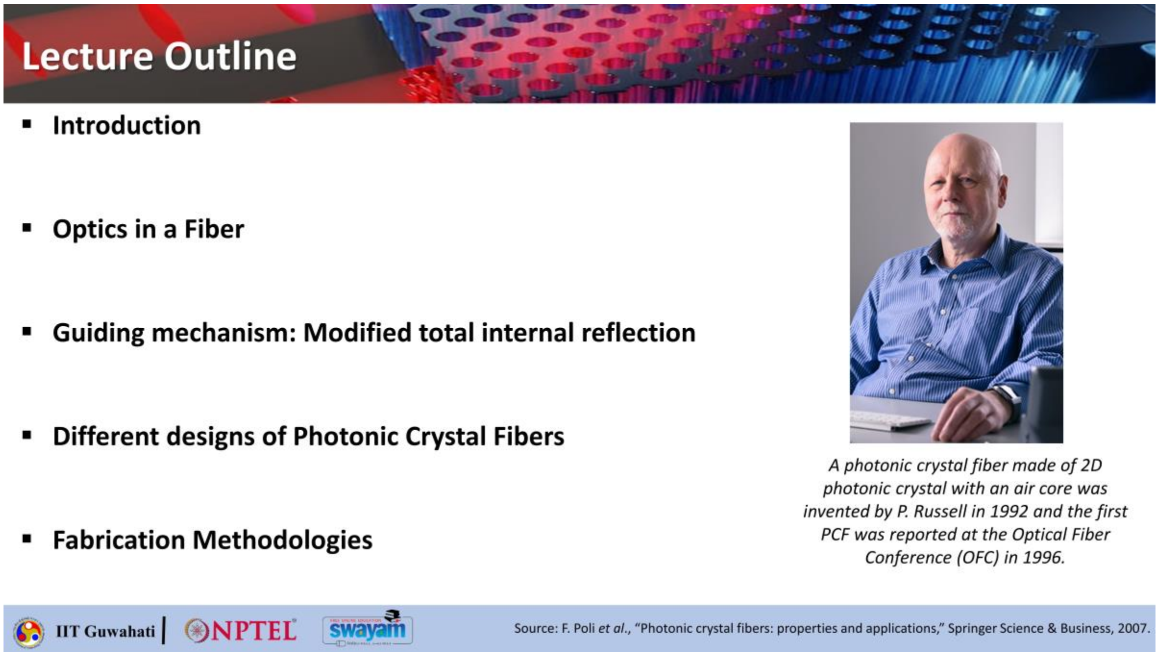
Hello students, welcome to lecture 25 of the online course on Photonic Crystals Fundamentals and Applications.



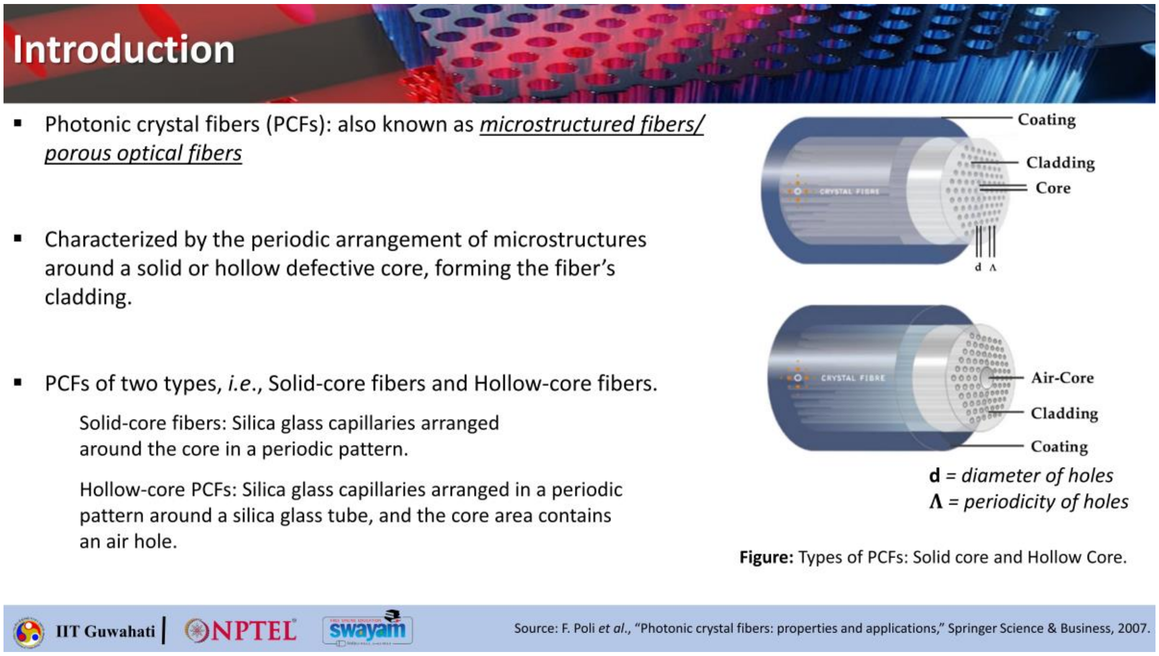
Lecture Outline

- **Introduction**
- **Optics in a Fiber**
- **Guiding mechanism: Modified total internal reflection**
- **Different designs of Photonic Crystal Fibers**
- **Fabrication Methodologies**

A photonic crystal fiber made of 2D photonic crystal with an air core was invented by P. Russell in 1992 and the first PCF was reported at the Optical Fiber Conference (OFC) in 1996.

Source: F. Poli *et al.*, "Photonic crystal fibers: properties and applications," Springer Science & Business, 2007.

Today's lecture will be on Overview of Photonic Crystal Fibers. So, here is the lecture outline, we will have a brief introduction, then we will discuss about Optics in a Fiber. We will also talk about the guiding mechanism which will be modified total internal reflection will present different designs of photonic crystal fibers and talk about the fabrication methodologies. So, when you talk about photonic crystal fiber. This gentleman comes to your mind because a photonic crystal fiber made of 2D photonic crystal with an air core was invented by this gentleman P. Russell in 1992. And the first photonic crystal fiber was reported at the Optical Fiber Conference, popularly known as OFC in 1996.



Introduction

- Photonic crystal fibers (PCFs): also known as *microstructured fibers/ porous optical fibers*
- Characterized by the periodic arrangement of microstructures around a solid or hollow defective core, forming the fiber's cladding.
- PCFs of two types, *i.e.*, Solid-core fibers and Hollow-core fibers.

  Solid-core fibers: Silica glass capillaries arranged around the core in a periodic pattern.

  Hollow-core PCFs: Silica glass capillaries arranged in a periodic pattern around a silica glass tube, and the core area contains an air hole.

d = *diameter of holes*
Λ = *periodicity of holes*

Figure: Types of PCFs: Solid core and Hollow Core.

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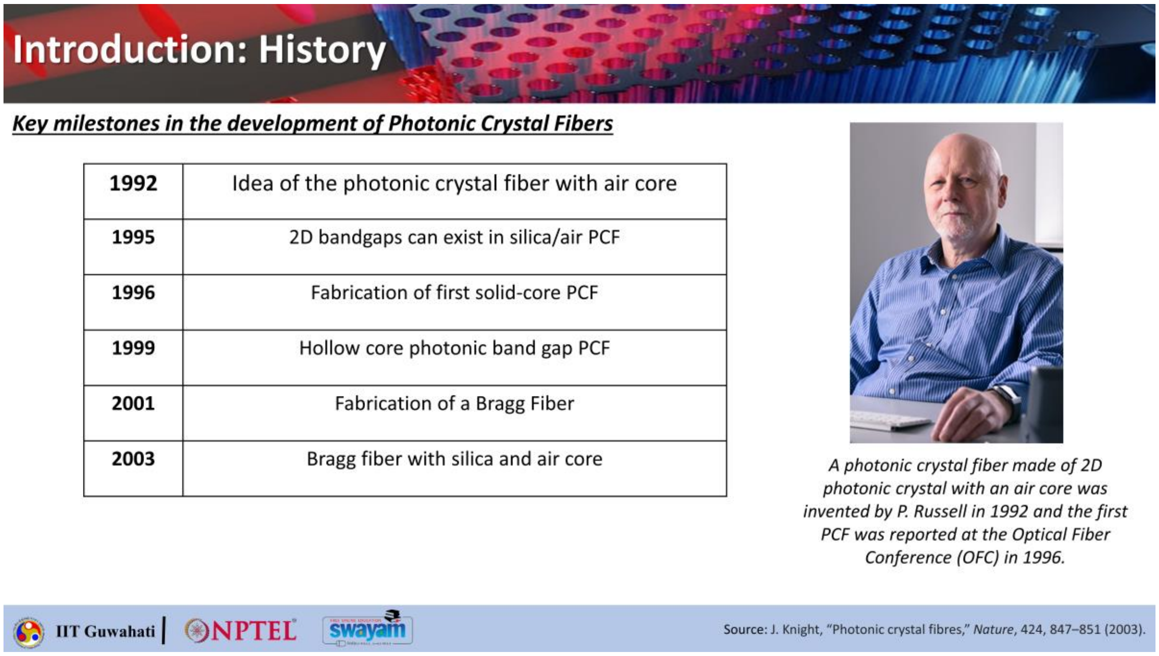
Source: F. Poli *et al.*, "Photonic crystal fibers: properties and applications," Springer Science & Business, 2007.

So, photocrystal fibers which are also known as microstructured fibers or porous optical fibers, this is how they typically look like. So, there are two types of core as you can see okay.

So, one is a solid core and one is a hollow core. So, what you see here is that the core then you have a cladding and then you have coating which is basically a plastic protection to protect your fiber. Now you can see here that the cladding is basically having this periodic arrangement of microstructures right which is a 2D photonic crystal. Now what is this core? The core can have two options as I mentioned it can be solid or it can be hollow right. So, you can think of you know in the solid core fiber you have the silica glass capillaries which are arranged around the core in a periodic fashion and you can take the diameter of these capillaries as d and the periodicity to be **Λ**. Same you can think of you know in the hollow core photonic crystal fiber you can again think of silica glass capillaries which are arranged around a glass tube okay and this tube contains the core area which is basically hollow or it is basically a air hole. So what is important here is that you know in the first case you can see or in this one it is very obvious that the refractive index of the core material is higher than that of the cladding isn't it. But in this case you know it is something interesting because the core is hollow so it is basically air. So, how does you know light is being guided in this particular case and what is interesting that when you have hollow core you do not have any material it is like air. So, there is no non-linearity there is no dispersion.

So, it is an amazing feature to have a hollow core fiber. So, as you can understand that photonic crystal fibers have wavelength scale morphological microstructure which are basically running down the length of the fiber. So, this structure enables light to be controlled within the fiber. in a way that was not possible by the conventional fibers and it was not even imaginable. So our understanding of what an optical fiber is and what it does is changing because of the development of this new technology. okay and a broad range of applications are coming up based on this particular principle.



