CONTROLLING THE FLOW OF CLASSICAL WAVES

- INTRODUCTION
- GAPS IN CLASSICAL WAVE PROPAGATION
- CALCULATIONAL METHODS
- DOPING, MINI STOP BANDS, DISORDER
- RECENT DEVELOPMENTS (BRIEFLY & SELECTIVELY)
- PHOTONIC "CRYSTALS" AS NEGATIVE INDEX MATERIALS

E.N. ECONOMOU
DEPT. OF PHYSICS, U. of CRETE
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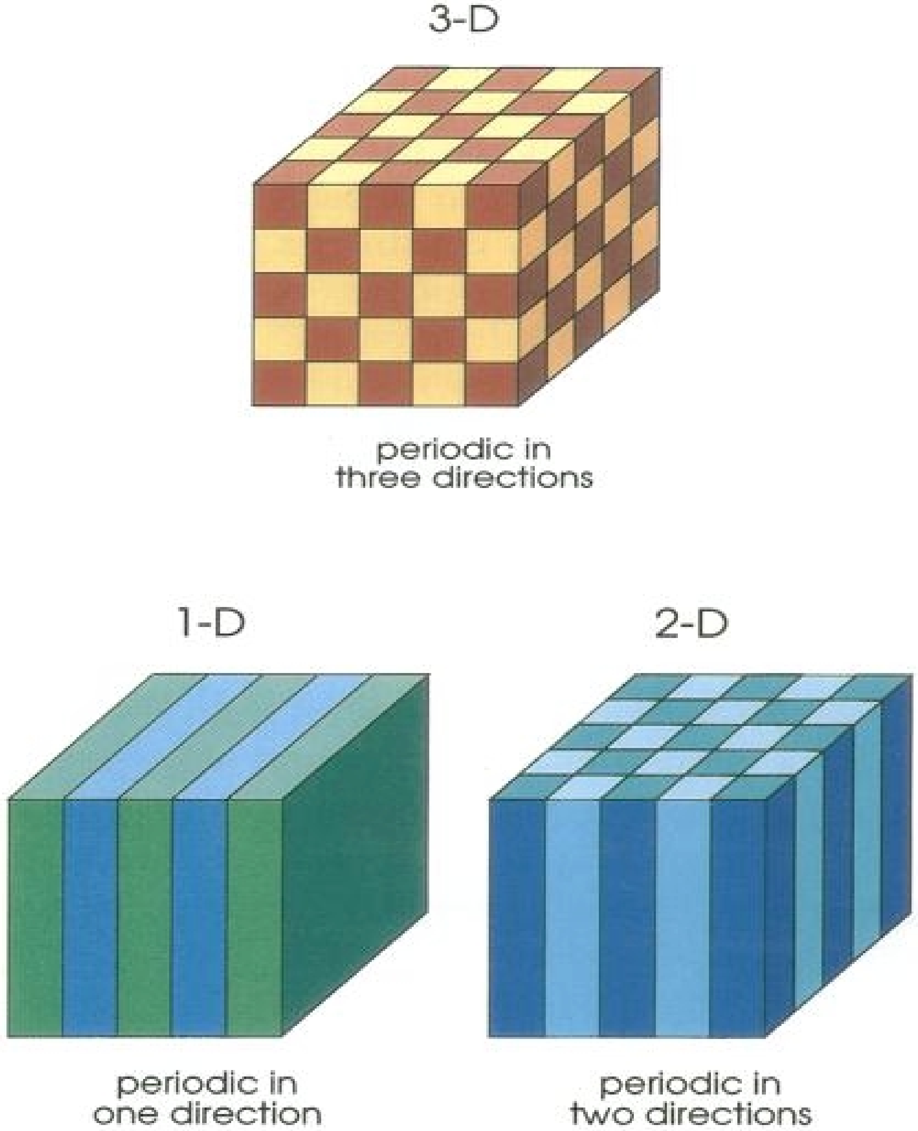
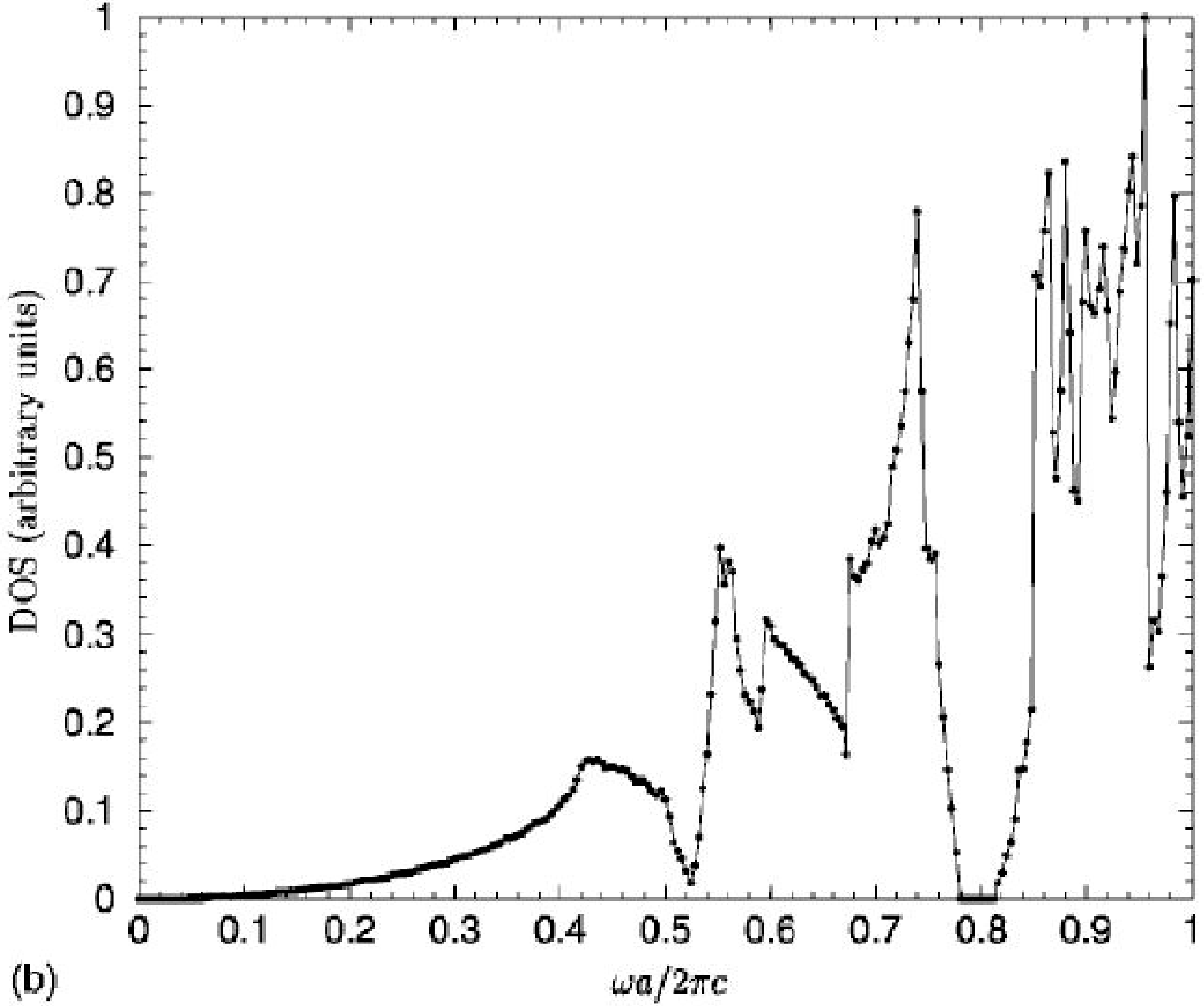
PHOTONIC “CRYSTALS”:

ARTIFICIAL PERIODIC STRUCTURES (1μ ˇ α ˇ 1cm) EXHIBITING SPECTRAL GAPS (or PSEUDOGAPS) IN THE PHOTON DOS, DUE TO STRONG SCATTERING AND DESTRUCTIVE INTERFERENCE

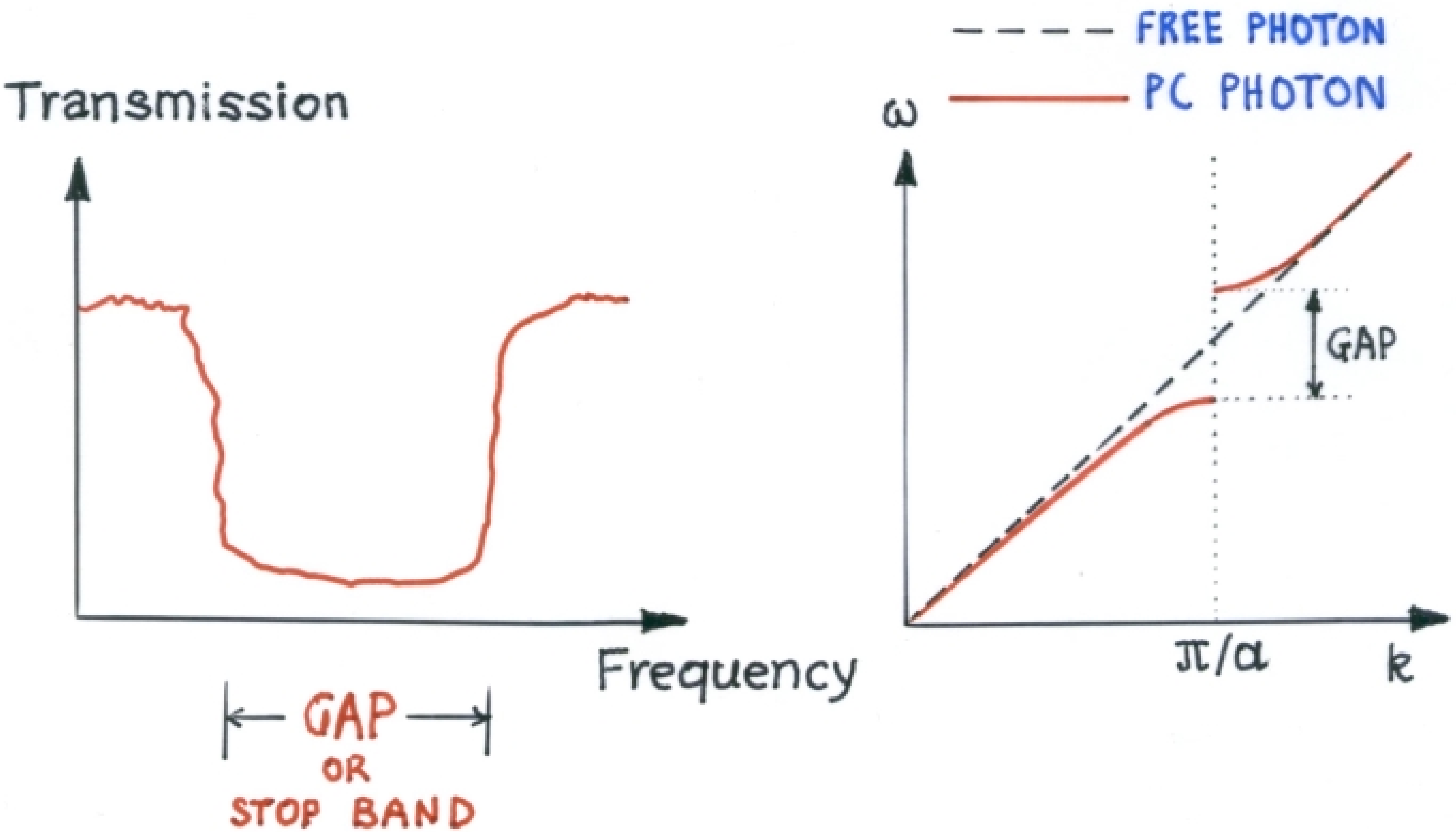
TRUE PC


3-D
periodic in
three directions
1-D
periodic in
one direction
2-D
periodic in
two directions

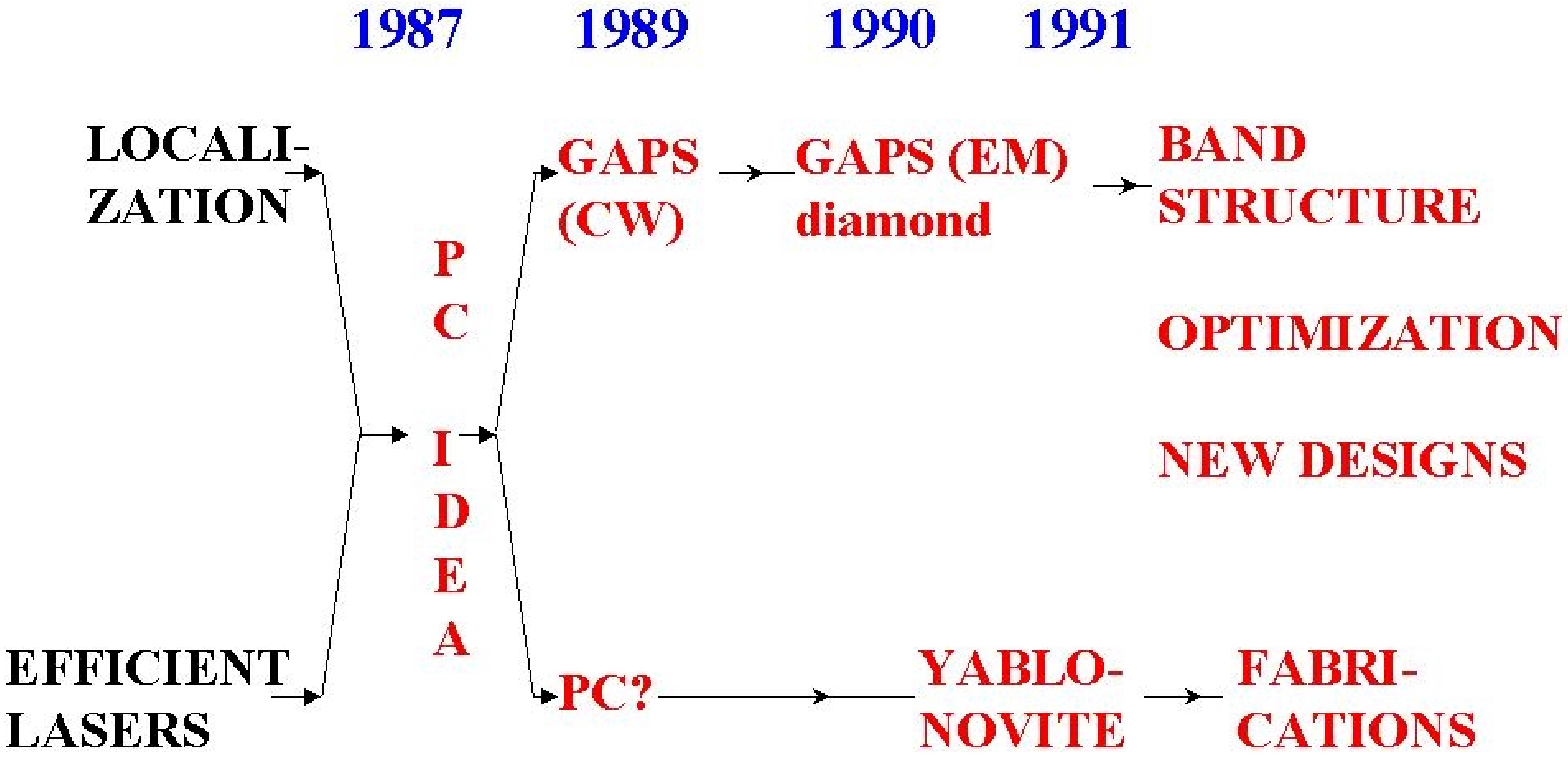
DOS for a close-packed fcc lattice of air spheres in silicon

