Lec 27: Band-gap guidance in Holey Fibers

Hello students, welcome to lecture 27 of the online course on Photonic Crystals Fundamentals and Applications. Today's lecture will be on Bandgap Guidance in Holey Fibre.

Lecture Outline

- **Problem Statement for Light Guidance in Holey Fibers**
- **Origin of the band gap in Holey fibers**
  - ❑ **Metal Cylinders**
  - ❑ **Air Holes**
- **Guided modes in a hollow core**
  - ❑ **Surface States**
  - ❑ **Mode Profiles**

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

So here is the lecture outline. We will first discuss about the mystery about the light guidance in holey fibers and then we will discuss about the origin of band gap in holey fibers. We will take examples of metal cylinders and then you know compare to that with air hole arrays okay. And we will also then discuss the guided modes in a hollow core.

discuss about the surface states and go into the details of the mode profiles.

Problem Statement for Light Guidance in Holey Fibers

- Index guiding can be relied upon to confine light only within regions of higher effective index.
- In contrast, a photonic band gap can localize light in a waveguide with a *lower* index, such as the hollow core.
- Of course, a fiber cannot have a complete band gap, because of its continuous translational symmetry in the z direction, but a complete band gap is not necessary.
- Because of the translational symmetry, the wave vector k_z is conserved, and it is therefore still useful to have a band gap over some finite range of k_z.
- But how might such a gap arise in silica holey fibers such as those of the previous sections?
- And how can we use it to confine light in air?

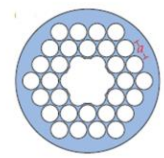

Figure: Two-dimensionally periodic structure (a triangular lattice of air holes, or "holey fiber"), confining light in a hollow core by a band gap.

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Source: J. D. Joannopoulos, S. G. Johnson, J. N. Winn & R. D. Meade, "Photonics Crystals: Molding the Flow of Light", Princeton Univ. Press, 2008.

So, index guiding that we know that it can be relied upon you know how to confine light within the regions of higher index ok that is how index guiding takes place. So, index guiding is typically done based on the principle of modified total internal reflection right. So, in contrast to that when you have a photonic band gap.

as a principle for light guiding. There you have to think of you know that this band gap can localize light in a waveguide. which has a lower index such as a hollow core so it's a very different concept altogether than the traditional concepts used for light guiding in optical fibers or even you know index guiding fibers so here's an example or figure you can say for the two-dimensional periodic structure which is in the form of a triangular lattice of air holes so this is called a holey fiber and this is a which is the period of the holes. So this can be used for confining light into this hollow core using the principle of bandgap. So of course, a fiber cannot have a complete bandgap because of its continuous translational symmetry in the z dimension.

So you can think this is x and y, and you can think of z going into the plane of the screen. So, the fibers are continuously you know they are infinitely long you can think of that. So, you actually have continuous translational symmetry along the z direction and you know. So, a complete band gap may not be possible for this kind of structure, but because of this translational symmetry the wave factor k_z is conserved. And it is therefore still useful to have a bandgap over some finite range of k_z.

So that way, this photonic crystal fibers with two-dimensional periodic structures are really useful. But how might such a gap arise in case of a silica holy fiber as compared such as those we have seen in the previous sections or previous lectures? And how can we use it? to confine light in air?

Origin of the band gap in Holey fibers

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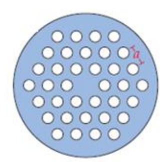
Origin of the band gap in Holey fibers

- Let us begin by considering the periodic cladding by itself, without any core.
- At any given k_z value, the solutions are the usual Bloch modes, comprising a band structure in a two-dimensional Brillouin zone.
- Find a range of k_z for which the band structure has a gap between two bands.
- Are the previously discussed two-dimensional gaps of any use here?
- The answer, unfortunately, is *no*, because the earlier two-dimensional gaps correspond to $k_z = 0$.
- In order to be useful in a waveguide, the gaps must extend over a range of nonzero k_z.



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Source: J. D. Joannopoulos, S. G. Johnson, J. N. Winn & R. D. Meade, "Photonics Crystals: Molding the Flow of Light", Princeton Univ. Press, 2008.

So these are a couple of interesting questions or mysteries that is there in the case of holey fibers where you are using a air hole as your core to guide light. So to understand that, let us look into the origin of the band gap in holey fibers. So let us begin by considering the periodic cladding by itself without any core. So, you do not have a core you just consider completely you know filled periodic cladding.

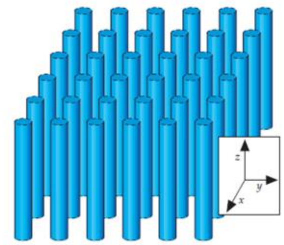
You can also think of a uniform air hole at the center to just you know think of the cladding okay. So, at any value k_z okay the solutions are usual block modes comprising a band structure in a two-dimensional Brillouin zone. what is important here we need to find the range of k_z for which the band structure gives us you know a band gap that is a gap between the two bands isn't it okay and the previously discussed two-dimensional gaps of any use here that we have done for two-dimensional slabs? The answer is unfortunately no, because in the earlier cases of these two-dimensional gaps, they all correspond to k_z equals 0, but this is an infinitely long structure, okay? So you cannot actually have k_z equals 0. Rather, you need to find gaps that exist for a range of non-zero k_z, and then only it will be useful for this kind of waveguide, okay.

