The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

1932-19

Winter College on Micro and Nano Photonics for Life Sciences

11 - 22 February 2008

Photonic crystals

Marco CENTINI

Università degli Studi di Roma 'La Sapienza'
Rome, Italy

The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
and Cultural Organization

International Atomic
Energy Agency

Winter College on Micro and Nano Photonics for Life Sciences
(11-22 February 2008)

Photonic Crystals:

A Glimpse

M.Centini
Universita' di Roma, "La Sapienza", Roma, Italy

Outline

- Photonic Crystals: definititions and brief introduction;

- Natural Photonic crystals;

- Fabrication technologies: overview;

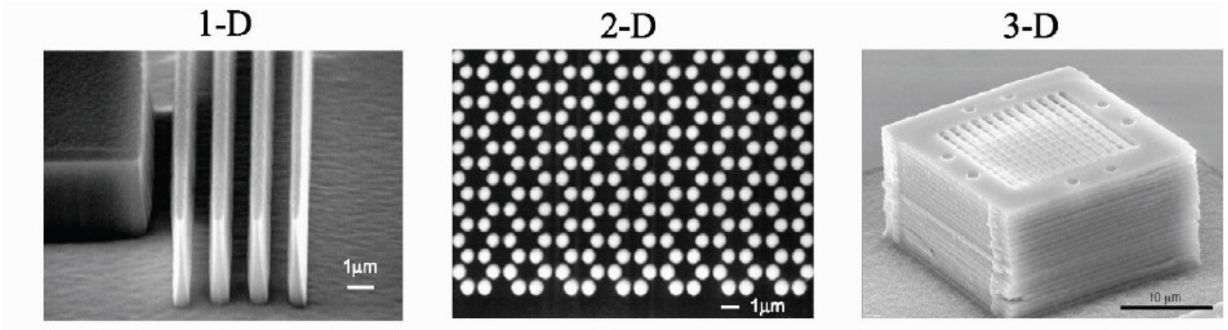
- Properties of bulk photonic crystals;

- Super Prism effect: Autocollimation, negative refraction;

- Band edge laser;

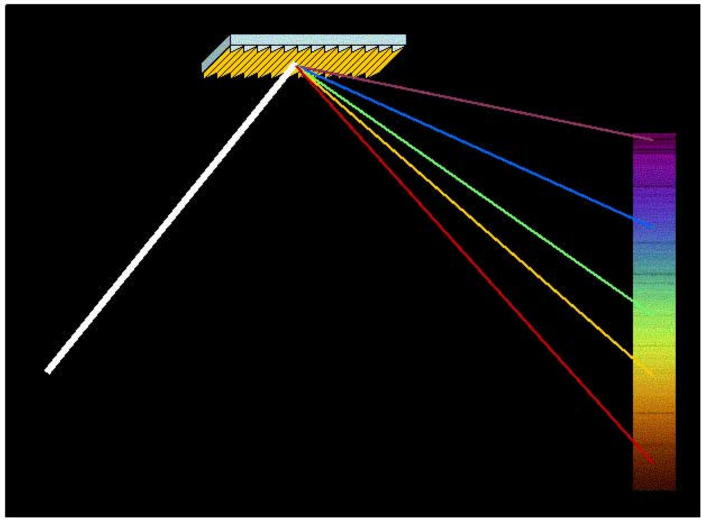
- Photonic Crystals: intentional defects, cavities and waveguides;

Photonic Crystals



Multi- dimensional periodic structures with a period of the order of optical wavelength.

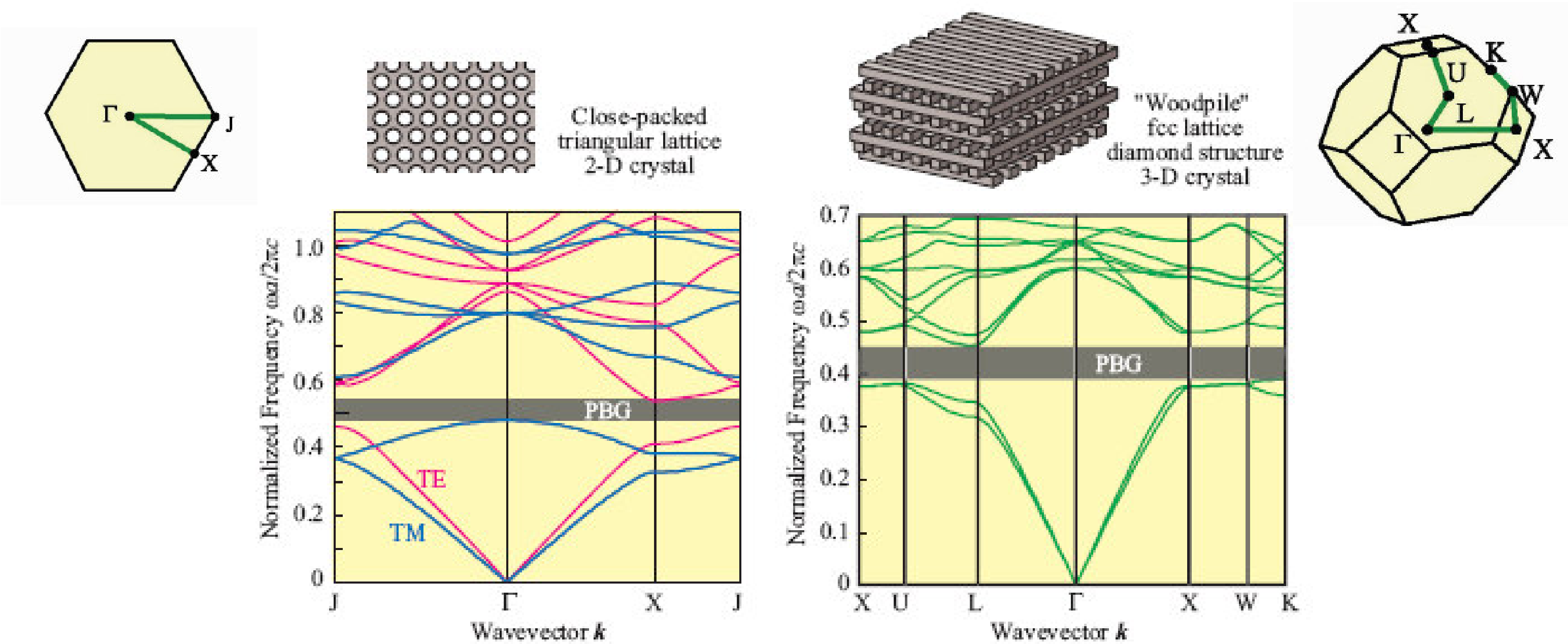
Periodicity comparable to incident light wavelengths can be responsible for constructive interferences among scattered light by every lattice point. A well known manifestation of this phenomenon is observed in diffraction gratings.



Coherent scattering of light

Photonic Crystals

Band diagrams $\omega = \omega(\vec{K});$



"Photonic crystals" **, K Inoue & K. Ohtaka, (** ***Springer, NewYork,2003*****).**

For a quick refresh on band diagrams and Brillouin zone see the lecture notes of " Photonic Crystal Basics", held at the Winter college preparatory school 4-8 Feb. 2008

From Bragg Gratings to Photonic Crystals in 5 Steps

1785: The first man-made diffraction grating was made by David Rittenhouse, who strung hairs between two finely threaded screws. (Fraunhofer 1821)

1913: Bragg formulation of X-ray diffraction by cristalline solids

1928: Bloch's Theorem describe the conduction of electrons in crystalline solids. (Math developed by Floquet in 1D case in 1883)

1976: A.Yariv and P. Yeh, study of dielectric multilayer stacks, waveguides and bragg fibers.

1987: Prediction of photonic crystals

S. John, Phys. Rev. Lett. 58,2486 (1987), "*Strong localization of photons in certain dielectric superlattices*"

E. Yablonovitch, Phys. Rev. Lett. 58 2059 (1987), "*Inhibited spontaneous emission in solid state physics and electronics*"

Brief Photonic Crystal History

1987: Prediction of photonic crystals

S. John, Phys. Rev. Lett. 58,2486 (1987), "*Strong localization of photons in certain dielectric superlattices*"
E. Yablonovitch, Phys. Rev. Lett. 58 2059 (1987), "*Inhibited spontaneous emission in solid state physics and electronics*"

1990: Computational demonstration of photonic crystal

K. M. Ho, C. T Chan, and C. M. Soukoulis, Phys. Rev. Lett. 65, 3152 (1990)

1991: Experimental demonstration of microwave photonic crystals

E. Yablonovitch, T. J. Mitter, K. M. Leung, Phys. Rev. Lett. 67, 2295 (1991)

Brief Photonic Crystal History

1995: ”Large” scale 2D photonic crystals in Visible

U. Gruning, V. Lehman, C.M. Englehardt, Appl. Phys. Lett. 66 (1995)

1998: ”Small” scale photonic crystals in near Visible;

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

“Large” scale inverted opals

Zakhidov et al., Science 282, 897 (1998)

Photonic Crystal Fibres

J.C. Knight et al, Science 282, 1476 (1998).

Brief Photonic Crystal History

1999: First photonic crystal based optical devices;

M. Meier et al., Appl. Phys. Lett. 74, 1 (1999) (PhC Laser)
T. Zijlstra et al., *J. Vac. Sci. Technol. B17*, 2734 (1999). (PhC Waveguides)
R.F. Cregan et al., Science 285, 1537 (1999) (holey fibers)

2000-present: Large number of applications, devices and new fabrication technologies proposed and realized

Websites:

http://www.pbglink.com **for Extensive web listing of PBG information**

http://ab-initio.mit.edu/mpb **MIT photonic- band package**

http://homepages.udayton.edu/~sarangan **Dayton Univ. Lectures on Photonic crystals**

Suggested readings

Books:

Photonic Crystals: Towards Nanoscale Photonic Devices, J-M Lourtioz et al. Springer (2003)

Roadmap on Photonic Crystals by Susumu Noda (Editor), Toshihiko Baba (Editor), Kluwer Academic Publishers; (2003).

Nonlinear Photonic Crystals by R. E. Slusher and B. J. Eggleton Eds., (2003).

Photonic Crystals: The Road from Theory to Practice: S. G. Johnson and J. D.Joannopoulos, Kluwer (2002).

Optical Properties of Photonic Crystals K. Sakoda, Springer (2001).

Quantum Electronics 3° edition A. Yariv, Wiley (1989).

Optical waves in Layered media Pochi Yeh, Wiley (1988).

Photonic Crystal Fibres A. Bjarklev *et al*, Kluwer (2003)

Photonic Crystal Fibre PJ Russel, Wiley (2005)

Bloch's Theorem

for e.m waves in photonic crystals

Starting point: Maxwell equations and constitutive relations.

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t},$$

$$\nabla \times \vec{H} = \frac{\partial \vec{D}}{\partial t} + \cancel{\vec{j}},$$

$$\nabla \cdot \vec{D} = \cancel{\rho},$$

$$\nabla \cdot \vec{B} = 0.$$

If the e.m field is time-harmonic and if the bodies are at rest or in very slow motion relative to each other:

$$\vec{j} = \sigma \vec{E}, \quad \vec{D} = \varepsilon_0 \hat{\varepsilon}_r \vec{E}, \quad \vec{B} = \mu_0 \hat{\mu}_r \vec{H}.$$

Neutral Insulators or dielectrics: $\rho=0$
σ**(conductivity) is negligibly small;** non magnetically active μ_r**=1;**

If we seek solutions of the form: $\vec{E}(\vec{r},t) = \vec{E}(\vec{r})e^{-i\omega t}; \quad \vec{H}(\vec{r},t) = \vec{H}(\vec{r})e^{-i\omega t};$

We have….

Ashcroft & Mermin, Solid State Physics, Saunders College Publishing for a proof of the theorem

Bloch's Theorem

for e.m waves in photonic crystals

…the following eigenvalue equations:

$$\hat{\Gamma}_E \vec{E}(\vec{r}) = \frac{1}{\varepsilon_r(\vec{r})} \vec{\nabla} \times \left\{ \vec{\nabla} \times \vec{E}(\vec{r}) \right\} = \frac{\omega^2}{c^2} \vec{E}(\vec{r}),$$

$$\hat{\Gamma}_H \vec{H}(\vec{r}) = \vec{\nabla} \times \left\{ \frac{1}{\varepsilon_r(\vec{r})} \vec{\nabla} \times \vec{H}(\vec{r}) \right\} = \frac{\omega^2}{c^2} \vec{H}(\vec{r}),$$

If ε_r is a periodic function of the spatial coordinate Bloch's Theorem states that fields solutions are characterized by a **Bloch wave vector K**, a band index n and have the form:

$$\vec{E}(\vec{r}) = \vec{E}_{\vec{K}n}(\vec{r}) e^{i\vec{K}\cdot\vec{r}}; \qquad \vec{H}(\vec{r}) = \vec{H}_{\vec{K}n}(\vec{r}) e^{i\vec{K}\cdot\vec{r}};$$

with:

$$\varepsilon_r(\vec{r}) = \varepsilon_r(\vec{r} + \vec{a}_i);$$

$$\vec{E}_{\vec{K}n}(\vec{r}) = \vec{E}_{\vec{K}n}(\vec{r} + \vec{a}_i); \qquad i = 1,2,3.$$

$$\vec{H}_{\vec{K}n}(\vec{r}) = \vec{H}_{\vec{K}n}(\vec{r} + \vec{a}_i);$$

$\vec{a}_1;$ $\vec{a}_2;$ $\vec{a}_3;$ Primitive vectors of the periodic lattice

Bloch's Theorem

for e.m waves in photonic crystals

Substituting Bloch's solution into eigenvalue equations it is possible to calculate:

Eigen-angular frequencies: $\omega_{\vec{K}n}$;

Bloch modes (eigenvectors): $\vec{E}_{\vec{K}n}(\vec{r})$; $\vec{H}_{\vec{K}n}(\vec{r})$;

If we consider infinite periodic structures, real values of ε (i.e lossless case), Γ_E and Γ_H are Hermitian eigen-operators:

$$\omega_{\vec{K}n} \in R$$

$\vec{E}_{\vec{K}n}(\vec{r})$; $\vec{H}_{\vec{K}n}(\vec{r})$; Are a complete set of orthogonal eigen-functions.

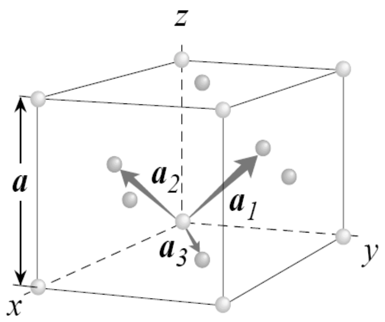
Solving equations for several values of K and w it is possible to calculate and plot band diagrams (dispersion relations)

Photonic Crystals

Photonic crystals are characterized by a lattice, and a dielectric function (periodic over the lattice).

Primitive vectors

$$\vec{a}_1; \quad \vec{a}_2; \quad \vec{a}_3;$$



Primitive basis vectors for the face-centered cubic lattice.

$$\varepsilon(\vec{r} + n\vec{a}_1 + m\vec{a}_2 + l\vec{a}_3) = \varepsilon(\vec{r})$$

$$n, m, l = 0, \pm 1, \pm 2, \ldots; \vec{r} \in u.c.$$

A periodic function can be expanded according to Fourier series:

$$\varepsilon(\vec{r}) = \sum_{\vec{G}} e^{i\vec{G}\cdot\vec{r}} F(\vec{G});$$

RECIPROCAL LATTICE

The set of G vectors are selected in order to have a periodic oscillating function over the unit cell. This means that in a lattice point identified by vector **R**:

$$e^{i\vec{G}\cdot\vec{R}} = 1$$

$$\vec{R} = n\vec{a}_1 + m\vec{a}_2 + l\vec{a}_3;$$

$$n, m, l = 0, \pm 1, \pm 2, \ldots$$

Photonic Crystals

Primitive vectors for the reciprocal lattice:

$$\vec{g}_1 = 2\pi \frac{\vec{a}_2 \times \vec{a}_3}{\vec{a}_1 \cdot (\vec{a}_2 \times \vec{a}_3)};$$

$$\vec{g}_2 = 2\pi \frac{\vec{a}_3 \times \vec{a}_1}{\vec{a}_2 \cdot (\vec{a}_3 \times \vec{a}_1)};$$

$$\vec{g}_3 = 2\pi \frac{\vec{a}_1 \times \vec{a}_2}{\vec{a}_3 \cdot (\vec{a}_1 \times \vec{a}_2)};$$

For a given Bloch wavevector **K**

$$\vec{E}(\vec{r}) = \vec{E}_{\vec{K}}(\vec{r}) e^{i\vec{K}\cdot\vec{r}}$$

If we consider the solution for **K'=K+G:**

$$\vec{E}(\vec{r}) = \vec{E}_{\vec{K}'}(\vec{r}) e^{i\vec{G}\cdot\vec{r}} e^{i\vec{K}\cdot\vec{r}}$$

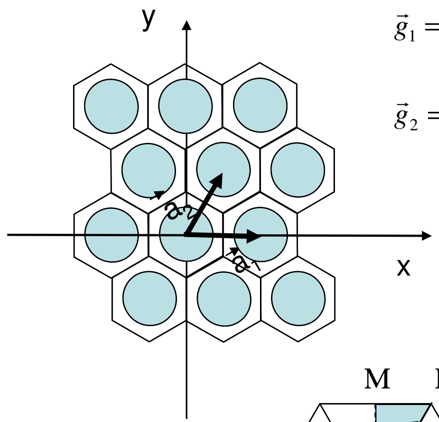
Fulfill same equation

$$\omega = \omega(\vec{K}) = \omega(\vec{K} + \vec{G});$$

The Brillouin zone for a Bravais lattice is the primitive unit cell of the reciprocal lattice.

As a consequence, for a given lattice, band diagrams are periodic functions over its reciprocal lattice.

