电磁学系列讲座之——

光子晶体

Photonic Crystals: Periodic Surprises in Electromagnetism

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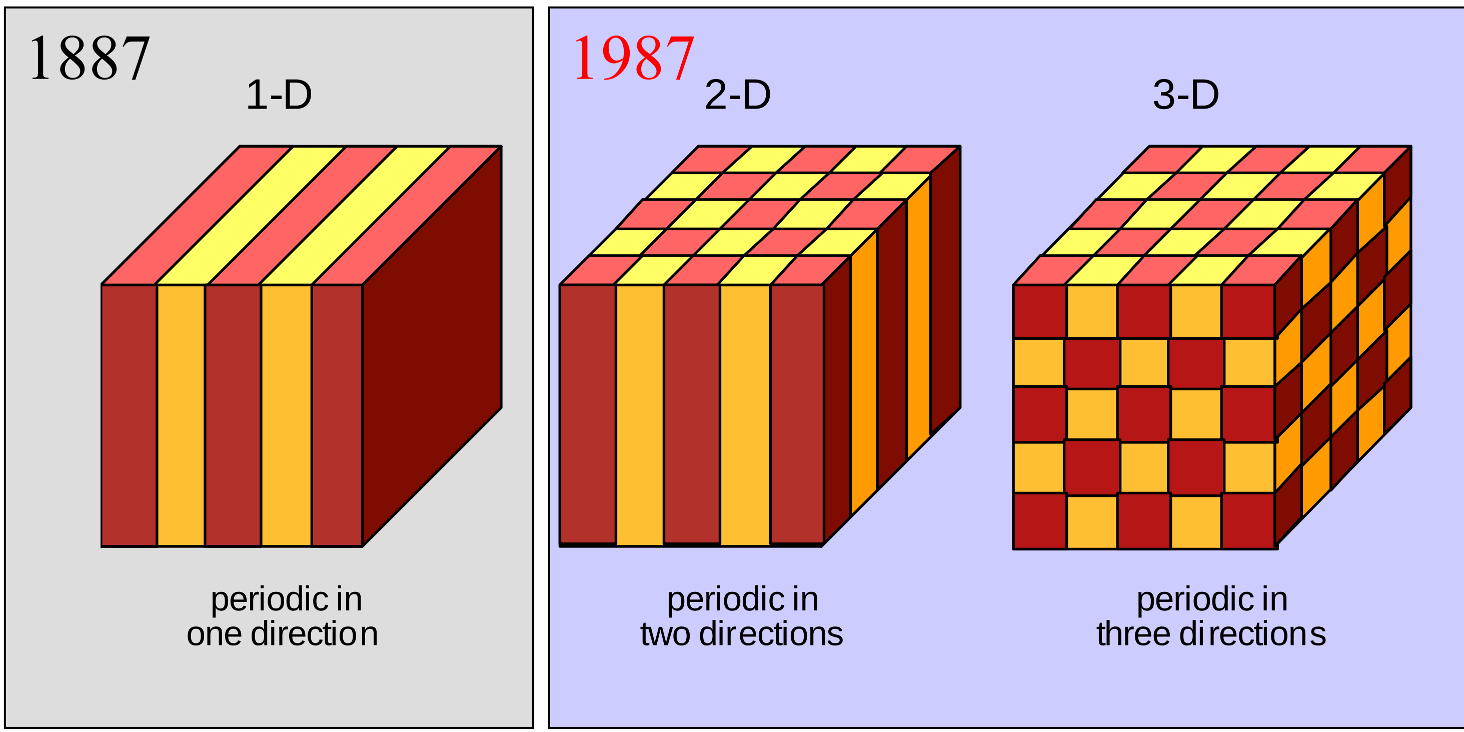
内容提要

- 光子晶体的提出
- 光子的能带
- 光子晶体的制造
- 光子晶体的应用

Photonic Crystals

periodic electromagnetic media



光子晶体研究被Science选为十大热点领域之一 文章以每年70%以上的速度递增

科学意义：

- 建立了光子的能带理论，打开了控制光的传播及光与物质相互作用的新领域—凝聚态物理和光学的新交叉领域。
- 创造了一种人工设计的新材料---光子半导体。
- 为发展新型光子器件奠定了物理基础。

应用领域：

光通讯，激光器，光子器件，

Inhibited Spontaneous Emission in Solid-State Physics and Electronics

Eli Yablonowitch

Physical Review Letters 58(1987) 2059

➡ **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.**

➡ **If a three dimensional periodic dielectric structure has an electromagnetic band gap which overlaps the electronic band gap, then spontaneous emission can be rigorously forbidden.**

Strong Localization of Photos in Certain Disordered Dielectric Superlattices

Sajeev John

Physical Review Letters 58(1987) 2486

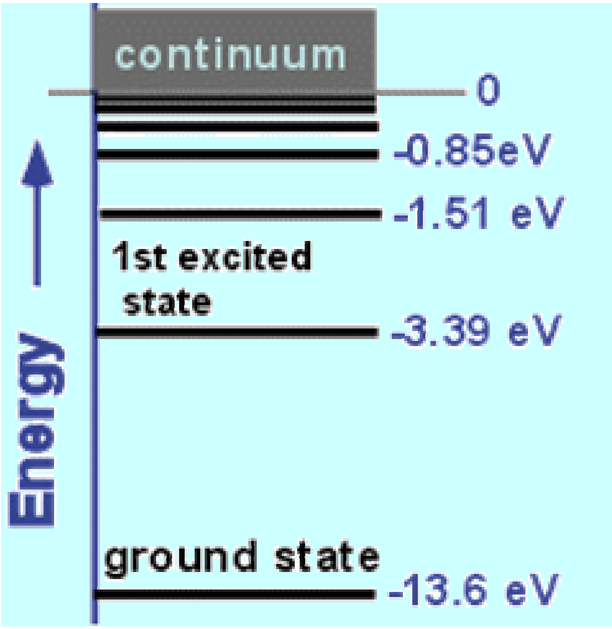
➡ **Strong Anderson localization of photons may occure in certain disordered superlattice microstructures of sufficiently high dielectric contrast.**

➡ **In three dimension,two photon mobility edges separate high- and low frequency extended states from an intermediate-frequency pseudo-gap of localized states arising from remnant geometric Bragg resonances.**

能级

单个原子处于束缚态时，受到原子核和同原子中其他电子的相互作用，电子能量是量子化的，只能具有一系列不连续的能量值，这一系列不连续的能量值称为原子中电子的能级。

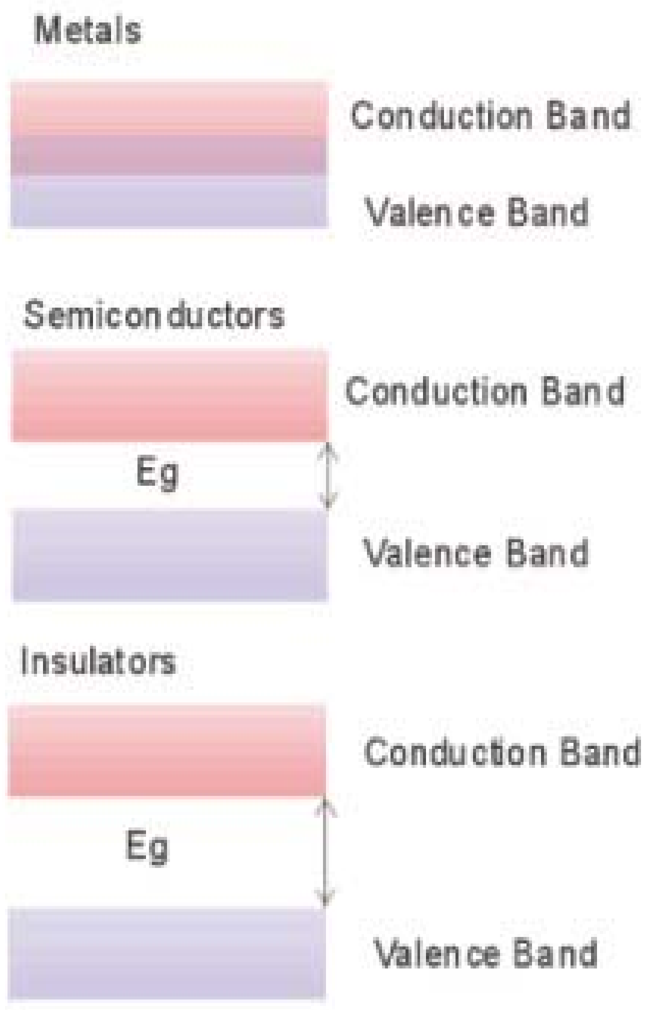
The simplest energy-level diagram is for Hydrogen

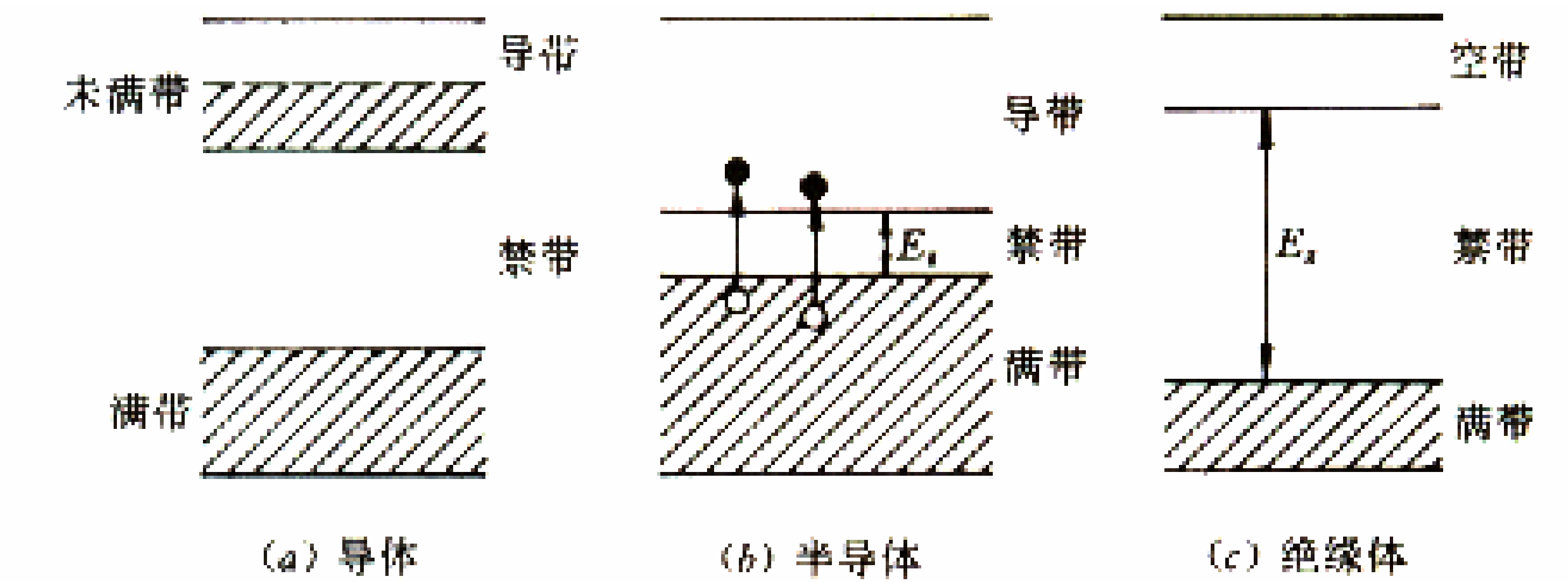


能带

当大量原子组成晶体后，由于原子之间的距离和原子自身的线度皆为10^{-10}米的量级，所以一个原子中的电子还将受到周围原子的作用。晶体中电子所处的能量状态由孤立原子中的一系列能级变为一系列能带。对N个原子组成的晶体,每个能带由N个能差非常小的能级组成。

