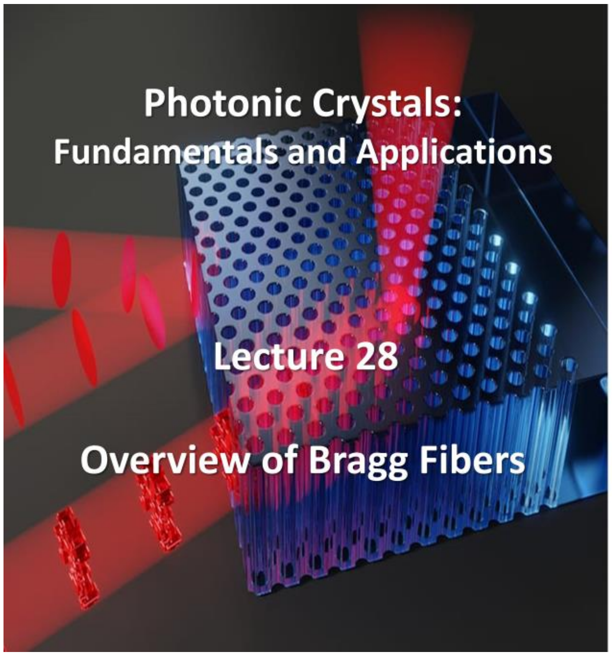
Lec 28: Overview of Bragg Fibers



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 28 of the online course of Photonic Crystals Fundamentals and Applications.

Lecture Outline

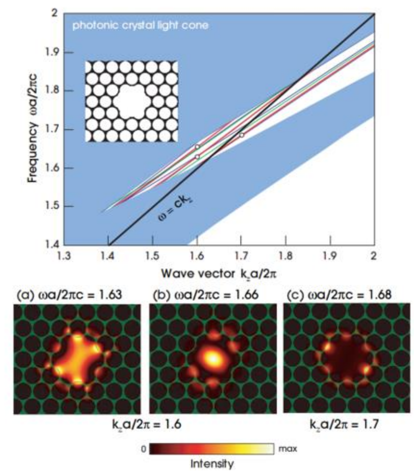
- **Effect of Core Termination**
- **Bragg Fibers**
- **Analysis of cylindrical fibers**
- **Band gaps of Bragg fibers**
- **Guided modes of Bragg fibers**

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

Today's lecture we will be covering the overview of Bragg Fibers in details. So, here is the lecture outline. We will first talk about the effect of core termination in Bragg Fibers. We will discuss about the analysis of cylindrical fibers. band gaps of brake fibers and also the guided modes.

Effect of Core Termination

- As discussed earlier, 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.
- E.g, scattering due to surface roughness is much worse for a mode concentrated at the surface than for a mode concentrated in 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.

So, let us first discuss about this effect of co-termination. So, we have discussed this earlier that the existence of the surface states depends on how we basically terminate the crystal. So, this was the point at $k_z a/2\pi$ equals 1.7 where we found a surface state okay.

So, the question comes you know does the edge of the air core basically occurs at the edge of the holes or it basically cuts them in half ok. So, there could be possibility to improve the performance of the fiber by adjusting this termination that could eliminate the surface states. So, surface modes basically degrade a fiber's performance primarily because they may have greater loss than the other guided modes. So, here you can see there are two possible air core modes that can be the guided modes. So, one example why you know the surface modes would degrade the fibers performance the mainly because of the scattering that comes from the surface roughness which is much worse for a mode that is concentrated at the surface than the mode which is concentrated in the core.

Effect of Core Termination

- The effect of an alternate core termination is shown in **figure**, for which we have used a defect hole of an enlarged radius $1.4a$.
- Perhaps counterintuitively, enlarging the defect has *reduced* the number of defect modes.
- This is because the new termination has eliminated the surface states.
- In fact, there is only one doubly degenerate mode in this fiber core that is of the correct symmetry to couple to plane-wave input light (thick red line).