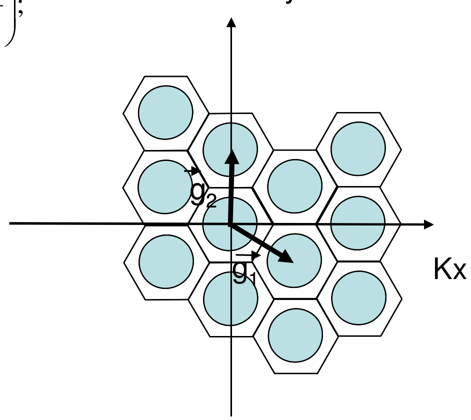
Triangular lattice



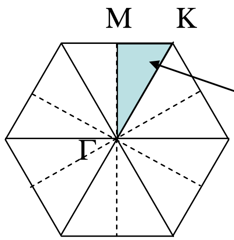
$$\vec{g}_1 = \frac{4\pi}{a\sqrt{3}}\left(\frac{\hat{x}\sqrt{3}}{2} - \frac{\hat{y}}{2}\right);$$

$$\vec{g}_2 = \frac{4\pi}{a\sqrt{3}}\hat{y};$$

Reciprocal lattice



Brillouin zone:

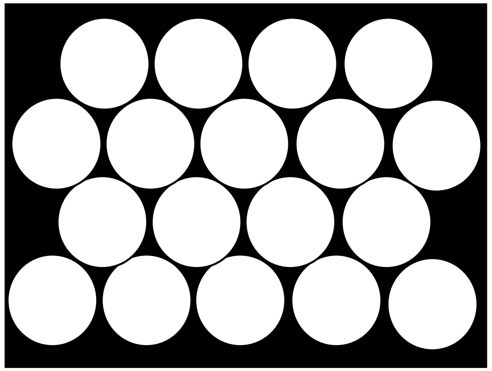


Irreducible Brillouin zone

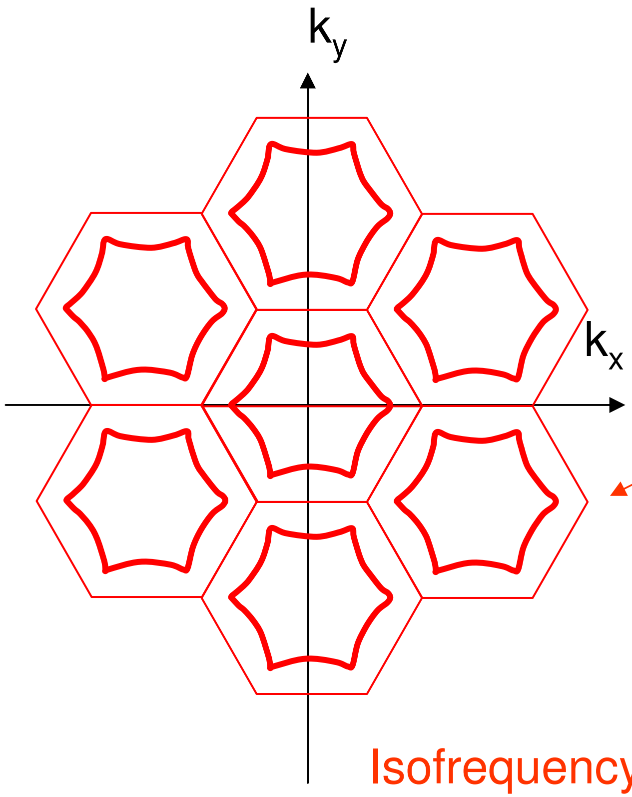
K Middle of an edge joining two hexagonal faces

Analysis of 2D and 3D Photonic crystals

Examples in 2D



Triangular lattice



Isofrequency curves

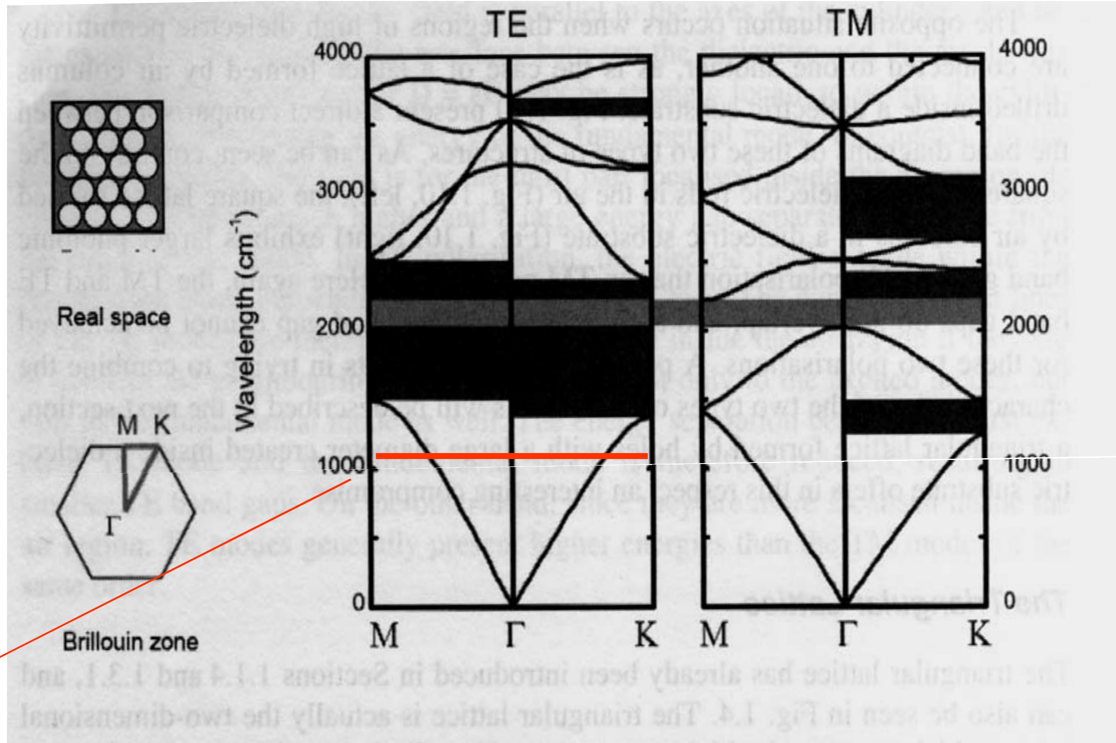


Fig. 1.11. ***Left.*** Triangular lattice formed by pores created in a dielectric substrate and corresponding Brillouin zone. ***Right.*** Band diagram calculated for a dielectric substrate with a permittivity $\varepsilon = 11.7$ and a period $a = 2\mu m$, while the radius of the pores is $r/a = 0.45$. The band gaps are indicated by grey bands

Computational Tools

Plane Wave Expansion (PWE) Method

-CPU time demanding and considerations on the truncation of the Fourier expansion of the dielectric constant have to be done to check convergence

Koringa-Kohn-Rostker (KKR) Method

- based on spherical waves expansion. Scattering matrix approach used for the elementary cell. it provides the Green function for the periodic structure on the basis of spherical harmonics.

Transfer matrix method

- Developed by Pendry's group at Imperial College.
It also provides amplitude and phase information.
- Rigorous Coupled-wave analysis RCWA

Numerical simulations:

- Finite difference time-domain computation (Sakoda's book)
- Modified FFT-TD Beam propagation method (papers by M. Scalora, J. Haus)

Plane Wave Method

Maxwell's equations in the frequency representation

$$\vec{E}_\omega(\vec{r}) = e^{i\vec{k}\cdot\vec{r}} \sum_{\vec{G}} \vec{E}_\omega(\vec{G}) e^{i\vec{G}\cdot\vec{r}}$$

Reciprocal lattice vectors

$$\vec{\nabla}\times\left(\vec{\nabla}\times\vec{E}_\omega(\vec{r})\right) = -\frac{\omega^2}{c^2}\tilde{\tilde{\varepsilon}}_\omega(\vec{r})\cdot\vec{E}_\omega(\vec{r})$$

E-method

$$(\vec{G}+\vec{k})\times((\vec{G}+\vec{k})\times\vec{E}(\vec{G})) = \frac{\omega^2}{c^2}\sum_{\vec{G}'}\tilde{\tilde{\varepsilon}}(\vec{G}-\vec{G}')\cdot\vec{E}(\vec{G}')$$

eigenvalue

$$\vec{\nabla}\times\left(\tilde{\tilde{\eta}}_\omega(\vec{r})\cdot\vec{\nabla}\times\vec{H}_\omega(\vec{r})\right) = -\frac{\omega^2}{c^2}\vec{H}_\omega(\vec{r})$$

H-method

$$(\vec{G}+\vec{k})\times\left(\sum_{\vec{G}'}\tilde{\tilde{\eta}}(\vec{G}-\vec{G}')\cdot(\vec{G}'+\vec{k})\times\vec{H}(\vec{G}')\right) = \frac{\omega^2}{c^2}\vec{H}(\vec{G})$$

$$\tilde{\tilde{\eta}}_\omega(\vec{r}) = \tilde{\tilde{\varepsilon}}_\omega(\vec{r})^{-1}$$

2D simplification scalar equations

- E-polarization $\vec{E} = E(x,y)\hat{z}$
  - **k** in the 2D plane
  - Scalar equation

$$|\vec{G}+\vec{k}|^2 \; E(\vec{G}) = \frac{\omega^2}{c^2}\sum_{\vec{G}'}\varepsilon_z(\vec{G}-\vec{G}')E(\vec{G}')$$

- H-polarization $\vec{H} = H(x,y)\hat{z}$
  - **k** in the 2D plane
  - Scalar equation

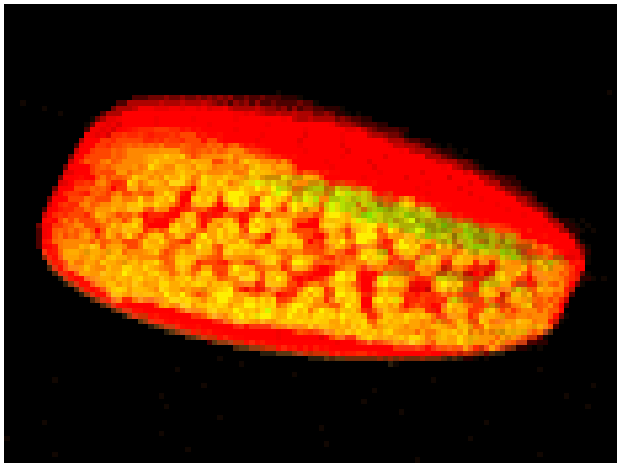
$$\left(\sum_{\vec{G}'}(\vec{G}+\vec{k})\cdot\tilde{\tilde{\eta}}(\vec{G}-\vec{G}')\cdot(\vec{G}'+\vec{k})H(\vec{G}')\right) = \frac{\omega^2}{c^2}H(\vec{G})$$

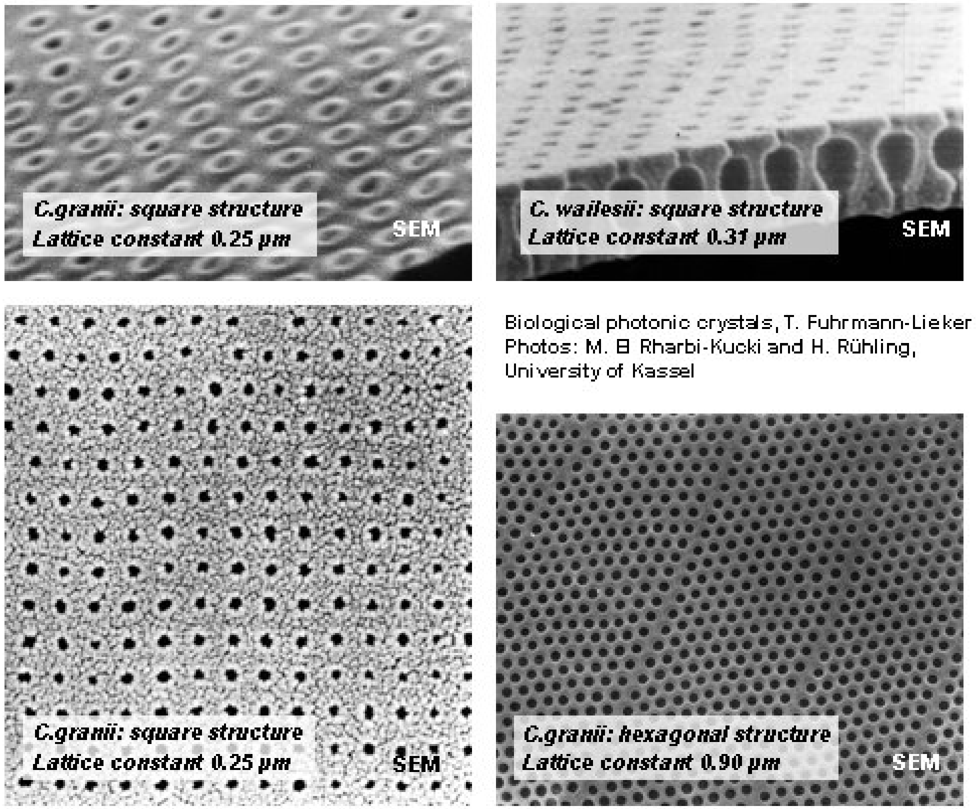
To solve these eigenvalue equations the number of terms is truncated. In some cases a high number of equations must be considered. Convergence tests must be performed.

Natural Photonic Crystals

Nature has produced nanoscopic periodic structures that inspire researchers to create entirely new solutions to persistent problems.

Diatom (unicellular algae) convert sunlight into chemical energy.

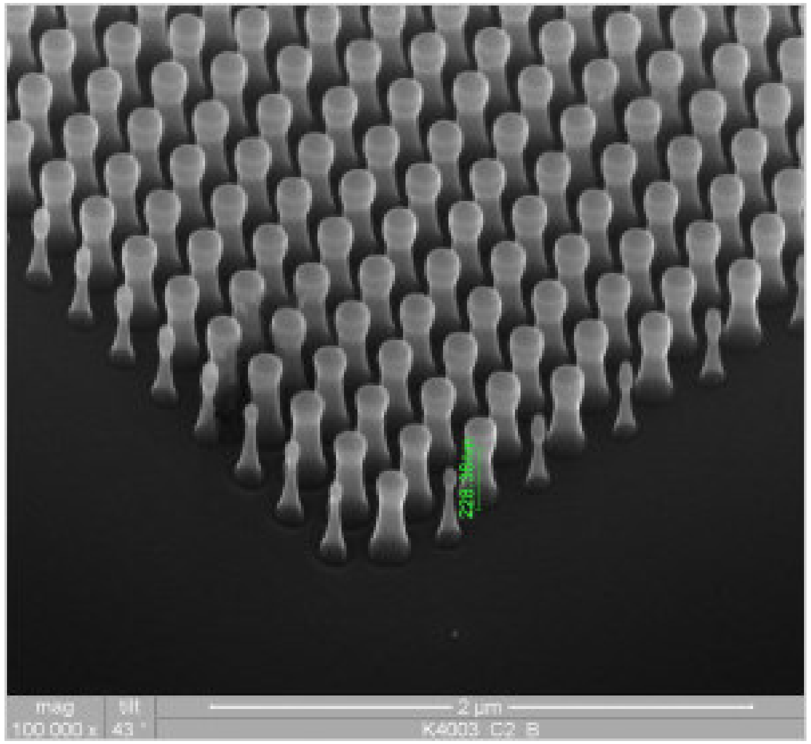




Details of the silica shell structure of the diatom species *Coscinodiscus granii* and *Coscinodiscus wailesii*

"Inspired by Nature" Photonic Crystals

BIOMIMETICS: emerging science of mimicking the properties that nature produces on its own. For example:



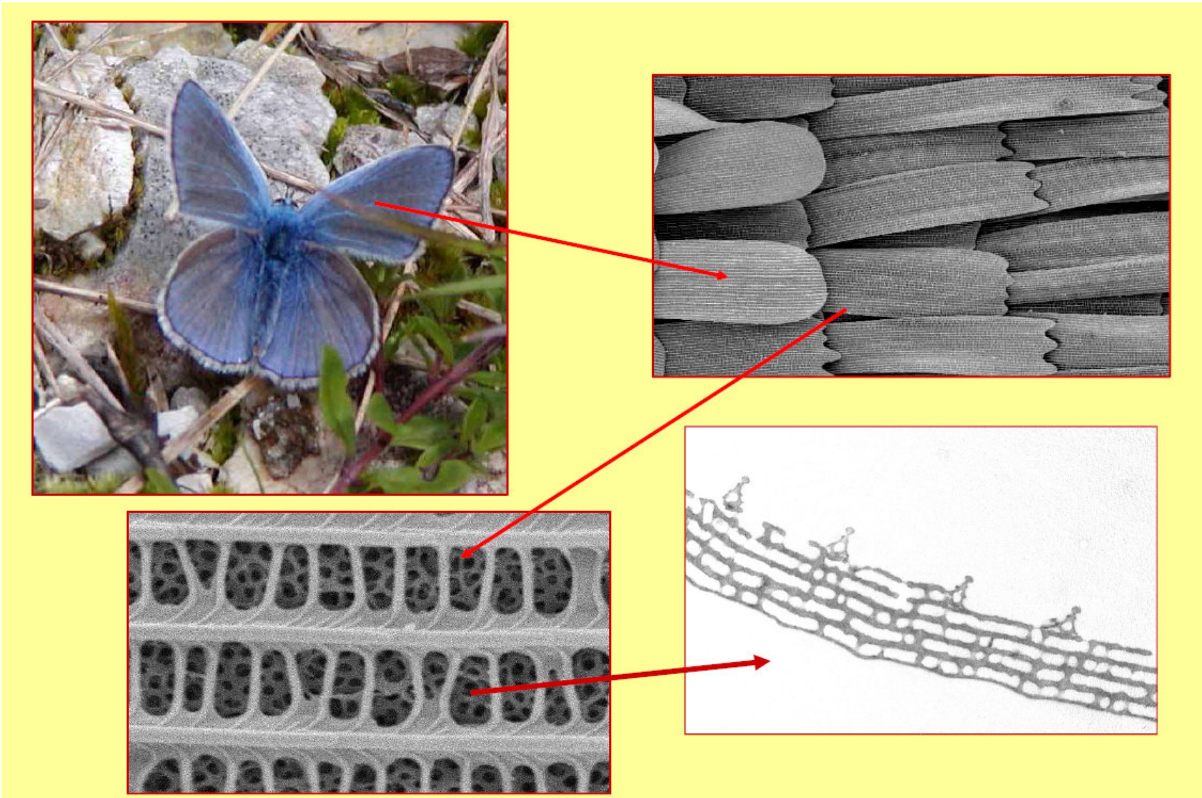
Darren Bagnall at the Southhampton University nanofab facility has patterned silicon after the structure of a night flying moth cornea. The moth cornea allows very little light to escape making it an excellent anti-reflective coating.

Natural Photonic Crystals

Coloration in Butterfly wings

Pigments found in butterflies, (melanins, pterins) can produce yellow, orange-yellow, red, black and brown colors.

Blue, violet and green colors are results of the scales micro and nanostructure of the wings.