根据量子理论中的泡利不相容原理，在孤立原子中每个能级上只能容纳有限个电子，所以每个能带上的电子数也是有限的。在基态时，总是最低能量的能带先被占据，逐步往上填。



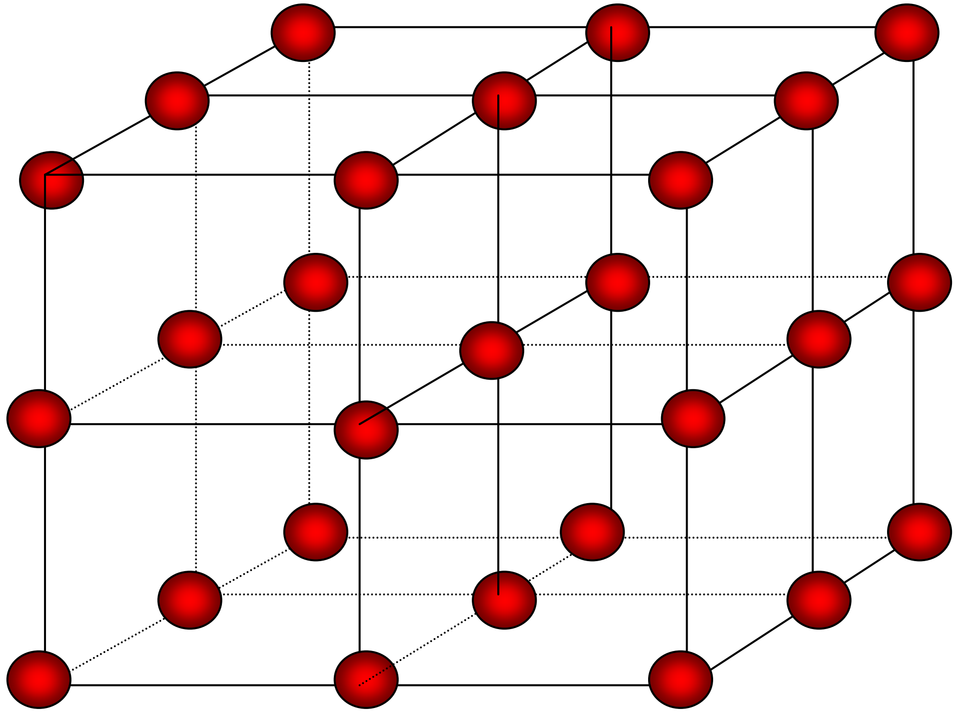


价带：由价电子所填充的带

满带：价带中所有电子都被价电子占满

导带：未被占满的价带

空带：没有电子的能带



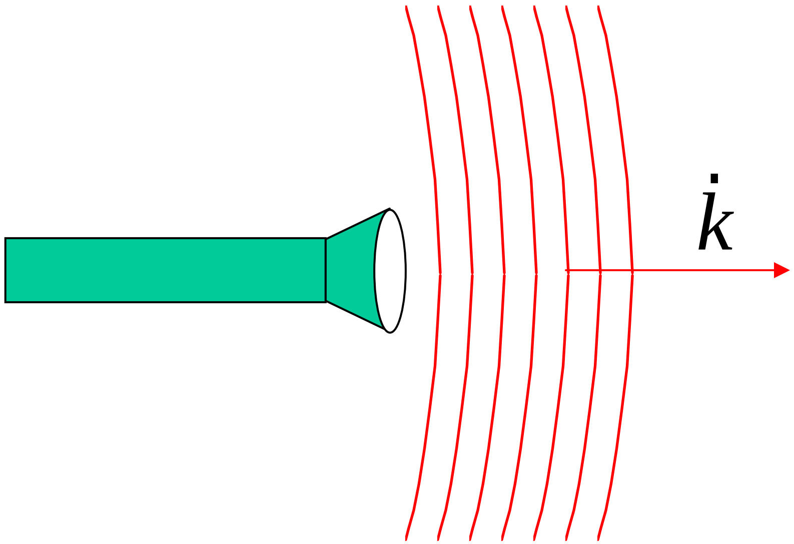
普通晶体 ⟷ 光子晶体

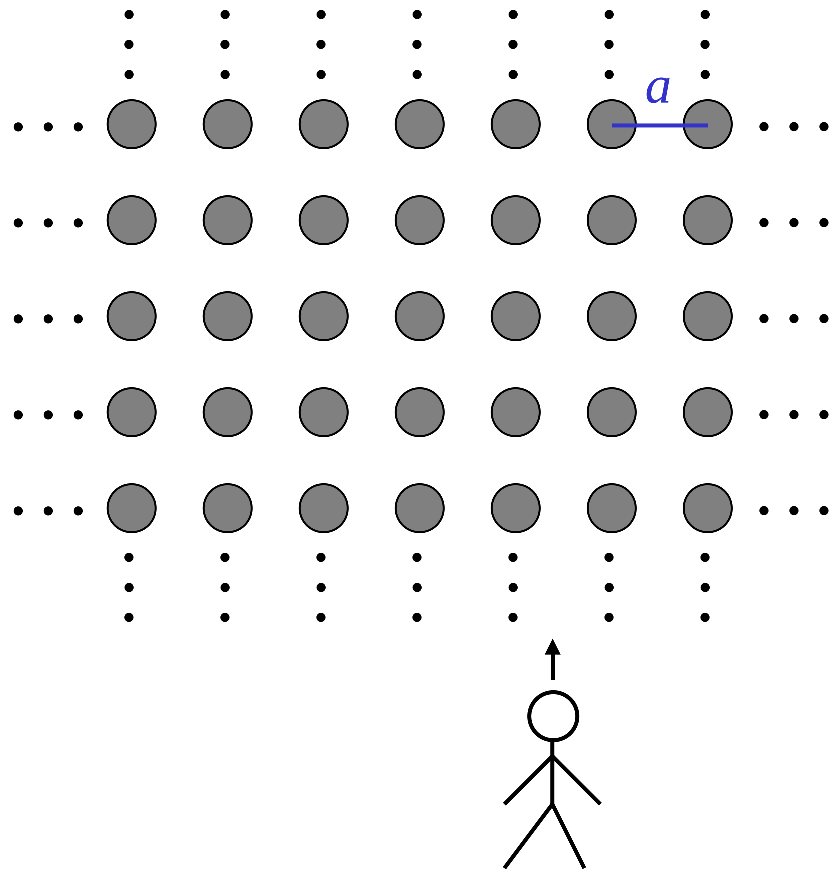
材料：原子（离子) ⟷ 介电物质

周期：几纳米 ⟷ 电磁波波长

能带结构，带隙 ⟷ ？

To Begin: A Cartoon in 2d





planewave

$$\vec{E},\vec{H} \sim e^{i(\vec{k}\cdot\vec{x}-\omega t)}$$

$$|\vec{k}| = \omega / c = \frac{2\pi}{\lambda}$$

for most λ, beam(s) propagate through crystal without scattering (scattering cancels coherently)

...but for some λ (~ 2*a*), no light can propagate: a photonic band gap

Photonic band gap (PBG):

The most important characteristic of PCs is the possible existence of PBG.

The propagation is forbidden for the light with a frequency in PBG.

什么是光子带隙？

光子带隙是一个频率区域，当入射光的频率落在其中时，它被全反射，不能穿过光子晶体。处于具有完全带隙（所有方向的入射都被全反射）光子晶体中的原子自发辐射被禁戒

物理上，光子带隙来源于：

被周期性介电结构强散射的光之间的干涉

1，光子晶体的空间结构—能否相干

2，构成光子晶体材料介电常数之比—散射足够强

Conditions of the appearance of PBG:

- The lattice constance (*a*) is on the order of the wavelength.
- The contrast of the refractive indices is large enough.
- Proper configurations of constituting materials.

光子能带和电子能带

电子在周期性势场中薛定鄂方程：

$$-\frac{\hbar^2}{2m}\nabla^2\Psi + V(r)\Psi = E\Psi$$

$V(r) = V(r+R)$

R： 晶格矢量

单频光在介电常数周期性变化结构中麦克斯韦方程：

$$-\nabla^2\vec{E} + \nabla(\nabla\bullet\vec{E}) - \frac{\omega^2}{c^2}\varepsilon_1(r)\vec{E} = \frac{\omega^2}{c^2}\varepsilon_0\vec{E}，$$

ε_0：平均介电常数

$\varepsilon_1(a+r) = \varepsilon_1(r)$：周期变化介电常数

$$\varepsilon_1(r) \Leftrightarrow V(r), \varepsilon_0\frac{\omega^2}{c^2} \Leftrightarrow E$$

介电常数变化~~位能的变化

在介电常数以光波长周期变化的结构中
光子的运动规律类似于晶体中电子的运动。

- 光子和电子都是波粒二象性的

对光子　先认识其波动性（赫兹实验）

描写：麦克斯韦方程

又认识其粒子性（光电效应等）

对电子　先认识其粒子性（汤姆孙实验）

又认识其波动性（电子衍射等）

描写：薛定谔方程（低速）

- 薛定谔方程的解依赖于作用势

无作用势V(r)=0 → 平面波函数 → 能级连续

库仑势 → 氢原子波函数 → 能级分立

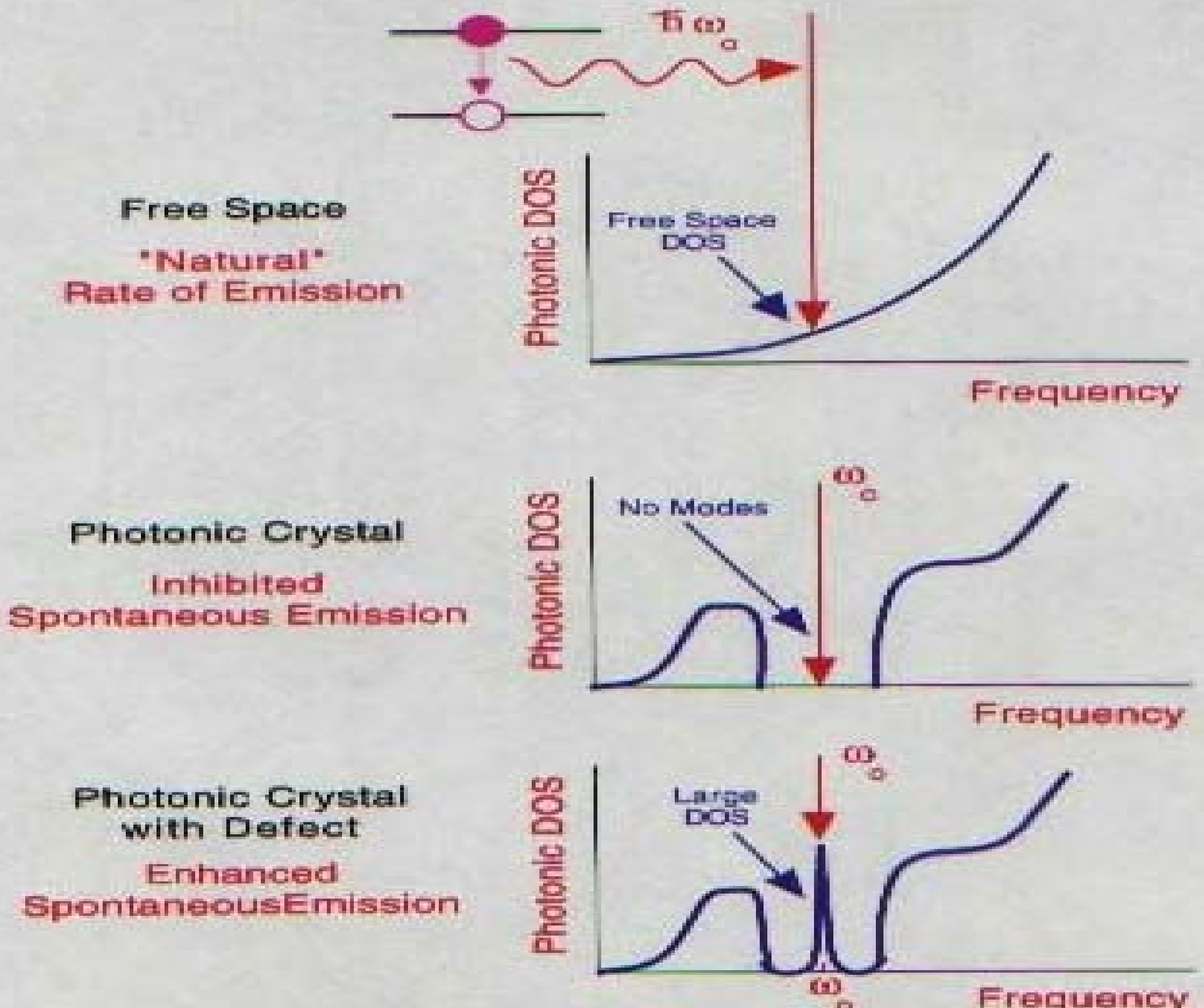
固体中周期势 → 勃洛赫波函数 → 能带

- 麦克斯韦方程的解依赖于传播介质

无限自由空间→平面波→频率连续

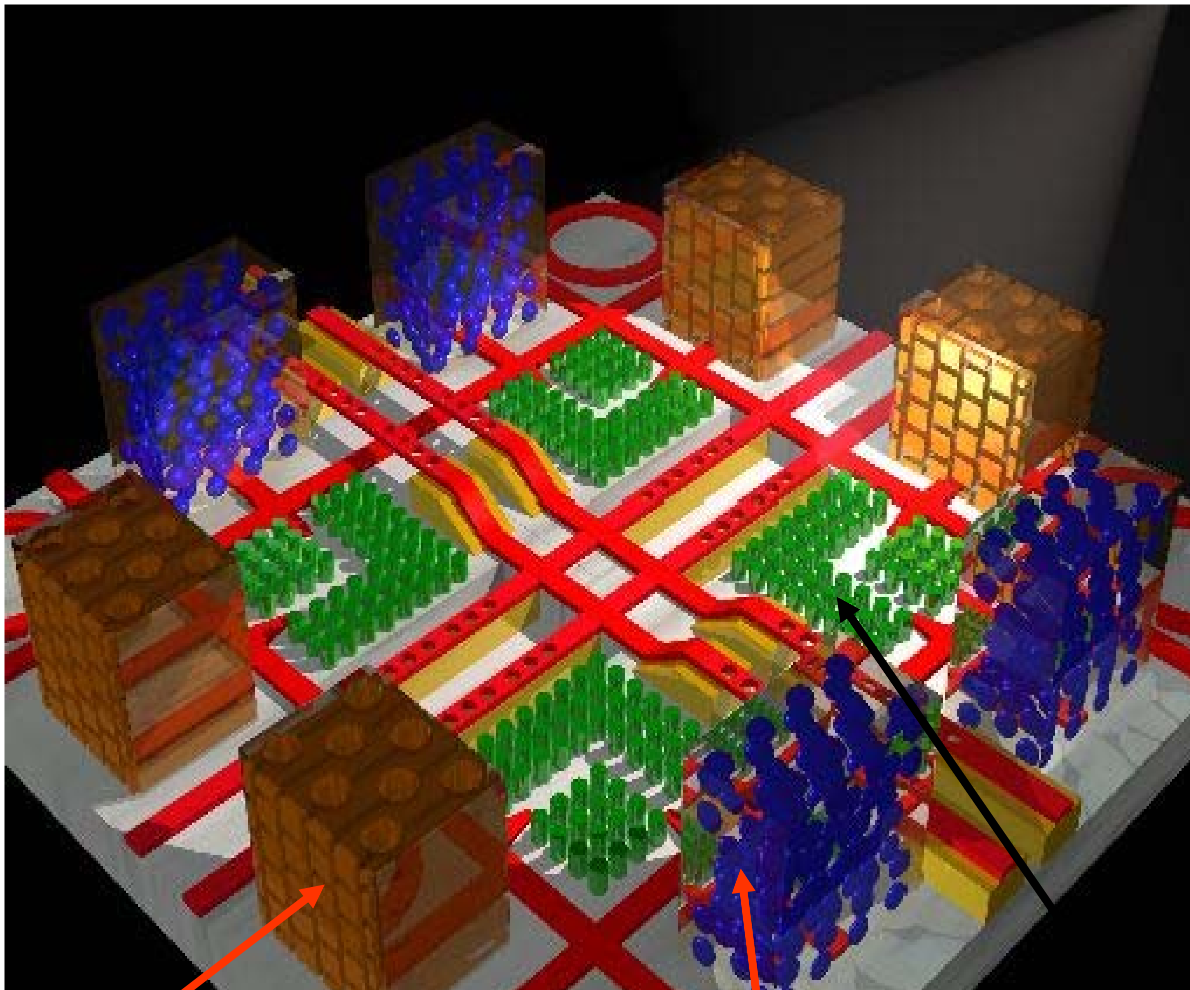
波导管→TE、TM型波→截止频率

介电常数周期结构→？→能带？



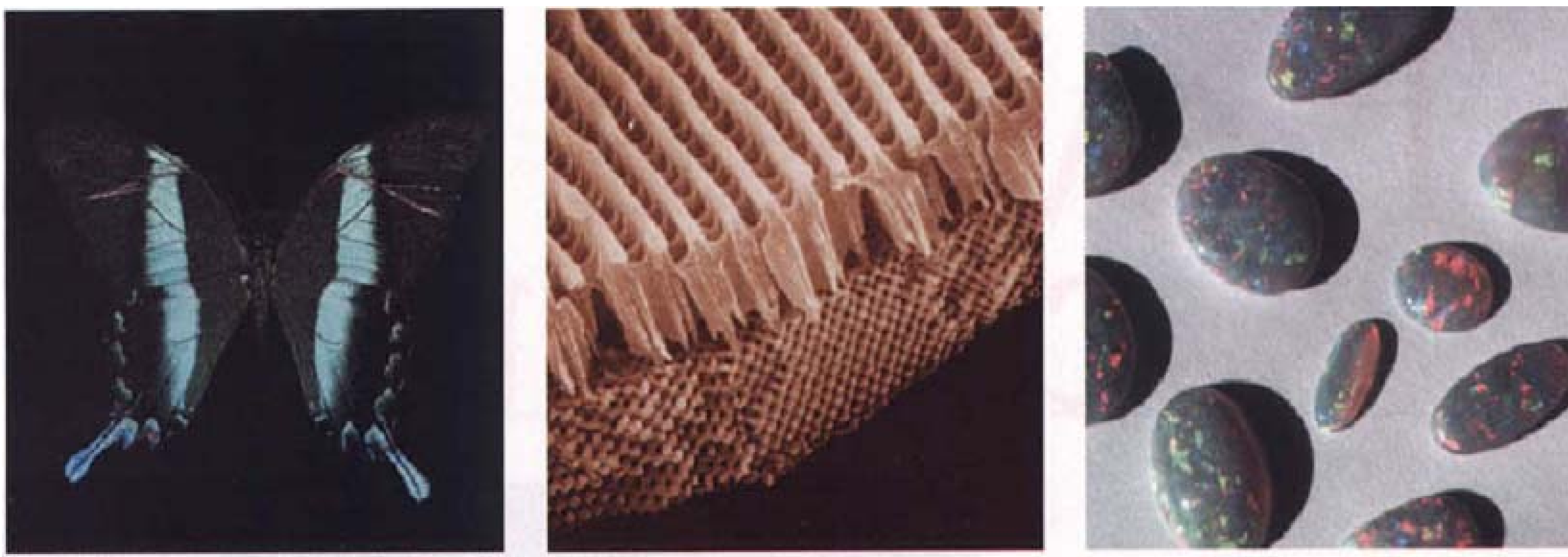
ħω₀
Free Space
"Natural"
Rate of Emission
Photonic DOS
Free Space
DOS
Frequency
Photonic Crystal
Inhibited
Spontaneous Emission
ω₀
No Modes
Photonic DOS
Frequency
Photonic Crystal
with Defect
Enhanced
SpontaneousEmission
ω₀
Large
DOS
Photonic DOS
ω₀
Frequency

The Photonic Micropolis



三维光子晶体　　金属球金刚石结构　　二维光子晶体及直角波导

自然界存在的微米量级的介质周期结构



NATURAL PHOTONIC BAND GAPS occur in some butterfly wings [*left*] and in opals [*right*]. In both cases, the band gap is incomplete—it is not effective in every direction—but it produces iridescent colors. A micrograph of a fractured iridescent green butterfly scale [*center*] shows the submicron-size face-centered cubic structure inside. Opals consist of submicron-size silica spheres arranged in a face-centered cubic [close-packed] structure.