Introduction: History

Key milestones in the development of Photonic Crystal Fibers

1992	Idea of the photonic crystal fiber with air core
1995	2D bandgaps can exist in silica/air PCF
1996	Fabrication of first solid-core PCF
1999	Hollow core photonic band gap PCF
2001	Fabrication of a Bragg Fiber
2003	Bragg fiber with silica and air core

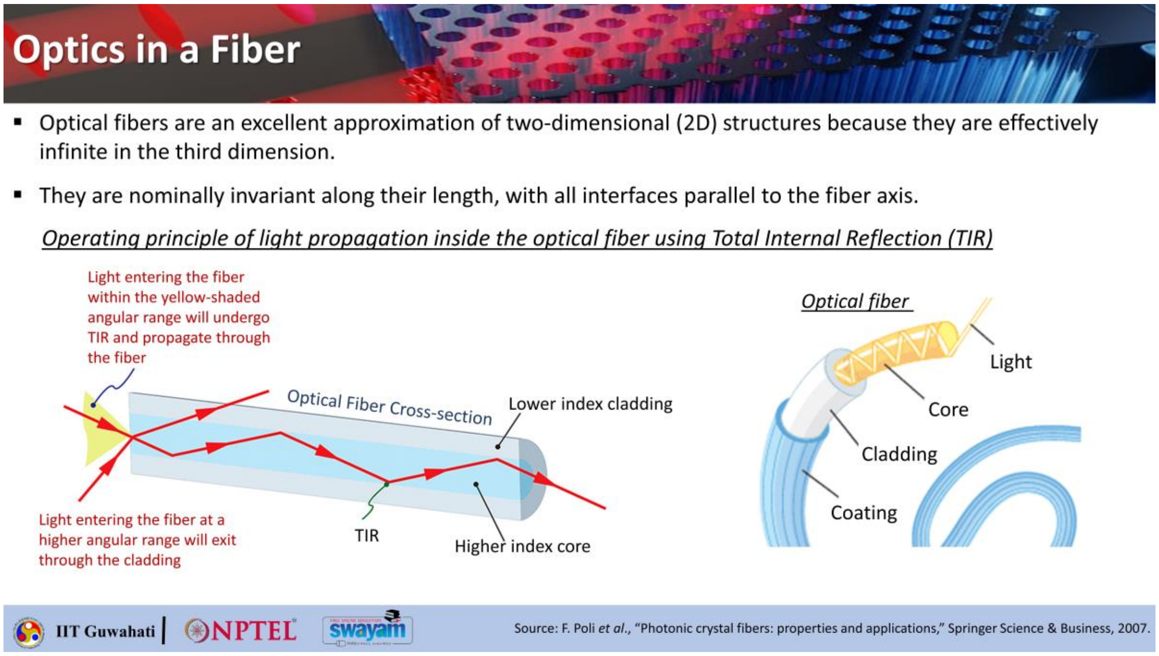
A photonic crystal fiber made of 2D photonic crystal with an air core was invented by P. Russell in 1992 and the first PCF was reported at the Optical Fiber Conference (OFC) in 1996.

Source: J. Knight, "Photonic crystal fibres," *Nature*, 424, 847–851 (2003).

So, let us look into a quick history of this photonic crystal fibers and again this gentleman should be a part of that because he invented it. So, 1992 was the year when the idea of photonic crystal fiber with air core was thought of. That is something amazing. We always know that in optical fiber the core should be having higher refractive index than the cladding.

So who would have imagined that a fiber with air core or hollow core is possible is able to you know carry light. In 1995 they actually showed that you know 2D bandgap exists in this kind of silica air photonic crystal fiber. In 1996 they completed the fabrication of the first hollow core photonic crystal fiber. In 1999 you know hollow core photonic bandgap photonic crystal fiber was made okay and deployed. Then in 2001 fabrication of Bragg fiber was done and 2003 Bragg fiber with you know silica and air core was also demonstrated.

So, these are different types of photonic crystal fibers and we will go into the details of each of these slowly.



Optics in a Fiber

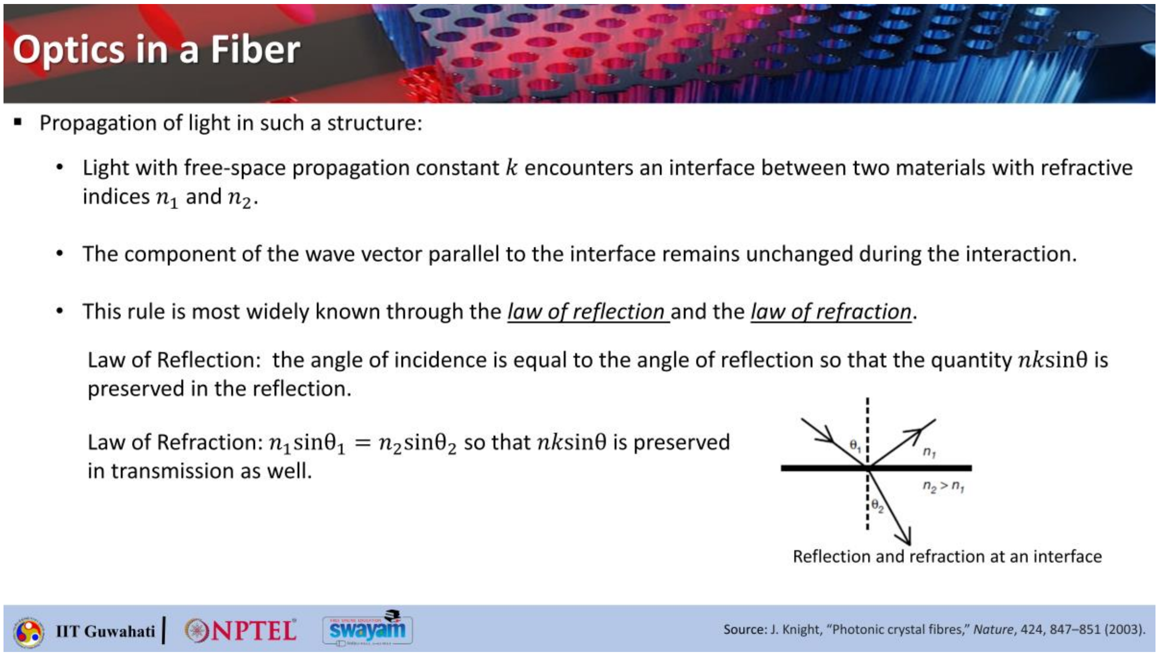
- Optical fibers are an excellent approximation of two-dimensional (2D) structures because they are effectively infinite in the third dimension.
- They are nominally invariant along their length, with all interfaces parallel to the fiber axis.

Operating principle of light propagation inside the optical fiber using Total Internal Reflection (TIR)

Source: F. Poli *et al.*, "Photonic crystal fibers: properties and applications," Springer Science & Business, 2007.

So, let us look into how optics behave inside a fiber. So optical fibers are basically an excellent approximation to two dimensional structures as they are basically infinitely long in the third dimension. So they are nominally invariant along their length and all the interfaces are basically parallel to the fiber axis. So, the operating principle of light travelling inside optical fibre is well known to us and that is total internal reflection.

So, you can actually see from this figure that this yellow portion shows the angle which is allowed. for the light to go in. So, that they can actually you know get total internally reflected from the boundary of the core and cladding and that is how they will be guided. So, the reflection here is total internal reflection. So, you can think of the light entering the fibre within this yellow shaded angular region to be captured and propagate that will be allowed to propagate through the fiber.



Optics in a Fiber

- Propagation of light in such a structure:
  - Light with free-space propagation constant k encounters an interface between two materials with refractive indices n_1 and n_2.
  - The component of the wave vector parallel to the interface remains unchanged during the interaction.
  - This rule is most widely known through the *law of reflection* and the *law of refraction*.

Law of Reflection: the angle of incidence is equal to the angle of reflection so that the quantity $nk\sin\theta$ is preserved in the reflection.

Law of Refraction: $n_1\sin\theta_1 = n_2\sin\theta_2$ so that $nk\sin\theta$ is preserved in transmission as well.

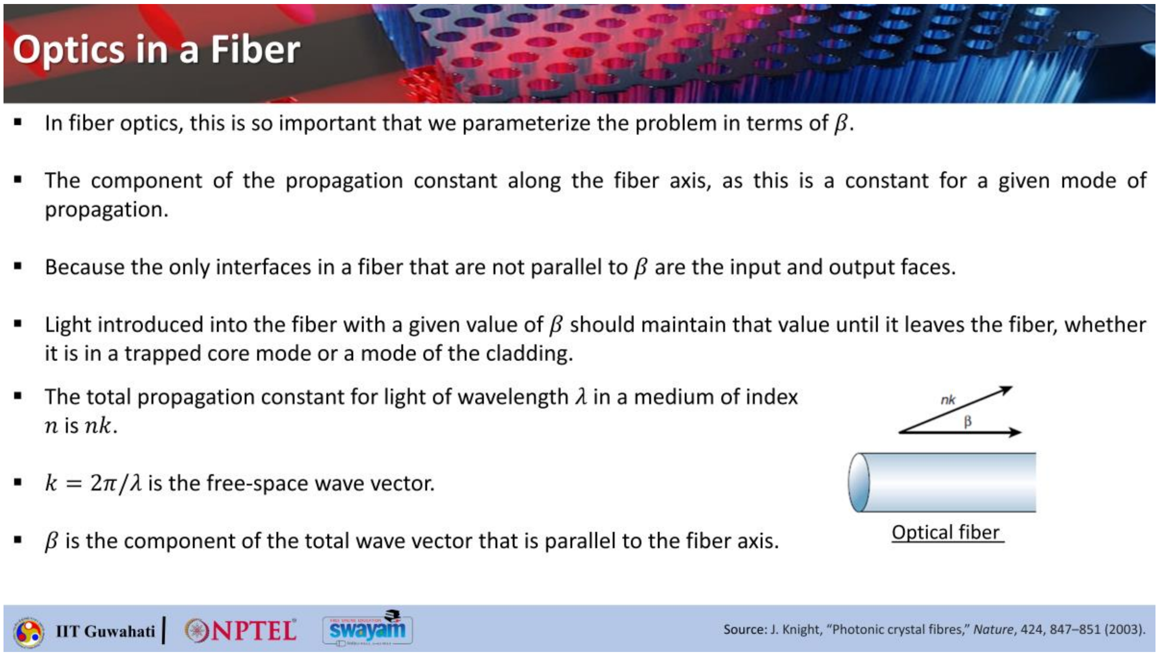
Reflection and refraction at an interface

Source: J. Knight, "Photonic crystal fibres," *Nature*, 424, 847–851 (2003).

Any light which is outside this incident angle will not be guided right, they will simply exit through the cladding. So, you can think of like this. So, light enters and it is totally internally reflected from both ends and then it keeps on travelling like that. So, this is the core, this is cladding. And on top of that there is a protection layer which is called coating.

So, propagation light in such a structure happens in the following manner okay. So, light with free space propagation constant k encounters an interface between two materials which is called refractive index n_1 and n_2. So, the component of the wave vector parallel to the interface will remain unchanged during this interaction and that is basically the rule that we all know through the law of reflection and the law of refraction. So, what happens in law of reflection you know that the angle of incidence becomes equal to the angle of reflection. So, that whatever is the you know parallel component to the interface which is $n$ksinθ that is preserved.

So, the same amount is this component will be continuous or preserved for from reflection. In the case of refraction again you can think of you know n_1 sinθ1 will be equal to n_2 sinθ_2 okay so that $n$ksinθ is preserved in transmission as well. So that is how you know the laws of reflection and refraction works.



Optics in a Fiber

- In fiber optics, this is so important that we parameterize the problem in terms of β.
- The component of the propagation constant along the fiber axis, as this is a constant for a given mode of propagation.
- Because the only interfaces in a fiber that are not parallel to β are the input and output faces.
- Light introduced into the fiber with a given value of β should maintain that value until it leaves the fiber, whether it is in a trapped core mode or a mode of the cladding.
- The total propagation constant for light of wavelength λ in a medium of index n is nk.
- $k = 2\pi/\lambda$ is the free-space wave vector.
- β is the component of the total wave vector that is parallel to the fiber axis.