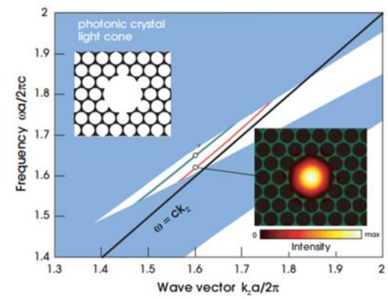


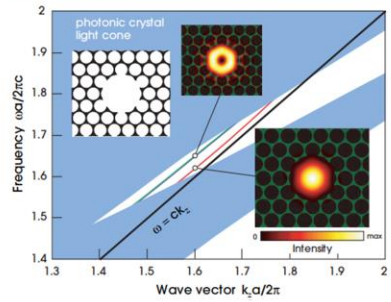
Figure: Band diagram and mode intensity patterns (insets) of a hollow-core holey fiber with a larger air core (radius $1.4a$, left inset) corresponding to a crystal termination that eliminates surface states.

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 now we will see that you know if we try to change the core termination. So this is an alternate code termination which is shown in this figure. So here you can see this air code is basically terminated. not along the lines of the air holes, but it is slightly larger. So the defect hole has been now enlarged to a radius of 1.4a. So in doing so, now you can see this. Yeah, here it is like this. So it is basically following the boundary of the air holes. But in this case, it actually cut opens all the air holes in the periphery.

Effect of Core Termination

- The intensity pattern of this mode is shown in the inset, and is strongly localized in the air core.
- Indeed it is even more strongly localized than in the previous structure, a consequence of the lack of surface states to interact with.
- Thin blue and green lines indicate other symmetries: blue is nondegenerate and green is doubly degenerate.



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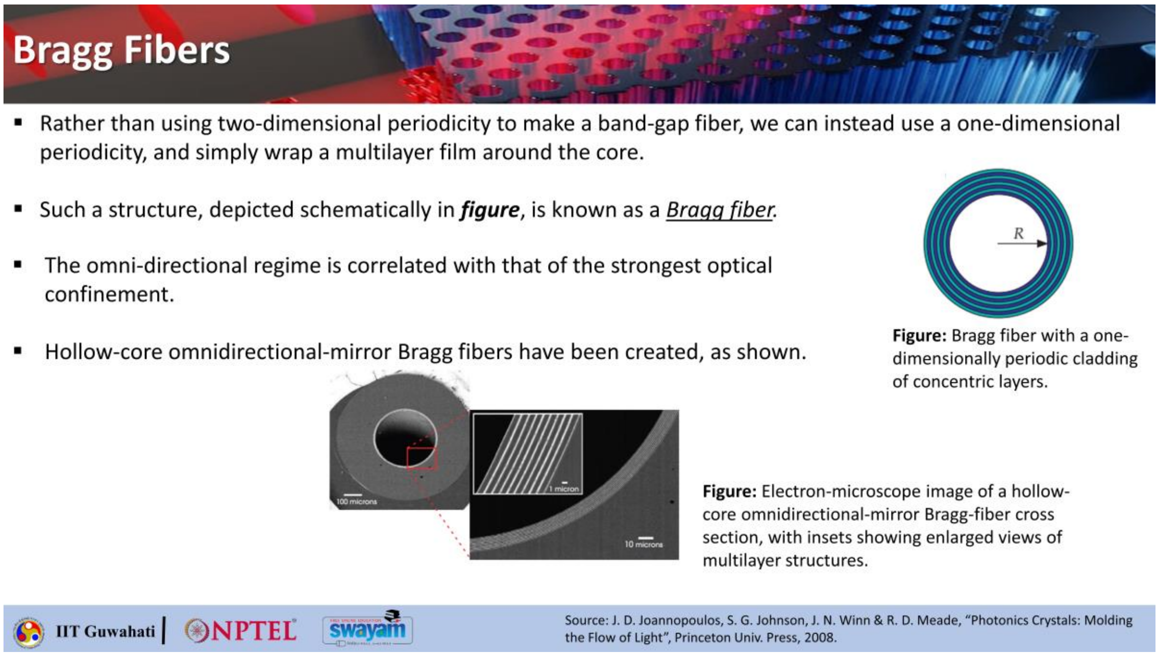
Right. So Perhaps counter-intuitively, enlarging this defect has reduced the number of defect modes. So, if you do the bandgap analysis for this particular fiber, you will see that you know there are only two modes appearing here. The surface mode does not appear in this case, okay. And this is because the new termination is able to eliminate the surface states. In fact, there is only one doubly degenerate mode in this fiber core that is of the correct symmetry to couple to plane wave input light as you can see in the thick red line.

