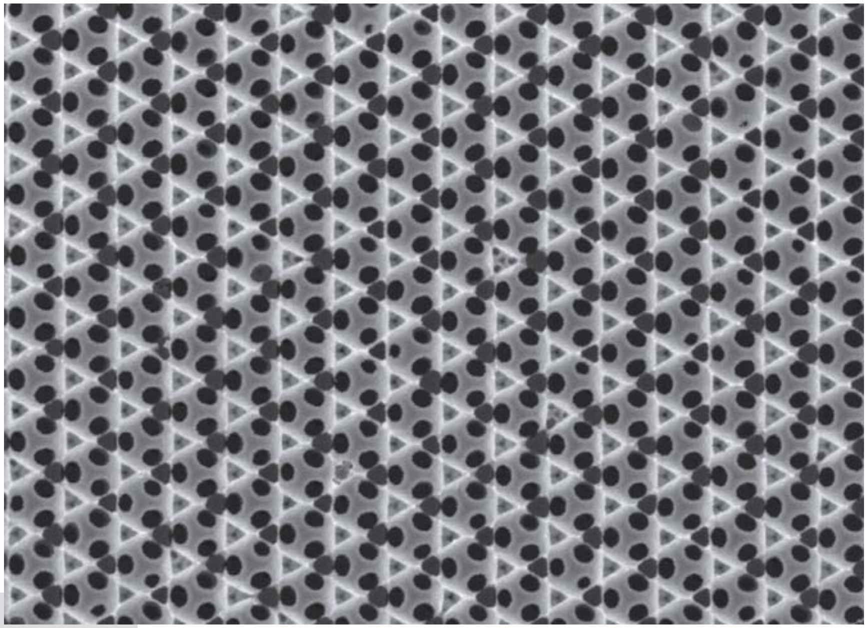
The Photonic Band Gap and Colloidal Crystals

David J. Norris
Chemical Engineering & Materials Science
University of Minnesota



Focus: Photonic Band Gap

- What is it?
- Why is it interesting?
- How do colloidal particles fit in?

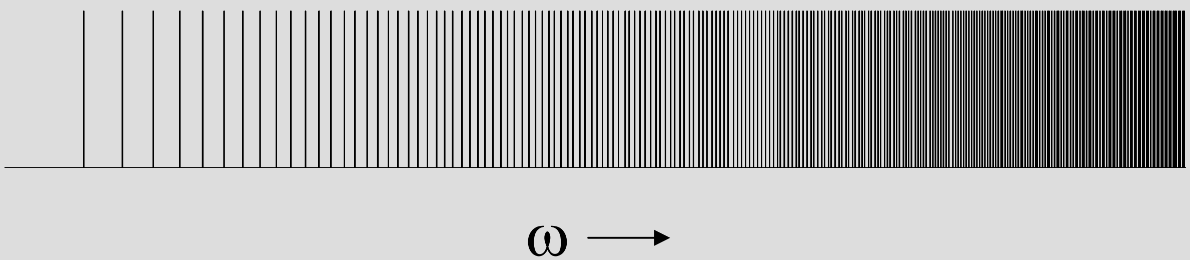
Your job is to ask questions as we go!

To understand the photonic band gap:

start from a basic concept . . .

Density of States (DOS)

$$\rho(\omega) = \frac{\text{Number of states}}{\text{Unit frequency} \times \text{Unit Volume}}$$

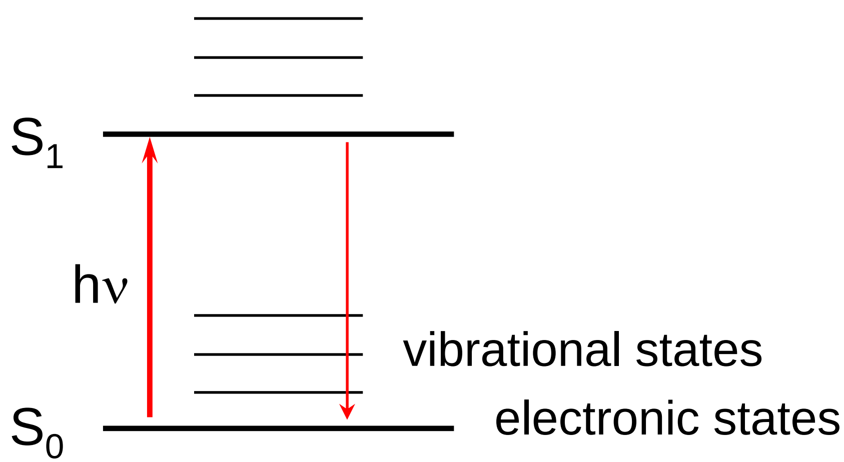


States can be electronic, vibronic (phonons), or optical (photonic)

Why does the electronic DOS matter?

Fermi's Golden Rule

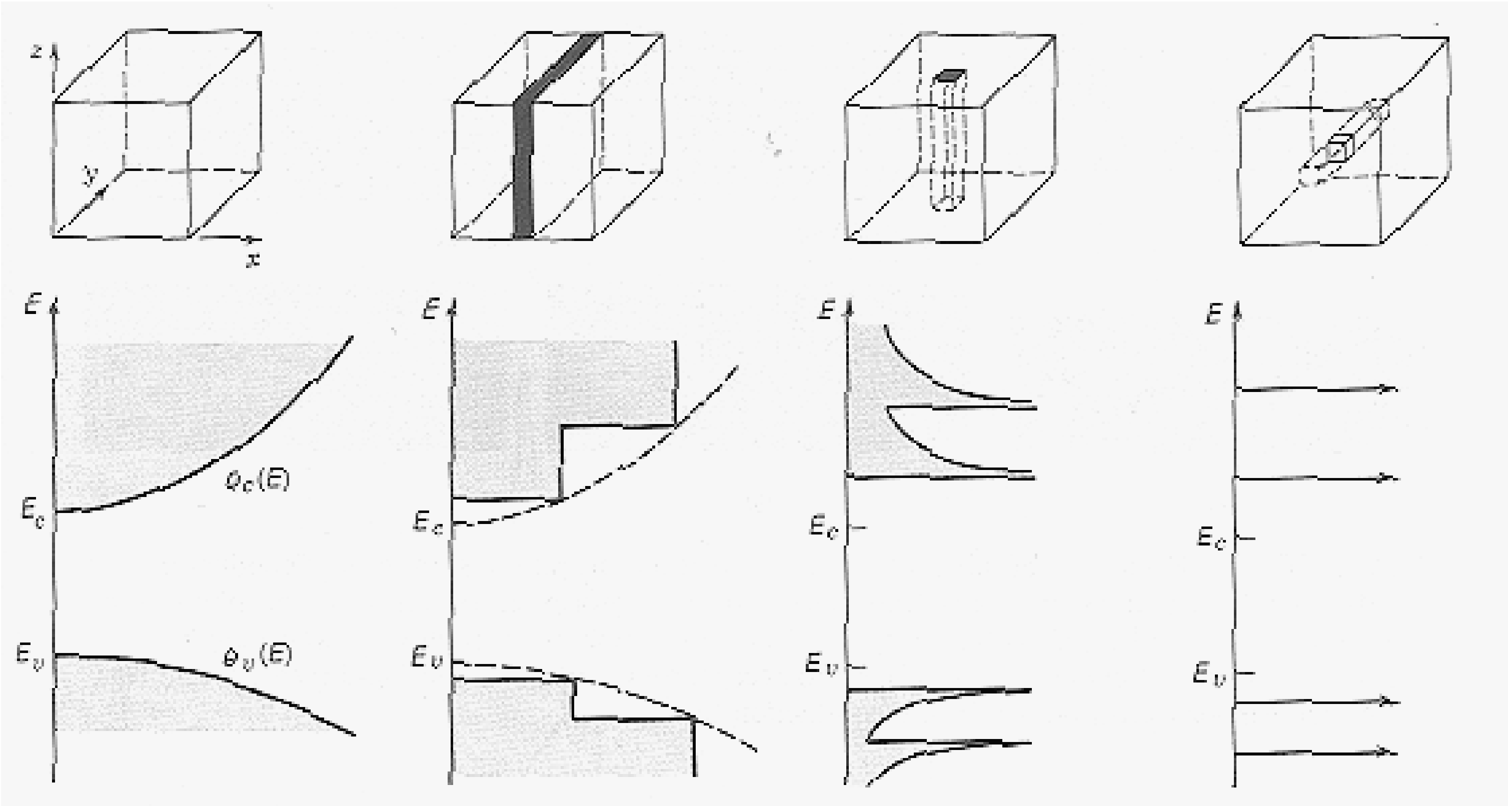
$$\text{Rate} \equiv \Gamma_o \propto \rho(\omega)$$



i.e., "speed" of a process depends on the number of available states

Controlling Electronic DOS:

Early motivation for nano-structures



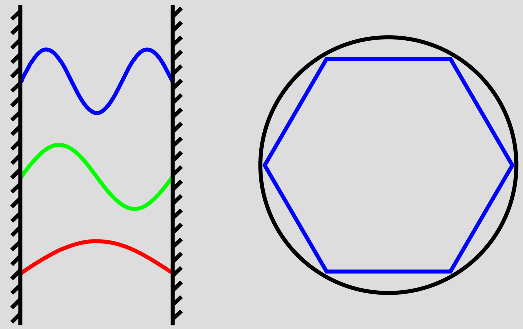
Saleh

modification of electronic density of states

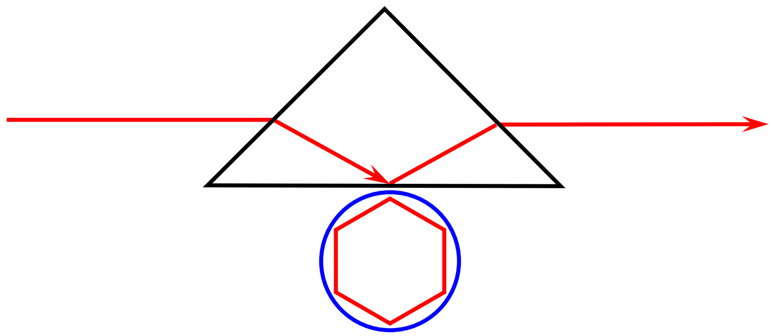
What about the photonic density of states?

$$\rho_{phot}(\omega) = \frac{\text{Number of photon states}}{\text{Unit frequency x Unit Volume}}$$

optical microcavities



Cool lab demo: “marble” microcavity

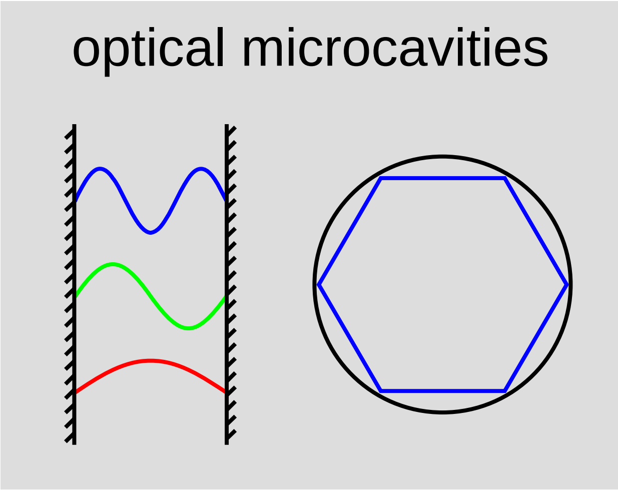


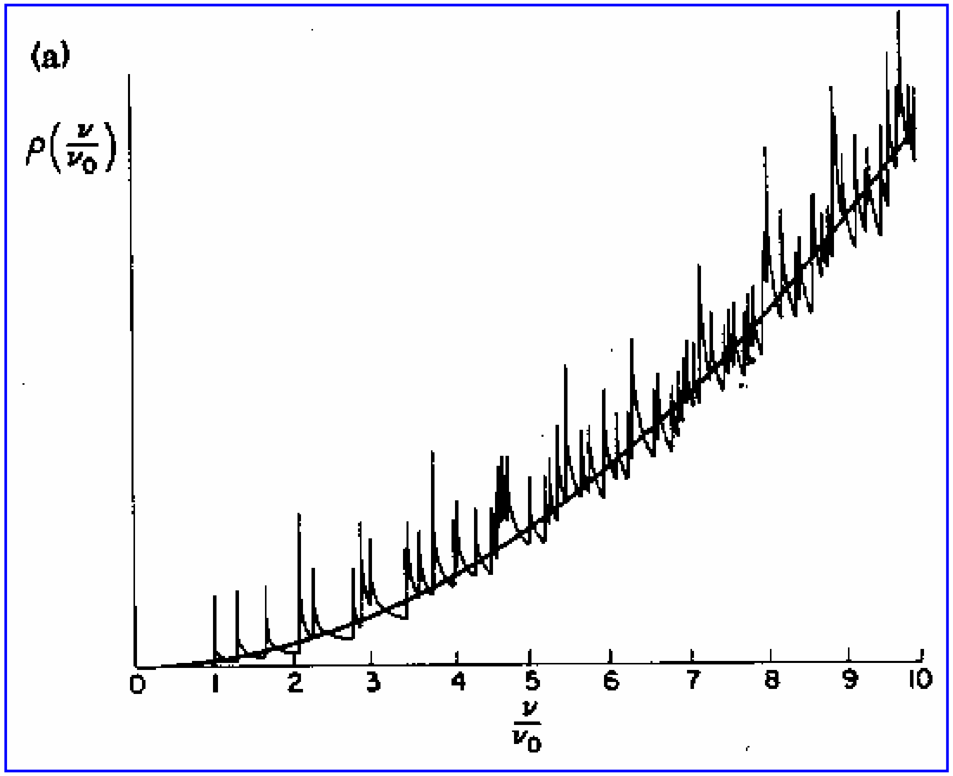
- Total internal reflection off prism
- Photons leak into the cavity
- Circulate in cavity mode

Controlling Photonic Density of States

Early motivation for photonic microstructures

$$\rho_{phot}(\omega) = \frac{\text{Number of photon states}}{\text{Unit frequency} \times \text{Unit Volume}}$$





Kleppner, Phys. Rev. Lett. **47**, 233 (1981).

Purcell Effect - Control Spontaneous Emission

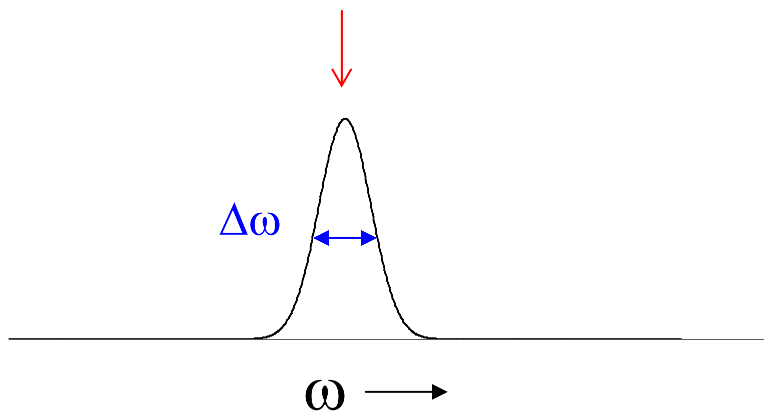
B10. Spontaneous Emission Probabilities at Radio Frequencies. E. M. PURCELL, *Harvard University.*—For nuclear magnetic moment transitions at radio frequencies the probability of spontaneous emission, computed from

$$A_\nu = (8\pi\nu^2/c^3)h\nu(8\pi^3\mu^2/3h^2) \text{ sec.}^{-1},$$

is so small that this process is not effective in bringing a spin system into thermal equilibrium with its surroundings. At 300°K, for $\nu = 10^7$ sec.$^{-1}$, $\mu = 1$ nuclear magneton, the corresponding relaxation time would be 5×10^{21} seconds! However, for a system coupled to a resonant electrical circuit, the factor $8\pi\nu^2/c^3$ no longer gives correctly the number of radiation oscillators per unit volume, in unit frequency range, there being now *one* oscillator in the frequency range ν/Q associated with the circuit. The spontaneous emission probability is thereby increased, and the relaxation time reduced, by a factor $f = 3Q\lambda^3/4\pi^2 V$, where V is the volume of the resonator. If a is a dimension characteristic of the circuit so that $V\sim a^3$, and if δ is the skin-depth at frequency ν, $f\sim\lambda^3/a^2\delta$. For a non-resonant circuit $f\sim\lambda^3/a^3$, and for $a<\delta$ it can be shown that $f\sim\lambda^3/a\delta^2$. If small metallic particles, of diameter 10^{-3} cm are mixed with a nuclear-magnetic medium at room temperature, spontaneous emission should establish thermal equilibrium in a time of the order of minutes, for $\nu = 10^7$ sec.$^{-1}$.