Origin of the band gap in Holey fibers

- If the crystal has a *complete* (overlapping TE and TM) gap at $k_z = 0$, then indeed there will be a range of values of $k_z = 0$ over which the gap will persist.

- But the silica/air dielectric contrast of 2.1: 1 is not sufficient to obtain such a complete two-dimensional gap (at least, not for these simple periodic geometries).

- With different materials, on the other hand, a complete gap is possible at $k_z = 0$, for example, some chalcogenide glasses have indices of 2.7 or higher, which is theoretically sufficient for this purpose.



Source: J. D. Joannopoulos, S. G. Johnson, J. N. Winn & R. D. Meade, "Photonics Crystals: Molding the Flow of Light", Princeton Univ. Press, 2008.

So, if the crystal has a complete band gap that is you know overlapping TE and TM gaps at k_z equals 0, then indeed there will be a range of values of k_z equals 0 over which you know the gap will persist.

But you know the silica air dielectric contrast which is typically 2 is to 2.1 is to 1 okay it is typically not sufficient to obtain such a complete two-dimensional band gap okay at least not for this kind of simple periodic geometries. So, if you take this as an example, here you have silica air structure and this can have a TE gap but not an overlapping TM gap. For case that not equals 0 case, you will see that the gap basically disappear because the TE gap and TM gap do not overlap. With different materials, a complete band gap is possible at k_z equals 0, something like, you know, something like chalcogenide glasses, which have indices of 2.7 or higher.

Origin of the band gap: Metal Cylinders

- What other recourse do we have to find a gap in a holey fiber?
- Since $k_z = 0$ was unhelpful, let us consider $k_z \to \infty$ instead.
- In this limit, the system is again equivalent to a two-dimensional system
  —one in which the holes are replaced by perfect-metal rods and only an analogue of the TM polarization is present.

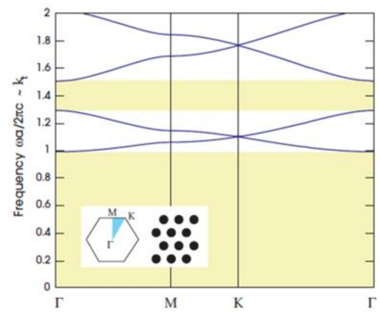


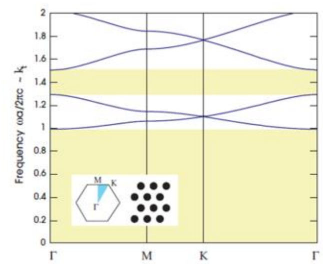
Figure: Band diagram for TM-polarized modes of a two-dimensional triangular lattice of perfect-metal cylinders.

Source: J. D. Joannopoulos, S. G. Johnson, J. N. Winn & R. D. Meade, "Photonics Crystals: Molding the Flow of Light", Princeton Univ. Press, 2008.

So instead of silica, you've got to use this kind of glasses for which complete band gap can be possible for this kind of, you know, like glass-air kind of structure. So, what other alternative do we have to find a gap in a holey fiber? So, since k_z equals 0 was not useful in this case, let us consider the other extreme that is you know k_z tends to infinity. And in this limit, the system is again equivalent to a two-dimensional system OK, so here the holes will now get replaced by perfect metal rods and only an analog of the TM polarization will be present in this case, right. So this is the band diagram over a Brillouin zone or irreducible Brillouin zone for a triangular array of metallic cylinders positioned like this. This is the normalized frequency and this is the vectorial band diagram because it shows different direction okay and you can see that the band gaps are basically shaded in yellow. So, the lowest band here has a low frequency cutoff okay like this which is characteristic of the metallic structures. and there is another band as well between the second and the third band. So, there is another band gap here okay and this bands are equivalent to the modes of the holey fiber in the scalar limit for large k_z okay.

Origin of the band gap: Metal Cylinders

- Such a structure can indeed have a gap between two bands.
- A metallic rod radius of $r = 0.3a$ led to a gap between the second and third bands.
- Moreover, this band gap will appear not only for silica/air structures, but for *any* index contrast with the same geometry, as long as we go to a large enough k_z.



Source: J. D. Joannopoulos, S. G. Johnson, J. N. Winn & R. D. Meade, "Photonics Crystals: Molding the Flow of Light", Princeton Univ. Press, 2008.

So, that is why we are taking this particular structure to understand ok. So, as you can see here that the structure indeed have a gap between two bands. So, the metallic rod here has a radius $r = 0.3a$ ok and that has given us this gap between the second and the third band. And this is basically a cutoff frequency concept which comes from the metal.

Now, this band gap that you have seen between the second and the third band will appear not only for silica air structure, but you can also get this appear make this appear for any index contrast with the same geometry as long as you go to a large enough k_z value.

Origin of the band gap: Metal Cylinders

- Such a structure can indeed have a gap between two bands.
- A metallic rod radius of $r = 0.3a$ led to a gap between the second and third bands.
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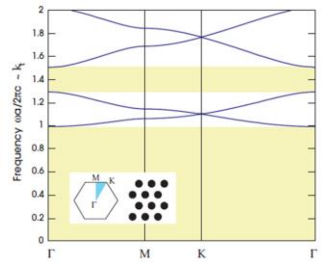


IIT Guwahati | NPTEL swayam — Source: J. D. Joannopoulos, S. G. Johnson, J. N. Winn & R. D. Meade, "Photonics Crystals: Molding the Flow of Light", Princeton Univ. Press, 2008.