So, you can also see this particular image. mode profile that basically shows that the it is a beautiful mode that is appearing only in the center of the air code right. So, this will be a perfect mode to guide your light signals because there is nothing close to the termination edges so that the scattering losses will be really low. So, indeed you can see that is it is even more strongly localized than the previous structure. So, if you compare with the previous structure okay.

So as compared to this structure or these two modes which were these two doubly degenerate modes, now you can see that here the localization is even actually better okay. And this is because the lack of surface states to interact with. And the thin blue line here basically indicates the other symmetry. So, the blue actually shows non degenerate and the green one shows doubly degenerate and this is another mode that will be able to sustain, right. So, there are actually two blue lines which are difficult to distinguish here.

So what we do here, we have shown the intensity patterns for $k_Z a/ 2\pi$ = 1.6, okay, which are basically indicated by these two dots, okay. So the four higher order modes all have similar intensity pattern. and a non-degenerate mode is basically shown here, okay. Next, we move on to the Bragg fiber.

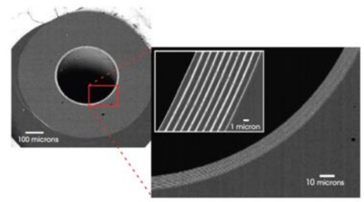


So, when we talk about Bragg fiber, so rather than using two-dimensional periodicity to make a bandgap fiber, here we basically use a one-dimensional periodicity and simply wrap a multi-directional film like this with around the core. So, this particular structure is known as the Bragg fiber which has got a radius of r and you can see here you know alternating dielectric material is basically forming this cladding right. So, you can say that it is a one-dimensionally periodic cladding of concentric layers. So, the omnidimensional regime is correlated with that of the strongest optical confinement So, here you can see the picture of an it is an electron microscope image of a hollow core omnidirectional mirror Bragg fiber okay. So, you can zoom this particular portion and it looks like this.

So, the two different colors shows two different refractive indices of the material being used okay. So, there are many alternating layers. can look at the you know bar here that will give you some idea about the scale of this particular structure. Like here the scale bar is 100 micron, here it is 1 micron and here it is 10 micron. So, from here we zoomed into this part and then again we look into this particular thing in more details over here right.

Bragg Fibers

- Bragg fibers with layers made of a low-index polymer and a high-index chalcogenide glass have compatible thermal properties for drawing fibers.
- Such fibers can confine light within a hollow core, much like the holey fibers.
- In fact, they have already been used to guide high-power lasers for endoscopic surgery at wavelengths for which solid materials are too lossy.
- Thin white layers are a chalcogenide glass and gray regions are a polymer.
- This fiber was designed to operate at a wavelength of 10.6 μm.