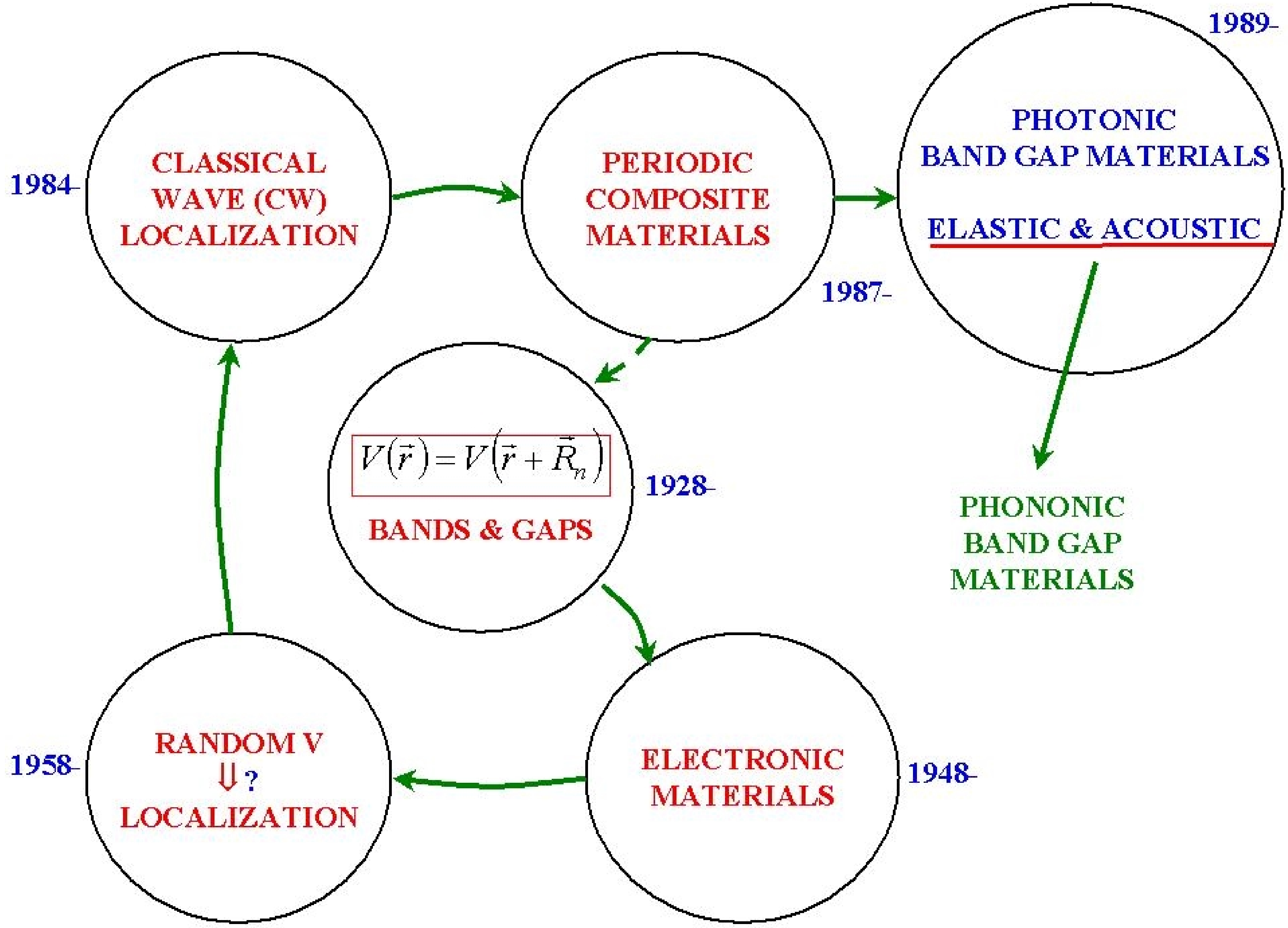


Busch and John, PRE 58, 3896 (1998)



Transmission
Frequency
GAP
OR
STOP BAND
FREE PHOTON
PC PHOTON
ω
GAP
π/a
k


1987
1989
1990
1991
LOCALI-
ZATION
EFFICIENT
LASERS
P
C
I
D
E
A
GAPS
(CW)
PC?
GAPS (EM)
diamond
YABLO-
NOVITE
BAND
STRUCTURE
OPTIMIZATION
NEW DESIGNS
FABRI-
CATIONS



1984-
CLASSICAL
WAVE (CW)
LOCALIZATION
PERIODIC
COMPOSITE
MATERIALS
1987-
1989-
PHOTONIC
BAND GAP MATERIALS
ELASTIC & ACOUSTIC
PHONONIC
BAND GAP
MATERIALS
$V(\vec{r}) = V(\vec{r} + \vec{R}_n)$
BANDS & GAPS
1928-
1958-
RANDOM V
⇓ ?
LOCALIZATION
ELECTRONIC
MATERIALS
1948-

WE SHALL NOT CEASE FROM EXPLORATION
AND THE END OF OUR EXPLORING
WILL BE TO ARRIVE WHERE WE STARTED
AND KNOW THE PLACE FOR THE FIRST TIME

T.S. ELIOT

II. GAPS IN CLASSICAL WAVE PROPAGATION

GAP FORMATION MORE DIFFICULT FOR CWs THAN e-Ws

SCHRÖDINGER (dV ≡ V-V$_{max}$):

$$\nabla^2 \psi + \frac{2m}{\hbar^2}\left(E - V_{\max}\right)\psi - \frac{2m}{\hbar^2}\delta V \psi = 0$$

ACOUSTIC IN FLUIDS (?=const.):

$$\nabla^2 p + \frac{\omega^2}{c_{\max}^2} p - \omega^2 \left(\frac{1}{c_{\max}^2} - \frac{1}{c^2}\right) p = 0$$

$$\frac{\omega^2}{c_{max}^2} \leftrightarrow \frac{2m}{\hbar^2}\left(E - V_{max}\right) \Rightarrow$$

$E > V_{max}$

$$\omega^2\left(\frac{1}{c_{max}^2} - \frac{1}{c^2}\right) \leftrightarrow \frac{2m}{\hbar^2}\delta V \Rightarrow$$

ω^2 x fluctuations * $\leftrightarrow$ äV

$\Rightarrow$ ***low c*** $\leftrightarrow$ potential well

*** σ ~ |ω² x fluctuations|² ~ ω⁴, RAYLEIGH**

CONCLUSIONS FOR GAP FORMATION:

- **fcc lattice**
- **LOW ε INCLUSIONS IN HIGH ε MATRIX (CERMET TOPOLOGY)**

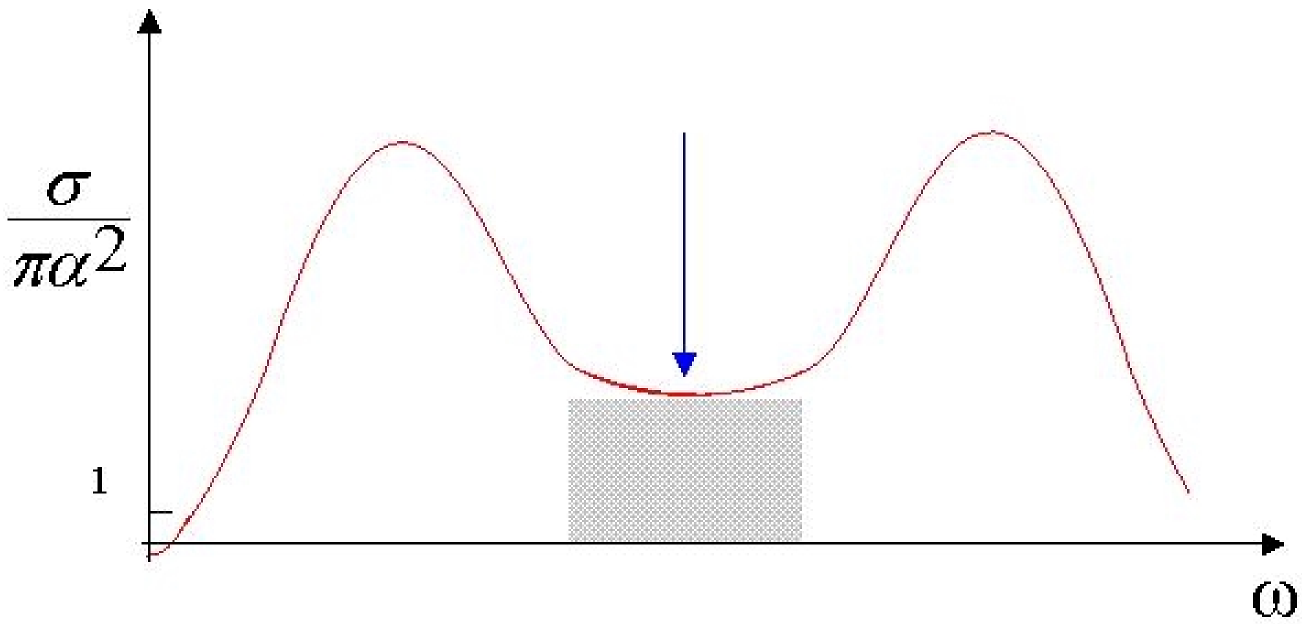
- **? ~ d** FOR MIE RESONANCES
- **? ~ a** FOR BRAGG INTERFERENCE
- **d ~ a** ⇒ f : VOLUME FRACTION (f ~ 20%)

- **TWO CHANNELS OF PROPAGATION:**

  √ THROUGH THE MATRIX

  √ HOPPING AMONG N.N. M.R. (LCAO-like)

- **GAPS WHERE BOTH CHANNELS ARE BLOCKED (s vs ?)**



BUT …

CW EQUATIONS MORE COMPLICATED

- **EM:**

$$\nabla^2 \vec{E} - \nabla\left(\nabla \cdot \vec{E}\right) - \frac{\in \mu}{c^2}\omega^2 \vec{E} + \frac{1}{\mu}\left(\nabla \mu\right) \times \left(\nabla \times \vec{E}\right) = 0$$

$$\nabla \cdot \left(\in \vec{E}\right) = 0$$

- **ACOUSTIC IN FLUIDS:**

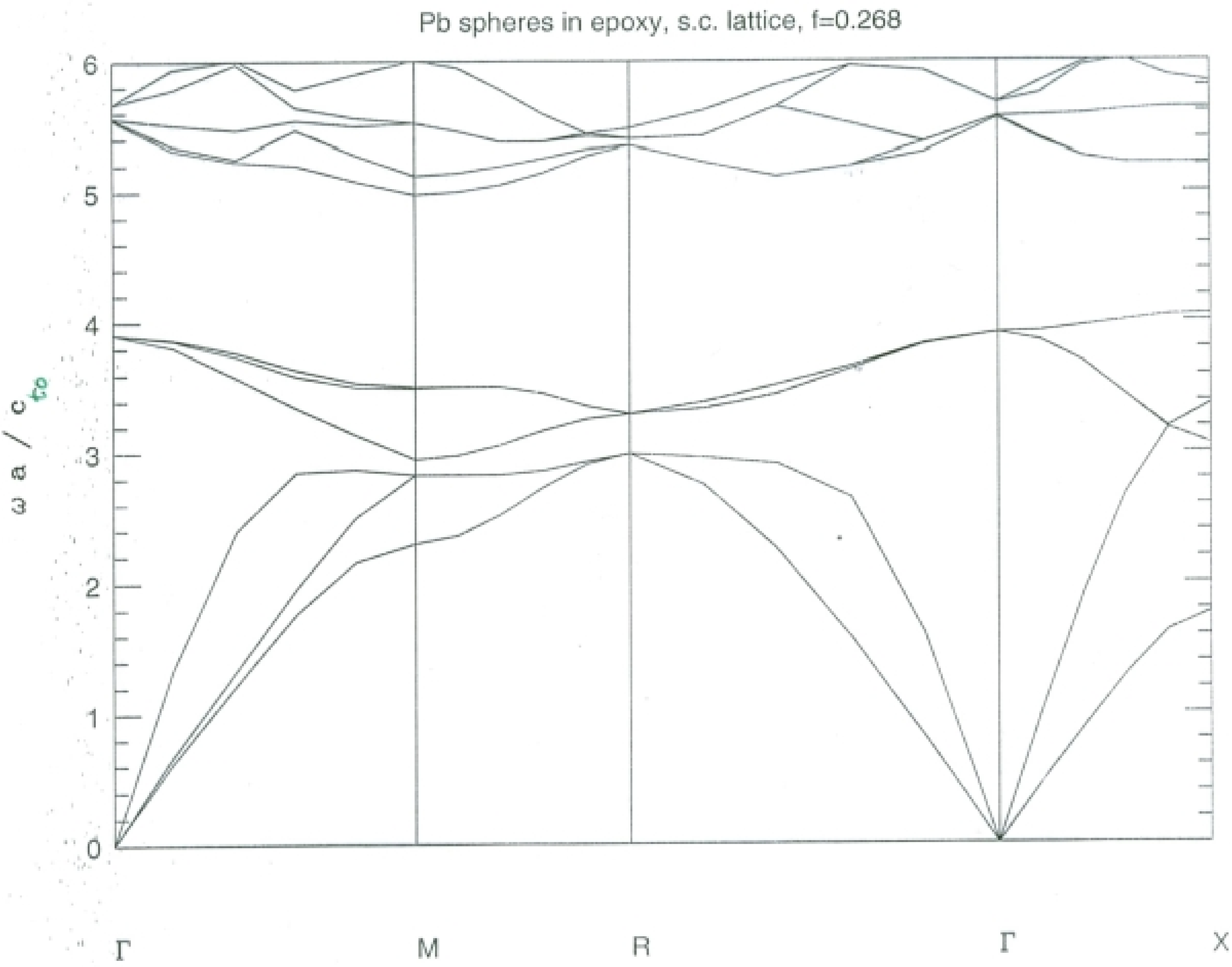
$$\nabla^2 p + \rho\left(\nabla \frac{1}{\rho}\right) \cdot \nabla p + \frac{\omega^2}{c^2} p = 0$$