Optical fiber

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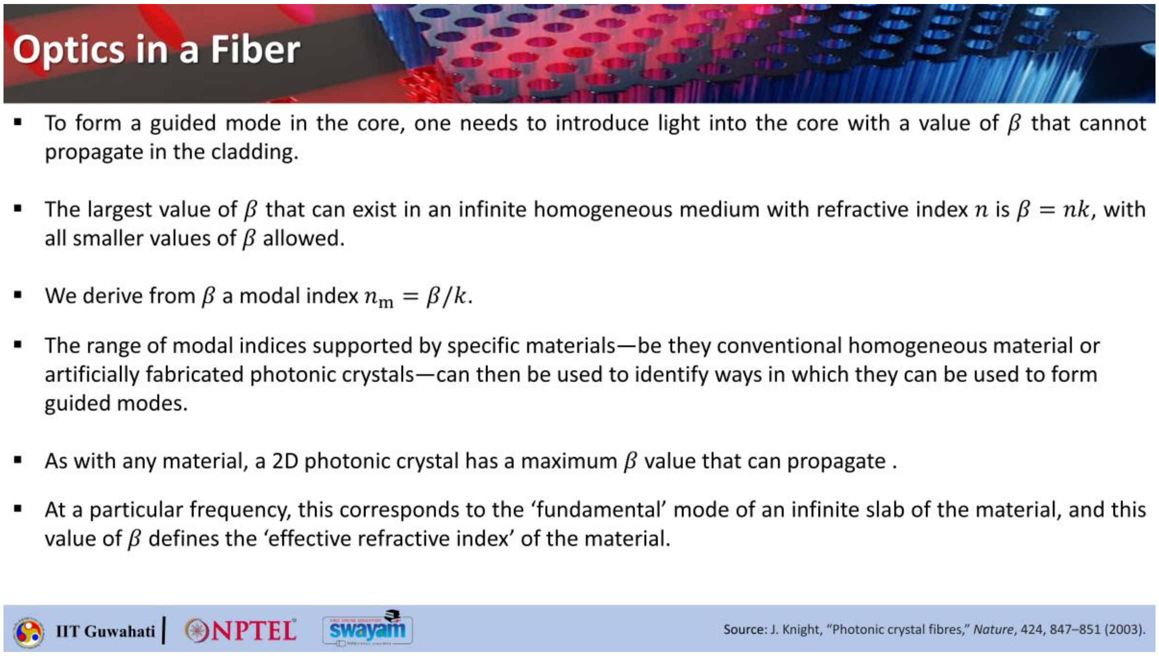
Source: J. Knight, “Photonic crystal fibres,” *Nature*, 424, 847–851 (2003).

Now in optical fiber or you can say in fiber optics this is so important that we parameterize the problem in terms of β. Now what is this β? This is basically the component of propagation constant along the fiber axis okay as this is a constant for a given mode of propagation okay, so that is β.

Now, because only interfaces in a fiber that are not parallel to β are basically the you know input and the output phases. So, here you can see this is β. So, light introduced into the fiber will be given a value of β and that should maintain that value until it leaves the fiber. whether it is in a trapped core mode or you know a mode in the cladding. So, always remember that when light enters the fiber it with a value of propagation constant β and that should remain same for that light mode throughout the fiber.

So, total propagation constant for light of wavelength wavelength λ in a medium of index n is nk. where k is basically $2\pi/\lambda$ where it denotes the free space wave vector. So, what is β then? The β is basically a component of the total wave vector which lies parallel to the fiber axis right. So, this is where your k lies ok and one component of it lies along the fiber axis and that is β. To form a guided mode in the core, one needs to introduce light into the core with the value of β that cannot propagate in the cladding.



Optics in a Fiber

- To form a guided mode in the core, one needs to introduce light into the core with a value of β that cannot propagate in the cladding.
- The largest value of β that can exist in an infinite homogeneous medium with refractive index n is $\beta = nk$, with all smaller values of β allowed.
- We derive from β a modal index $n_{\mathrm{m}} = \beta/k$.
- The range of modal indices supported by specific materials—be they conventional homogeneous material or artificially fabricated photonic crystals—can then be used to identify ways in which they can be used to form guided modes.
- As with any material, a 2D photonic crystal has a maximum β value that can propagate .
- At a particular frequency, this corresponds to the 'fundamental' mode of an infinite slab of the material, and this value of β defines the 'effective refractive index' of the material.

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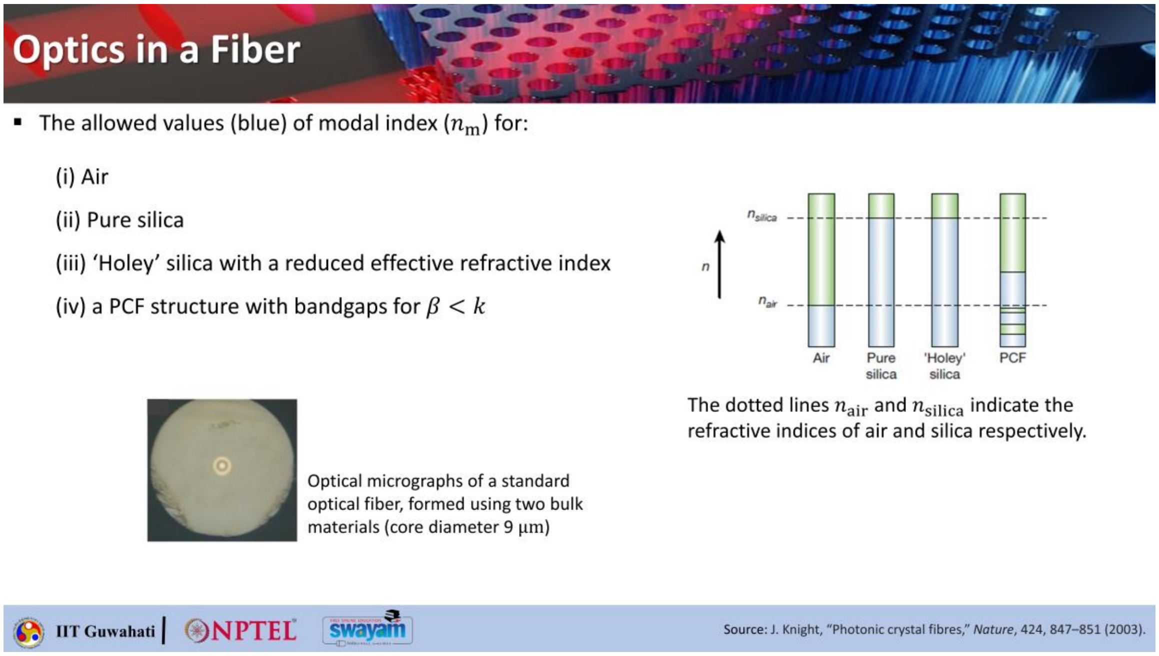
Source: J. Knight, "Photonic crystal fibres," *Nature*, 424, 847–851 (2003).

So, if that is allowed to propagate in the cladding, it will simply escape, right. So, the largest value of β that can exist in an infinite homogeneous medium with refractive index n will be equal to, so you can write β equals nk. with all smaller values of β being allowed. So, we derive from β a modal index which is written as n_m that is simply β/k. The range of modal indices supported by specific materials be they conventional homogeneous material or artificially fabricated photonic crystal There can be anything.

So this kind of modal indices can be used to identify ways in which they can be used to form guided modes. So as with any material, a 2D photonic crystal has a maximum β value that can propagate. So at a particular frequency, this corresponds to the fundamental mode of an infinite slab of a material. And this value of β defines the effective refractive index of the material. So the allowed values which are basically blue of the modal index.



Optics in a Fiber

- The allowed values (blue) of modal index (n_{m}) for:

  (i) Air

  (ii) Pure silica

  (iii) 'Holey' silica with a reduced effective refractive index

  (iv) a PCF structure with bandgaps for $\beta < k$

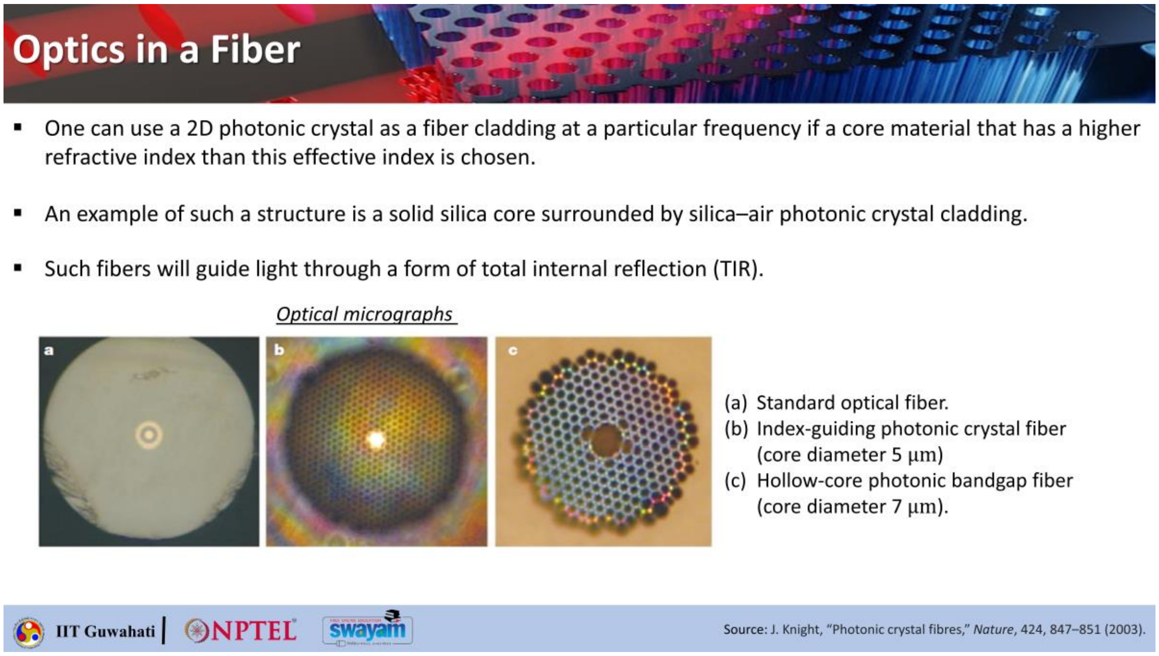
The dotted lines n_{air} and n_{silica} indicate the refractive indices of air and silica respectively.

Optical micrographs of a standard optical fiber, formed using two bulk materials (core diameter 9 μm)

Source: J. Knight, "Photonic crystal fibres," *Nature*, 424, 847–851 (2003).

So this is shown for air, pure silica. So these two dotted horizontal line marks the refractive index of silica and air. So, what is allowed in air is only up to this much, for pure silica it can go up to here, for holy silica also it can go up to here ok, but it is with slightly reduced effective index and a photonic crystal structure or you can say a PCF photonic crystal fiber structure with band gaps ok, it will look simply look like you know this where β is less than k. So this is an optical micrograph of a standard optical fiber. So you can see this is the fiber and this is the core.

So this is formed using two bulk materials. Here the core diameter is 9 micrometer. okay. So, one can use the 2D photon crystal as a fiber cladding at a particular frequency if the core material has a higher refractive index then this effective index is chosen okay.



Optics in a Fiber

- One can use a 2D photonic crystal as a fiber cladding at a particular frequency if a core material that has a higher refractive index than this effective index is chosen.
- An example of such a structure is a solid silica core surrounded by silica–air photonic crystal cladding.
- Such fibers will guide light through a form of total internal reflection (TIR).