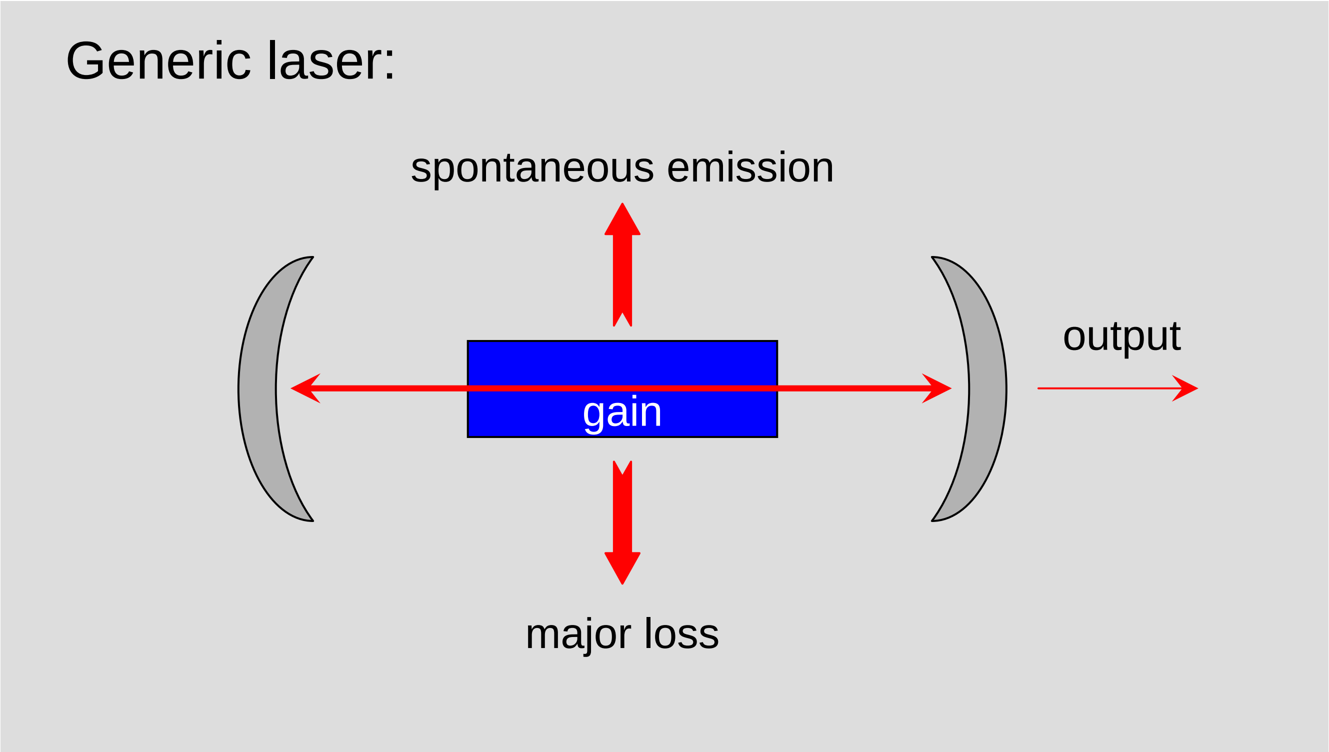
Purcell, Phys. Rev. **69**, 681 (1946).

$$\Gamma_o \propto \rho_{elec}(\omega)\cdot\rho_{phot}(\omega)$$



$$\eta = \frac{\Gamma_c}{\Gamma_o} \propto \frac{Q\,\lambda^3}{V_c}$$

Device Implications:



Early idea:

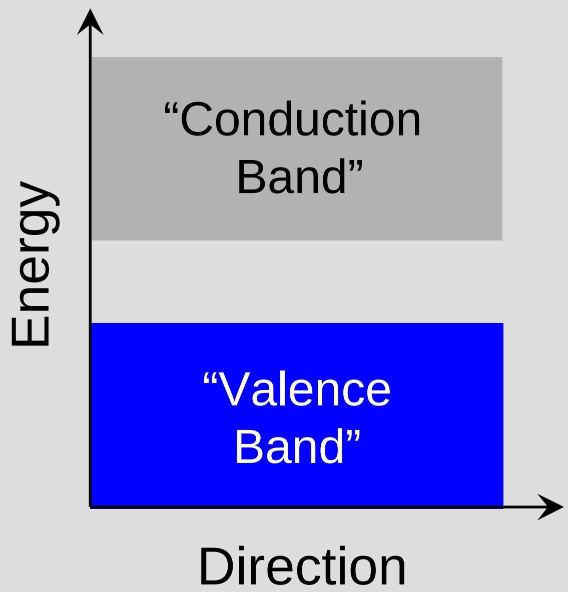
Control spontaneous emission = better laser

How do we do this?

Optical microcavities are one option . . .

but is there another approach?

gedanken experiment - photonic analog of semiconductor?



photonic band gap

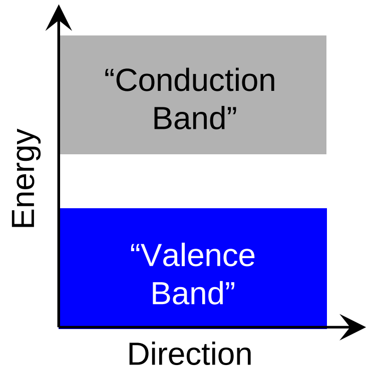
(Yablonovitch and John, 1987)

Can such materials exist?

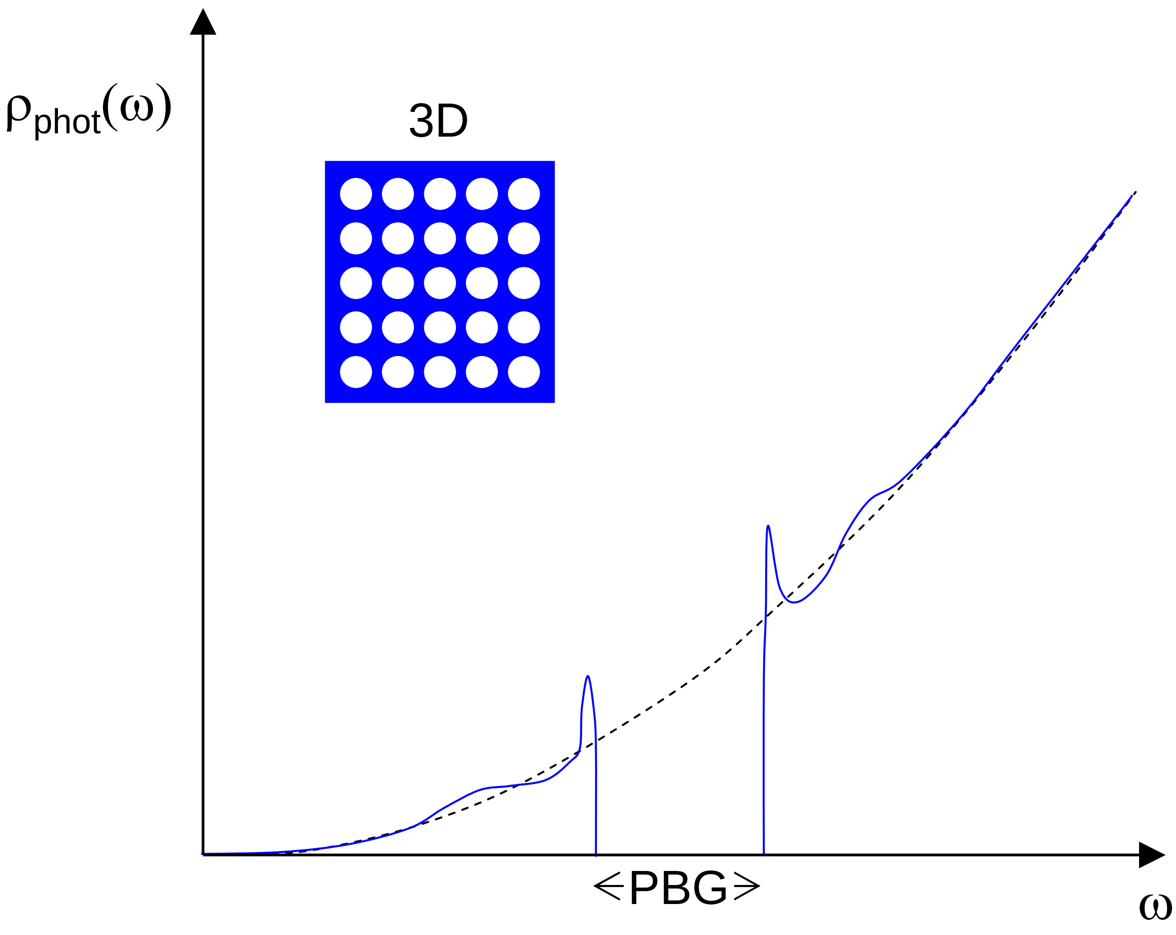
What are the implications of a photonic band gap?

Photonic Band Gap:

Ultimate control over the photonic density of states

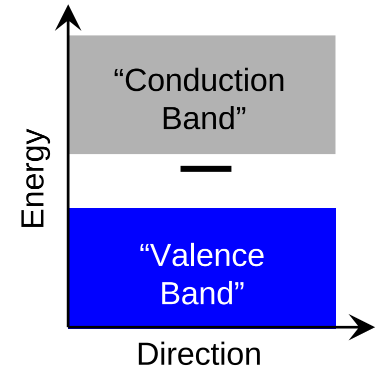


$$\Gamma_o \propto \rho_{elec}(\omega) \cdot \rho_{phot}(\omega)$$

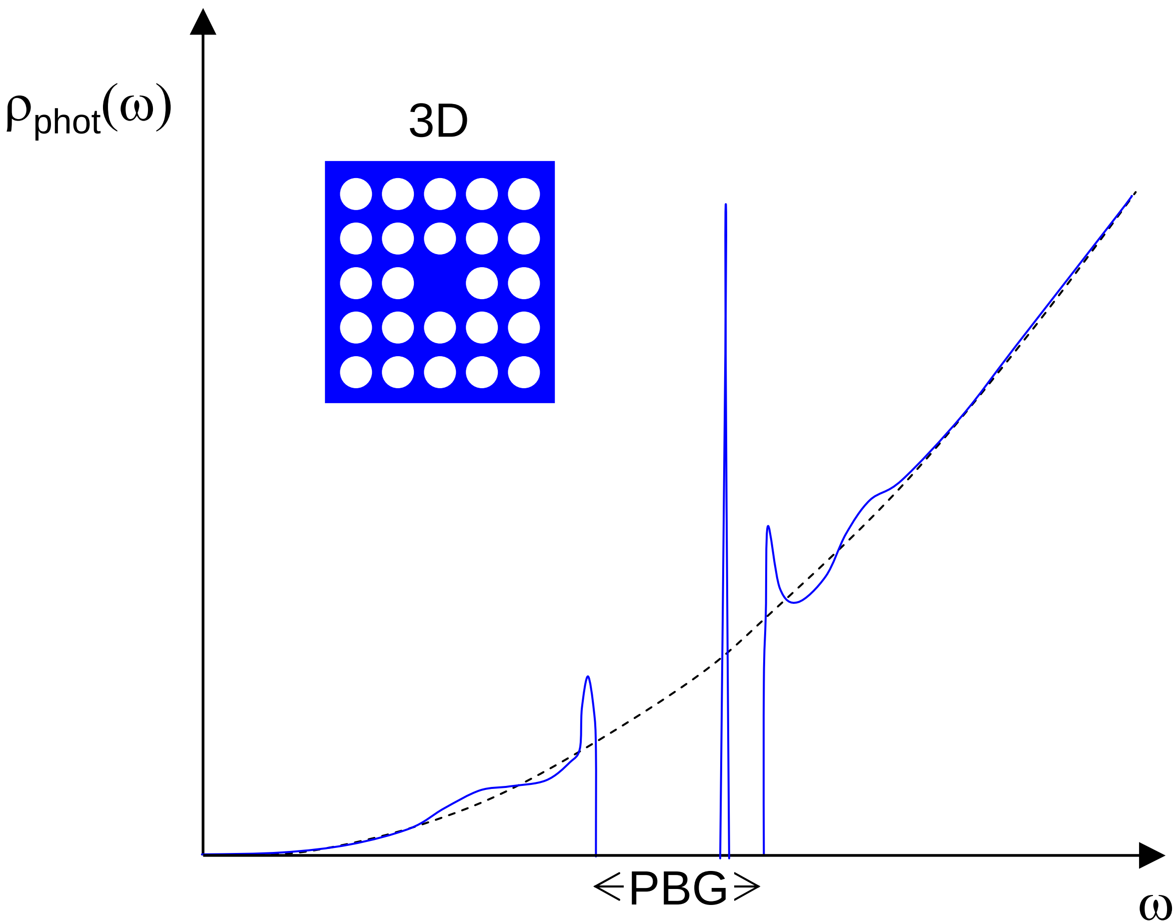


Photonic Band Gap:

Ultimate control over the photonic density of states

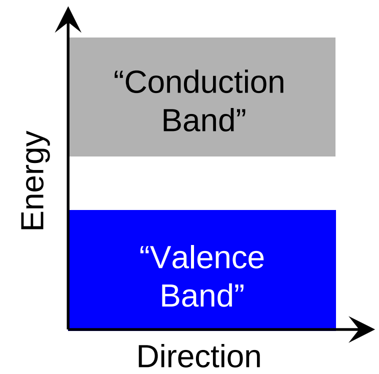


$$\Gamma_o \propto \rho_{elec}(\omega) \cdot \rho_{phot}(\omega)$$



Photonic Band Gap:

Ultimate control over the photonic density of states



$$\Gamma_o \propto \rho_{elec}(\omega) \cdot \rho_{phot}(\omega)$$

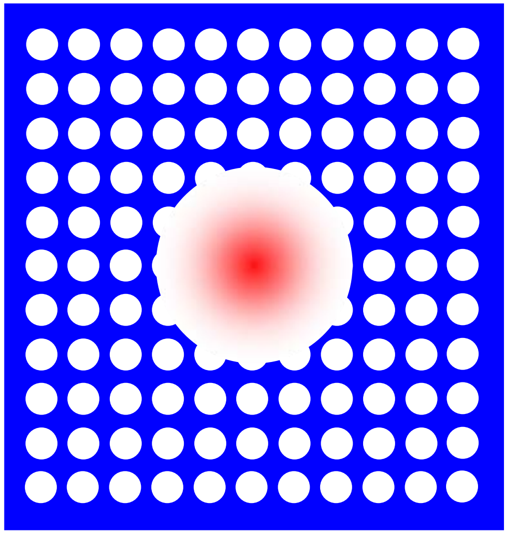
Implications:

Control photonic density of states
From zero to extremely high values!

But what causes a material to have a PBG?