- **ELASTIC:**

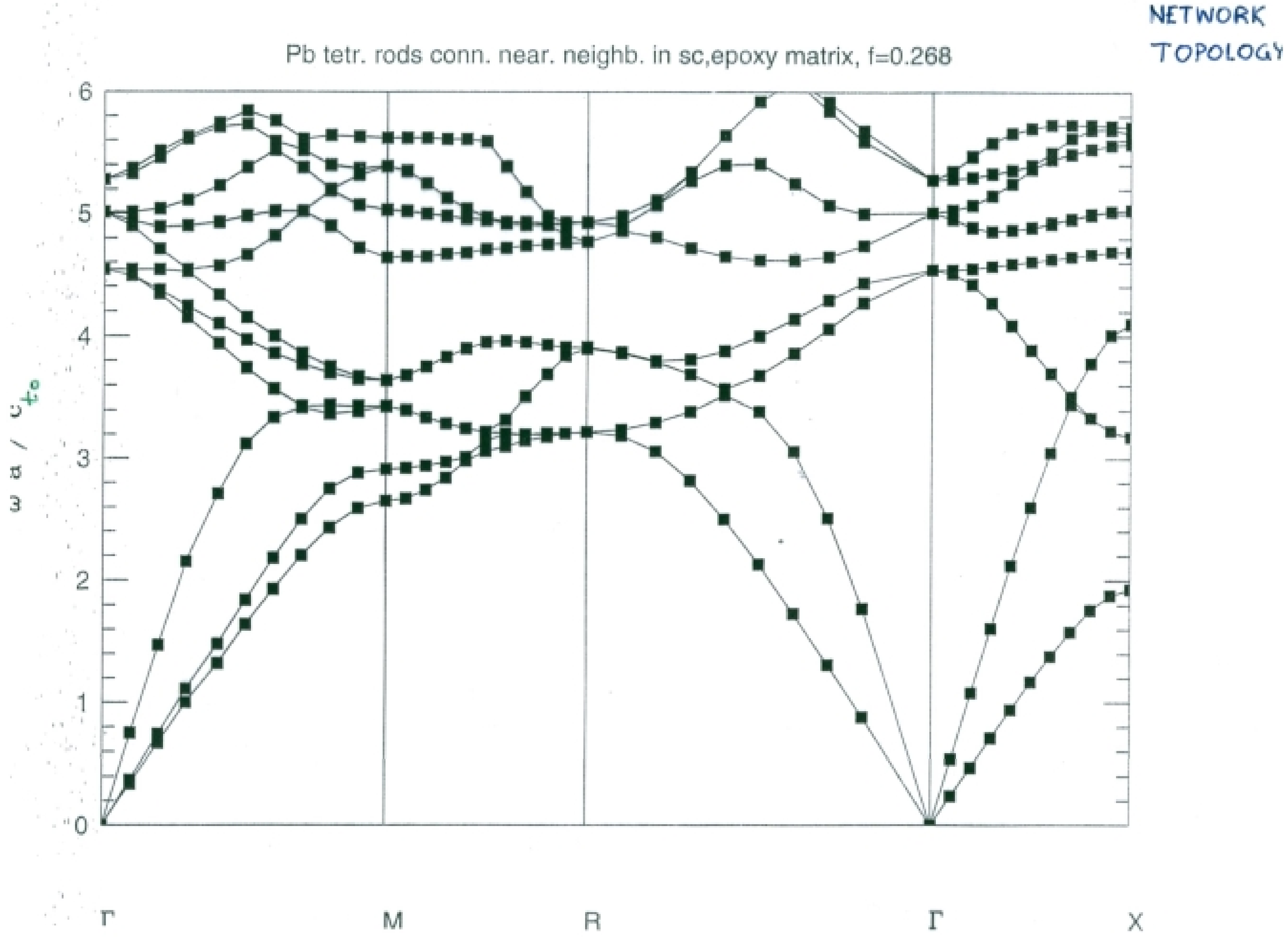
$$\frac{1}{\rho}\left\{\frac{\partial}{\partial x_i}\left(\lambda\frac{\partial u^\ell}{\partial x_\ell}\right)+\frac{\partial}{\partial x_\ell}\left[\mu\left(\frac{\partial u^i}{\partial x_\ell}+\frac{\partial u^\ell}{\partial x_i}\right)\right]\right\}+\omega^2 u^i=0$$

$$\vec{u}\equiv u^i\vec{j}_i\ ,\qquad \mu\equiv\rho c_t^2\ ,\ \ \lambda\equiv\rho\left(c_\ell^2-2c_t^2\right)$$

ARE OUR CONCLUSIONS VALID FOR THESE EQUATIONS AS WELL?



Pb spheres in epoxy, s.c. lattice, f=0.268
ω a / c
0
1
2
3
4
5
6
Γ
M
R
Γ
X


NETWORK
TOPOLOGY
Pb tetr. rods conn. near. neighb. in sc,epoxy matrix, f=0.268
ω a / c_t0
0
1
2
3
4
5
6
Γ
M
R
Γ
X

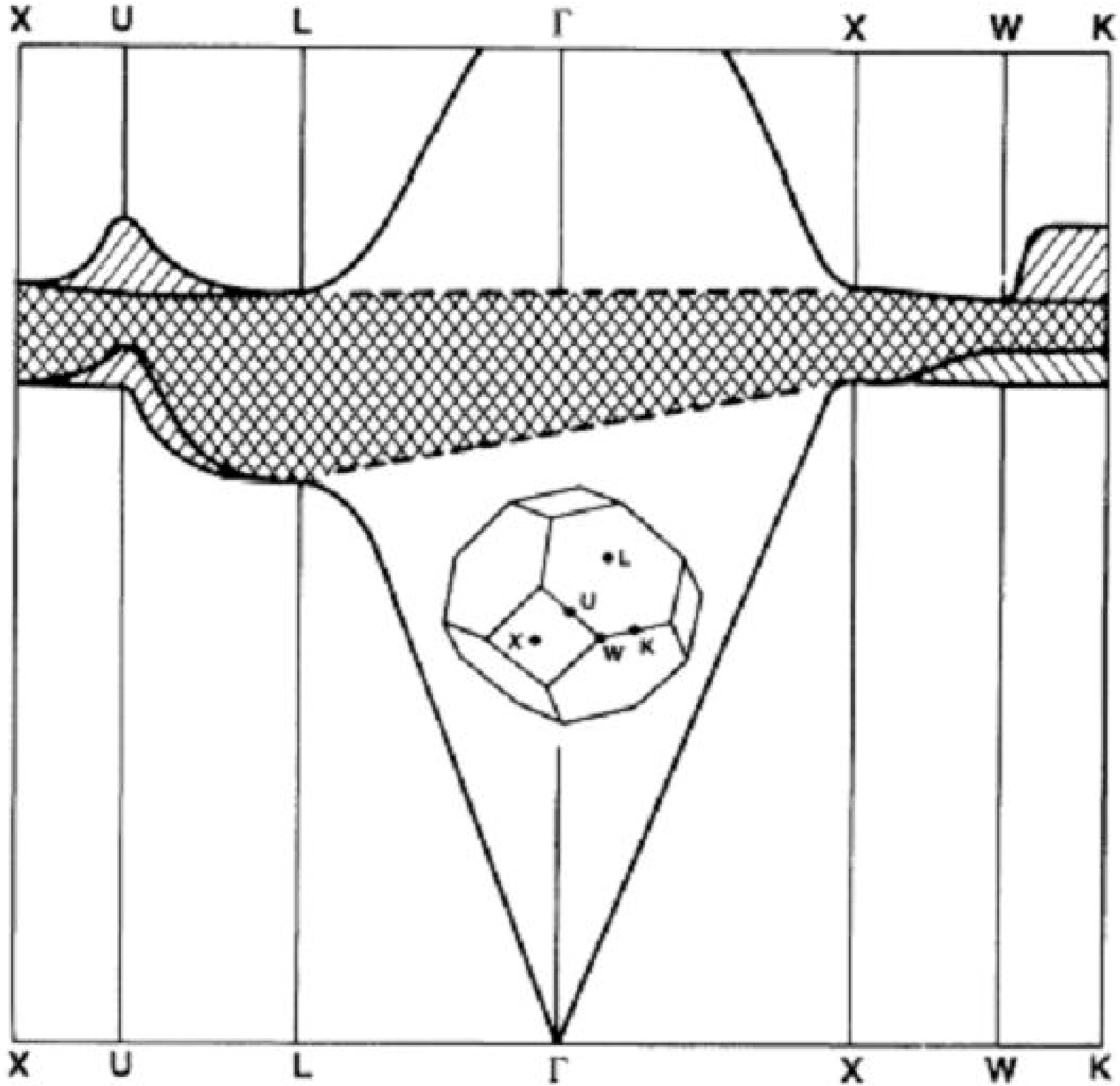
NOT FOR EM WAVES

- **NETWORK TOPOLOGY MORE FAVORABLE**
- **DIAMOND OR DIAMOND-LIKE STRUCTURES MORE FAVORABLE**

EXPLANATIONS ?

Experimental band structure of a fcc lattice of air spheres

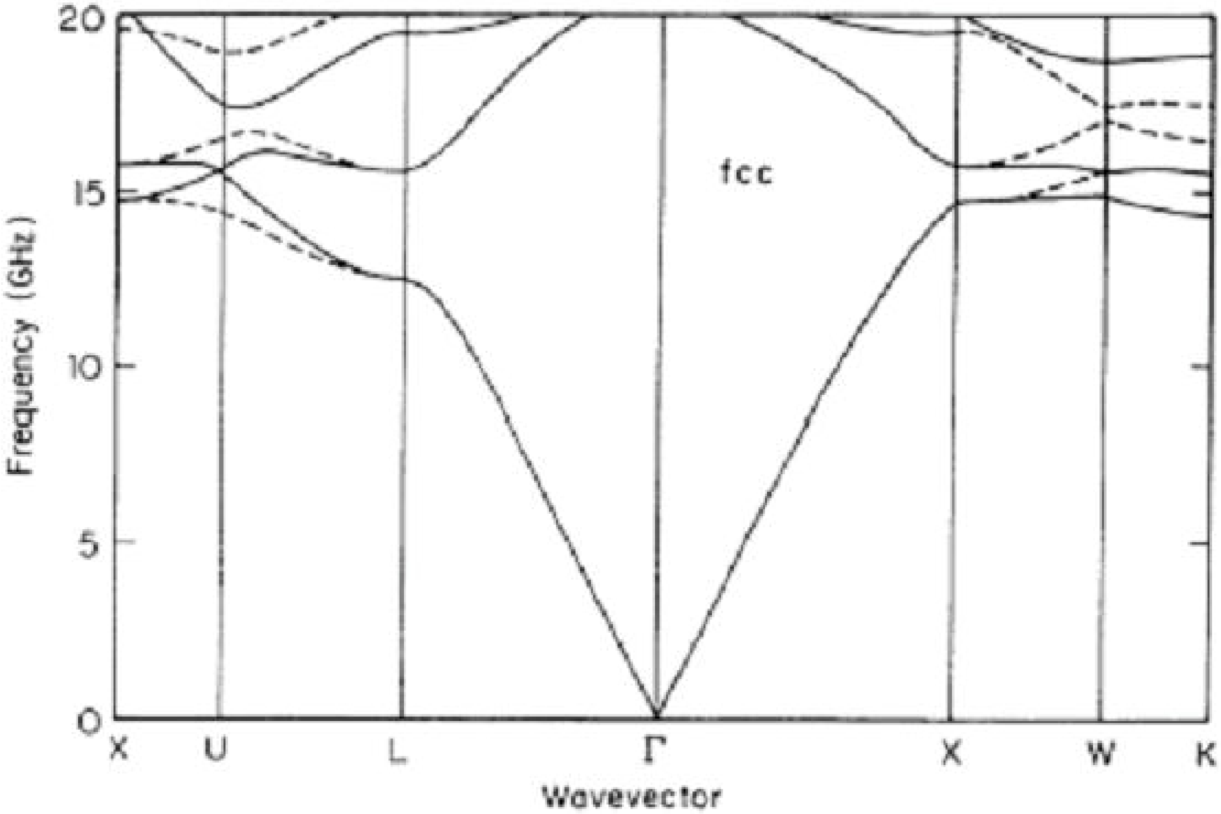
Gap →



Fcc
Airball(86%)
n=3.5

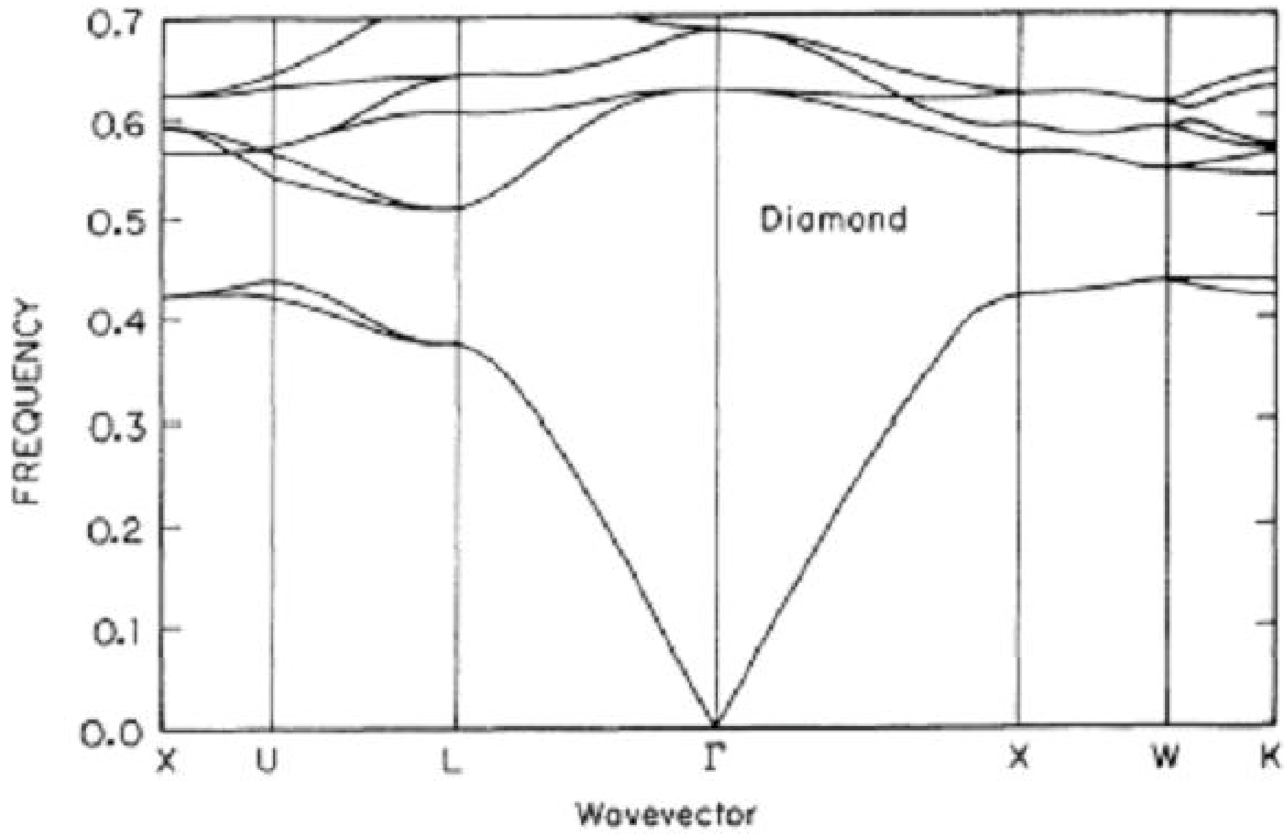
Yablonovitch & Gmitter, PRL 63, 1950 (1989)