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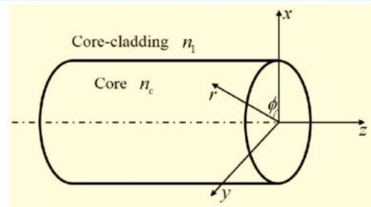
So, braag fibres with layers made of low index polymer and high index chalcogenate glass okay have compatible thermal properties for drawing the fibres. So, these are the two materials being used okay and such fibres can confine light within a hollow core very much similar to the holey fibres. In fact, they have already been used to guide high power lasers for endoscopic surgery at wavelengths for which the solid materials are typically very lossy, okay. So, the thin white layers that you see over here are basically chalcogenide glass and the gray regions are basically the polymer. So, this fiber is basically designed to operate at a wavelength of 10.66 micrometer, right.

Analysis of cylindrical fibers

- The analysis of Bragg fibers is greatly simplified because of their rotational symmetry.
- The continuous translational symmetry in z means that the z dependence of the fields can be chosen as $e^{ik_z z}$ for some wave vector k_z.



- By exactly the same reasoning, the continuous rotational symmetry in φ (the azimuthal angle) means that the φ dependence of the fields can be chosen as $e^{im\varphi}$ for some number m, which is known as the **angular mode number**.
- It must be an integer because $\varphi = 0$ and $\varphi = 2\pi$ are equivalent, and consequently $e^{im2\pi} = 1$.

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So, now we will do the analysis of cylindrical fibers. So, to analyze the Bragg fiber you can actually take help of the rotational symmetry. So, here you can see that you know the fiber axis can be marked. So, this is x this is y and this is z, but then for a cylindrical fiber you can also use the cylindrical coordinate system. So, this is r this is the azimuthal angle ϕ and this is your z.

So, it is ρ ϕ z or you can say r ϕ z, this axis also you can use, ok. So, here you can see that the continuous translational symmetry is along the z, ok. That means the z dependence on the film fields can be chosen as e^$(ik$_$z\ )z$ for some wave vector k_z. By exactly the same reasoning the continuous rotational symmetry in ϕ which is the azimuthal angle, it means that the ϕ dependence of the fields can be chosen as e to the power imϕ for some number m which is basically known as the angular mode number, okay. Because for ϕ also you have a continuous rotational symmetry.

it must be an integer because ϕ equals 0 and ϕ equals 2π are basically equivalent. So, consequently you should be able to write e to the power im2π should be equal to 1. right. So, the field of an eigenstate in that case can be written in the separable form. So, H_(kzm) can be written as e^$(ik$_$z\ z+im\varphi)$ $\mathbf{h}$_$(k$_$z,m(r))$ and this is the radial dependency, right.

So, this has been reduced to a one-dimensional problem for the radial dependence of this. right. Because here it is a continuous translational and symmetry along z and continuous rotational symmetry along φ. So, the equation basically corresponds to a circularly polarized mode okay. Since by including the time dependence like e to the power i(mϕ-ωt) time dependence e to the power i(mϕ-ωt) we see that the field pattern at a fixed z is basically rotating with an angular phase velocity of ω/m where m is non-zero right yeah.

So, the field of the eigenstate ok you can see that what happens that instead use a ϕ dependence of $\sin(m\phi)$ or $\cos(m\phi)$ forming linearly polarized states that are not rotating okay. So, although the polarization is not generally uniform over the cross section. So, in this case what happens the mirror symmetry that is you know the ϕ can be replaced by -ϕ it implies that you know plus minus m eigen modes are basically degenerate. and one can therefore form $e^{(+im\phi)} \pm e^{(-im\phi)}$ combinations that can give you cosines and sines. So, as mentioned earlier m is basically called angular momentum in analogy to the quantum mechanics where the angular momentum L_z of such a wave function is basically $\hbar m$.

okay and the equation for $\mathbf{h}_{(k_z,m}(r))$ which has radial dependency in a region of uniform refractive index would turn out to be analytically solvable in terms of Bessel's function. So, in a multilayer fiber the Bessel's solution in each layer are then connected by means of transfer matrix that match the boundary condition at each interface and you will be able to find out the solution for the entire multilayer coating, okay. Now, let us see how we calculate the bandgaps of this Bragg fiber. So, in order to understand confinement in Bragg fiber, we should must solve for the bandgaps of that fiber. So, this might seem at first like a difficult task because you know you have concentric rings that are not periodic structure in sense that is required for the block theorem.