Photonic Band Gap:

3D PBG Material



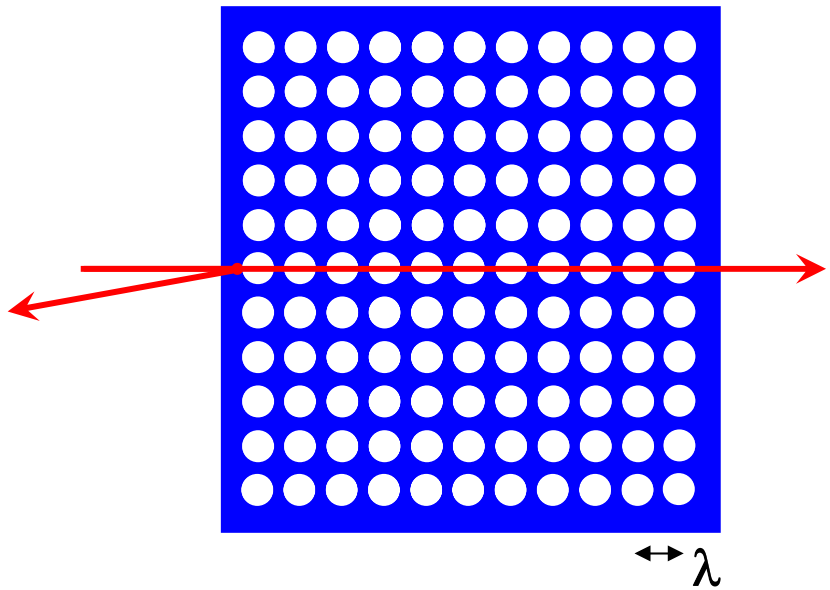
Structure always scatters light backward

- Light cannot travel through the material
- Because density of states is zero
- Instead, light is Bragg diffracted backwards
- Light can become trapped at a defect site where the density of states is high

Strong Bragg Diffraction:

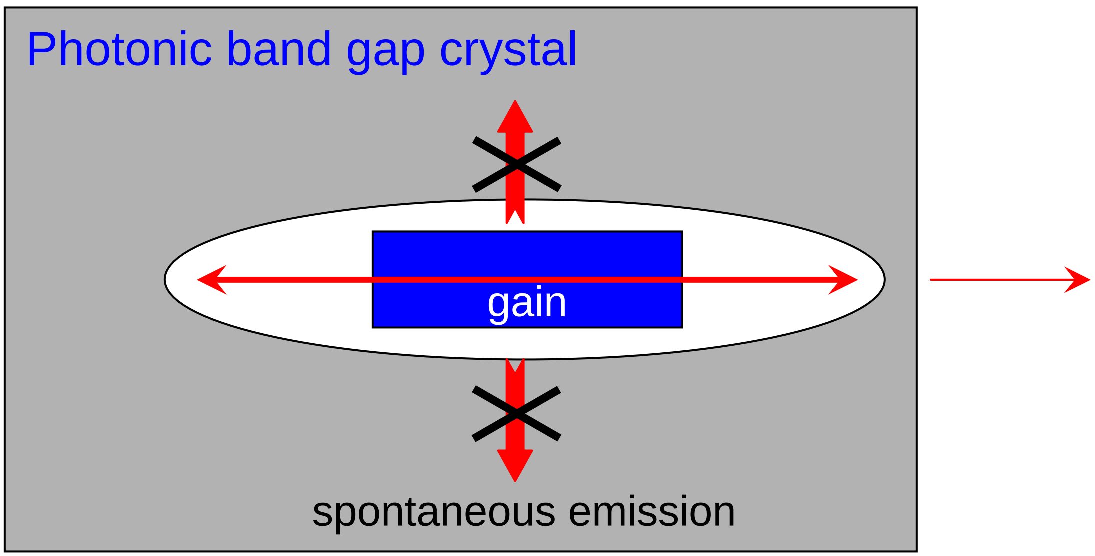
Implies periodic structure is necessary:

- Analogy with X-ray diffraction
- Here diffracted wave is an optical beam
- Thus, photonic crystal must be periodic on an optical length scale
- Need strong scattering, so must have a high refractive index contrast



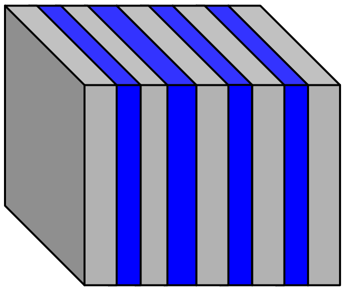
Yablonovitch's original idea:

Device inside photonic crystal:

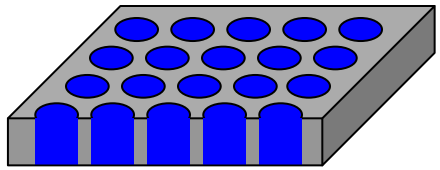


Complete control over wasteful spontaneous emission in unwanted directions

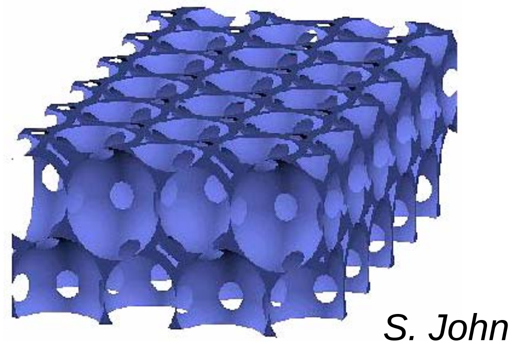
Photonic crystals: experiment



1D



2D

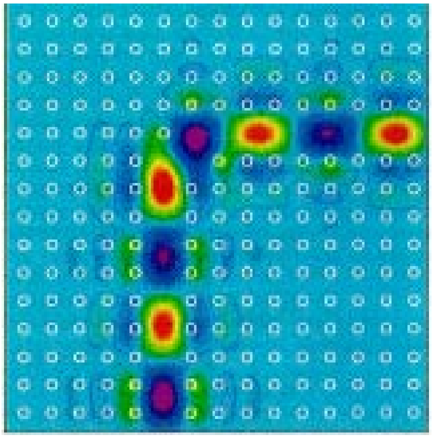


3D

Original Idea: 3D Crystal

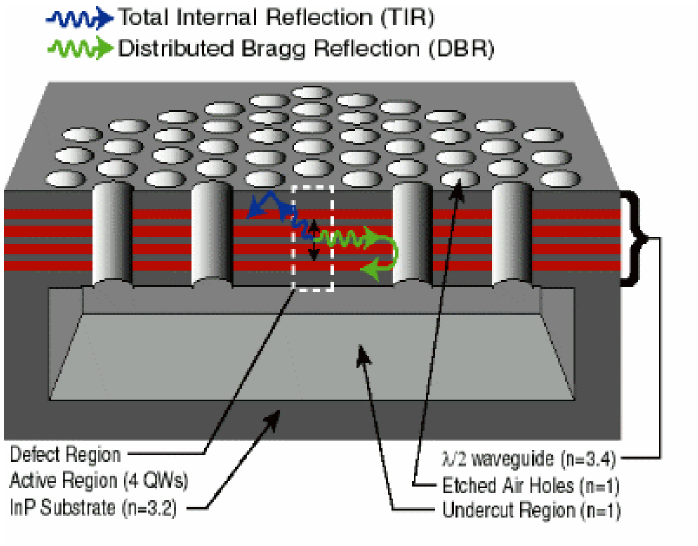
- Only 3D crystal can have a “complete” PBG
- But difficult to fabricate
- Researchers explored 1D and 2D crystals

Tremendous progress in 2D photonic crystals



photonic crystal
waveguides

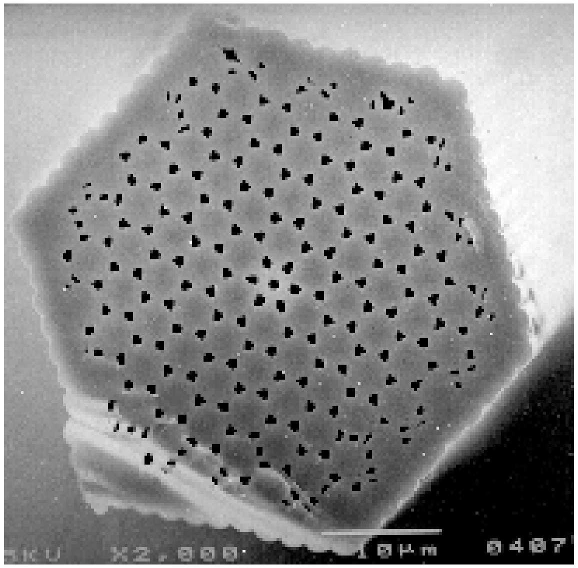
*Mekis et al., PRL **77**, 3787 (1996)*



photonic crystal
laser

*Painter et al., Science **284**, 1819 (1999)*

Photonic Crystal Fibers



Russell Group (Bath)

photonic crystal fibers

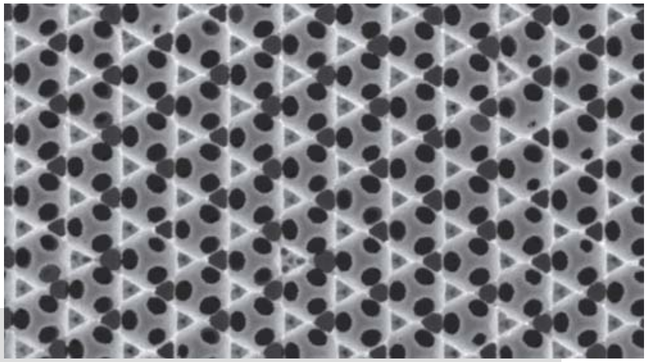
Guiding light in air:

13dB/km - *Venkataraman et al.*

Enhanced optical nonlinearities:

Low Threshold Stimulated Raman
*Benabid et al., Science **298**, 399 (2002)*

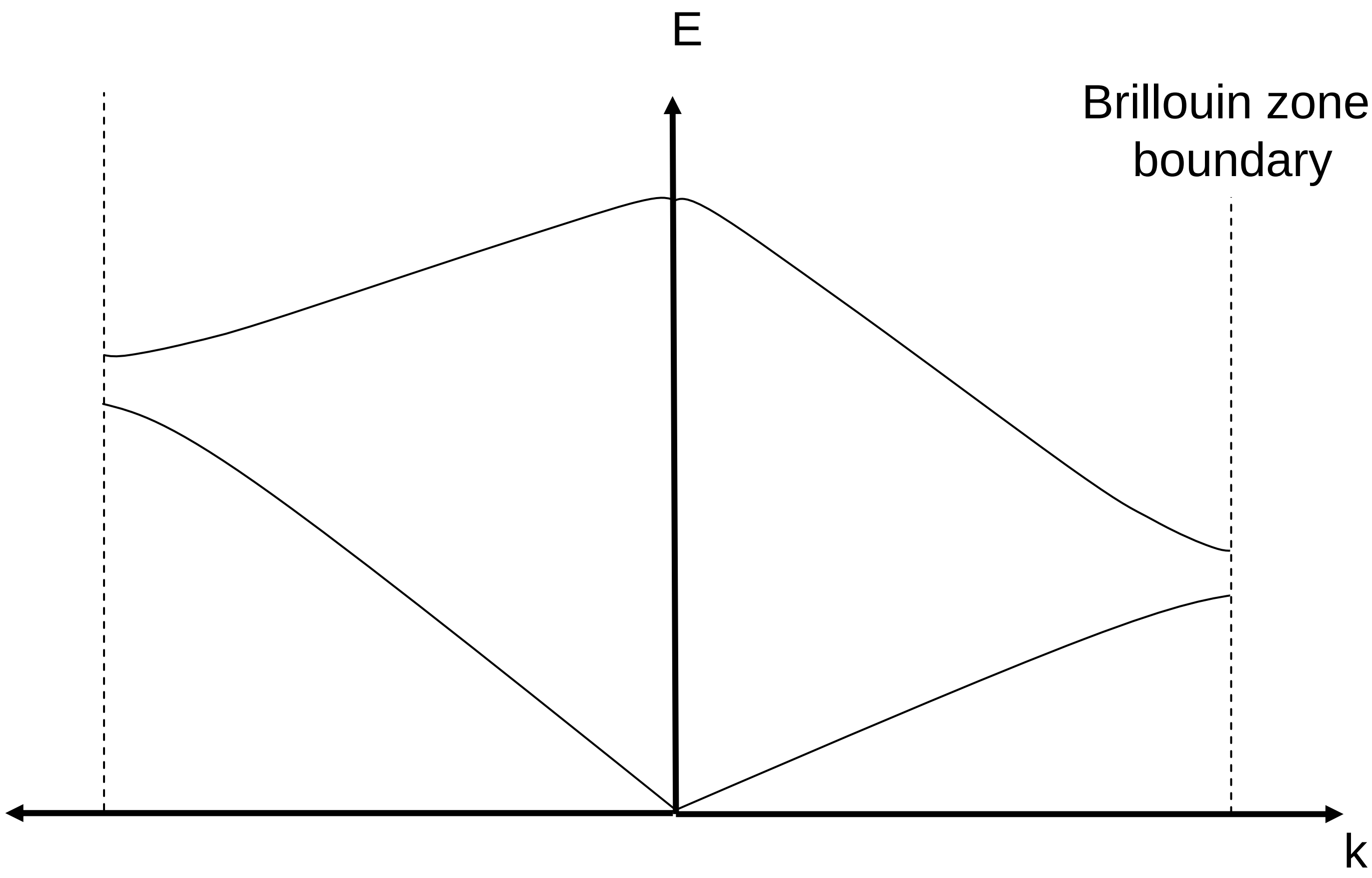
Beyond 2D Photonic Crystals:



- Complete photonic band gap requires 3D photonic crystal
- Much more challenging to fabricate
- What structure do we need?
- Best approach to make?

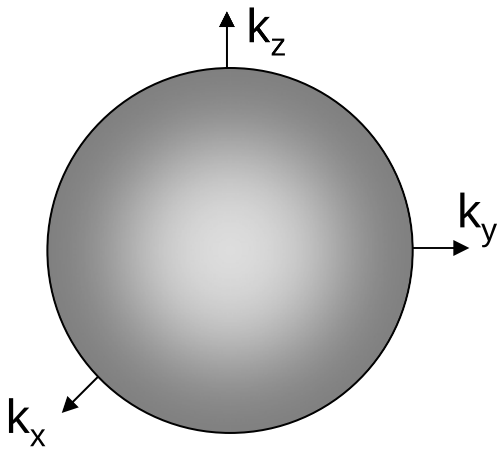
Which Crystal Structure?

We need intuition . . .

