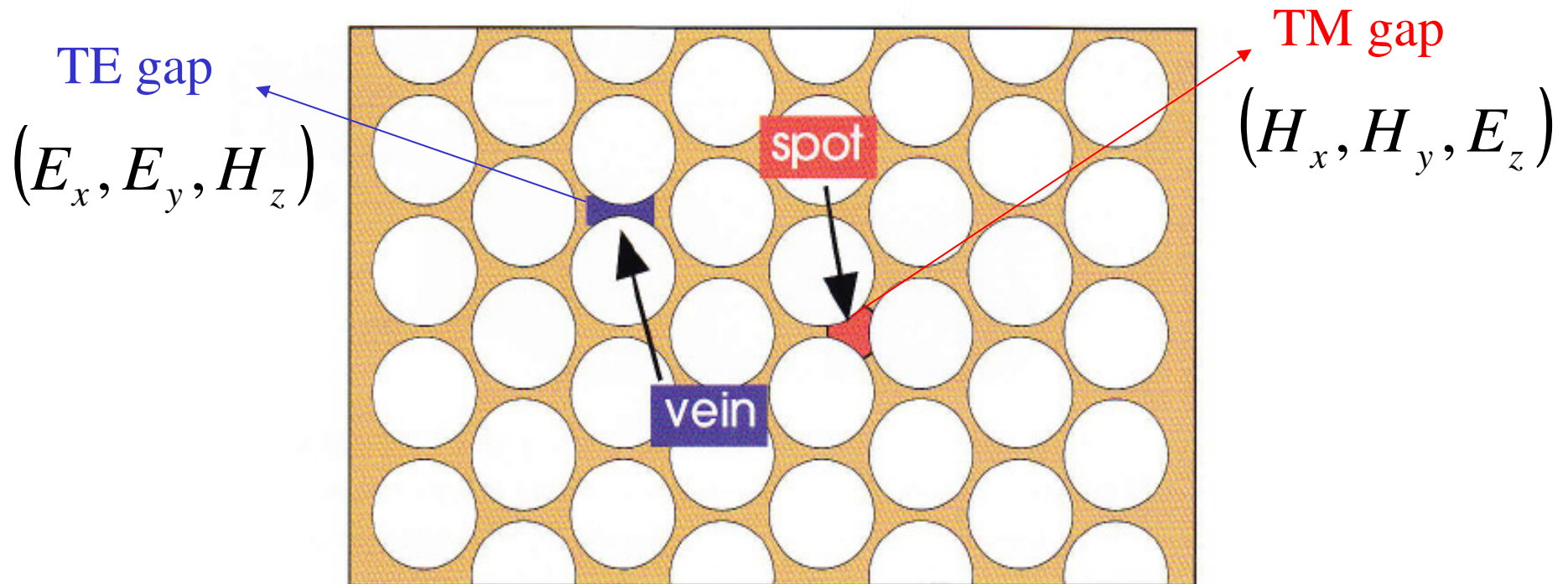


# Fotonica 3D

## Ricetta per un band gap completo: caso 2D



**Figure 9:** The spots and veins of a triangular lattice. Between the columns are narrow veins, connecting the spots surrounded by three columns.

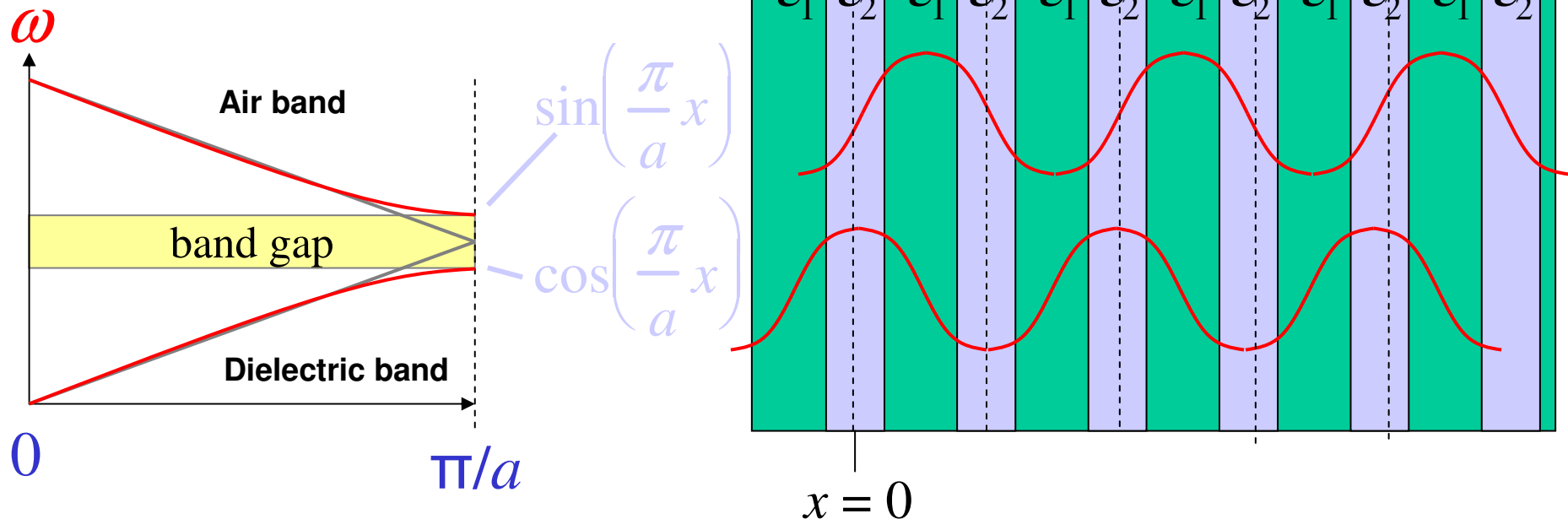
- Interconnessioni nella direzione di E
- Alto contrasto di indice

# Bang gap si apre al bordo della FBZ Richiamo esempio 1D

Aggiungiamo una  
piccola anisotropia

$$\varepsilon_2 = \varepsilon_1 + \Delta\varepsilon$$

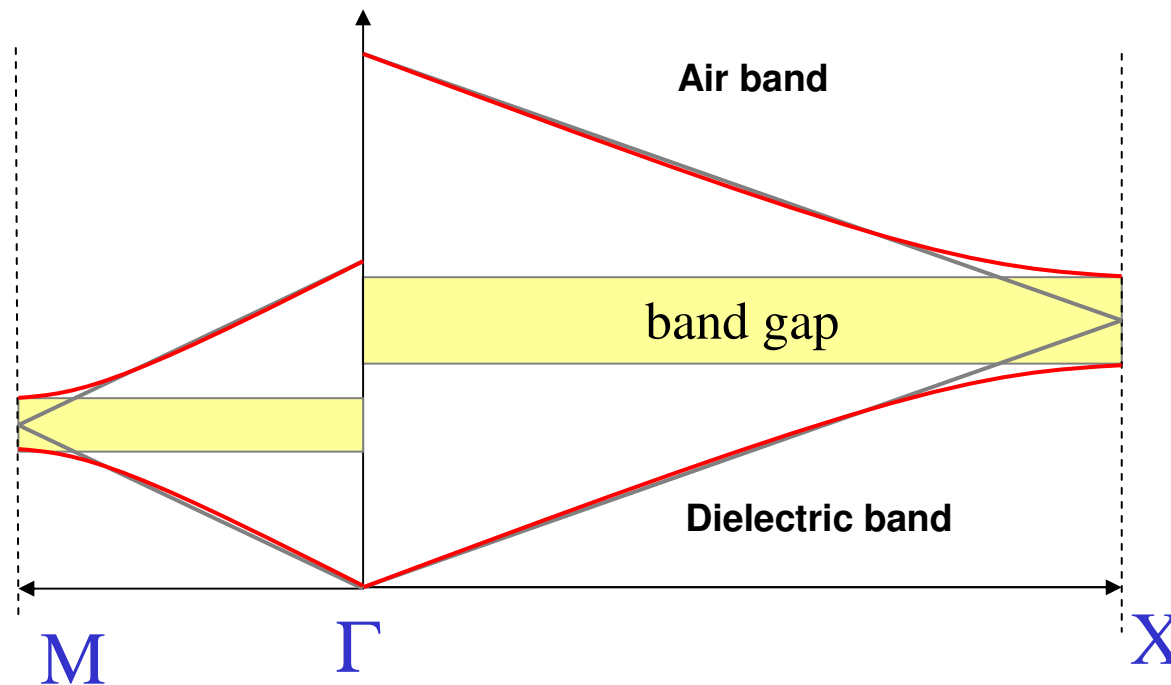
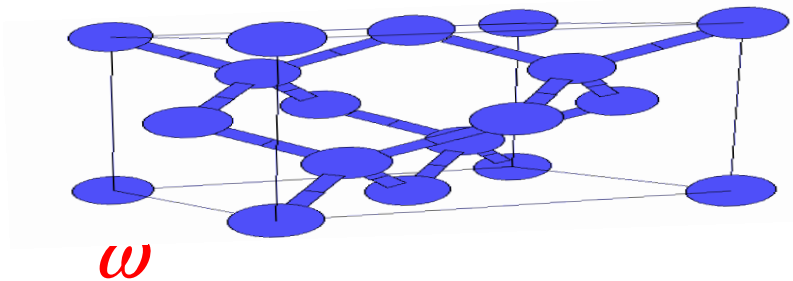
**Splitting** della degenerazione:  
state concentrated in **higher index** ( $\varepsilon_2$ )  
has **lower frequency**



## Band gap si apre al bordo della FBZ



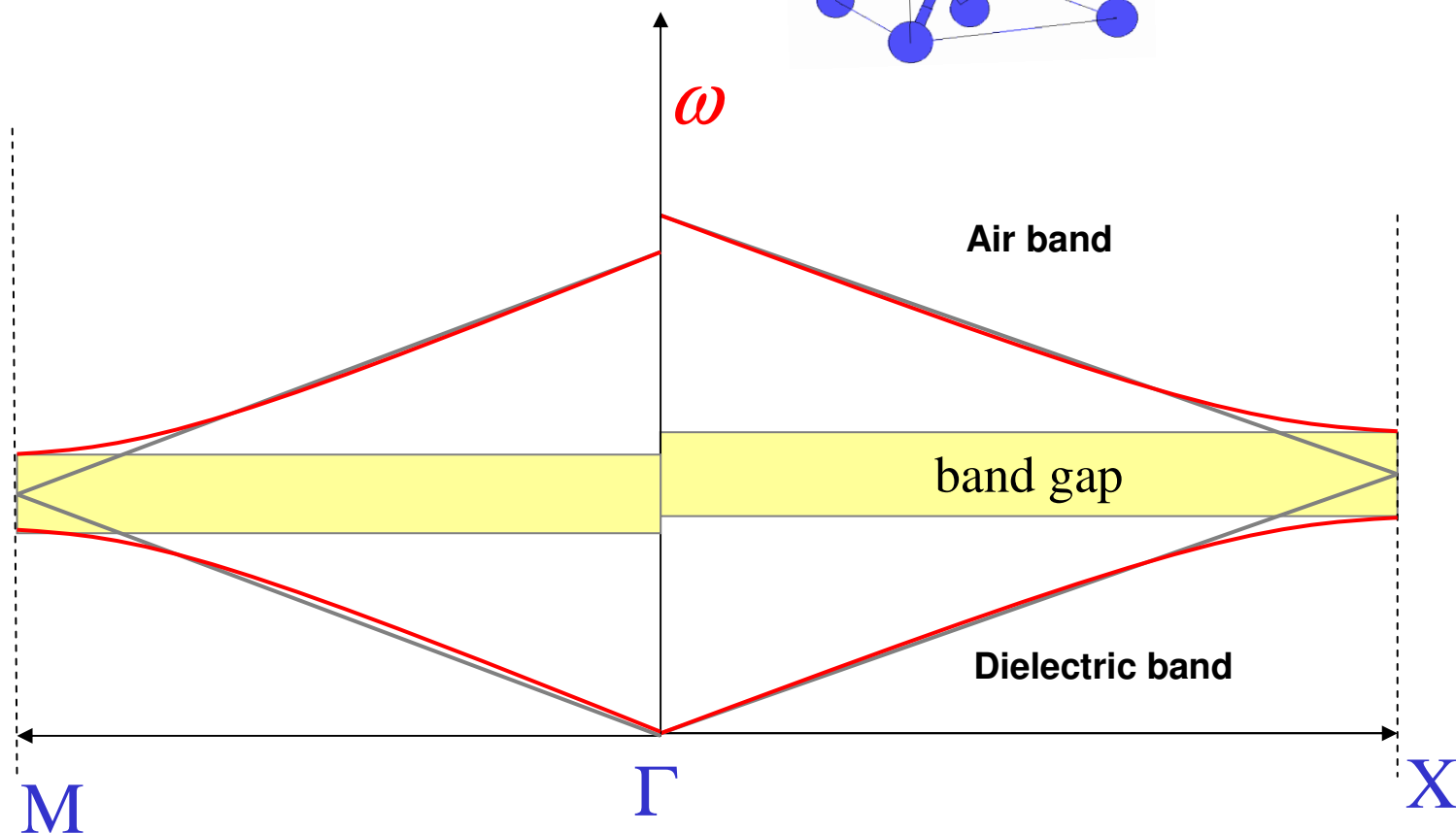
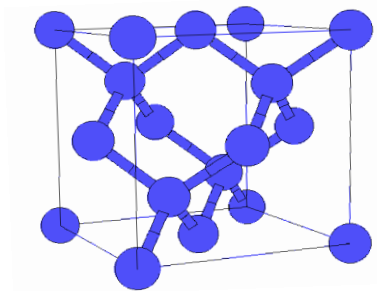
Se sistema anisotropo  
non c'è sovrapposizione  
di gap.



## Band gap si apre al bordo della FBZ



Se sistema isotropo  
c'è sovrapposizione di gap.




---

## Inhibited Spontaneous Emission in Solid-State Physics and Electronics

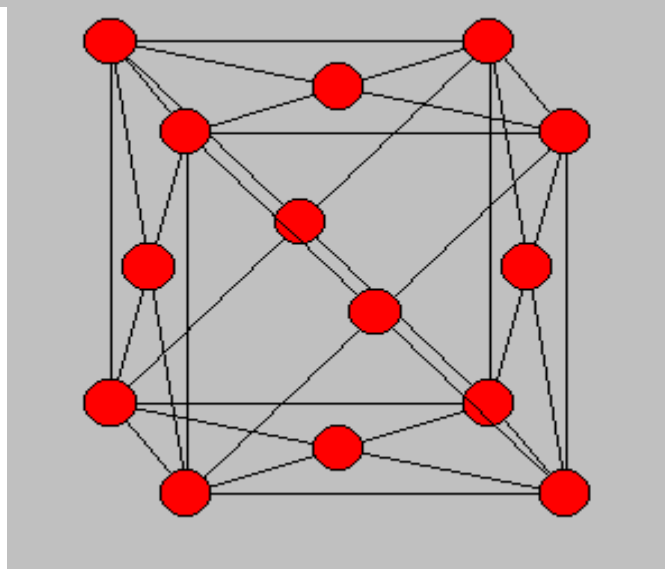
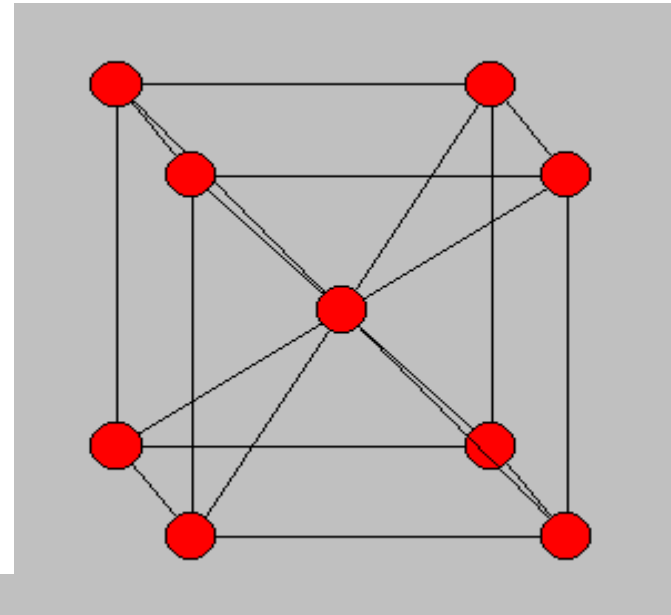
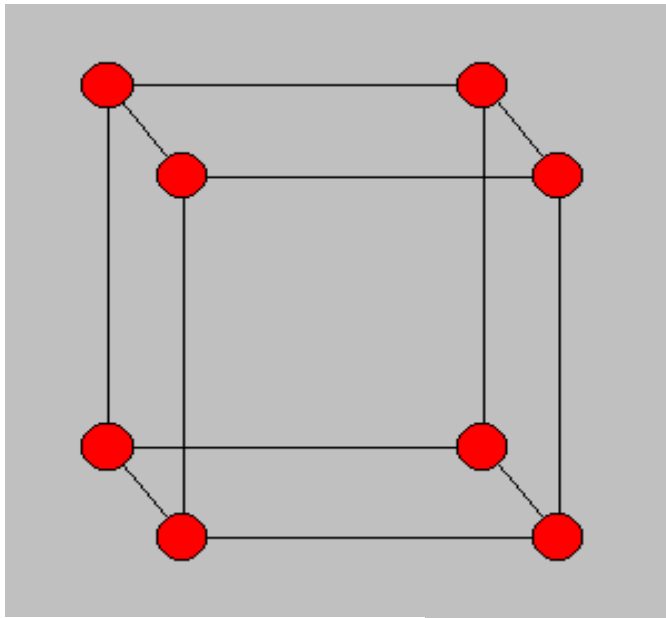
Eli Yablonovitch

*Bell Communications Research, Navesink Research Center, Red Bank, New Jersey 07701*

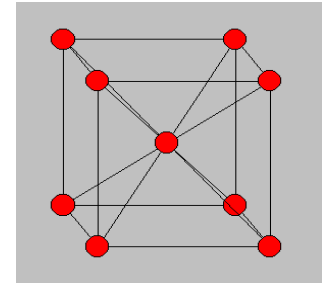
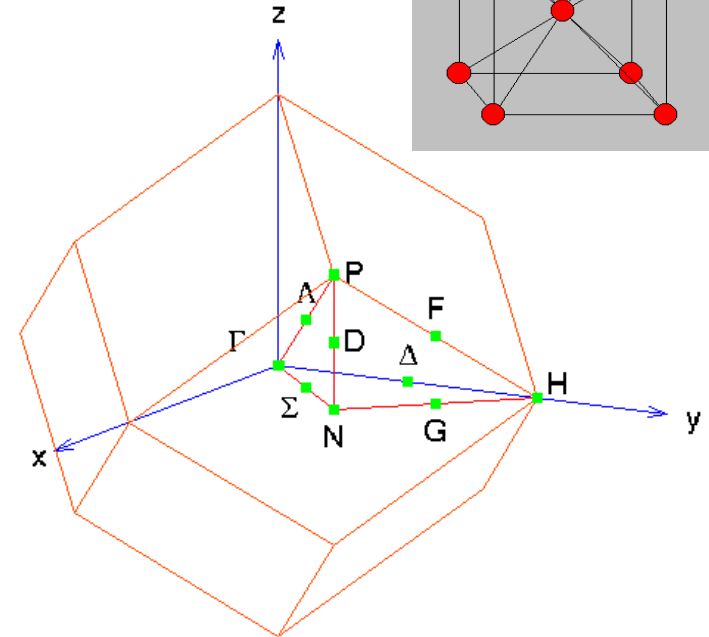
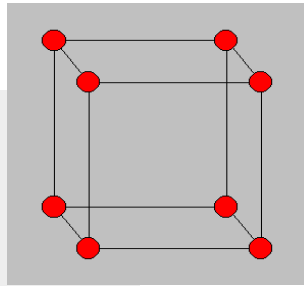
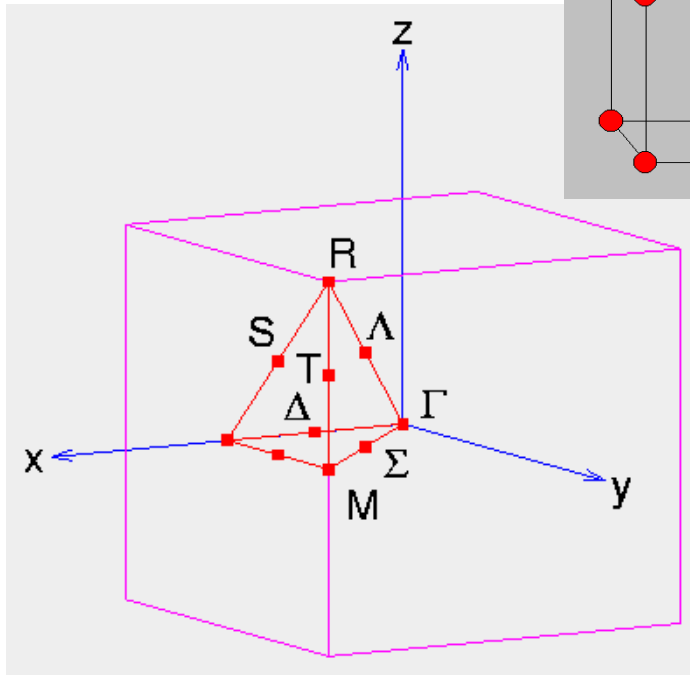
(Received 23 December 1986)

It has been recognized for some time that the spontaneous emission by atoms is not necessarily a fixed and immutable property of the coupling between matter and space, but that it can be controlled by modification of the properties of the radiation field. This is equally true in the solid state, where spontaneous emission plays a fundamental role in limiting the performance of semiconductor lasers, heterojunction bipolar transistors, and solar cells. If a three-dimensionally periodic dielectric structure has an  which overlaps the electronic *band edge*, then spontaneous emission can be rigorously forbidden.