Because here the curvature basically decreases with r, okay. It means they would like to now say flatten out when you keep on increasing the radius. But however, all that matters for light is to be confined, okay, so that it cannot escape to r equal, r tending to infinity. So, in this limit, you know, of r tending to infinity, the curvature of the ring would approximate 0, that means it will look like a planar multilayer film, which is shown here. So, if you study the band diagram for this one which you have already done previously.

So, this band diagram of the flat multilayer structure would give us an exact solution in the r tending to infinity limit. So, here as I mentioned this is basically you know high low high low different kind of multilayer film. So, this is a one dimensional periodic crystal and Here it is the band structure that plots the normalized frequency versus normalized wave vector. So here there are two parts. You can see the on axis bands, which are basically 0,0,k_z.

So this is shown here on the left side. And on the right side, you are basically having the off axis band structure. So it is for k_y. So you can see the marking here. So this is x, this is y, and vertically this is z.

So, what is plotted here is basically as function of k_y. So, if you look carefully that for the on axis case the bands basically overlap that means they are degenerate. But for the off axis case along k_y, the bands basically split into two different polarizations. So, you can see a blue color, red color, the red color tells you about TE polarization, but basically the polarization is along YZ plane and the blue one shows TM polarization where the field is along electric field is along x.

So, these are the different cases. that you can see. Now, if the wave factor k_z and the frequency ω of a mode lie in one of the one-dimensional gaps, that mode will not be able to escape to the large radii. So, it will be rather localized in the fiber core. So for the multilayer film, the optical confinement was obtained for quarter wave stack that you have seen earlier. So if you consider a quarter wave stack here, so the dense medium is the red color one and the rarer medium is this light color one.

And this is basically the one dimensional multilayer film and this is a quarter wave stack. So each thickness of each layer is basically $\lambda/4$. And this is the medium in which the light is incidenting. So, if you see carefully, this one is omega 1, sorry, ε_1. The permittivity for the dense medium is ε_2 and this is ε_a.

That is ε_{air}. So what you see here, it is basically plotted as a function of square root of $\varepsilon_2/\varepsilon_2$. And here it is square root of $\varepsilon_1/\varepsilon_a$, right? So this tells you about the size of the omnidirectional gap. So these are basically different gap, mid-gap ratios, which are plotted for this kind of a case, which is shown here. So silicon-silica in air, this kind of pattern will have a you know gap mid gap between 20 percent and 30 percent over here. So, I hope it is clear that this particular figure, what you see here, these curvatures are basically showing you the gap mid gap frequency ratios.

So, this system tells you in which light is incident from an ambient medium of permittivity ε_a. And you basically have two materials of dielectric constant ε_1 and ε_2 and we are considering ε_2 greater than ε_1. And it basically does not matter which material forms the edge of the mirror. So, this pink shaded area is basically showing you the region in which there is a non-zero omnidirectional gap. So, some common materials such as silicon, silica, air combination can also give you this kind of omnidirectional gap and you can see that has been marked over here, okay.

Now, what is the link of brake fibers to this quarter wave stack? So, omnidirectional mirror is curved around a hollow sphere or cylinder. In that case, the continuous rotational symmetry can substitute for the translational symmetry and using that light can be localized within the core. So, as with the planar mirror the leakage rate from the core to the exterior decreases exponentially with the number of layers. So, the cylindrical case which is called Bragg fiber by Yeh et al and they published this work in 1978 and the spherical case was dubbed as Bragg-Onion which we briefly discussed in one of our previous lectures that was done in 2003 by Xu's group. So, here one did not require omnidirectional mirrors to obtain localized modes because the modes rotational symmetry would impose restrictions on the angle that can escape into a large radii, fine.