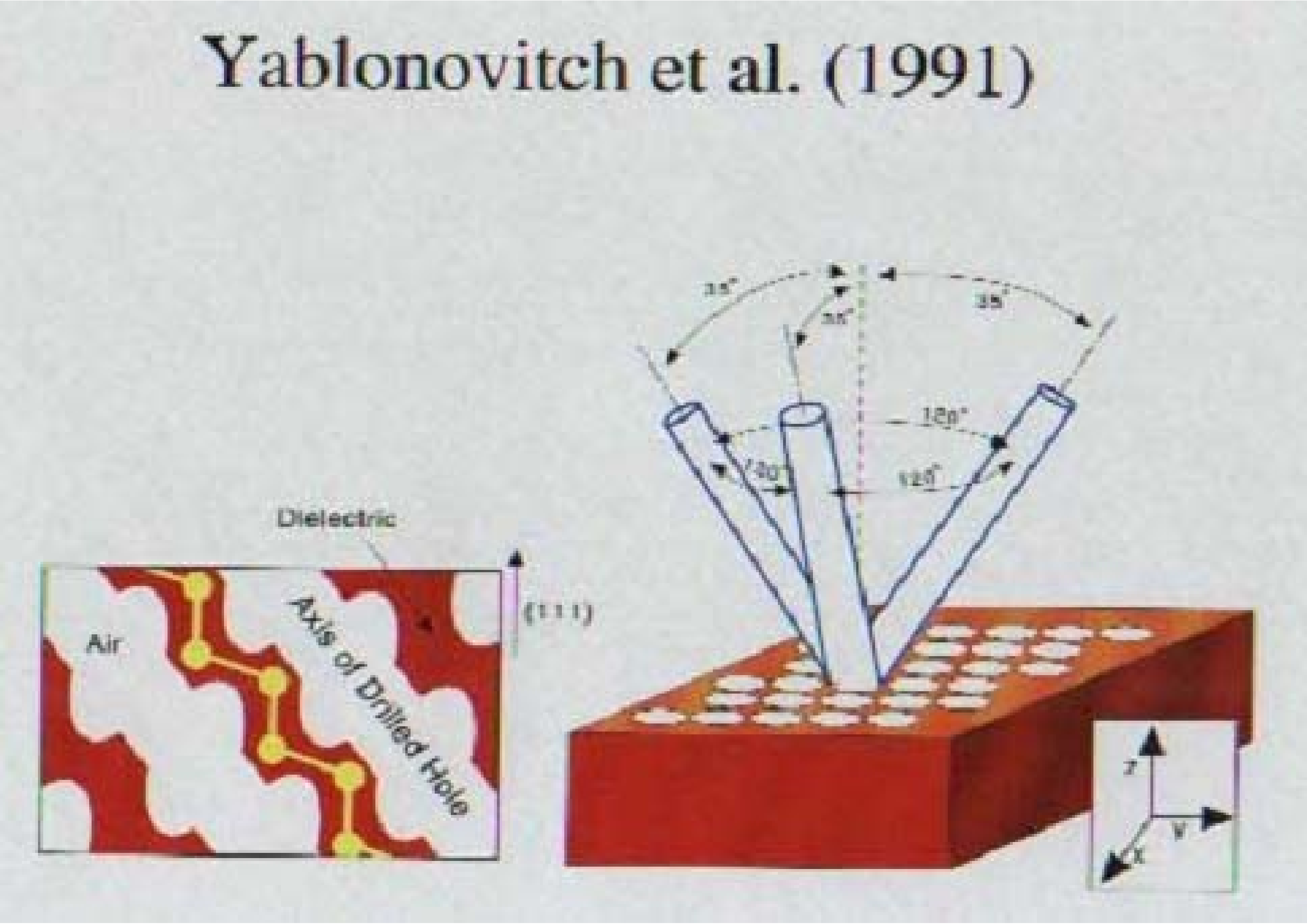
光子晶体的制作

光子晶体结构的周期是相应光波的波长量级

可见光：亚微米；红外光：微米-毫米；微波：毫米-厘米

- 堆积或打孔：砖头，电子（离子）束
- 多光束干涉产生光强周期分布：排列微粒，全息光刻
- 微粒的自组装及相关的方法
- 微加工，微刻蚀技术

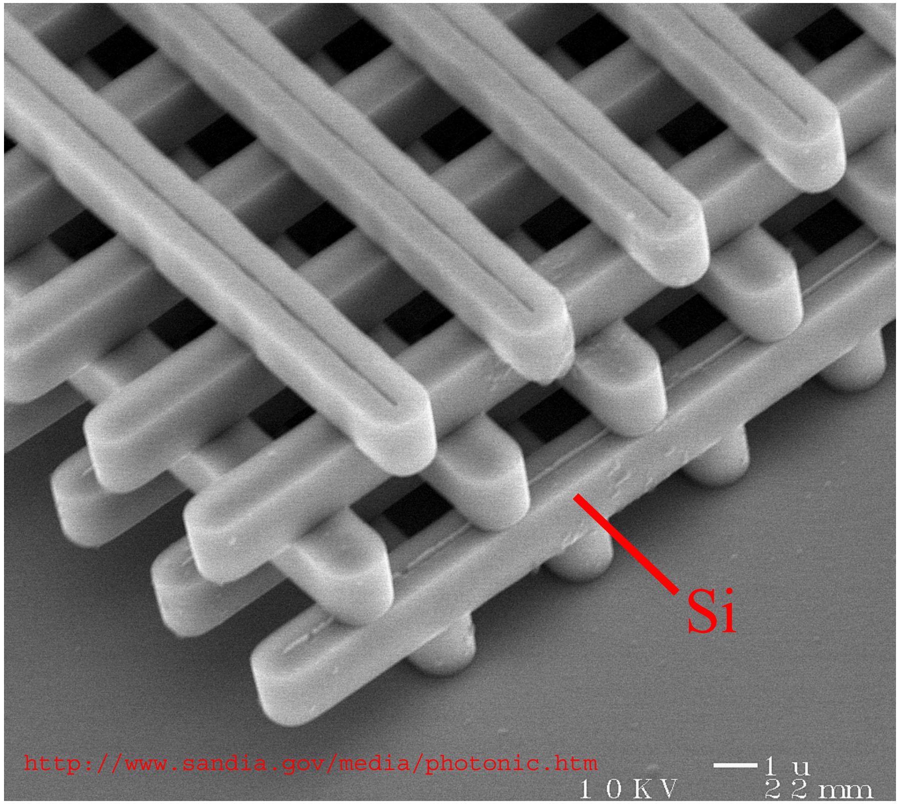
用打孔的方法构成的面心立方光子晶体

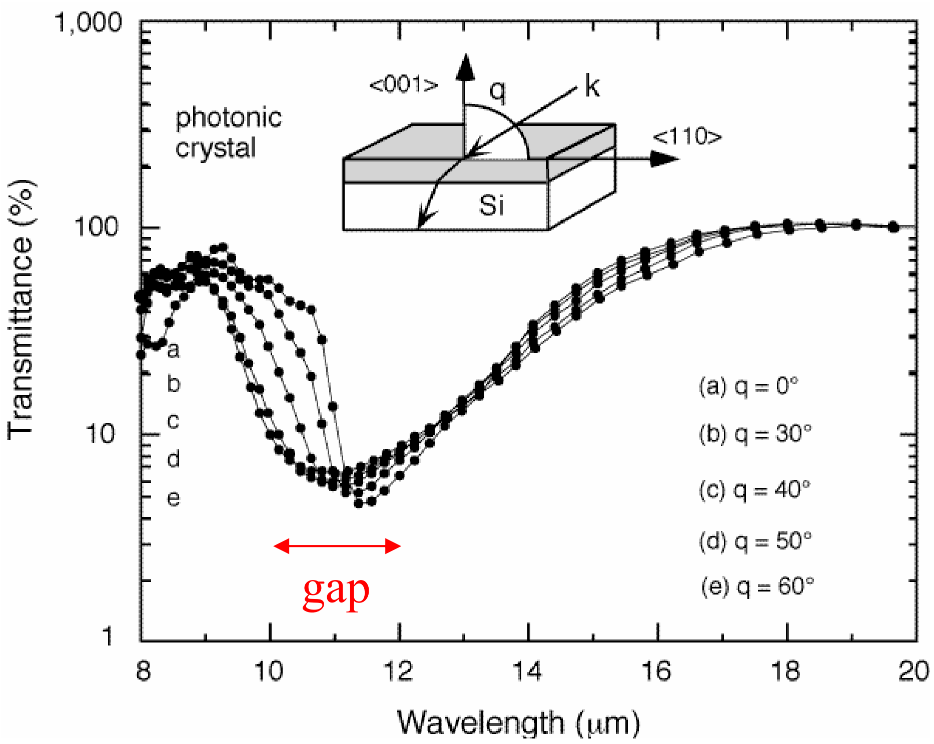


1.25 Periods of the Woodpile

(4 "log" layers = 1 period)

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



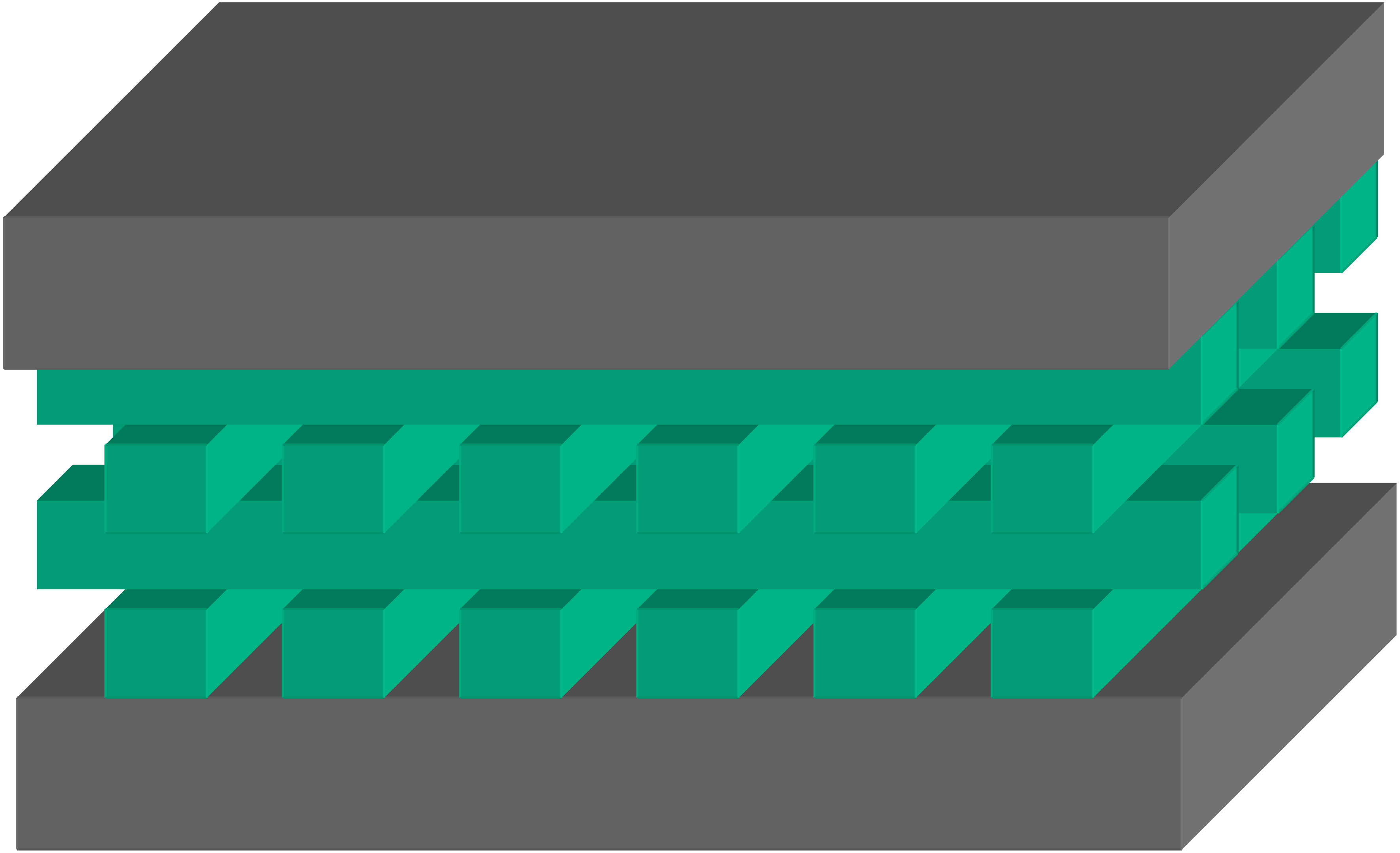


"UV Stepper:" e-beam mask at ~4x size
+ UV through mask, focused on substrate

Good: high resolution, mass production Bad: expensive ($20 million)