Natural Photonic Crystals

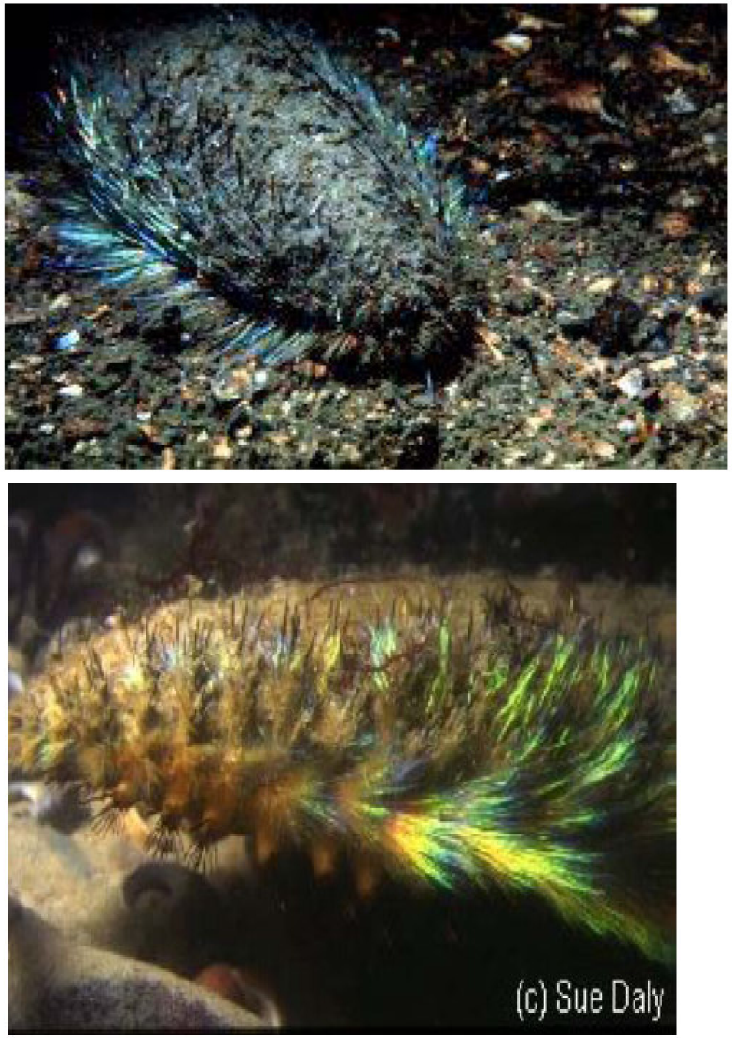


Fig. 1: A sea mouse or *Aphrodita* (note the iridescent felt on the edge of its body). From Sue Daly, *Marine Life of the Channel Islands*, 1998 (with permission).

The sea mouse-Aphrodita sp.
(Polychaeta: Aphroditidae)

N·H
ELSEVIER

Available online at www.sciencedirect.com
SCIENCE DIRECT®

Physica B 338 (2003) 182–185

PHYSICA B

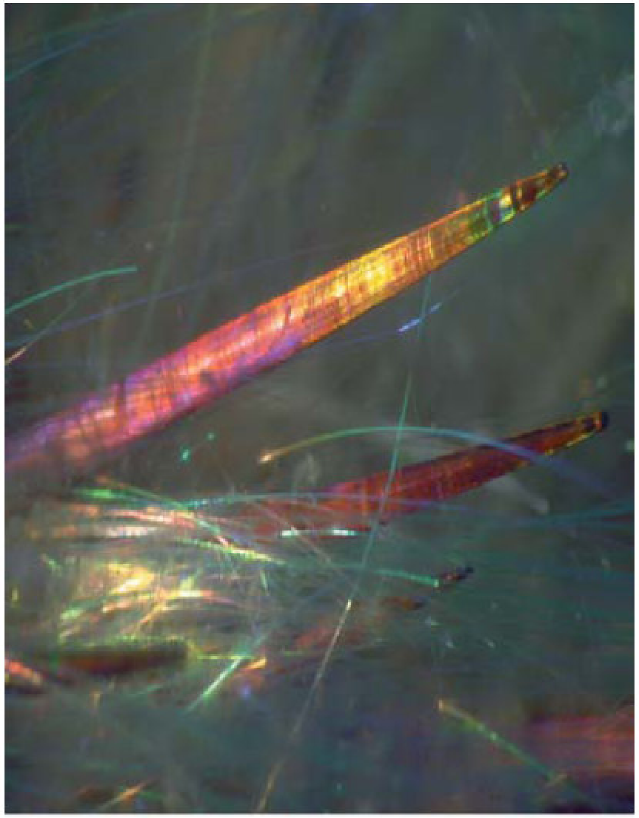
www.elsevier.com/locate/physb

Structural colours through photonic crystals

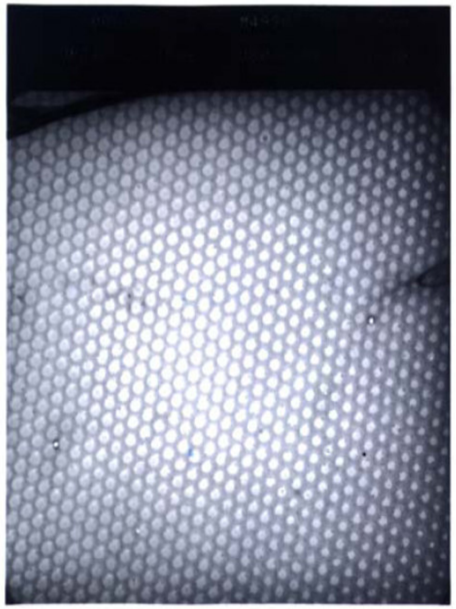
R.C. McPhedran[a,*], N.A. Nicorovici[a], D.R. McKenzie[a], G.W. Rouse[b], L.C. Botten[c], V. Welch[d], A.R. Parker[d], M. Wohlgennant[e], V. Vardeny[e]

[a] *Department of Theoretical Physics, School of Physics, University of Sydney, NSW 2006, Australia*
[b] *School of Biological Sciences, University of Sydney, NSW 2006, Australia*
[c] *School of Mathematical Sciences, University of Technology, Sydney, P.O Box 123, Broadway, NSW 2007, Australia*
[d] *Department of Zoology, University of Oxford, South Parks Road, Oxford OX1 3PS, UK*
[e] *Department of Physics, University of Utah, Salt Lake City, UT 84112, USA*

Natural Photonic Crystals



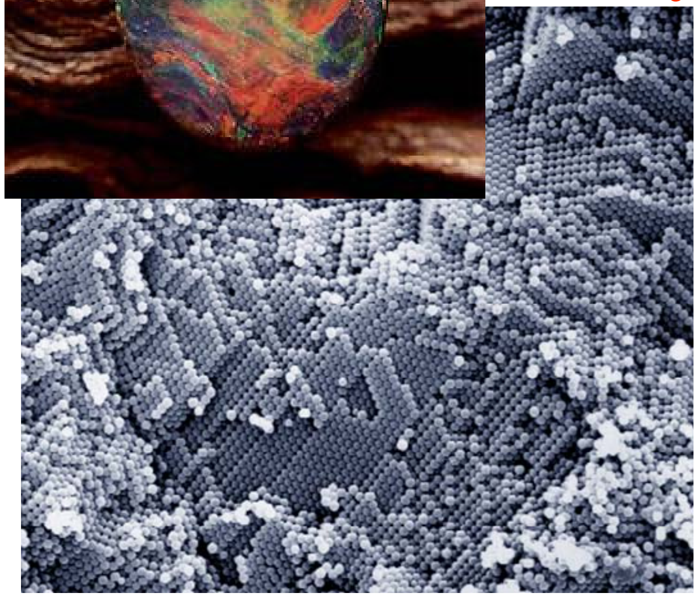
- Electronmicrographs of a spine and a felt hair. Both contain close packed voids of water in chitin (refractive index 1.52). The spine has 88 layers of holes with a spacing of 0.51 μm.

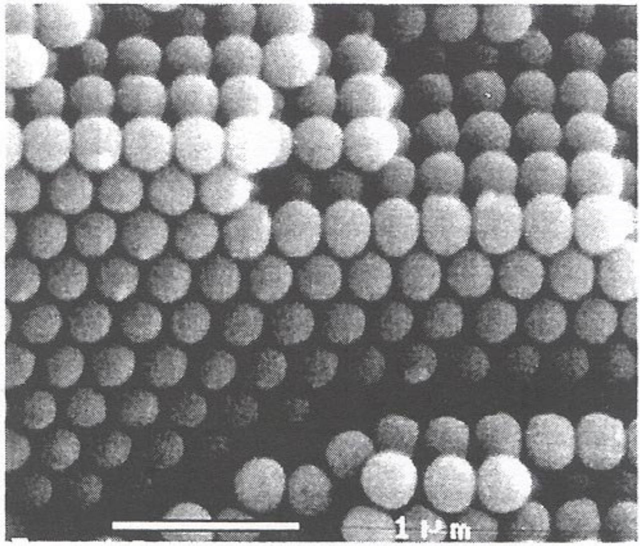


Natural Photonic Crystals

Opal - silica spheres

Close packed spheres form a FCC lattice. 3D photonic crystals.





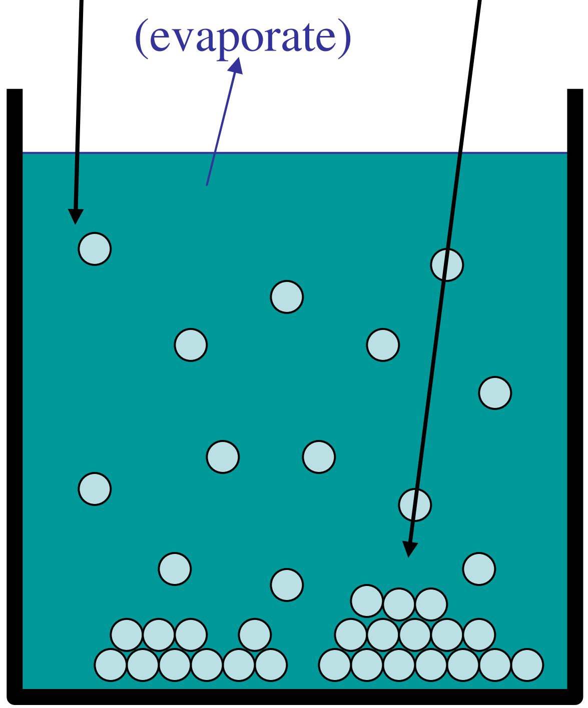
Zakhidov et al., Science 282, 897 (1998)

Colloids, artificial opals

silica (SiO_2)

microspheres (diameter < 1μm)

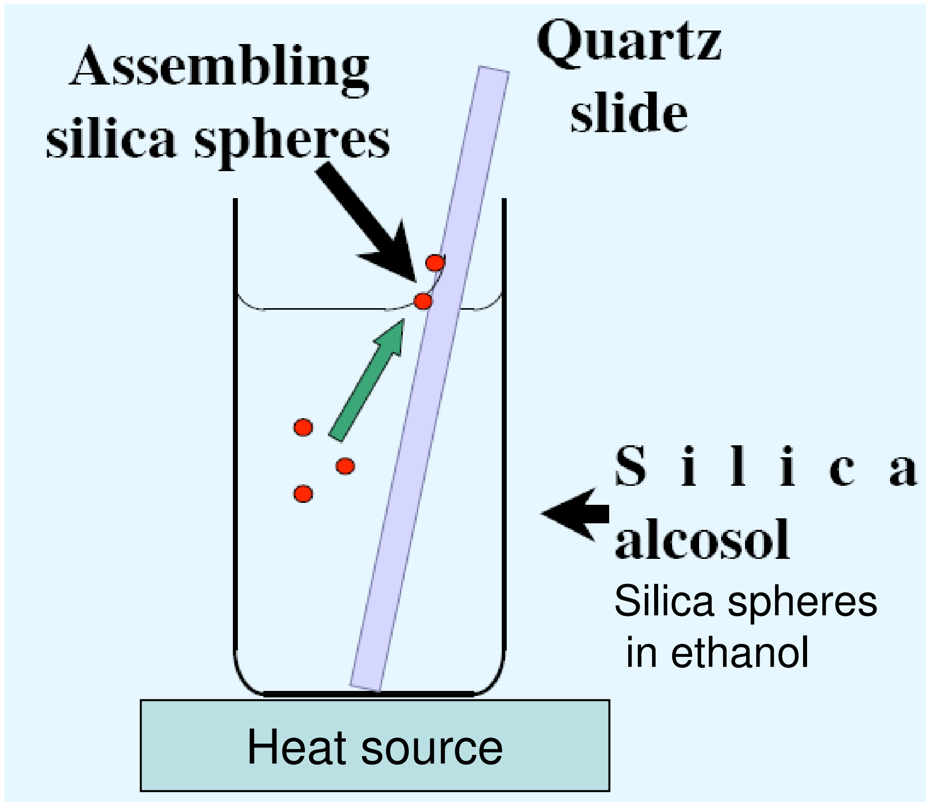
sediment by gravity into close-packed fcc lattice!



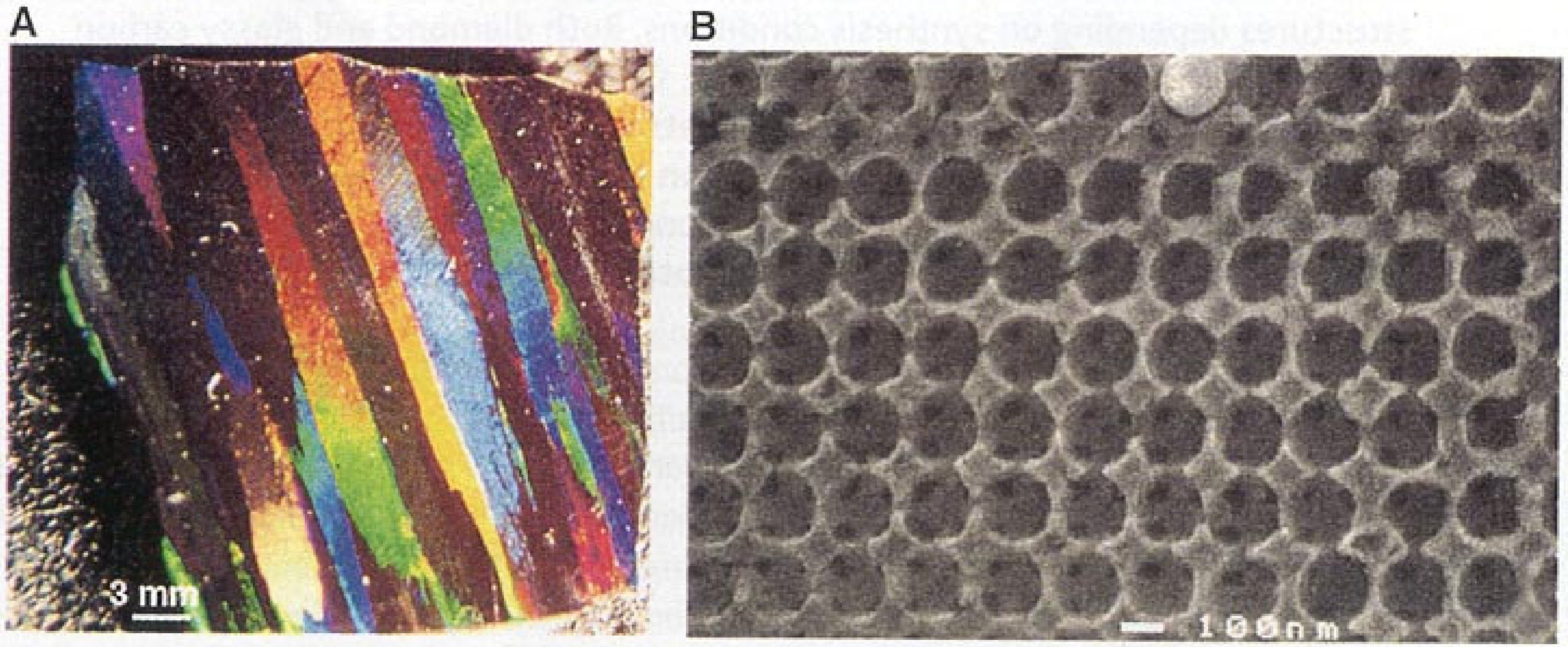
Convective Assembly

[Nagayama, Velev, *et al.*, *Nature* (1993)
Colvin *et al.*, *Chem. Mater.* (1999)]

Capillary forces during drying cause assembly in the meniscus. Flat, thin films, large area opals are acheived

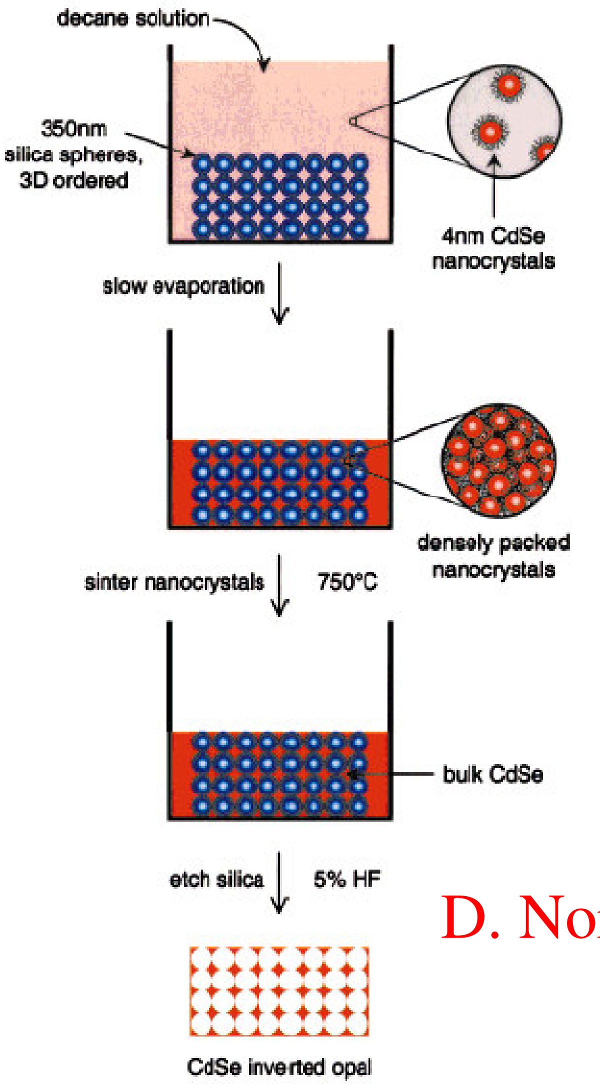


Inverse Opals



Zakhidov et al., Science 282, 897 (1998)