Origin of the band gap: Air Holes

- When guiding in an air core, it is important that the gap open up when k_z is not too large, in order for the gap to extend above the light line of air ($\omega = ck_z$).
- Therefore, we increase the strength of the gap by enlarging the holes to $r = 0.47a$.
- The resulting projected band diagram is shown in **figure**, where we plot all the modes of this *periodic cladding* (no defect/core) as a function of k_z.
- This is the *light cone* of the crystal, but unlike the light cone of a uniform medium it has openings *above* its lowermost boundary: the photonic band gaps.

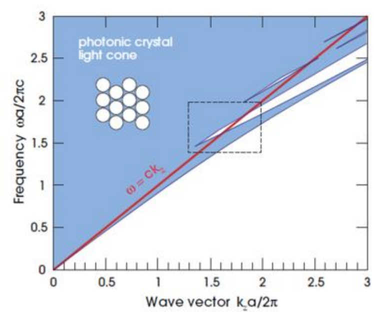


Figure : Projected band diagram, as a function of out-of-plane wave vector k_z, for a triangular lattice of air holes (inset: period a, radius $0.47a$) in $\varepsilon = 2.1$.

IIT Guwahati | NPTEL swayam — Source: J. D. Joannopoulos, S. G. Johnson, J. N. Winn & R. D. Meade, "Photonics Crystals: Molding the Flow of Light", Princeton Univ. Press, 2008.

So, in this case the first two bands in the scalar limit would correspond to four vectorial modes which we will see later okay and so we can expect to see a gap open between the fourth and the fifth bands as well okay which are not shown here but then this will be if each of these are having two modes okay in that case there will be fourth and here will be fifth so you will actually see a gap between the fourth and the fifth bands for sufficiently large k_z values. We will come to that. So let us look into the origin of bandgaps for air hole structures now. So when guiding in an air core, it is important that the gap open up when k_z is not too large.

in order for that gap to extend above the, you know, light line of air that is given by $\omega = ck$, okay? Or you can write $\omega = ck_z$. So, therefore, we increase the strength of the gap by enlarging the holes to r equals 0.47a. So, what it was previously? It was like this, okay? So, increased it and then this is what we get okay the resulting projected band diagram is shown here in this particular figure right where we plot all the modes of the periodic cladding. So, this is the cladding without any core okay and this is plotted the normalized frequency is plotted as a function of the normalized wave vector k_z.

So here you can see we plot from 0 to 3. Here also it goes from 0 to 3. And in this case the period is a and the whole radius is 0.47a. And the material is taken as 2.1. So, here you can see that this forms the light cone of the crystal. So, you can also call it photonic crystal light cone. And the lower boundary is marked by this particular red line as it is done also for the uniform medium. But there is something interesting here. Something like this, you know, there are some dashed regions highlighted which show some opening.

above the lowermost boundary. So you see there is a white region above this particular line. So there is a photonic band gap here above the light line.

Origin of the band gap: Air Holes

- This can be seen in the exact vectorial band diagram for the $r = 0.47a$ holey fiber at a particular $k_z a/2\pi = 1.7$, shown in **figure**.
- There is, of course, a gap below the first band, corresponding to the index-guided region below the light cone, and the next gap is after the fourth band.

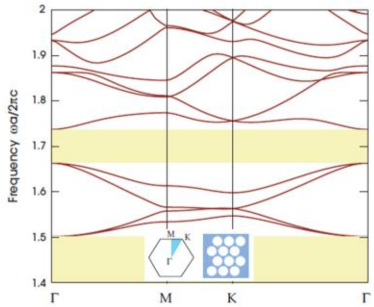


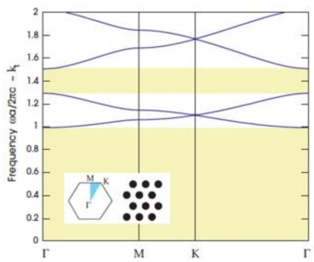
Figure: Band diagram versus in-plane wave vector in the irreducible Brillouin zone (inset) for the triangular lattice of air holes, at an out-of-plane wave vector $k_z a/2\pi = 1.7$.

Source: J. D. Joannopoulos, S. G. Johnson, J. N. Winn & R. D. Meade, "Photonics Crystals: Molding the Flow of Light", Princeton Univ. Press, 2008.

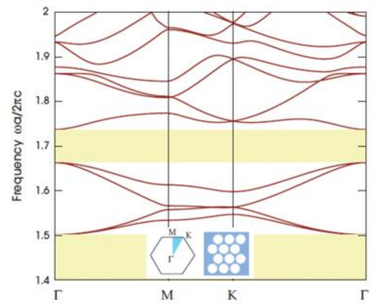
So you can actually see this better in this particular diagram. So what is happening here? This is the vectorial band diagram for the same case where the radius of the air holes taken as 0.47 a and this is the holy fiber and what we are doing here this is plotted for a particular value of k_z. So, here you can see that at $k_z\, a/2\pi$ = 1.7 this is the case ok, you actually have this opening. So, you plot this particular vectorial diagram at this particular value of k_z ok. So, what you see here? You actually see band gap.