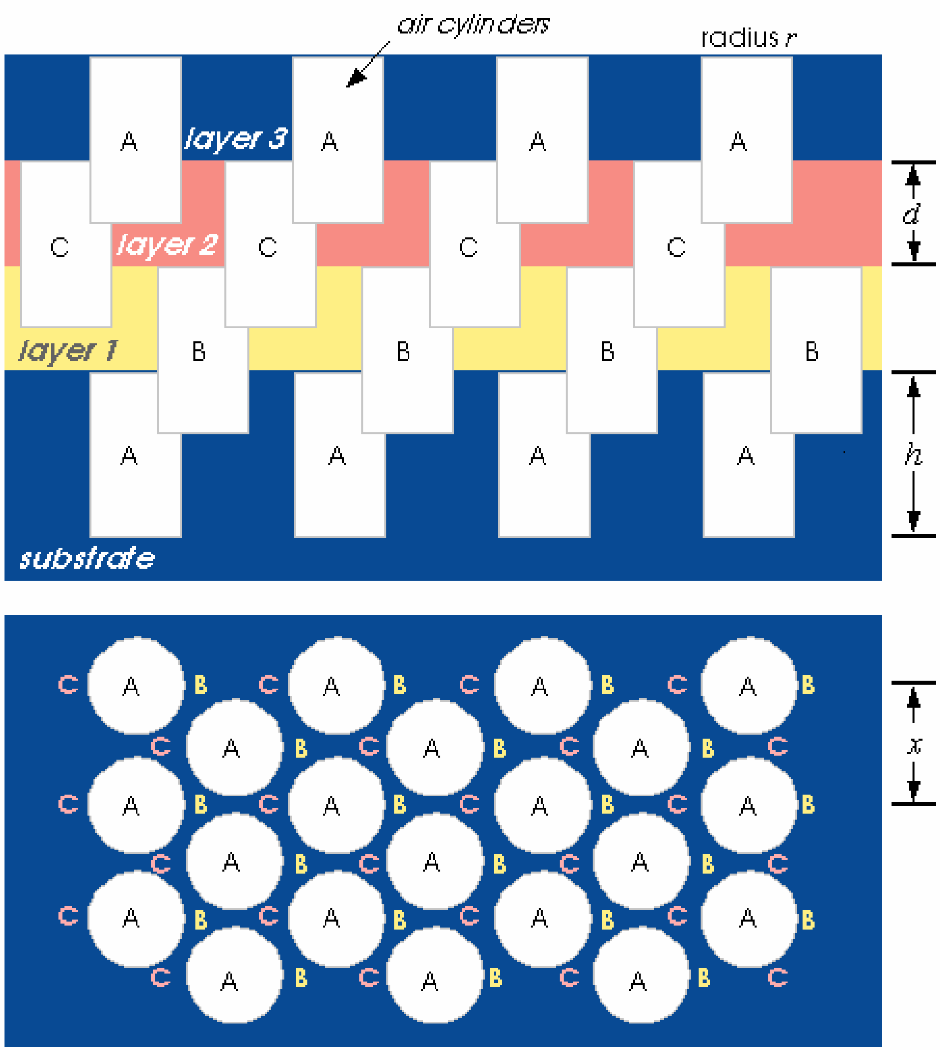
Woodpile by Wafer Fusion

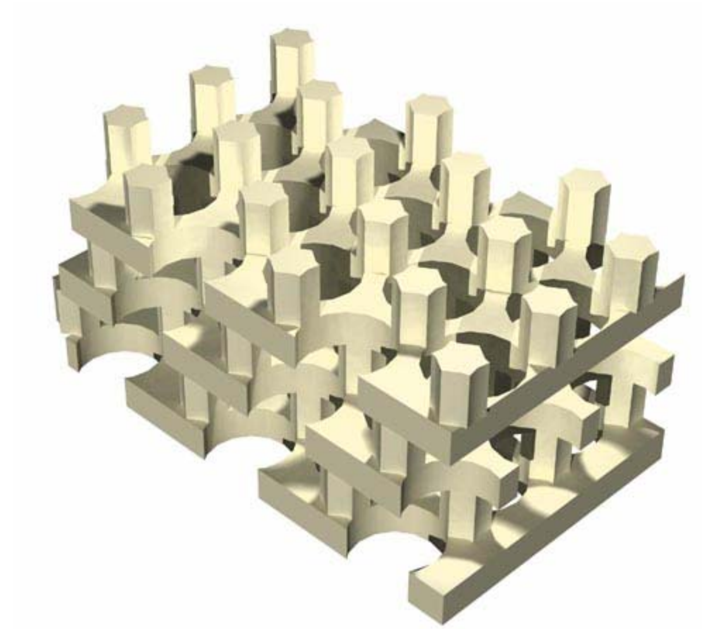
double, double, toil and trouble…



[S. Noda *et al.*, *Science* **289**, 604 (2000)]

装配式三维光子晶体





面心立方--三维完全能隙，

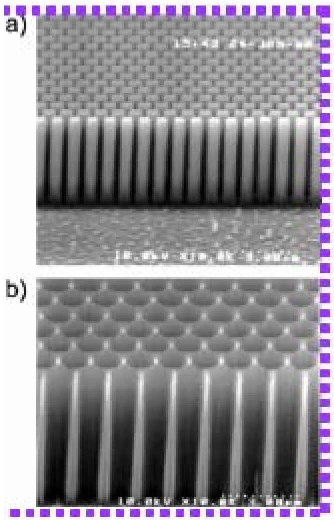
相对宽度：**21%（Si/air）**

8%（Si/SiO_2)