FCC lattice has only a pseudogap



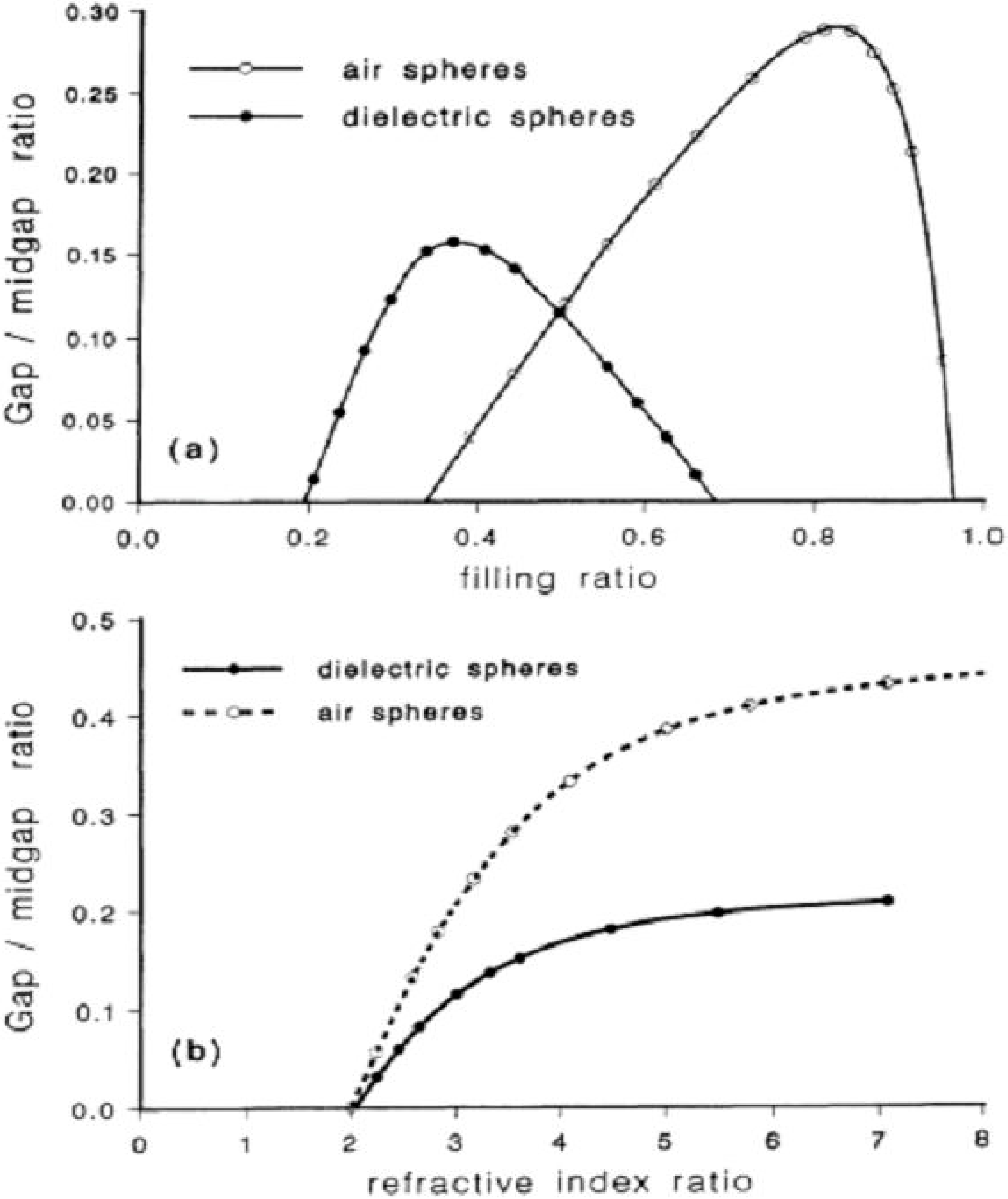
Ho, Chan and Soukoulis, PRL 65, 3152 (1990)

Diamond lattice gives the largest photonic band gap



Ho, Chan and Soukoulis, PRL 65, 3152 (1990)

Diamond lattice



Ho, Chan and Soukoulis, PRL 65, 3152 (1990)

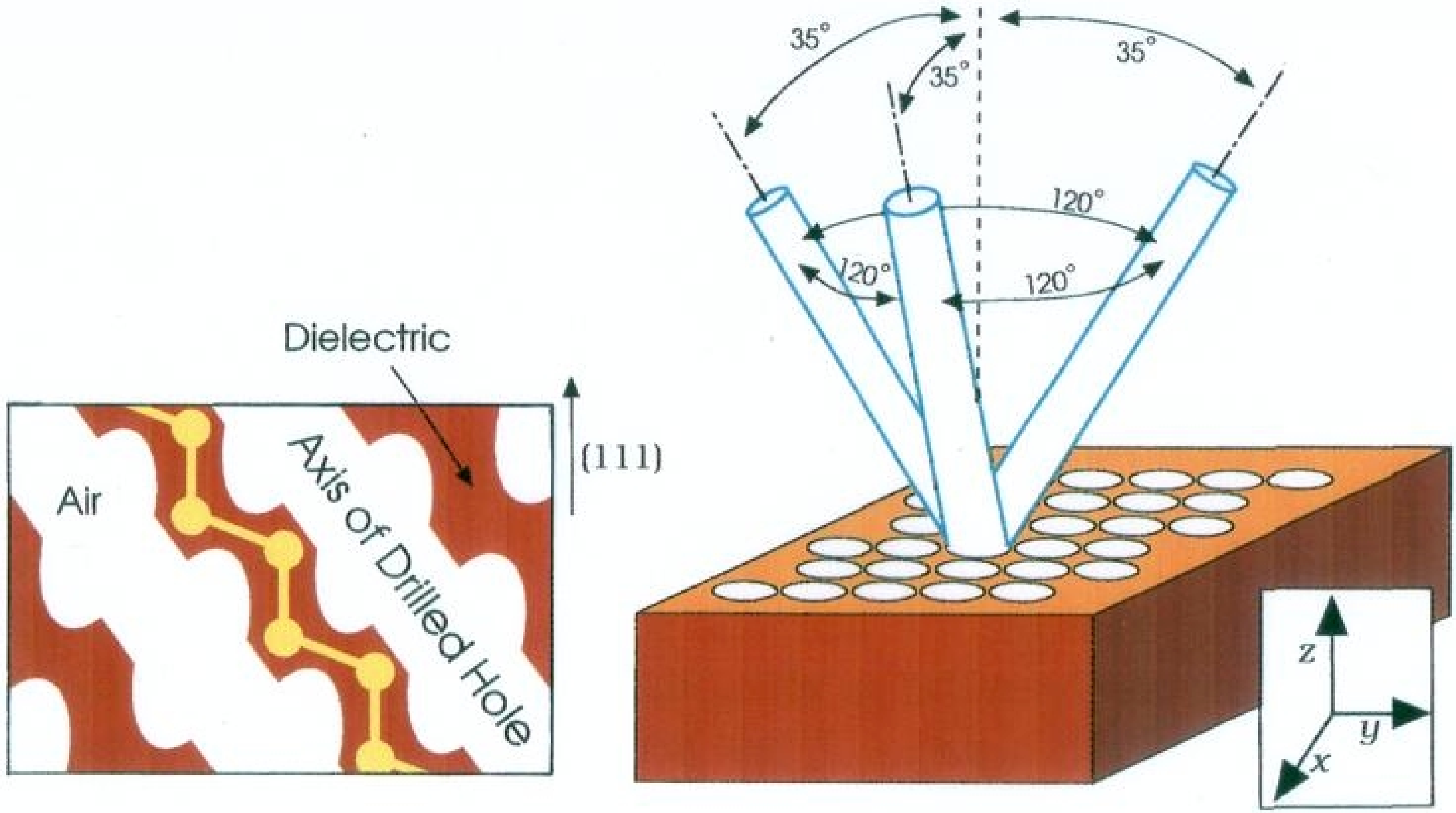


Figure 4 The method for constructing Yablonovite: a slab of dielectric is covered by a mask consisting of a triangular array of holes. Each hole is drilled three times, at an angle of 35.26° away from the normal, and spread out 120° on the azimuth. This results in a three dimensional structure whose $(1\bar{1}0)$ 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 $(1\bar{1}\bar{1})$.

JOANNOPOULOS et al, opp. cit.

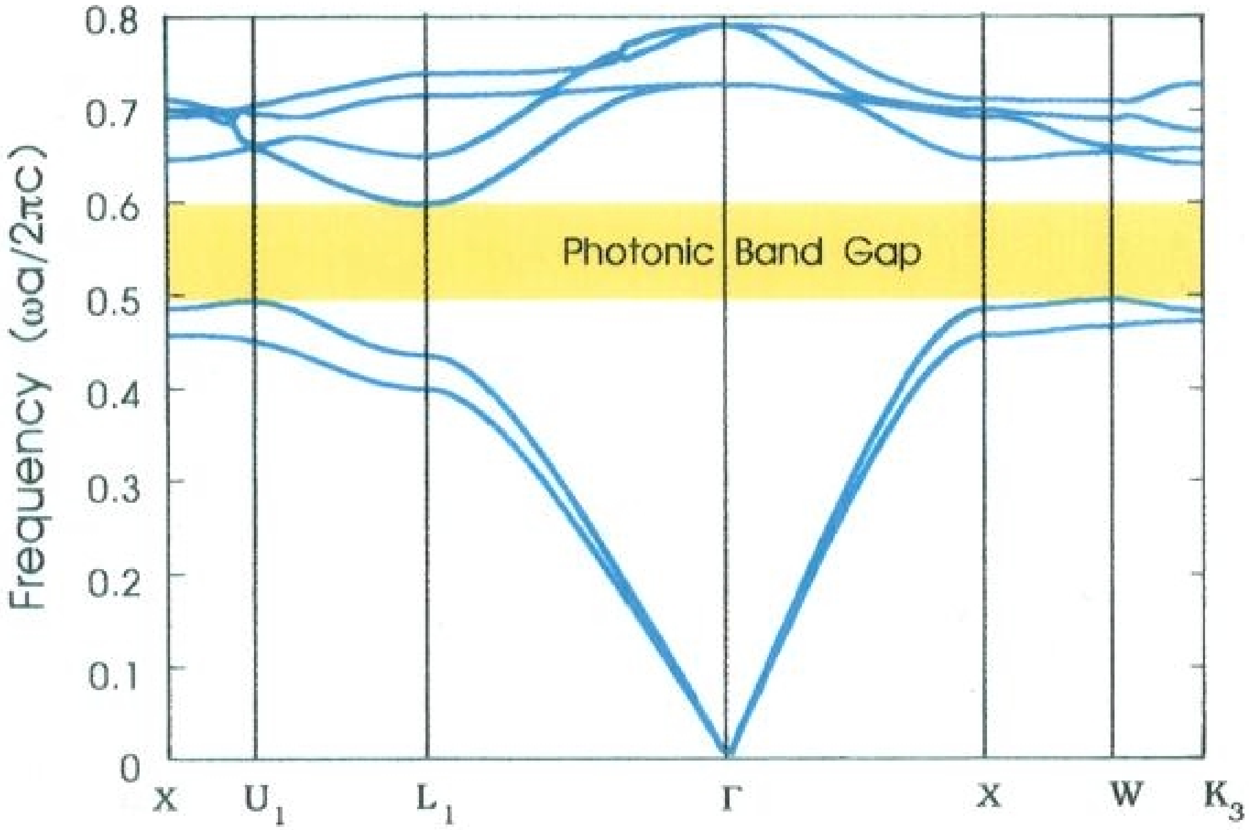


Figure 5 The photonic band structure for the six lowest bands of Yablonovite. A detailed discussion of this band structure can be found in Yablonovitch et al. (1991a).