Origin of the band gap: Air Holes

- Even the shape of the first four bands is reminiscent of the scalar band diagram from figure (left), where each of the scalar bands has been split into two vectorial bands.
- Since this gap comes from the scalar limit, it remains open (and indeed, increases monotonically) as k_z is increased.
- For larger k_z, higher-order gaps from the scalar limit also open.



Triangular lattice of perfect-metal cylinders



Triangular lattice of air holes

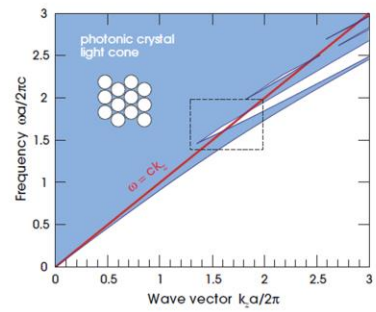
Source: J. D. Joannopoulos, S. G. Johnson, J. N. Winn & R. D. Meade, "Photonics Crystals: Molding the Flow of Light", Princeton Univ. Press, 2008.

So, the band gaps are shaded in yellow So once again, the lower gap is basically coming from the index guided region. So for this kind of structure also, you have a lower gap. So once again, it comes from the index guiding region. And the upper gap, this one, corresponds to one of the band gap inside the light cone where guiding in air core is possible. And this is because of this phenomena.

So it is a band gap inside the light cone. And that is why guiding of light in this air core will be possible. So this gap, since this gap comes from the scalar limit, it remains open. And indeed, it increases monotonically as k_z is increased. So here you can see that particular feature that this gap actually increases monotonically with k_z.

Origin of the band gap: Air Holes

- Interestingly, there is at least one small gap visible in figure that does *not* correspond directly to a gap in the scalar limit and therefore is harder to anticipate.
- This gap opens around $k_z a/2\pi = 1.85$ and then closes at a *finite* wave vector around $k_z a/2\pi = 2.5$.
- In complicated high-contrast structures, gaps that have no simple analytical explanation are not unusual.



Triangular lattice of air holes

Source: J. D. Joannopoulos, S. G. Johnson, J. N. Winn & R. D. Meade, "Photonics Crystals: Molding the Flow of Light", Princeton Univ. Press, 2008.

So this is basically the band diagram for or you can say this is the ω-k relationship or dispersion relationship for the triangular lattice of air holes. And this is particularly the vectorial band diagram at a particular value of k and this is mainly showing you the different directions fine. So, what we understand from here is that you know this forms of the light cone of the holy fiber with gaps appearing inside that as this open regions and for larger case that you can see that higher order gaps are also appearing in the scalar limit. So, what is this red line? This red line basically shows you the light line of air and that is marked as ω equals ck_z and this dashed boxes basically indicate those defect modes which we are trying to excite for light propagation inside the holey core fiber. So there are two interesting gap properties that can be understood from the scalar limit.

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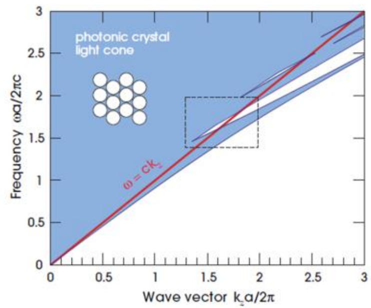
Origin of the band gap: Air Holes

- There are two other interesting gap properties that can be understood from the scalar limit.
- First: two-dimensional band gaps open only for some minimum index contrast (around 1.4: 1 for the triangular lattice of circular holes), this is not true for fibers.



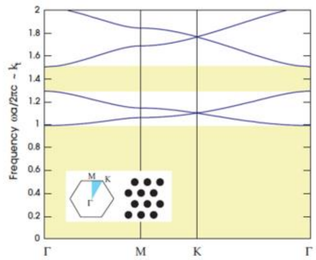
Triangular lattice of air holes

Source: J. D. Joannopoulos, S. G. Johnson, J. N. Winn & R. D. Meade, "Photonics Crystals: Molding the Flow of Light", Princeton Univ. Press, 2008.

The first is that two-dimensional bandgaps open only for some minimum index contrast, which is around 1.4:1 for this kind of assembly, like triangular lattice of circular holes. And that is not true for the fibers because fibers have slightly different comment as we discussed earlier.

Origin of the band gap in Holey fibers

- There are two other interesting gap properties that can be understood from the scalar limit.
- The band structure approaches a scalar limit of "metallic" rods, with the *same* gaps, for *any* index contrast, no matter how small, although for a small index contrast the gaps may open only for a large k_z far below the air light line.



Triangular lattice of perfect-metal cylinders

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Source: J. D. Joannopoulos, S. G. Johnson, J. N. Winn & R. D. Meade, "Photonics Crystals: Molding the Flow of Light", Princeton Univ. Press, 2008.

And the band structure approaches a scalar limit of the metallic rods with same gaps and for any index contrast and no matter how small okay although a small index contrast for a small index contrast a gap may open for very large k_z value which is far below the air light line okay. So, so this is basically the situation that you can expect at very large k_z values right that is why we are like referring to this case one limit case all the time.