So, with this you know we could understand the comparison with the multilayer film. that for multi-layer film optical confinement was obtained for the case of quarter wave stack and this criteria must be modified in the case of Bragg fiber because waveguide modes will not be generally normally incident on the layers. In particular, when you are guiding light in hollow core, the low order modes will basically approach glancing incidents. It means the incident angle will be very large as the core size will be increased. So, almost the rays will be parallel to the interface of the core and cladding.

So, that way you can say that they approach the light line which is ω equals ck_z. So, in this particular limit the quarter wave condition for the thickness of d_1 and d_2 of the material with indices n_1 and n_2 would become you know d_1 n_1 tilde and d_2 n_2 tilde where n tilde is basically showing this which is you know $n^2-(ckz)^2/\omega^2$. So, you can simplify it to square root of n^2-1. Now this formula arises from the fact that the radial wave vector k_r in n can be written as k_r equals you know square root of $n^2-(ckz)^2/\omega^2$ and in that case the quarter wave condition would look like k_r d that is d is the thickness will be equal to $\pi/2$. So, if you consider this kind of you know refractive indices, you can find out the corresponding quarter wave frequency which is $\omega a/2\pi c$ and it can be obtained as $\tilde{n}_1+\tilde{n}_2 /4\tilde{n}_1 \tilde{n}_2$.

So, what we have seen here? that we must have n_1,2 greater than 1 in order to have you know this parameter positive and that should also satisfy the glancing angle quarter wave condition with finite thickness layers. So, quarter wave thickness are not basically required in this case for guidance. The gap arise from any periodic layers, but they help us to optimize the confinement for a given index contrast. So, here you can see you know the projected band diagram which is plotted you know for frequency normalized frequency versus normalized wave factor. okay and for glancing angle quarter wave stack where the indices n_1 equals 1.

6 and n2 equals 2.7 that is similar to the polymer and chalcogenate indices. So, this is the same structure which has been you know modeled here and what we see we see numerous band gaps here okay that shows that that are been shown up as open spaces. So, what are these colors representing that will come to, but here the yellow mark region shows the omnidirectional band gap right. So, this is basically giving you omnidirectional reflection from an air medium and that is where it is having a boundary with the black light line ω equals ck_z. So, this particular line the black line that you see is basically the light line in air okay and this gives you the frequency range of omnidirectional reflection from air medium.

So, omnidirectional property is not required for guidance in this kind of fiber as you can see that any gap at of the modes will actually do, but its appearance is not a coincidence. So, for strong confinement we will generally want to have you know large contrast between the refractive indices and we will also want both the refractive indices to be greater than 1, so that it satisfies the glancing angle quarter wave condition that we discussed before. So, here the regions show where the propagating modes exist. So, if you look into the color code, you can see the blue color shows where the TM modes that is where the electric field is out of the incidence plane that exist for the red ones are for you know TE So, that is where the electric field lies along the incidence plane and the purple color is for both TM and TE. So, this actually tells you where the propagation modes basically exist in such a structure.

So these two criteria are precisely the ingredients for the omnidirectional reflection. So additionally, an omnidirectional gap has potential advantages when one wants to trap light incident from many different directions. So it may seem that we are forgetting something important by considering only modes that are propagating in the r-z plane. So you remember the r-z plane, r is the radial vector and z is that the axis of the fiber. So, in fact, if we include the modes which are propagating out of this plane correspond to light traveling in the azimuthal direction, we will find no band gap at all.

But fortunately you know such modes are basically excluded for any finite angular mode number m as when r tends to infinity the corresponding azimuthal vector would basically tends to 0. because you can write $k\_\phi=m/r$. So, when r tends to infinity this ratio will actually tend to 0. So, if you put it in another way you can say that the conservation of angular momentum prevents a mode in the waveguide core from escaping into a mode that is travelling in the azimuthal direction infinitely far away. So, this conservation law makes gap and especially gaps at k_z near 0 which are much easier to create in Bragg fibers than in fibers that has got two-dimensional periodicity.