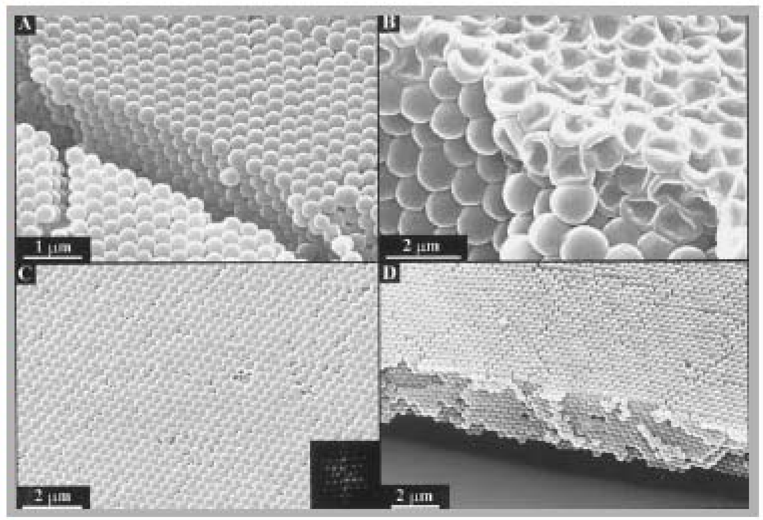
也能用光刻实现微结构

Fabrication of Photonic Crystal

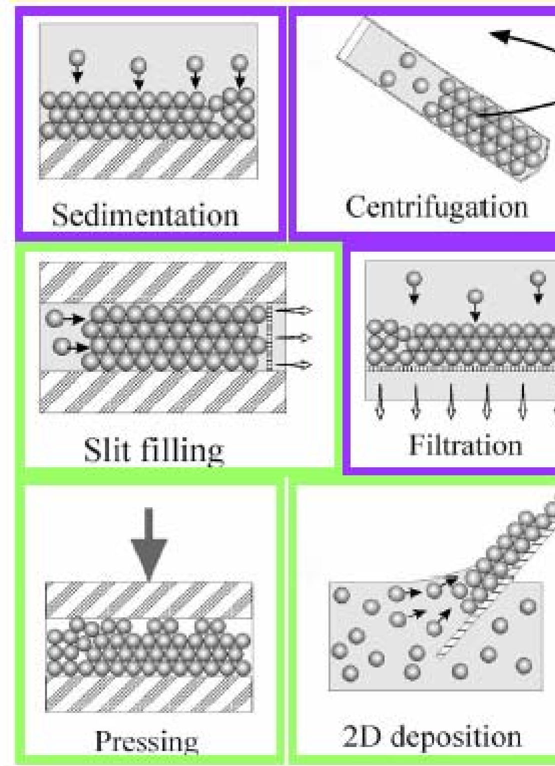
Microelectronics



Monodispersed Colloid particles

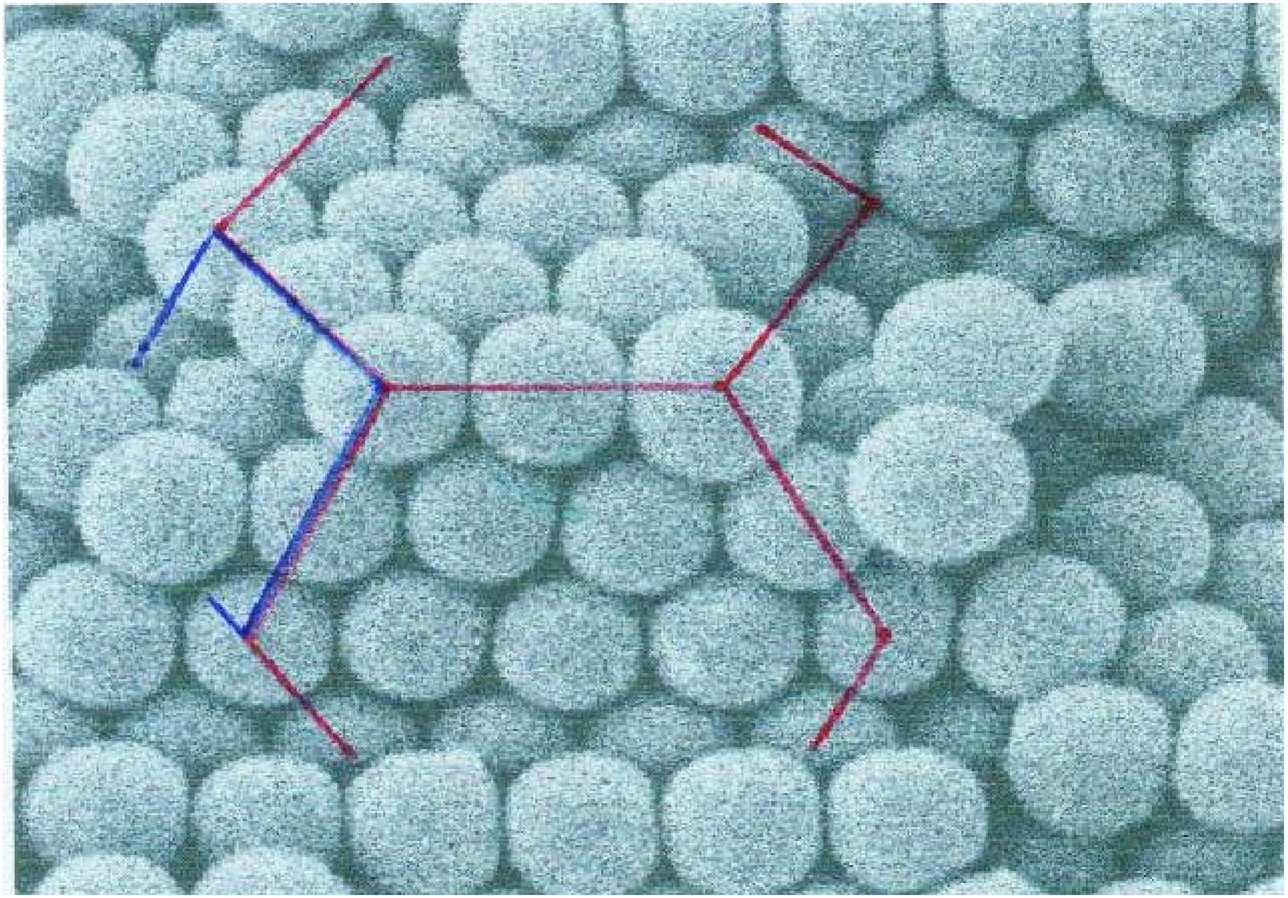


Opal Structure

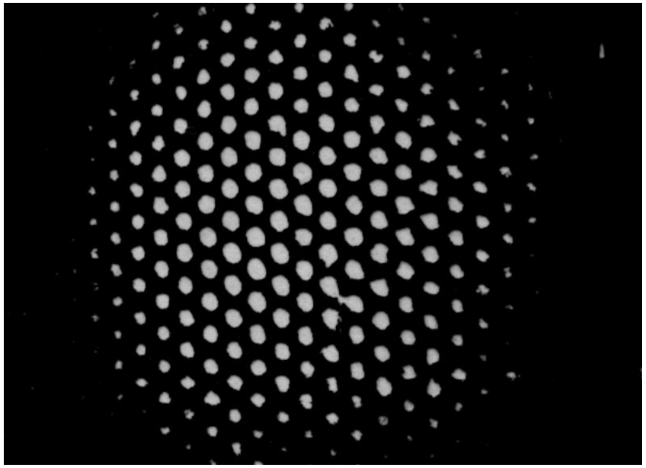


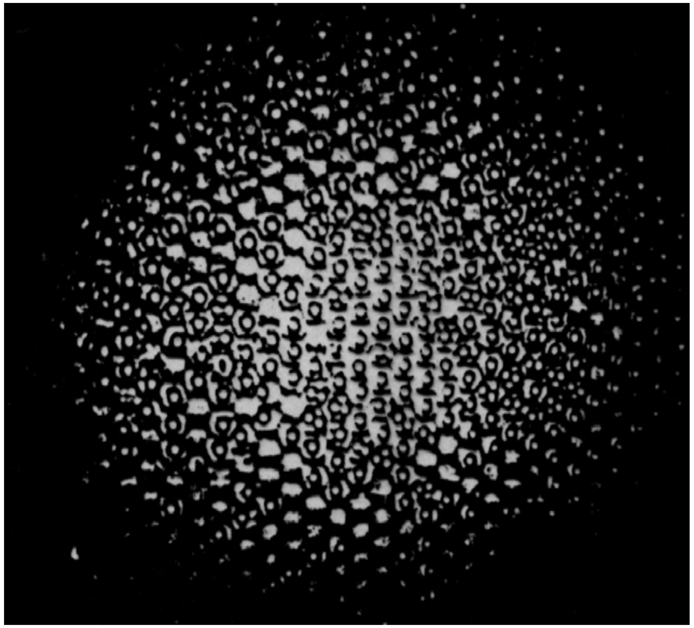
Major parameter

- Particle Size Distribution
- Particle Size
- Concentration of colloid



三束光干涉图案及小颗粒排列





微加工技术，光刻

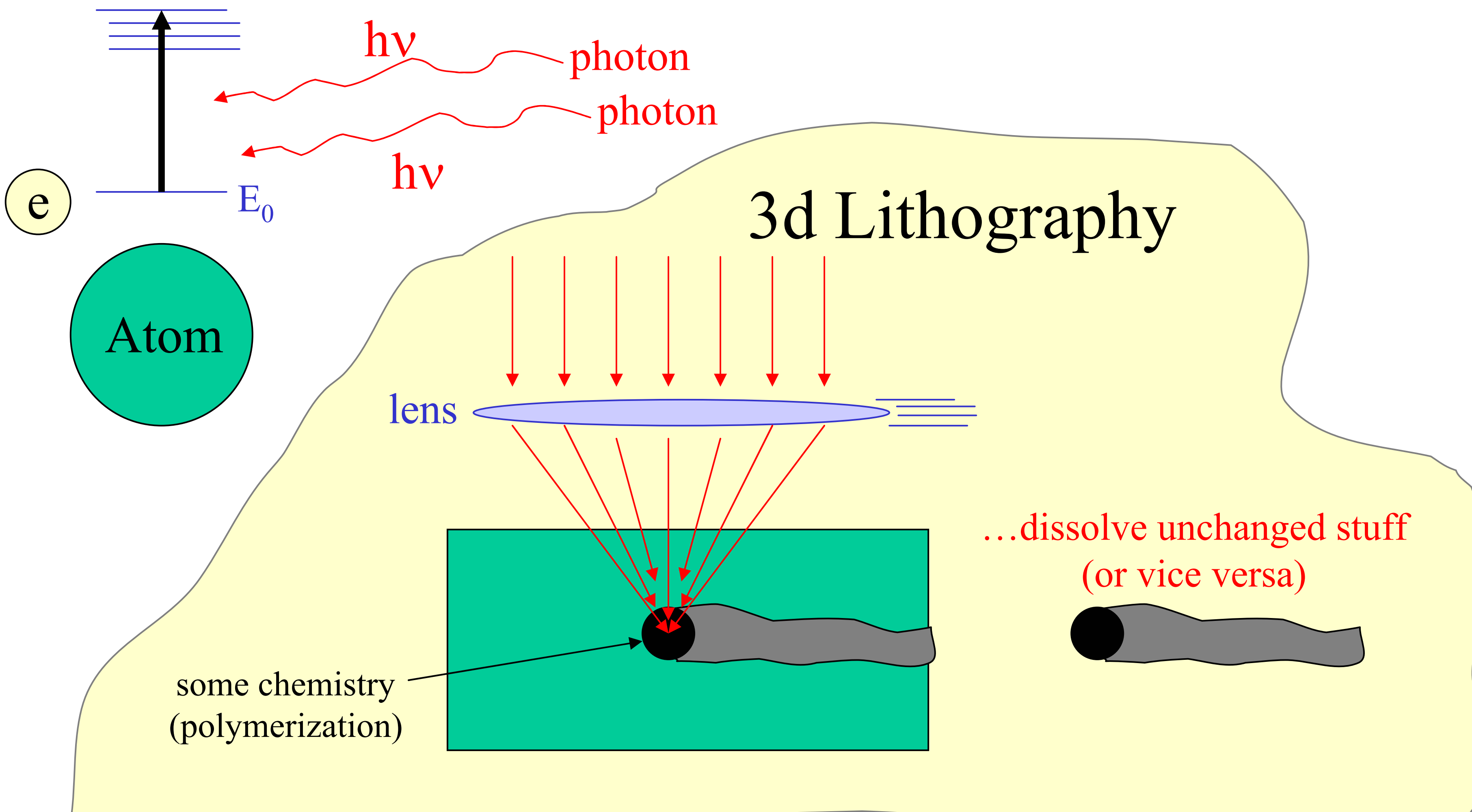
- 得到完整的光子晶体
- 进行光电器件的集成
- 设备及加工技术复杂，价格昂贵

目前主要在有成熟工艺的**Si**和 **GeAs**基底上加工

Two-Photon Lithography

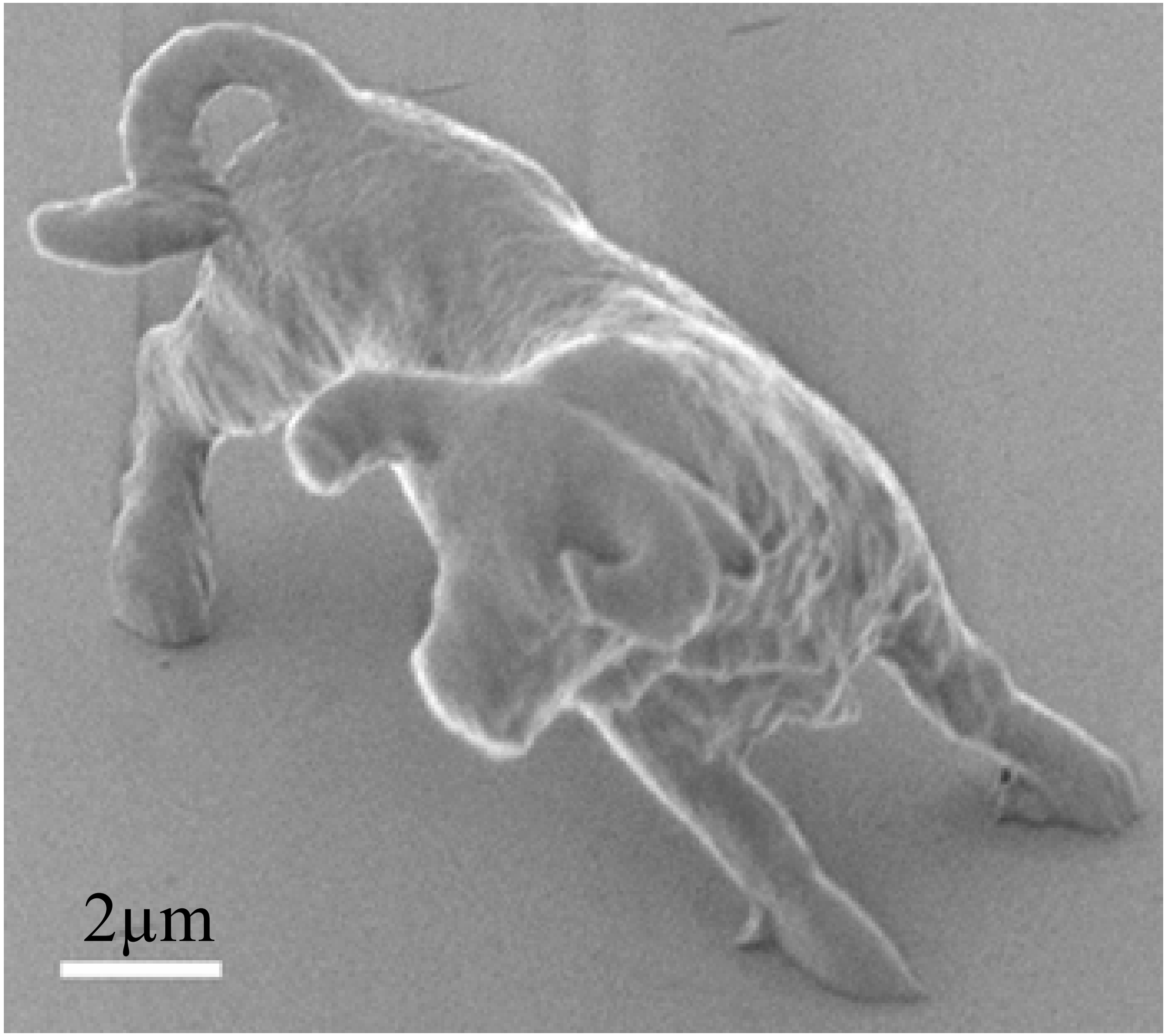
$2\,h\nu = \Delta E$

2-photon probability ~ (light intensity)^2



Lithography is a Beast

[S. Kawata *et al.*, *Nature* **412**, 697 (2001)]



λ = 780nm

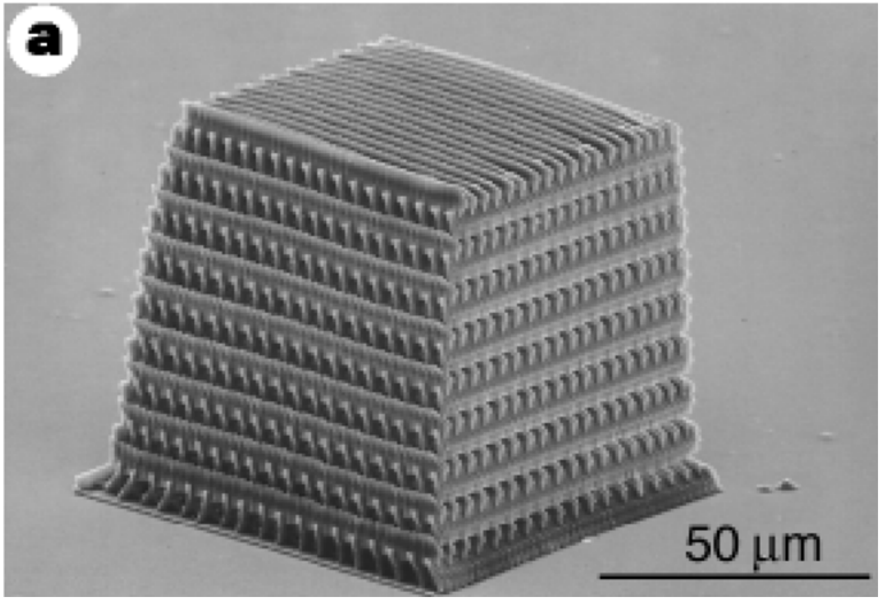
resolution = 150nm

7μm

(3 hours to make)

A Two-Photon Woodpile Crystal

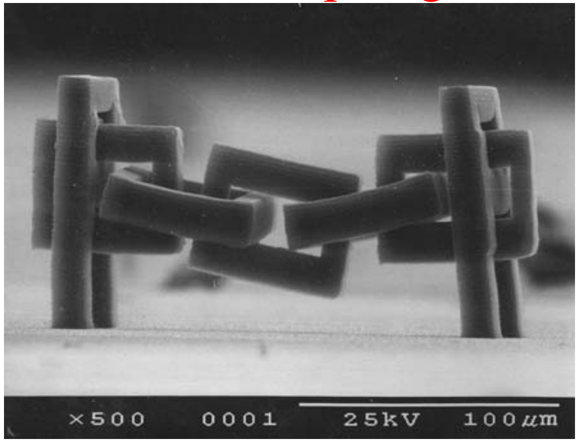
[B. H. Cumpston *et al*., *Nature* **398**, 51 (1999)]



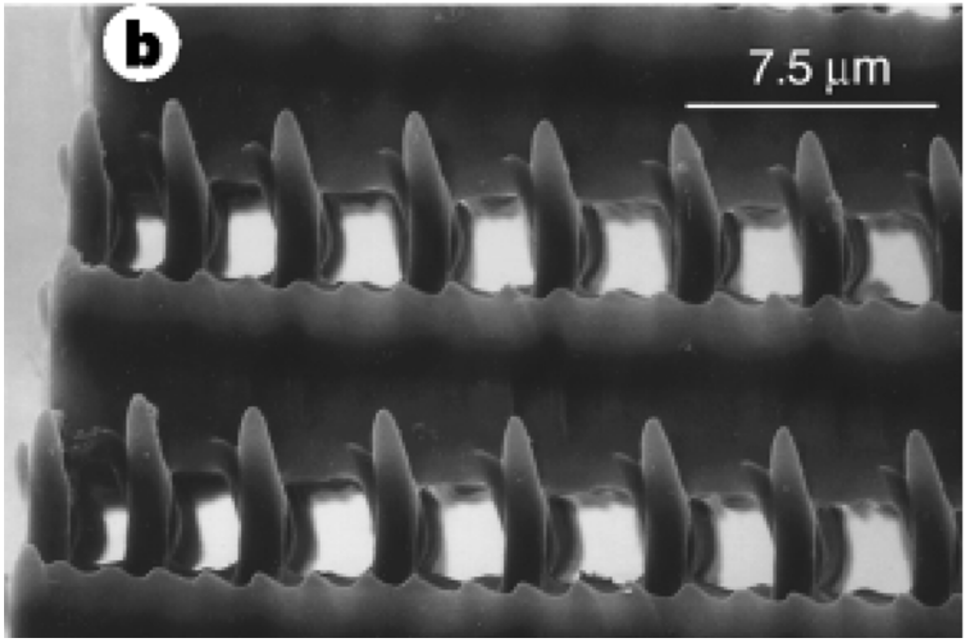
(much work on materials
with lower power 2-photon process)

- Arbitrary lattice
- No "mask"
- Fast/cheap prototyping

Difficult topologies



[fig. courtesy J. W. Perry, U. Arizona]



光子晶体研究的几个重要方面

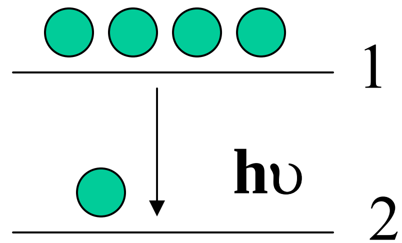
- 具有完全能隙的光子晶体：特殊空间结构
  特殊性质材料
  可见，近红外波段
- 光子晶体中光与物质作用的新效应:自发辐射改变
- 其它物理量周期性变化的结构：二阶非线性极化率