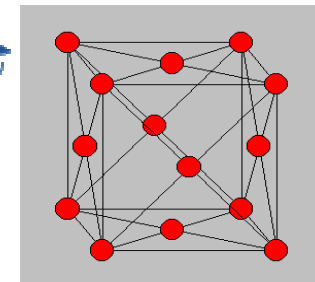
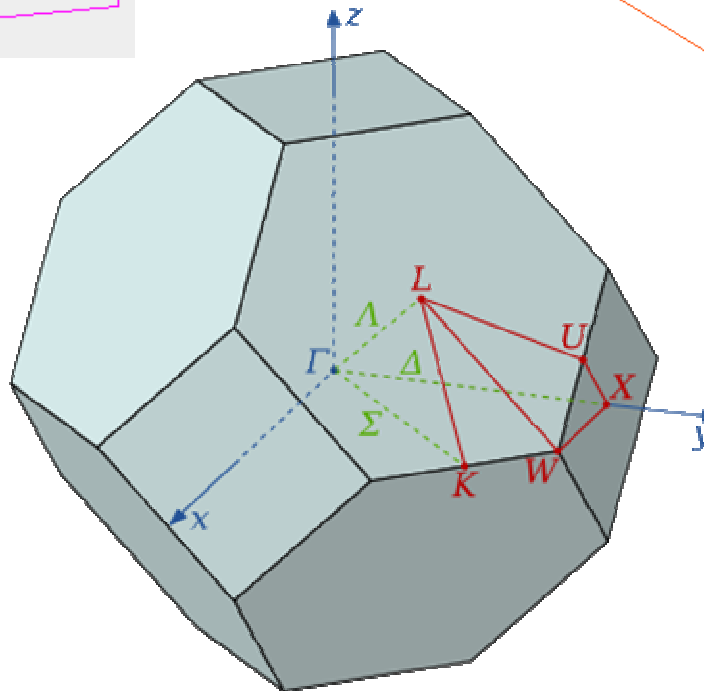
# Reticoli cubici



# FBZ



FCC ha FBZ  
più simmetrico





# FCC non ha PhC band gap

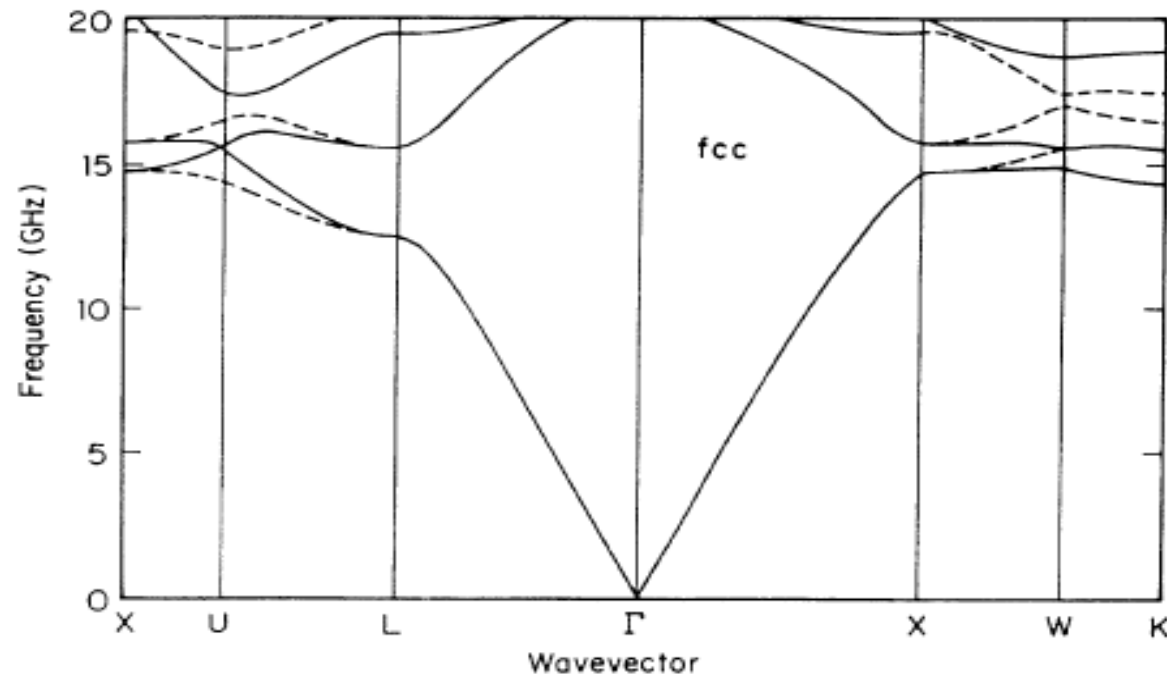
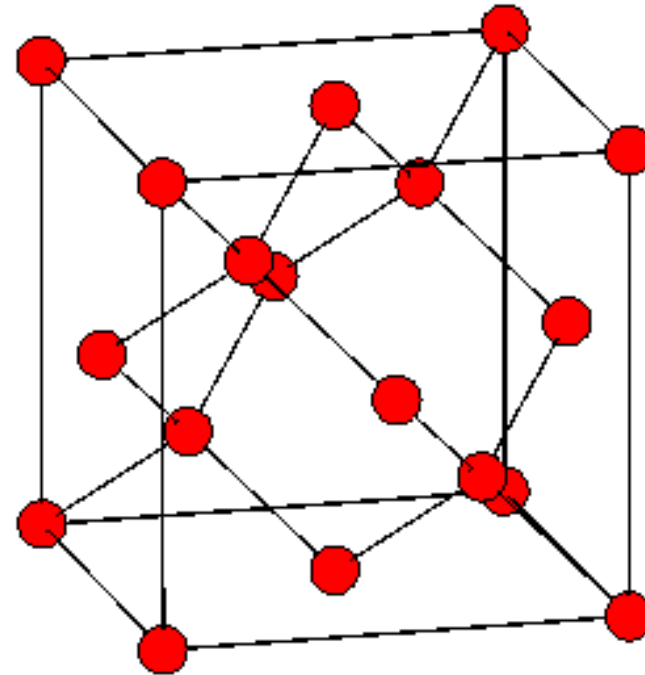
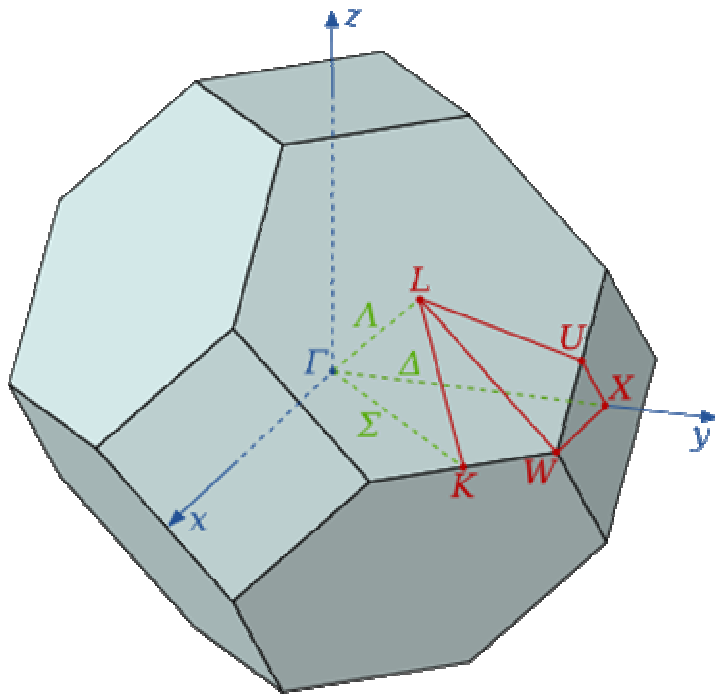


FIG. 1. Calculated photonic band structure along important symmetry lines in the Brillouin zone for a fcc dielectric structure composing of air spheres in a dielectric background of refractive index 3.5. The filling ratio is 86% air and 14% dielectric material. Along  $X$ - $U$ - $L$  and  $X$ - $W$ - $K$ , the dotted and solid lines indicate bands which couple only to  $s$  and  $p$  polarized light, respectively, in the experiment of Ref. 11.

# Diamond PhC with band gap



fcc (face-centered-cubic)  
with two “atoms” per unit cell.

- Same FBZ of fcc
- Closer packing

---

## Existence of a Photonic Gap in Periodic Dielectric Structures

K. M. Ho, C. T. Chan, and C. M. Soukoulis

*Ames Laboratory and Department of Physics, Iowa State University, Ames, Iowa 50011*

(Received 4 September 1990)

Using a plane-wave expansion method, we have solved Maxwell's equations for the propagation of electromagnetic waves in a periodic lattice of dielectric spheres (dielectric constant  $\epsilon_a$ ) in a uniform dielectric background ( $\epsilon_b$ ). Contrary to experiment, we find that fcc dielectric structures do not have a "photonic band gap" that extends throughout the Brillouin zone. However, we have determined that dielectric spheres arranged in the diamond structure do possess a full photonic band gap. This gap exists for refractive-index contrasts as low as 2.

# Diamante ha PhC band gap

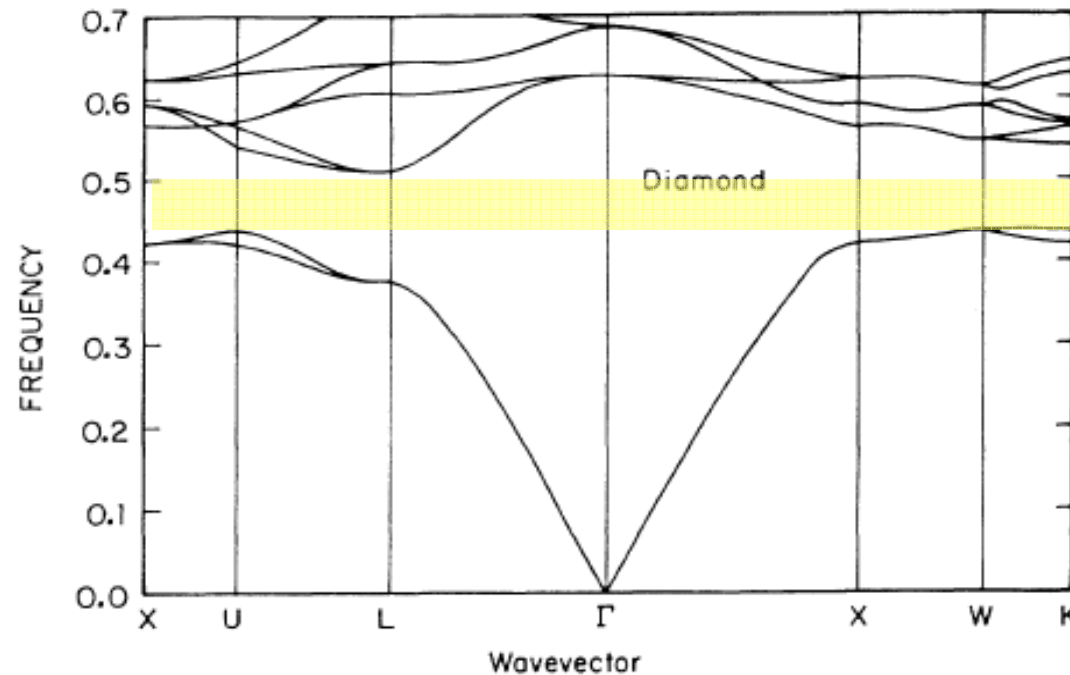
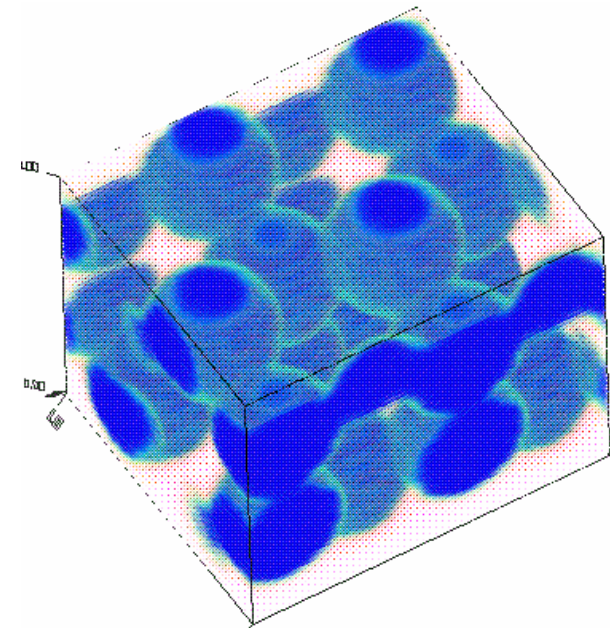


FIG. 2. Calculated photonic band structure for a diamond dielectric structure consisting of dielectric spheres of refractive index 3.6 in an air background. The filling ratio of the dielectric material is 34%. The frequency is given in units of  $c/a$ , where  $a$  is the cubic lattice constant of the diamond lattice.



overlapping Si spheres

# Diamante ha PhC band gap

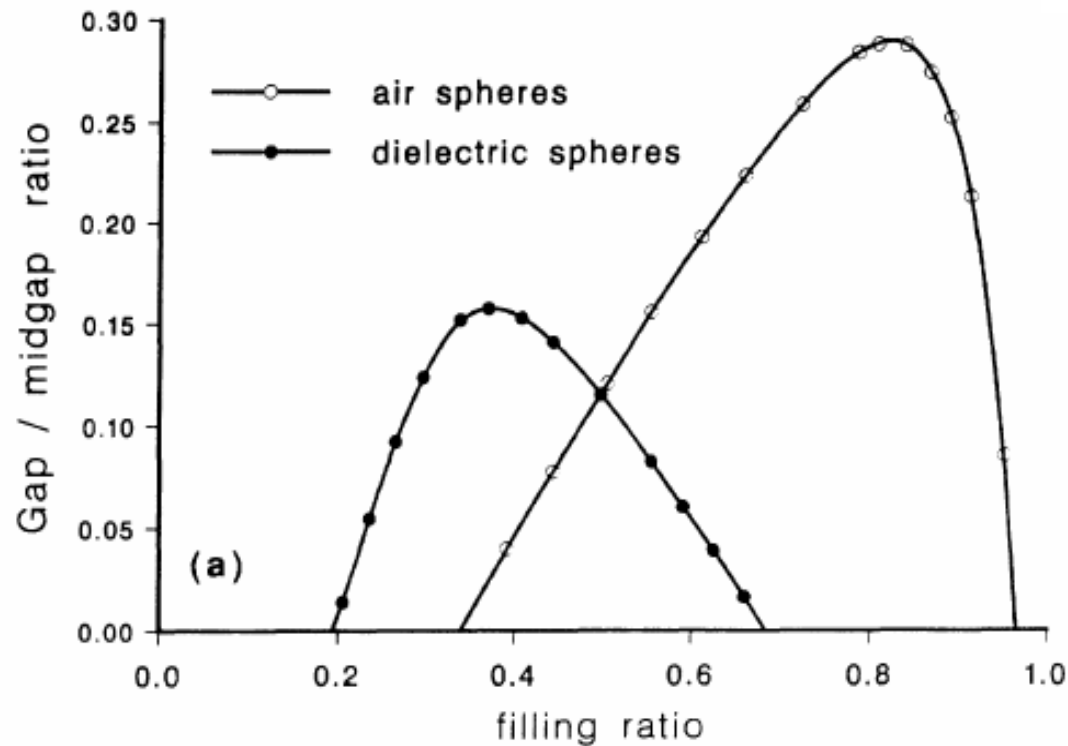
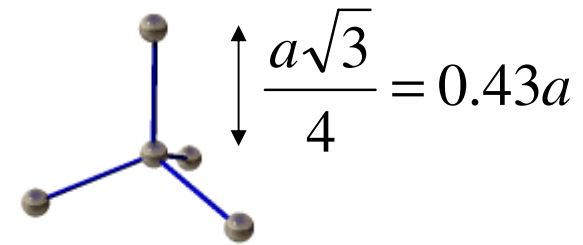


FIG. 3. (a) Gap to midgap frequency ratio ( $\Delta\omega/\omega_g$ ) as a function of filling ratio for the case of dielectric spheres in air and air spheres in dielectric. The refractive index of the material is chosen to be 3.6. (b)  $\Delta\omega/\omega_g$  as a function of refractive

# Diamante ha PhC band gap

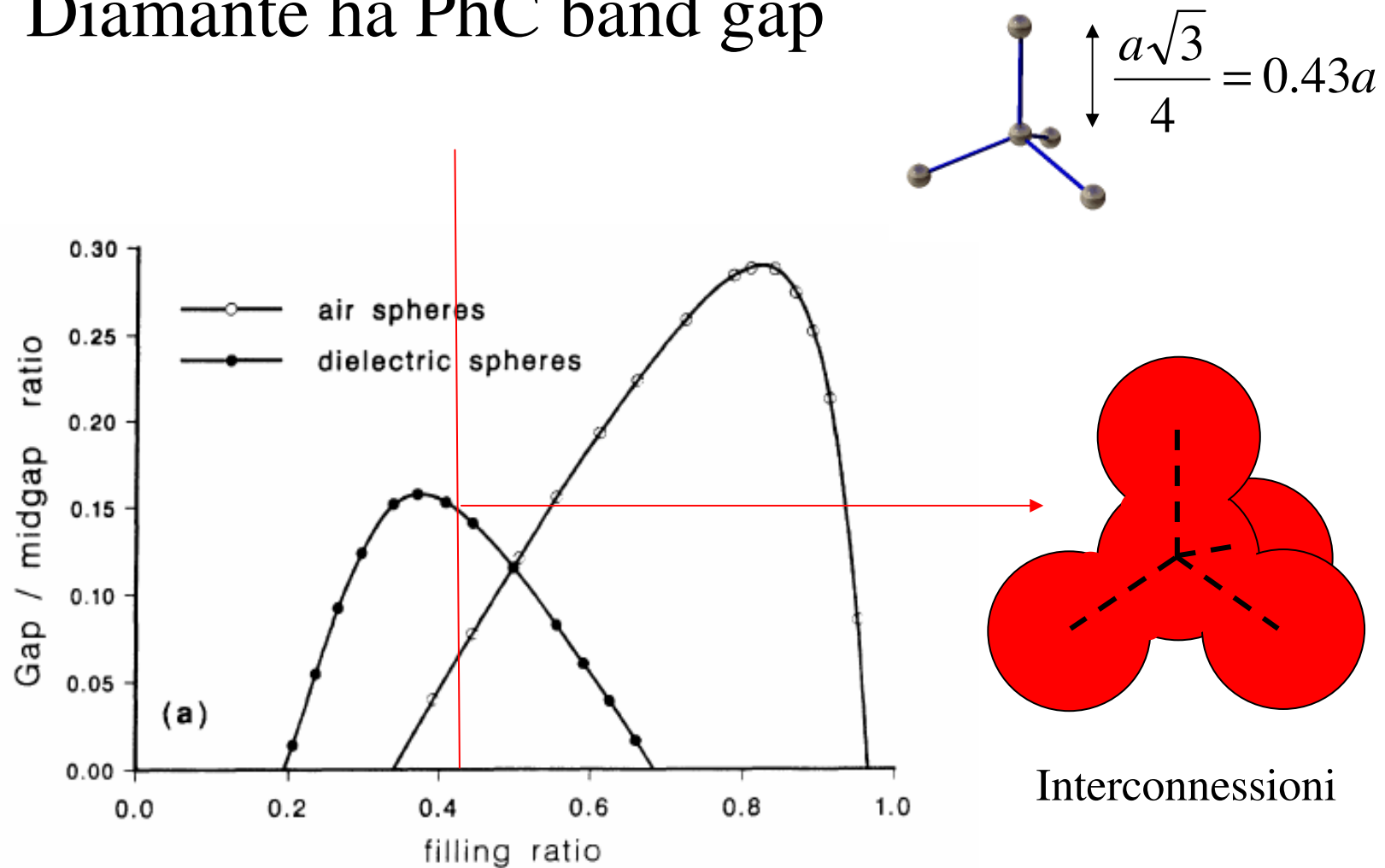
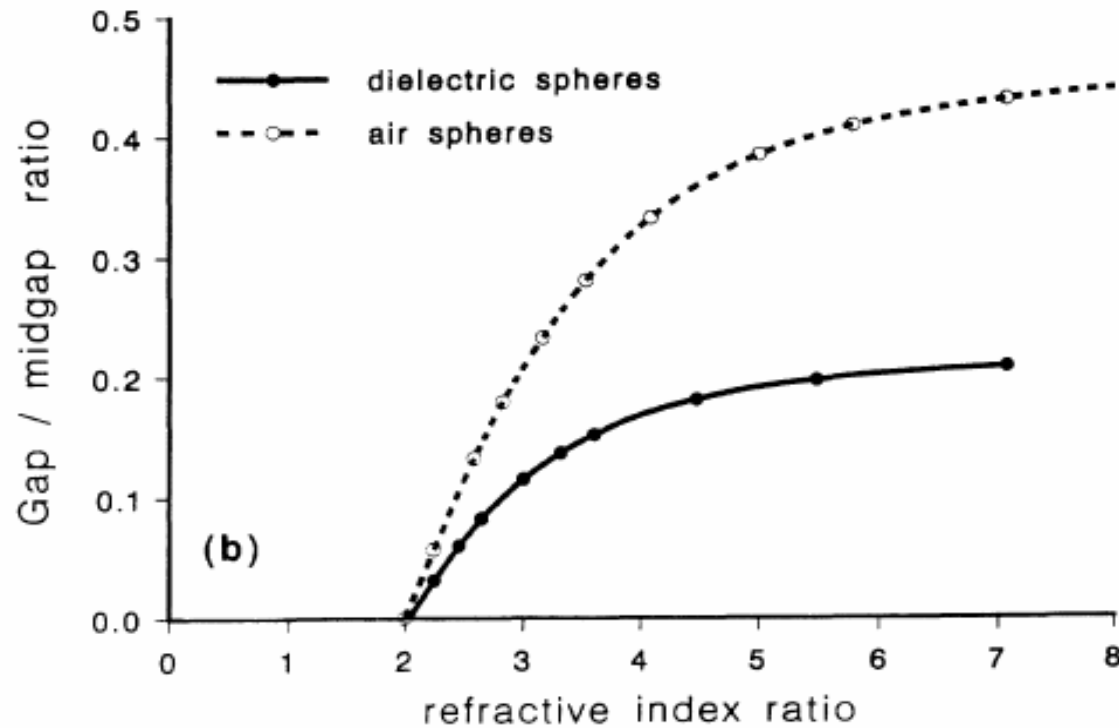
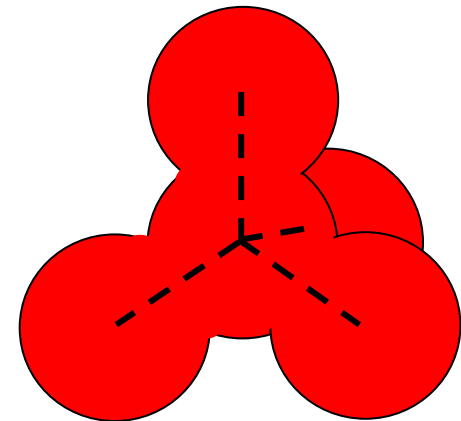