JOANNOPOULOS et al

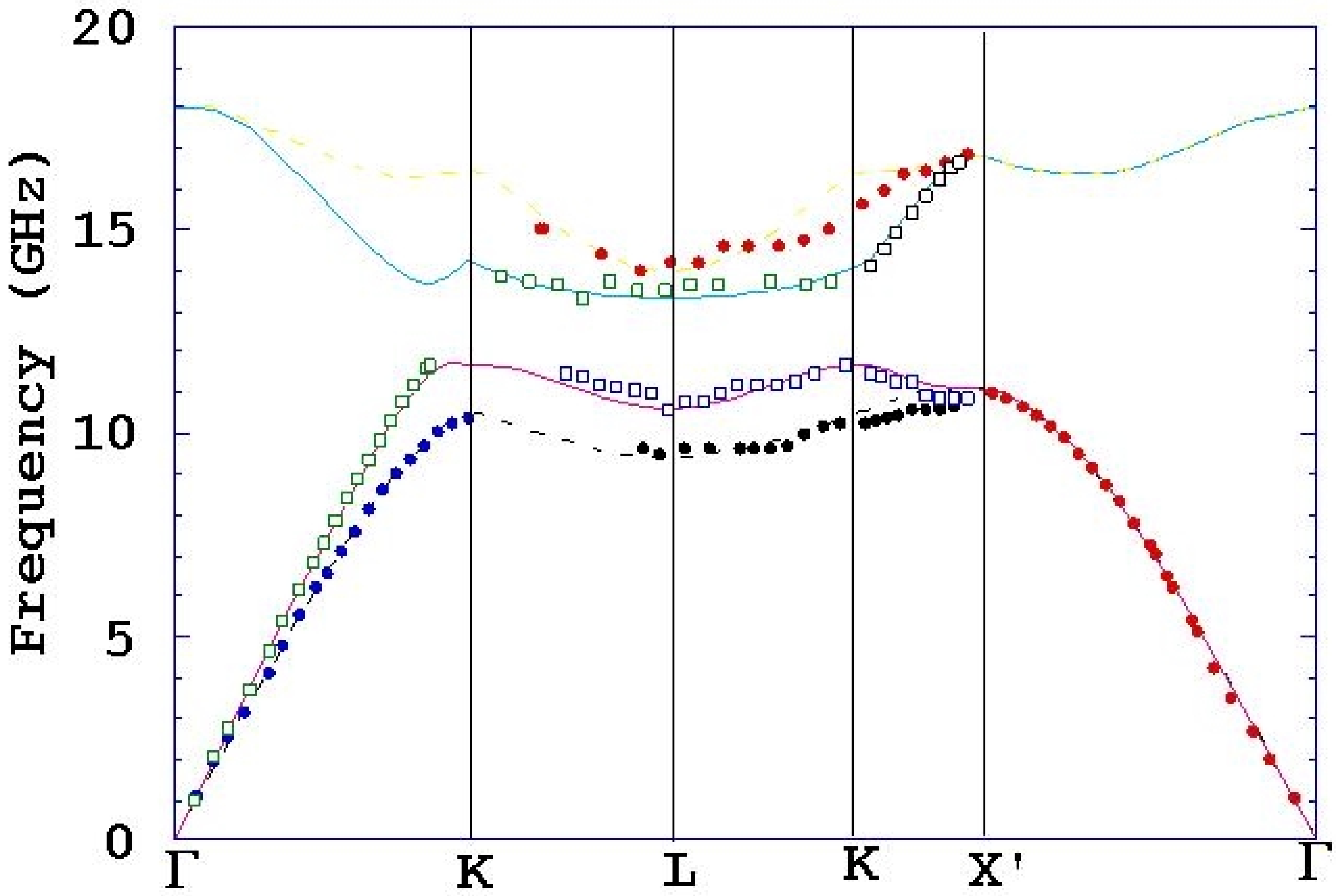
III. CALCULATIONAL TECHNIQUES

- **PW (PLANE WAVE) : *PERIODIC, NO LOSSES***
- **TM (TRANSFER MATRIX) :**

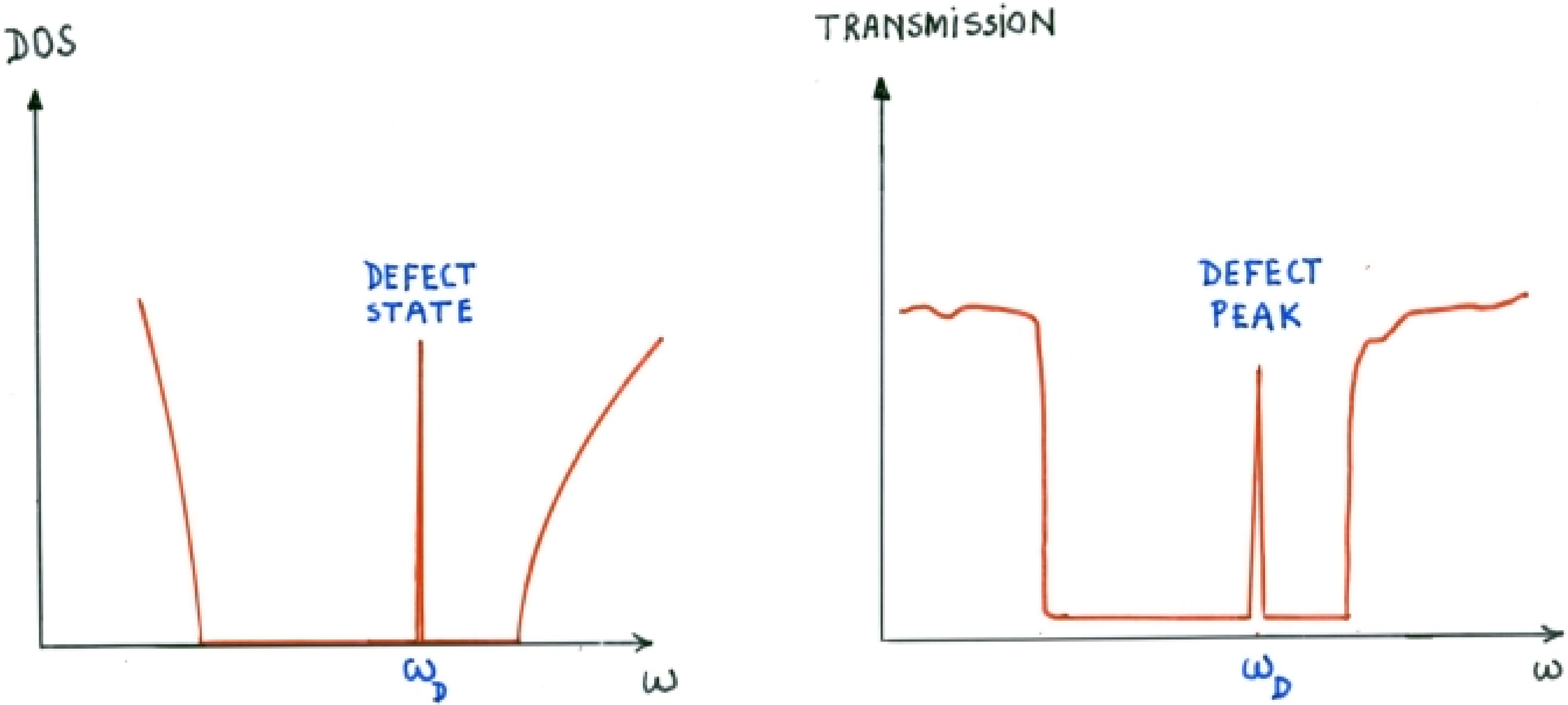
  PARTIAL PERIODICITY OR FINITE № CHAN.
- **MS (MULTIPLE SCATTERING): *LOW FREQUENCIES***
- **FDTD (FINITE DIFFERENCE TIME DOMAIN) √**

NO UNCONTROLLABLE APPROXIMATIONS
NO ADJUSTABLE PARAMETERS

Theory and experiment are in excellent agreement

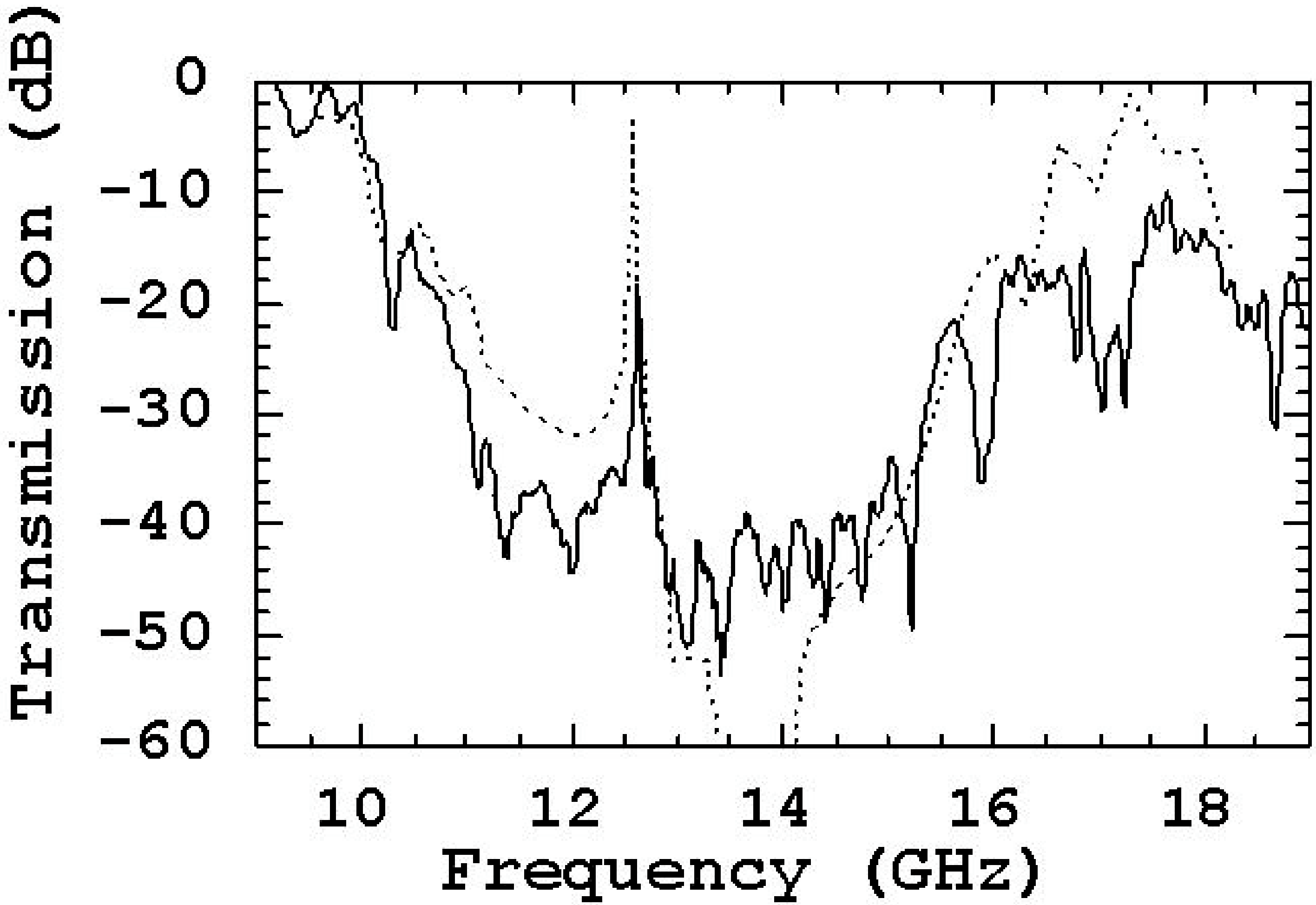


IV. DOPING, MINI STOP BANDS



DOS
DEFECT
STATE
ω_D
ω
TRANSMISSION
DEFECT
PEAK
ω_D
ω

Theoretical (dashed line) and experimental (solid line) transmission characteristics of the defect structure



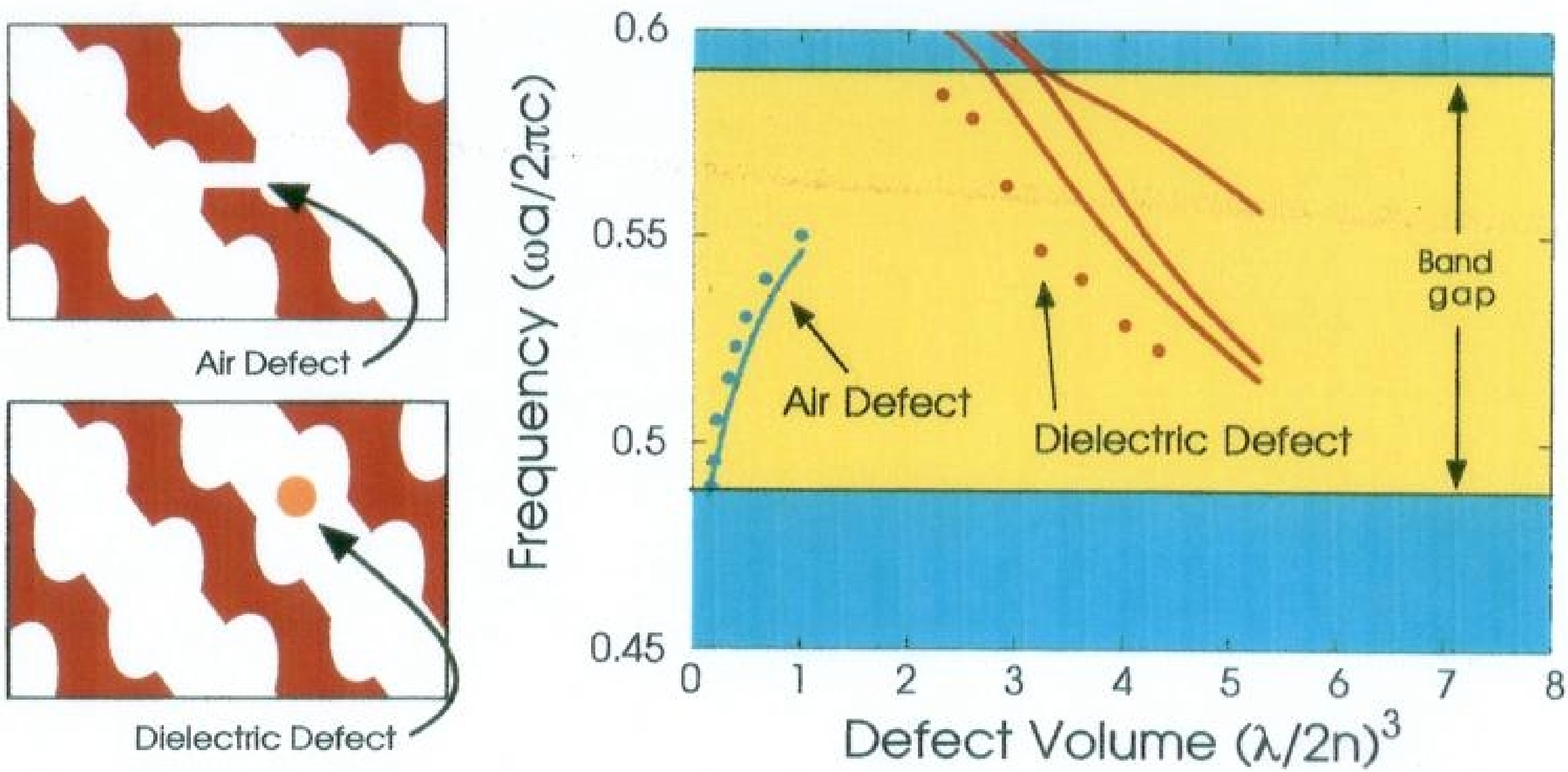
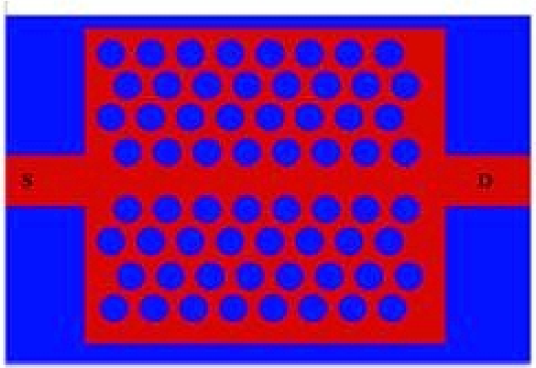


Figure 6 Plotted are the frequencies of the localized modes of Yablonovite as the defect size varies. The dots indicate measured values (Yablonovitch et al. 1991b), the lines indicate computed values (Meade et al. 1993a), and the yellow region is the photonic band gap. The modes on the blue line result from an air defect, while the modes on the red lines result from a dielectric defect. The defect volume is expressed in units of $(\lambda/2n)^3$, where λ is the midgap vacuum wavelength and n is the index of refraction of the dielectric material.

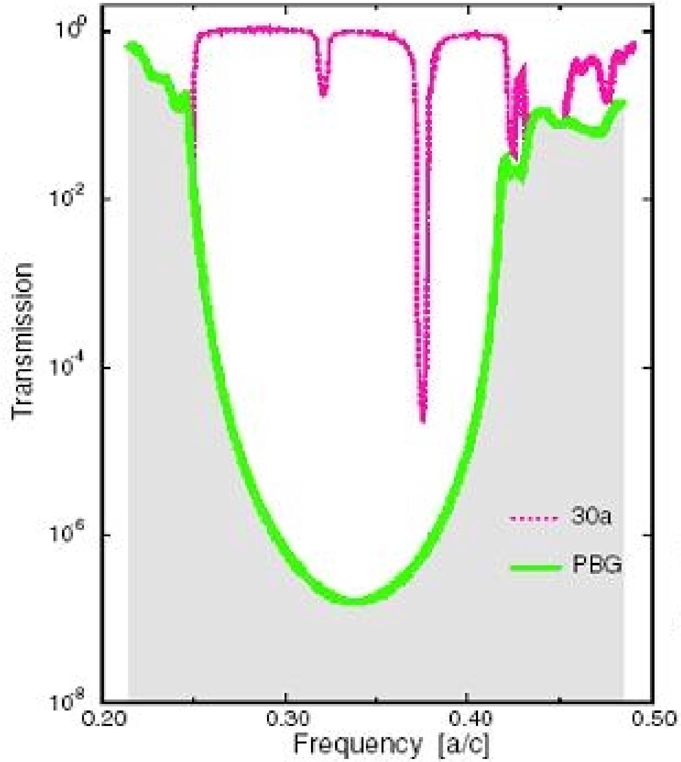
JOANNOPOULOS et al

Mini Stop Bands in PC Waveguides:

Physical origin? Dependence on the parameters of the problem (guide length, air filling ratio, losses)?