CdSe inverse Opal synthesis



1. Silica PBG immersed in solution of CdSe nanoparticles

2. Solution evaporates leaving the CdSe particles behind

3. Sintering leads to densification of the CdSe particles.

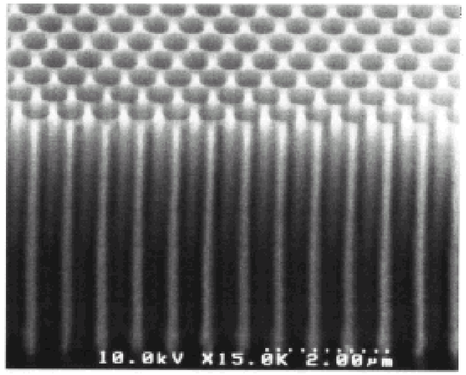
4. Silica is etches away, leaving CdSe matrix

D. Norris and Y. Vlasov, Adv. Mat. 13, 371 (2001)

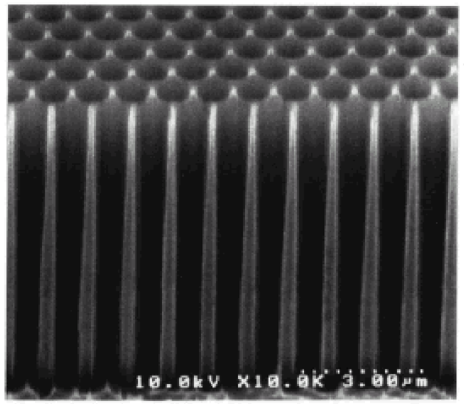
Semiconductor Processing

Fabrication of high-aspect-ratio two-dimensional silicon-based photonic crystal chips

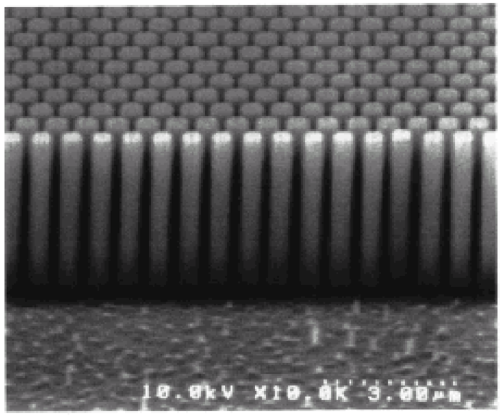
Y. Xu et al., J. Opt. Soc. Am. B**18**, 1084 (2001)



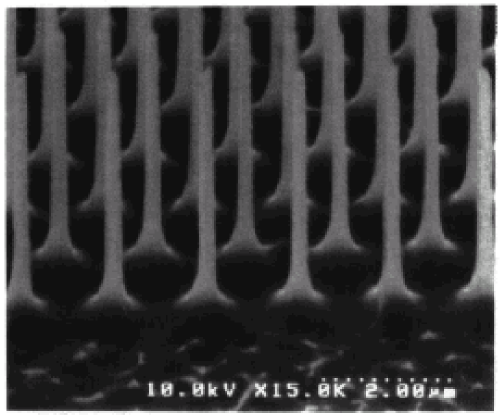
(a)



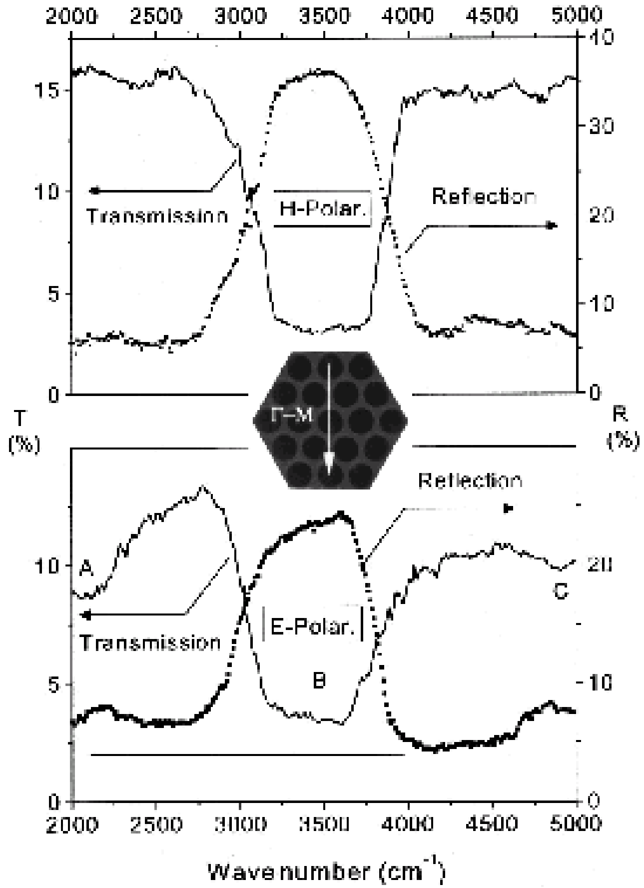
(b)



(a)



(b)



Combination of e-beam lithography and dry etching

III-V semiconductor techniques for 3D photonic crystal fabrication

Multilayer Growth (Heteroepitaxy): MBE or MOVPE.

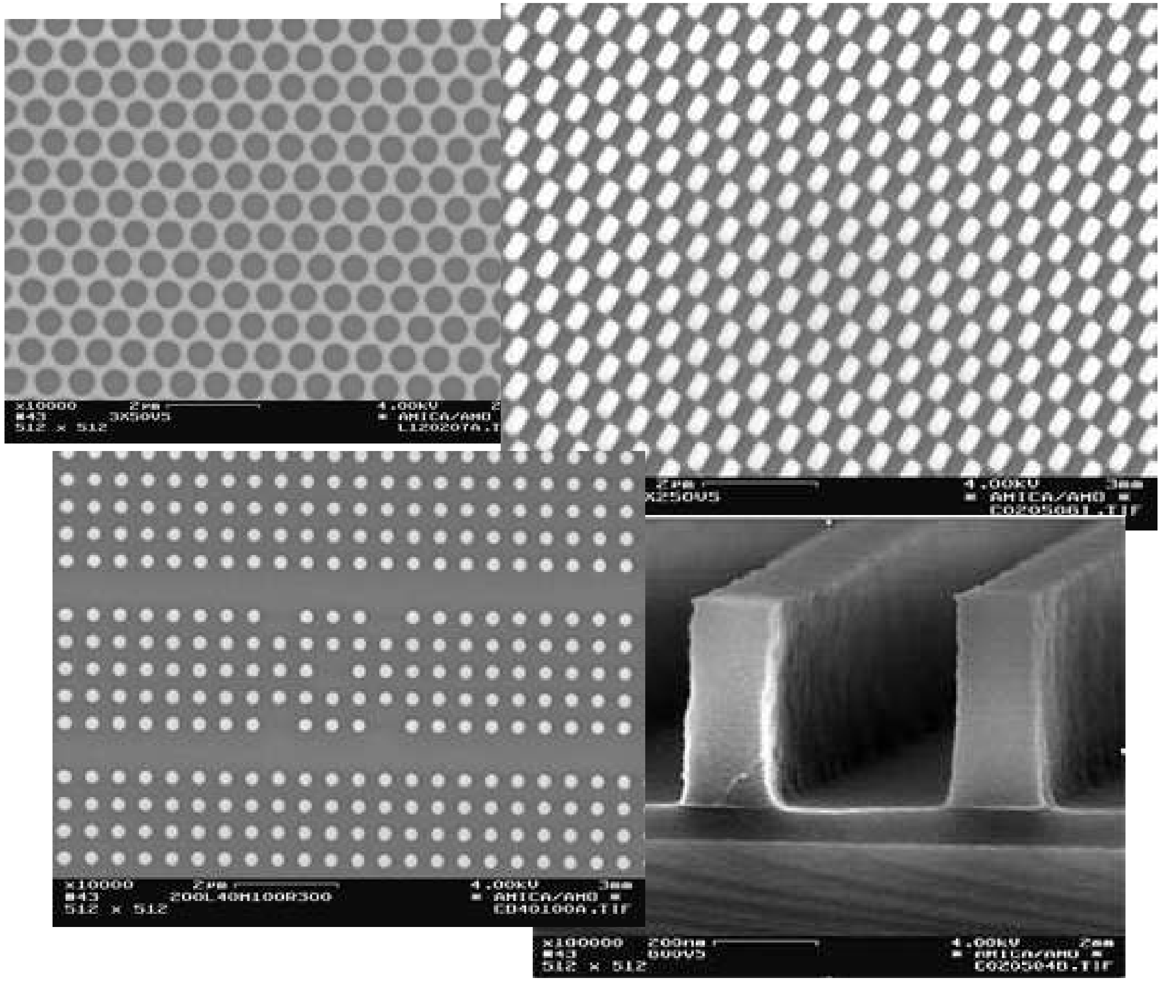
Lithography: electron beam lithography or deep UV.

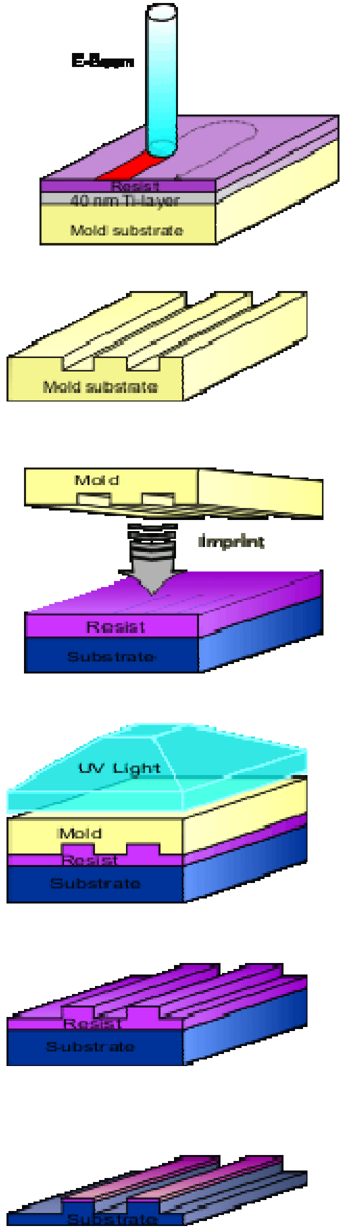
Dry etching: reactive ion etching (RIE), chemically assisted ion beam etching (CAIBE), inductively coupled plasma (ICP).

Selective Wet Oxidation in high (differential) Al-fraction arsenides and phosphides.

Nanoimprint

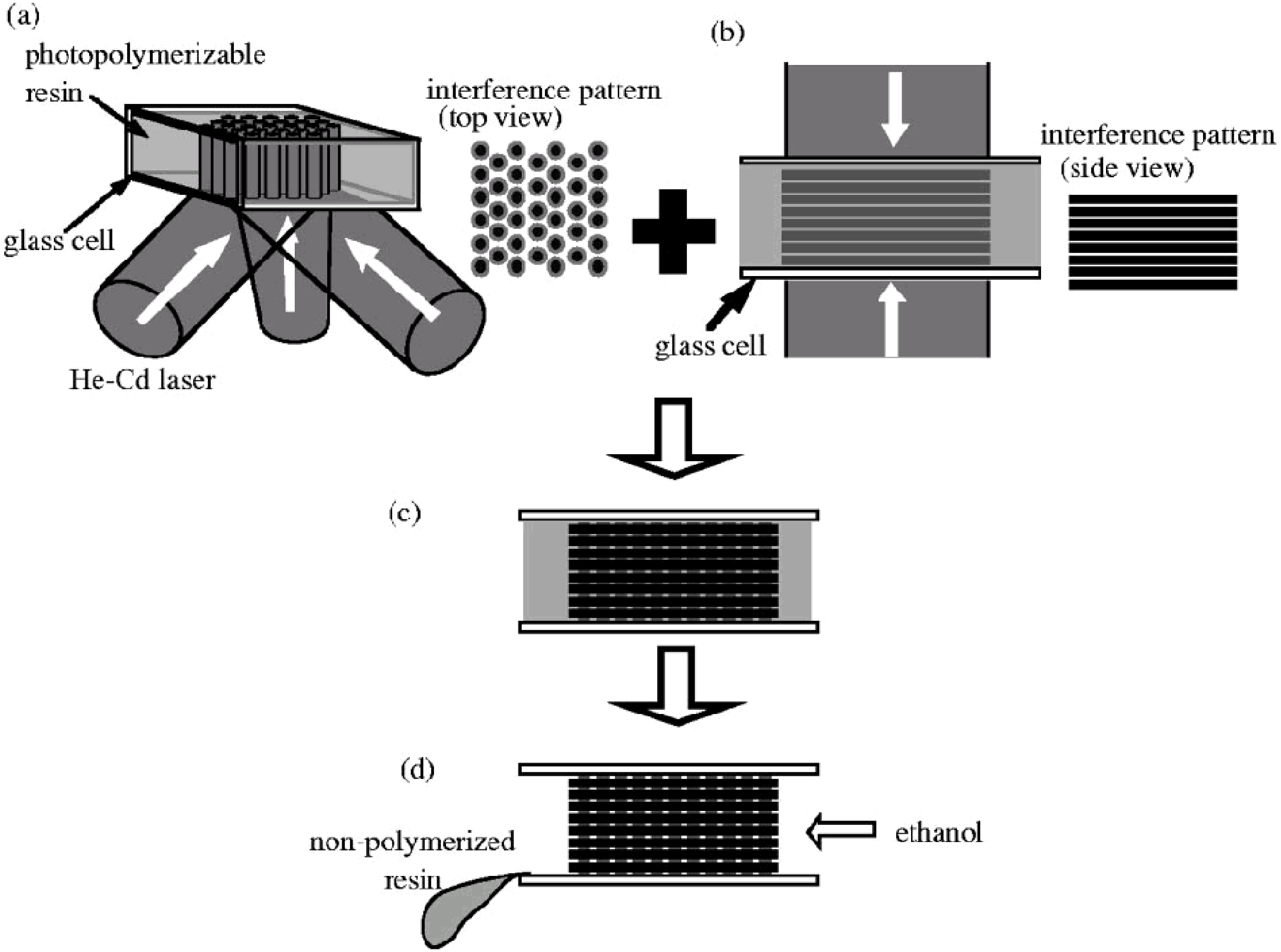
Transfers the desired structure to a substrate covered with PR. 10 nm accuracy achieved.

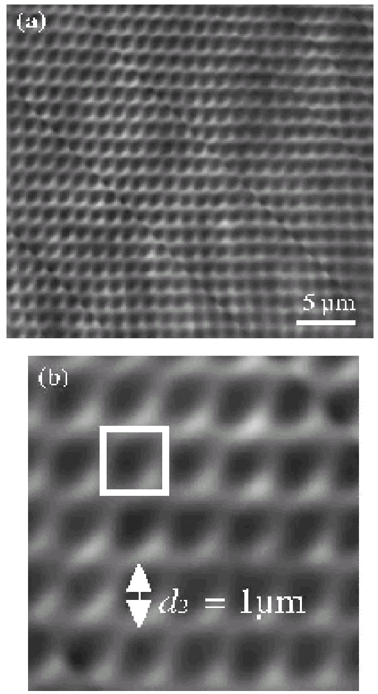




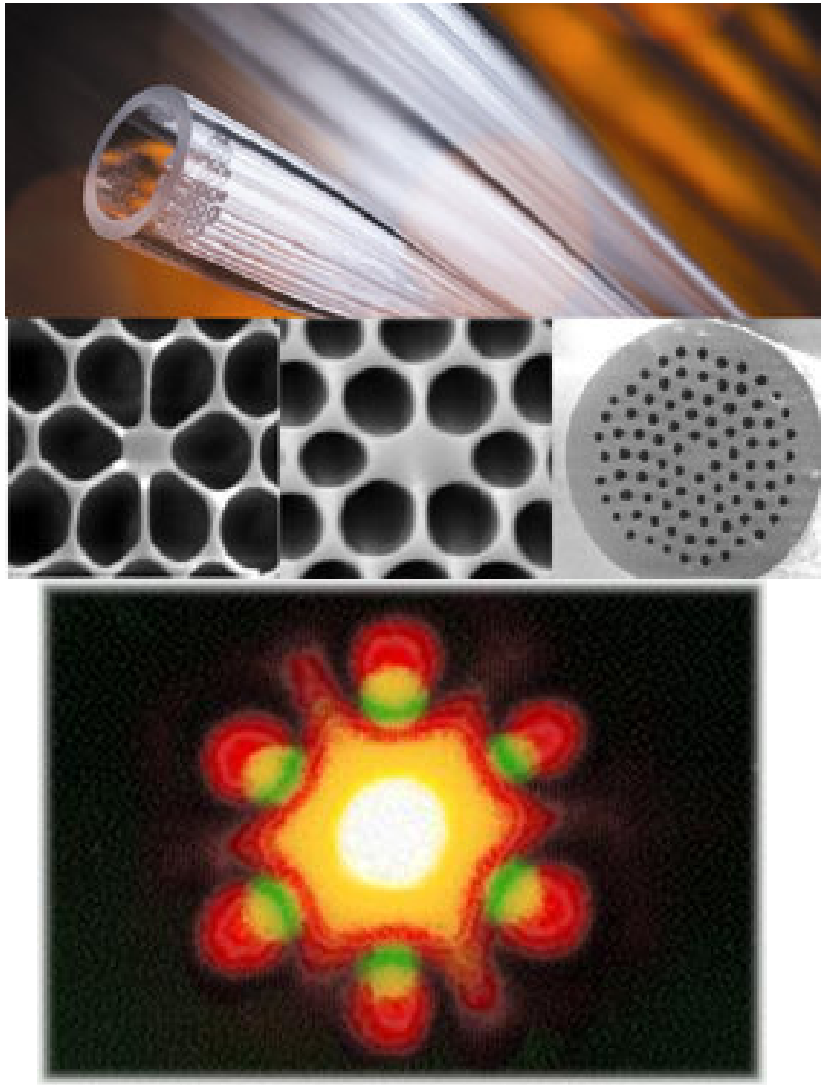
Photofabrication - Polymers

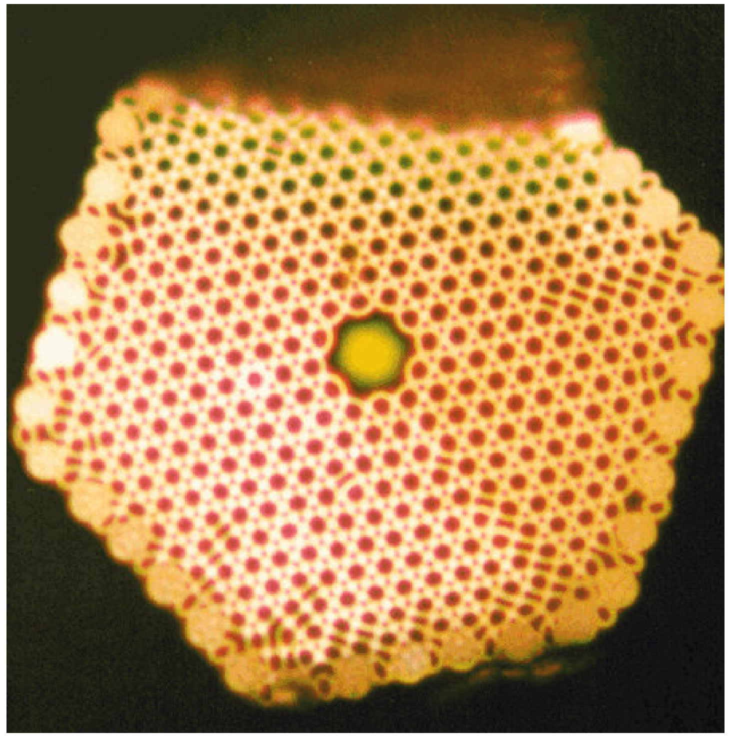
S. Shoji et al, Multibeam laser interference into a photopolymerizable resin Appl. Phys. Lett. **76**, 8 (2000).