★ 以光电器件为背景，在光子晶体中控制光的研究

波导，微腔，缺陷模式，光纤，各种特殊结构-------

原子自发辐射速率的改变

二能级原子系统：



$h\upsilon = E_1 - E_2$

辐射场：谐振子能级， 基态零点能： $h\upsilon/2$

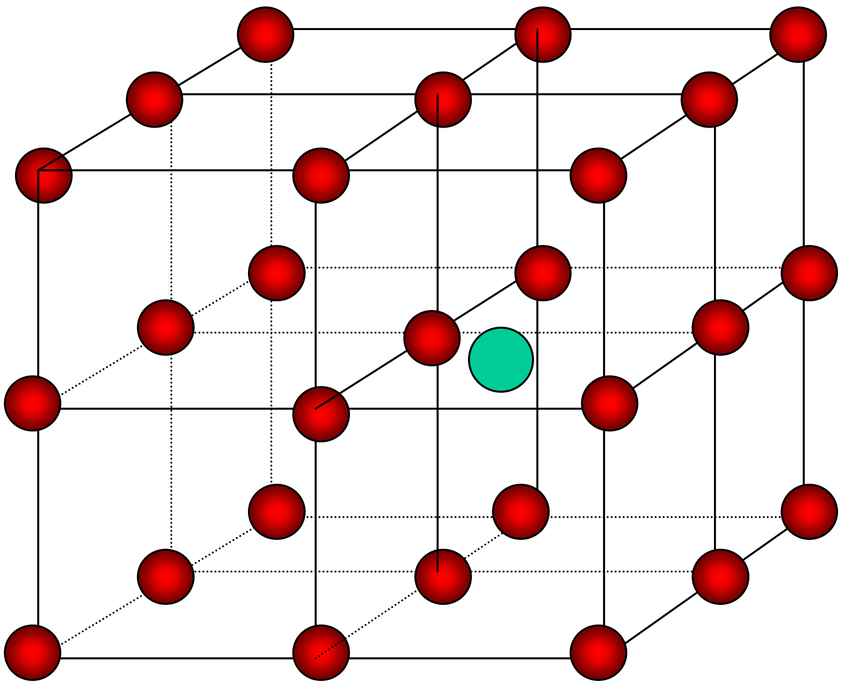
在自由空间：原子能向任意模式辐射光子（能量，动量守恒）

什麼时候辐射，向哪个特定模式辐射是不确定的

自发辐射速率 $A \propto \Omega_{ef} \cdot \rho(\nu)$

通过改变光子态密度来改变自发辐射速率

光子晶体中原子自发辐射的抑制和改变



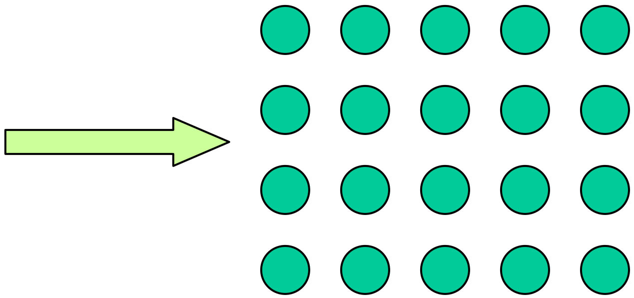
完全光子能隙：$\rho(\nu)$=0

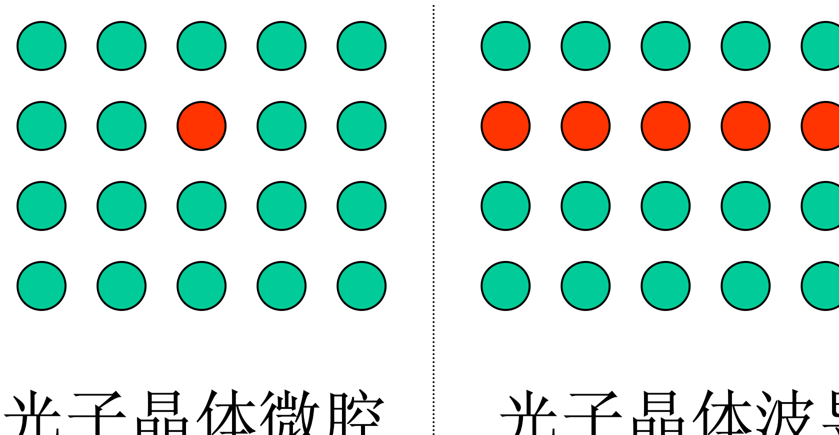
不完全能隙 $\rho(\nu)$ 被改变

当处于光子晶体中的原子的辐射频率落在完全光子能隙中
，
自发辐射被抑制，落在不完全能隙中时自发辐射的速率被改变

完整的光子晶体

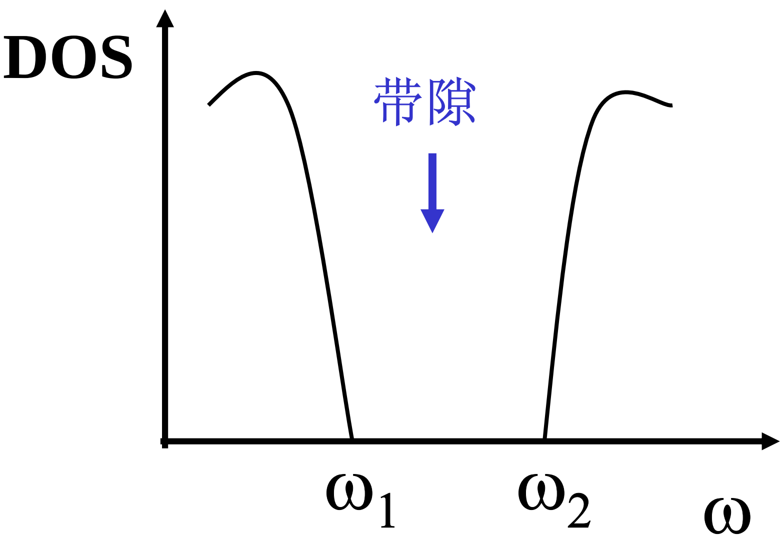
有缺陷的光子晶体

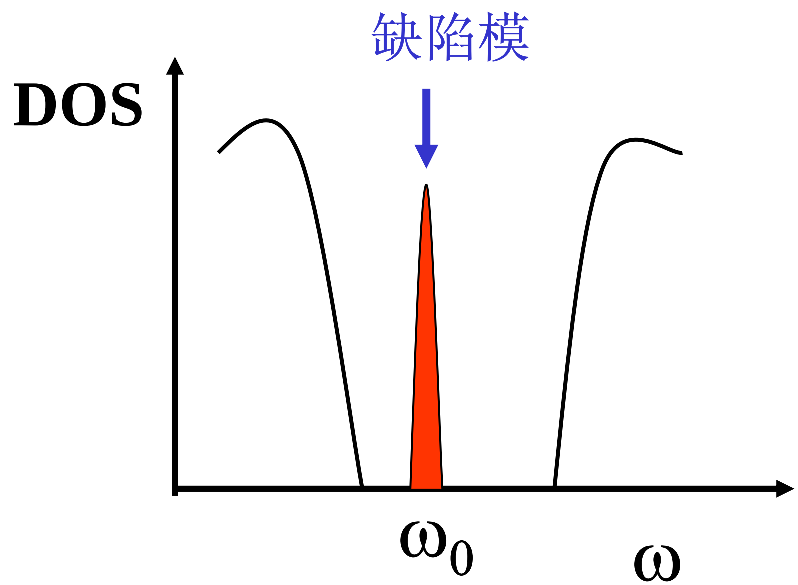




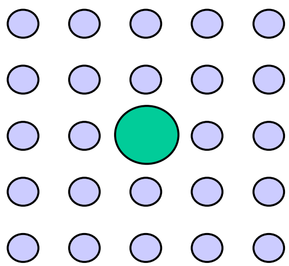
光子晶体微腔

光子晶体波导





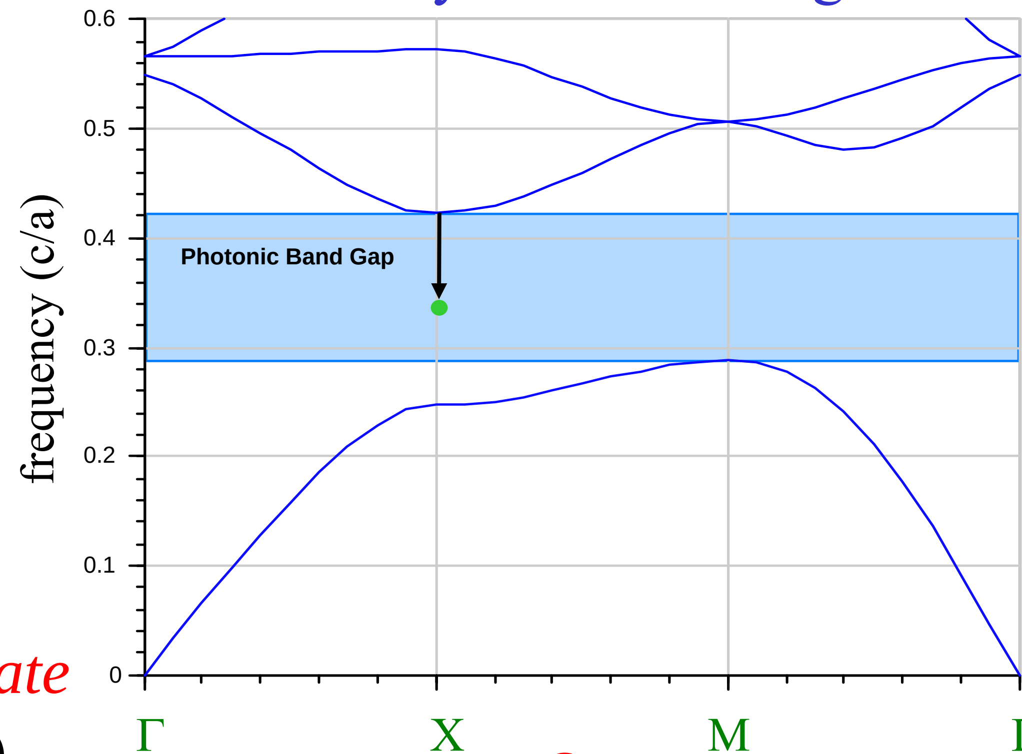
"Single"-Mode Cavity

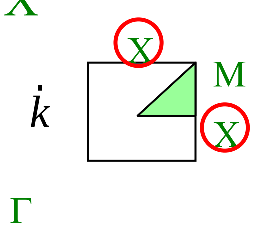


A *point defect* can pull down a "single" mode

…here, doubly-*degenerate* (*two* states at *same* ω)

Bulk Crystal Band Diagram

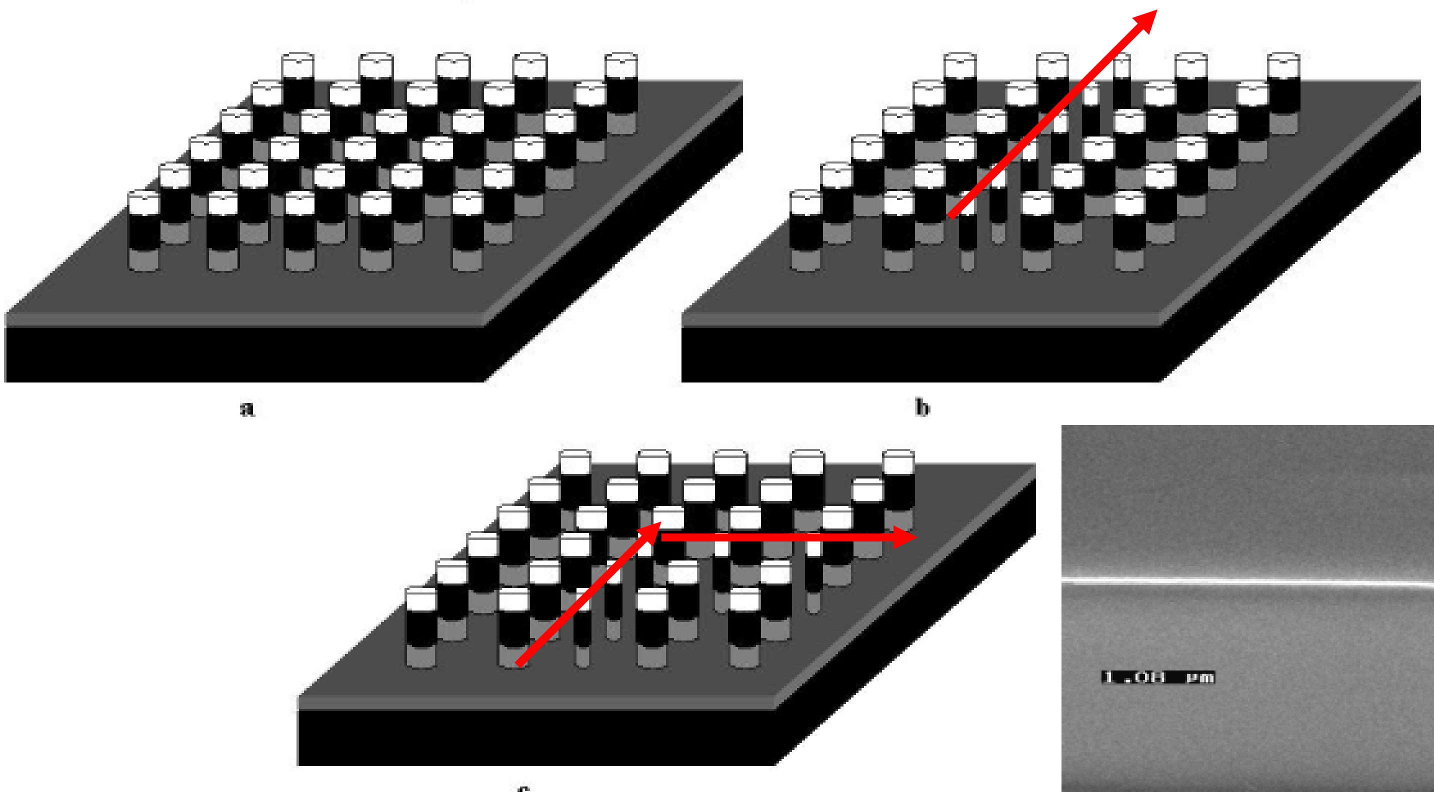


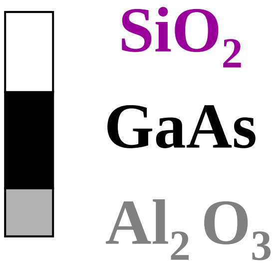


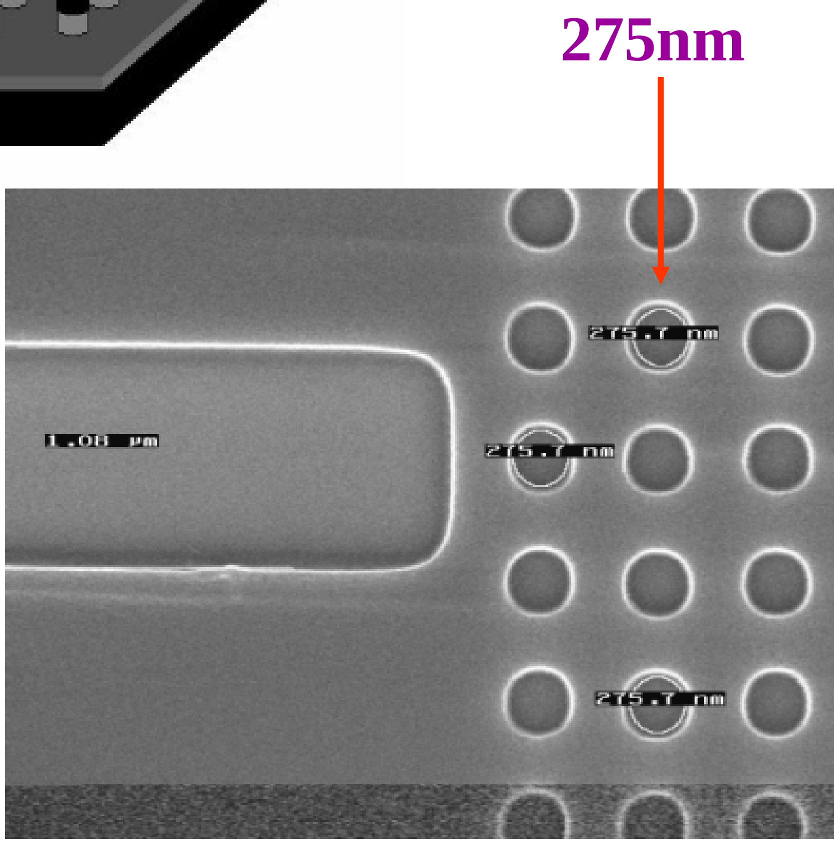
(k not conserved)

平面波导结构——光子晶体结构+全内反射

目的：避免在垂直方向光泄漏





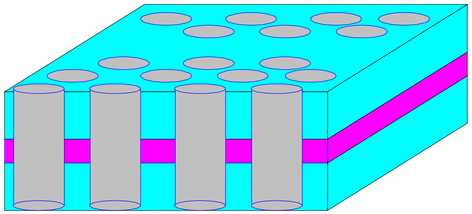


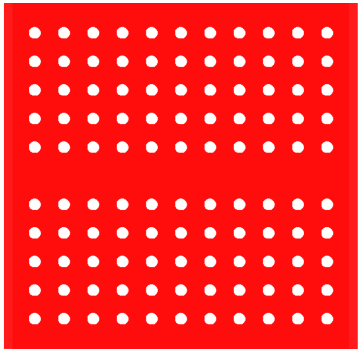
(a) photonic crystal

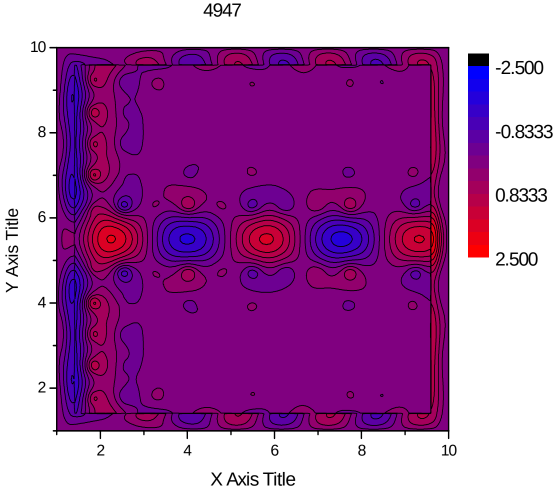
(b) linear waveguide

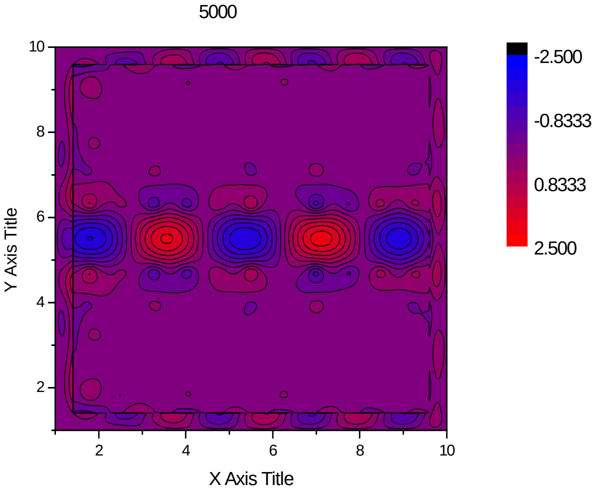
(c) 90 degree bend waveguide.