FIG. 3. (a) Gap to midgap frequency ratio ( $\Delta\omega/\omega_g$ ) as a function of filling ratio for the case of dielectric spheres in air and air spheres in dielectric. The refractive index of the material is chosen to be 3.6.

# Diamante ha PhC band gap



(b)  $\Delta\omega/\omega_g$  as a function of refractive index contrast for a fixed dielectric structure. The dotted line is for the case of air spheres in dielectric with a filling ratio of 81%, and the solid line is for dielectric spheres in air with a filling ratio of 34%.



## Regole generali per un PhC 3D

- PhC band gap è raro
- Per ogni reticolo c'è un valore di soglia del contrasto di indice sopra il quale si apre il gap
- Soglia inferiore se sistema ha FBZ poco isotropa
- Il gap cresce con il contrasto
- Esistono valori ottimali (raggio sfere, lunghezza tubi).

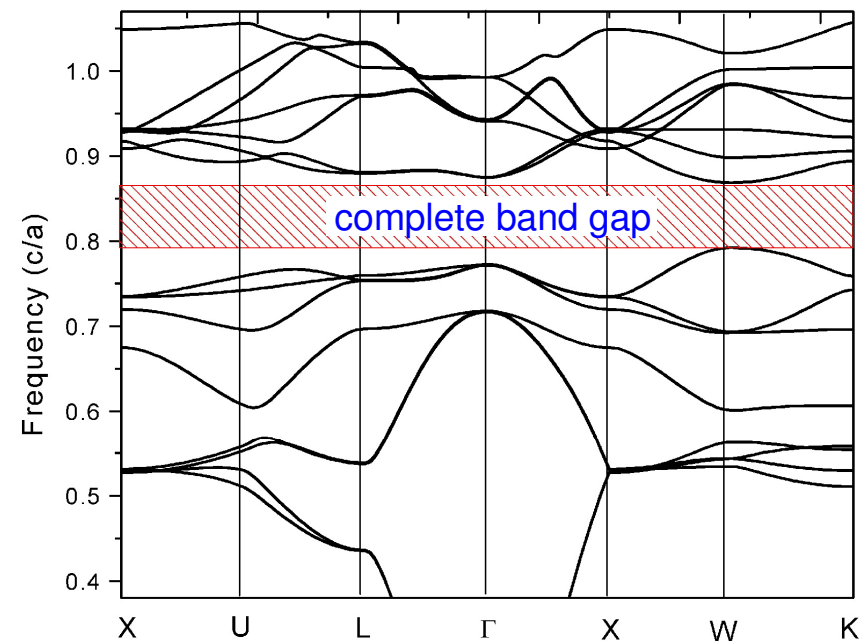
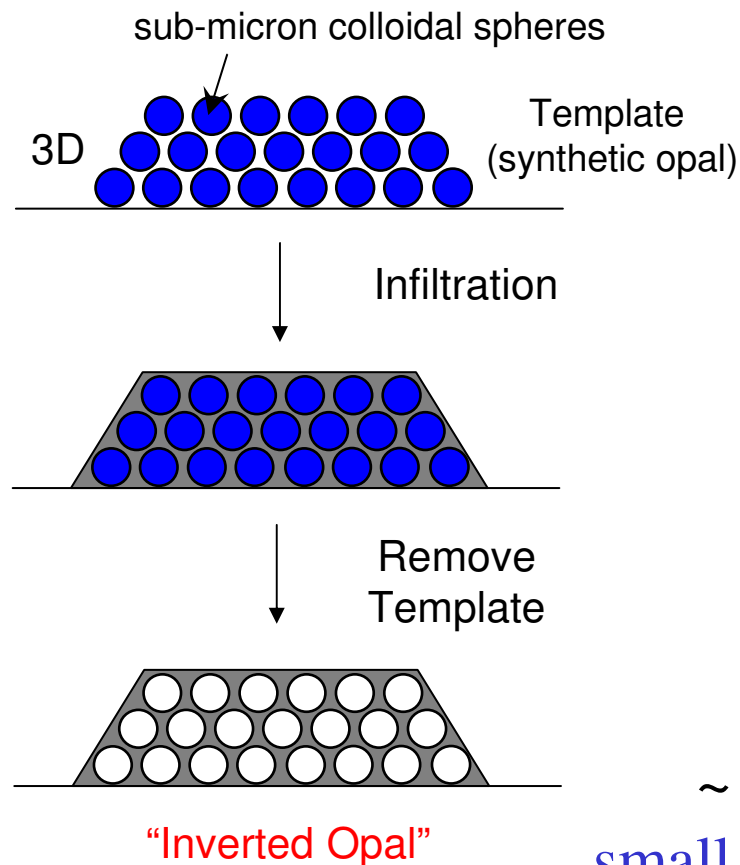


[ figs courtesy  
D. Norris, UMN ]

# Inverse Opals

fcc solid spheres do not have a gap...

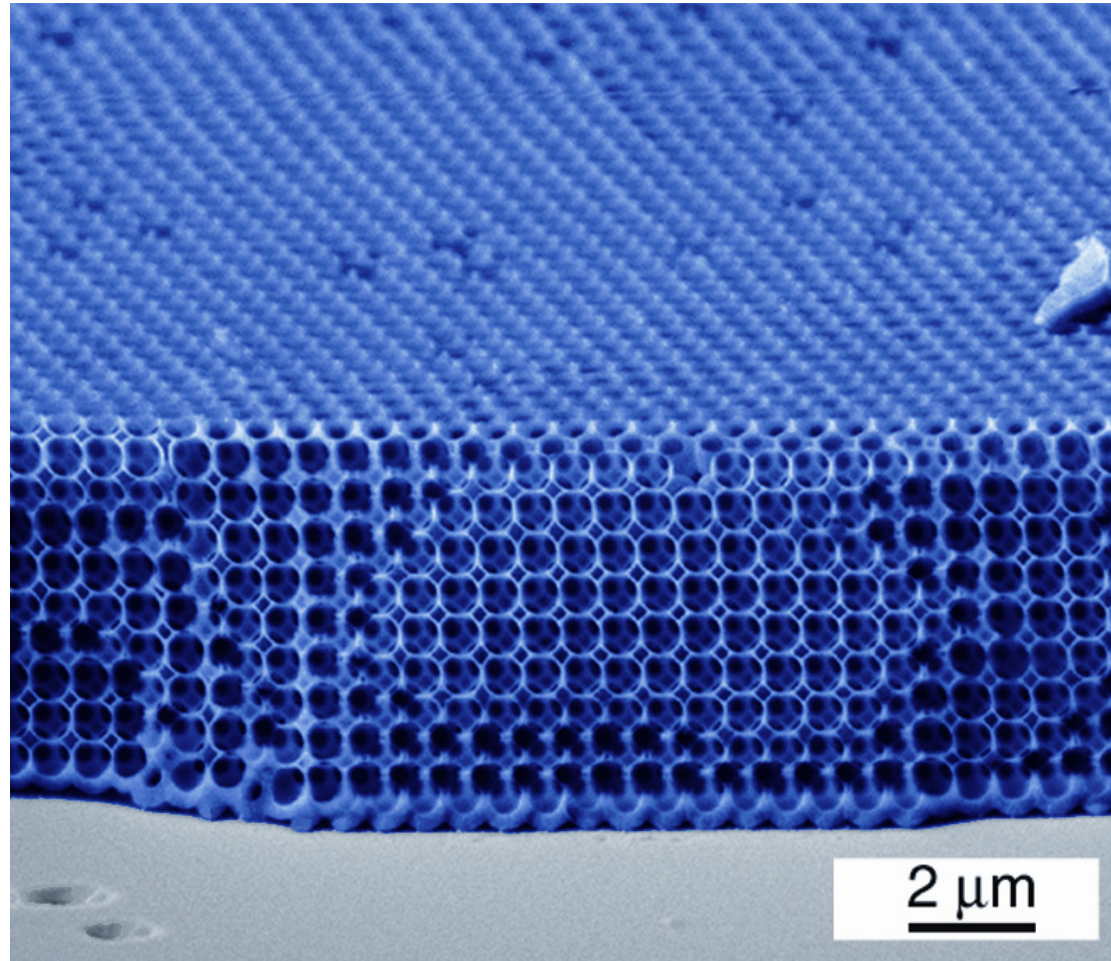
...but fcc spherical **holes in Si *do* have a gap**



~ **10% gap** between 8th & 9th bands  
small gap, **upper bands**: sensitive to disorder

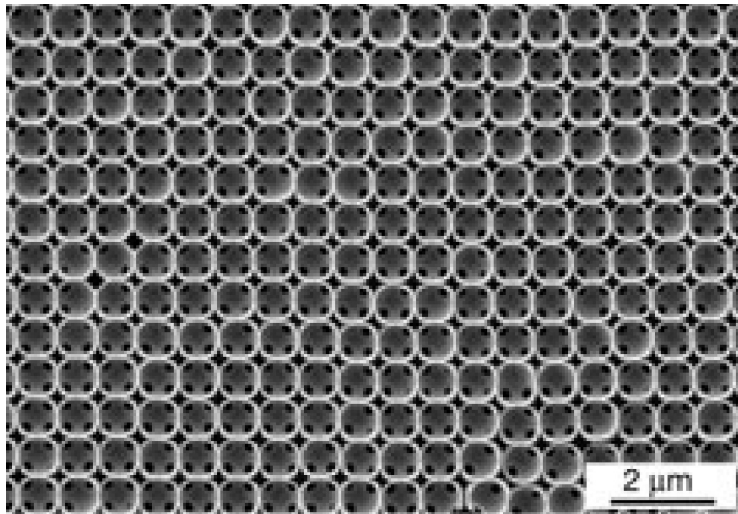
# Inverse-Opal Photonic Crystal

[ fig courtesy  
D. Norris, UMN ]

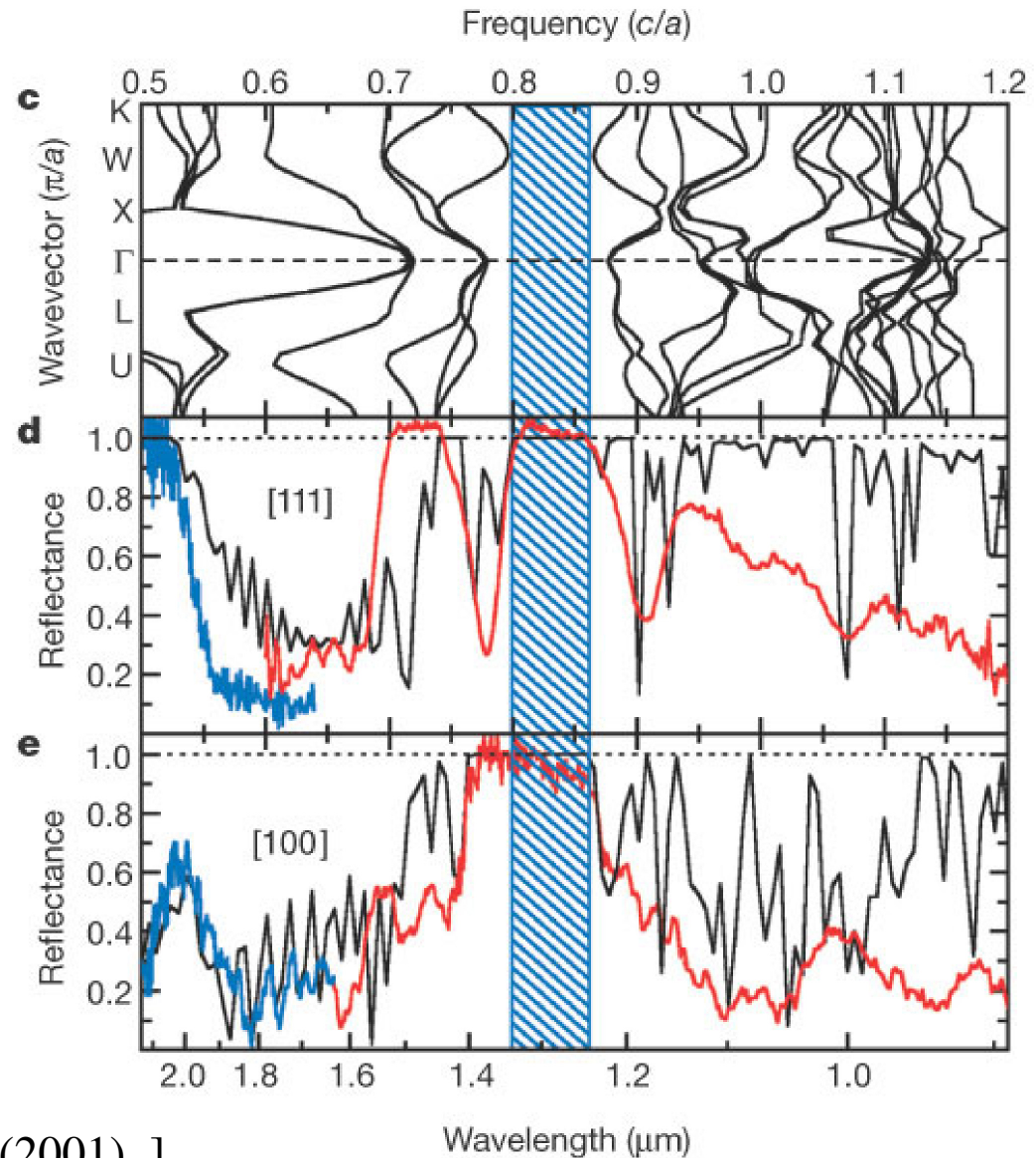


[ Y. A. Vlasov *et al.*, *Nature* **414**, 289 (2001). ]

# Inverse-Opal Band Gap



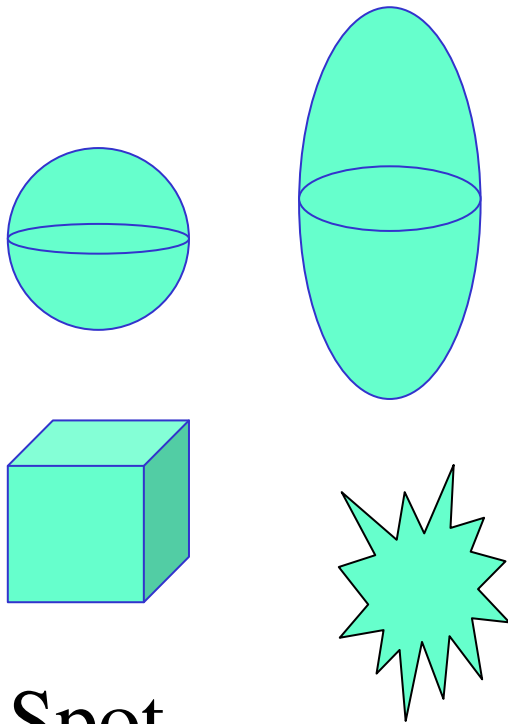
good agreement  
between **theory** (black)  
& **experiment** (red/blue)



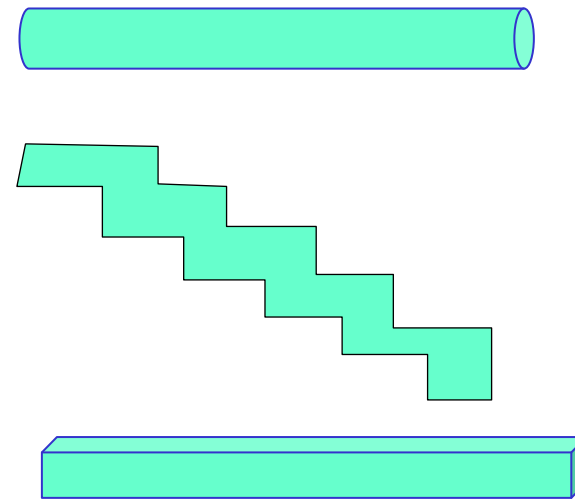
[ Y. A. Vlasov *et al.*, *Nature* **414**, 289 (2001). ]

# Elementi unitari per un PhC 3D

Molti gradi di libertà



Spot



Vein

## Photonic Band Structure: The Face-Centered-Cubic Case Employing Nonspherical Atoms

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*Bell Communications Research, Navesink Research Center, Red Bank, New Jersey 07701-7040*

K. M. Leung

*Department of Physics, Polytechnic University, Brooklyn, New York 11201*

(Received 26 December 1990)

We introduce a practical, new, face-centered-cubic dielectric structure which simultaneously solves two of the outstanding problems in photonic band structure. In this new "photonic crystal" the atoms are nonspherical, lifting the degeneracy at the  $W$  point of the Brillouin zone, and permitting a full photonic band gap rather than a pseudogap. Furthermore, this fully three-dimensional fcc structure lends itself readily to microfabrication on the scale of optical wavelengths. It is created by simply drilling three sets of holes  $35.26^\circ$  off vertical into the top surface of a solid slab or wafer, as can be done, for example, by chemical-beam-assisted ion etching.

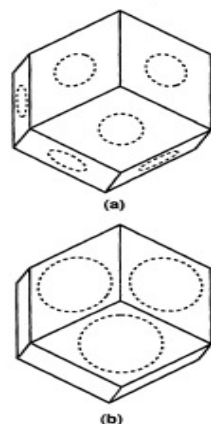


FIG. 1. The Wigner-Seitz real-space unit cell of the fcc lattice is a rhombic dodecahedron. In Ref. [8], slightly oversized spherical voids were inscribed into the unit cell, breaking through the faces, as illustrated by the dashed lines in (a). The current structure, shown in (b), is nonspherical. Cylindrical holes are drilled through the top three facets of the rhombic dodecahedron and exit through the bottom three facets. The resulting atoms are roughly cylindrical, and have a preferred axis in the vertical direction.