Optical micrographs

(a) Standard optical fiber.
(b) Index-guiding photonic crystal fiber (core diameter 5 μm)
(c) Hollow-core photonic bandgap fiber (core diameter 7 μm).

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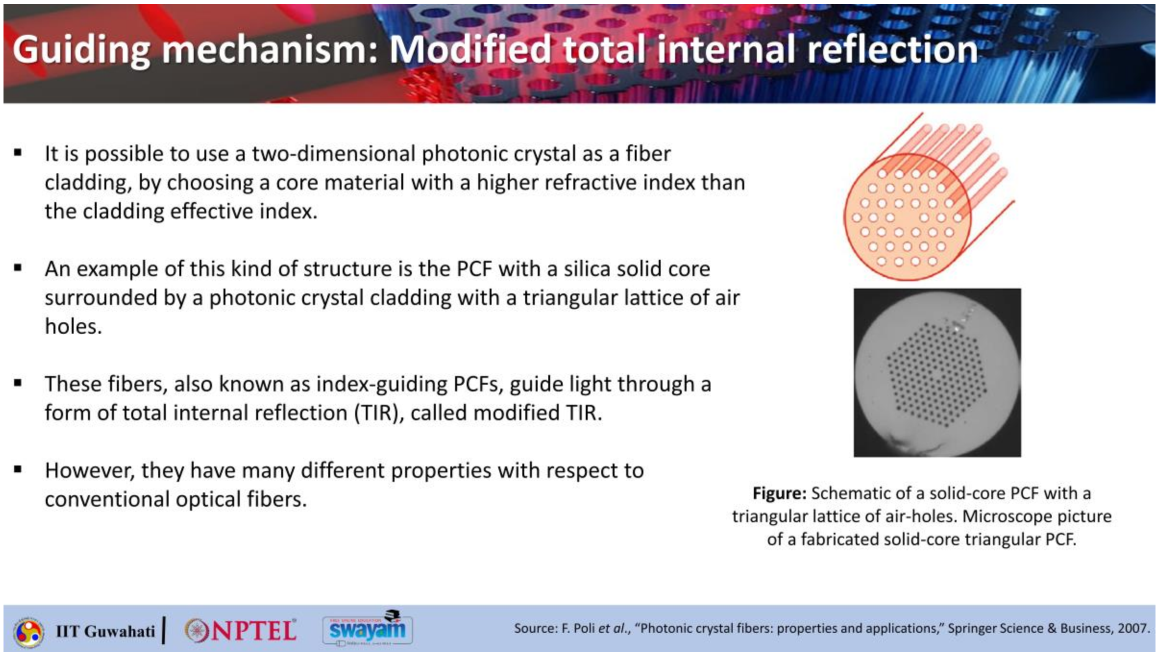
Source: J. Knight, "Photonic crystal fibres," *Nature*, 424, 847–851 (2003).

An example of such a structure is basically a solid silica core which is surrounded by a silica air. photon crystal cladding. So, such fiber will then guide light through a form of total internal reflection. So, though it is not a purely you know total internal reflection because the cladding here is basically silica air matrix, but it will definitely have you can intuitively guess that you know this solid core which is made of silica and then this region is kind of you know silica and lot of air holes periodically done. So, the effective index of this material will be lower than the silica core. So, it will also work like you know core cladding and then total internal reflection can be the guiding mechanism in this case as well. So, what we call this is the standard optical fiber, this is also index guiding photonic crystal fiber because here also it is guided mainly based on the difference between the refractive indices of core and cladding material.

So, the core diameter here is 5 micron. This is the one which is basically a hollow core photonic band gap fiber. So, here the guiding mechanism is completely different. So, it is basically guiding light because of the band gap. So, you have to create a 2D photonic crystal and the light that you are launching in the hollow core should lie within the bandgap frequencies or bandgap wavelengths.

So, that the light cannot escape into this cladding. So, it will be helplessly travelling through this core because there is no other route to escape. So, as we understood that This is in the case of a solid core photonic crystal fiber the guiding mechanism is basically a modified total internal reflection. So, it is possible to use a two-dimensional photonic crystal as the fiber cladding by choosing a core material with a higher refractive index than the cladding effective index right. So, it makes sense.



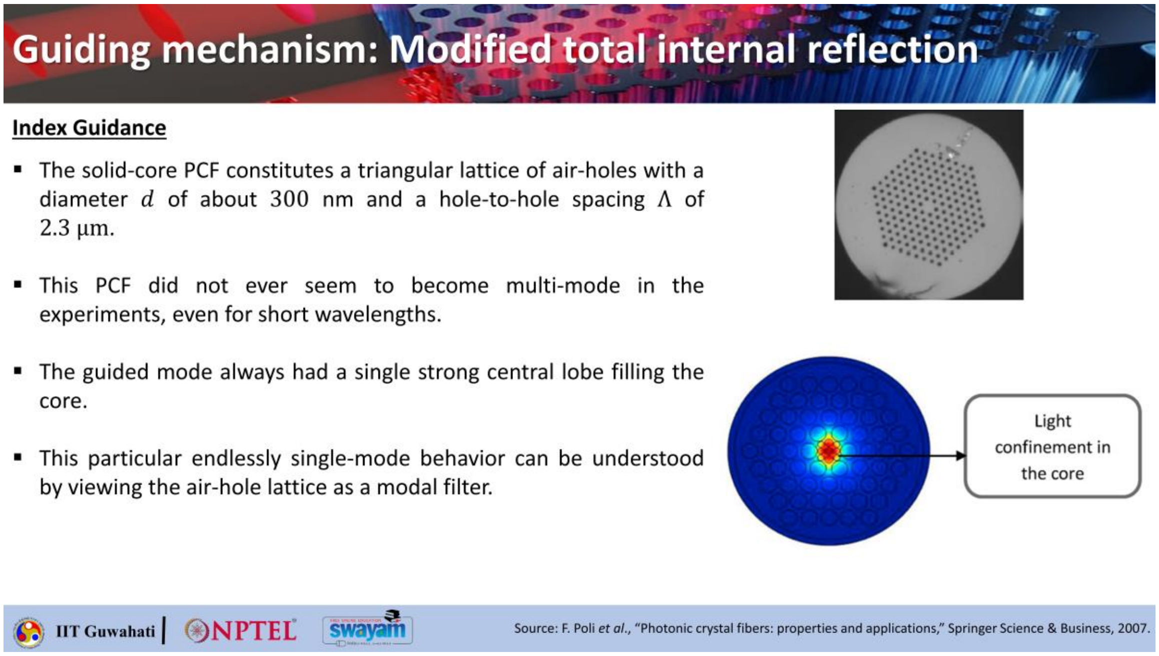
Guiding mechanism: Modified total internal reflection

- It is possible to use a two-dimensional photonic crystal as a fiber cladding, by choosing a core material with a higher refractive index than the cladding effective index.
- An example of this kind of structure is the PCF with a silica solid core surrounded by a photonic crystal cladding with a triangular lattice of air holes.
- These fibers, also known as index-guiding PCFs, guide light through a form of total internal reflection (TIR), called modified TIR.
- However, they have many different properties with respect to conventional optical fibers.

Figure: Schematic of a solid-core PCF with a triangular lattice of air-holes. Microscope picture of a fabricated solid-core triangular PCF.

Source: F. Poli *et al.*, "Photonic crystal fibers: properties and applications," Springer Science & Business, 2007.

An example of this kind of structure is the photonic crystal fiber with silica solid core which is surrounded by a photonic crystal cladding that is in the form of a triangular lattice of air holes. So, these fibers are also known as index guiding photon crystal fibers because they are basically guiding light through a form of total internal reflection which can be called as modified TIR or modified total internal reflection just to tell you that it is not the conventional total internal reflection mechanism. However, they have many different properties with respect to the conventional optical fibers right. So, this is a schematic of a solid core photonic crystal fiber with the triangular lattice of air holes and you can see these holes are going across the length of the fiber and this is a you know microscope image of that fabricated solid core fiber which has got you know this kind of triangular lattice of air holes drilled.



Guiding mechanism: Modified total internal reflection

Index Guidance

- The solid-core PCF constitutes a triangular lattice of air-holes with a diameter d of about 300 nm and a hole-to-hole spacing Λ of 2.3 μm.
- This PCF did not ever seem to become multi-mode in the experiments, even for short wavelengths.
- The guided mode always had a single strong central lobe filling the core.
- This particular endlessly single-mode behavior can be understood by viewing the air-hole lattice as a modal filter.

Light confinement in the core

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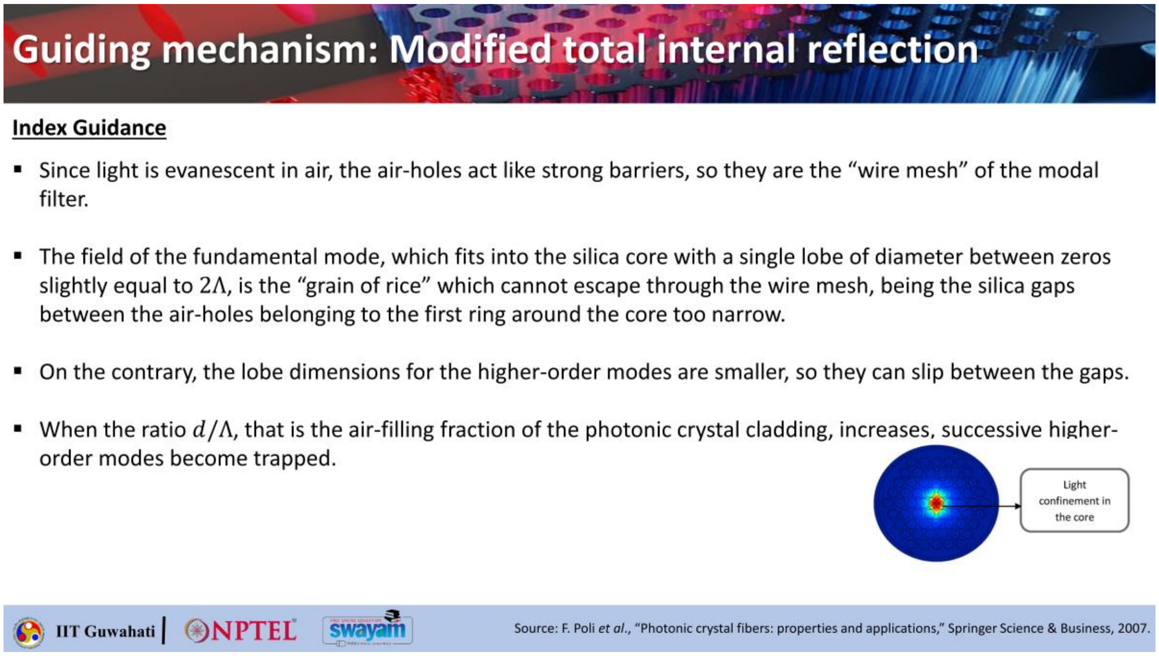
Source: F. Poli *et al.*, "Photonic crystal fibers: properties and applications," Springer Science & Business, 2007.

Now the solid core photonic crystal fiber constitutes a triangular lattice of air holes and we can consider the hole diameter d to be about 300 nanometer and hole to hole spacing which is basically the period Λ and that is taken to be 2.3 micrometer. this PCF photonic crystal fiber did not ever seem to become multimode in the experiments even for the shorter wavelengths. So, it actually only work as a single mode fiber which is very good. So, the guided mode always had a strong single central lobe which is filling the core.

So, this is the light confinement shown in this particular fiber. So, here you can see this you know circles which actually small small circles which mark the you know holes which are drilled into the fiber. So, what happens you know this particular endlessly single mode behavior can be understood by viewing the air hole lattice as a modal filter.