Waveguide






4947
Y Axis Title
X Axis Title
-2.500
-0.8333
0.8333
2.500


5000
Y Axis Title
X Axis Title
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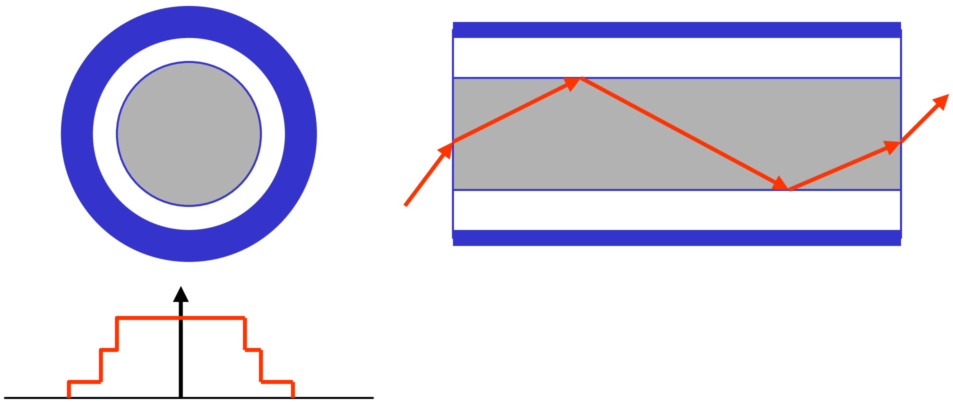
-0.8333
0.8333
2.500

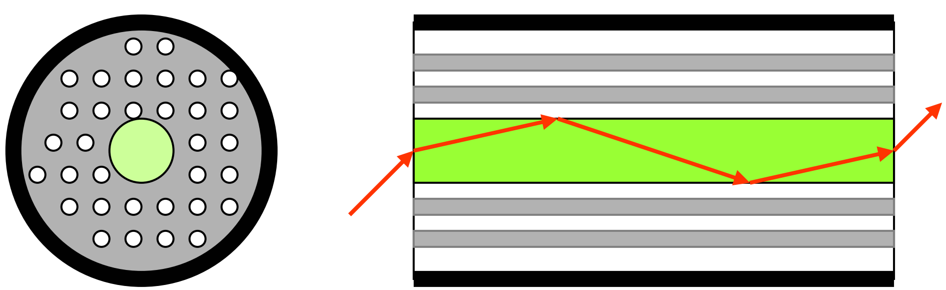
普通光纤：全内反射



折射率分布

损耗，色散，
单模光纤直径小
单模波长有限
特定的工作波长

光子晶体光纤：光子能隙全反射

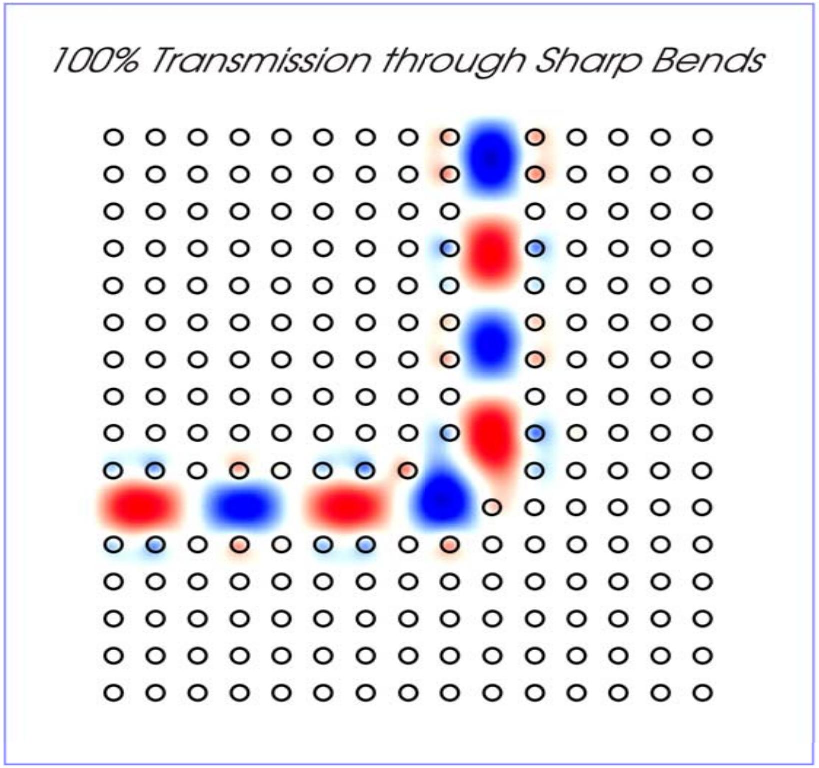


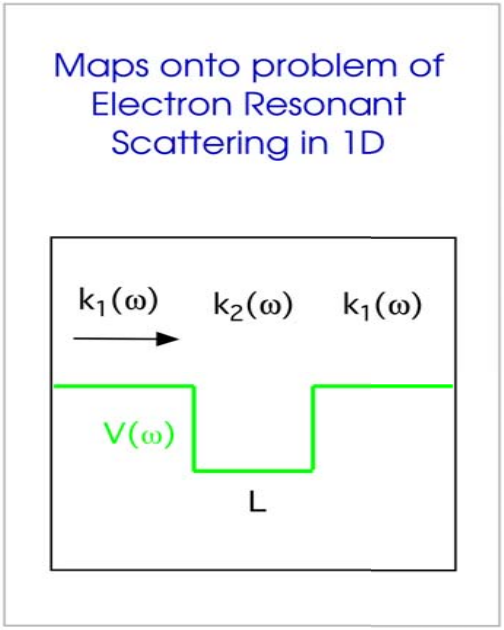
无损耗，色散可设计，

大直径单模光纤

所有波长能单模工作

Lossless Bends



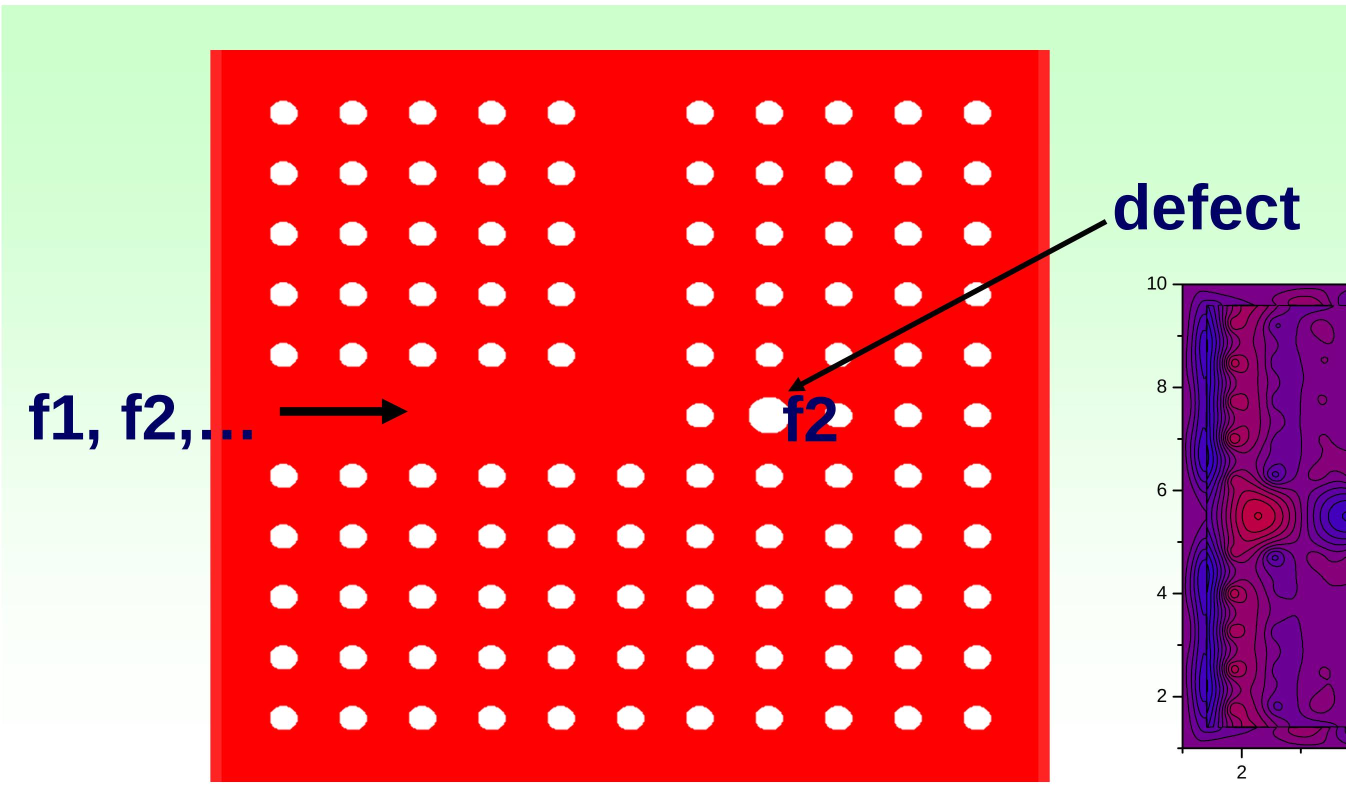


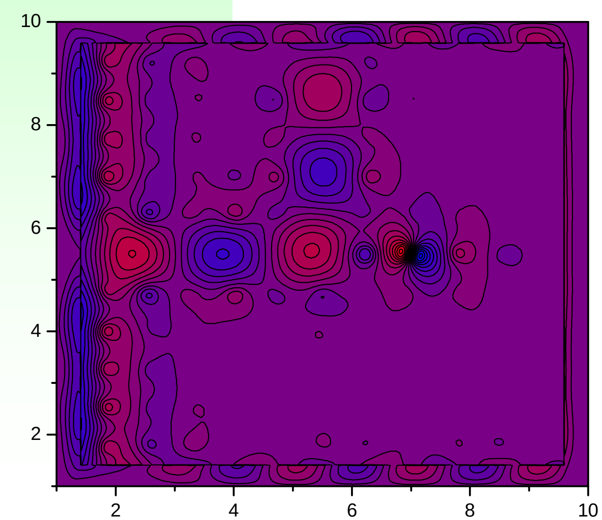
[A. Mekis *et al.*,
Phys. Rev. Lett. **77**, 3787 (1996)]

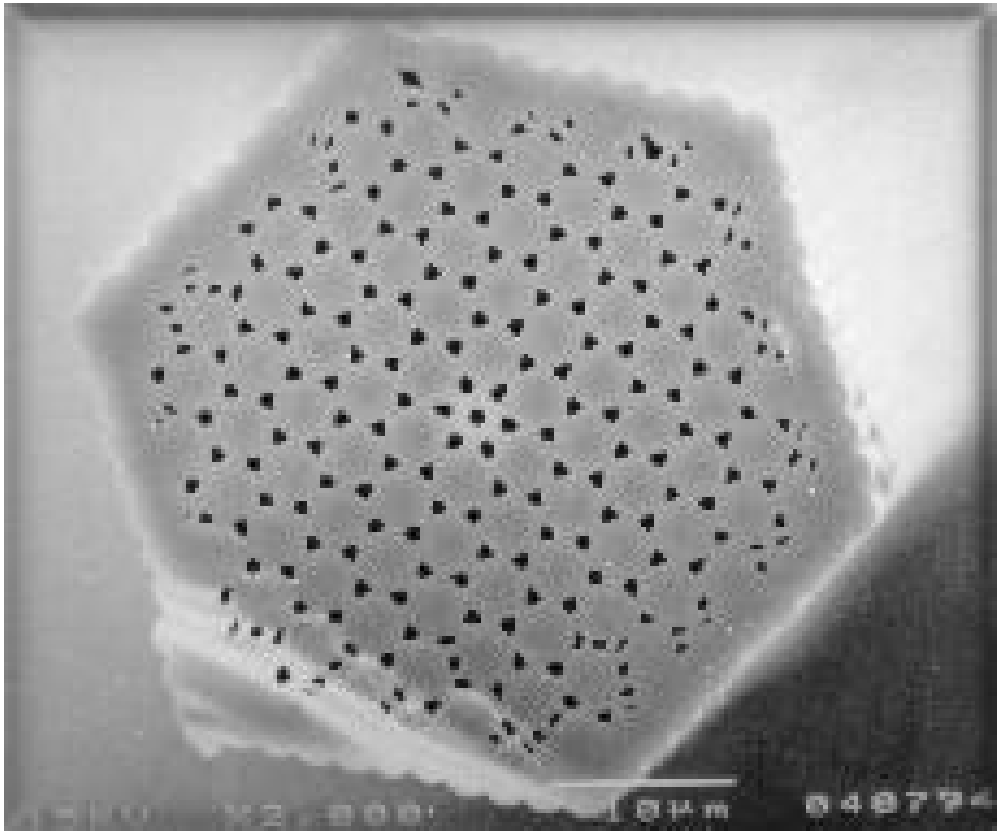
symmetry + single-mode + “1d” = resonances of 100% transmission