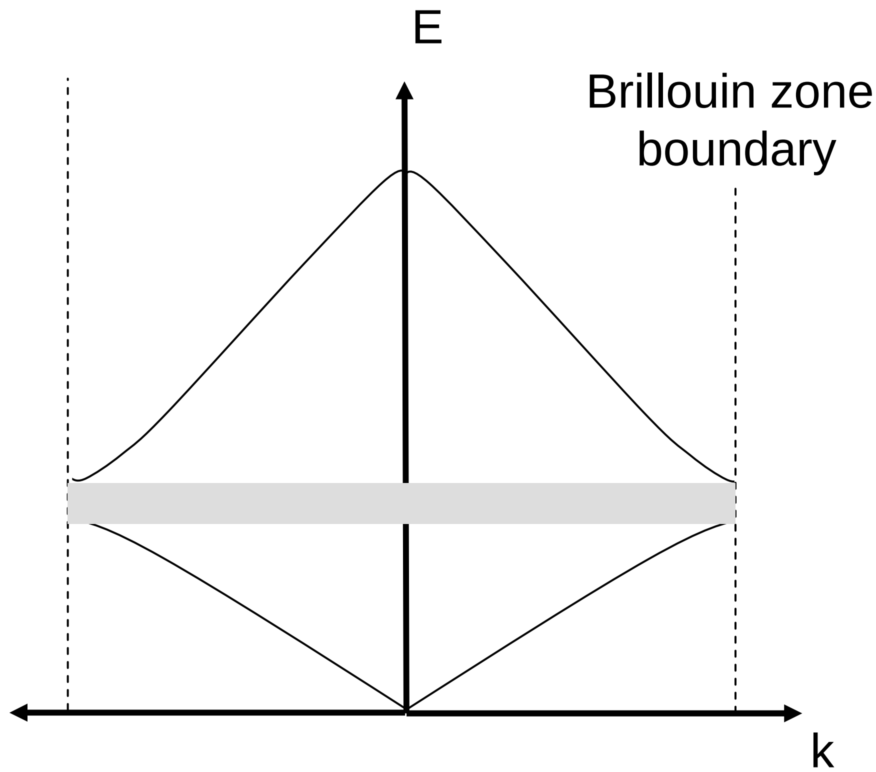


For complete gap want spherical Brillouin zone

ideal

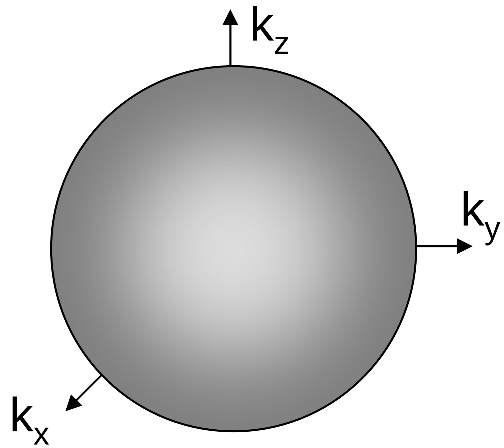


Brillouin zone
in reciprocal space



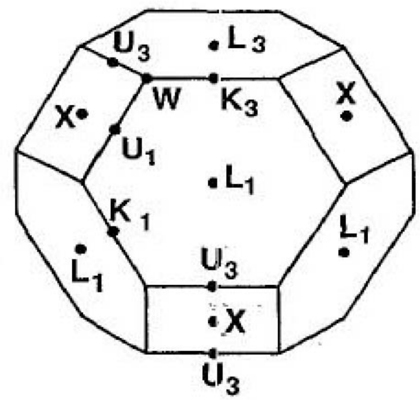
Unfortunately, nature does not provide this . . .

ideal



Brillouin zone
in reciprocal space

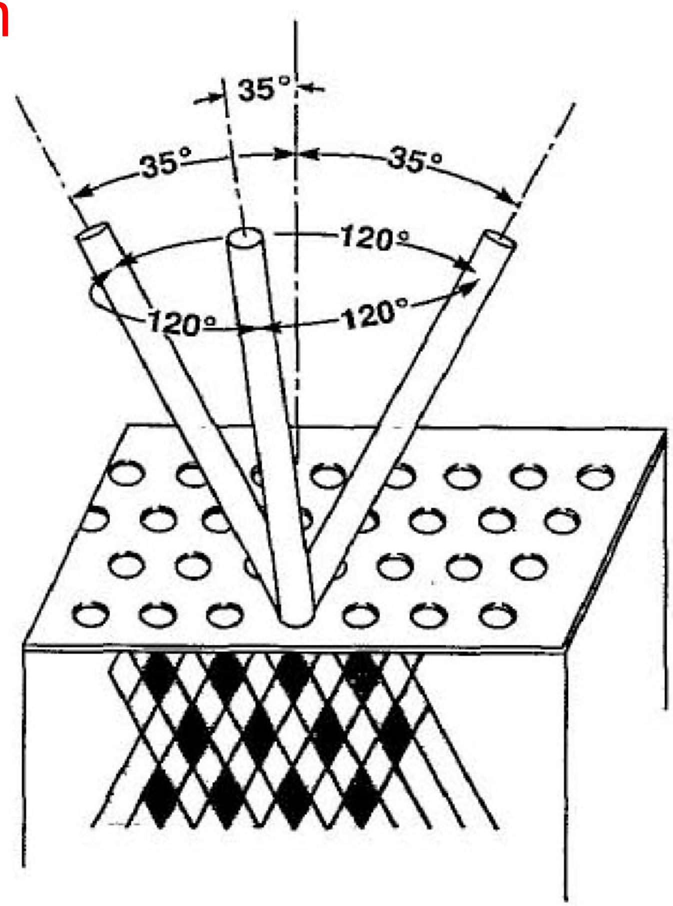
fcc



Most sphere-like

Experimental realization

fcc with non-spherical atoms

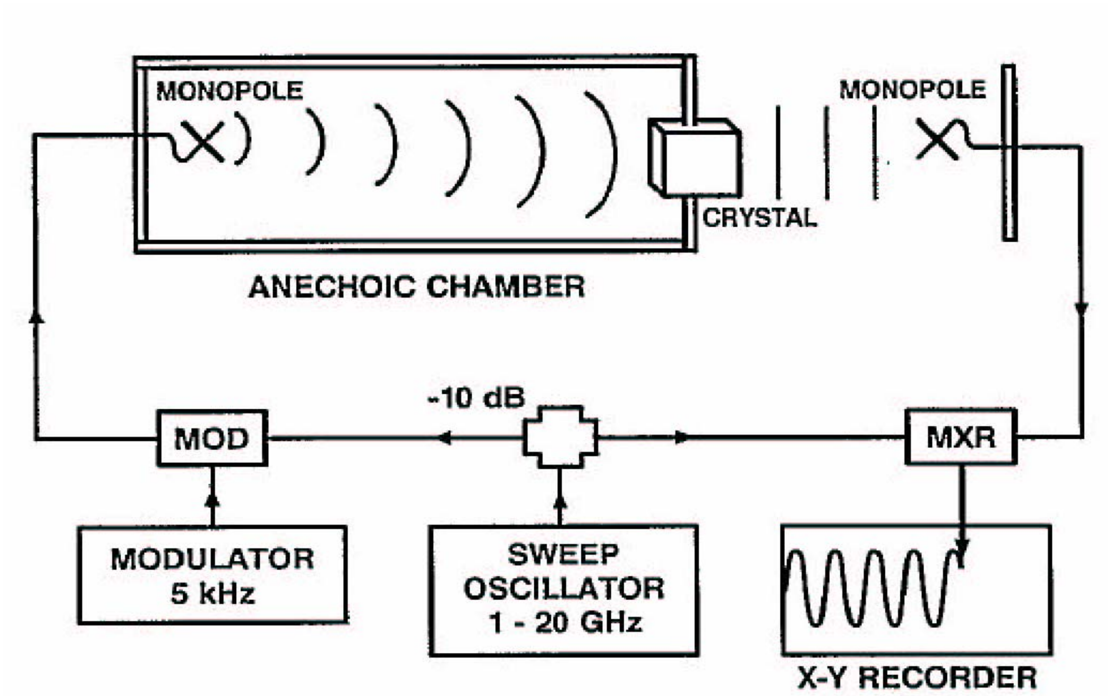


Expt: Yablonovitch & Gmitter; PRL **61**, 1950 (1989).
Yablonovitch, Gmitter, & Leung; PRL **67**, 2295 (1991).

Theory: Leung & Liu; PRL **65**, 2646 (1990).
Zhang & Satpathy; PRL **65**, 2650 (1990).
Ho, Chan, & Soukoulis, PRL **65**, 3152 (1990).

Measurement of the photonic band gap

Microwave Structures:

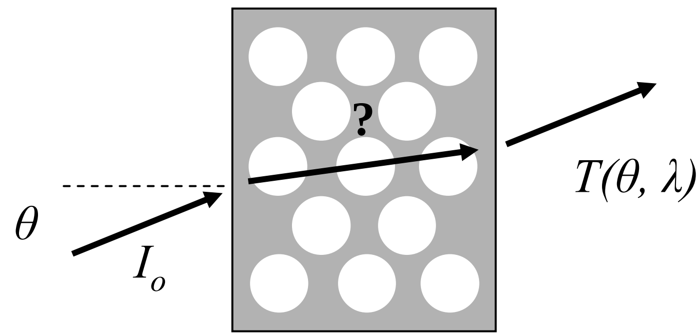


probe transmission for all directions of the Brillouin zone

Yablonovitch, Gmitter, & Leung; PRL **67**, 2295 (1991).

Experimental difficulty:

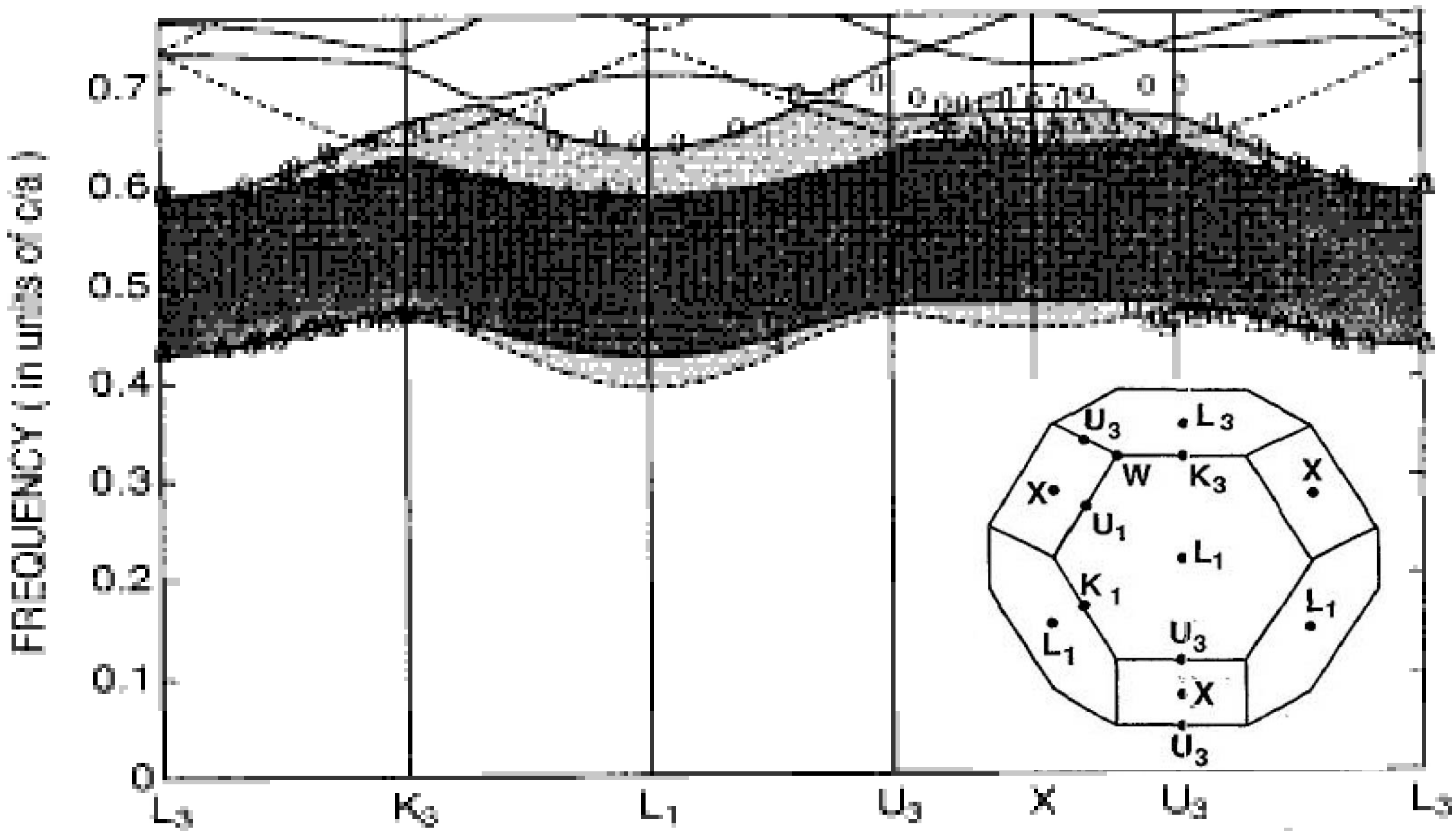
Breakdown of Snell's law



- measure transmission vs. propagation direction
- refractive index varies near photonic band gap
- don't know internal propagation direction
- solution: measure phase of transmitted photons

Demonstration of a photonic band gap

Microwave Structures:



Yablonovitch, Gmitter, & Leung; PRL **67**, 2295 (1991).

What about an optical photonic band gap?

Photon physics is exactly the same

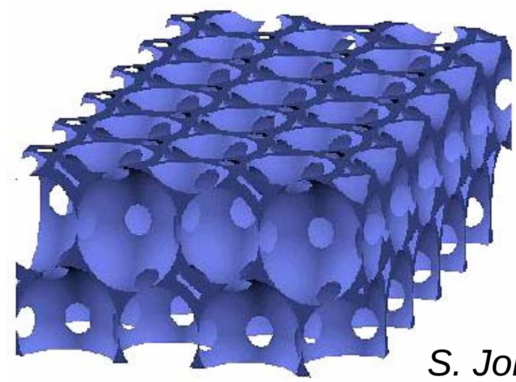
Requirements:

- 3D periodicity
- size of unit cell on the order of λ
- ideal structure is mostly "air"

  ~80%
- large refractive index necessary

  >2 (ideal case)

  >3 (typical)

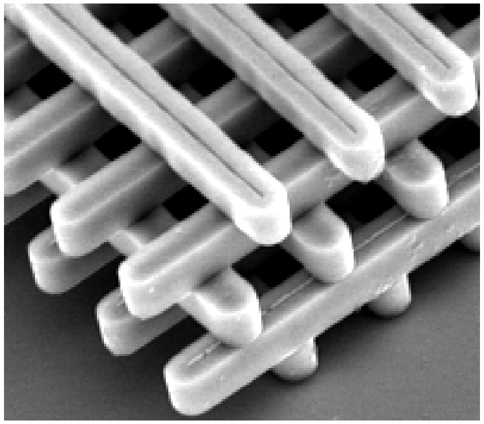


S. John

Best material: semiconductors

- high refractive index
- convenient electronic and optical properties
- integrate photonic crystals into optoelectronics

But how do we make 3D photonic band gap crystals?