Photonic crystal fibers

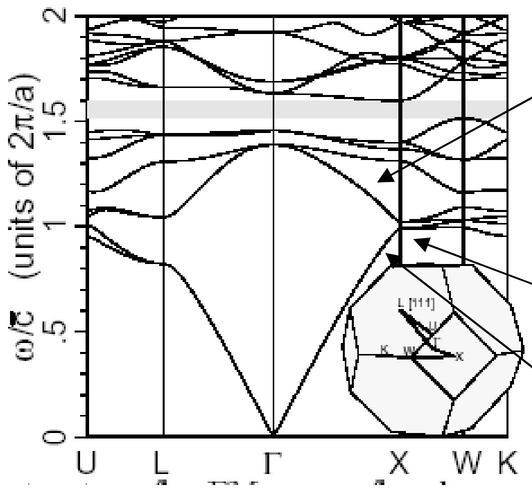




Air-core confined light

J. C. Knight, Nature **424**, 847-851 (2003)

Bulk Photonic crystals properties



Complex band structure

backwards slope:

negative refraction

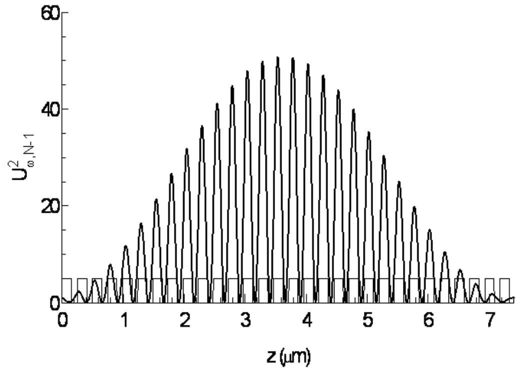
dω/d*k* → 0: slow light

(e.g. DFB lasers)

strong curvature:

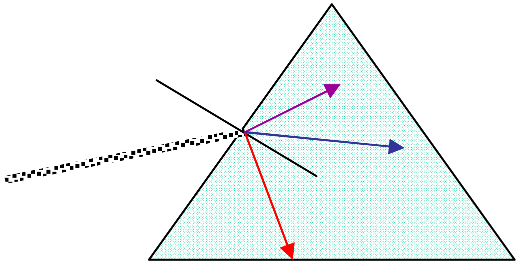
super-prisms, …

(+ negative refraction)



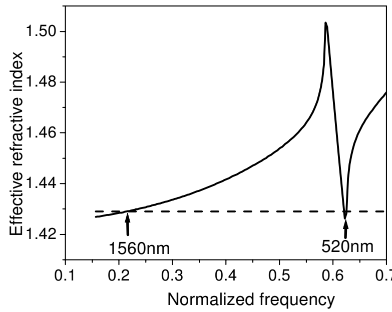
Internal field enhancement

- Low threshold lasing
- Enhanced nonlinear optical effects



Spatial dispersion (Superprism effect)

- Negative refraction
- Large angle deflection 500x
- Self-collimation



Dispersive refractive index dispersion

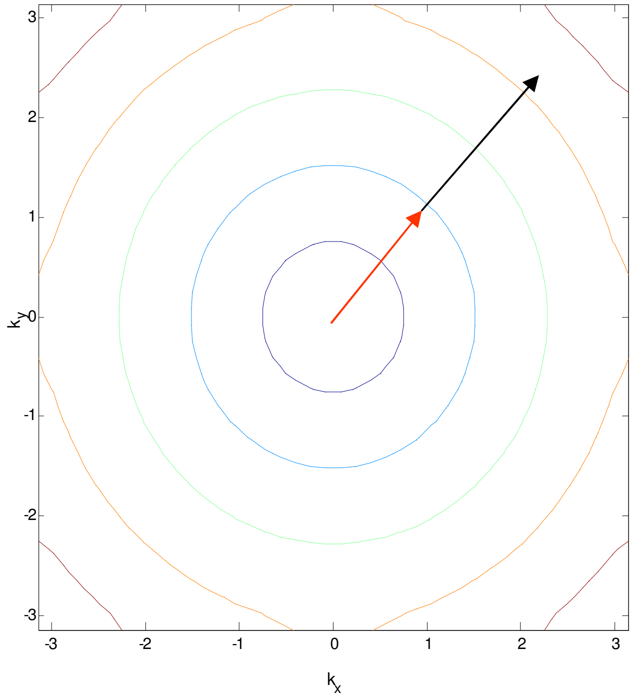
- Control of light propagation
- Phase-matching for harmonic generation

Group Velocity and isofrequency curves

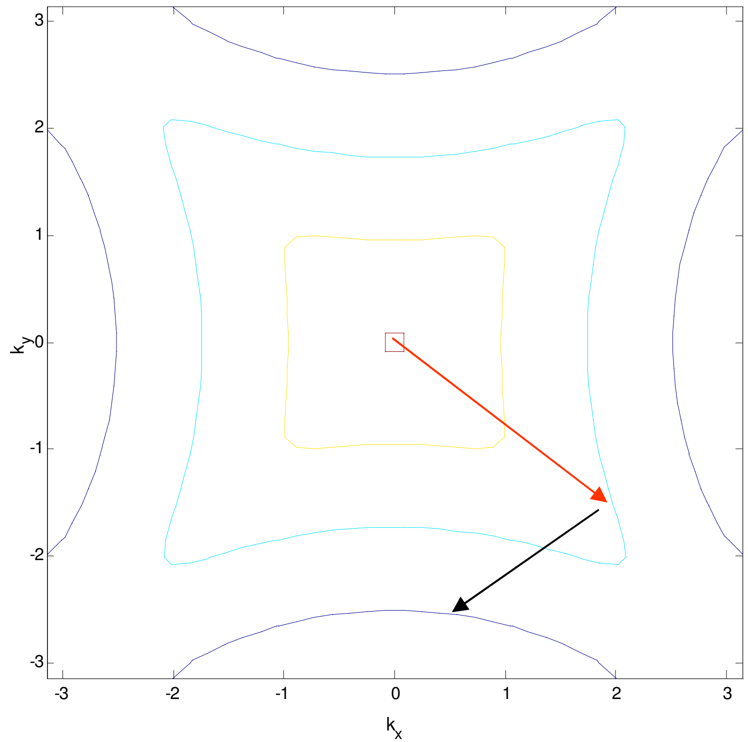
Group velocity=Energy velocity (proof: Yariv's Optical waves in crystals; Lossless case)

$$\vec{v}_g = \vec{\nabla}\omega(\vec{K})\Big|_{\vec{K}=\vec{K}_0}$$

Band 1



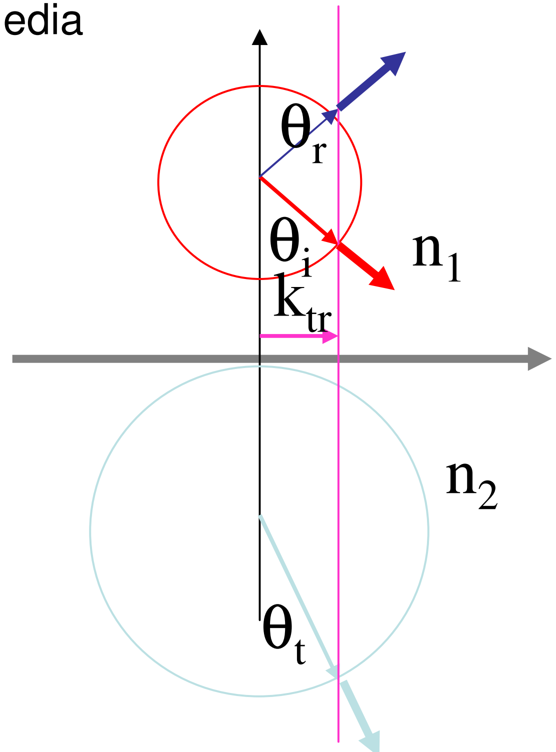
Band 2

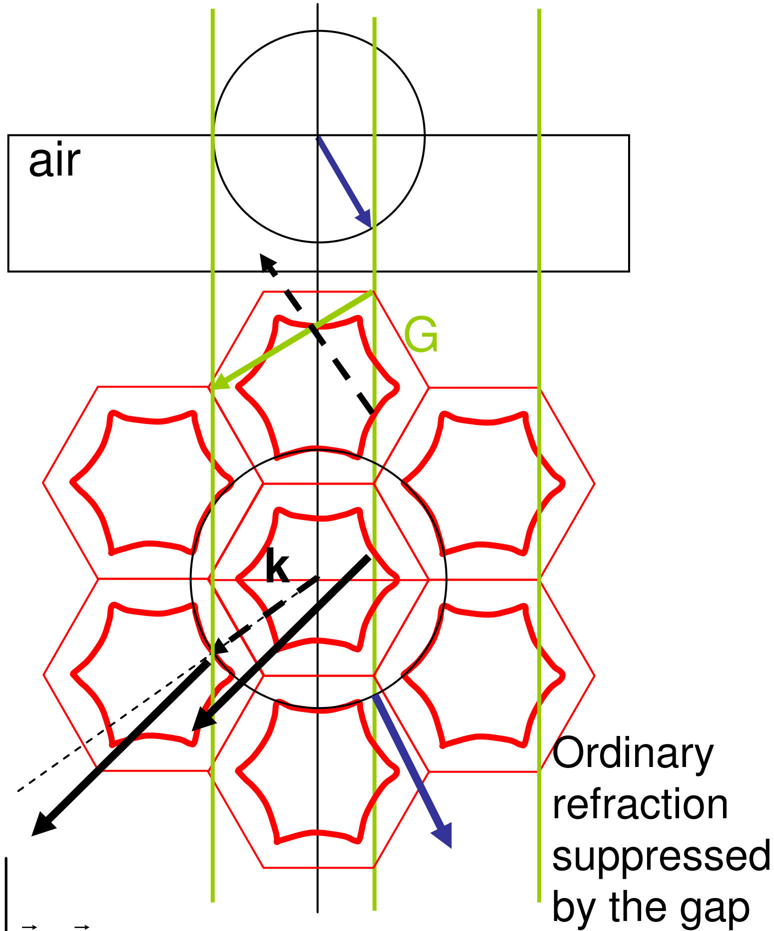


Superprism effect and Negative refraction in Photonic crystals

The superprism is a function of a photonic crystal which allows wide-angle deflection of a light beam by a slight change of wavelength and incident angle.

Snell's law: Reflection and refraction at interface between two homogeneous media





$$\vec{v}_g = \vec{\nabla}\omega(\vec{K})\Big|_{\vec{K}=\vec{K}_0}$$

$k_{\|}$ is conserved

$k_{\|}$ is conserved

Superprism effect and Negative refraction in Photonic crystals

H. Kosaka et al, Appl. Phys. Lett. 74, 1370, 1999

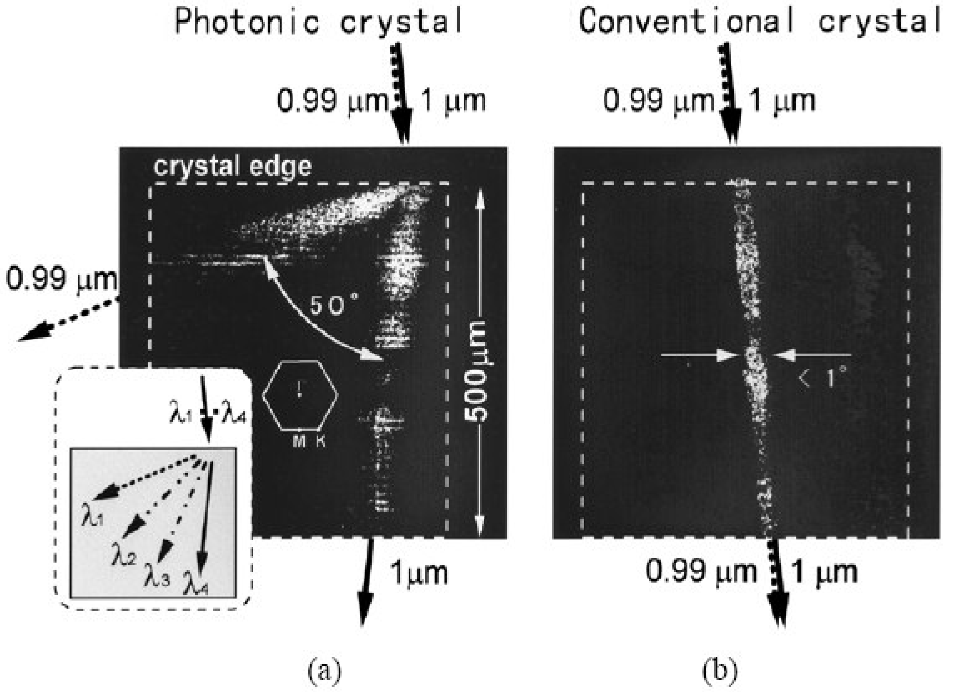


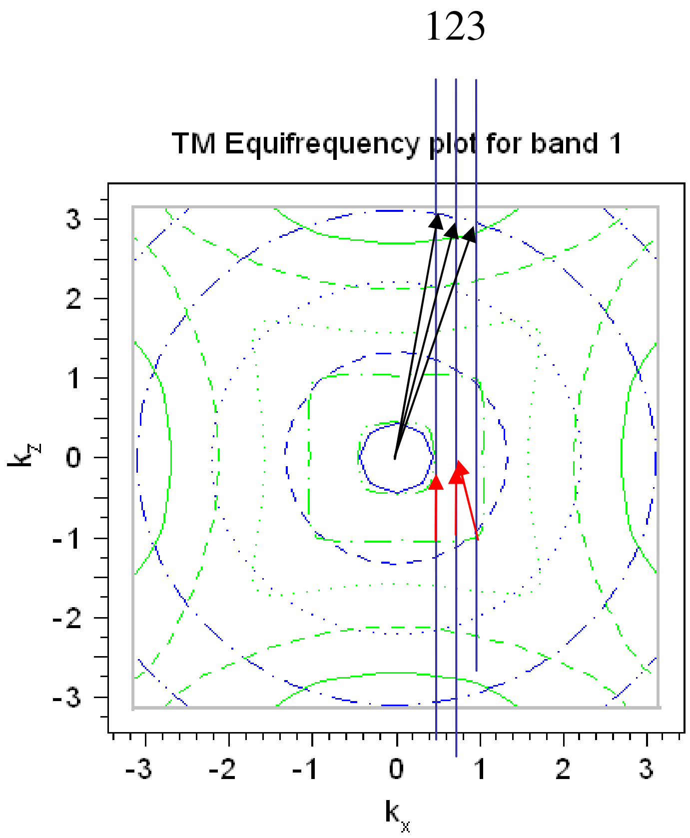
Fig. 4. Photographs demonstrating the superprism phenomena—Wavelength sensitive propagation: (a) light paths inside a PC with incident light of 0.99-μm and 1.0-μm wavelengths. A large swing reaching 50° was achieved with a slight wavelength change of 1%. The incident light was polarized in the TM mode and tilted at 15° from normal to the crystal edge and (b) light propagation in a conventional Si crystal under the same condition as (a). The two beams with different wavelengths traced almost the same paths.