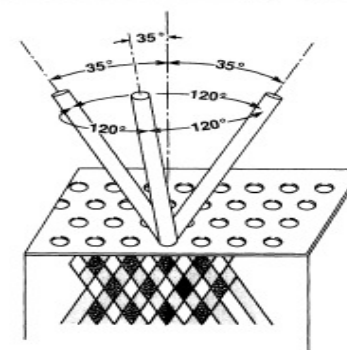
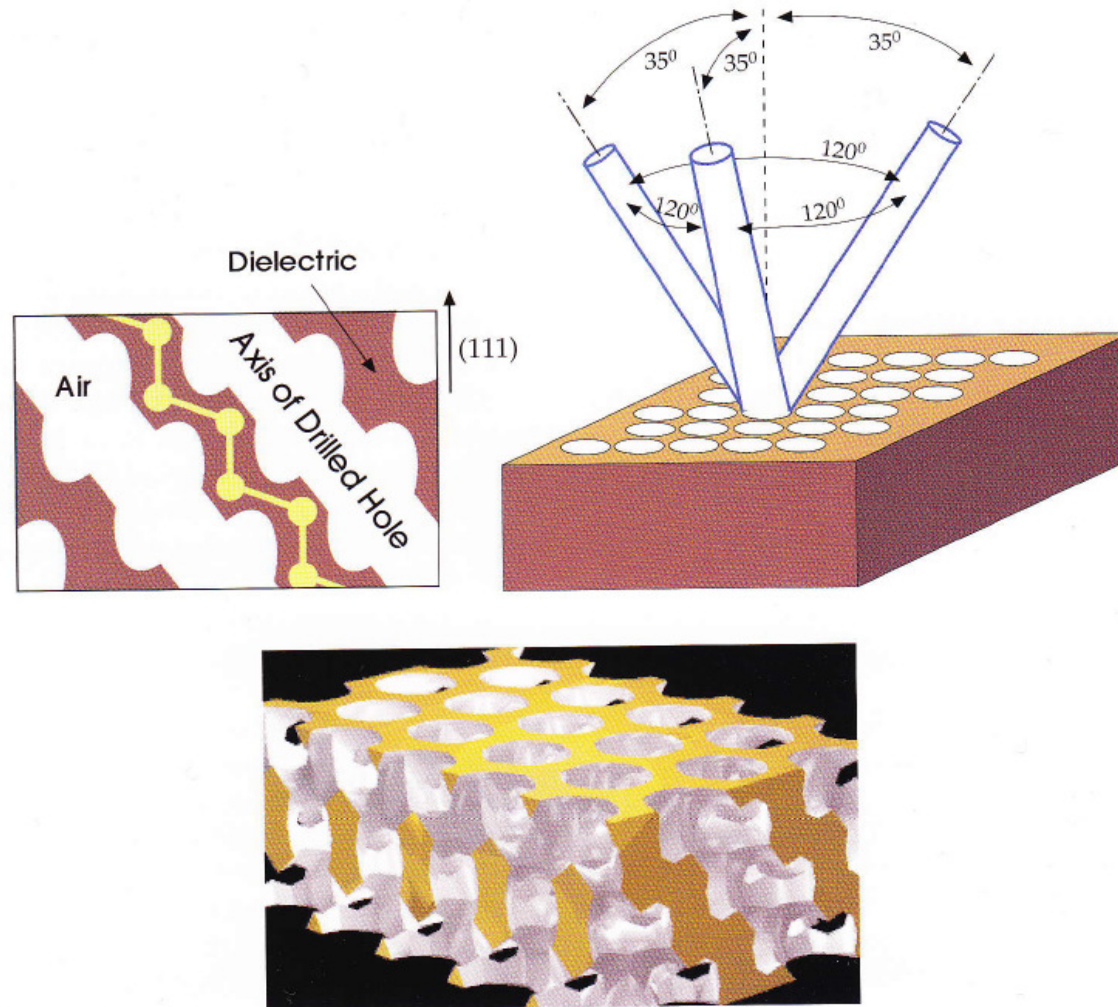


FIG. 2. The method of constructing an fcc lattice of the Wigner-Seitz cells as shown in Fig. 1(b). A slab of material is covered by a mask consisting of a triangular array of holes. Each hole is drilled through 3 times, at an angle  $35.26^\circ$  away from normal, and spread out  $120^\circ$  on the azimuth. The resulting crisscross of holes below the surface of the slab, suggested by the cross hatching shown here, produces a fully three-dimensionally periodic fcc structure, with unit cells as given by Fig. 1(b). The drilling can be done by a real drill bit for microwave work, or by reactive ion etching to create an fcc structure at optical wavelengths.

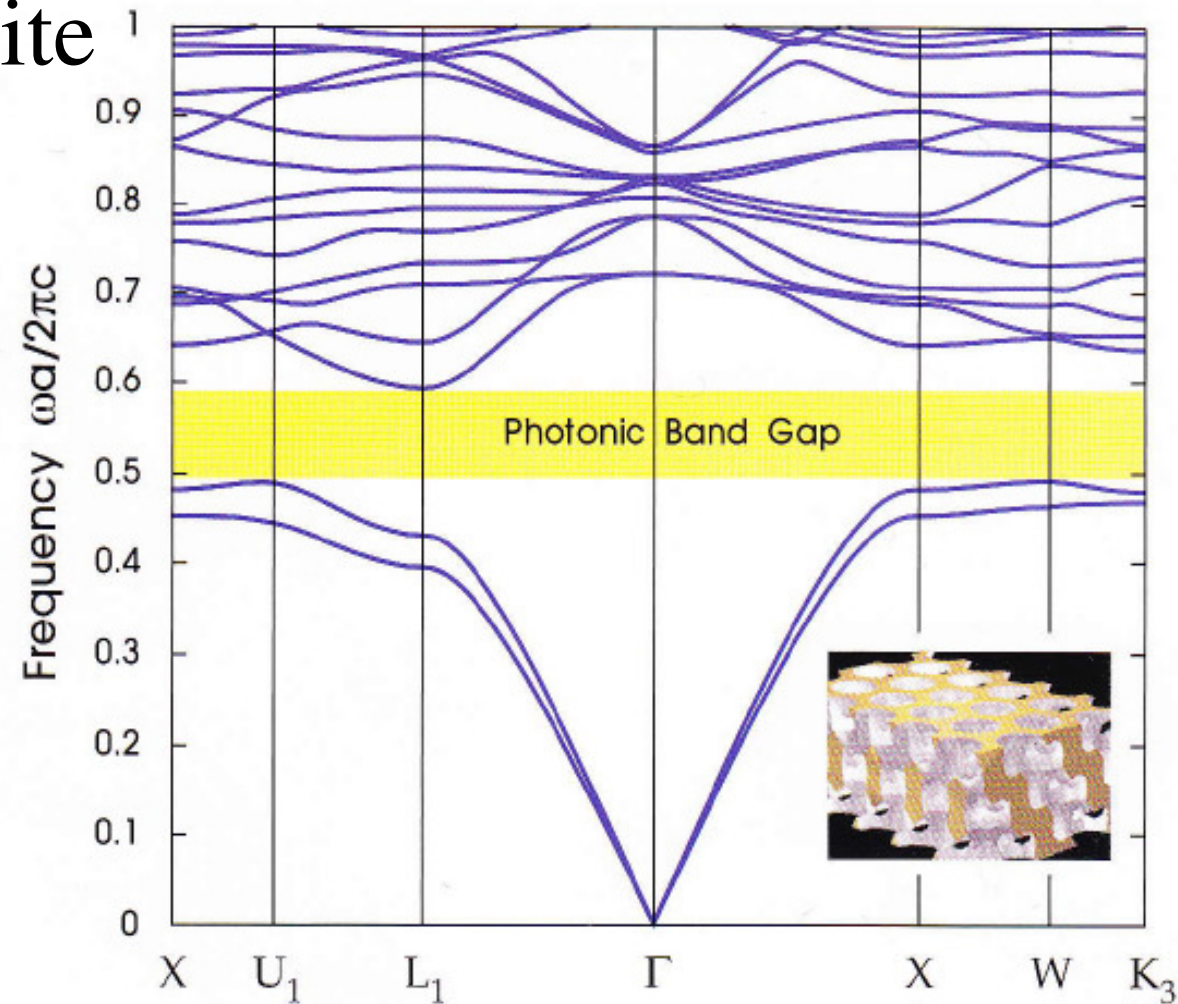


# Yablonovite



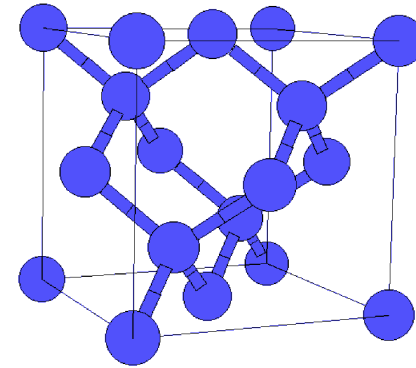
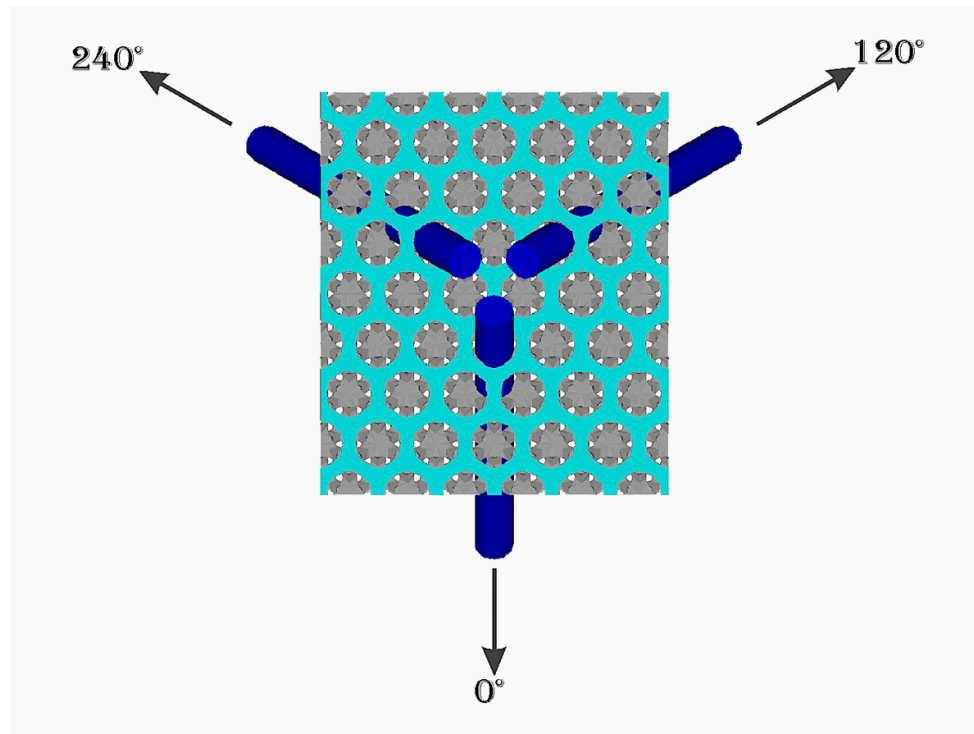
**Figure 4:** The method for constructing Yablonovite: a slab of dielectric is covered by a mask consisting of a triangular array of holes. Each hole is drilled three times (right), at an angle of  $35.26^\circ$  away from the normal and spread out  $120^\circ$  on the azimuth. This results in a three-dimensional structure whose  $(1\bar{1}0)$  cross section is shown on the left. The dielectric connects the sites of a diamond lattice, shown schematically in yellow. The dielectric veins oriented vertically  $[111]$  have greater width than those oriented diagonally  $[11\bar{1}]$ . *Bottom:* computer rendering of the structure (image courtesy E. Yablonovitch).

# Yablonovite

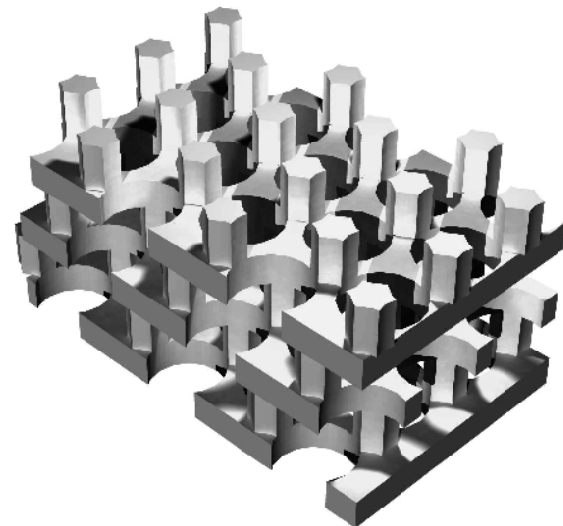


**Figure 5:** The photonic band structure for the lowest bands of Yablonovite (inset, from figure 4). Wave vectors are shown for a portion of the irreducible Brillouin zone that includes the edges of the complete gap (yellow). A detailed discussion of this band structure can be found in Yablonovitch et al. (1991a).

# New diamond-like fcc crystal

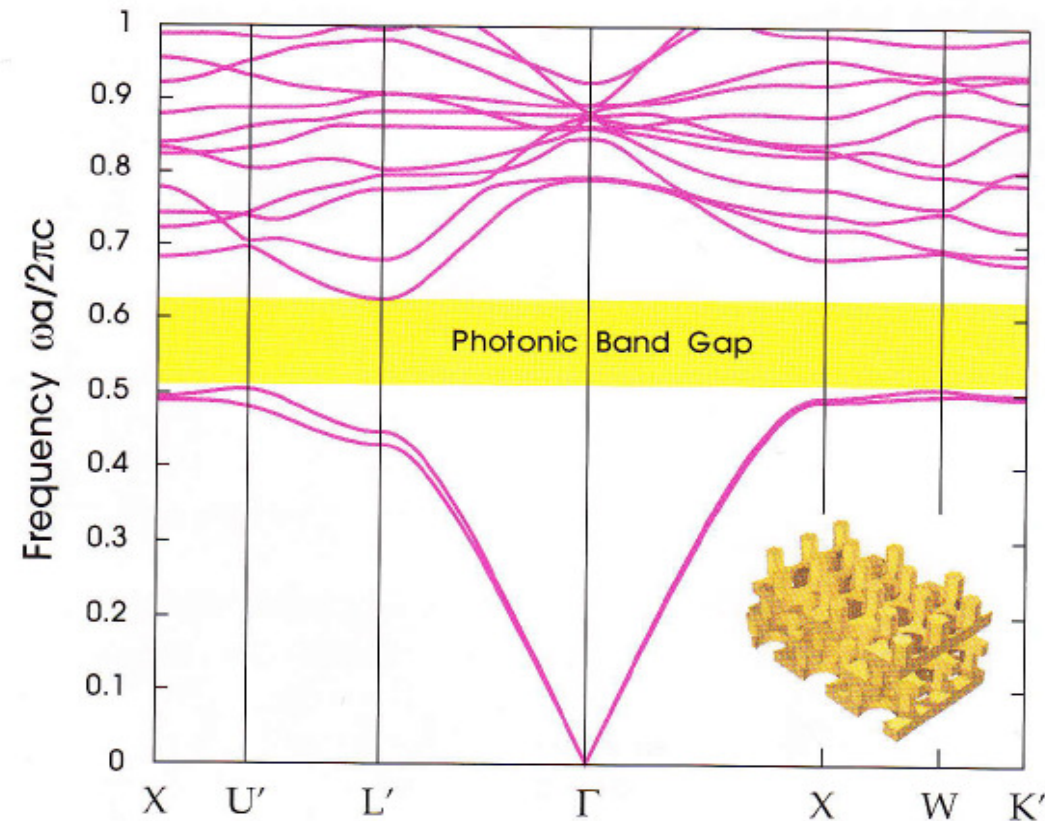


(Topology is very similar to 2000 layer-by-layer crystal)



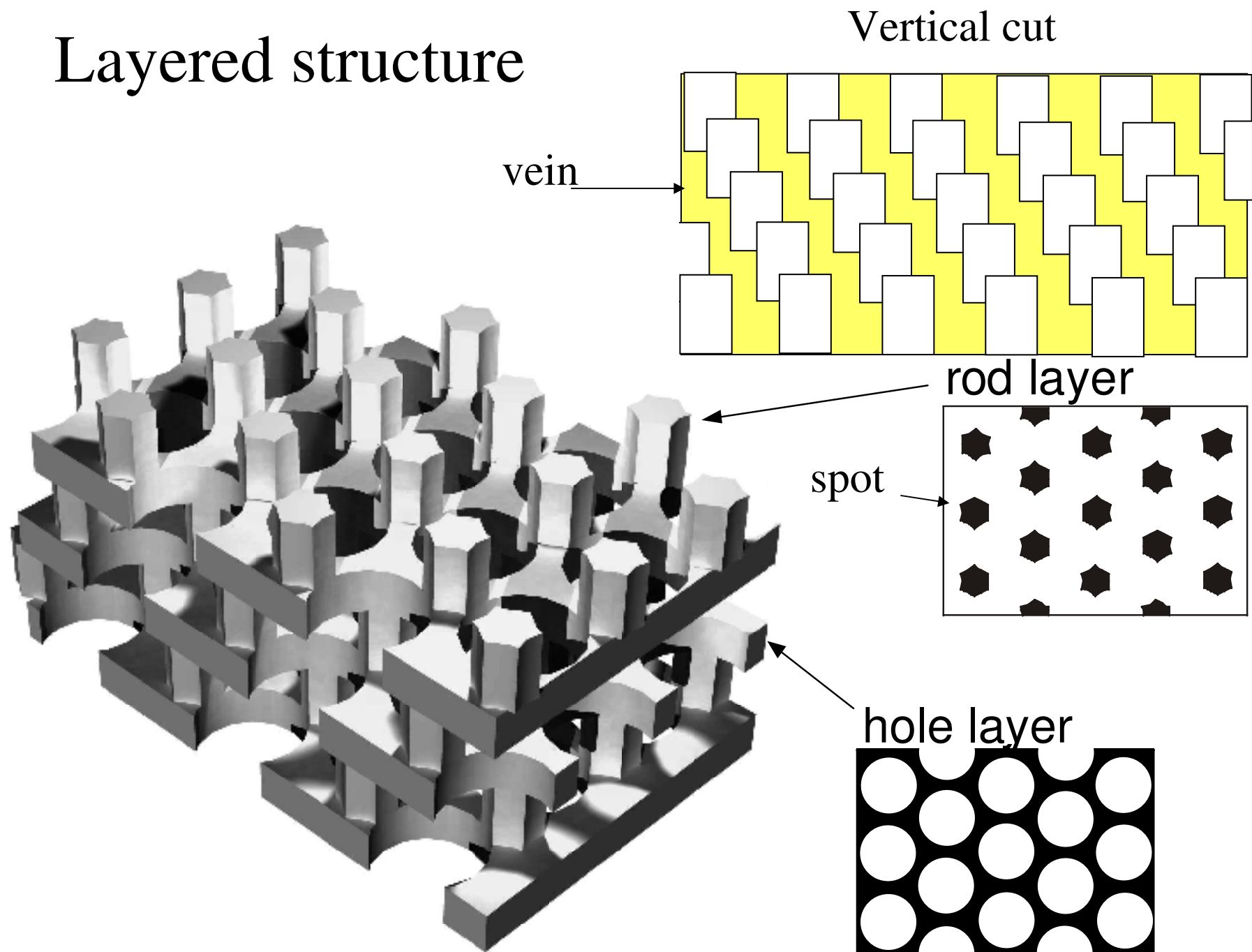


# New diamond-like fcc crystal



**Figure 11:** The photonic band structure for the lowest bands of the layered structure from figure 10 (inset). The irreducible Brillouin zone is larger than that of the fcc lattice described in appendix B, because of reduced symmetry—only a portion is shown, including the edges of the complete photonic band gap (yellow). A more detailed discussion of this band structure can be found in Johnson and Joannopoulos (2000).