Guiding mechanism: Modified total internal reflection

Index Guidance

- Since light is evanescent in air, the air-holes act like strong barriers, so they are the “wire mesh” of the modal filter.
- The field of the fundamental mode, which fits into the silica core with a single lobe of diameter between zeros slightly equal to 2Λ, is the “grain of rice” which cannot escape through the wire mesh, being the silica gaps between the air-holes belonging to the first ring around the core too narrow.
- On the contrary, the lobe dimensions for the higher-order modes are smaller, so they can slip between the gaps.
- When the ratio d/Λ, that is the air-filling fraction of the photonic crystal cladding, increases, successive higher-order modes become trapped.

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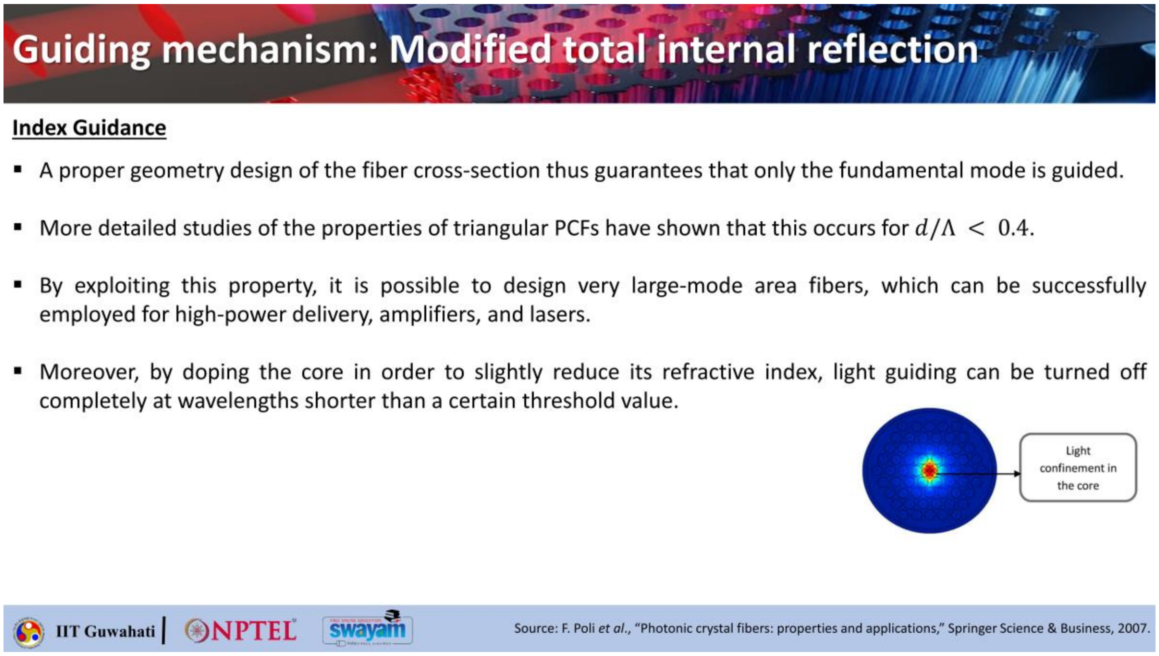
Source: F. Poli *et al.*, “Photonic crystal fibers: properties and applications,” Springer Science & Business, 2007.

So, what is that modal filter? So, since light is evanescent in air, the air holes act like you know strong barrier okay. So, they are the wire mesh of this particular filter.

So, it is like a mesh that can you know hold this particular fundamental mode only okay. So, the field of the fundamental mode which fits into the silica core with a single loop of diameter okay between zeros is slightly equal to 2Λ okay. You can think it of as a grain of rice that cannot escape a wire mesh okay. So it is something that it is actually blocked here.

So it will be there. And the silica gaps between the air holes belonging to the first ring around the core is too narrow. On the other hand, you can think of the lobe dimension of the higher order modes becomes smaller. So they can actually slip between the gaps. and that is how they are able to escape. So, what is important as you can see the ratio d/Λ, d is the you know diameter of the air holes and Λ is the periodicity.



Guiding mechanism: Modified total internal reflection

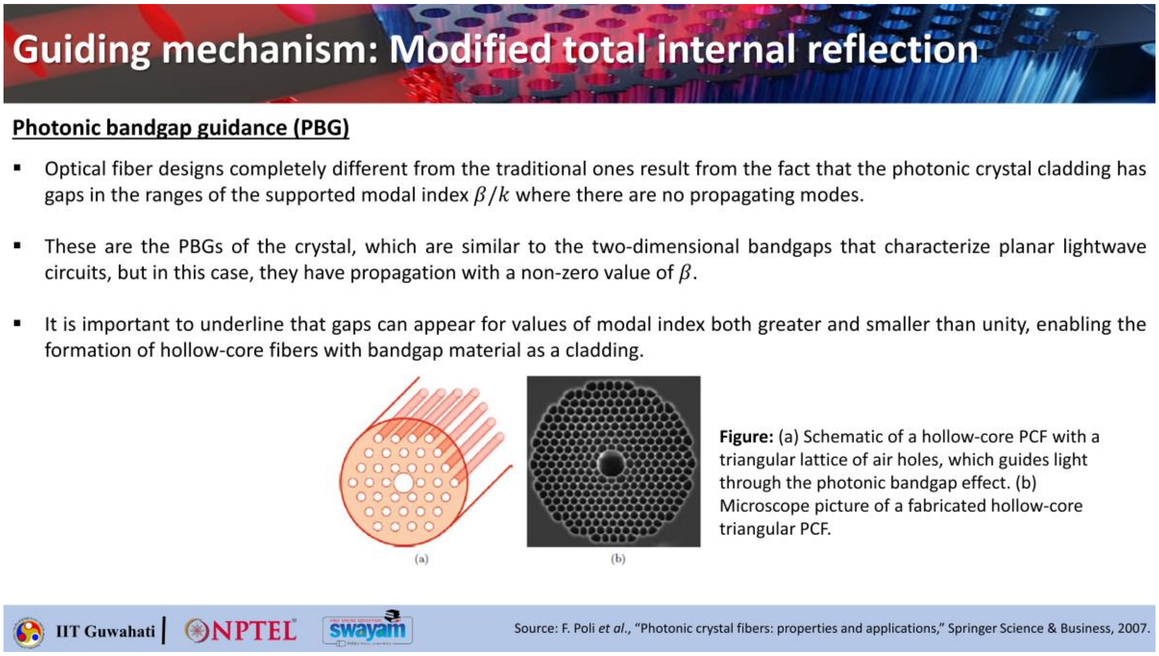
Index Guidance

- A proper geometry design of the fiber cross-section thus guarantees that only the fundamental mode is guided.
- More detailed studies of the properties of triangular PCFs have shown that this occurs for $d/\Lambda < 0.4$.
- By exploiting this property, it is possible to design very large-mode area fibers, which can be successfully employed for high-power delivery, amplifiers, and lasers.
- Moreover, by doping the core in order to slightly reduce its refractive index, light guiding can be turned off completely at wavelengths shorter than a certain threshold value.

Light confinement in the core

Source: F. Poli *et al.*, "Photonic crystal fibers: properties and applications," Springer Science & Business, 2007.

So, this fraction that is basically the air filling fraction of the photonic crystal cladding is important and if this fraction increases successive higher order modes will become trapped. So, you can do a proper geometry design of this fiber cross section to guarantee that only the fundamental mode stays there only the single mode of the fundamental mode gets guided all other you know modes will leak out. So, it becomes an endlessly single mode fiber which is very very important for long distance or long haul communication. For triangular photocrystal fibers this occur at d/Λ less than 0.4. If you maintain this particular ratio you will be able to achieve that fit okay. So, by exploiting this geometry it is possible to design very large mode area fibers which can be successfully employed for high power delivery amplifiers and even lasers. Moreover by doping the core okay in order to slightly reduce its refractive index light guiding can be turned off completely at wavelengths shorter than a certain threshold value right.



Guiding mechanism: Modified total internal reflection

Photonic bandgap guidance (PBG)

- Optical fiber designs completely different from the traditional ones result from the fact that the photonic crystal cladding has gaps in the ranges of the supported modal index β/k where there are no propagating modes.
- These are the PBGs of the crystal, which are similar to the two-dimensional bandgaps that characterize planar lightwave circuits, but in this case, they have propagation with a non-zero value of β.
- It is important to underline that gaps can appear for values of modal index both greater and smaller than unity, enabling the formation of hollow-core fibers with bandgap material as a cladding.

Figure: (a) Schematic of a hollow-core PCF with a triangular lattice of air holes, which guides light through the photonic bandgap effect. (b) Microscope picture of a fabricated hollow-core triangular PCF.

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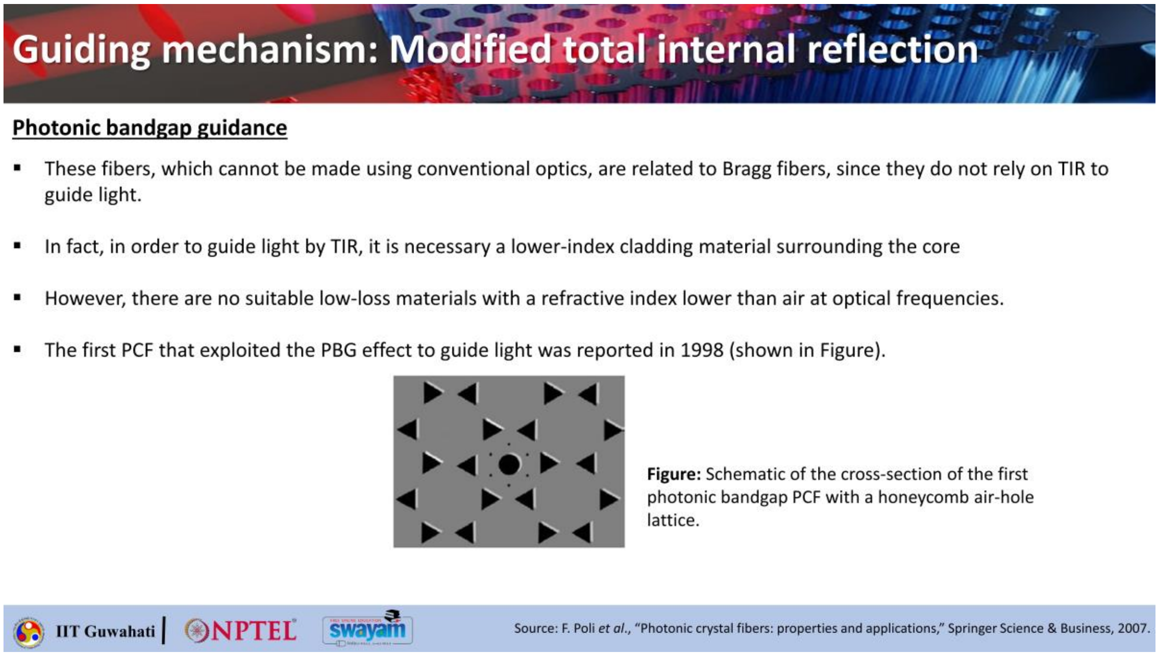
Source: F. Poli *et al.*, “Photonic crystal fibers: properties and applications,” Springer Science & Business, 2007.

So, those kind of functionalities can be added when you dope the silica core. So, optical fiber designs are completely different from the traditional ones okay which result from the fact that the photonic crystal cladding has gaps in the range of the supported modal index which is β/k where there are no propagating modes.