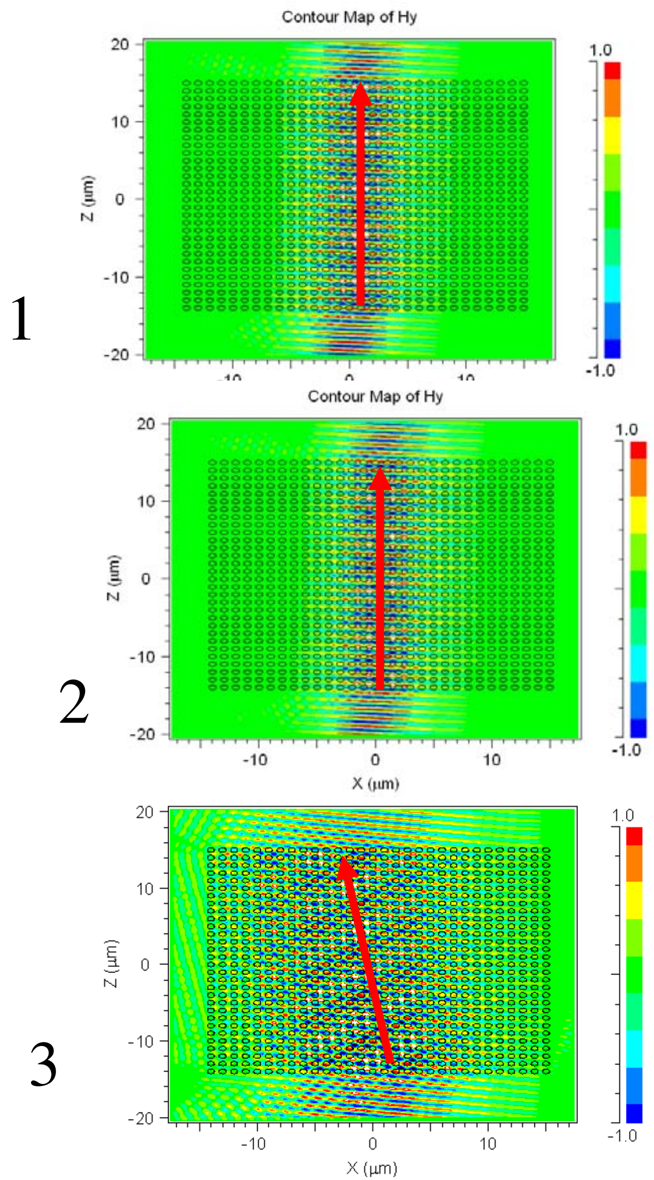
H. Kosaka et al. JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 17, NO. 11, NOVEMBER 1999

Autocollimation

Background Index 2.55, Cylinder 1.64, a/λ =0.366

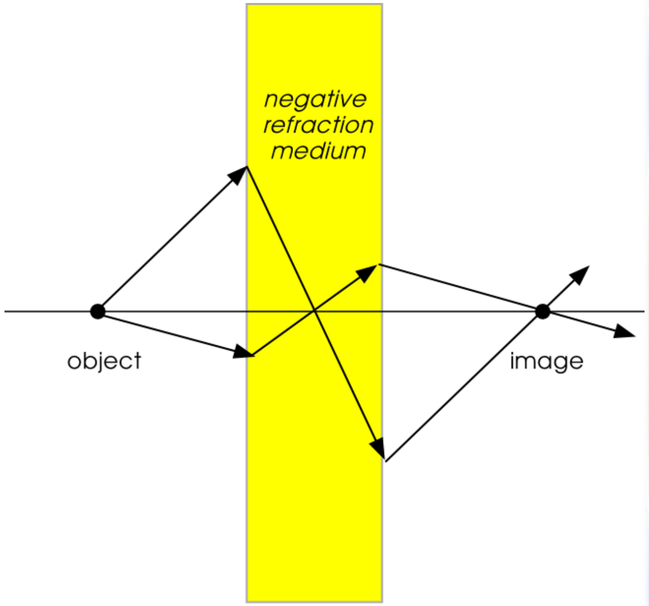
Group velocity $$v_g = \vec{\nabla}_{\vec{k}}\,\omega(\vec{k})$$

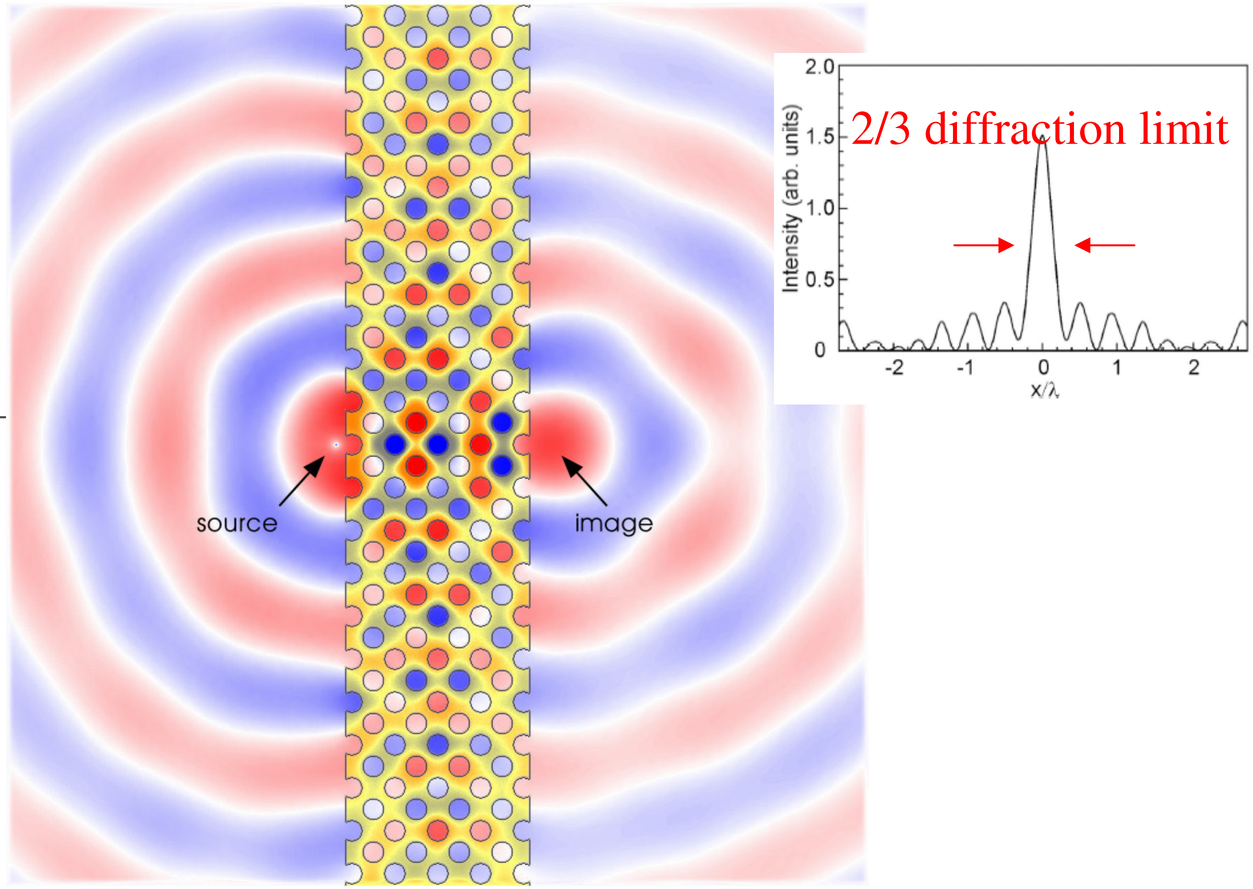




Superlensing with Photonic Crystals

[Luo *et al*, *PRB* **68**, 045115 (2003).]





Here, using *positive* effective index but negative “effective mass”…

The Band Edge Laser

J.P. Dowling et al, J. Appl. Phys. 75, 1896-1899 (1994).

The group velocity near the bandedge is zero because of coupling between the Bloch waves. Photons in the PC can then interact with an active material for a lengthy period, which results in lasing operation.
Micro lasers with large emitting areas can be obtained without resorting to the use of cavity mirrors. 2 D Photonic crystals allow slow light in plane propagation and extraction of laser light form the whole surface of the crystal.

S.H. Kwon et al. APPLIED PHYSICS LETTERS VOLUME 83, NUMBER 19 (2003)

Square-lattice bandedge lasers are realized by room-temperature optical pumping of photonic crystal air-bridge slabs of InGaAsP quantum wells emitting at 1.5 mm.

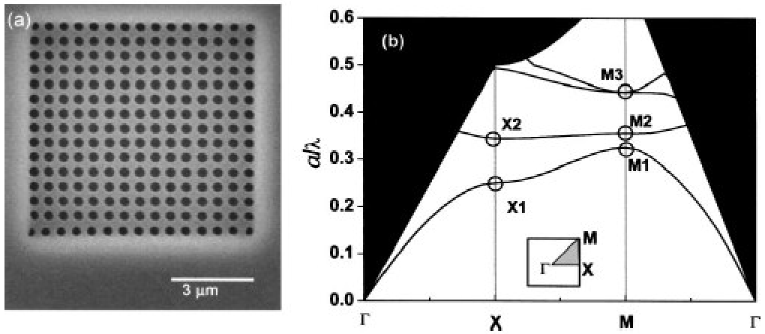


FIG. 1. (a) Top-view scanning electron microscope image of a fabricated square-lattice photonic crystal free-standing slab. The lattice constant and air–hole radius are 550 nm and 210 nm, respectively. Thickness of the slab is 200 nm. (b) The corresponding band structure calculated by the PWE method.

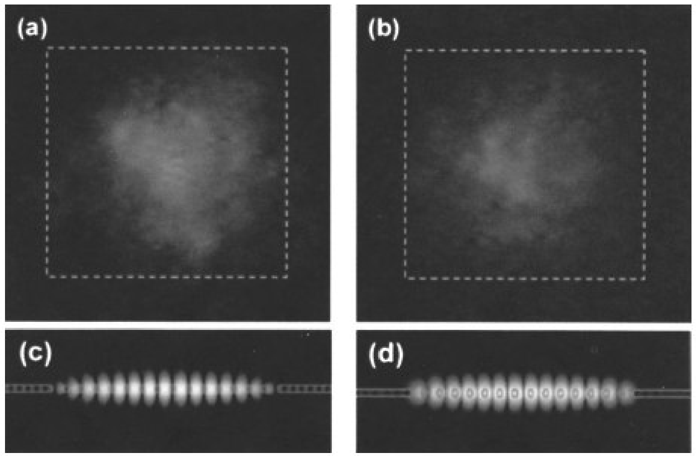
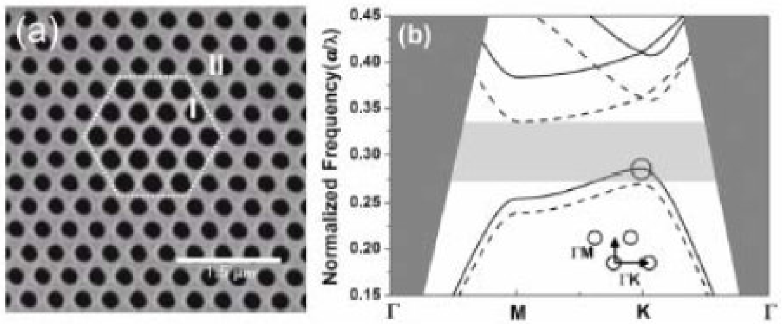
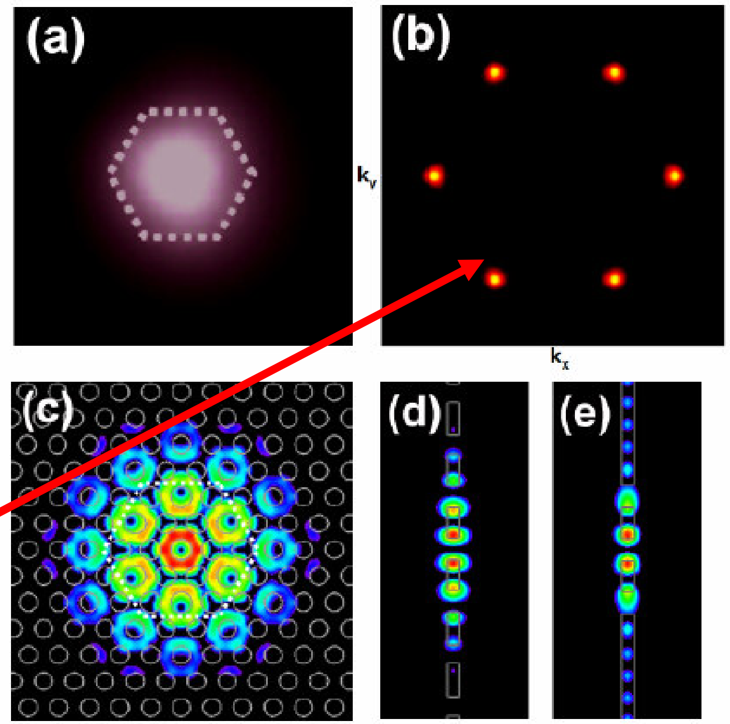


FIG. 2. Mode pattern images of (a) the second X and (b) the second M points bandedge lasers taken by a CCD camera. The dotted squares represent the boundary of the photonic crystal lasers. The side views of the intensity profiles of (c) the second X and (d) the second M points bandedge modes.

The Band Edge Laser

S.H. Kwon et al., Optics Express 12, 5356-5361 (2004).





Note that the wave vectors are localized at the six K points in the Fourier space and these six unparallel wave vectors construct the mode simultaneously

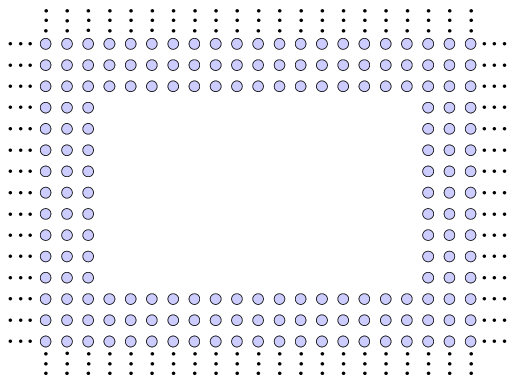
Fig. 2. (a) Typical mode pattern images of PBG-BE lasers taken by an infrared camera. The dotted white hexagon represents the boundaries of the photonic bandedge mode region, which is same with the central region (I) of the SEM image. (b) Fourier space field pattern of the PBG-BE mode. (c) Top-view and (d) side-view of the calculated electric-field intensity profile of the PBG-BE mode. The dotted white hexagon indicates the boundary of the bandedge mode region. (e) side-view of the first K point bandedge mode operating at the finite PC pattern with no surrounding air hole. The intensity is indicated by a logarithm scale.

Control of Electromagnetic Waves

Using Photonic Crystals with intentional defects

Photonic GAPs can be used to confine light in a region of space

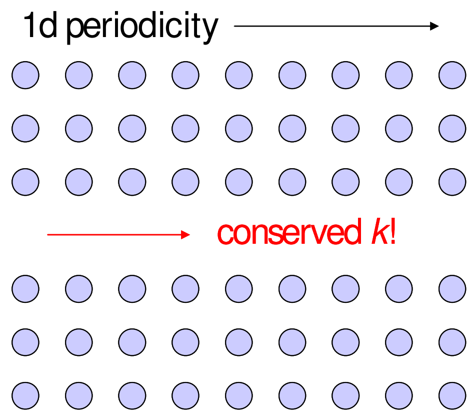
RESONANT CAVITIES



Light cannot propagate inside the crystal and it is confined in a finite region of space.

Mode of electromagnetic waves inside the cavity must fulfill proper boundary conditions
(discrete eigenfrequency spectrum)

WAVEGUIDES

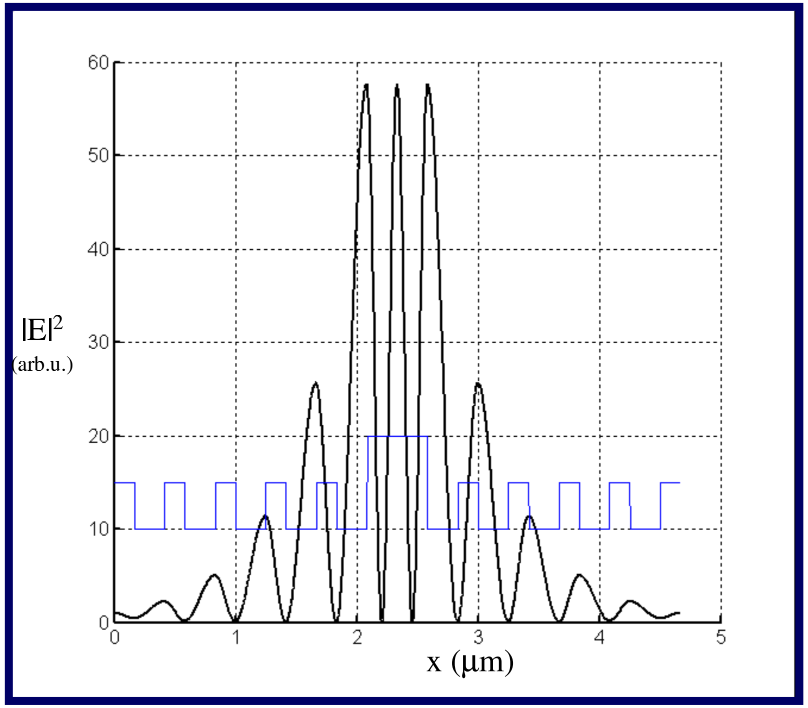


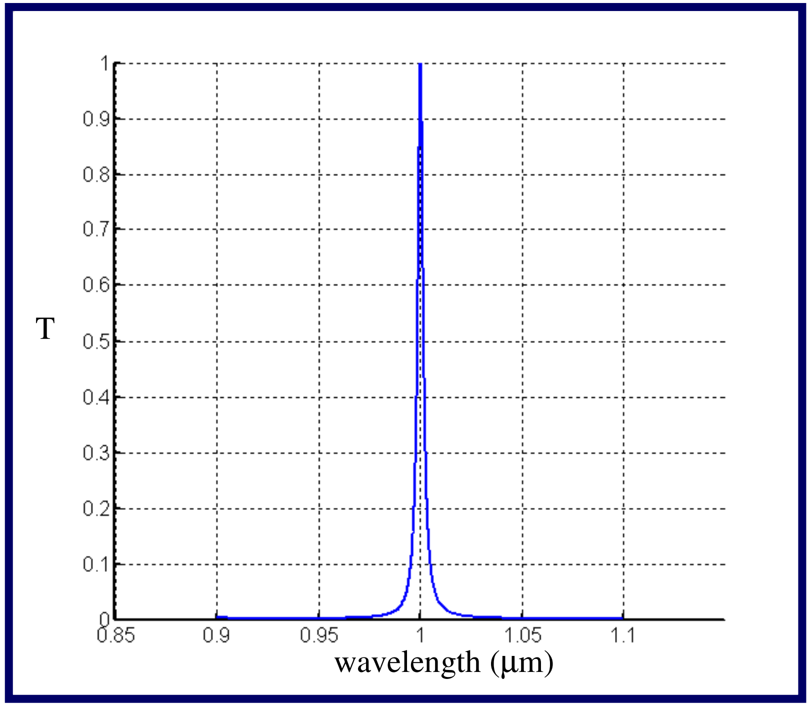
Light tuned in the gap cannot exit form the line defect which acts as a waveguide. Propagation constants of guided modes will appear in the gap of the perfectly periodic crystal's band diagram.

Control of Electromagnetic Waves

1D Micro-cavity

Micro-cavity sandwiched between two Bragg mirrors.
High Q factors, high fields intensity enhancement inside the structure.