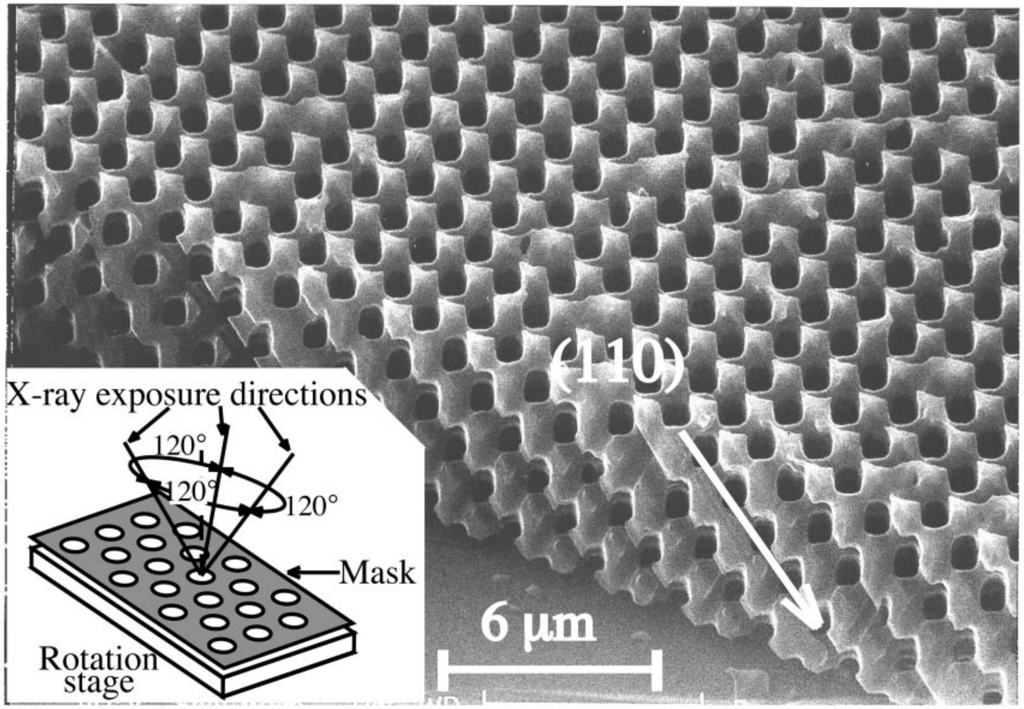
S. Lin et al., Nature ***394****, 251 (1998)*

"Layer by Layer" Nanofabrication:

Advantages:	excellent control of structure
	optical band gap demonstrated
Challenges:	expensive

Alternative Approaches: X-ray Lithography (LIGA)

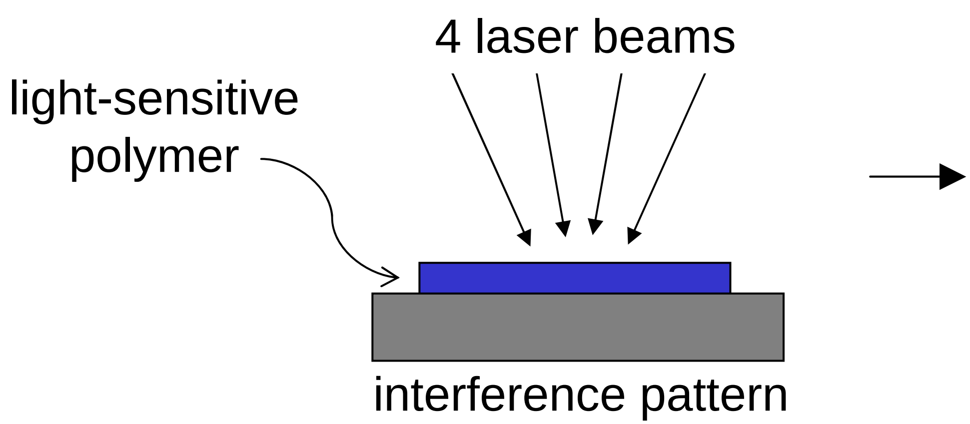
Feiertag et al., APL ***71****, 1441 (1997); C. Cuisin et al., APL* ***77****, 770 (2000).*

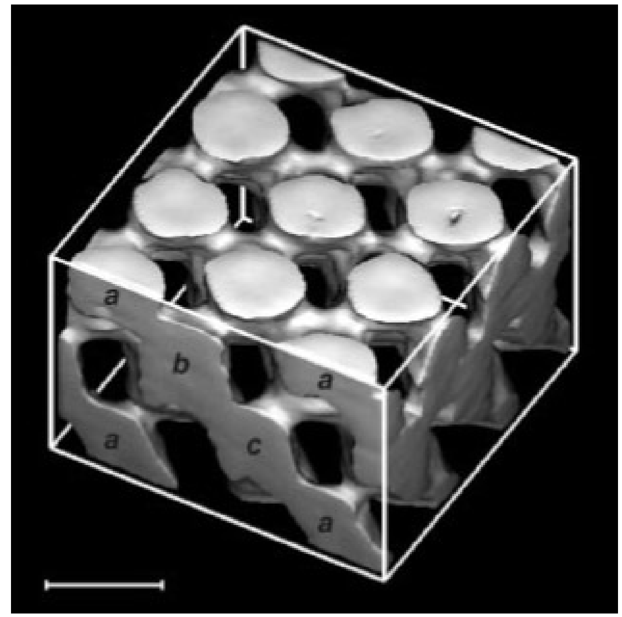


Advantages:	good control; makes Yablonovite
Challenges:	difficulties with mask
	makes polymer template
	to date: no photonic band gap

Alternative Approaches: Laser Holography

*M. Campbell et al., Nature **404**, 53 (2000).*

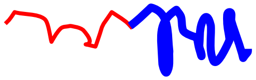




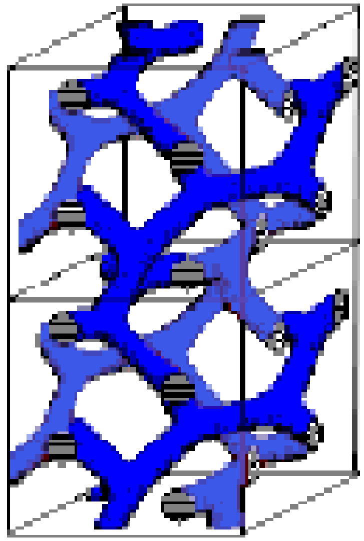
Advantages: simple “one shot”, good control
Challenges: makes polymer template
to date: no band gap

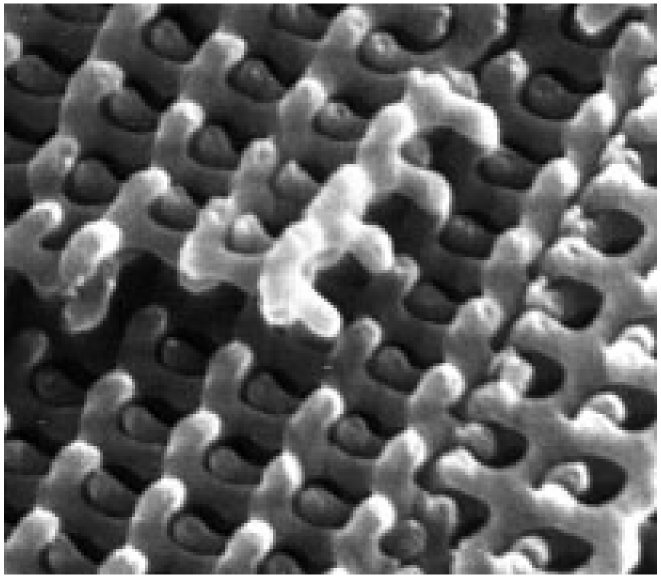
Alternative Approaches: Block Copolymers

Urbas, Maldovan, DeRege, and Thomas; Adv. Mater. ***14****, 1850 (2002).*



AB diblock

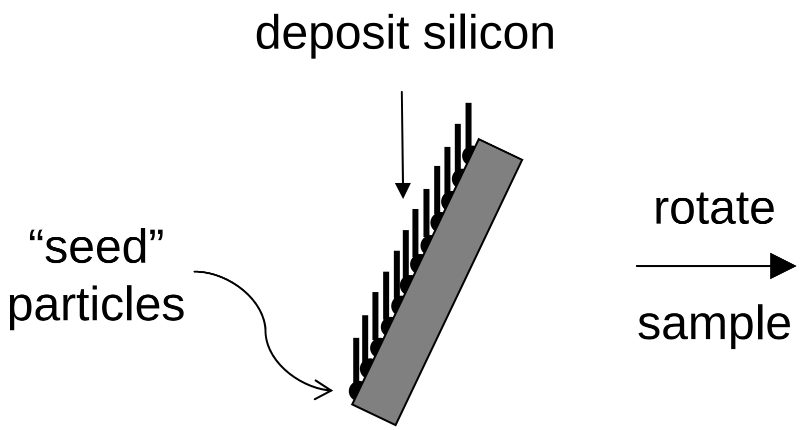


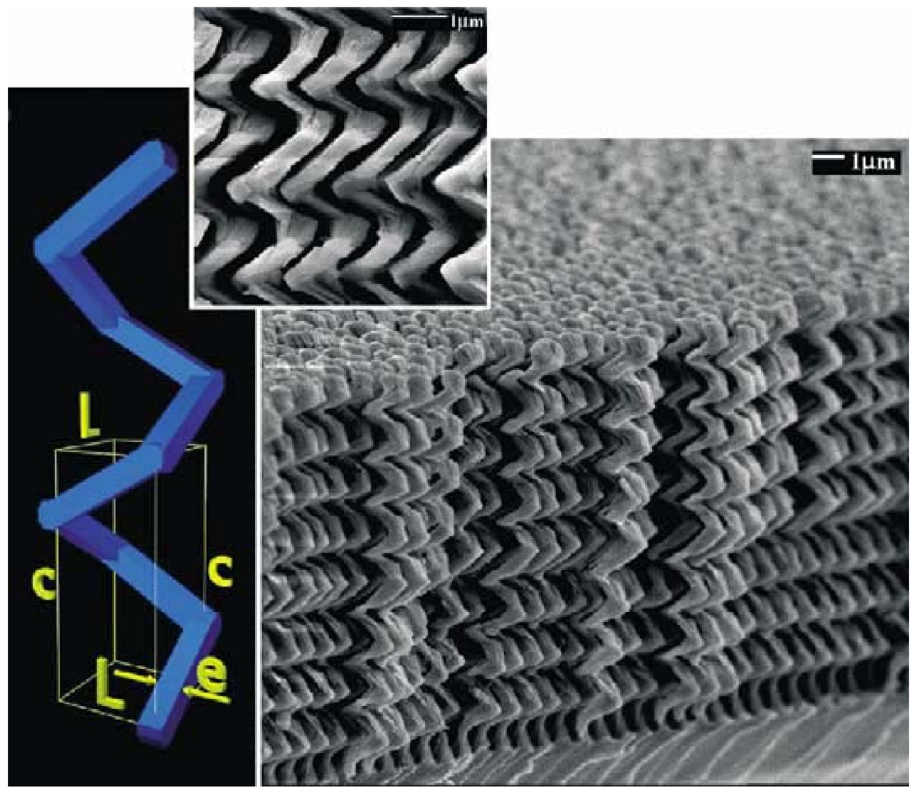


Advantages:	simple technique
Challenges:	makes polymer structure
	disorder?
	to date: no band gap

Alternative Approaches: Glancing Angle Deposition

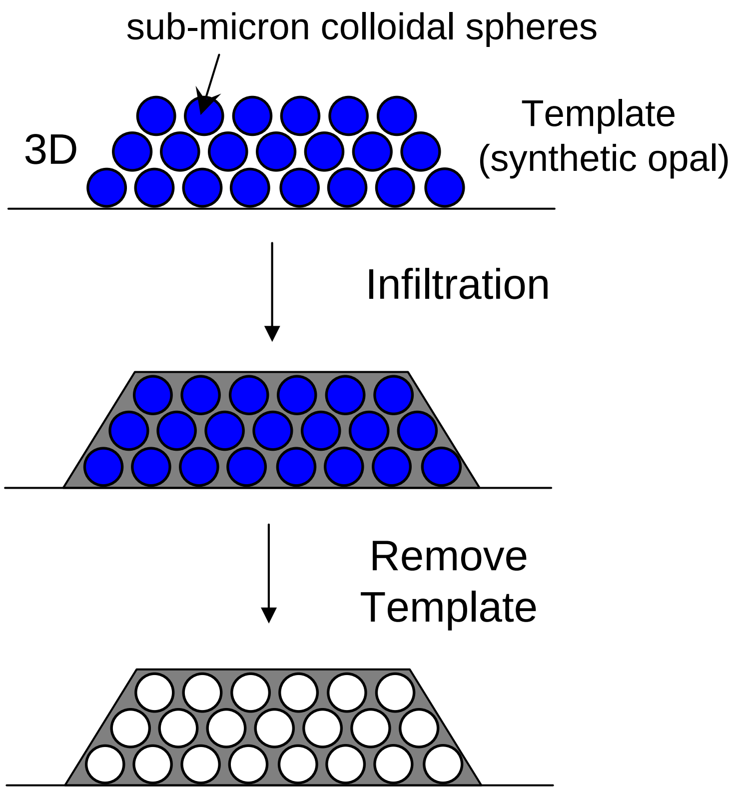
Kennedy, Brett, Miguez, Toader, and John; Photonics and Nanostructures ***1****, 37 (2003).*





Advantages:	simple technique
	band gap demonstrated
Challenges:	disorder under control?

Our Approach: Colloidal Self-Assembly



"Inverted Opal"

Literature Results:

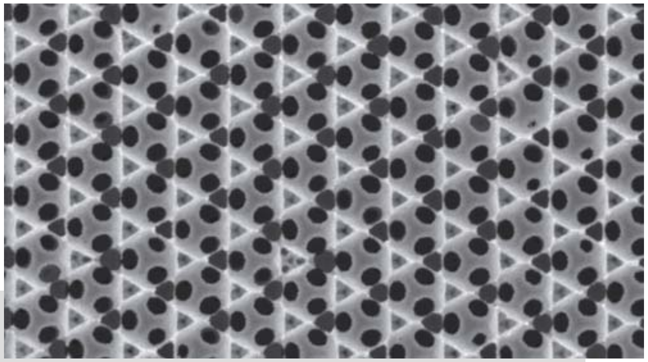
O. D. Velev *et al.*, *Nature* **1997**, *389*, 447.
D. Pine *et al.*, *Nature* **1997**, *389*, 948.
G. Stucky *et al.*, *Science* **1998**, *279*, 548.
A. Stein *et al.*, *Science* **1998**, *281*, 538.
W. Vos *et al.*, *Science* **1998**, *281*, 802.
A. A. Zakhidov *et al.*, *Science* **1998**, *282*, 897.
T. E. Mallouk *et al.*, *Science* **1999**, *283*, 963.
V. L. Colvin *et al.*, *PRL* **1999**, *83*, 300.
A. Blanco *et al.*, *Nature* **2000**, *405*, 437.

Theory: inverted opals have a PBG

Haus *et al.*, PRB, **45**, 13962 (1992).
Busch and John, PRE, **58**, 3896 (1998).