These are the photonic crystal, photonic bandgaps of the crystal okay which are similar to the two-dimensional bandgaps that could characterize the planar light wave circuits, okay. But in this case they have propagation with a non-zero value of β. So it is important to underline that gaps can appear for values of model index both greater and smaller than unity that enables the formation of you know hollow core fibers with band gap material as a cladding. So, because the model index less than unity or less than 1 is possible that is how you can actually think of this hollow core fiber.

So, here is the schematic of a hollow core fiber. This white region tells you that these are air holes. So, the core is basically larger air hole, okay. And this is the microscope image of this beautifully fabricated hollow core triangular photonic crystal fiber. And this is possible because the model index less than unity is supported.



Guiding mechanism: Modified total internal reflection

Photonic bandgap guidance

- These fibers, which cannot be made using conventional optics, are related to Bragg fibers, since they do not rely on TIR to guide light.
- In fact, in order to guide light by TIR, it is necessary a lower-index cladding material surrounding the core
- However, there are no suitable low-loss materials with a refractive index lower than air at optical frequencies.
- The first PCF that exploited the PBG effect to guide light was reported in 1998 (shown in Figure).

Figure: Schematic of the cross-section of the first photonic bandgap PCF with a honeycomb air-hole lattice.

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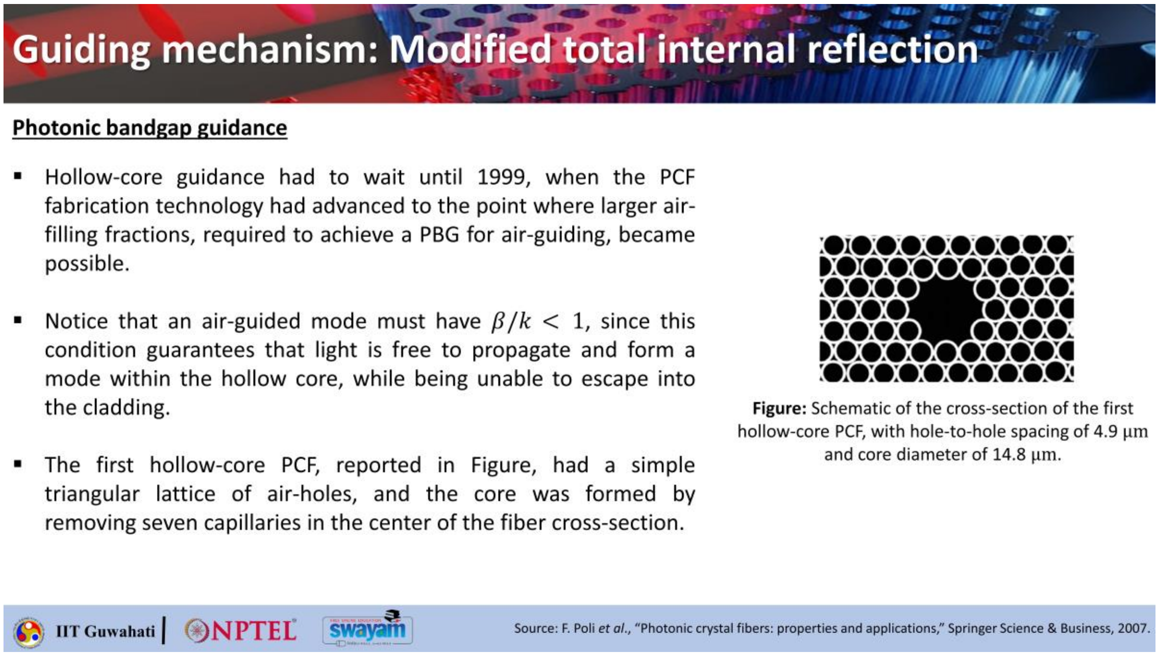
Source: F. Poli *et al.*, "Photonic crystal fibers: properties and applications," Springer Science & Business, 2007.

So, photonic bandgap guidance. These fibers which cannot be made using conventional optics are related to the Bragg fibers since they do not basically rely on total internal reflection for guiding light. In fact, in order to guide light by total internal reflection it is necessary to have you know a lower index cladding material surrounding the core. And here there are no suitable lowless material with refractive index lower than air at optical frequencies and that is how this fiber which is having a hollow core is the most less lossy fiber that you can think of. So, the first photonic crystal fiber that exploited this photonic bandgap effect to guide light was reported in 1998 and you can see this is the one okay that they made. So, this is the schematic of the cross section of the first photonic bandgap photonic crystal fiber okay with a honeycomb air hole lattice.



Guiding mechanism: Modified total internal reflection

Photonic bandgap guidance

- Hollow-core guidance had to wait until 1999, when the PCF fabrication technology had advanced to the point where larger air-filling fractions, required to achieve a PBG for air-guiding, became possible.
- Notice that an air-guided mode must have $\beta/k < 1$, since this condition guarantees that light is free to propagate and form a mode within the hollow core, while being unable to escape into the cladding.
- The first hollow-core PCF, reported in Figure, had a simple triangular lattice of air-holes, and the core was formed by removing seven capillaries in the center of the fiber cross-section.

Figure: Schematic of the cross-section of the first hollow-core PCF, with hole-to-hole spacing of 4.9 μm and core diameter of 14.8 μm.

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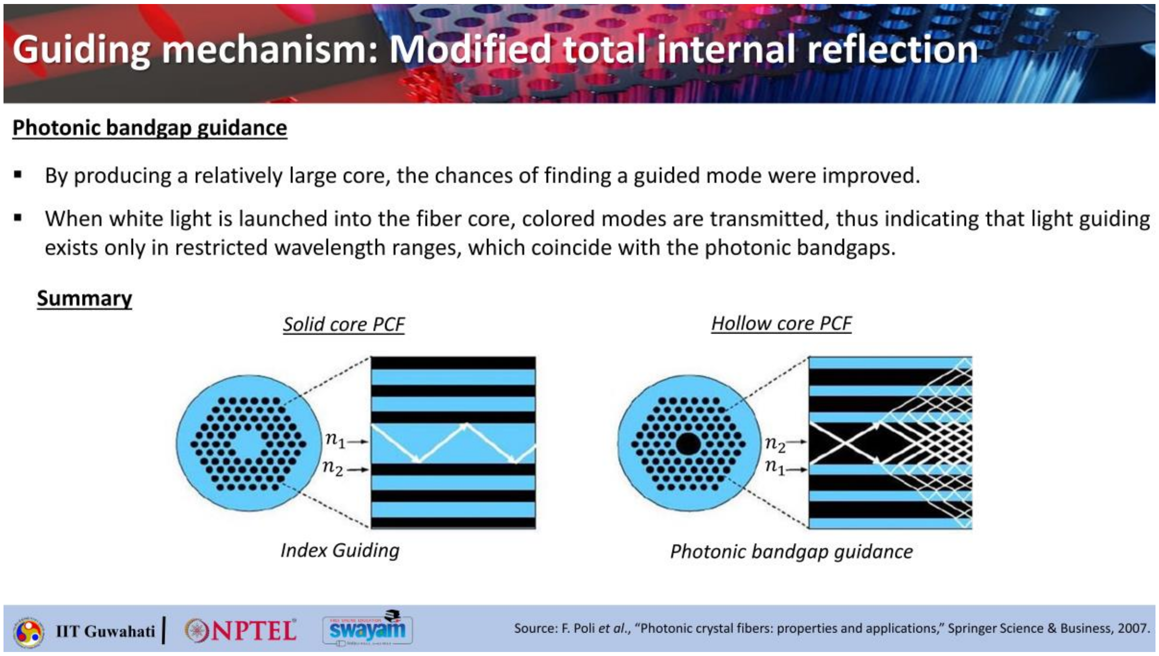
Source: F. Poli *et al.*, "Photonic crystal fibers: properties and applications," Springer Science & Business, 2007.

So, hollow core guidance had to wait until 1999. So, the first it was made in 1998 ok and in 99 ok hollow core guidance when the PCF fabrication technology had advanced to a point where larger air filling fractions required to achieve photonic band gap for air guiding became possible. So, with that you can notice here that an air guided mode must have β/k less than 1. Since this condition will guarantee that the light is free to propagate and form a mode within the hollow core and it will make it impossible for that mode to escape into the cladding. So, the first hollow core photonic crystal fiber was this one as you can see ok, had a simple triangular lattice of air holes ok. and the core was basically made of removing this 7 capillaries at the center of the fiber cross section.



Guiding mechanism: Modified total internal reflection

Photonic bandgap guidance

- By producing a relatively large core, the chances of finding a guided mode were improved.
- When white light is launched into the fiber core, colored modes are transmitted, thus indicating that light guiding exists only in restricted wavelength ranges, which coincide with the photonic bandgaps.

Summary

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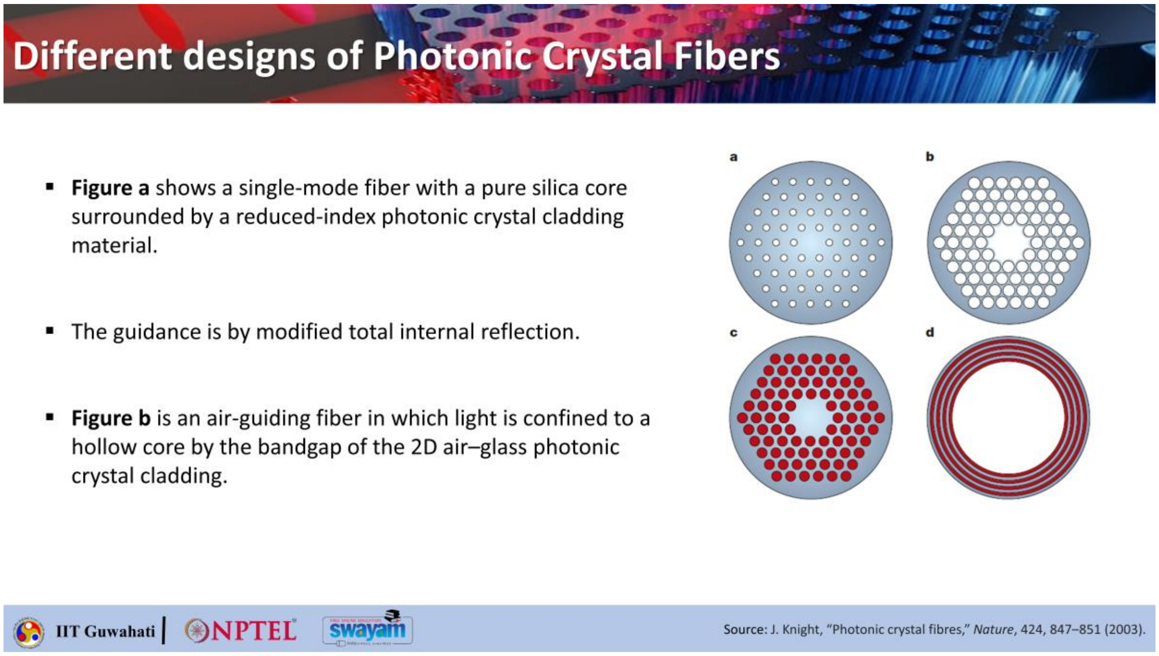
Source: F. Poli *et al.*, "Photonic crystal fibers: properties and applications," Springer Science & Business, 2007.