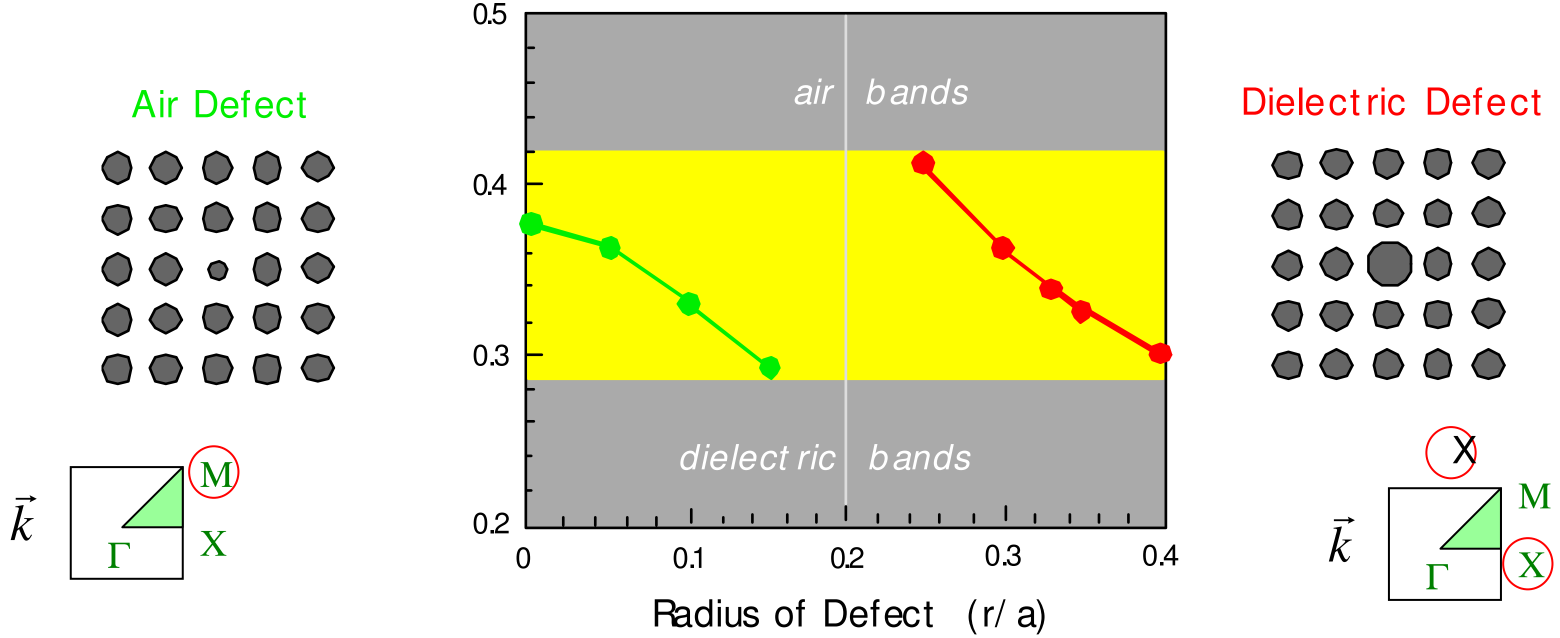


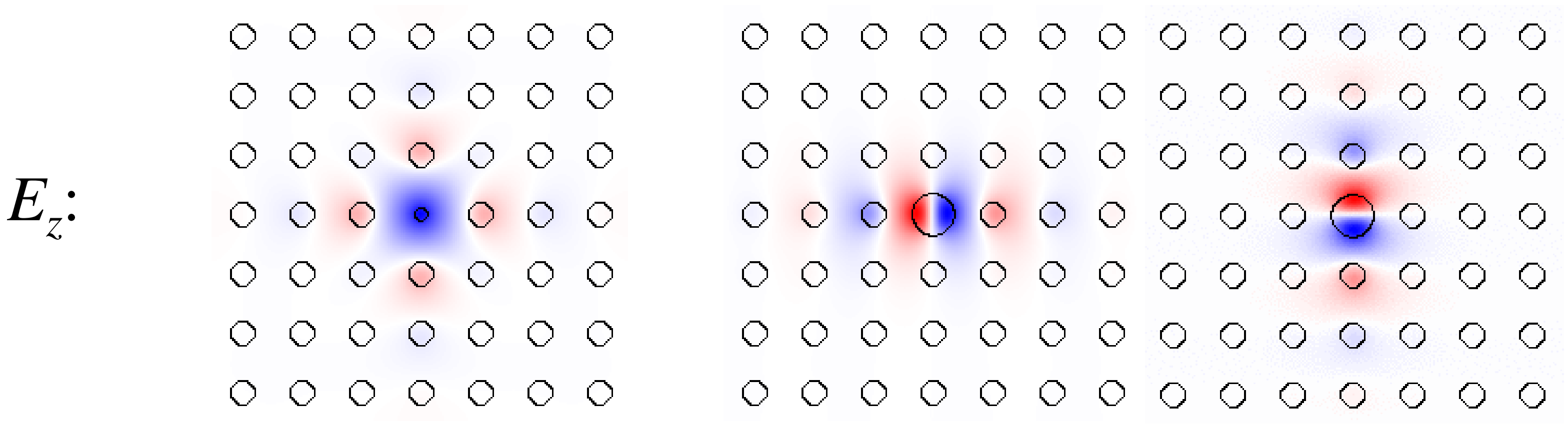


$$Q = 2\pi \frac{Stored\ Energy}{Energy\ lost\ per\ cicle} = \omega_0 \frac{\langle Energy \rangle}{\langle Power\ loss \rangle} \approx \frac{\omega_0}{\Delta\omega_0}$$

Control of Electromagnetic Waves

2D single mode Micro Cavity



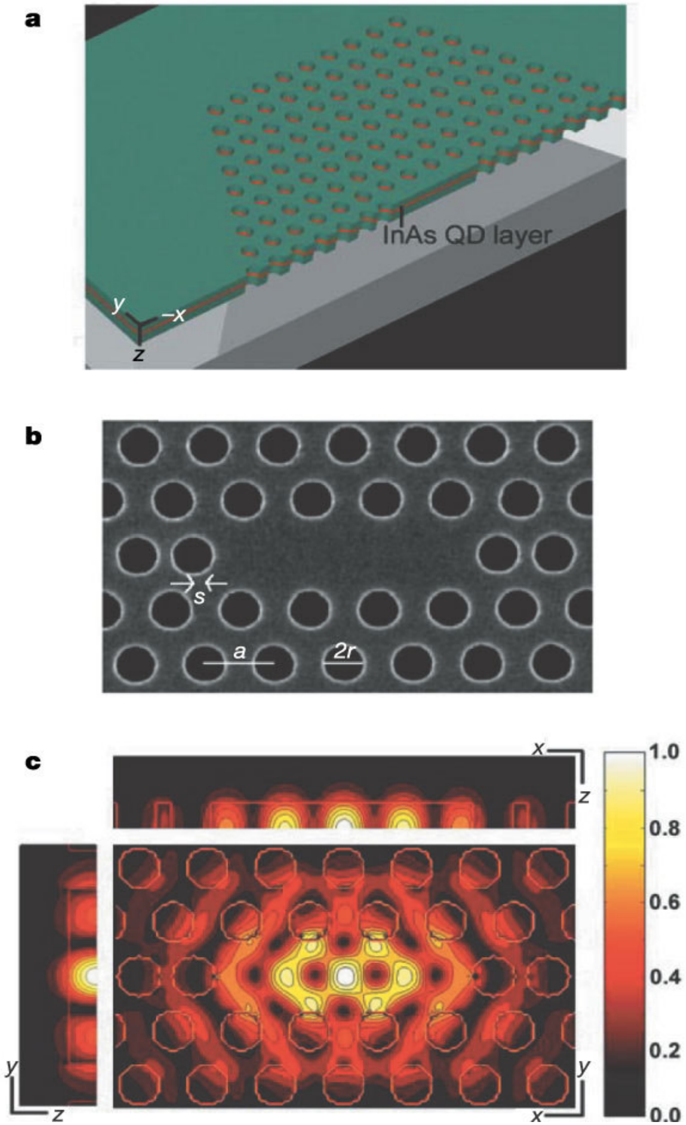


monopole

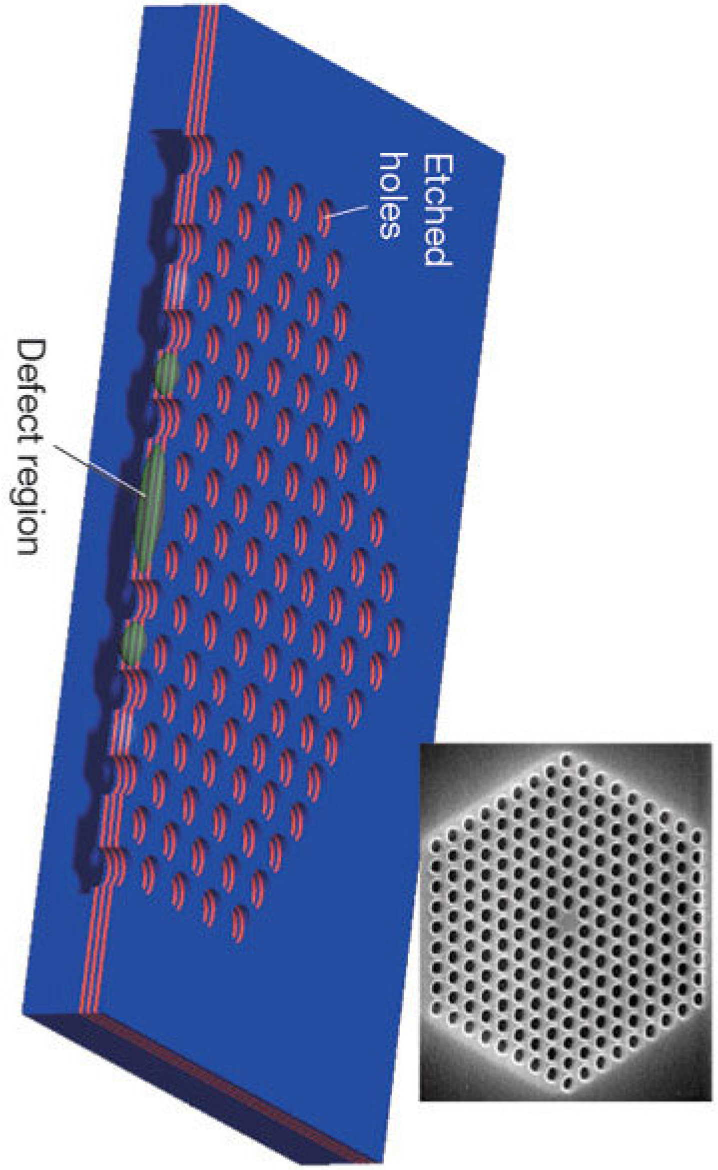
dipole

Control of Electromagnetic Waves

2D Micro Cavities



Yoshie et al., Nature 432, 200-203



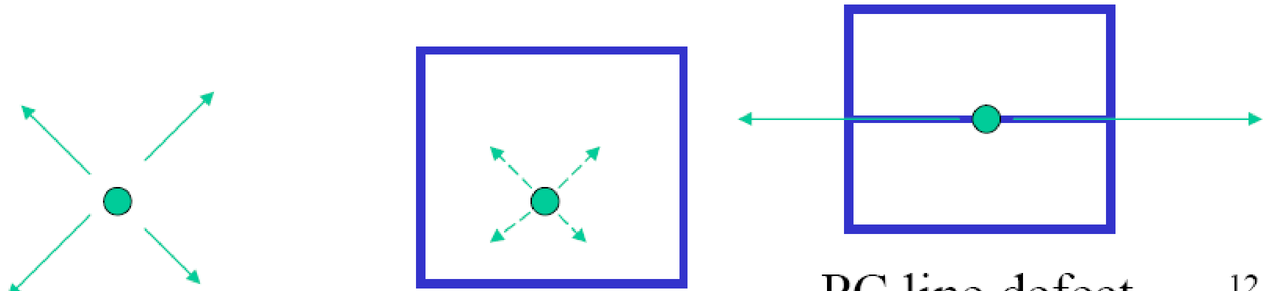
Vahala Nature 424, 839-846 (2003)

Control of Electromagnetic Waves

Spontaneous emission suppression

E. Yablonovitch, PRL (1987)

- Excited atoms in a Photonic crystal will not radiate; i.e. no radiation mode is available.
- Add a defect that introduces a single mode in the band gap. Now when an atom radiates its first photon it has no other choice except into the defect mode. Thereafter the atoms radiate by stimulated emission. Zero threshold laser.



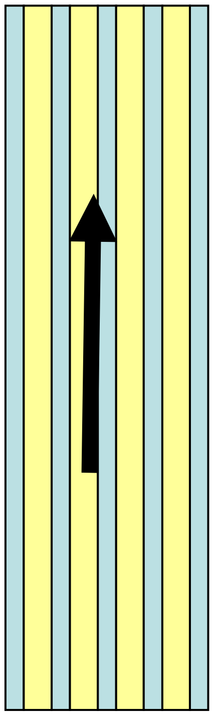
Free space   PC no defect   PC line defect

Several examples will be discussed in the next lecture “Applications of Photonic Crystals”

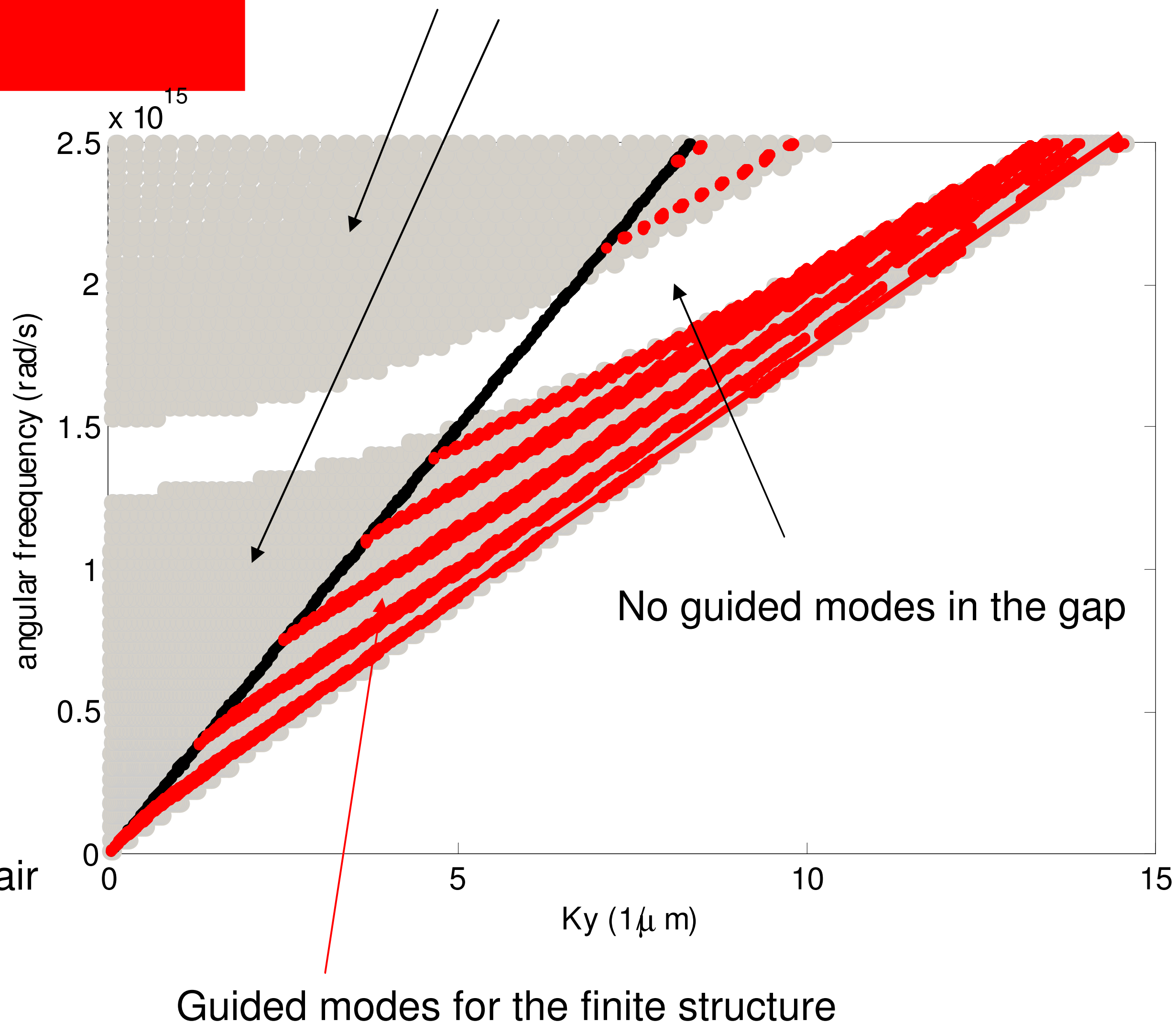
Control of Electromagnetic Waves

Photonic Crystal waveguides

Consider a finite stack as in the picture:
n1=1.5; d1=250 nm;
n2=2.0; d2=150 nm;