Requires refractive index > 2.85

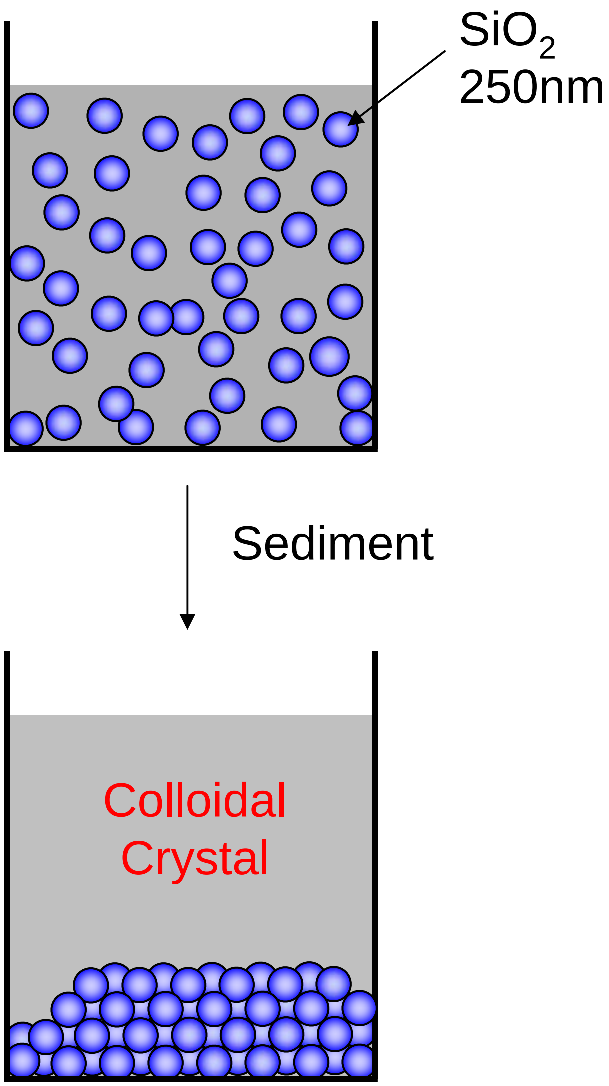
Colloidal Self-Assembly:

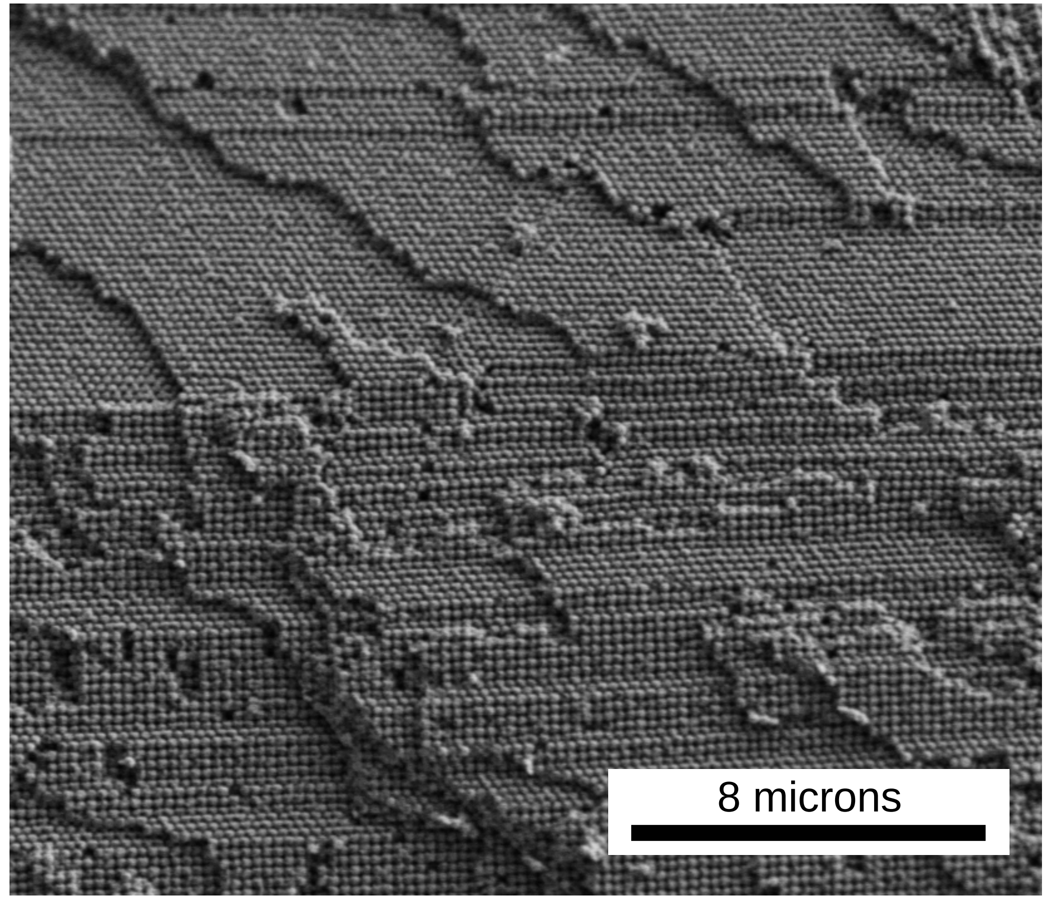


Challenges: control disorder?
devices?

Can this approach lead to useful photonic band gaps?

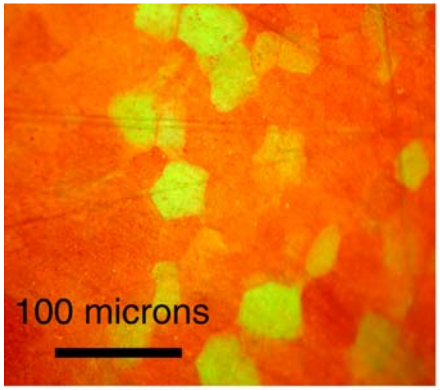
Initial approach to opals: sedimentation





dry and collect sediment → synthetic opal

What about disorder? Self-assembly makes mistakes!



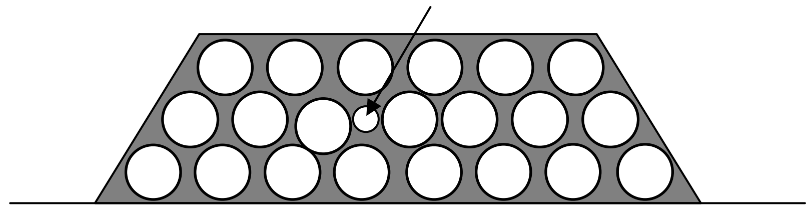
synthetic opal

natural gemstone opal

Problems

- Opals have disorder
- First, opals are polycrystalline
- Beautiful in gemstone; bad for photonics
- Also, other defects (vacancies, stacking faults, *etc.*)

Inverted Opals and Disorder:



Serious question:

- Will photonic band gap exist in self-assembled materials?

  disorder can destroy photonic band gap

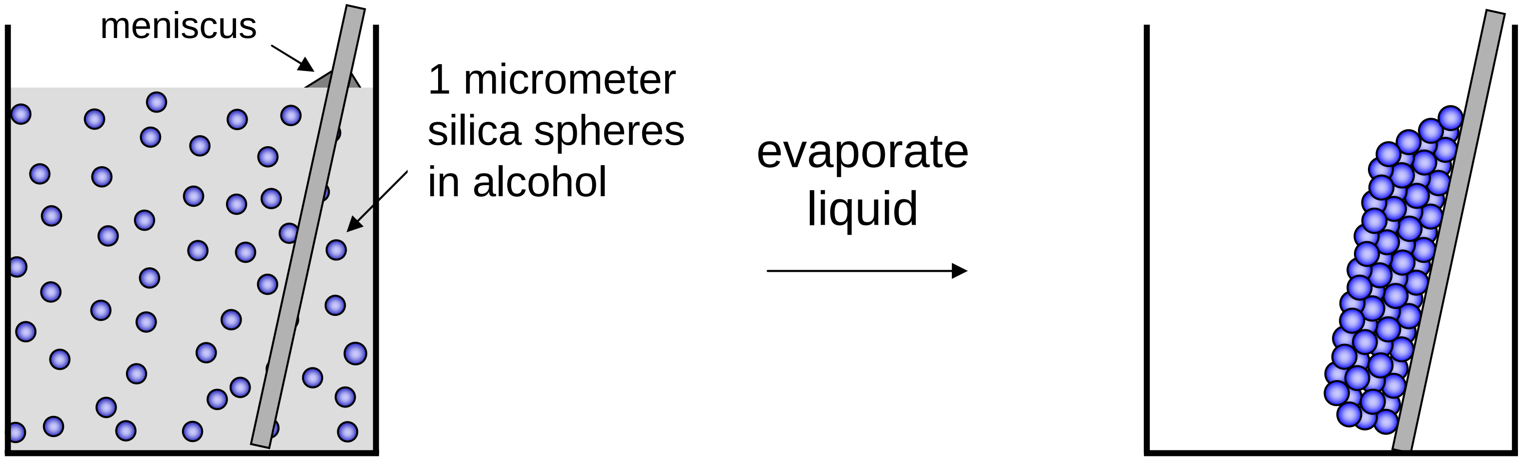
Theory: 4% deviation in “bubble spacing” closes band gap!

Li & Zhang, PRB ***62****, 1516 (2000).*

To reduce disorder: make better opals

"Convective Assembly"

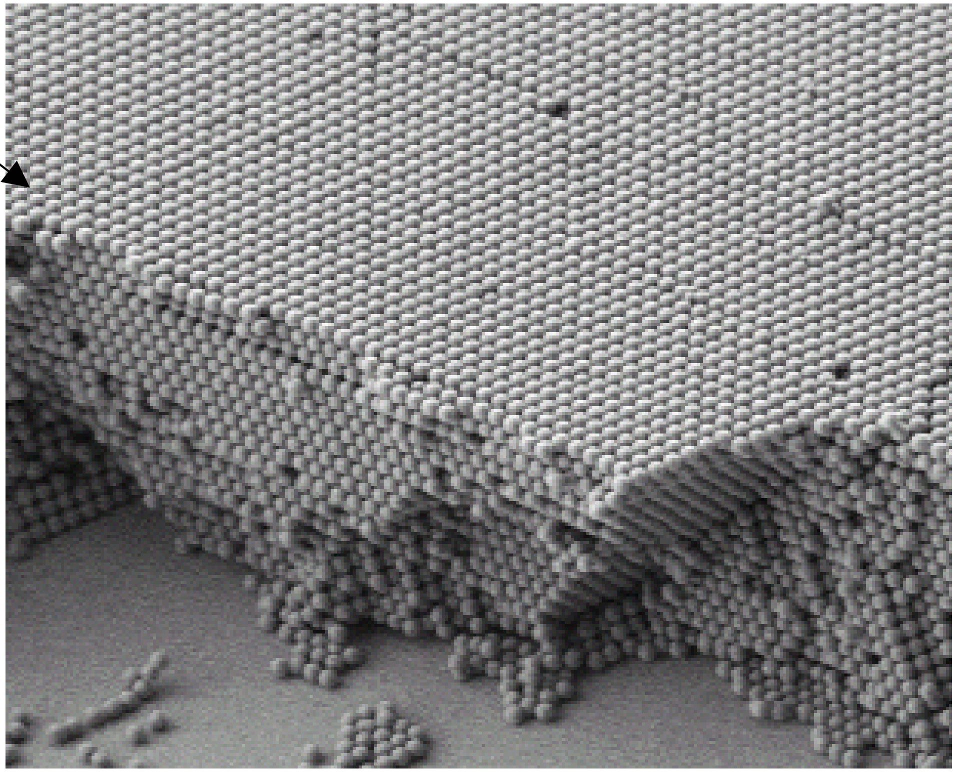
Nagayama, Velev, *et al.*, *Nature* (1993)
Colvin *et al.*, *Chem. Mater.* (1999)
Norris *et al.*, *Nature* (2001)



- Evaporating the liquid causes assembly in the meniscus
- Extremely flat, large-area opals of controllable thickness

Thin opaline coatings

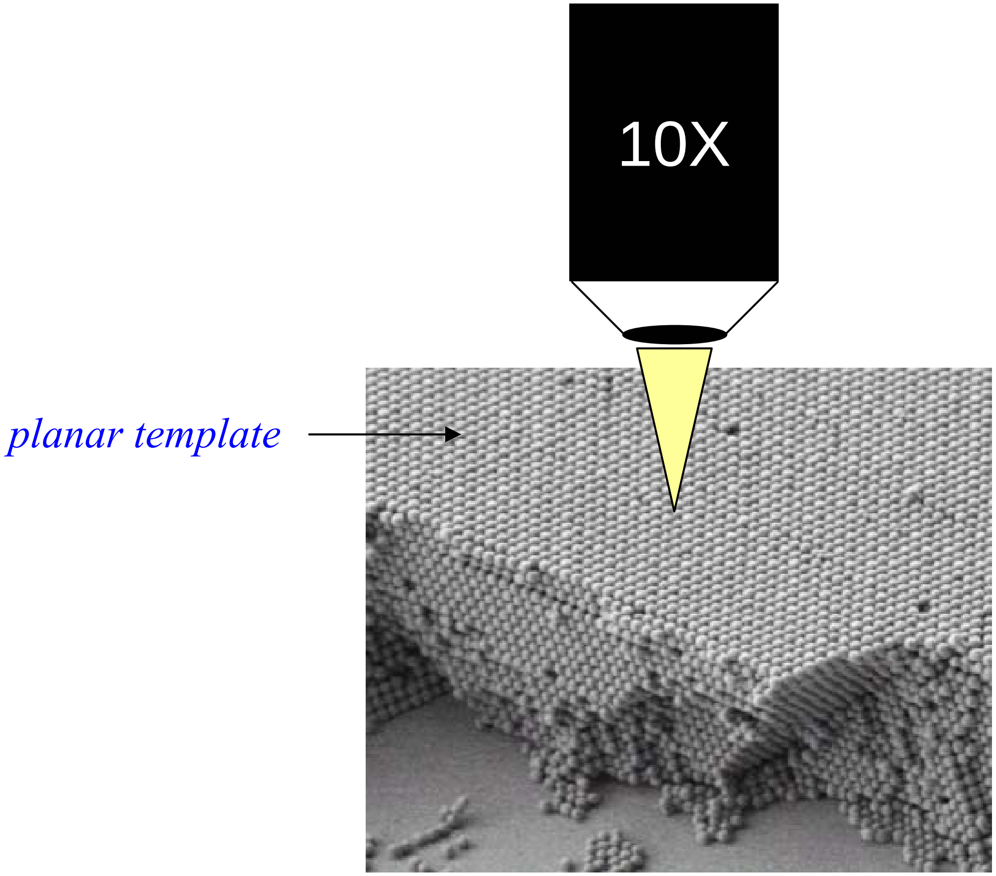
1μm
silica
spheres



infiltrate with semiconductor → photonic band gap in the infrared

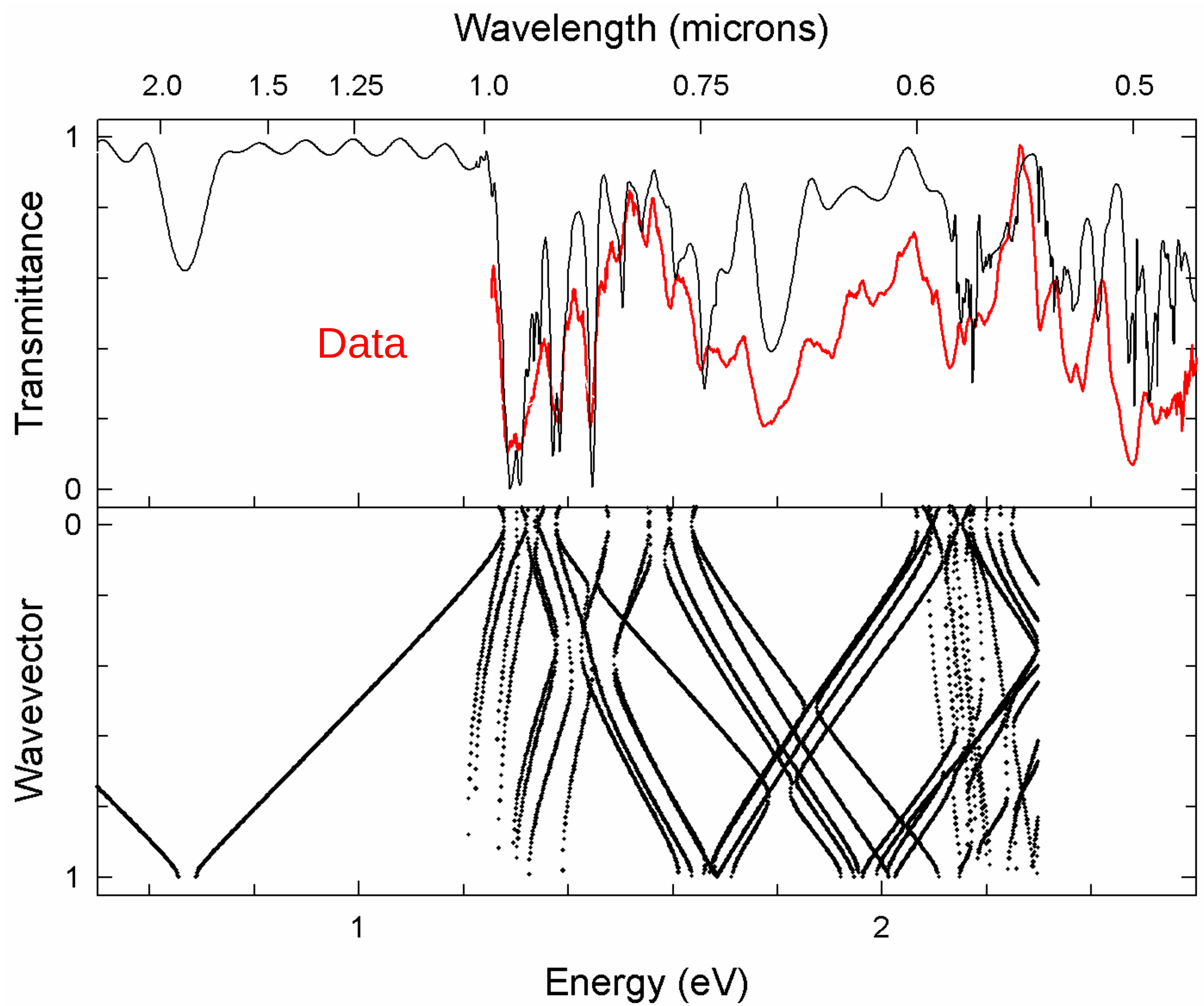
(potentially useful for applications at λ=1.55μm)

But First, What are the Optical Properties?