Origin of the band gap in Holey fibers

- Second, consider what happens for the inverse case of *higher*-index rods surrounded by a lower-index material.
- For this case, in the scalar limit one obtains light modes that are 100% confined inside the rods, yielding bands that are independent of the in-plane Bloch wavevector (k_x, k_y).
- The bandwidths of the lowest photonic bands become very narrow, approaching a discrete set of bands corresponding to the scalar modes in cylindrical metallic cavities.
- In between these bands are gaps, but the gaps are largely insensitive to the positions of the rods, since in the scalar limit the rods form non-interacting cavities whose frequencies are determined by the rod geometry alone.
- The localization of modes via this sort of phenomenon has been dubbed "anti-resonant reflecting optical waveguiding."

Source: J. D. Joannopoulos, S. G. Johnson, J. N. Winn & R. D. Meade, "Photonics Crystals: Molding the Flow of Light", Princeton Univ. Press, 2008.

okay and the second important point. So, there are two important gap properties as I mentioned first one is shown here the second one is this that consider what happens for the inverse case of higher index rods which are you know surrounded by lower index material. So, for that case you know in the scalar limit one obtains you know the light modes will be 100 percent confined inside the rods itself yielding the bands which are independent of the in plane block wave vector that is k_x and k_y. And the bandwidth of the lowest photonic bands become very narrow in that case approaching a discrete set of bands corresponding to the scalar modes of cylindrical metal cavities. So that will be like inverse of this particular structure where you have cylindrical metal cavities. In between these bands are the gaps but here the gaps will be largely insensitive to the position of the rods. Since in the you know scalar limit the rods will form non interacting cavities whose frequencies are basically determined by the rod geometry alone right. So, the bandgap guidance has been observed experimentally to be very low like you know for the index contrast as low as 1 percent in such cases ok. And the localization of modes via this sort of phenomena has been dubbed as anti resonant reflecting optical waveguiding.

Guided modes in a hollow core

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Guided modes in a hollow core

- By now we are familiar with the proposition that, given a band gap, introducing a defect in the crystal can produce localized states.
- This phenomenon is exploited to guide light in a hollow-core photonic-crystal fiber.
- Figure shows the cross-section of an experimental holey silica fiber with a hollow core covering the area of seven holes of the periodic structure.

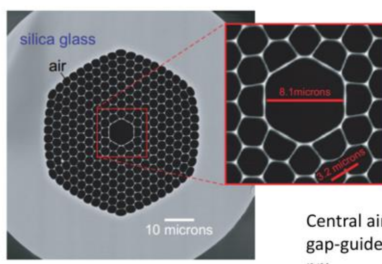

Figure: Electron-microscope image of hollow-core holey-fiber cross section (black regions are air holes, and gray regions are silica glass).

Central air defect, replacing 7 holes, supports gap-guided modes around a wavelength of 1060 nm.

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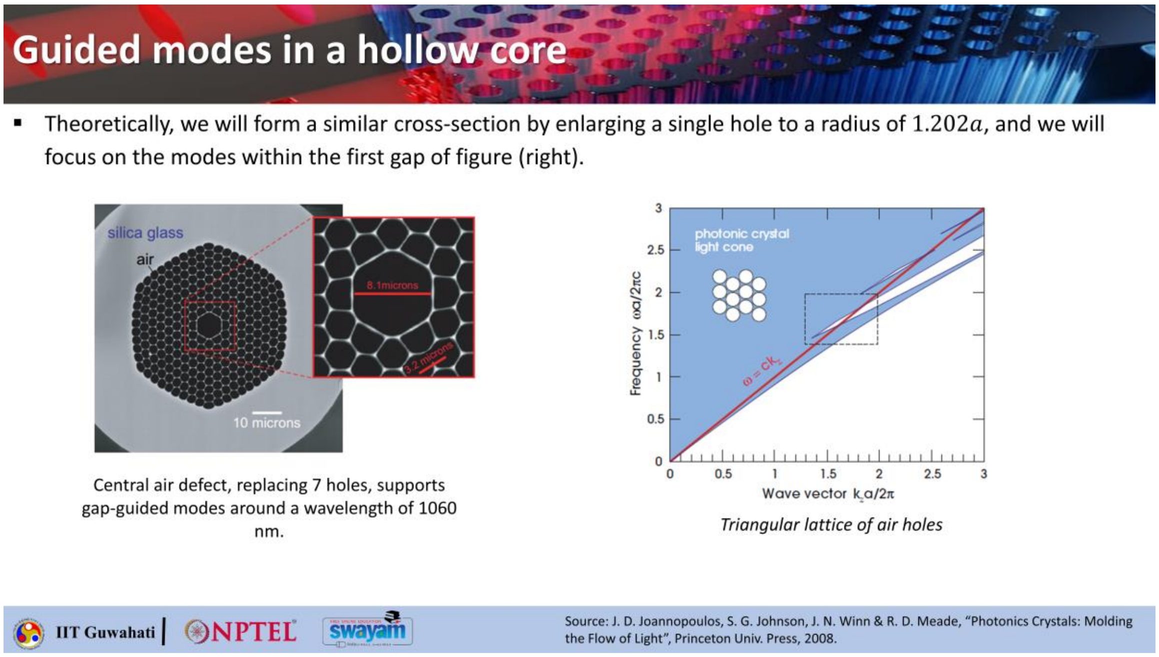
Source: J. D. Joannopoulos, S. G. Johnson, J. N. Winn & R. D. Meade, "Photonics Crystals: Molding the Flow of Light", Princeton Univ. Press, 2008.