W1



f=0.6
n=3.4

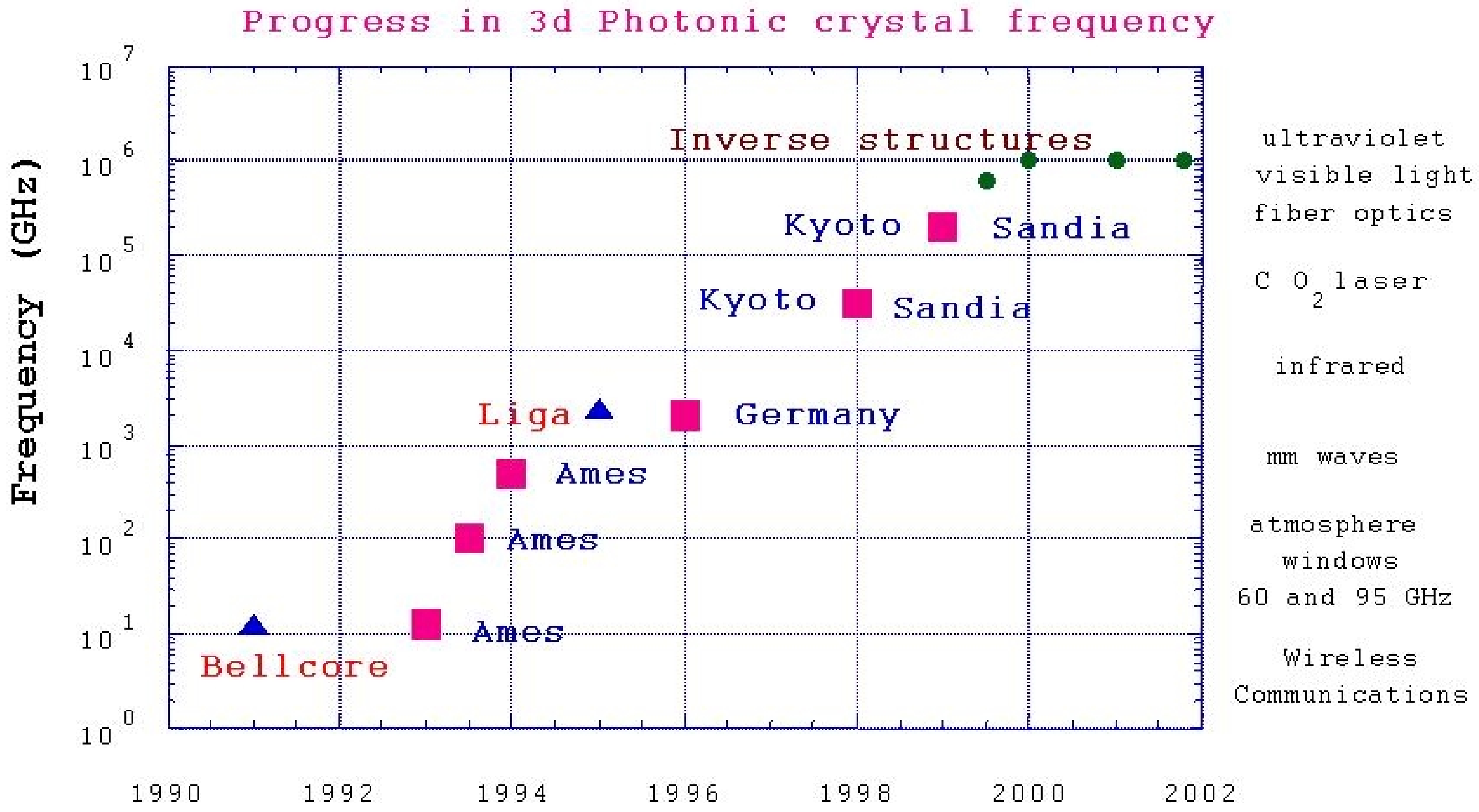
--Origin: Coupling of the guided modes

--For W1 and n=3.4 they appear for high f (f > 40%)

--Losses (conductivity) make them broader and less deep

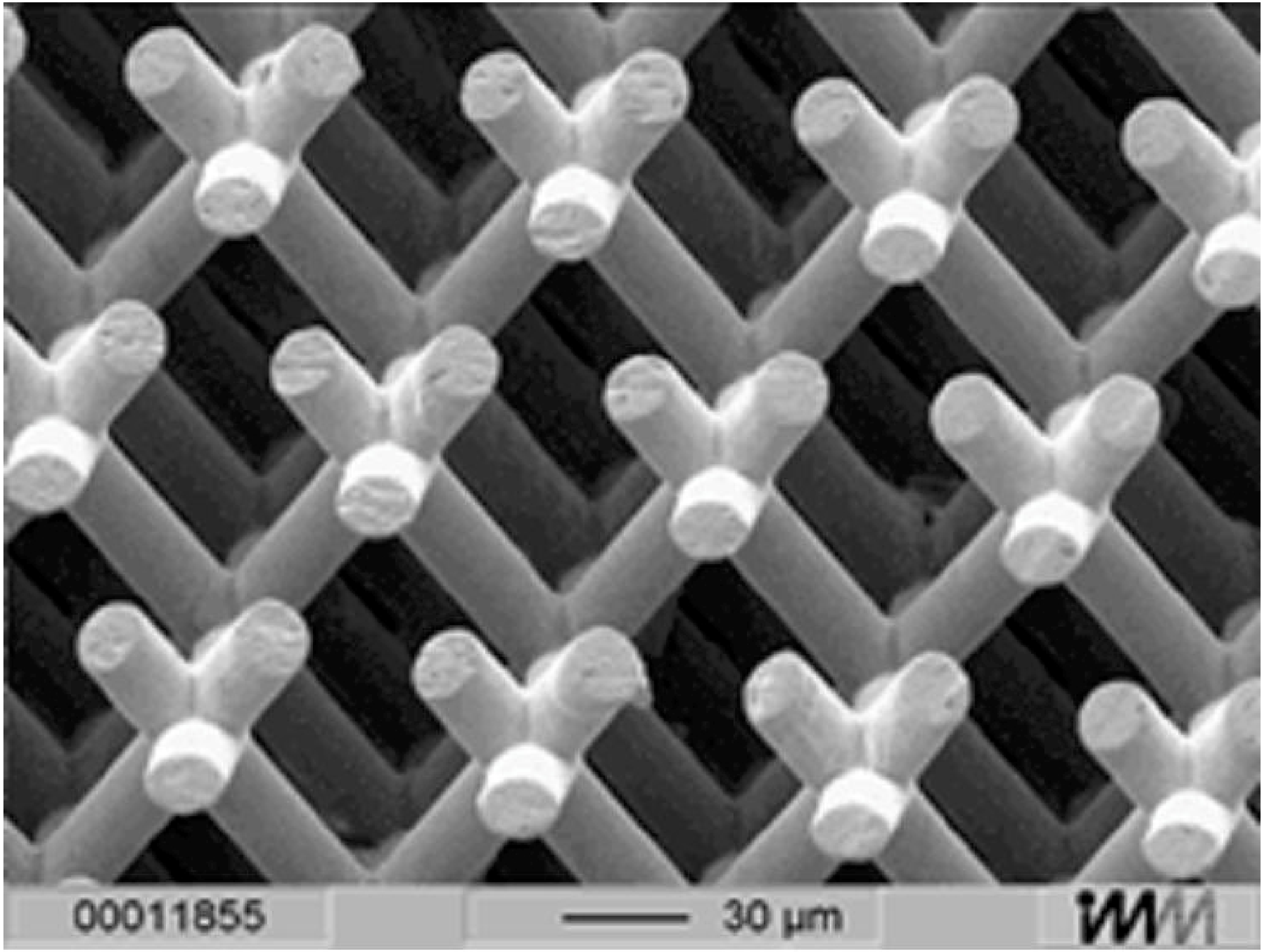
Agio and Soukoulis, PRE, 64, 055603R (2001)

V. RECENT DEVELOPMENTS



Progress in 3d Photonic crystal frequency
Frequency (GHz)
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
1990
1992
1994
1996
1998
2000
2002
Inverse structures
Kyoto
Sandia
Kyoto
Sandia
Liga
Germany
Ames
Ames
Ames
Bellcore
ultraviolet
visible light
fiber optics
C O2 laser
infrared
mm waves
atmosphere
windows
60 and 95 GHz
Wireless
Communications

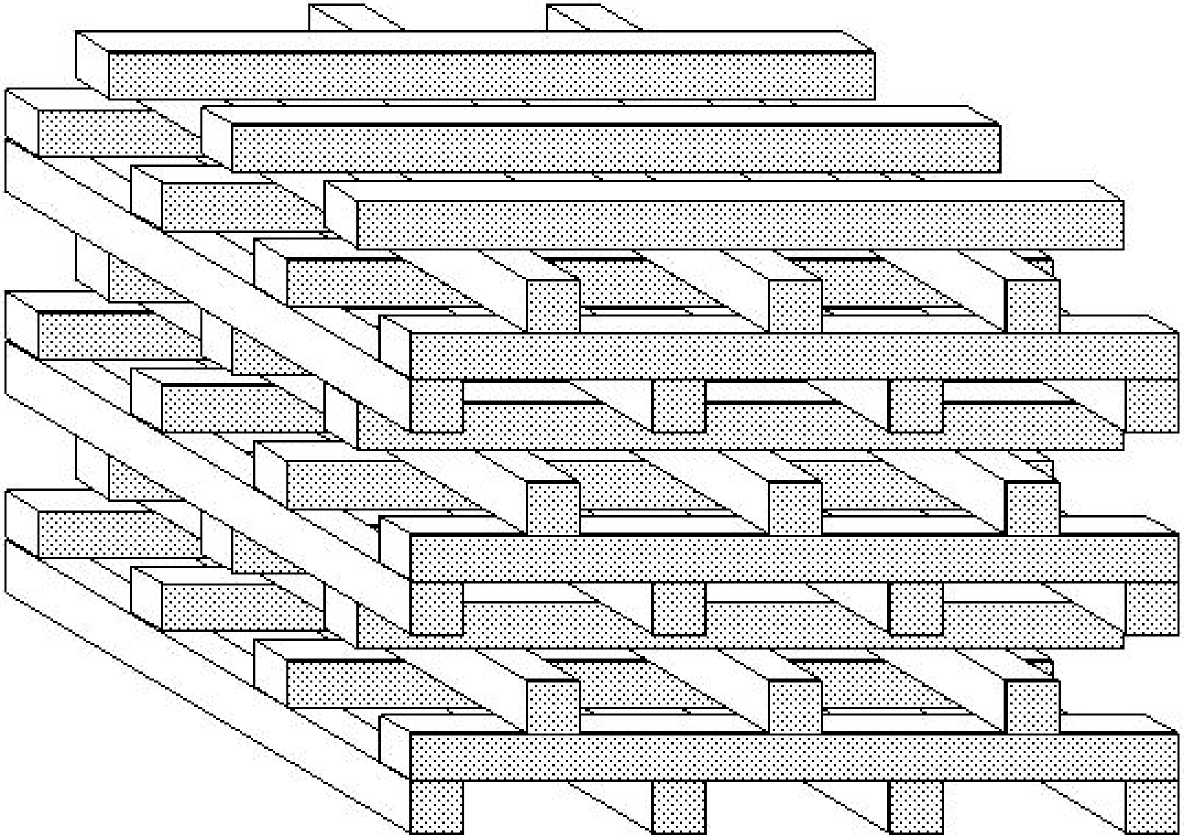
Fabrication of 3-cylinder structure by LIGA technique



ISU, FORTH and Mainz

Appl. Phys. Lett. 71, 1441 (1997)

A new easy-to-build structure with a full photonic band gap

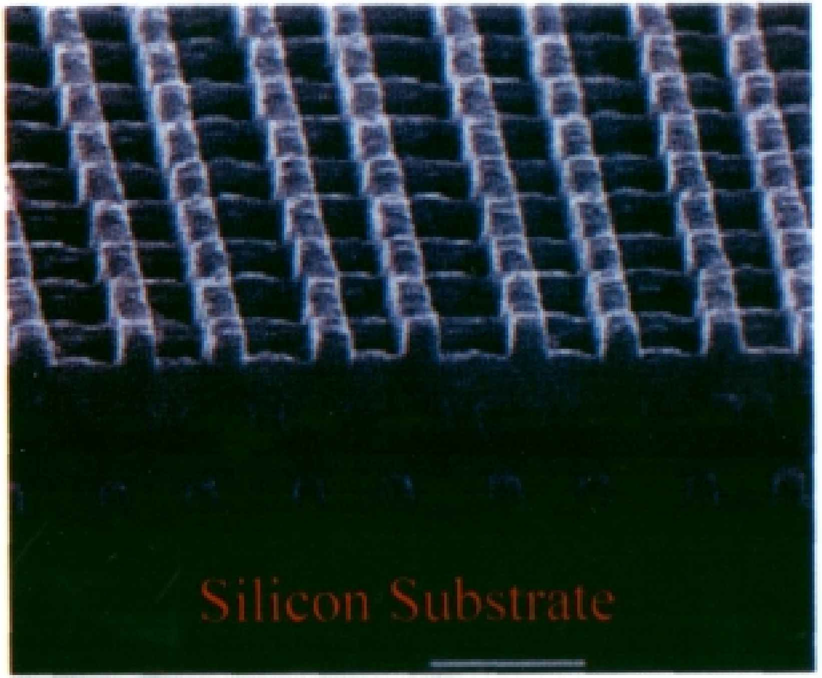


Iowa State layer-by-layer structure:

Science News 144, 199 (1993); Solid State Comm. 89, 413 (1994)

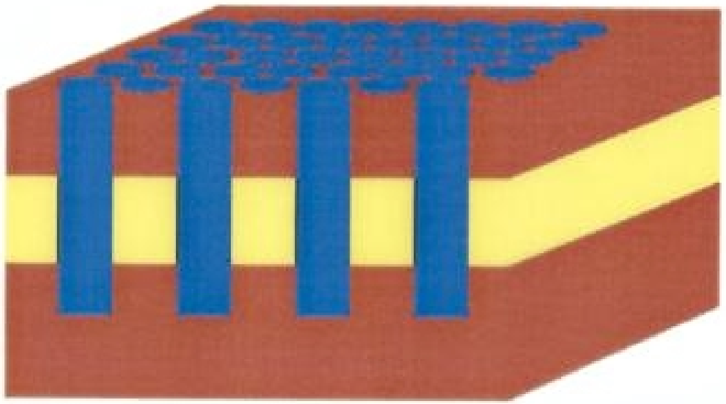
Phys. Rev. B 50, 1945 (1994)

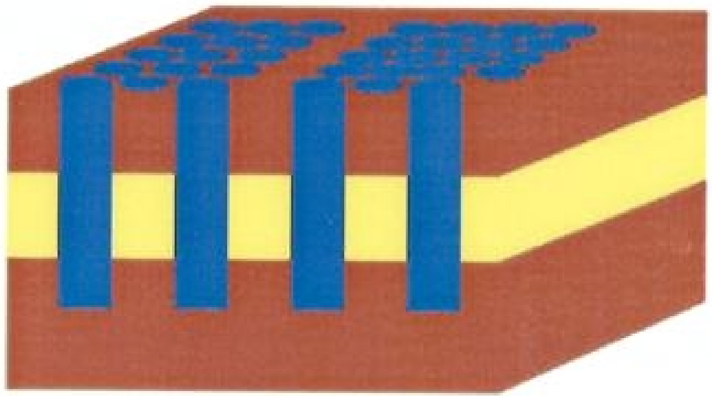
A 3-D Silicon Photonic Crystal Operating at λ=1.55μm