# Layered structure



# Layer-by-Layer Lithography

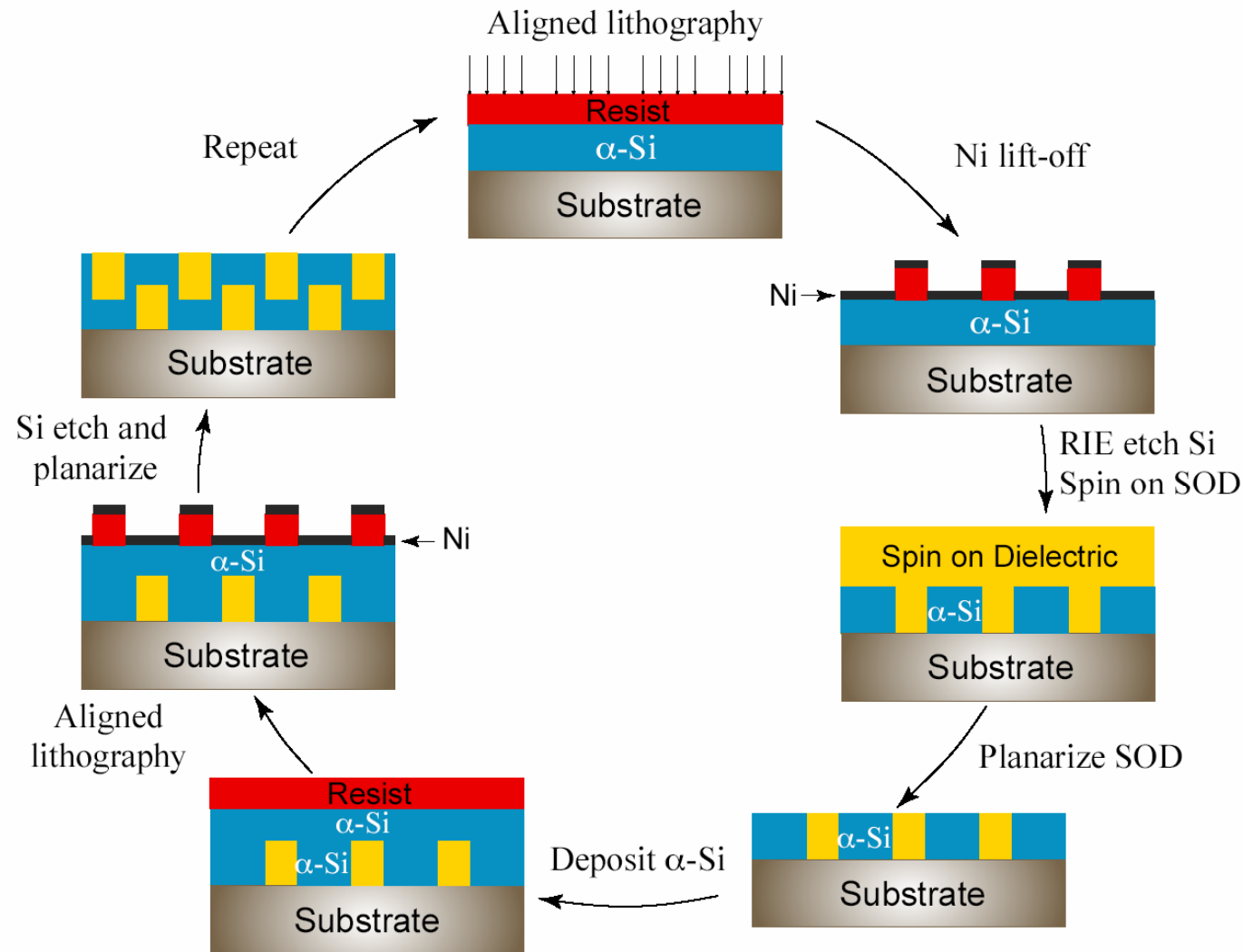
- Fabrication of 2d patterns in Si or GaAs is very advanced  
(think: Pentium IV, 50 million transistors)

...inter-layer alignment techniques are only slightly more exotic

So, make 3d structure one layer at a time

Need a 3d crystal with constant cross-section layers

# A More Realistic Schematic

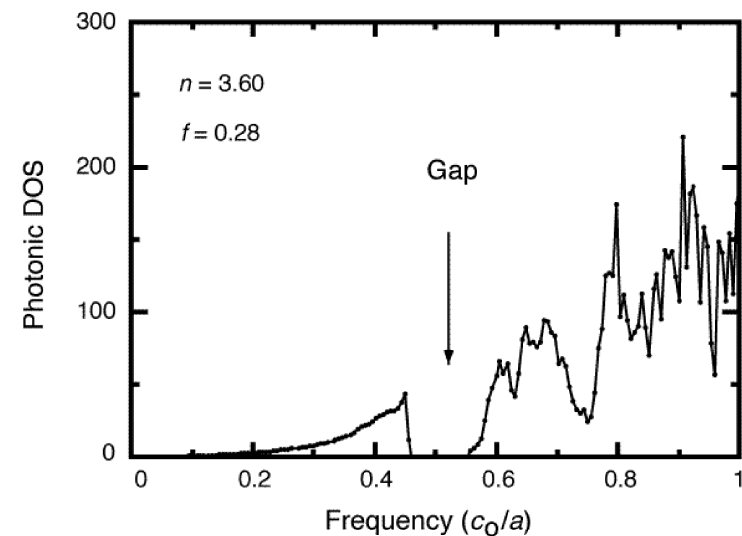
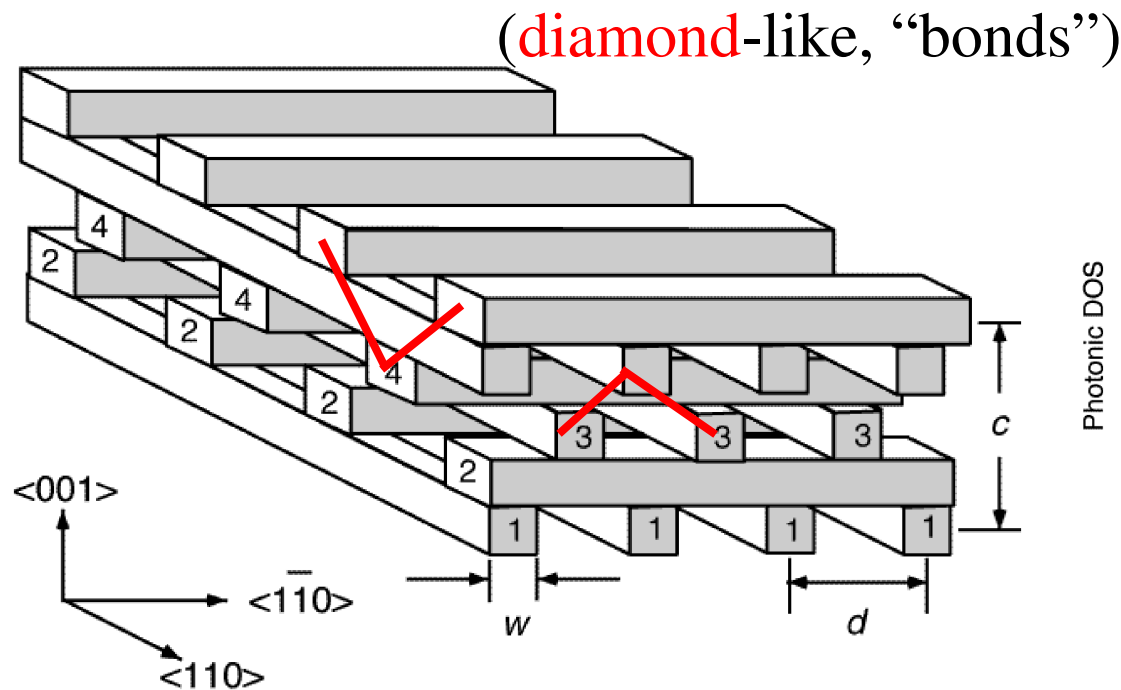


[ M. Qi, H. Smith, MIT ]

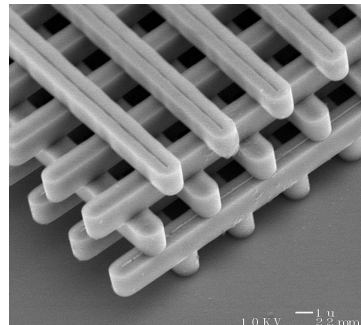
an earlier design:  
(& currently more popular)

# The Woodpile Crystal

[ K. Ho *et al.*, *Solid State Comm.* **89**, 413 (1994) ] [ H. S. Sözüer *et al.*, *J. Mod. Opt.* **41**, 231 (1994) ]

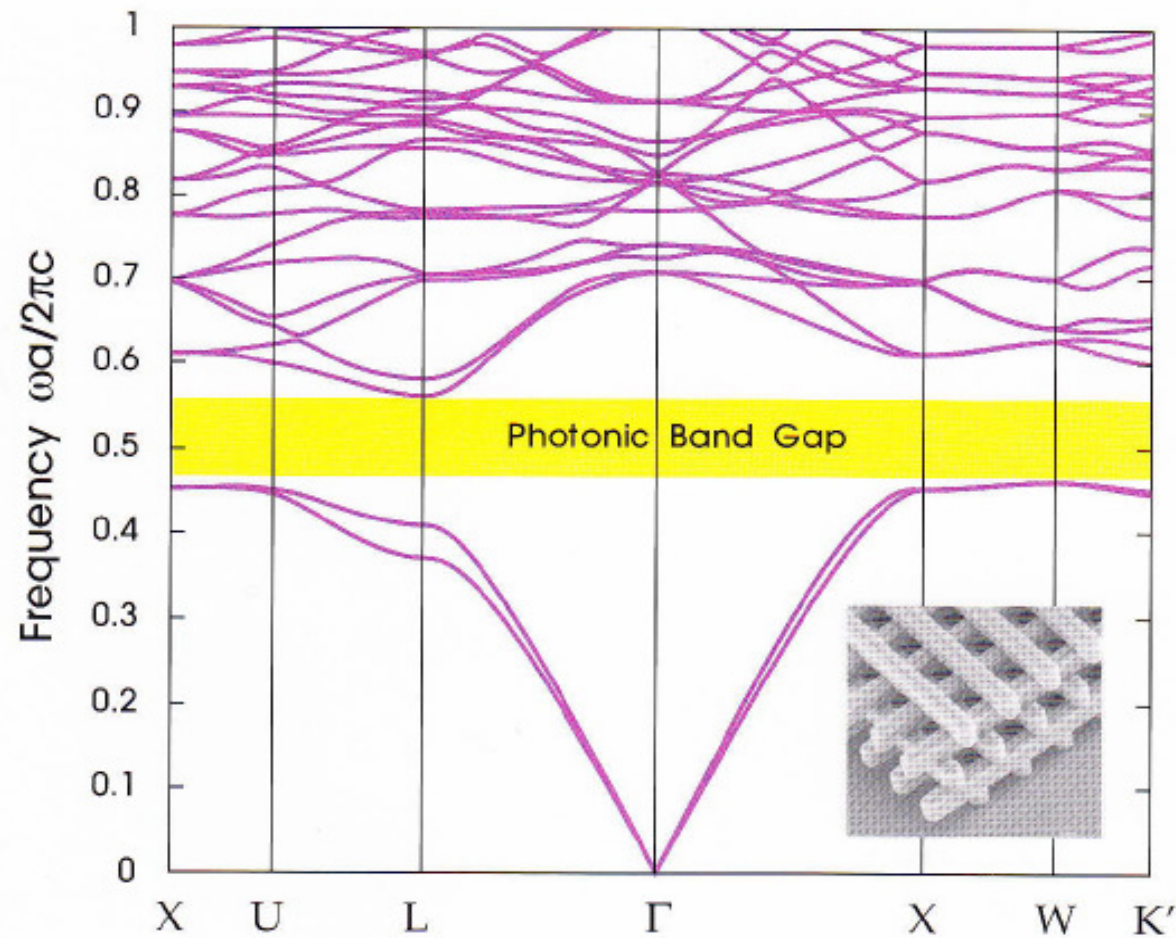


Up to ~ **17% gap** for Si/air



[ Figures from S. Y. Lin *et al.*, *Nature* **394**, 251 (1998) ]

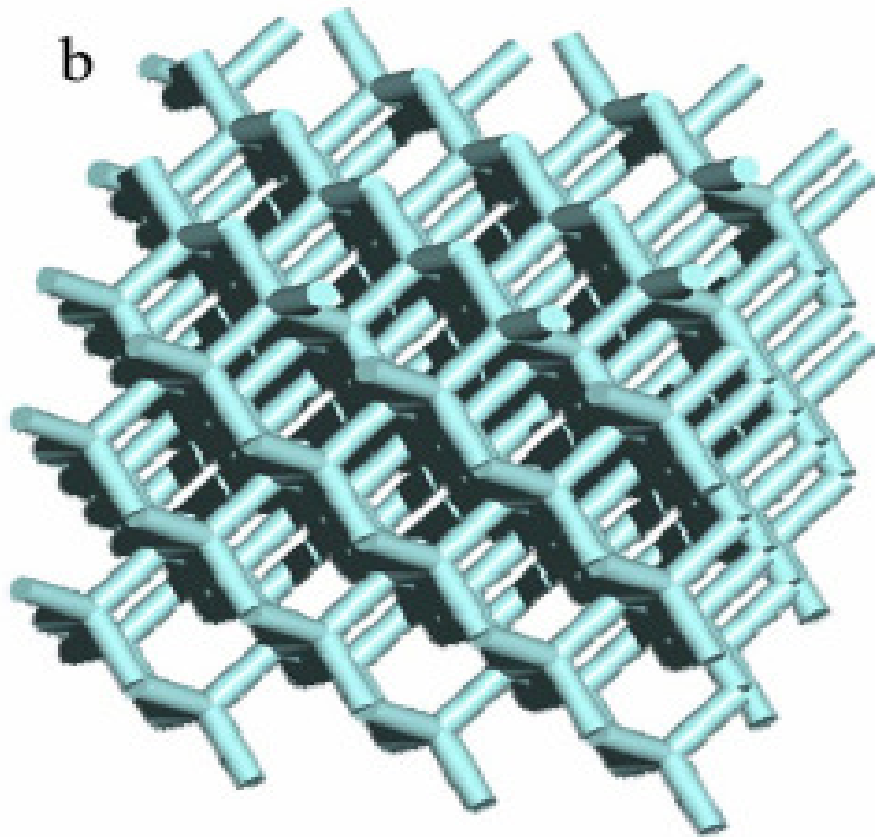
# The Woodpile Crystal



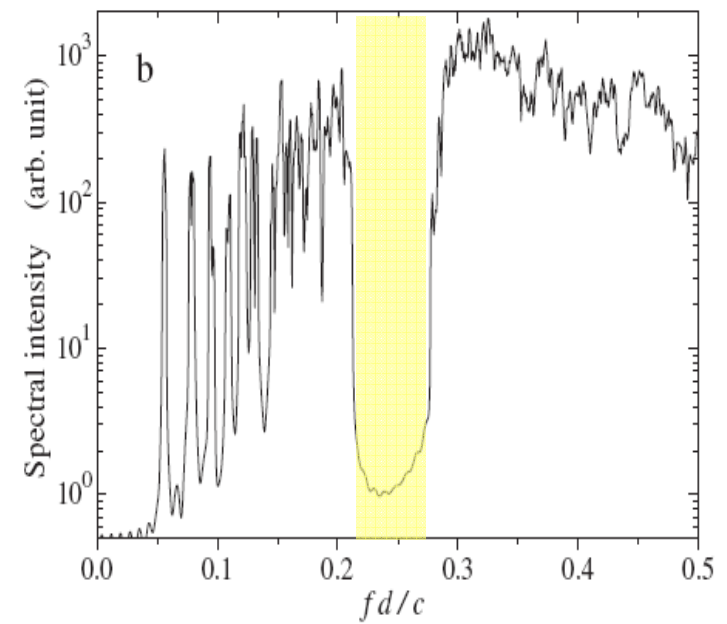
**Figure 7:** The photonic band structure for the lowest bands of the woodpile structure (inset, from figure 6) with  $\epsilon = 13$  logs in air. The irreducible Brillouin zone is larger than that of the fcc lattice described in appendix B, because of reduced symmetry—only a portion is shown, including the edges of the complete photonic band gap (yellow).



# Other diamond-like fcc crystal



There is a gap





# Photonic Amorphous Diamond Structure with a 3D Photonic Band Gap

Keiichi Edagawa,<sup>1</sup> Satoshi Kanoko,<sup>1</sup> and Masaya Notomi<sup>2,3</sup>

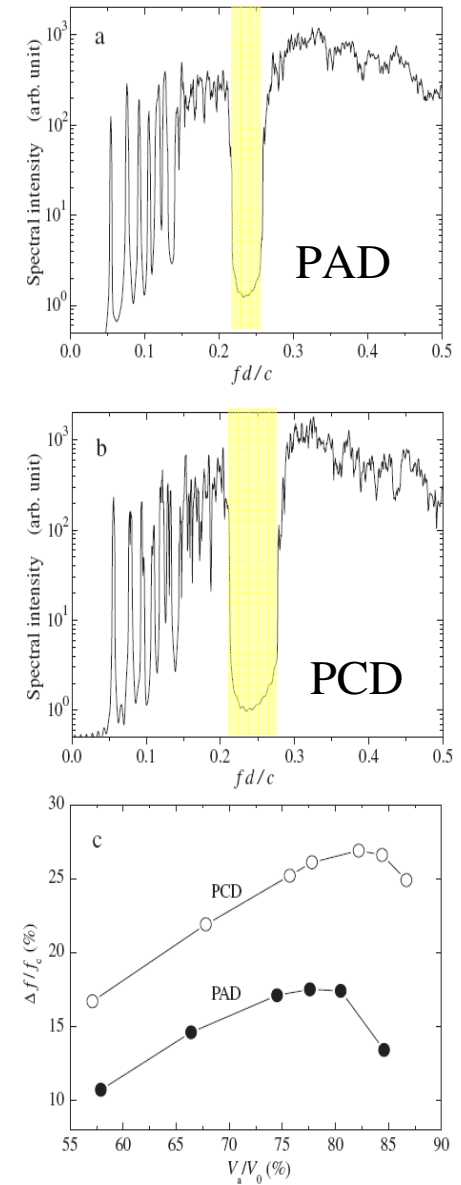
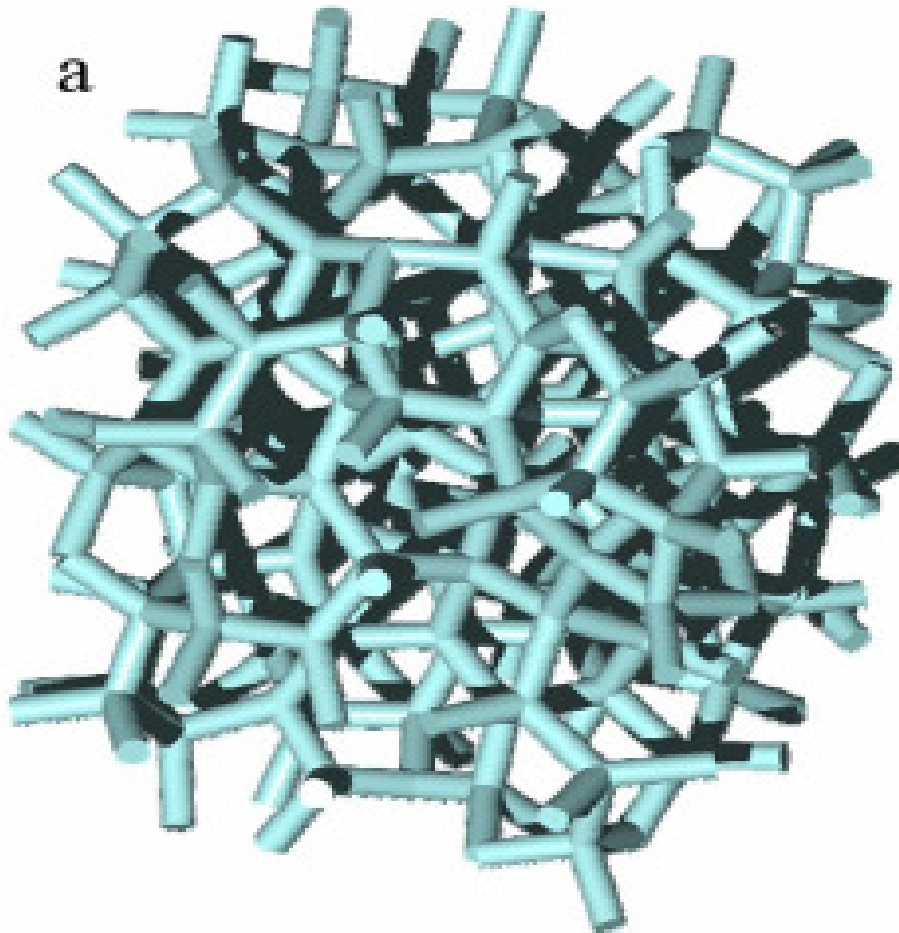
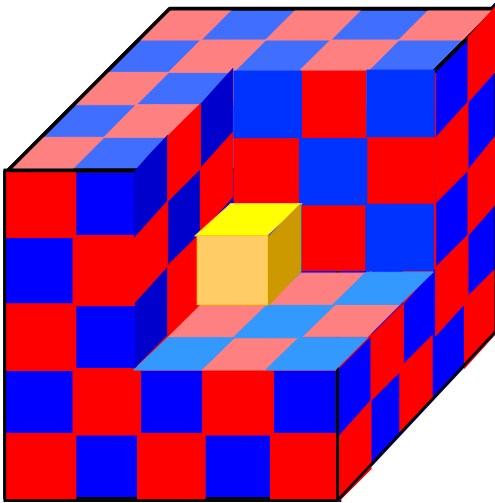


FIG. 3. Spectral intensities calculated for the photonic amorphous diamond (PAD) (a) and for the photonic crystalline diamond (PCD) (b). The air-volume fraction is  $V_a/V_0 = 78\%$  for the two structures. Air-volume-fraction dependences of the gap width for the PAD and PCD (c).