So, the parameters are given here the hole to hole spacing that is lambda was 4.9 micrometer and the core diameter here was 14.8 micrometer okay. So, by producing a relatively large score, the chances of finding a guided mode were improved.

ok. When white light was launched into the fiber, colored modes were transmitted. What does it indicate? It indicates that the light guiding exist only in restricted wavelength range ok and that range usually coincide with the photonic band gap of the surrounding medium of the cladding. So you can say that you know this is how the guiding takes place but this is your for the solid core you know that this is the solid medium and this is the photonic crystal that is around surrounding the core has a lower refractive index. So, you are basically having a modified total internal reflection which is also known as index guiding mechanism. In the case of hollow core you can see that you are basically taking help of photonic band gap.

So, if the light that is launched in the hollow core lies within the photonic band gap it cannot you know escape from the cladding and it will be guided throughout. So, this one is more or less very similar to the conventional fibers, but this is something very, very unique and it is coming from the photonic bandgaps. So, let us now discuss about different designs of photonic crystal fibers. So, here you can see the first one is basically a single mode fiber with pure silica core. So, this is a pure silica core and this is the cladding and how do you make the cladding to have slightly reduced refractive index than the solid silica core is by drilling holes periodic holes in it okay.



Different designs of Photonic Crystal Fibers

- **Figure a** shows a single-mode fiber with a pure silica core surrounded by a reduced-index photonic crystal cladding material.
- The guidance is by modified total internal reflection.
- **Figure b** is an air-guiding fiber in which light is confined to a hollow core by the bandgap of the 2D air–glass photonic crystal cladding.

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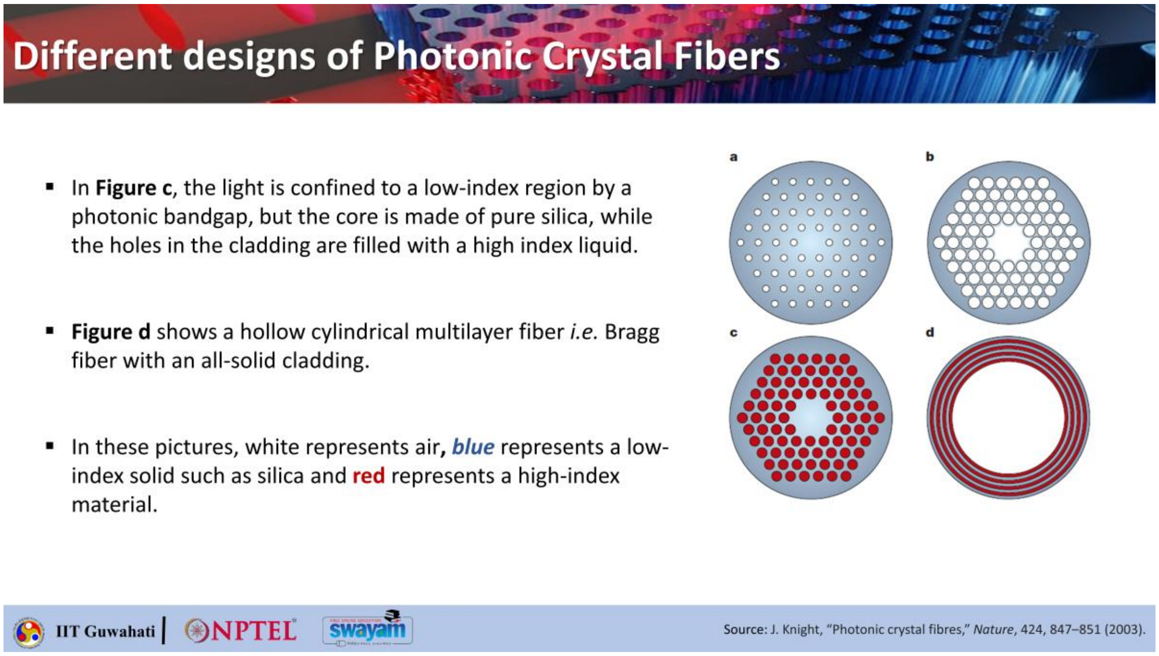
Source: J. Knight, "Photonic crystal fibres," *Nature*, 424, 847–851 (2003).

So, what is the mechanism of light guidance here it is again total internal reflection you can call it as modified TIR. This is what you have seen this is basically air guiding fiber that means you have a hollow core which is surrounded by a 2D photonic band gap crystal. So, that you know light cannot escape into this. So, here the guiding mechanism is completely different. This one is again a different one here the light is confined in a low index region by a photonic band gap.



Different designs of Photonic Crystal Fibers

- In **Figure c**, the light is confined to a low-index region by a photonic bandgap, but the core is made of pure silica, while the holes in the cladding are filled with a high index liquid.
- **Figure d** shows a hollow cylindrical multilayer fiber *i.e.* Bragg fiber with an all-solid cladding.
- In these pictures, white represents air, ***blue*** represents a low-index solid such as silica and **red** represents a high-index material.

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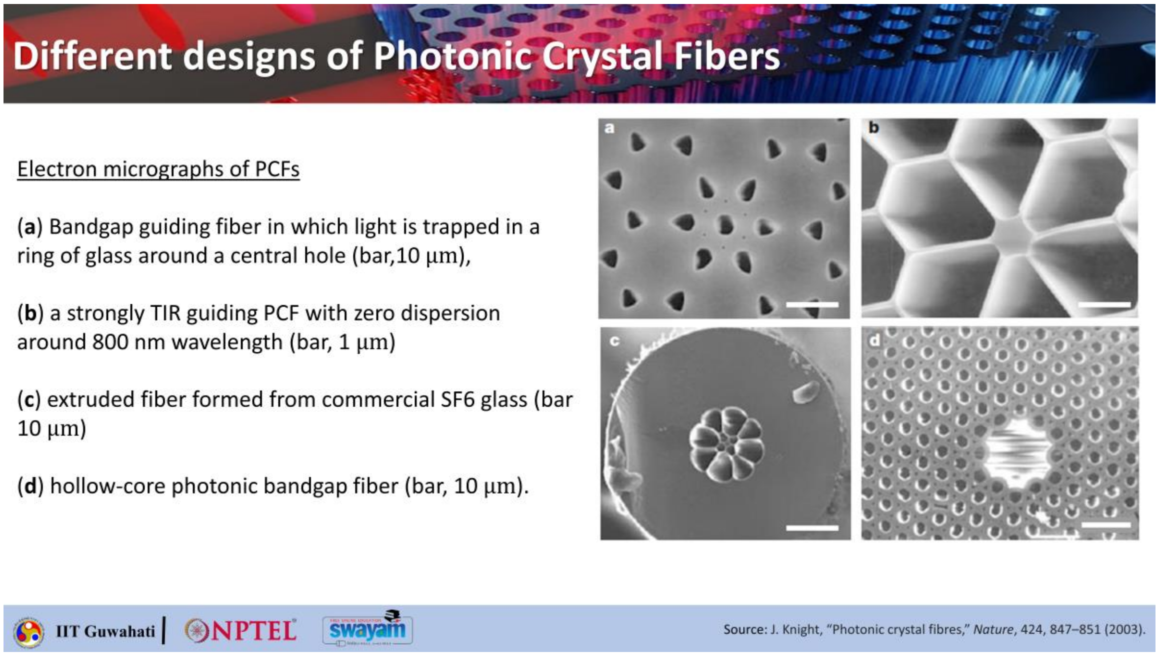
Source: J. Knight, "Photonic crystal fibres," *Nature*, 424, 847–851 (2003).

So, here the core is made not air core it is basically made of silica while the holes in the cladding are basically you know filled with high index liquid. So, similar kind of contrast in refractive index is created here. So, that the modal index that is β/k can be less than 1. And this is a hollow cylindrical multilayer fiber which is basically a Bragg fiber ok with a all solid cladding. So, you can see periodic Bragg reflector kind of arrangement over here.



Different designs of Photonic Crystal Fibers

Electron micrographs of PCFs

(**a**) Bandgap guiding fiber in which light is trapped in a ring of glass around a central hole (bar,10 μm),

(**b**) a strongly TIR guiding PCF with zero dispersion around 800 nm wavelength (bar, 1 μm)

(**c**) extruded fiber formed from commercial SF6 glass (bar 10 μm)

(**d**) hollow-core photonic bandgap fiber (bar, 10 μm).

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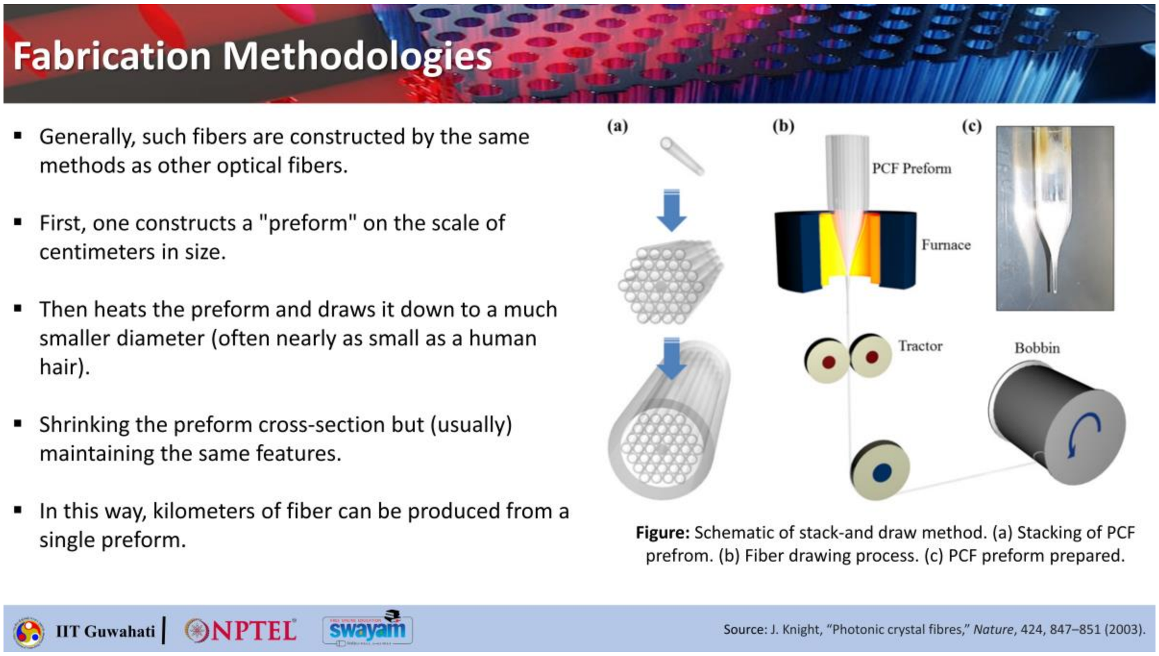
Source: J. Knight, "Photonic crystal fibres," *Nature*, 424, 847–851 (2003).

So now we will see electron micrographs of this PCF. The first one we have already seen okay. So this is basically a bandgap guiding fiber. So in which light is basically trapped in a ring of glass around the central hole okay like this. Figure B basically shows you a strongly total internal reflection guided PCF with 0 dispersion and it was achieved at 800 micrometer wavelength. Figure C shows you an extruded fiber which is formed from the commercial SF6 glass.

and figure D is the figure of showing in hollow core. So, this is basically air and it is a photonic bandgap fibre. So, now let us look into the fabrication methodologies. How do you make these amazing fibres? So, this is a schematic for making fibre. okay and this is a schematic of stack and draw method okay. So, first we will be stacking the preform of the photonic crystal fiber then this is the you know fiber drawing method where there is a furnace we will come to that okay and this is how the preform is prepared.



Fabrication Methodologies

- Generally, such fibers are constructed by the same methods as other optical fibers.
- First, one constructs a "preform" on the scale of centimeters in size.
- Then heats the preform and draws it down to a much smaller diameter (often nearly as small as a human hair).
- Shrinking the preform cross-section but (usually) maintaining the same features.
- In this way, kilometers of fiber can be produced from a single preform.