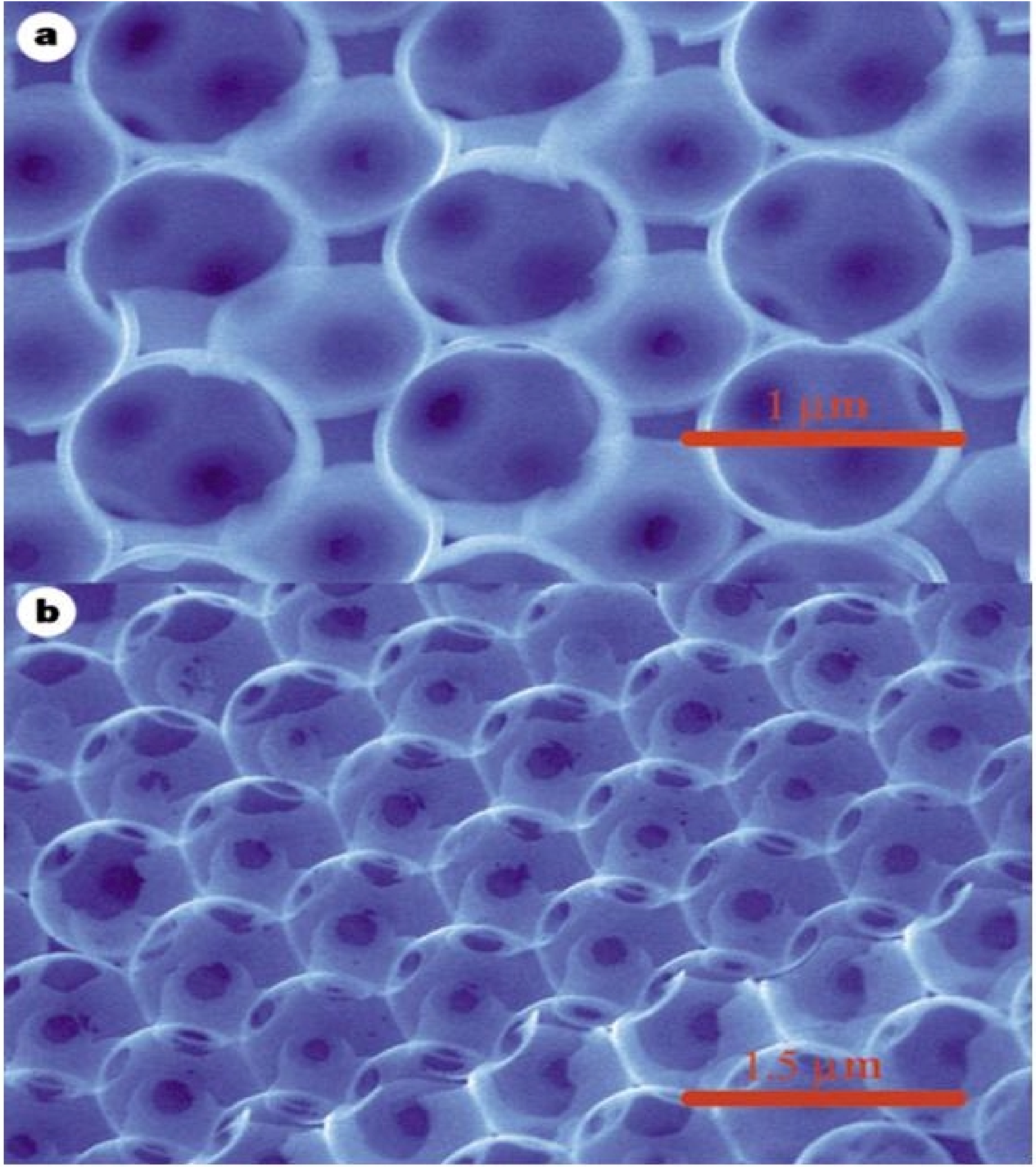
Sandia National Laboratories

2D PCs IN LAYERED STRUCTURES
(SANDWICHED OR SUSPENDED)



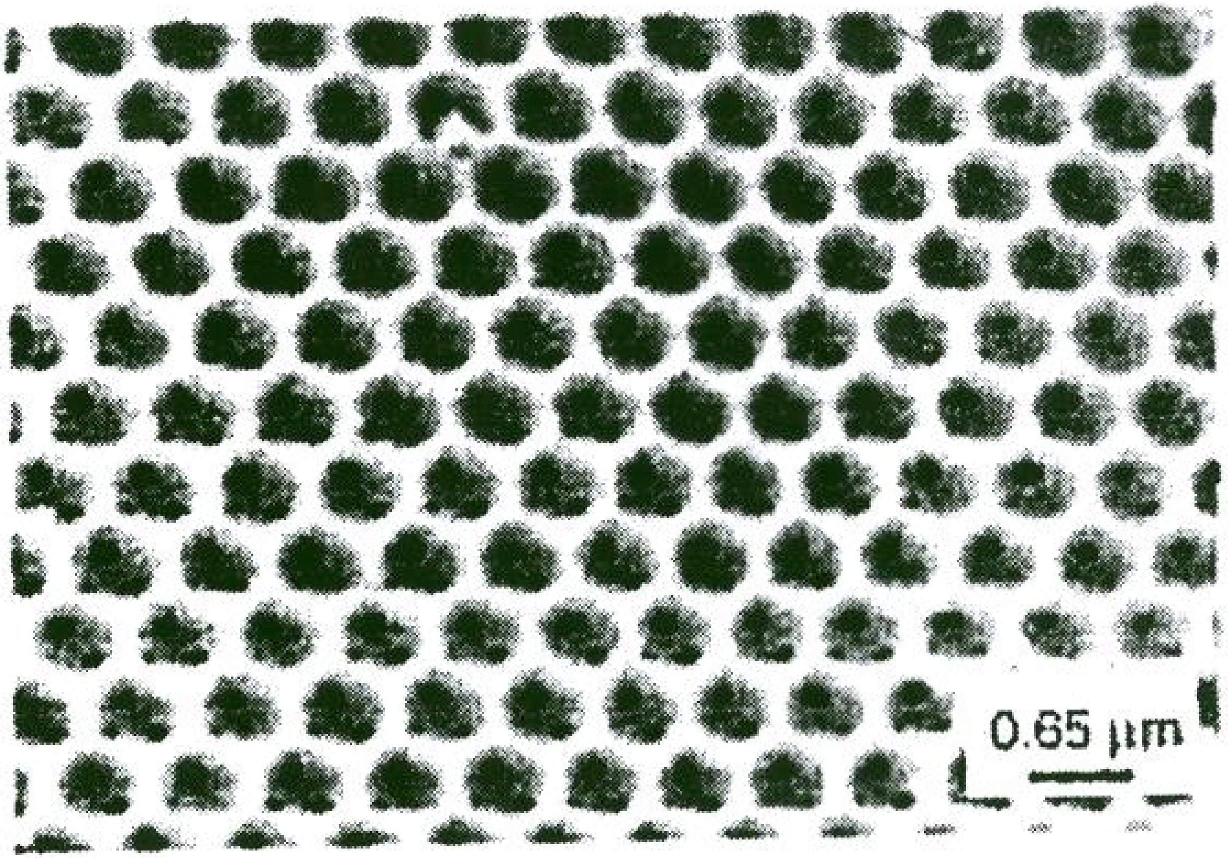


In – plane: **PC**
Out of plane: **usual waveguide**



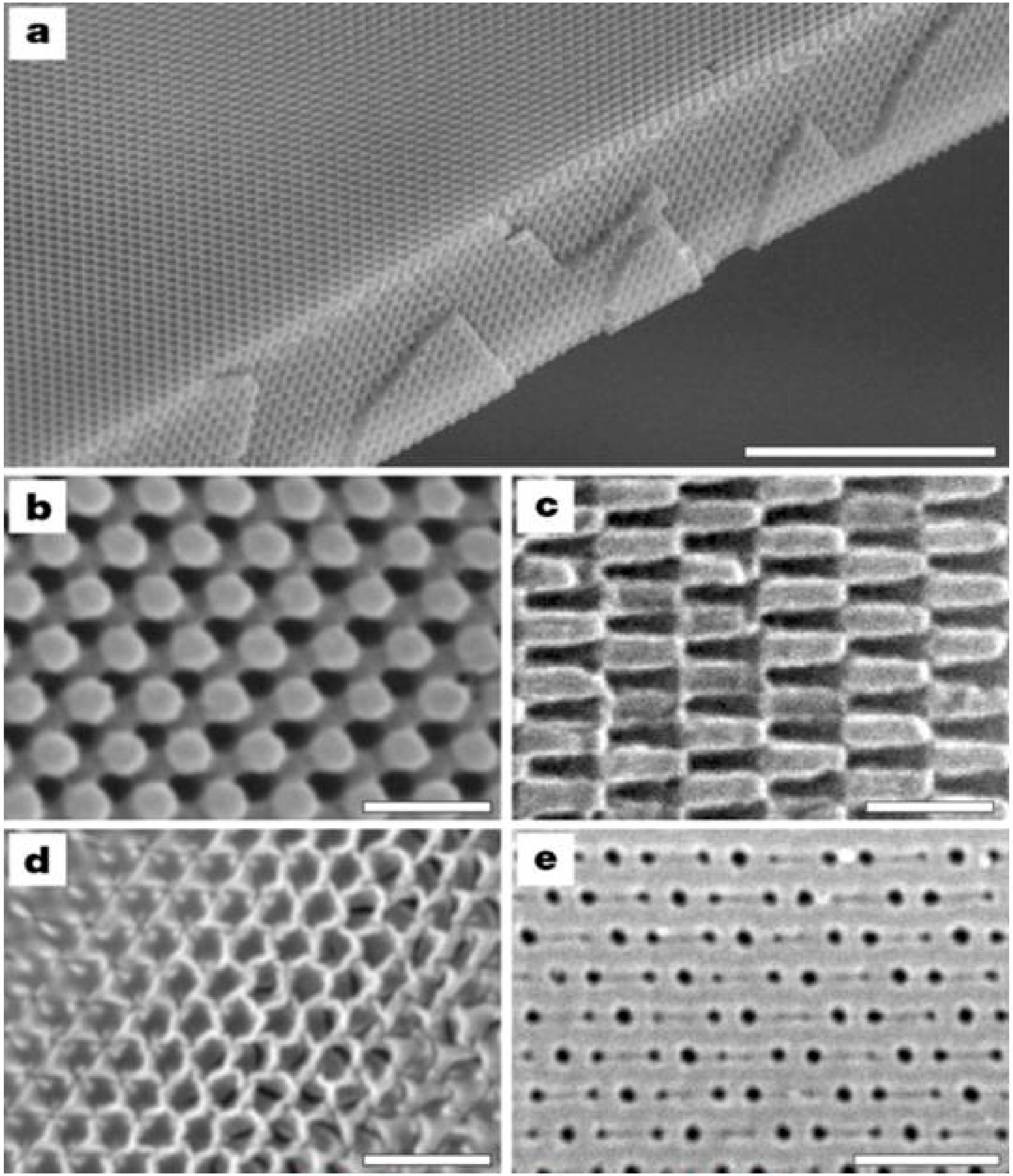
Silicon inverted opals

A. Blanco et. al. Nature 405, 437 (2002)



Vos et al, IN SOUKOULIS BOOK, p. 192

Fabrication of photonic crystals by holographic lithography



M.Campell et. al. Nature, 404, 53 (2000)

MATERIALS*

- **SEMICONDUCTORS**

  Si, Ge, GaAs, AlGaAs/GaAs

- **OXIDES**

  SiO_2, TiO

- **POLYMERS**

  PMMA

- **PROTEIN CRYSTALS**

- **METALS**

FABRICATION TECHNIQUES*

- **LITHOGRAPHIC METHODS**

  e-BEAM
  ION BEAM (FOCUSED)
  DRY ETCHING
  fs LASER PULSES

  \+

- **X-RAY LITHOGRAPHY**

  (LIGA)

- **HOLOGRAPHIC LITHOGRAPHY**

- **OTHER**
  Si_3N_4

- **SELF – ASSEMBLED COLLOIDAL PARTICLES *(SiO_2, PMMA)* OR CLUSTER OF PARTICLES AS TEMPLATES**

*** SEE, e.g.**
C.M. SOUKOULIS, ed., PHOTONIC CRYSTAL…
…IN THE 21st CENTURY

PHOTONIC NANOSTRUCTURES,
SAN DIEGO, Oct. 24-25, 2002

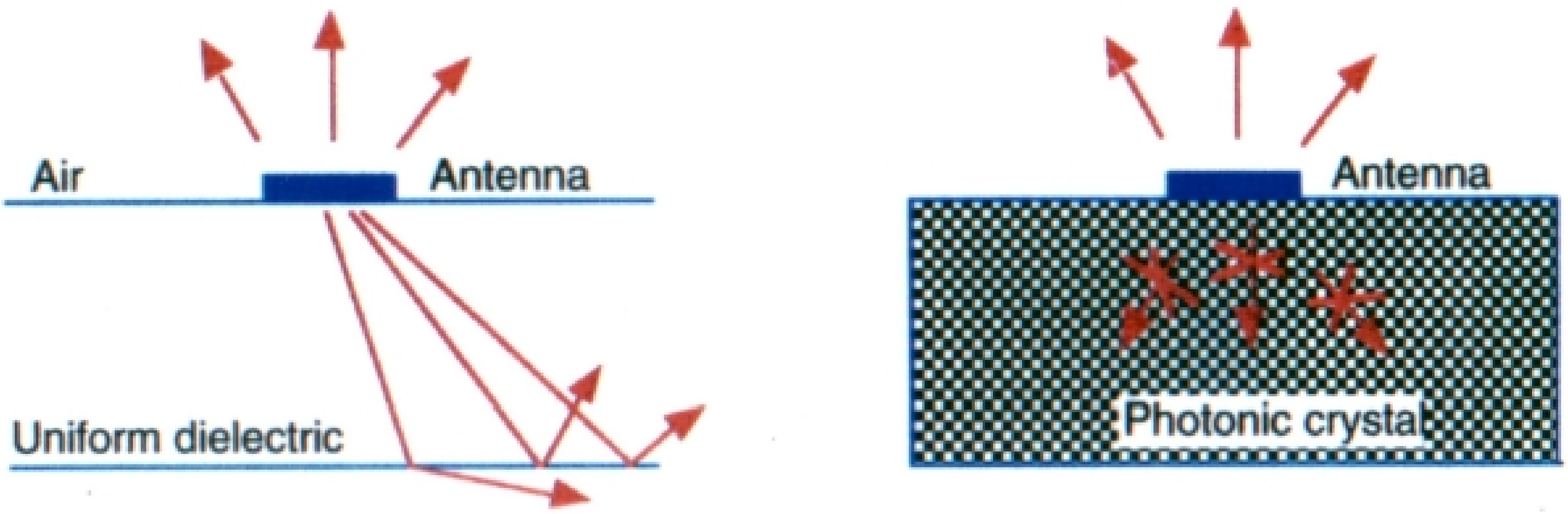
APPLICATIONS FOR PHOTONIC CRYSTALS

DEVICE	DESCRIPTION	STATUS
OPTICAL FIBERS	2-D band-gap material stretched along the third dimension	Early versions already commercialized
NANOSCOPIC LASERS	World's tiniest optical cavities and tiniest lasers; formed in a thin-film 2-D band-gap material	Demonstrated in the lab
ULTRAWHITE PIGMENT	Incomplete 3-D band-gap material, usually patterned as opal structure	Demonstrated; low-cost manufacturing methods under development
RADIO-FREQUENCY ANTENNAS, REFLECTORS	Uses inductors and capacitors in place of ordinary dielectric materials	Demonstrated for magnetic resonance imaging and antennas
LIGHT-EMITTING DIODES	Photonic band-gap structure can extract light very efficiently (better than 50%)	Demonstrated, but must compete with other methods of achieving the same goal
PHOTONIC INTEGRATED CIRCUITS	2-D thin films can be patterned like conventional integrated circuits to make channel filters, modulators, couplers and so on	Under development