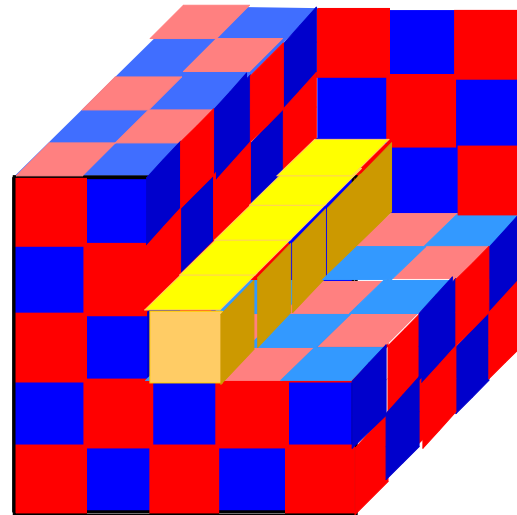


# Defects in 3D PhC

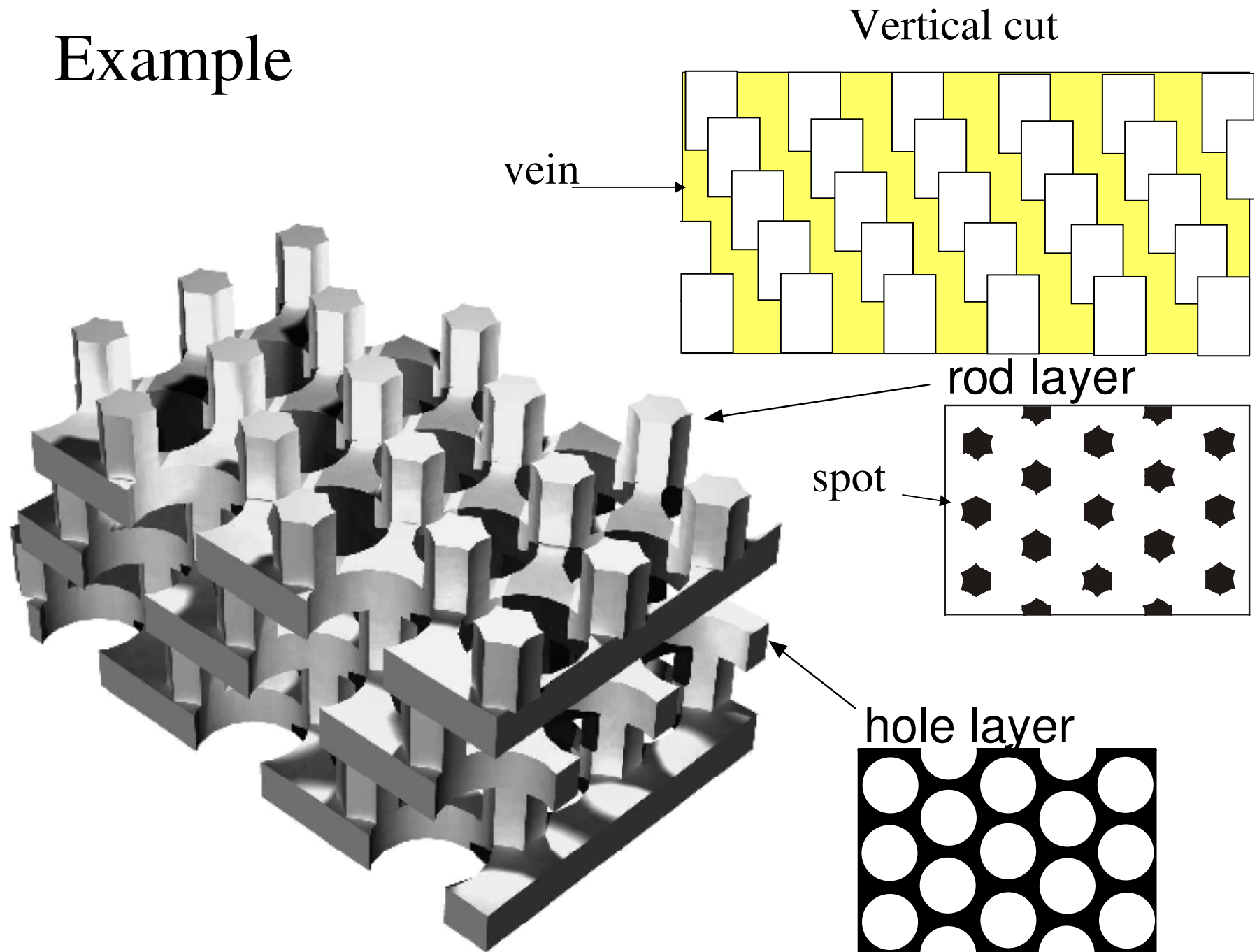
microcavities



waveguides (“wires”)



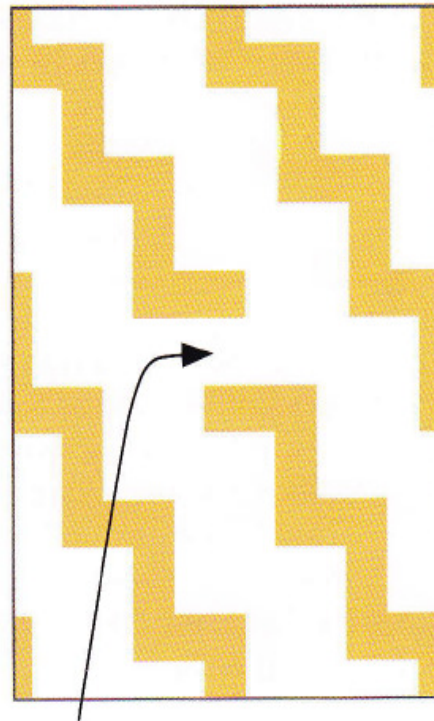
# Example



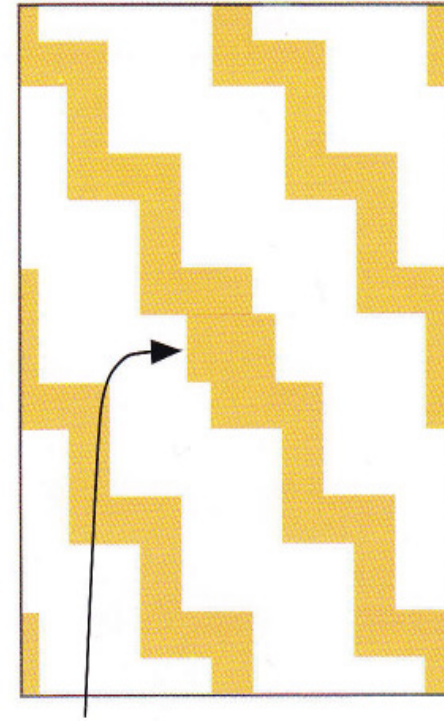
## Difetto di punto in un taglio verticale



PhC



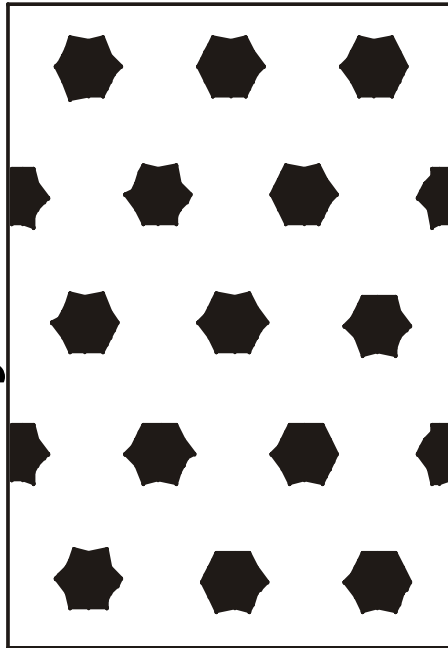
Air Defect



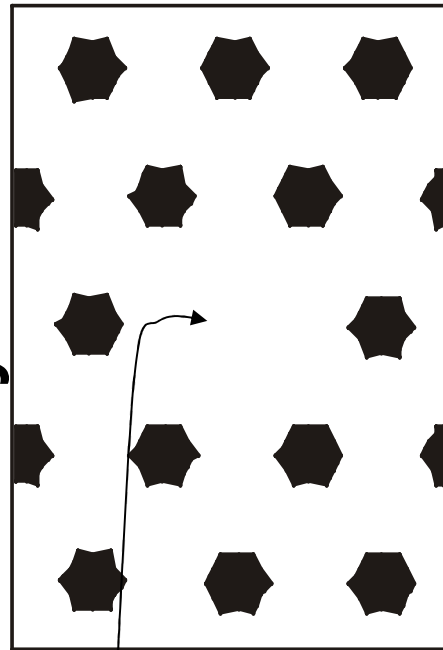
Dielectric Defect

**Figure 13:** Vertical cross section of the layered structure from figure 10, corresponding to the top panel of figure 12, showing examples of how a point defect may be created by modifying a *single rod*: a rod can be removed (left) to form an **air defect**, or the radius of a rod can be increased (right) to form a **dielectric defect**.

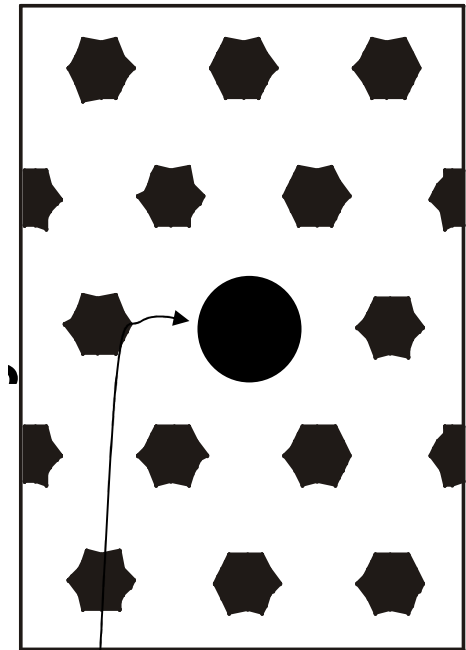
## Difetto di punto in un taglio orizzontale



PhC



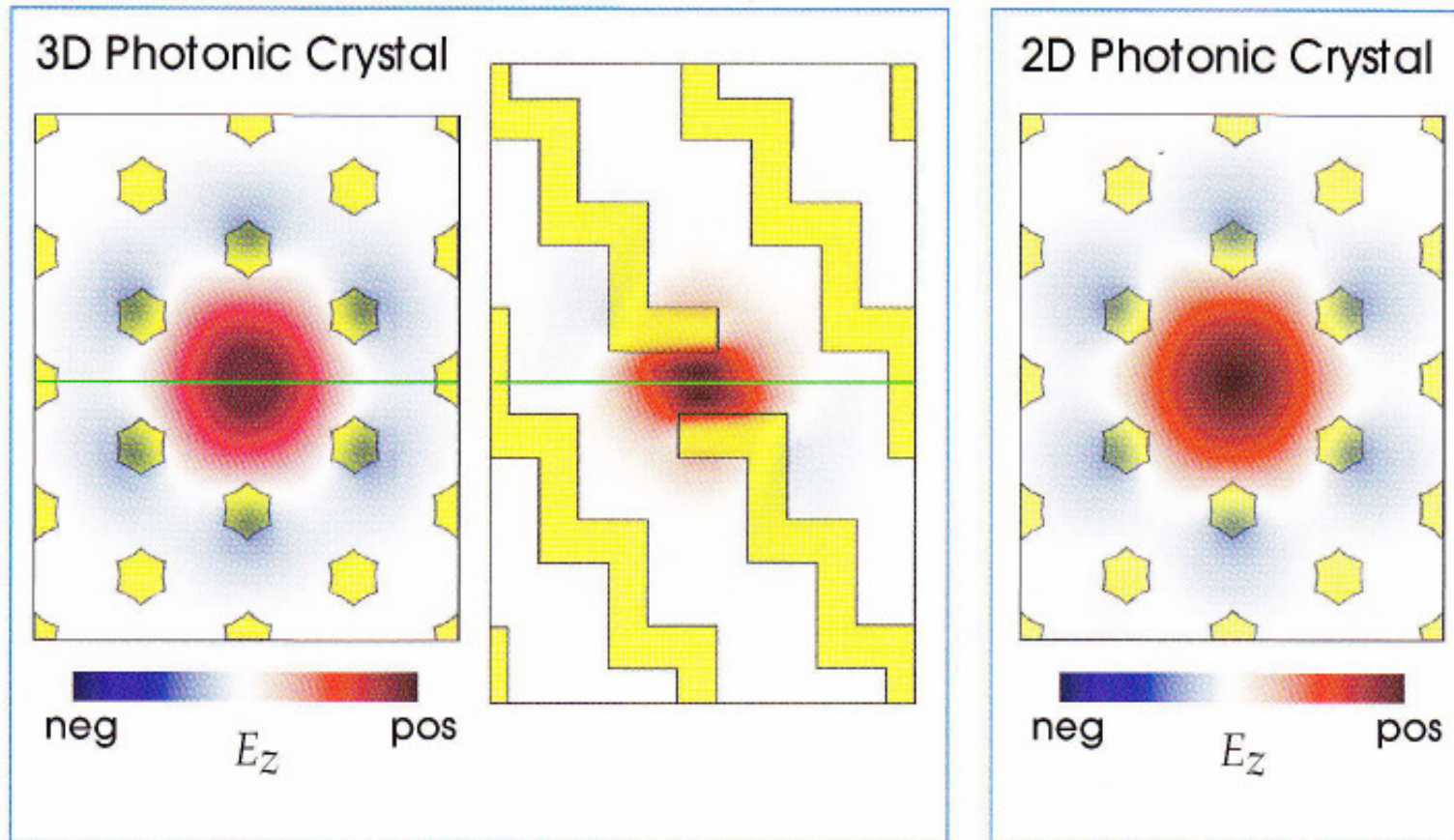
Air defect



Dielectric defect

## Difetto di aria (monopolo)

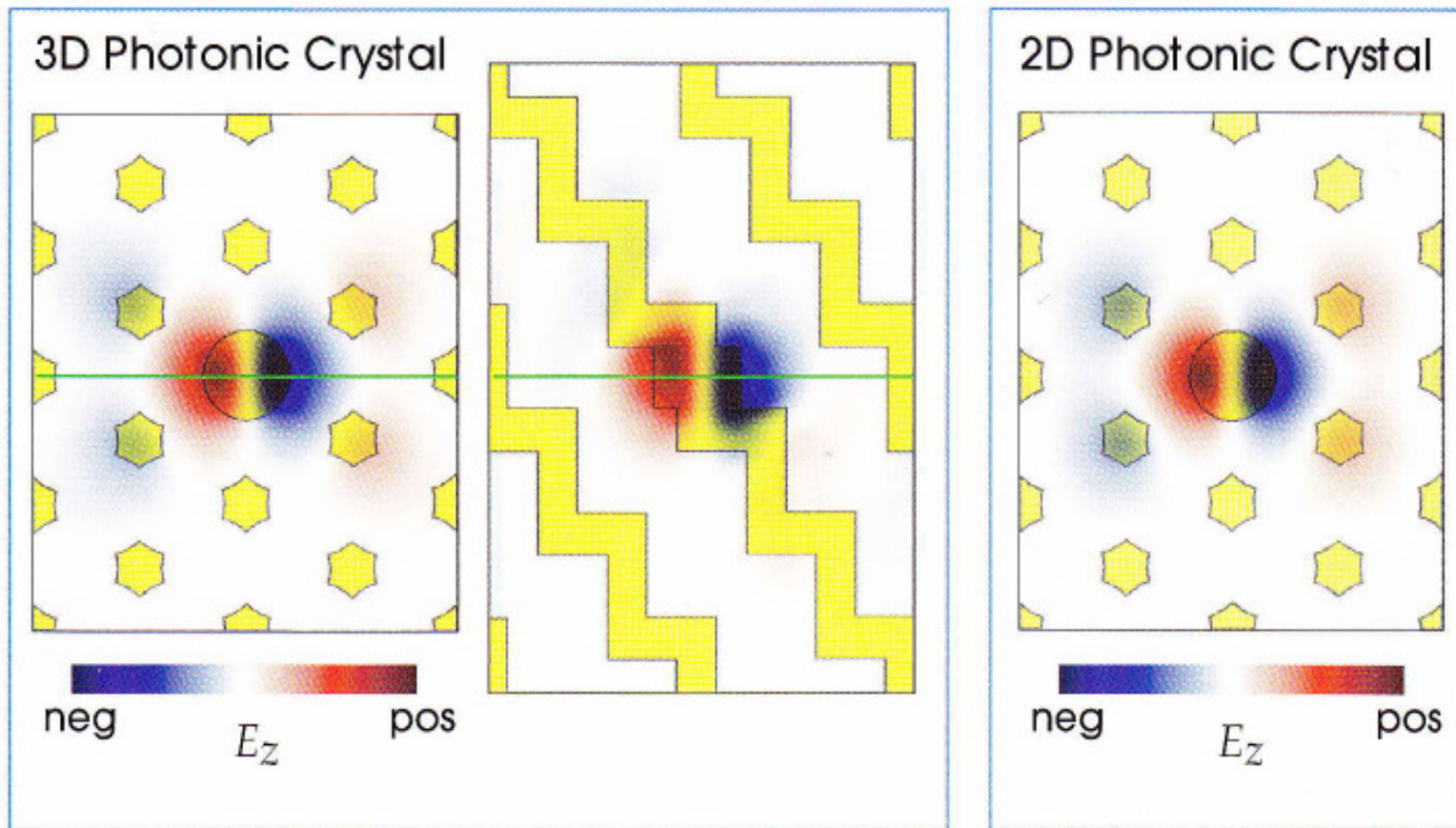
Air Defect (missing rod)





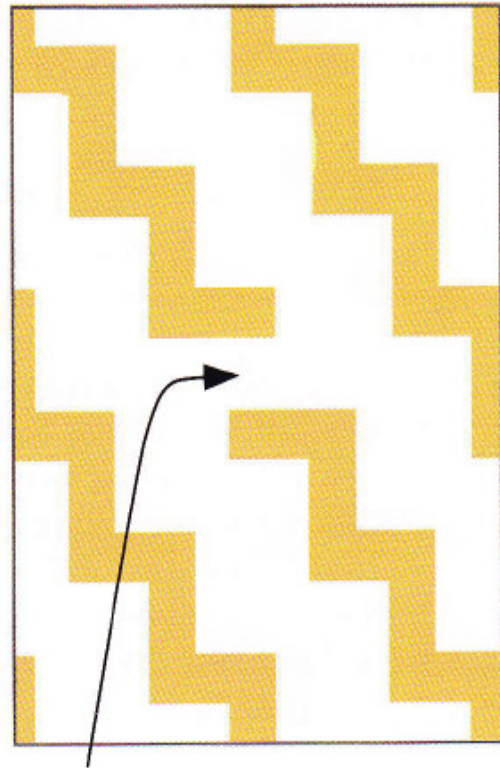
## Difetto di dielettrico (dipolo)