Something like the holey fibers which we have discussed in the previous lectures and previous sections. So, on the other hand, now holey fibres can be constructed from a single solid material something like you know silica, whereas bragg fibres would require two different solid materials to be found and that needs to be drawn together. There is a compatibility between those two material. So that is why those polymer and chalcogenide class makes a good combination.

Now we will look into the guided modes of Bragg fiber. So given the multi-layer mirror with the parameters discussed, let us form a hollow core fiber by wrapping the mirror around a air core. So this involves two important decision. What core radius R do we employ? And the second thing, how do we terminate the crystal? So the choice of R generally involves a trade-off between different loss mechanism.

So now simply we'll choose R equals 3a. a is the periodicity. So as for the termination, let us end the crystal at R with half of a high index layer and using a high index layer on the inner surface would confine modes in the core more strongly and using a half of a layer would eliminate the troublesome surface states that we have seen in the early beginning of the lecture today. So, the resulting band diagram focusing on the first band gap above the light line you can see from here. So, this is basically a comparison So the first one is the band diagram of a hollow core. Here the core radius is 3a.

And this is the black fiber where the two materials are taken as 2.7 and 1.6. So this is typically the chalcogenate class and of the polymer. And here you can see the gray regions indicate the extended modes that propagate in this multilayer mirror. And if you compare this with the band diagram of a perfect hollow perfect metal waveguide.

So, this is a solid metal okay and or you can say it is a perfect metal making a hollow waveguide and if you compare the band diagram of this one with that. You can see that you know here also you are able to see those extended modes that you you have seen in the Bragg mirror case. So, you can actually try to compare these two things. And here the modes are also leveled by polarization and angular mode numbers.

So, you can see some kind of mode numbering shown here. So, we will go into more details. So, what you see here that as the core is basically several wavelength in diameter. A number of modes are basically supported. So, it becomes a multimode. So, it turns out that these modes can be directly related to the modes of a much simpler waveguide which is a hollow perfect metal cylinder.

So, the modes basically correlate. So, the band diagram of a hollow metallic waveguide with the same R equals 3a. can have the Bragg mirror gap superimposed. So, you can actually superimpose this for comparison and by comparing the two band diagrams, we can see that there is one to one correspondence between the modes and the modes of the Bragg fiber are essentially given by the metallic modes that fall within the band gap. So what is this hollow perfect metal waveguide? This is basically a mirror wrapped around a hollow core. So the metal, perfect metal will also behave like a mirror, right? So it's like basically having the same functionality.

So with this thing in mind, it is perfect, not surprising to see that the mode structure of this case and the Bragg fiber is very, very similar. At least for large R, or in the omnidirectional regime where the multilayer mirror would act basically like a perfect metal to reflect all the modes. So, both structures have modes described by the angular index m which you can see here. But a metallic waveguide with a homogeneous interior has an additional special property that you can see that all modes are basically divided into two polarization states. However, TM and TE polarization or TM and TE the terms which are used in fiber literature you know, carry a slightly different meaning.

So, here let us use the lower cases to distinguish the meanings, the different meanings they convey. So, let us use small te. So, it tells you that the modes are having electric fields purely in the xy direction. So, you can take this plane as xy and the vertical dimension is z.

okay but the magnetic field may be in any dimension direction in the case of te. If you take tm here the modes with magnetic fields purely in the xy plane but electric fields can be in any direction. The modes of the cylindrical metallic waveguide okay can then be levelled as te_ml and tm_ml where m is the angular index and l is telling you about the radial order.