870nm silica spheres

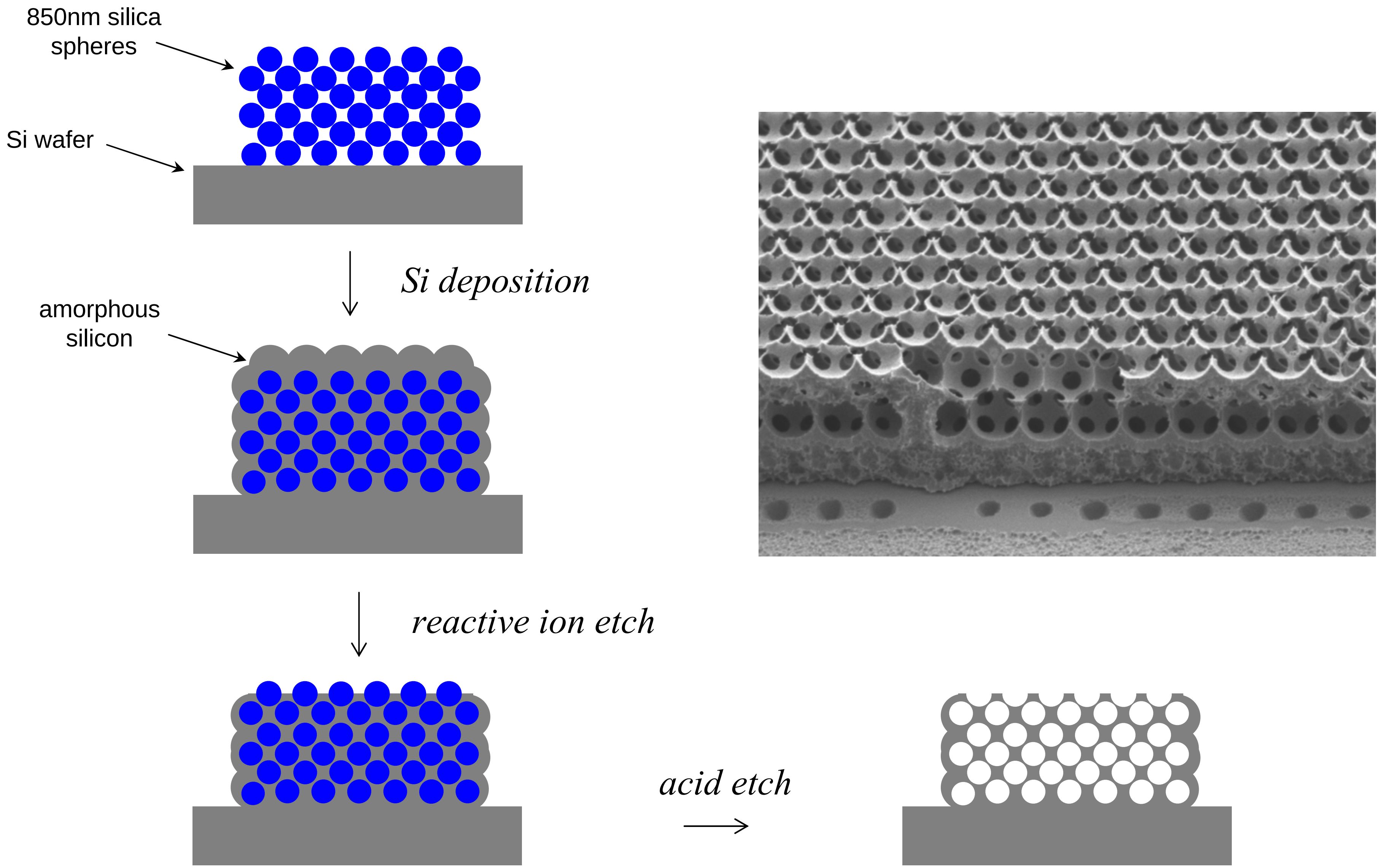
Measure transmission . . .



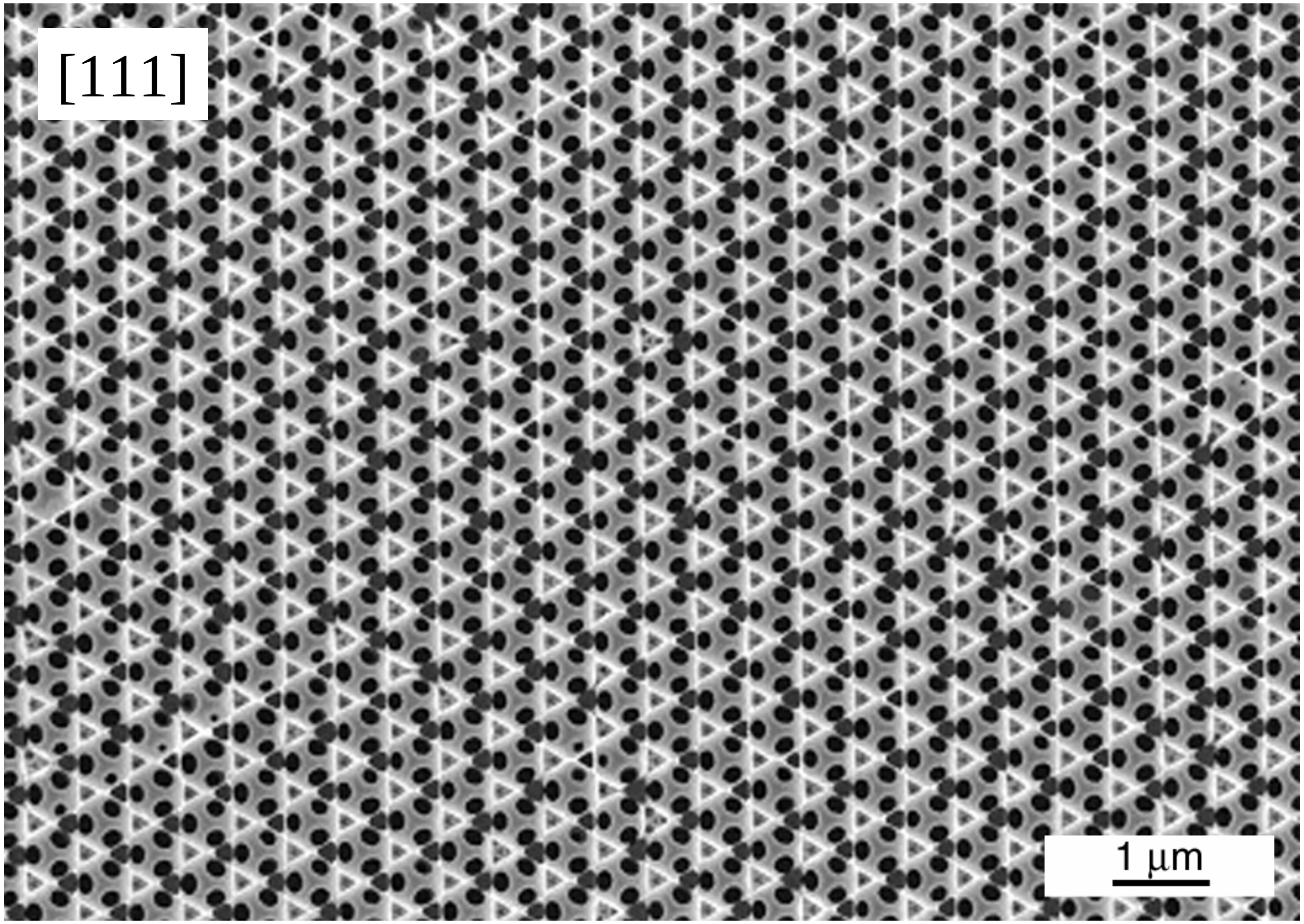
Wavelength (microns)
2.0
1.5
1.25
1.0
0.75
0.6
0.5
Transmittance
1
0
Data
Wavevector
0
1
1
2
Energy (eV)

Silicon Inverted Opal

in collaboration with X. –Z. Bo and J. Sturm (Princeton)

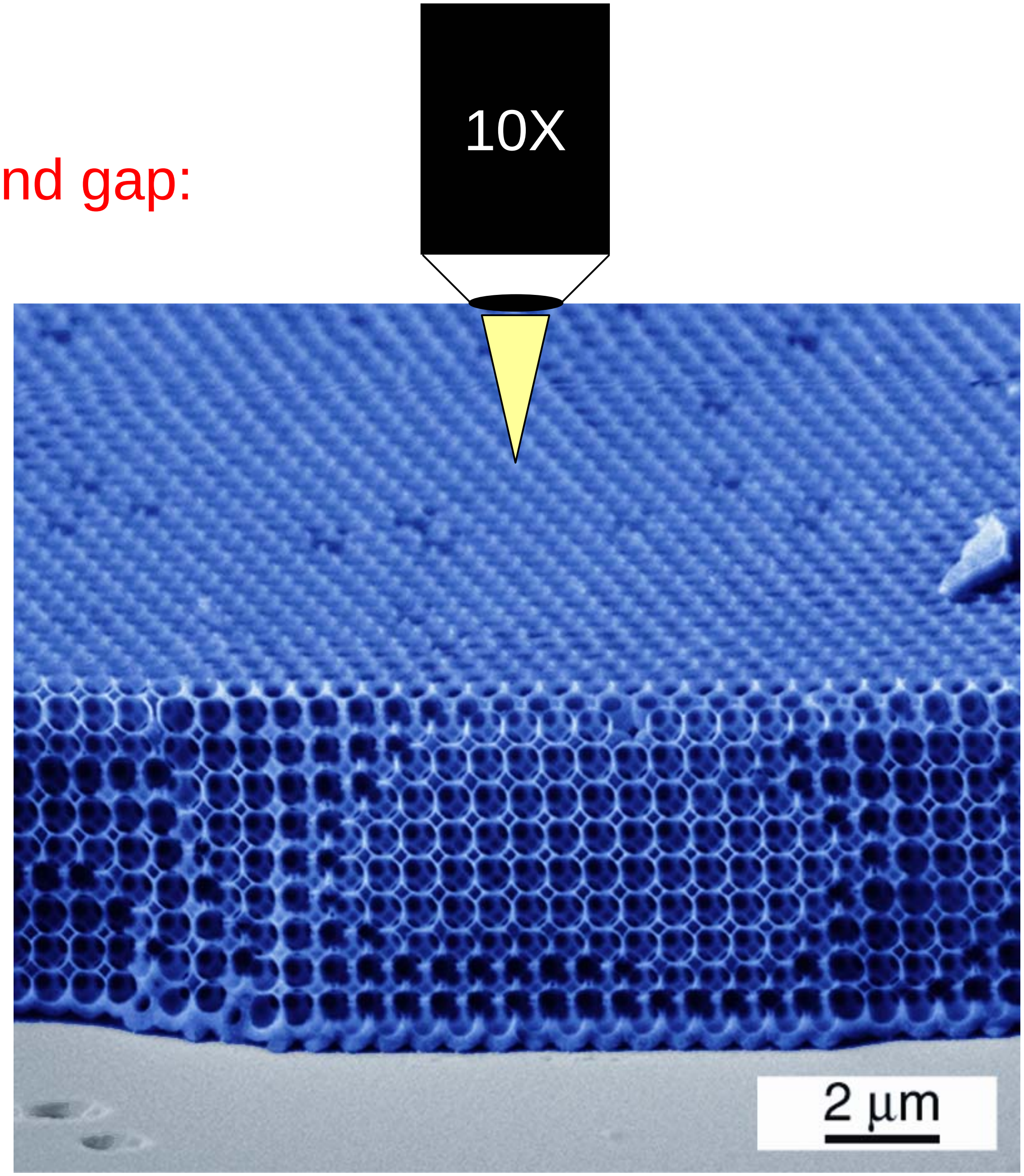


Si inverted opals



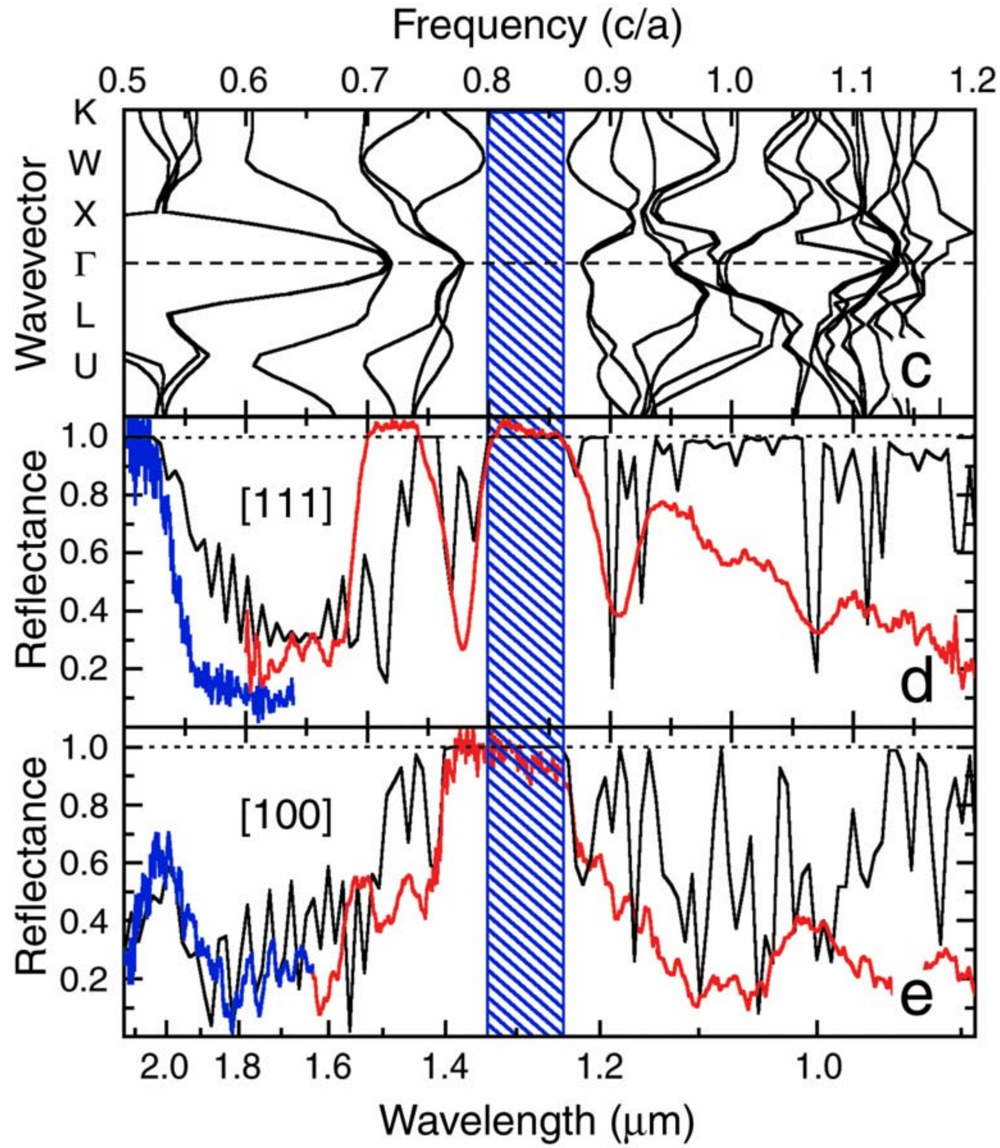
Vlasov, Bo, Sturm, & Norris; *Nature* **414**, 289 (2001).