### Dielectric Defect (larger rod)



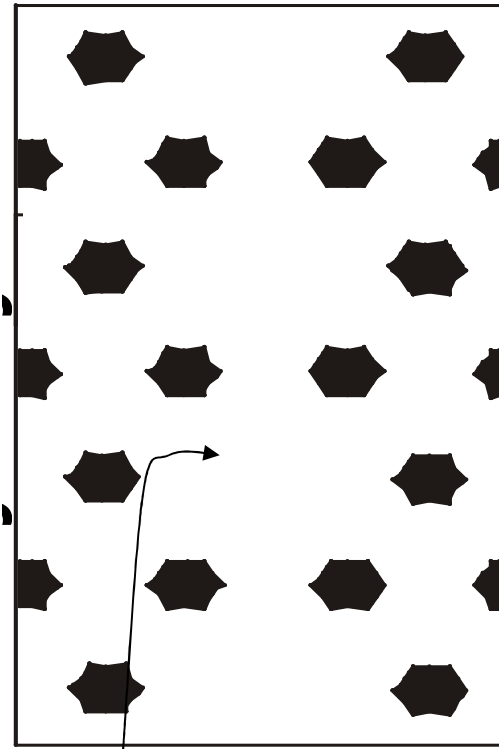
# Difetto di linea

Taglio verticale



Air Defect

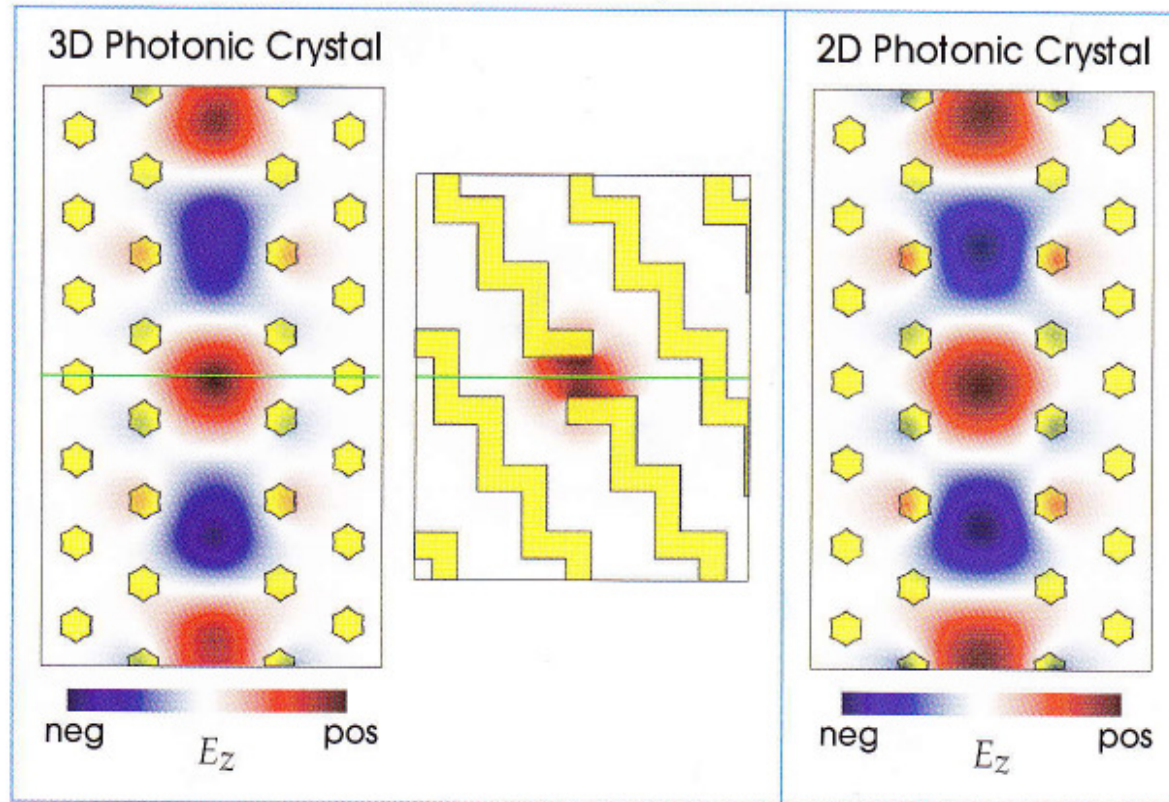
Taglio orizzontale



Air defect

# Difetto di linea

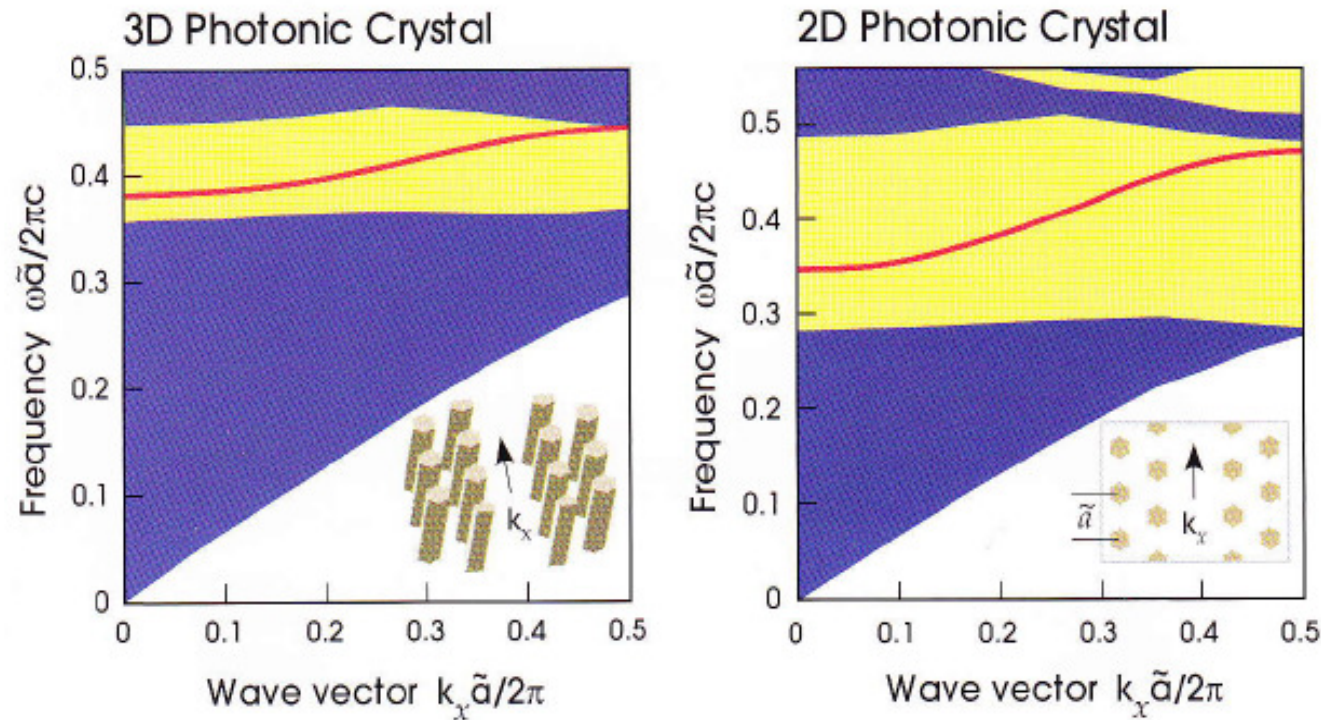
Line Defect (missing row of rods)



**Figure 17:** Horizontal and vertical cross sections (intersecting at green lines) of  $E_z$  field patterns of a linear defect in the layered structure (left), formed by removing a row of rods from a single rod layer, compared to the field for the corresponding TM state in a two-dimensional crystal (right) with the same *rod* cross section. These fields correspond to a wave vector  $k_x \tilde{a} / 2\pi = 0.3$  along the waveguide, where  $\tilde{a}$  is the in-plane lattice constant from figure 12. Dielectric material is shown in yellow.

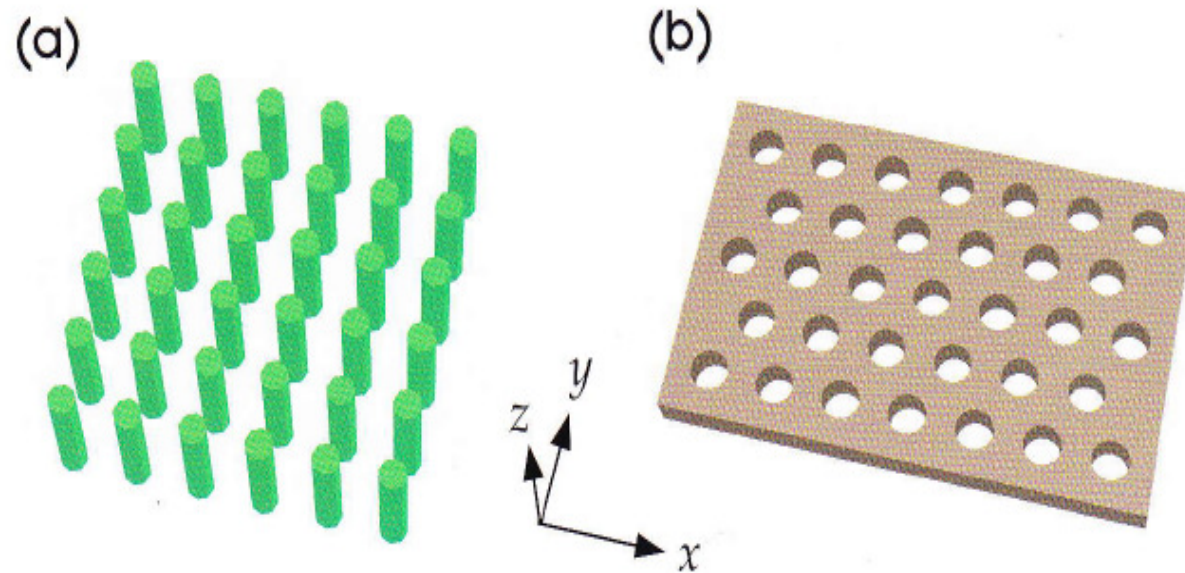


# Difetto di linea



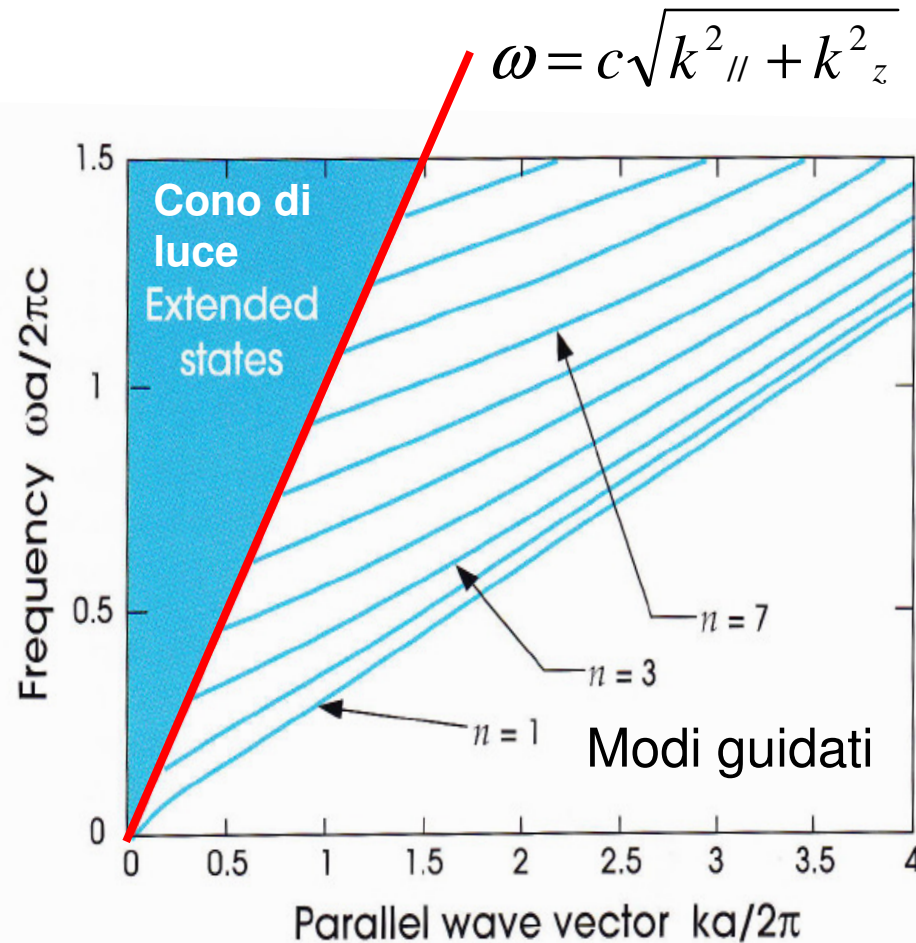
**Figure 18:** *Left:* Projected band diagram of the line defect from figure 17, formed by a missing row of rods from a single layer of the three-dimensional crystal from figure 10. The red line is the guided band in the complete photonic band gap (yellow). Inset shows a single rod layer with the defect (other layers of the crystal not shown). *Right:* Projected band diagram of TM states for the corresponding two-dimensional crystal with an identical rod cross section (inset).

# Fotonica su slab



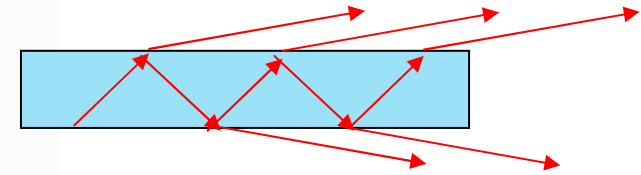
**Figure 1:** Examples of **photonic-crystal slabs**, which combine two-dimensional periodicity (in the  $xy$  directions) and index-guiding in the vertical ( $z$ ) direction. (a) The **rod slab**, a square lattice of dielectric rods in air. (b) The **hole slab**, a triangular lattice of air holes in a dielectric slab.

# Slab omogenea



**Figure 3:** Harmonic mode frequencies for a plane of glass of thickness  $a$  and  $\epsilon = 11.4$ . Blue lines correspond to modes that are localized in the glass. The shaded blue region is a continuum of states that extend into both the glass and the air around it. The red line is the **light line**  $\omega = ck$ . This plot shows modes of only one polarization, for which  $\mathbf{H}$  is perpendicular to both the  $z$  and  $k$  directions.

Entro il cono di luce



$$\omega \geq ck_{||} \rightarrow k_z = \sqrt{\frac{\omega^2}{c^2} - k_{||}^2}$$

Oltre il cono di luce



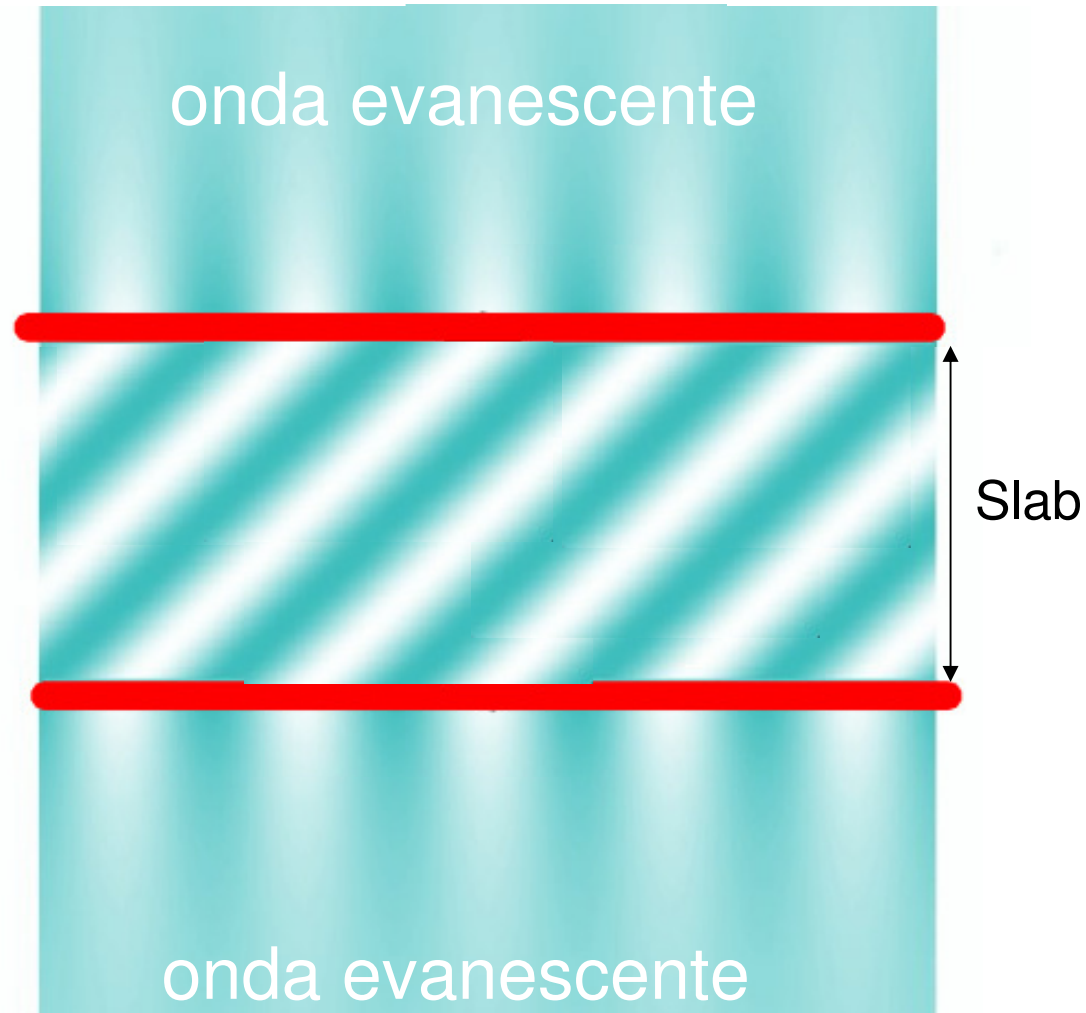
$$\omega < ck_{||} \rightarrow k_z = i\sqrt{k_{||}^2 - \frac{\omega^2}{c^2}}$$



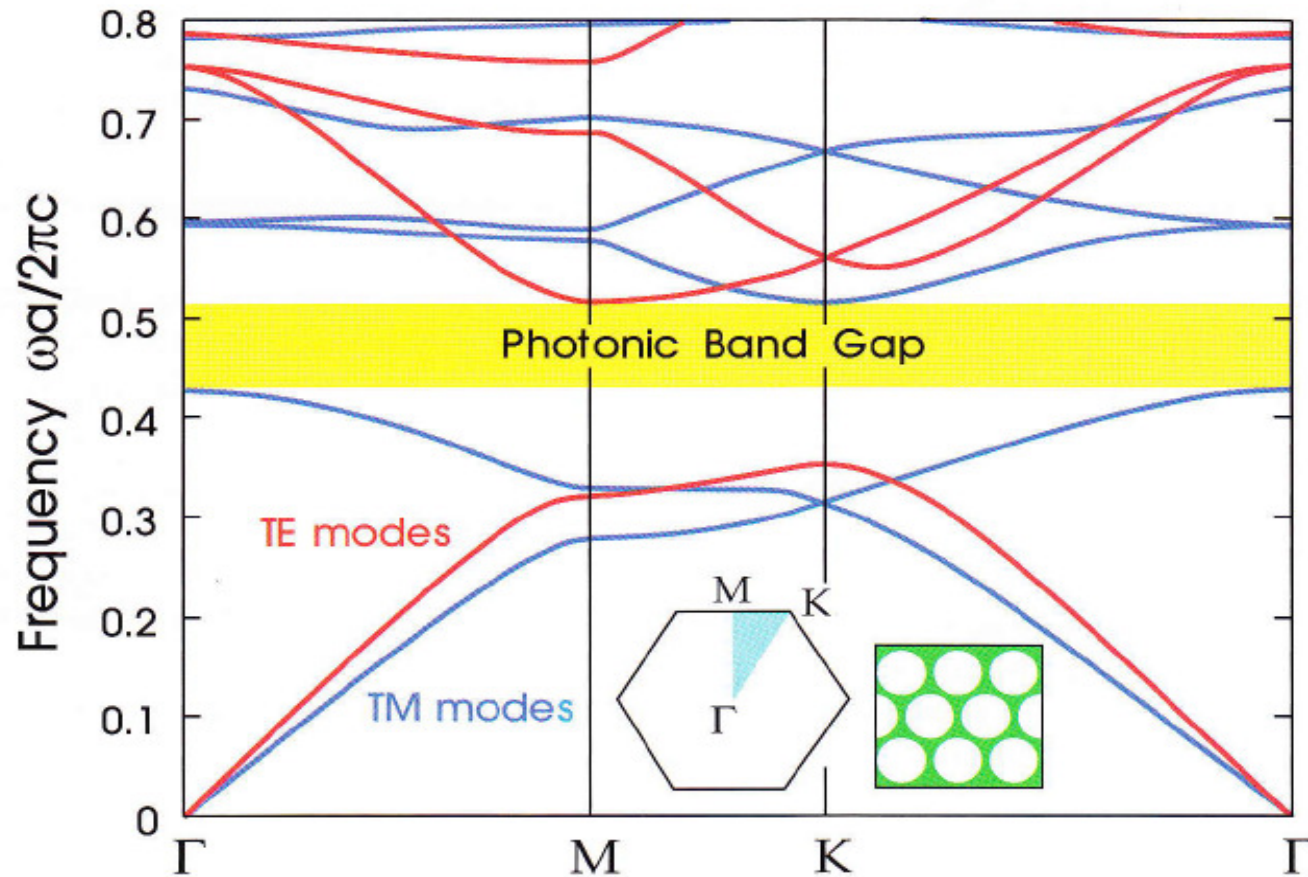
# Rappresentazione modi guidati: Confinamento 1D della luce

$$\sin \theta_i > \frac{n_2}{n_1}$$

Confinamento 1D  
della luce dovuto ad  
“index guiding”