So, it can be 1, 2, 3,........ So, here you can see that the lowest frequency mode in the case of the metallic one, is te_11 and then you have tm_01, te_21, then you have te_01, tm_11, those are very close to each other, that is why they are shown here separately, then you have te_31, tm_21 and so on. So of course any m not equal to 0 mode is doubly degenerate with a minus m mode. So you know you can think of you know that te_01 and tm_11 happen to be exactly degenerate. Now only the m equal to 0 modes remain purely polarized as a consequence of the mirror symmetry in ϕ the te_0L modes will have their electric fields purely in the ϕ direction and you can say that the tm_0L modes will have electric fields purely in the rz plane. So all of the m not equals 0 modes, however, are changed from te and tm into a hybrid polarization, which can be labeled as he and eh, depending on whether they are mostly te-like or tm-like.

So he means they are mostly like, these are hybrid, but mostly like te, and you know, the other one tells you that this is also hybrid, but mostly like tm. So for example, the te11 mode of the metal waveguide will become the he11 mode of the bragg fiber and so on. So this is how in the fiber, when you go to the hollow core fiber, this is how the modes will be mapped. So it turns out that the most important two modes for many practical applications are te sorry he11 and te01.

You can actually go back to the figure and correlate this. So, te01 is basically the one with the lowest loss in the case of both you know metallic fiber and Bragg fiber and he11 is usually the lowest loss m equals 1 mode. and the only m that can directly coupled to plane wave input light. There you can also see from here that the field intensity patterns are shown. So, you can see that they basically closely resemble the metallic waveguide modes.

So, they are basically the modes in hollow core bragg fiber. at quarter wave frequency. So, these are the two guided modes. So, the first one shows te01, this one is he11. And the color bar here shows the power intensity. And the transverse that is xy electric field pattern are basically shown as green arrows in both the plots. So, looking at these modes, we can classify the modes propagating in a multilayer structure by whether the electric field is parallel to the plane of propagation or it is perpendicular to the plane of propagation.

So, you can actually call whether it is TE or TM. So, here we can do the same thing for m equals 0 because in this case rz is basically a mirror plane for every ϕ, but what happens here the leveling convention is basically reversed. So the plane of propagation far away is basically the rz plane. So you can think of r this way z is going into the screen. So you can think of a rz plane. So now electric field can be parallel to that rz plane, which we are calling as tm_0L and electric field can be perpendicular to the rz plane, which we are now calling as te_0L.

So, this one. So, the te band gap, which was previously the TM band gap or the s polarized one is usually larger than the tm gap. but because the later one closes entirely at the Brewster's angle that you can also see from here. So, as a consequence every mode except for the te_0L mode.

is generally limited by the smaller tm gap. So, you can actually see in the figures. So, the te_0L mode on the other hand can have both larger bandwidth and stronger confinement because they see only the larger te gap. So, partly as a consequence of this the te mode would have the lowest predictive loss for sufficiently large R, R is basically the core radius. An analogous result is well known for the cylindrical metallic waveguide, although that comes from a very different region. So, for the case of a metallic waveguide, the boundary condition at r equals capital R is that the E_z and E_ϕ must be 0, while E_r can be non-zero. And in that case, the te_0L modes for which E_r equals 0 everywhere are the only modes that could have you know the vector E to be equal to 0 when you reach the boundary or you are exactly at the metal.

So, for an imperfect metal the, so those were considering the perfect metals. So, if you consider imperfect metal there will be field penetration into region into the metal as well. So, you can also see region which are greater than field will be there in the region r greater than equals R and that would cause ohmic loss. So, the te01 mode will have the smallest penetration into the metal since its electric field are nearly 0 at the interface and that is why this particular mode will also have the lowest ohmic loss. So in fact, a smaller filled node at r equals R is apparent from you know the Bragg fiber te_01 mode that you can see in the figure that here at the boundary it is almost 0, okay. And that means you know this particular mode is showing a very close resemblance to the metallic waveguide.

So, with that we will conclude this lecture. So, we will be discussing about the losses in hollow core fiber in the next lecture. If you have got any query regarding this one, you can drop an email to this email address mentioning MOOC Photonic Crystals and the lecture number on the subject line. Thank you.