Testing the
photonic band gap:



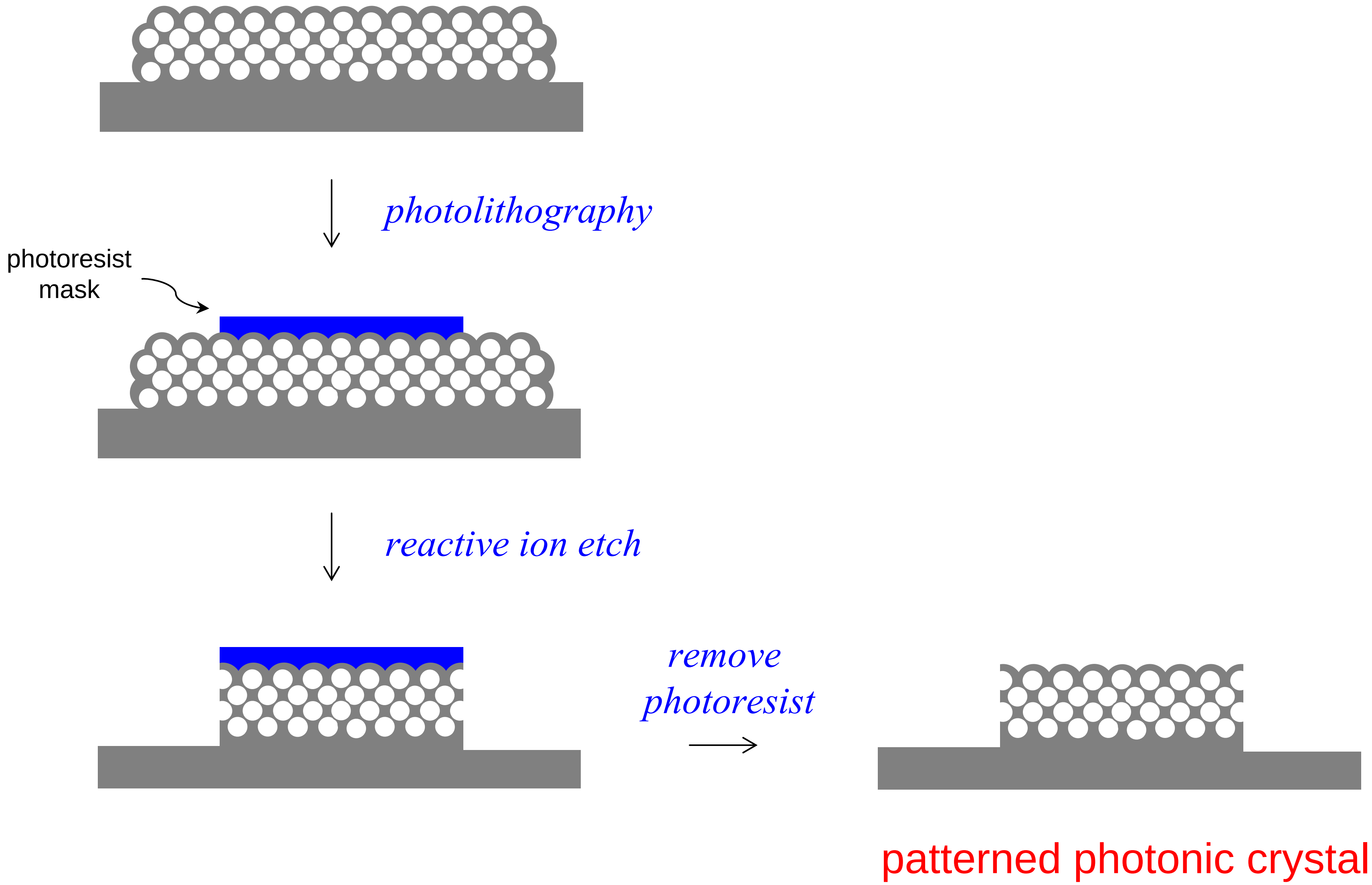
Measure reflection spectra

Testing the Photonic Band Gap

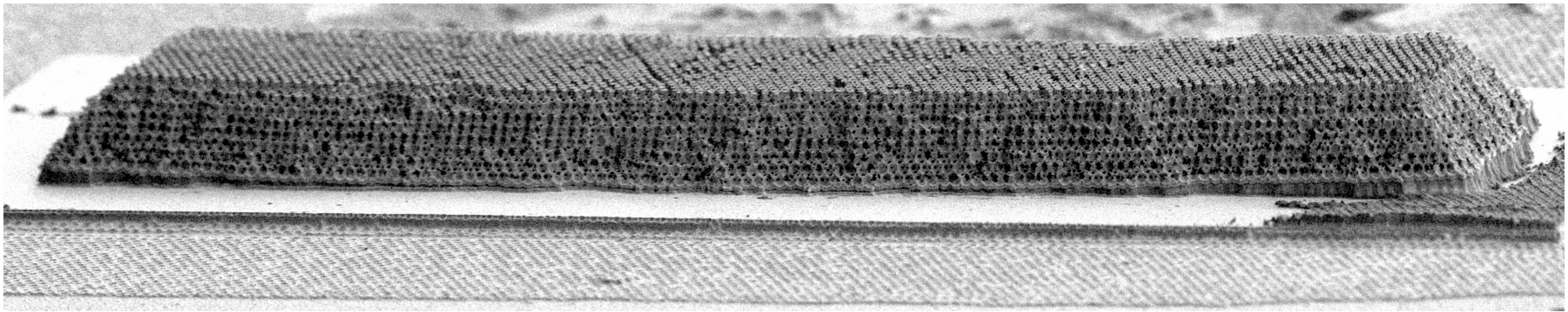


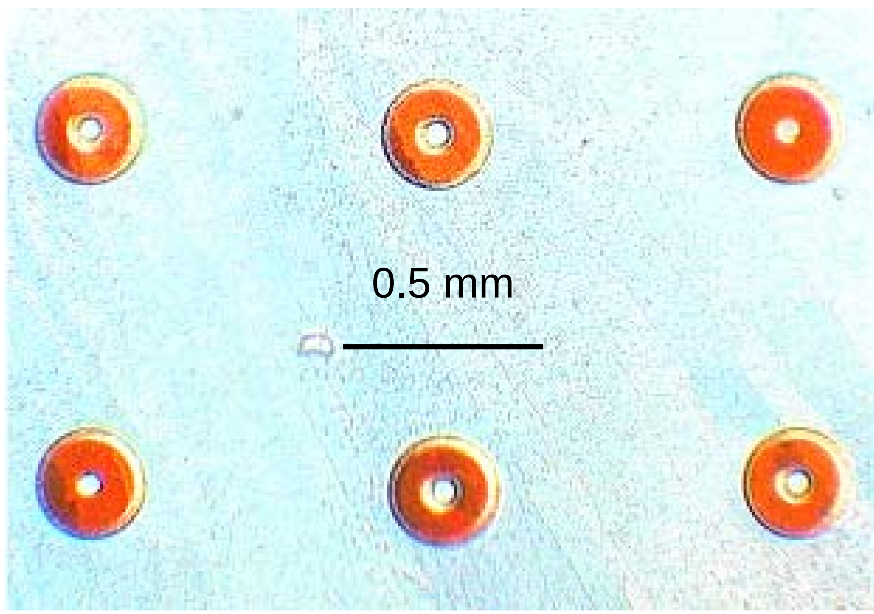
Nature (2001).

Once we have these photonic band gap coatings . . .



Patterned Si Photonic Band Gap Crystals

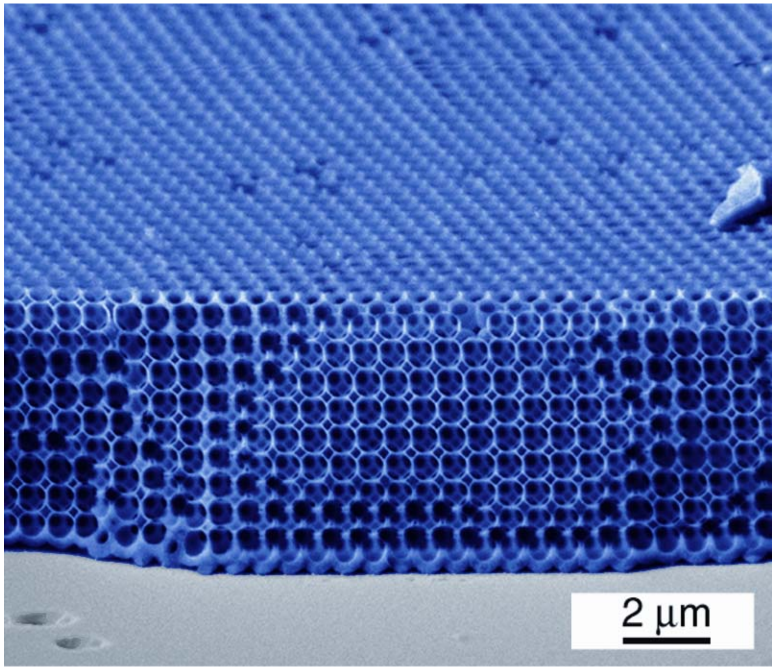




Conclusion:

- Self-assembly can yield structures that have optical properties consistent with a photonic band gap

- Photonic band gap coatings !



Questions:

- How do these materials behave?

- How can we best utilize?

- How does self-assembly work?

Another Possibility:

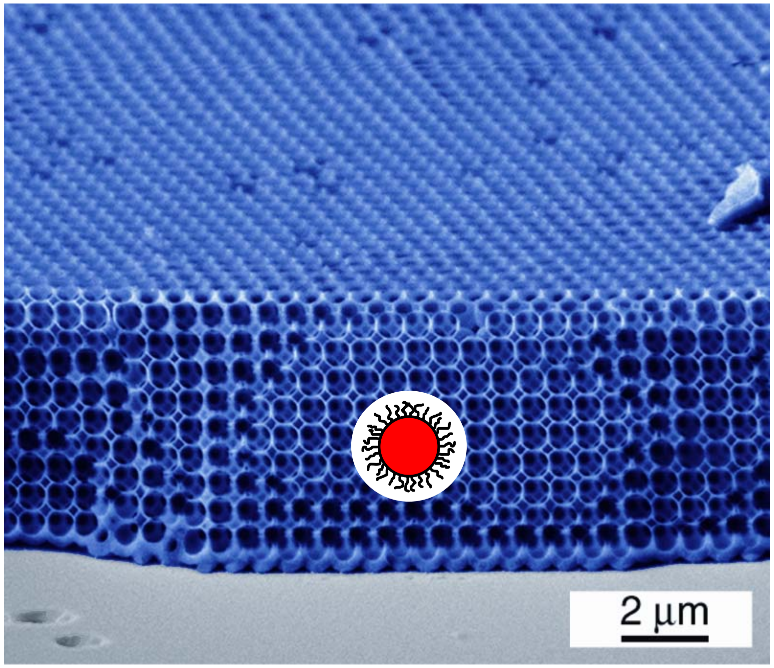
Back to Fermi's Golden Rule

$$\Gamma_o \propto \rho_{elec}(\omega) \cdot \rho_{phot}(\omega)$$

Enhance Both Electronic and Photonic DOS?

quantum dots + photonic crystals?

Combine with quantum dots?

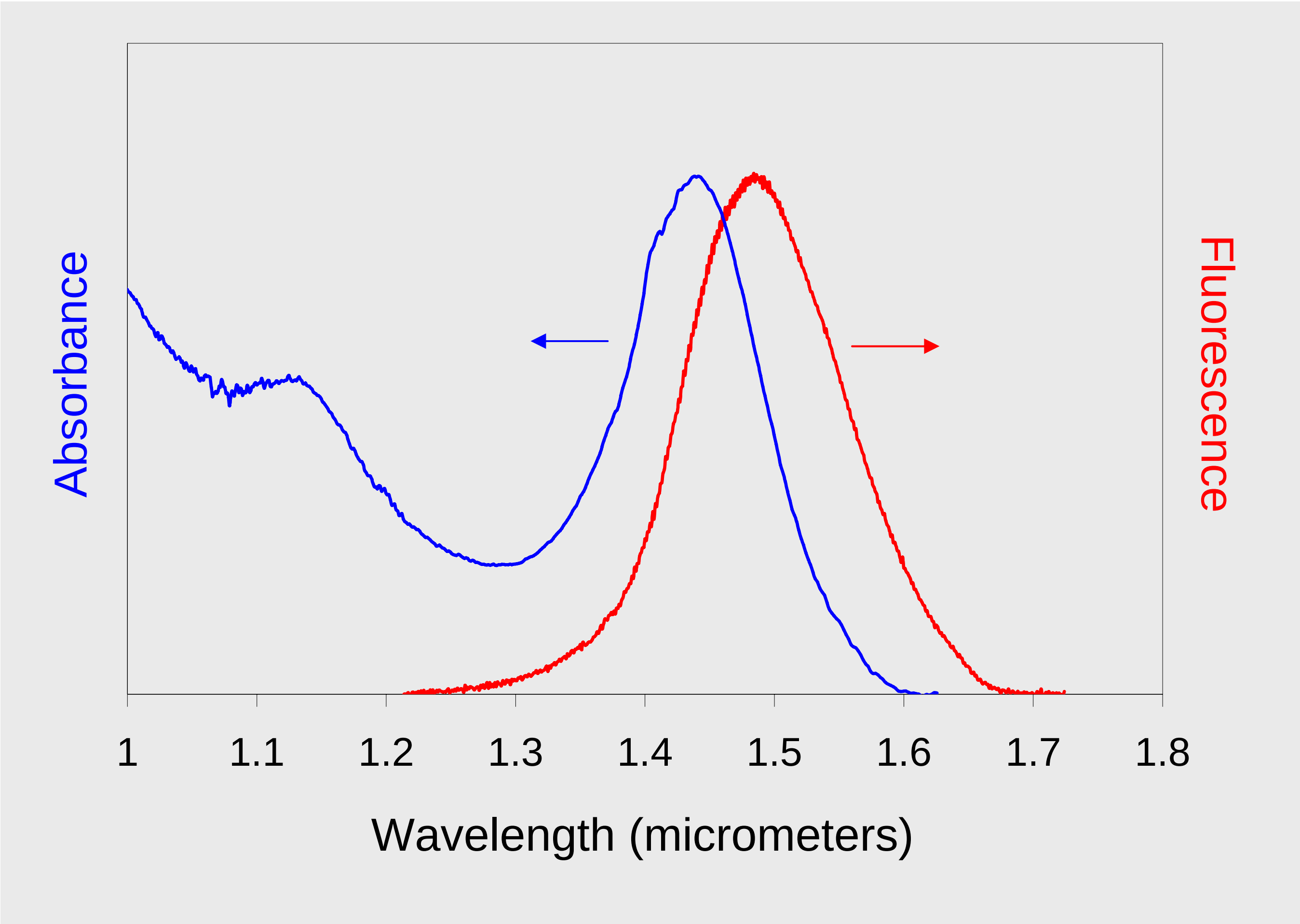


Challenge:

- IR emitting quantum dots?

PbSe Nanocrystals

F. Chen, K.L. Stokes, W. Zhou, J. Fang and C.B. Murray, *MRS Proc.* **685**.



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