So, these are two important phenomena that can happen in the fibers, holey fibers and we will see how the guided modes look like now in a hollow core. So, by now we are familiar with the fact that you know given a band gap if you are able to introduce a defect in the crystal you can produce localized states.

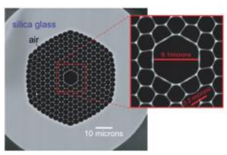
And this phenomena is basically exploited to guide light inside a hollow core photonic crystal fiber. So, this particular figure shows the cross section of an experimental holey silica fiber. So, you can see it is a hole array that is in the cladding and at the center 7 holes are basically merged to form a large gap. So, this is how experimentally this fiber has been made. okay and this is the image from an electron microscope and the the black region here shows you the air holes and this is basically silica glass okay and this is a zoomed in version for you guys to clearly see it and you can see that you know this black portions are basically air holes okay and this this core basically works like a central air defect because it is replacing seven holes okay and it can support gap guided modes at wavelength of 1060 nanometer okay.

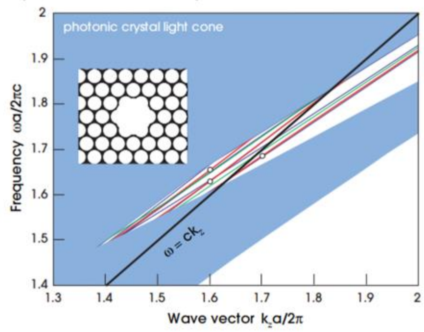


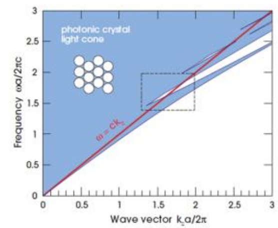
So, that is particular to this dimension if you change the dimension you will have a different band gap and you will be able to guide the wavelength of your choice. So, when you try to replicate this in simulation, what you can do? You can consider a single hole whose radius is basically enlarged from say 0.7a to 1.202a. and you will get something like that. So if you do that, so what is here? a is 33.2 microns okay and if you do 1.202a you will be able to get radius almost equal to this one. So, that is how you can actually simulate this particular structure in this fashion and why we are showing this because our focus will be to have something you know within this gap okay that was shown in the in this particular figure. So, we want our modes to be somewhere here okay and when you do the actual simulation with this then this is the structure that you are actually simulating.

Guided modes in a hollow core

- The resulting band diagram is shown in figure, and exhibits a bewildering variety of guided modes.
- *We can categorize these modes in two ways: by symmetry, and by whether they are surface states or air-core modes.*
- Lines in different colors correspond to different symmetries.







Triangular lattice of air holes

Figure: Band diagram showing guided modes of hollow-core holey-fiber structure (inset, similar to experimental structure of figure to the left), corresponding to dashed region of figure to the top.

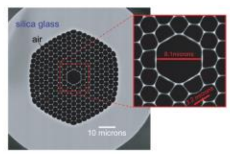
Source: J. D. Joannopoulos, S. G. Johnson, J. N. Winn & R. D. Meade, "Photonics Crystals: Molding the Flow of Light", Princeton Univ. Press, 2008.

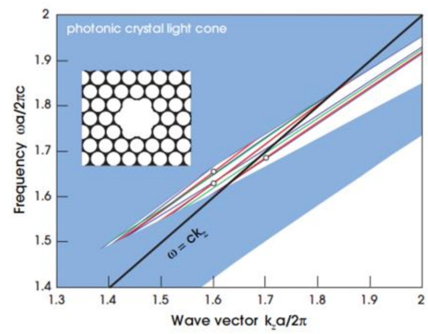
So, what you have done we have taken the central hole and set its radius to 1.20 to a and you came up with this kind of structure right and then when you computed the band diagram so this is how the band diagram looks like and you can see that there are some kind of you know interesting features over here so why i have shown this on this side here you can see that this is the experimental structure and we are basically trying to see what happens here. So, this is kind of a zoomed version ok. So, as you can see here it starts from 0 to 3 the normalized frequency whereas you are here only showing from 1.4 to 2 and you are also doing it for 1.3 to 2 that means you are somewhere here 1.3 to 2. So, more or less you are basically doing this box. So, we have zoomed into and studied this box for this particular geometry and this is what we observe right. Now, here we can categorize this modes the guided modes that you see in two ways by symmetry and by whether they are surface states or they are air core modes.

So, there are two ways of categorizing them. And the lines in different colors correspond to different symmetries. As you can see here, there are, you know, different color lines.

Guided modes in a hollow core: Surface States

- Three thick red lines indicate doubly degenerate bands that have the correct symmetry to couple to plane-wave input light.
- Thin green lines indicate doubly degenerate bands with a different symmetry, and thin blue lines indicate nondegenerate bands.
- Bands below the light line (thick black) are surface states confined to the edge of the core.