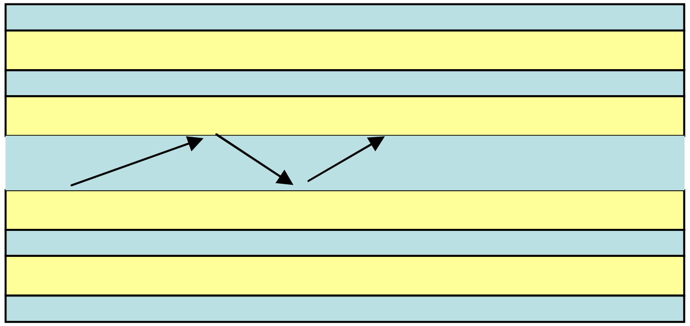
N=4 (HL)+1H; embedded in air

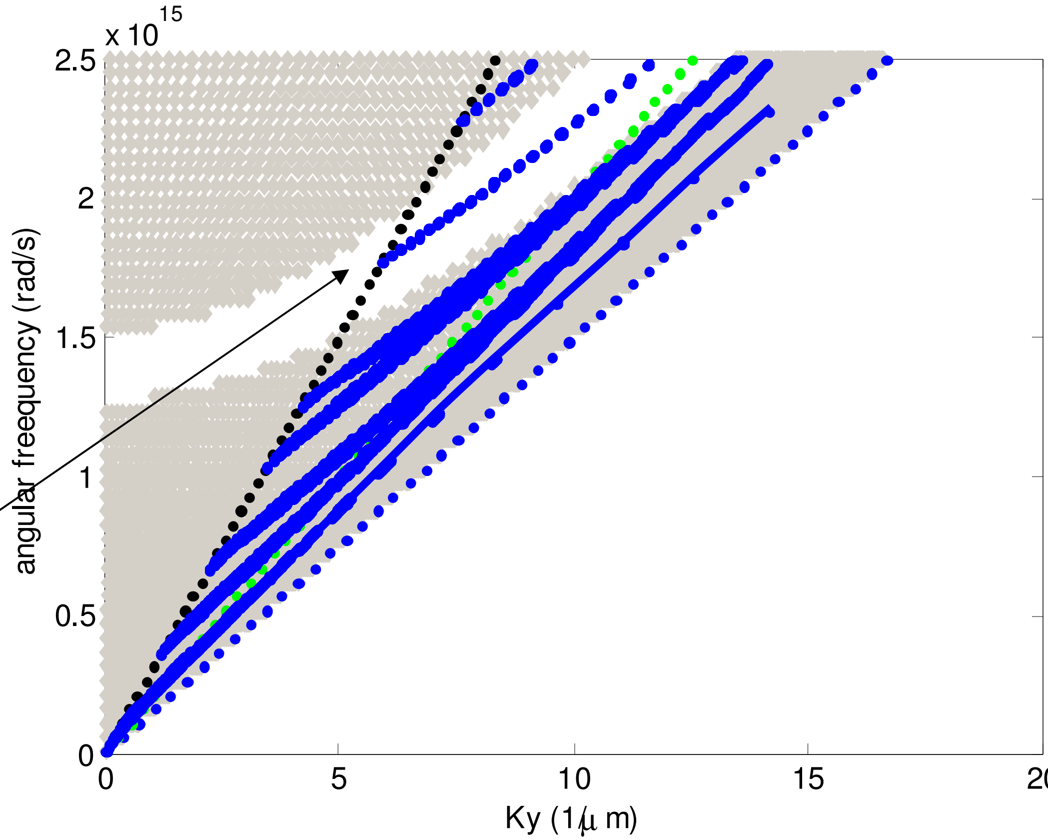


Control of Electromagnetic Waves

Photonic Crystal waveguides

We add a defect:





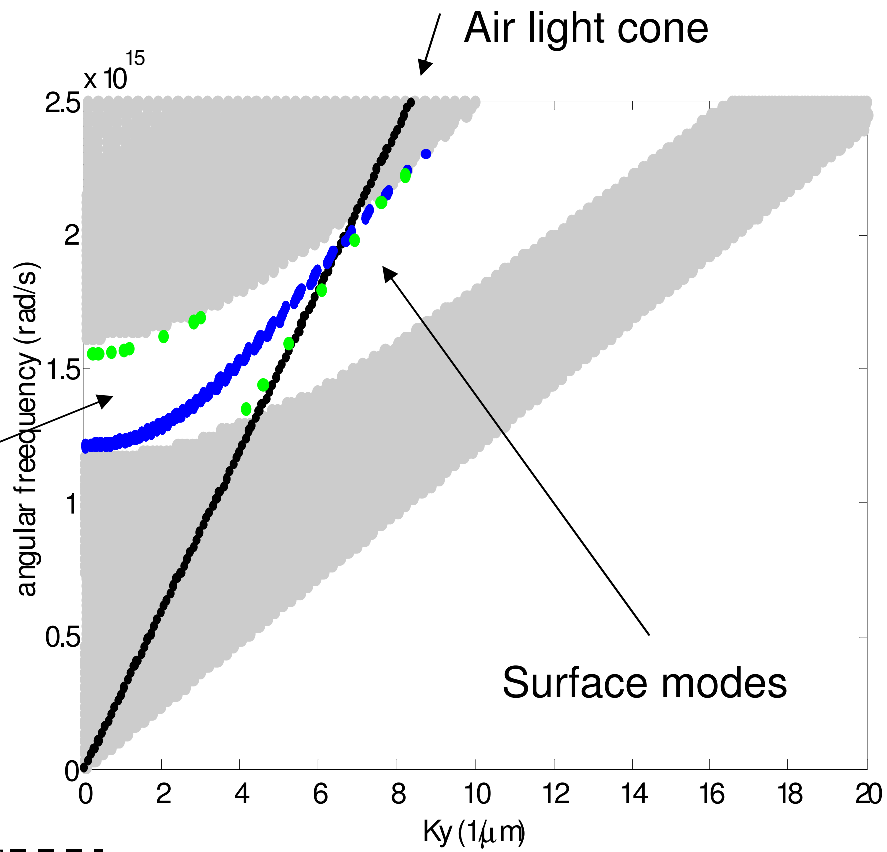
guided mode in the gap
Combination of index guiding and
photonic band gap guiding

Control of Electromagnetic Waves

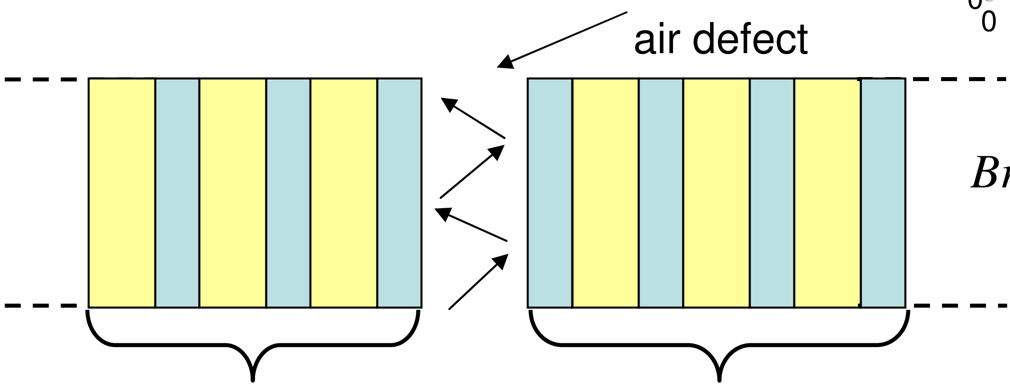
Hollow Bragg waveguides

Guided light in low index material, (for example air) is possible taking advntage of the photonic band gap.

For infinite structures guided modes are lossless (in principle). Finite number of layers is responsible for leaky guided modes.



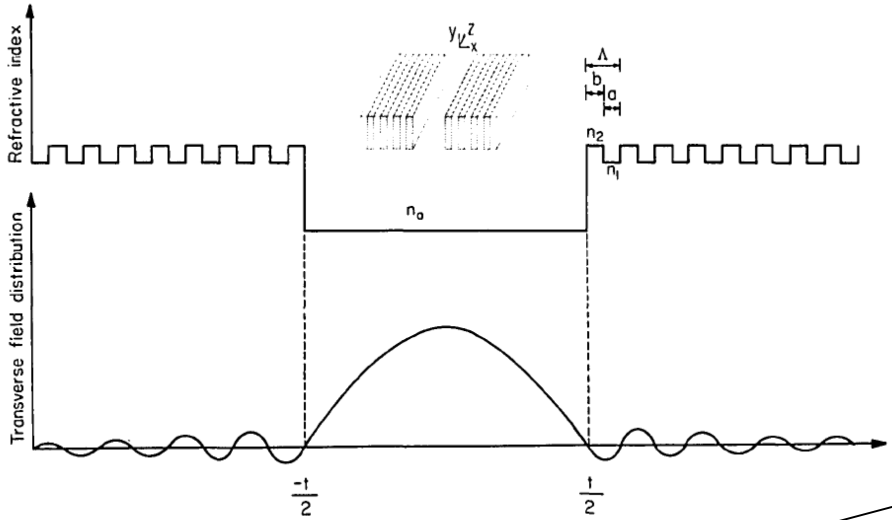
Air core guided modes
Even and odd modes



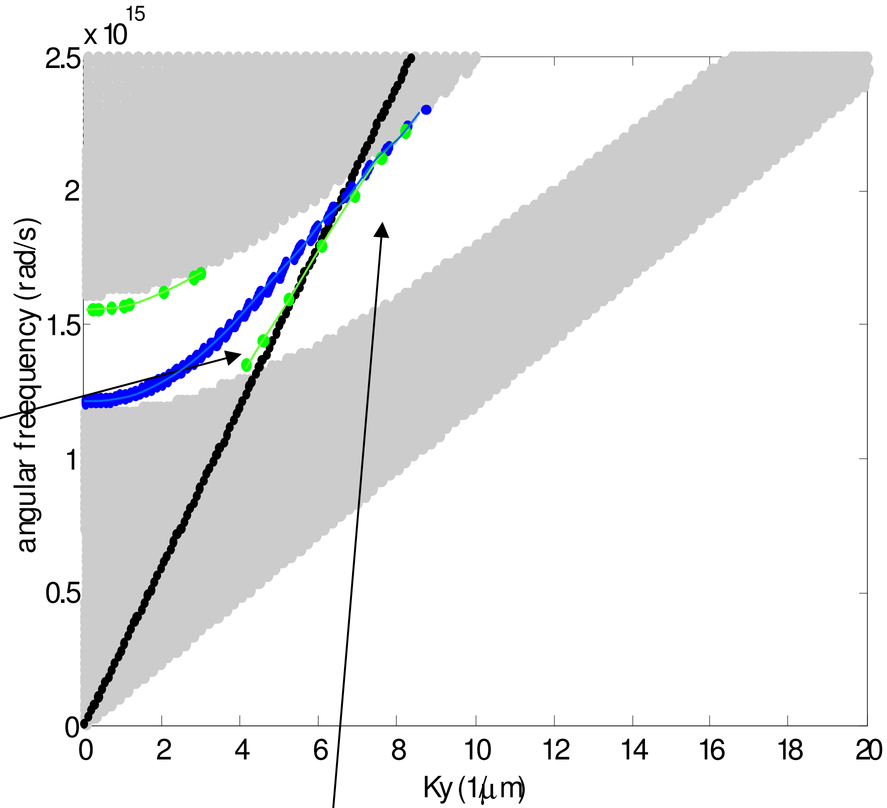
Bragg waveguides (Yeh 1978) are the basic principle for the OmniGuide:
B. Temelkuran et al.,
*Nature **420**, 650 (2002)*

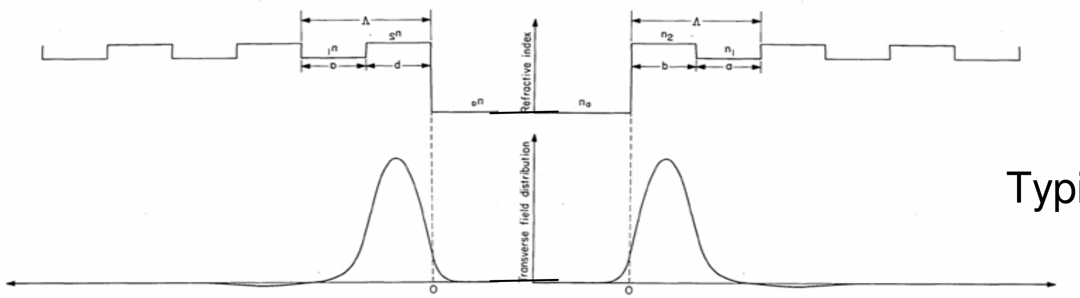
Control of Electromagnetic Waves

Hollow Bragg waveguides



Typical funamental air core guided mode

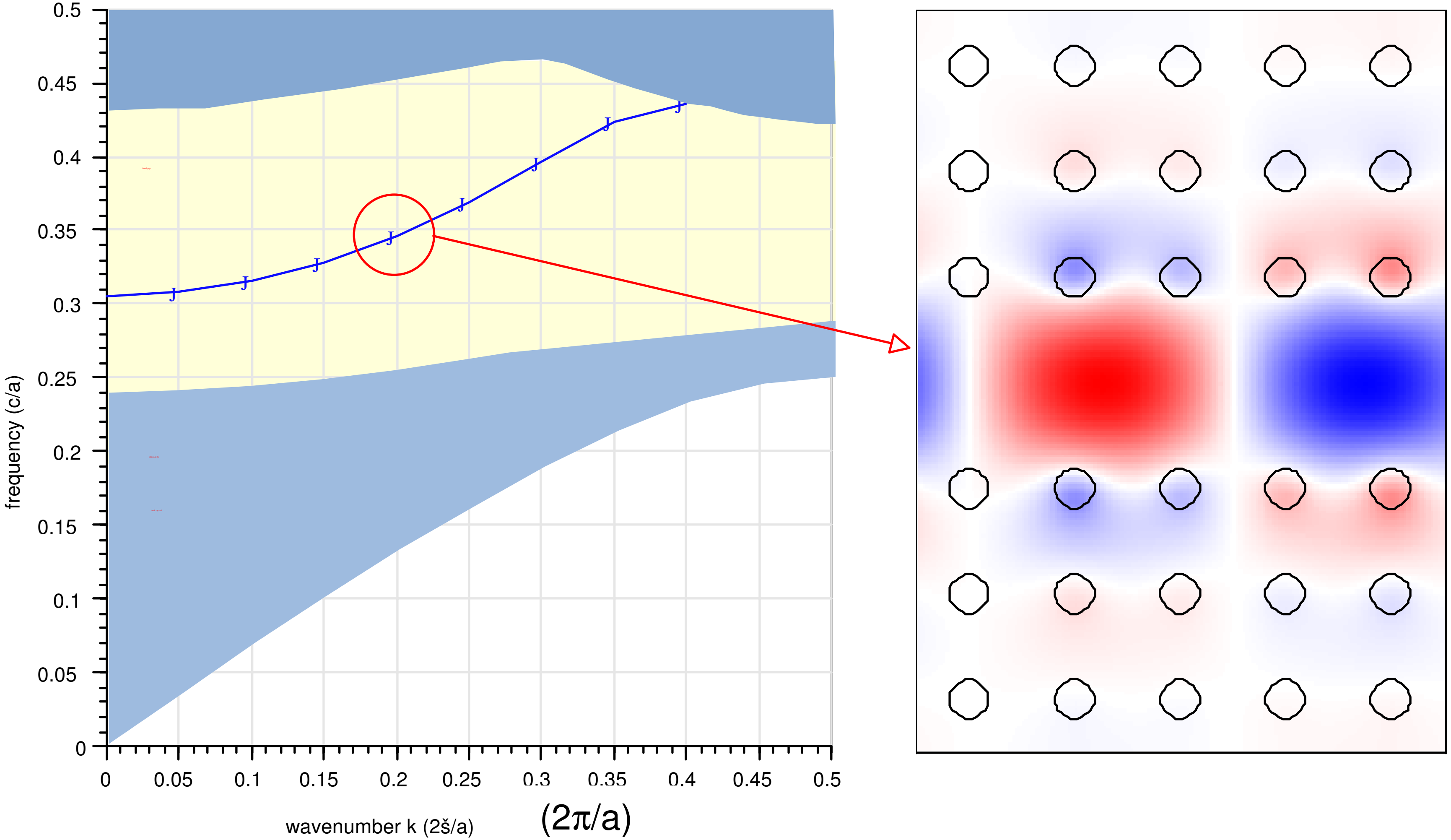




Typical Surface mode

Control of Electromagnetic Waves

2D waveguides

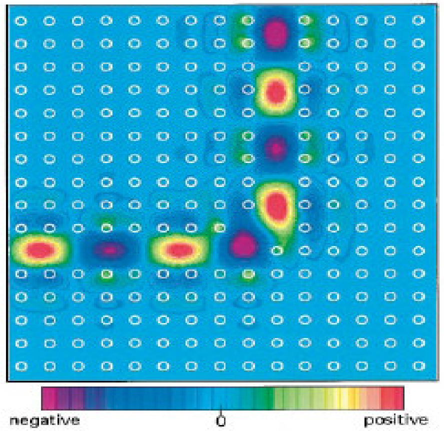


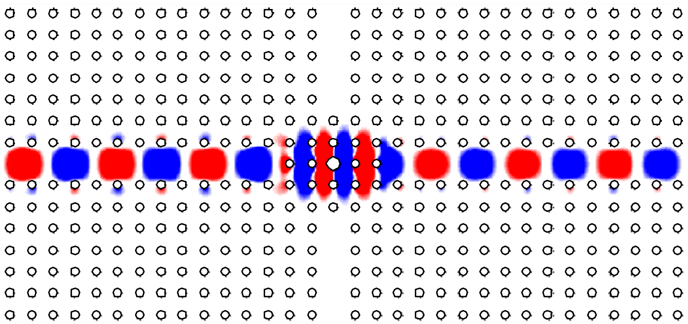
any state in the gap cannot couple to bulk crystal –> localized

Control of Electromagnetic Waves

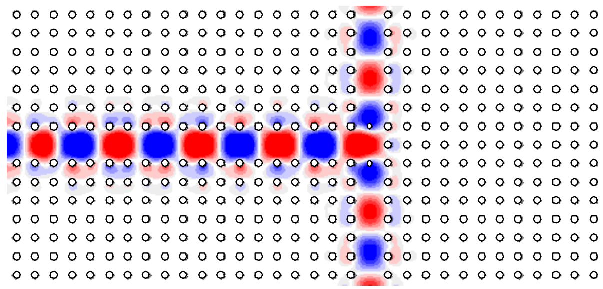
2D devices

100% transmission sharp bend
[A. Mekis *et al.*, *Phys. Rev. Lett.* **77**, 3787 (1996)]

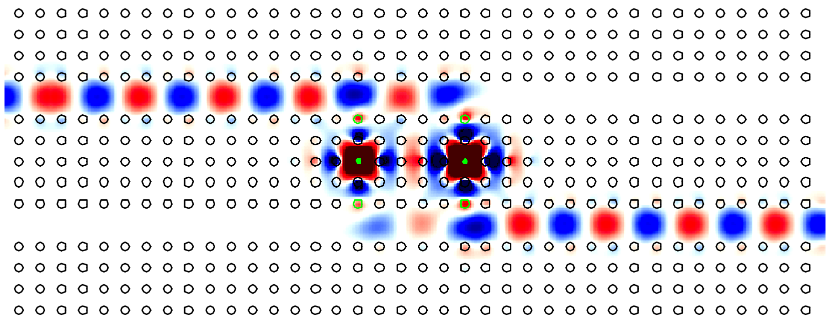




Waveguide crossings (waveguide + cavity)



Splitter



Channel drop filters (waveguide +cavity)

And many other applications for integrated optics and optical communications.

Outline second lecture

- Using Photonic Crystals properties for integrated sources and devices;
- Tailored DOS, Control of Spontaneous emission, Ph.C.microcavity
- Photonic Crystal Biosensors;
- Photonic crystal fibers and applications;
- Nonlinear effects enhancement, SHG and parametric fluorescence