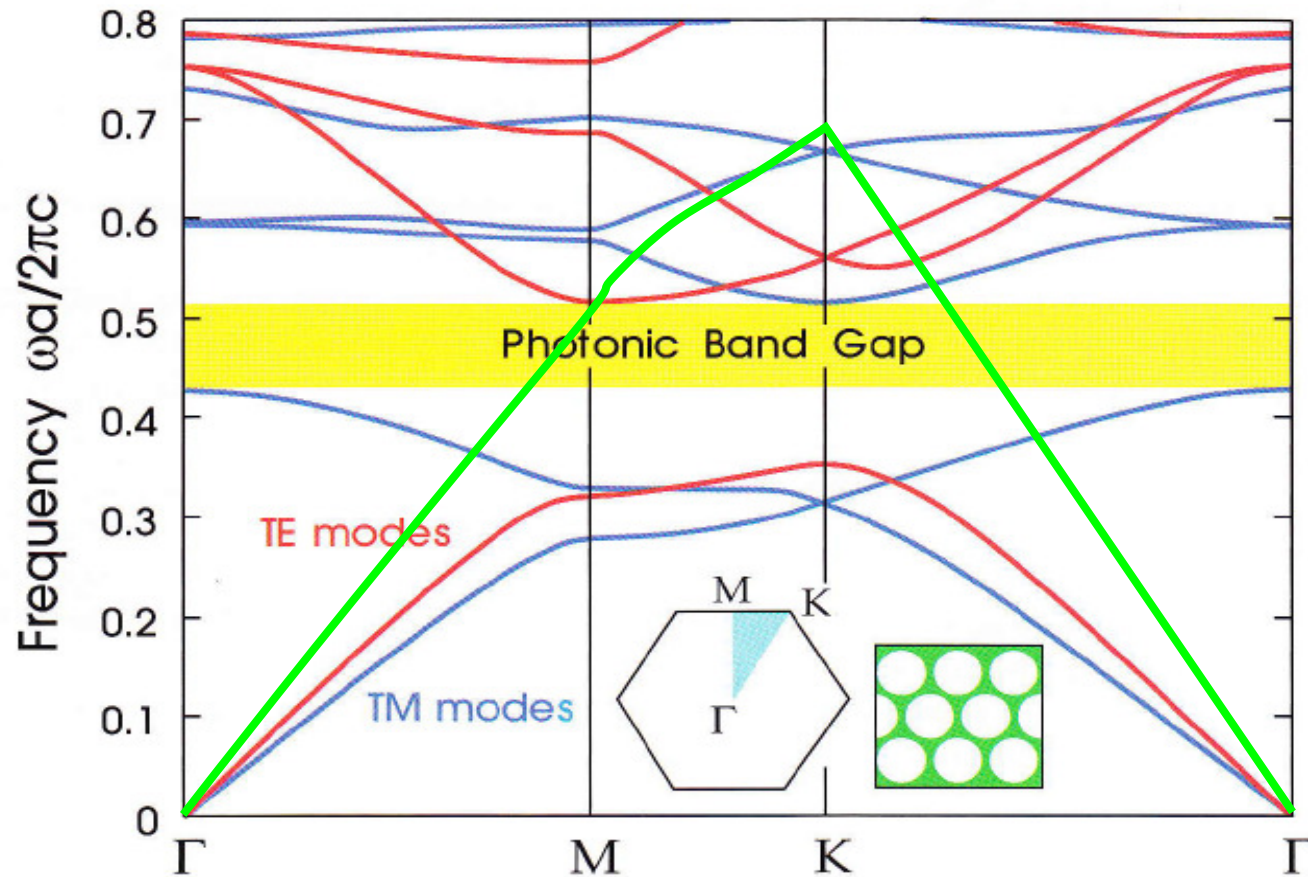


# Diagramma a bande 2D



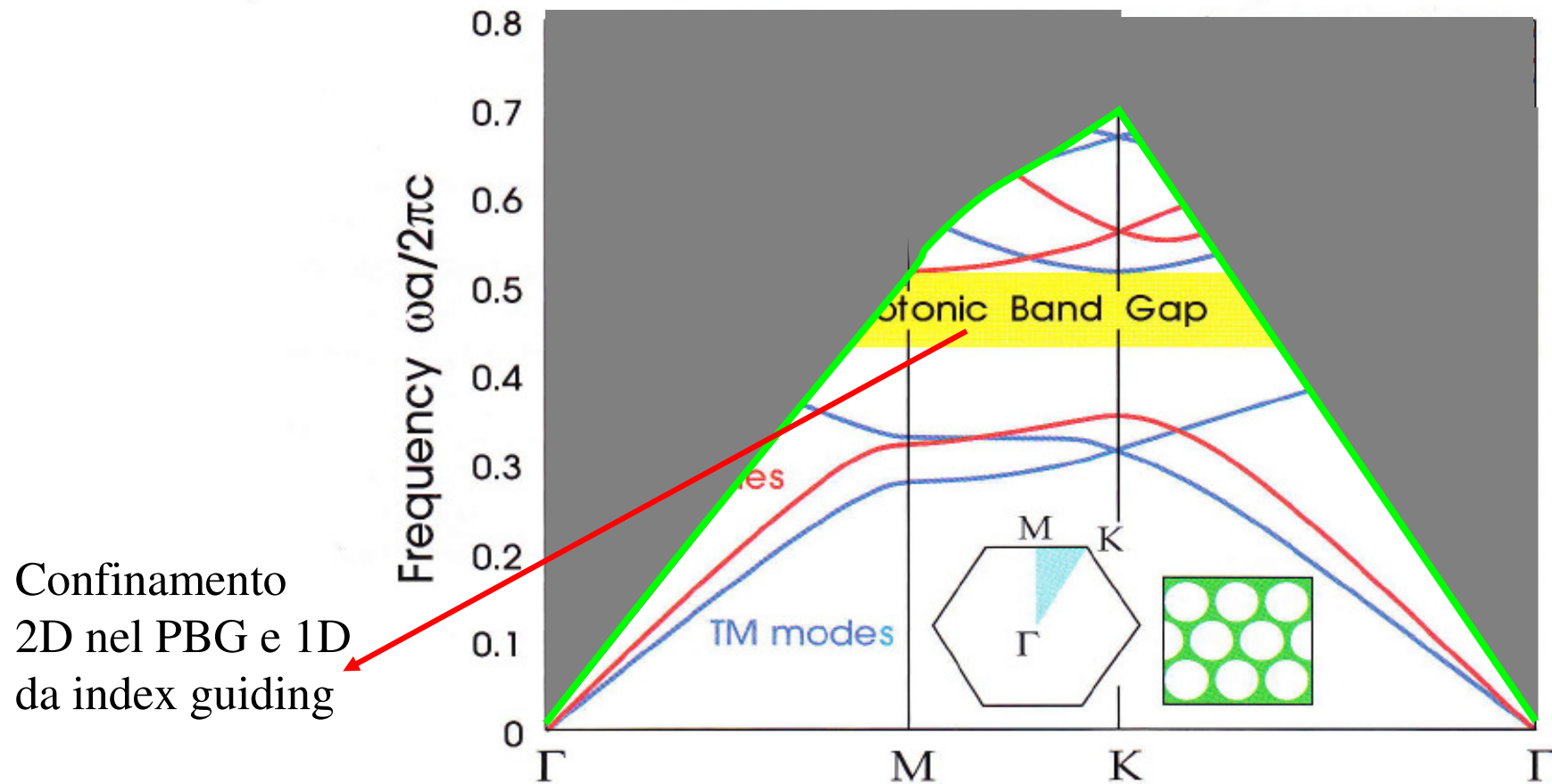
**Figure 10:** The photonic band structure for the modes of a triangular array of air columns drilled in a dielectric substrate ( $\epsilon = 13$ ). The blue lines represent TM bands and the red lines represent TE bands. The inset shows the high-symmetry points at the corners of the irreducible Brillouin zone (shaded light blue). Note the complete photonic band gap.

# Diagramma a bande 2D + cono di luce



**Figure 10:** The photonic band structure for the modes of a triangular array of air columns drilled in a dielectric substrate ( $\epsilon = 13$ ). The blue lines represent TM bands and the red lines represent TE bands. The inset shows the high-symmetry points at the corners of the irreducible Brillouin zone (shaded light blue). Note the complete photonic band gap.

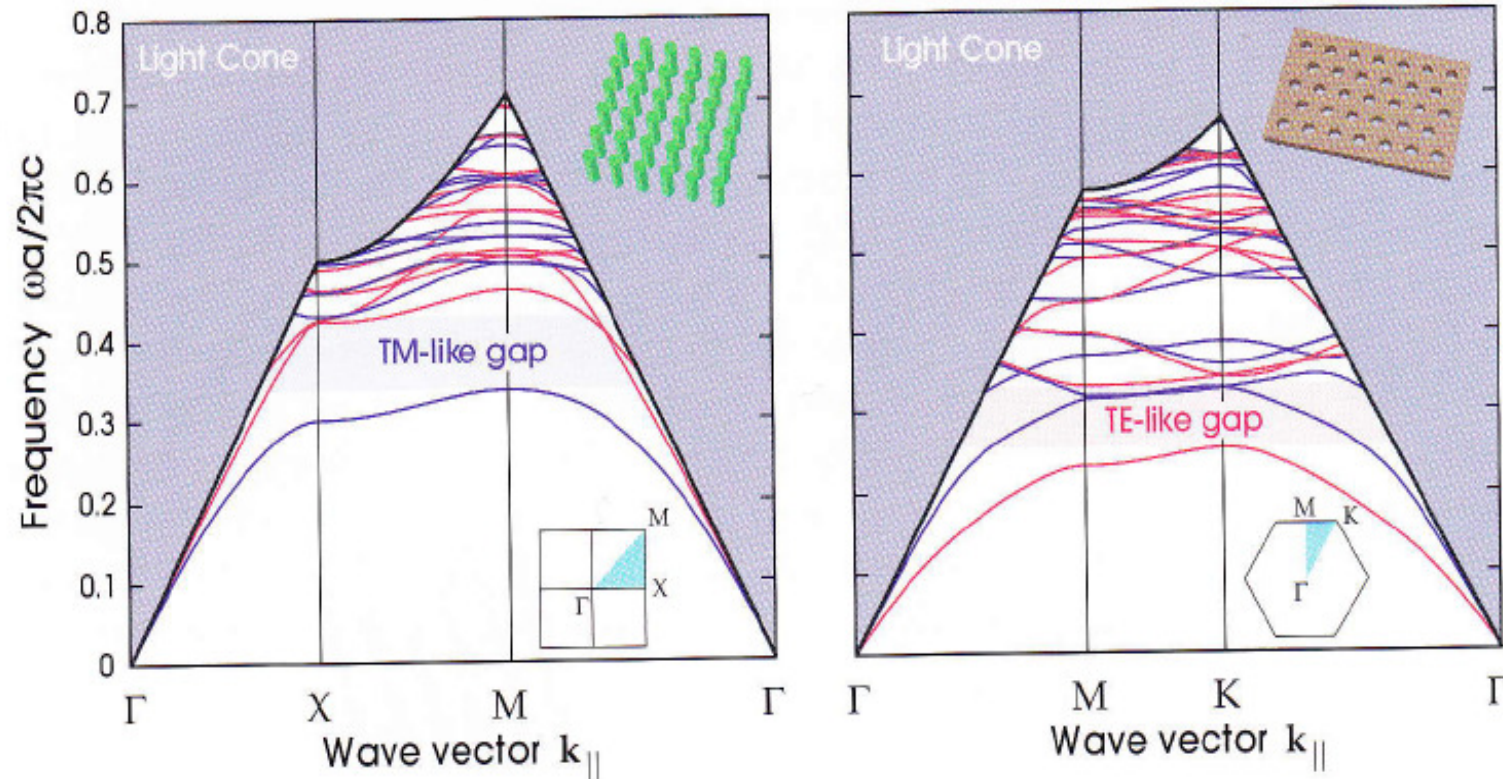
# Diagramma a bande slab



**Figure 10:** The photonic band structure for the modes of a triangular array of air columns drilled in a dielectric substrate ( $\epsilon = 13$ ). The blue lines represent TM bands and the red lines represent TE bands. The inset shows the high-symmetry points at the corners of the irreducible Brillouin zone (shaded light blue). Note the complete photonic band gap.



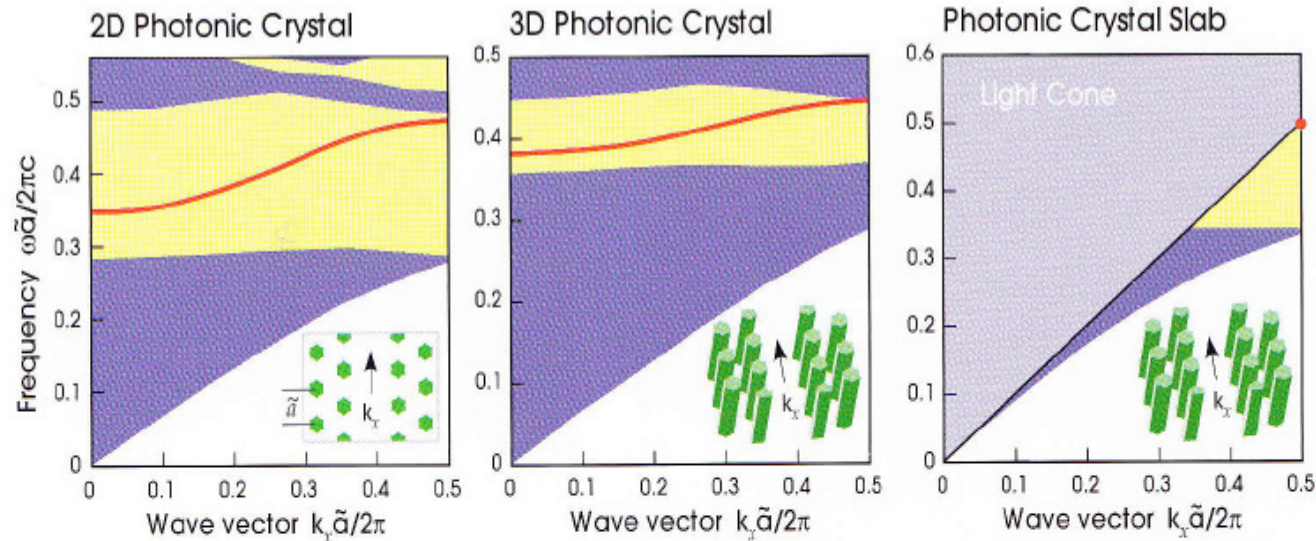
# Diagramma a bande slab



**Figure 2:** Band diagrams for photonic crystal slabs of figure 1, suspended in air (inset): the **rod slab** (left) and the **hole slab** (right). The blue shaded area is the *light cone*, all of the extended modes propagating in air. Below it are the guided bands localized to the slab: blue/red bands indicate TM/TE-like modes, respectively (odd/even with respect to the  $z = 0$  mirror plane). The rod/hole slabs have gaps in the TM/TE-like modes, which are shaded light blue/red respectively.

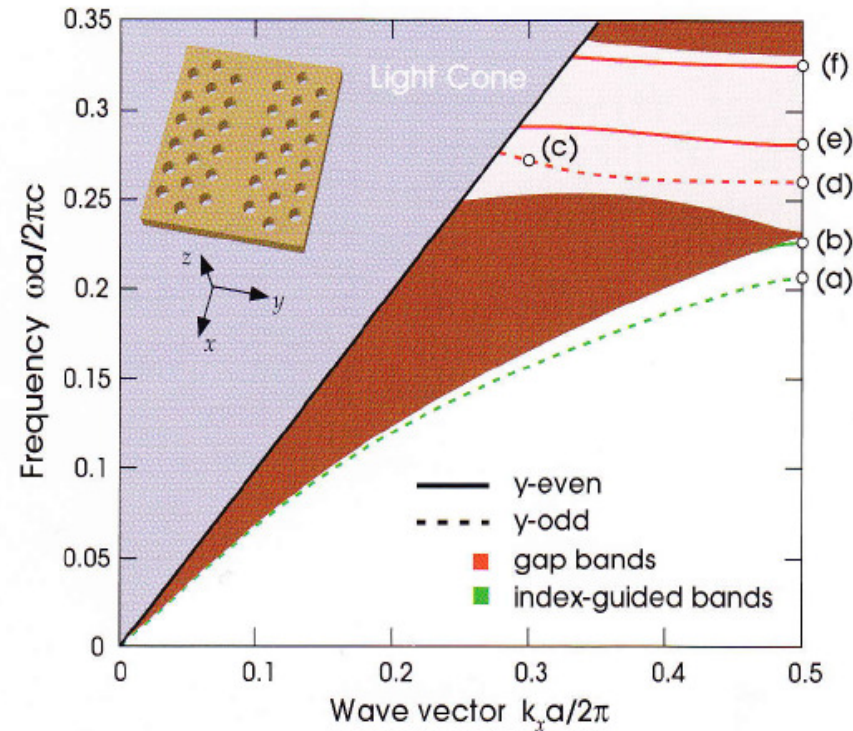


# Guide d'onda slab



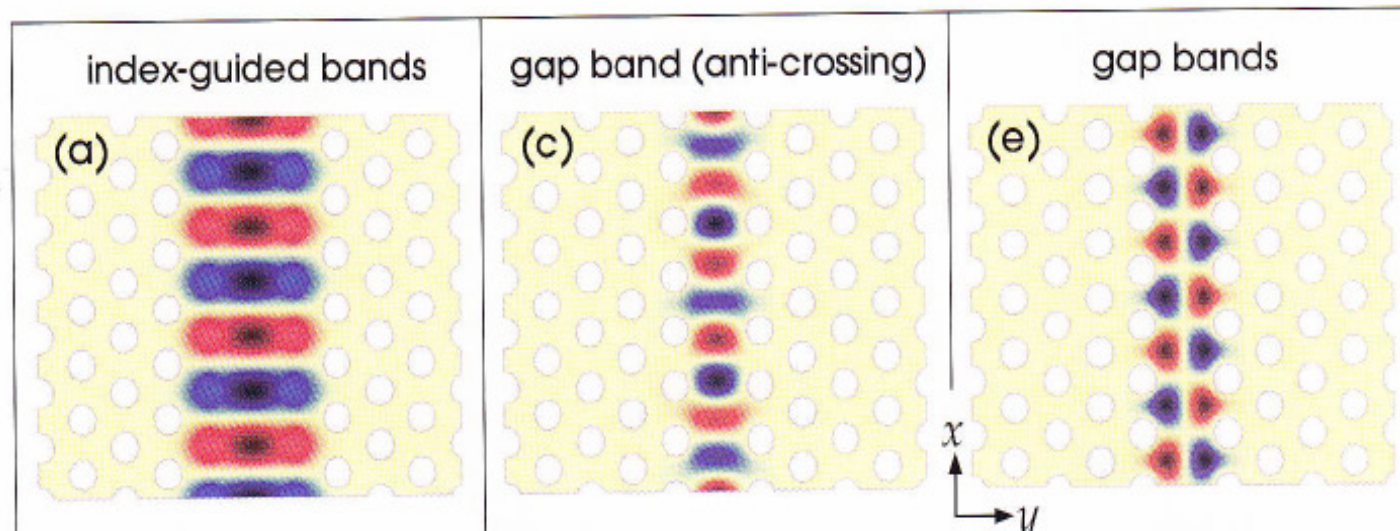
**Figure 7:** Projected band diagrams for three waveguides, all of whose cross sections are an identical triangular lattice (period  $\tilde{a}$ ) of dielectric ( $\epsilon = 12$ ) rods in air with a missing row of rods. The guided band is shown as a red line, and extended modes of the crystal are shown in shaded dark blue, with the band gap(s) shaded yellow. *Left:* TM mode of two-dimensional crystal (uniform in  $z$ ,  $k_z = 0$ ) with a TM gap. *Middle:* TM-like mode of the three-dimensional crystal from chapter 6 (see the section Localization at a Linear Defect), which has a *complete* band gap. *Right:* a slab of rods (thickness  $2a$ ) suspended in air, which has a gap in the TM-like modes; because of its light cone, it has at most a very weakly guided state right at the gap edge (red dot).

# Guide d'onda slab



**Figure 8:** Projected band diagram of TE-like (z-even) states for a "W1" defect in the hole slab of figure 2(right), formed by a missing row of nearest-neighbor holes along the  $x$  direction. Dark-red shaded regions indicate extended TE-like modes of the crystal. Guided modes are introduced both in the gap (red bands in pink shaded region) and below all of the extended modes of the crystal (green bands below red shaded region). The latter are index-guided. The guided modes are classified as  $y$ -even (solid lines) or  $y$ -odd (dashed lines) according to the  $y = 0$  mirror symmetry plane bisecting the waveguide. The fields corresponding to the labelled points (a-f) are shown in figure 10.

# Guide d'onda slab



Più confinamento con riflessione PCB