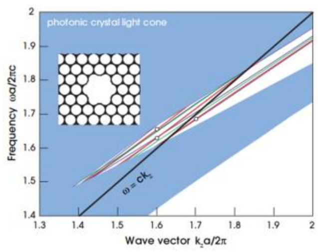
Source: J. D. Joannopoulos, S. G. Johnson, J. N. Winn & R. D. Meade, "Photonics Crystals: Molding the Flow of Light", Princeton Univ. Press, 2008.

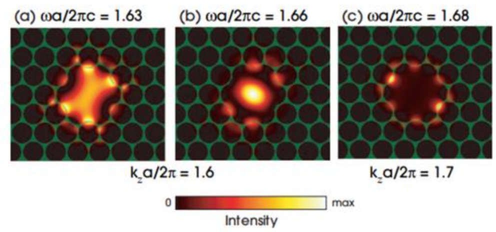
We'll go into the details. So, the three thick red lines here indicate doubly degenerate bands that have the correct symmetry to couple to plane wave input light. And there are also some thin green lines which indicate doubly degenerate bands with different symmetry and the thin blue lines indicate non-degenerate bands.

And the bands below this light line that is the thick black line here are basically the surface states. So, they will be basically confined to the edge of the core.

Guided modes in a hollow core: Mode Profile

- Three dots indicate the modes plotted in figure right.
- Intensity patterns ($\hat{\mathbf{z}}.\,\mathrm{Re}[\mathbf{E}^* \times \mathbf{H}]$) of three doubly degenerate modes of a hollow-core holey fiber (ε shaded green), corresponding to the dots on the thick red lines in figure left.
- (a) and (b) lie above the air light line at $k_z a/2\pi = 1.6$, while (c) is a surface state lying below the air light line at $k_z a/2\pi = 1.7$.





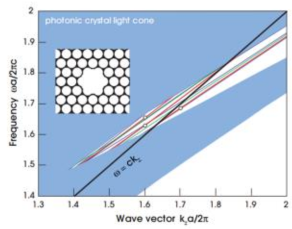
Source: J. D. Joannopoulos, S. G. Johnson, J. N. Winn & R. D. Meade, "Photonics Crystals: Molding the Flow of Light", Princeton Univ. Press, 2008.

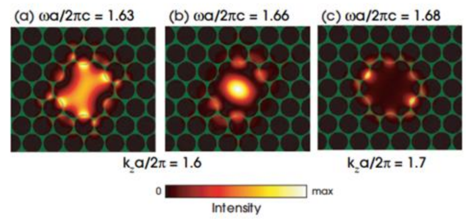
We will see that here through some simulation. So we will now focus on these three dots that you see. They basically indicate modes for this particular photonic crystal holey fiber.

this particular black line is the light line in air. So, that is $\omega = ck_z$ ok. So, when you do simulations and you first focus on this particular one. So, what we are plotting here is basically the intensity pattern ok that is real of E conjugate cross H that is basically giving you the pointing vector ok and the direction. So, you actually get you know intensity of this 3 doubly degenerate modes of this particular hollow core fibre. right so these are basically corresponding these three figures correspond to this three dots that you see okay and the normalized frequencies are marked here so you see the first one it is $\omega a/2\pi c$ equals 1.63 so this is this one the below one okay okay and the one on the top is $\omega a/2\pi c$ equals 1.66 and the one here has got the highest frequency that is 1.68 ok. So, they have also shown this. So, this these two are for the same k_z value where the normalized k_z or you can say $k_z a/2\pi$ is 1.6 and for this case it is 1.7.

Guided modes in a hollow core: Mode Profile

- The intensity patterns reveal a striking difference between the two bands that lie *above* the light line of air ($\omega = ck_z$) and the one band that lies *below* the light line of air.
- The former is concentrated in the air core, while the latter is concentrated around the *surface* of the air core.
- This is an example of a *surface state*.
- it is evanescent in the crystal because it is in the band gap, and is evanescent in the air core because it is below the air light line.





Source: J. D. Joannopoulos, S. G. Johnson, J. N. Winn & R. D. Meade, "Photonics Crystals: Molding the Flow of Light", Princeton Univ. Press, 2008.

So, the dark one means 0 intensity and the bright ones or white ones means the maximum intensity. So, what you see from this kind of plot? So, you can actually see that this A and B points are lying above the airline ok. So, they can give rise to some air core modes, but however this one, this particular dot, this is lying below the light line. So, this will give you a surface state and that you can also see from here. And that is what the intensity patterns also reveals a very important and striking difference between the two bands, which lie above the light line and the one below the light line.

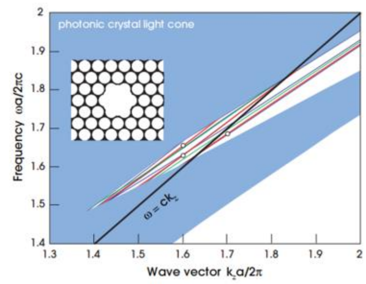
So this one is below the light line. So here you can see in these two case, the intensity is mainly concentrated in the air core. Whereas, in this particular case, the intensity is mostly concentrated around the surface of the air core. That is an example of surface state.

So, where they work, they actually appear below the light line. ok and it is evanescent in the crystal because it is within the band gap ok and it is also evanescent in air core because it lies below the light line.

If so if it was above the light line so it would have been you know a propagating mode or supported mode.