Figure: Schematic of stack-and draw method. (a) Stacking of PCF prefrom. (b) Fiber drawing process. (c) PCF preform prepared.

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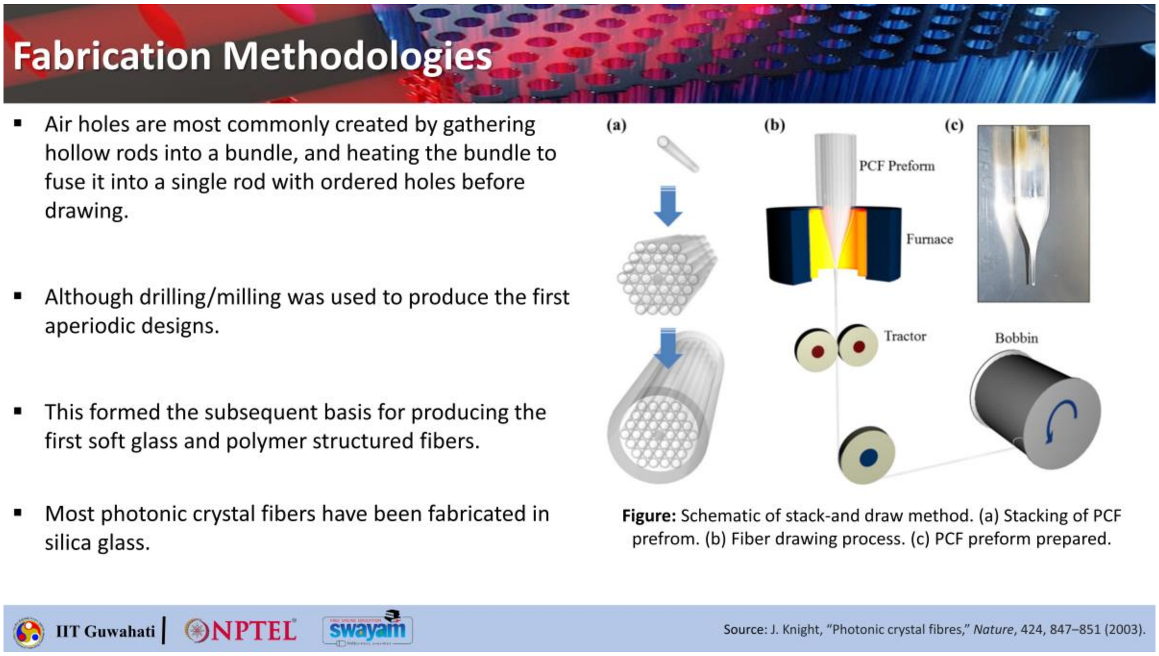
Source: J. Knight, "Photonic crystal fibres," *Nature*, 424, 847–851 (2003).

So, the method as you can see is generally similar to that used for other optical fibers. So, what is important here is to first make a preform which is of the scale of centimeter in size. So, this is how you know a preform PCF preform looks like and then you use heat to you know to heat up the preform and draw it down a much smaller diameter. And typically it is of the order of the diameter of human hair okay. And shrinking the preformed cross section okay but you have to maintain the same features.

So all these features of capillaries need to be maintained here. So what you are doing you are heating and passing it through a very small diameter so that you can get a diameter of the order of micrometers right. So, this way you know from a single preform kilometers several kilometers of optical fibers can be produced and it will be you know packed in a bobbin. air holes are most commonly created. So, you have to create air holes if you are talking about you know hollow core fibers. So, in that case you know you put a hollow rod in inside the bundle and when you heat up the bundle that fuse this hollow rod rods they fuse to a single rod okay and that is how you can create a you know large kind of whole area okay and this has to be done before drawing.



Fabrication Methodologies

- Air holes are most commonly created by gathering hollow rods into a bundle, and heating the bundle to fuse it into a single rod with ordered holes before drawing.
- Although drilling/milling was used to produce the first aperiodic designs.
- This formed the subsequent basis for producing the first soft glass and polymer structured fibers.
- Most photonic crystal fibers have been fabricated in silica glass.

Figure: Schematic of stack-and draw method. (a) Stacking of PCF prefrom. (b) Fiber drawing process. (c) PCF preform prepared.

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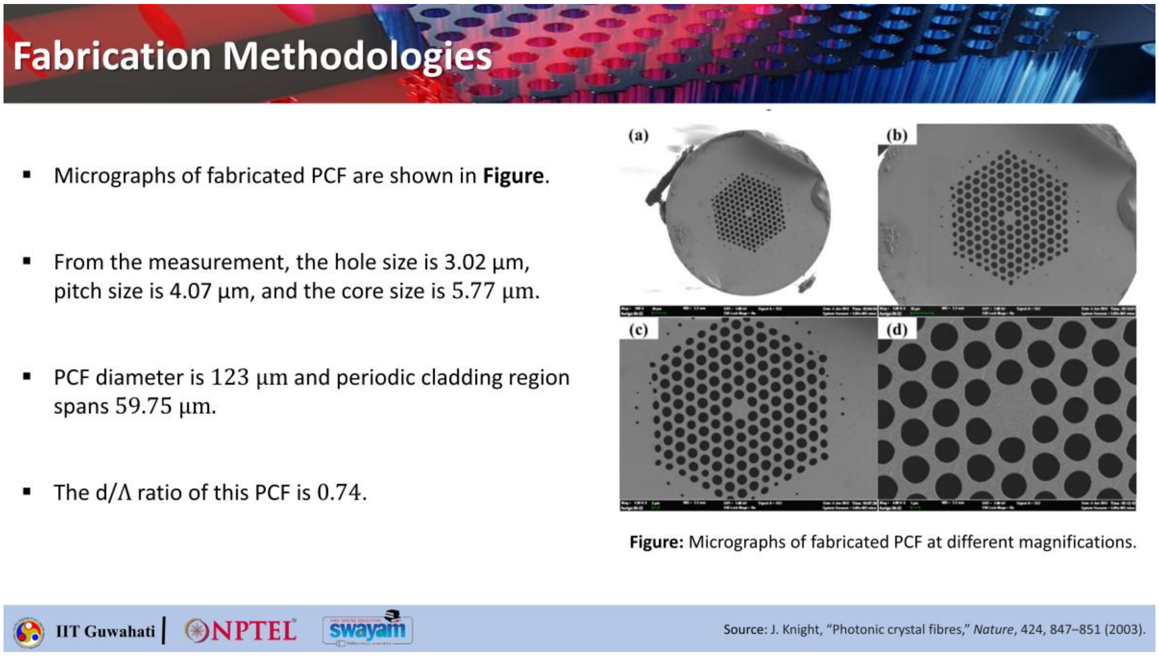
Source: J. Knight, “Photonic crystal fibres,” *Nature*, 424, 847–851 (2003).

So, this method is called drawing okay although drilling milling was used to produce the first a periodic design okay. But this form the subsequent basis for producing the first soft glass and polymer structured fibers. So now most photonic crystal fibers are basically fabricated in silica glass.



Fabrication Methodologies

- Micrographs of fabricated PCF are shown in **Figure**.
- From the measurement, the hole size is 3.02 μm, pitch size is 4.07 μm, and the core size is 5.77 μm.
- PCF diameter is 123 μm and periodic cladding region spans 59.75 μm.
- The d/Λ ratio of this PCF is 0.74.

Figure: Micrographs of fabricated PCF at different magnifications.

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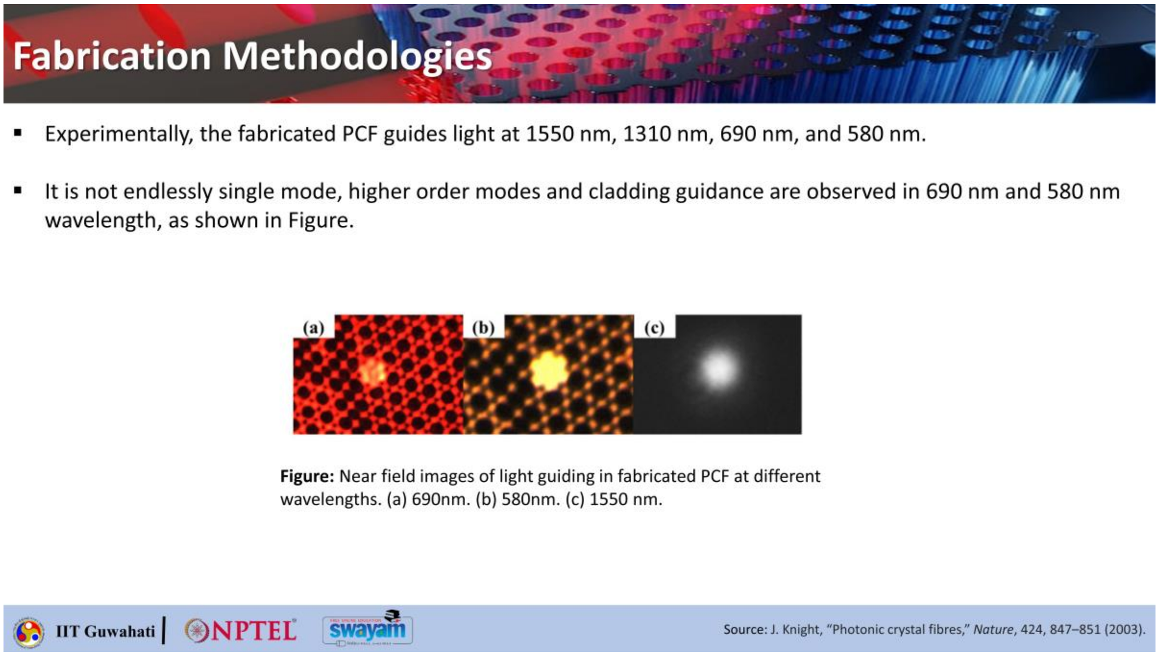
Source: J. Knight, “Photonic crystal fibres,” *Nature*, 424, 847–851 (2003).

So micrographs of fabricated PCFs are shown here. So this is the same fiber shown in different magnification so that you can clearly see what is the hole size that is 3.02 micrometer. The pitch or the periodicity is 4.07 micrometer and the core size that you can see here is basically 5.77 micrometer. And the overall diameter is 123 micrometer and the periodic cladding region is basically spanning over almost 60 micrometer. So, what is important here the d/Λ ratio for this fiber it was at 0.74 this is a solid core fiber right.



Fabrication Methodologies

- Experimentally, the fabricated PCF guides light at 1550 nm, 1310 nm, 690 nm, and 580 nm.
- It is not endlessly single mode, higher order modes and cladding guidance are observed in 690 nm and 580 nm wavelength, as shown in Figure.

Figure: Near field images of light guiding in fabricated PCF at different wavelengths. (a) 690nm. (b) 580nm. (c) 1550 nm.

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Source: J. Knight, "Photonic crystal fibres," *Nature*, 424, 847–851 (2003).

So, experimentally the fabricated PCFs guide light at 1550. So, this one guide lights at 1550 then you can have light guiding at 690, 580. So, all of them are showing different colours. okay. And note that in the case of you know 690 and 580, it is not endlessly single mode, some higher order modes were also seen okay and the cladding guidance was basically observed in this particular cases.

okay. So with that we will stop here. So we will start the discussion of in detailed analysis of index guiding photonic crystal fibers in the next lecture. If you have any doubt or query regarding any part of this lecture you can drop an email to this particular email address mentioning MOOC and photonic crystal on the subject line. Thank you.


Thank You