Multiplexer

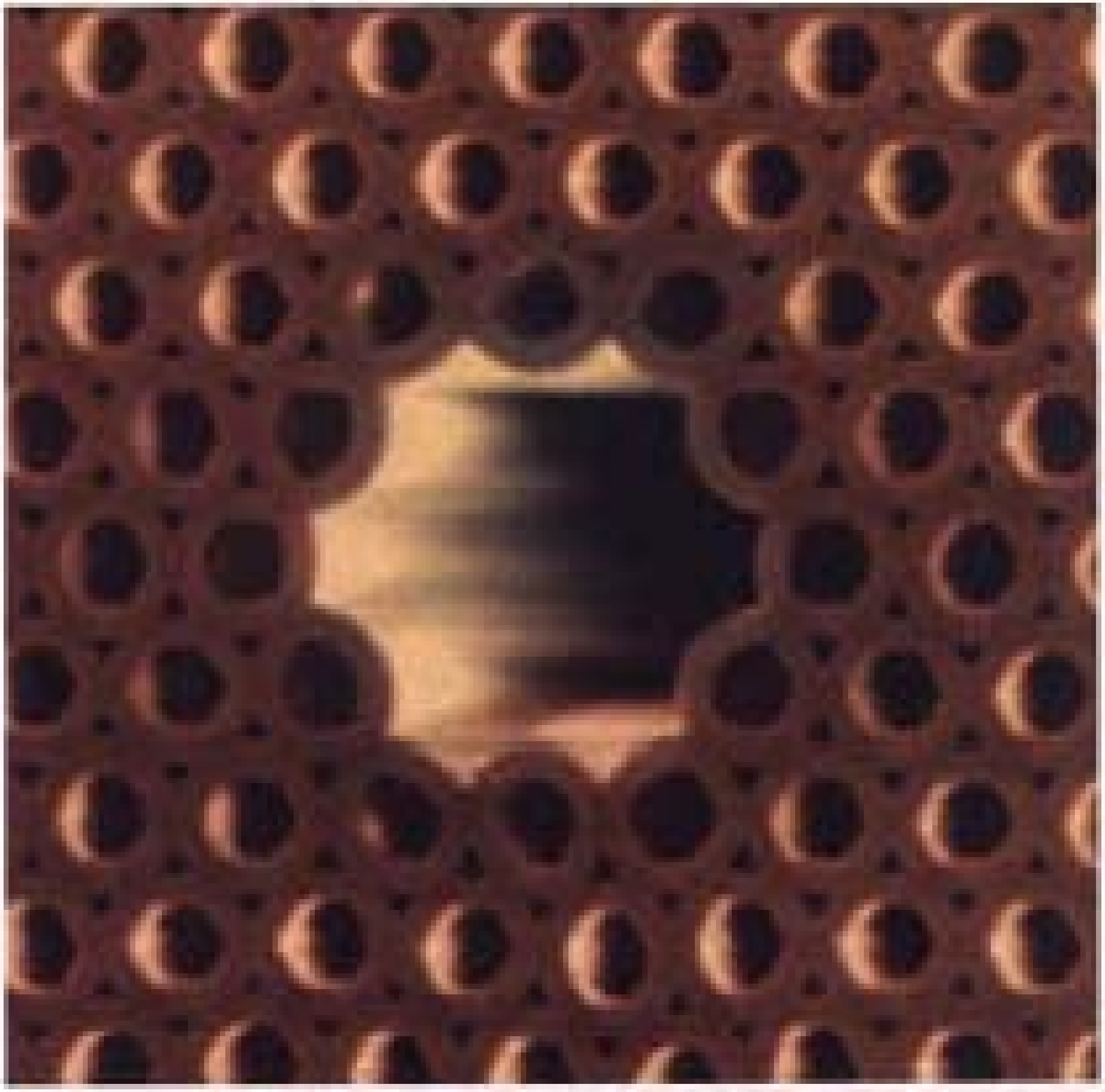
Coupling of guided modes and defect modes

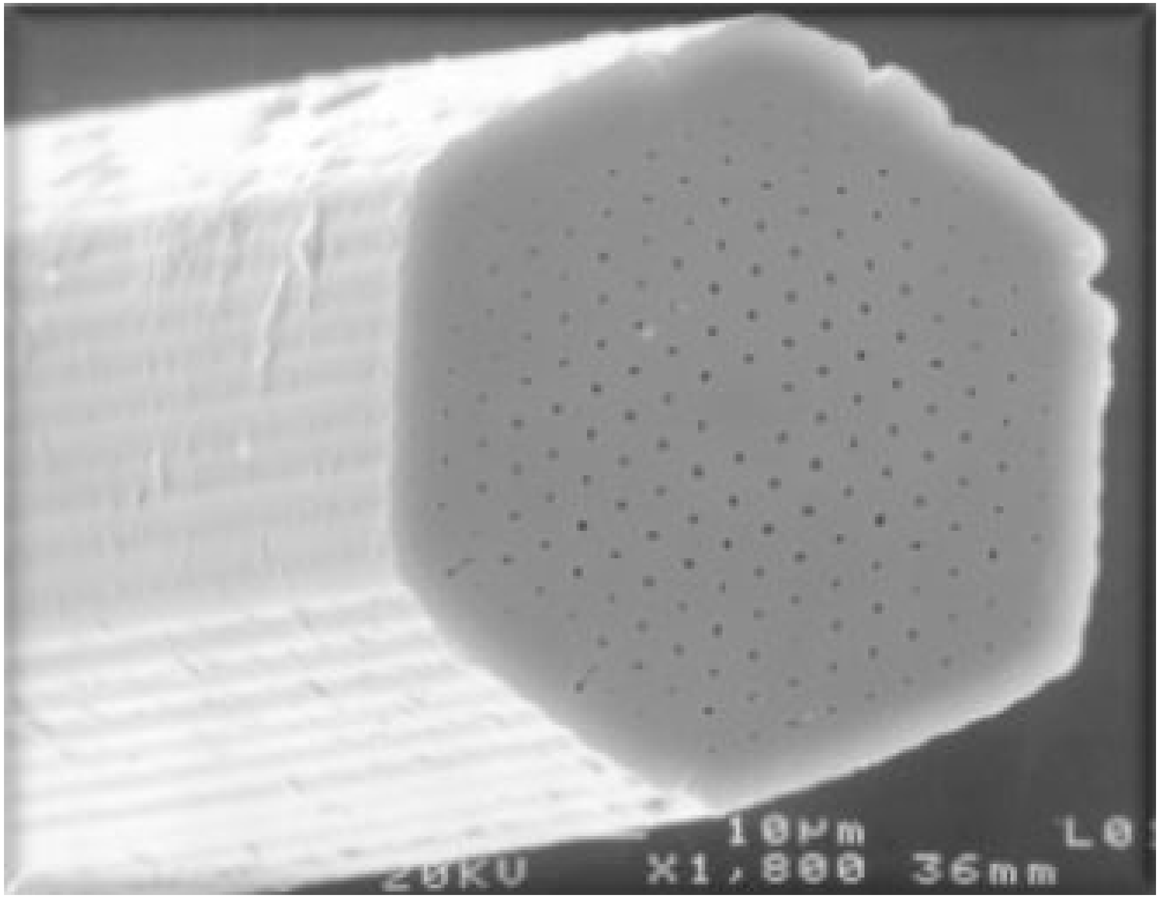




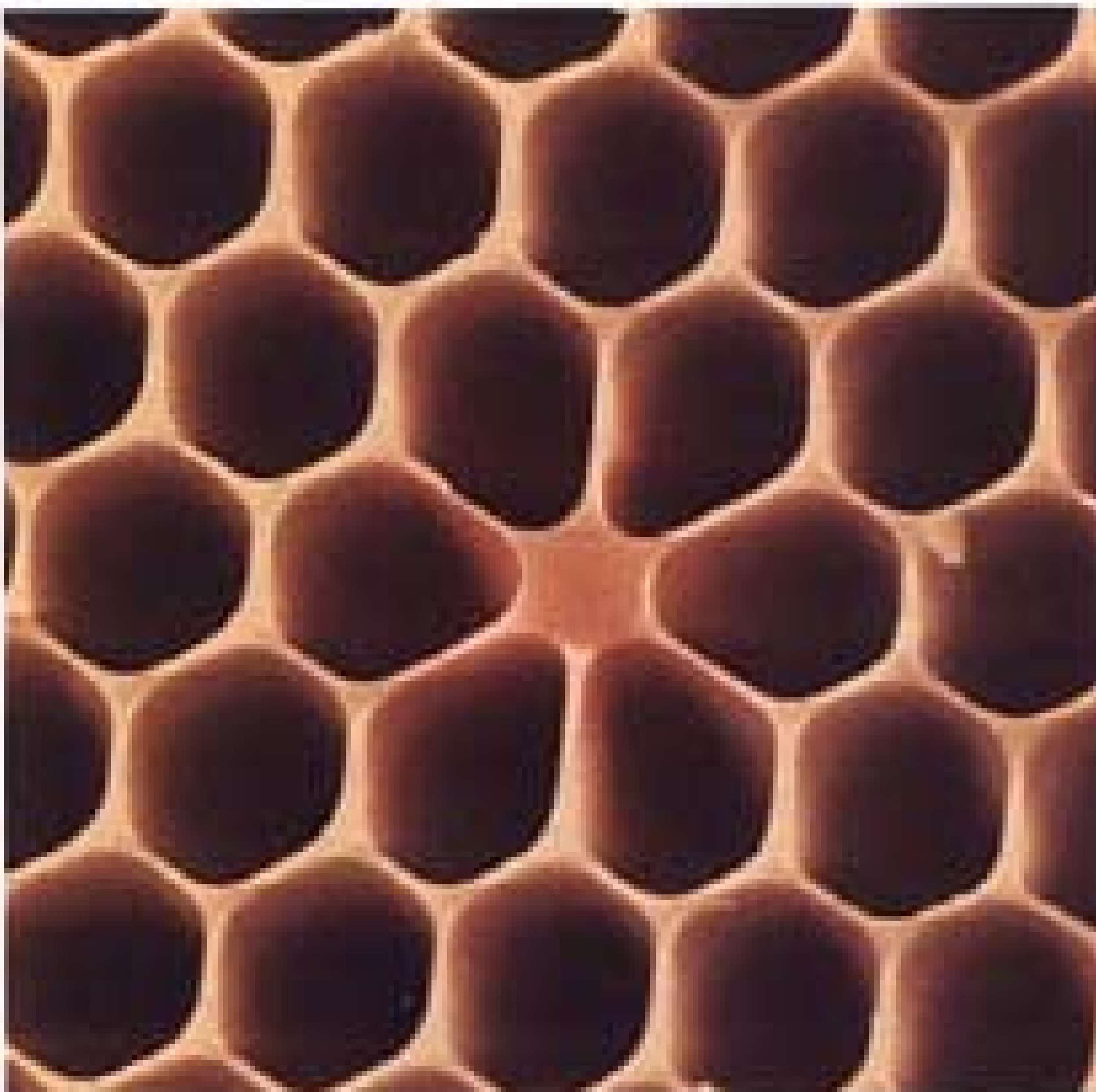


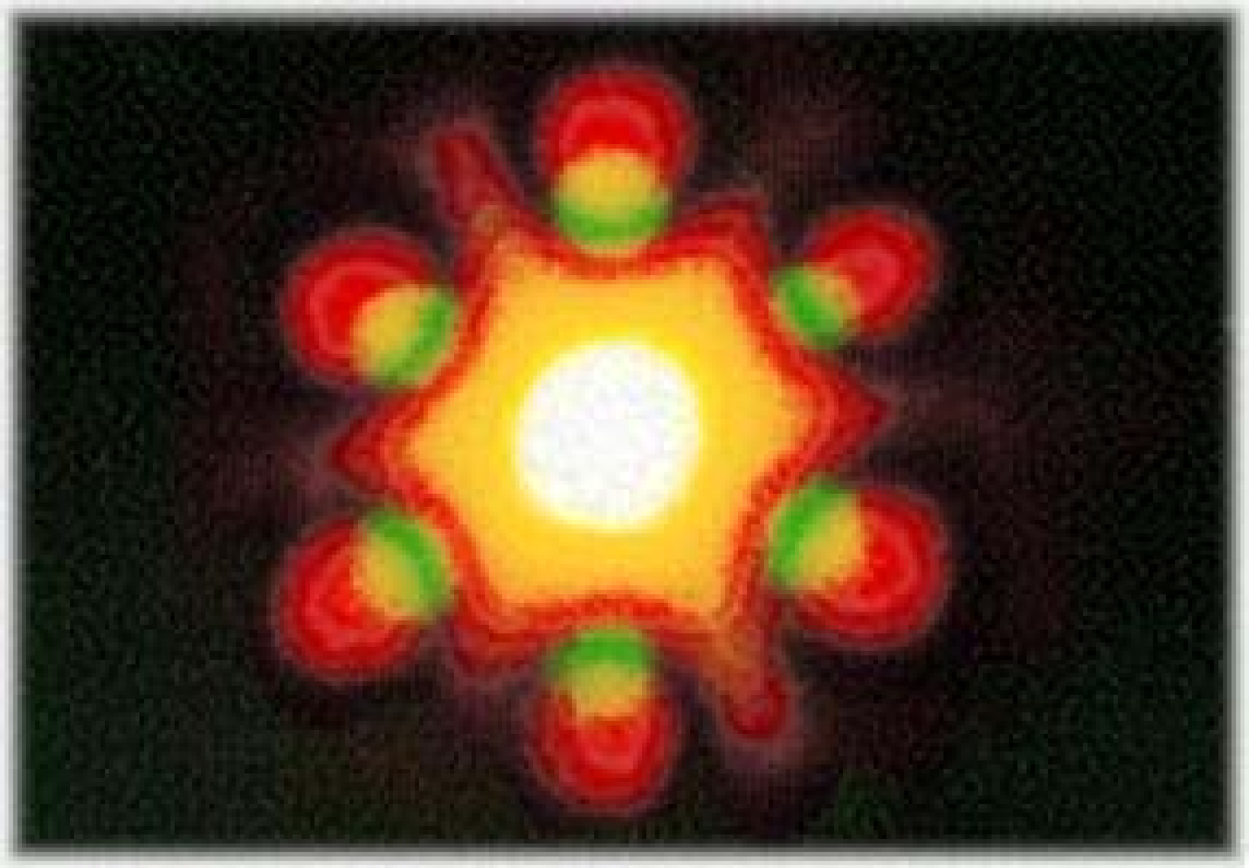
An SEM image of a photonic band-gap fibre. The region with the extra air hole in the centre acts as the core, in which light is guided by a photonic band-gap. The fibre is about 40 microns across.





An SEM image of a photonic crystal fibre. Note the periodic array of air holes, and the central defect (a missing hole) that acts as the fibre's core. The fibre is about 40 microns across.





A photograph of the far field pattern emerging from a photonic crystal fibre. The fibre was carrying red light from a helium-neon laser and green light from an argon ion laser.

You, too, can compute photonic eigenmodes!

晶体及电子运动规律
20世纪上半期

↓

晶体管及半导体器件
40-50年代

↓

集成化
60年代之后

↓

微电子产业

光子晶体概念提出
1987年

光子晶体特性及器件研究
90年代

光子晶体器件集成研究
至今

↓ **?**

光子产业


Thanks!