Guided modes in a hollow core: Surface States

- In fact, we see four surface states of various symmetries below the air light line.
- *Why so many?*
- To understand this, let us compare this case with the surface states of a two-dimensional crystal.
- In two dimensions, we considered only $k_Z = 0$, and we found a continuous band of surface states that propagated along a *flat* interface.

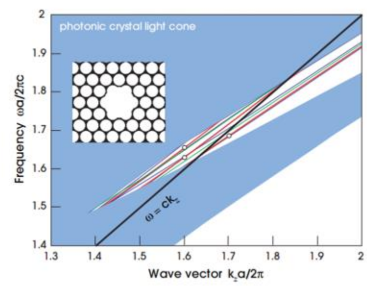


Source: J. D. Joannopoulos, S. G. Johnson, J. N. Winn & R. D. Meade, "Photonics Crystals: Molding the Flow of Light", Princeton Univ. Press, 2008.

So, you know if you look carefully we can figure out that there are four surface states of various symmetries below the light line. So, from this you can think of four different symmetric positions of the surface state and why so many? So, to understand this let us compare this case. with the surface states of a 2 dimensional crystal. In 2 dimensionals in 2 dimensions we considered only k_z equals 0 and then we found out a continuous band of surface states that propagated along a flat interface isn't it.

Guided modes in a hollow core: Surface States

- The existence of surface states depends on how we terminate the crystal.
- For example, does the edge of the air core occur at the edges of the holes, or does it cut them in half?
- It should be possible to improve the performance of the fiber by adjusting the termination to *eliminate* the surface states.
- Surface modes degrade a fiber's performance primarily because they may have greater losses than the other guided modes.
- For example, scattering due to surface roughness is much worse for a mode concentrated at the surface than for a mode concentrated in the core.



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Source: J. D. Joannopoulos, S. G. Johnson, J. N. Winn & R. D. Meade, "Photonics Crystals: Molding the Flow of Light", Princeton Univ. Press, 2008.

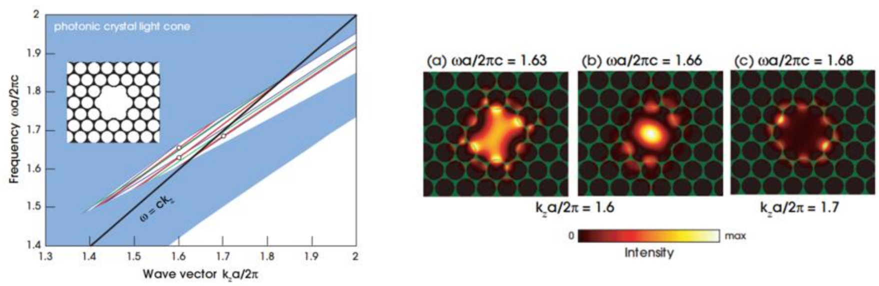
So, here we have a curved infinite interface. So, instead of a continuous set of surface states we will have you know discrete set of surface states here at each okay at each k_z which will form continuous bands as we vary this k_z. And this happens in much the same way that a finite piano string supports only discrete set of harmonics. So if we were to make the core larger and the interface longer, then we would get more surface states, which are more closely spaced. Makes sense. However, we must also take into account the crucial role of the crystal termination.

So, here we considered the crystal to be infinite along the x and y, but in practice that will also be terminated somewhere. So, the existence of surface states depend on how we terminate the crystal. For example does the edge of the air core occurs at the edge of the holes or you know so it's like this or do we cut them in half. okay how it is happening so this is like where you do not have a perfect circular air core because you are basically having the air holes complete and then you are curving this out isn't it so it should be possible to improve the performance of the fiber by adjusting the termination and that would eliminate you know the surface states So, the surface states has got a lot to do the way it is being terminated and the surface modes degrade a fibers performance primarily because they may have greater loss than the guided modes. So, you can take for example, you know the scattering due to surface roughness is much worse for a mode concentrated at the surface.

than you know for a mode that is concentrated in the core that is guided through air. So, surface roughness is not going to affect that air core mode right. So, one could attempt to operate exclusively in the air core mode of figure A that is this case ok. But you know what we plan may not happen all the time. So, sometimes it proves very difficult in practice to only work at this particular case ok.

Guided modes in a hollow core

- One could attempt to operate exclusively in the air-core mode of figure (a), but this proves difficult in practice.
- Any small imperfection or asymmetry will tend to couple energy from one mode to another, especially at the points where modes of different symmetry cross in the band diagram.



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Source: J. D. Joannopoulos, S. G. Johnson, J. N. Winn & R. D. Meade, "Photonics Crystals: Molding the Flow of Light", Princeton Univ. Press, 2008.

So, any small in imperfection in making this photonic crystal fiber or any asymmetry will tend to couple energy from one mode to another mode and especially at the points where the modes of different symmetry cross in the band diagram. So, that is where the coupling of the energy between one mode to another will be higher and then you will not be only able to excite the air core that you see in figure. So, you will have to you know live with the surface states as well. So, that is all for this lecture. So, we will be starting the discussion of the overview of Bragg fibers in the next lecture.

If you have any doubt regarding this concept okay or you can drop an email to this email address mentioning MOOC, Photonic crystal and lecture 27 on the subject line. so