E. YABLONOVITCH, SCIENTIFIC AMERICAN, Dec. 2001

Applications: Microwaves

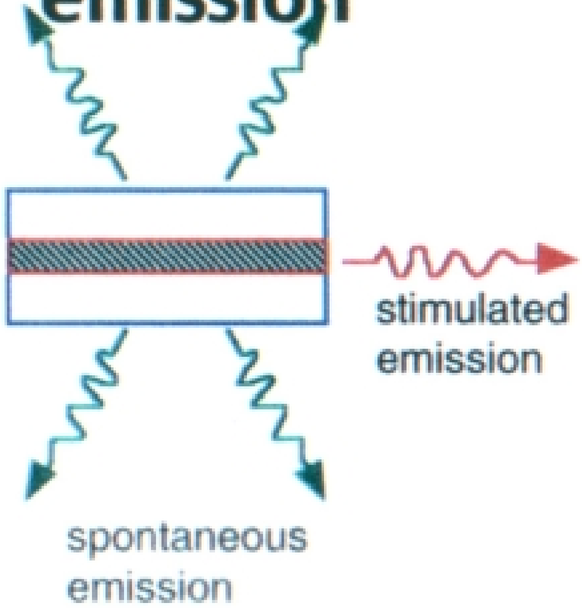
- **Efficient antennas, waveguide, isolators etc.**

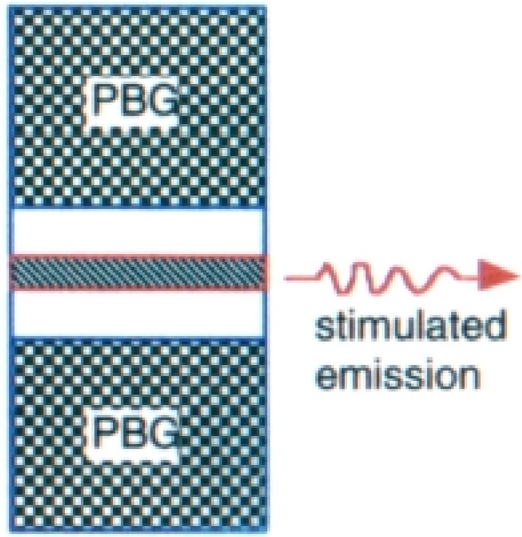


Efficient planar antenna

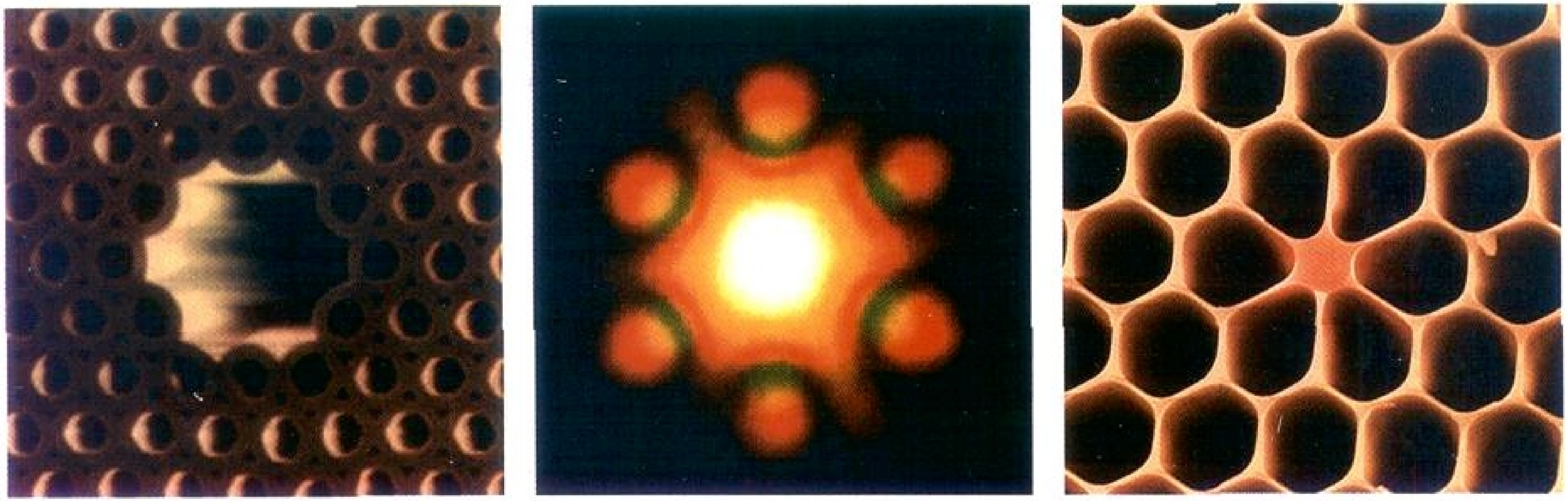
Applications: Optical range

- **Suppression of spontaneous emission**



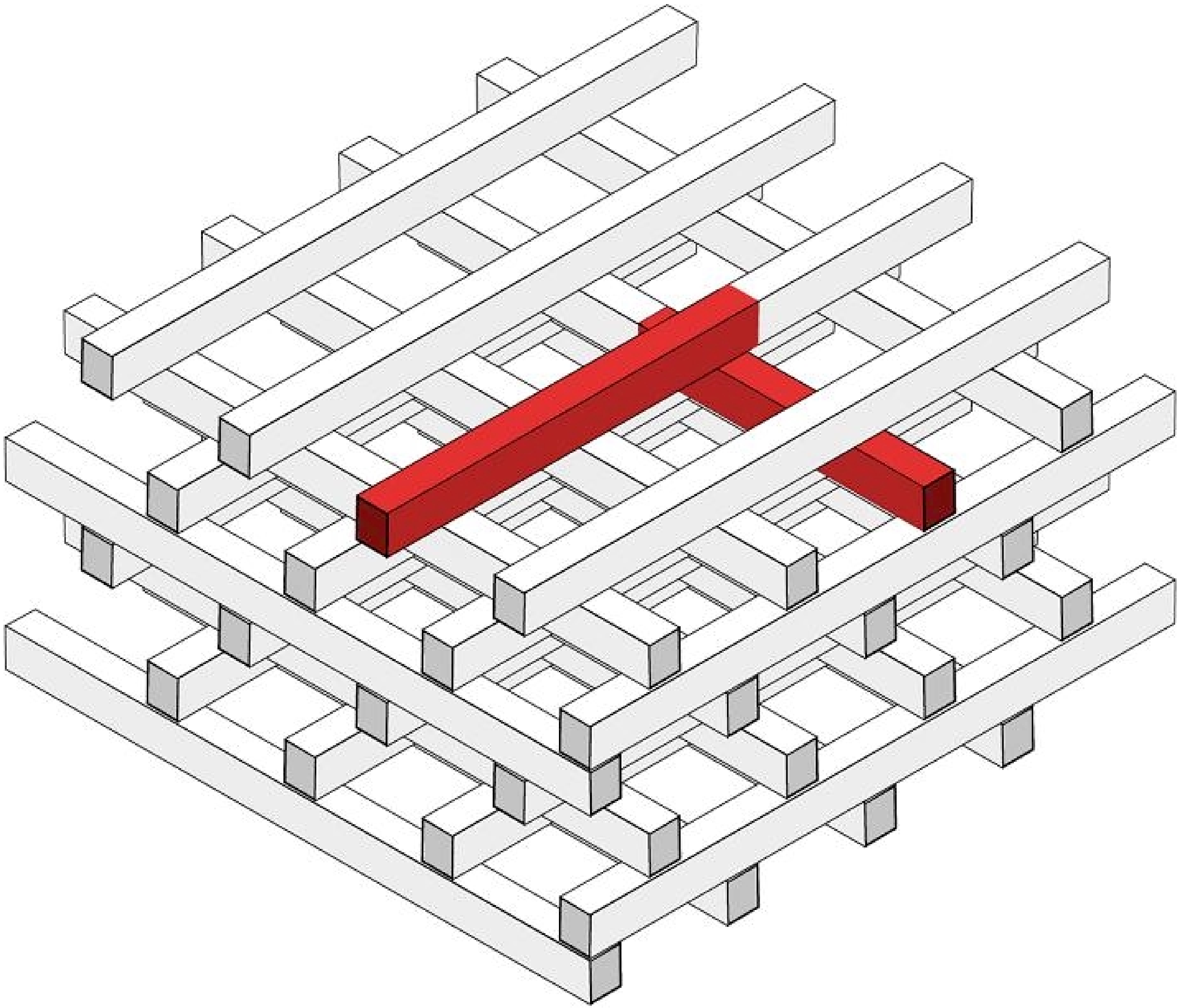


Low-threshold lasers, single-mode LEDs, mirrors, optical filters and waveguides

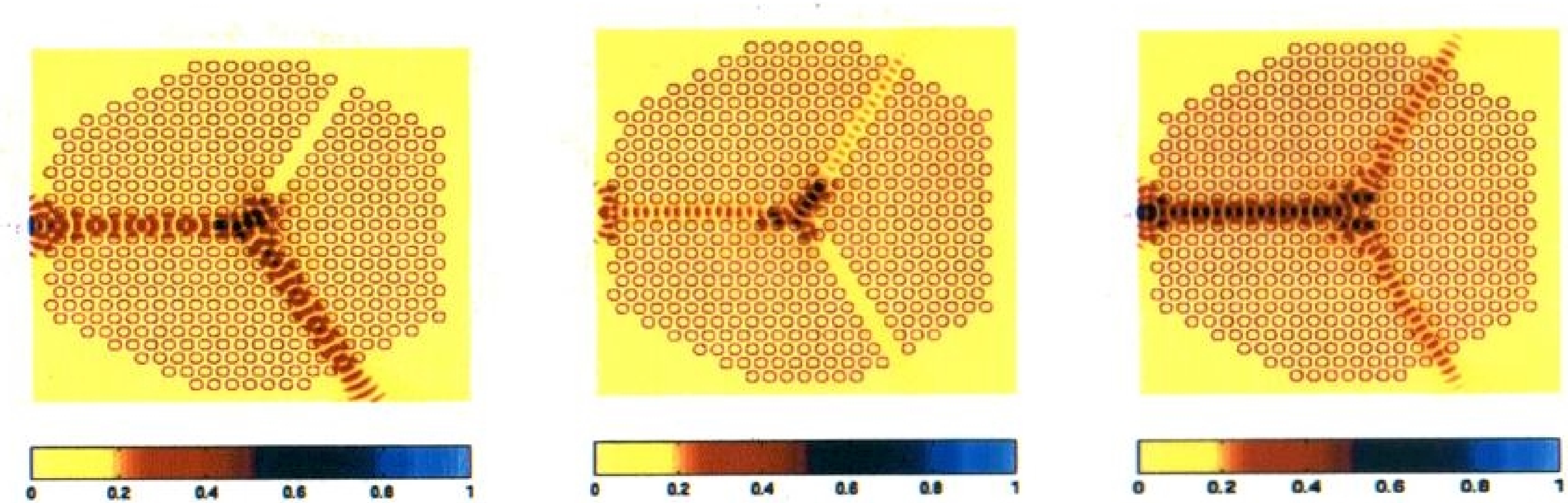


OPTICAL FIBERS can use the photonic band-gap principle to guide light. The cladding of several hundred silica capillary tubes forms an optical band-gap material that confines light to the central hole, which is about 15 microns in diameter (*left*). In the design at the right, in which the light is confined to the two-micron solid core, the fiber is highly nonlinear, which can be useful for switching and shaping light pulses. In the center, a pattern of colors illustrates how the confinement property of a band-gap fiber varies for different wavelengths of light.

E. YABLONOVITCH



Design of Y-splitters and Y-switches

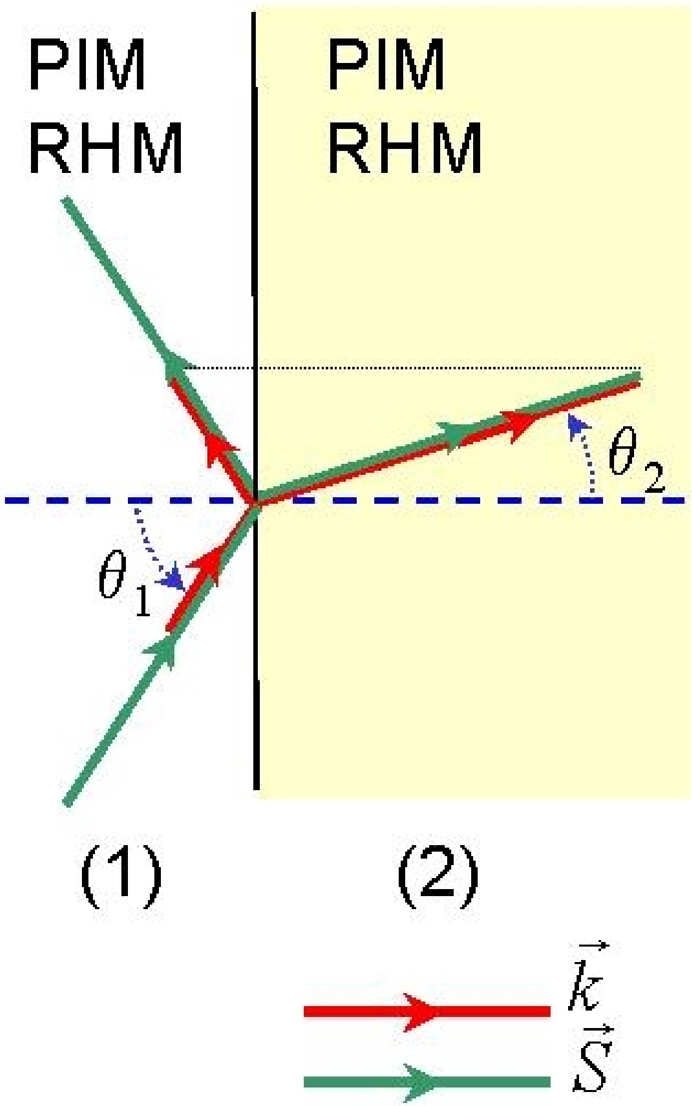


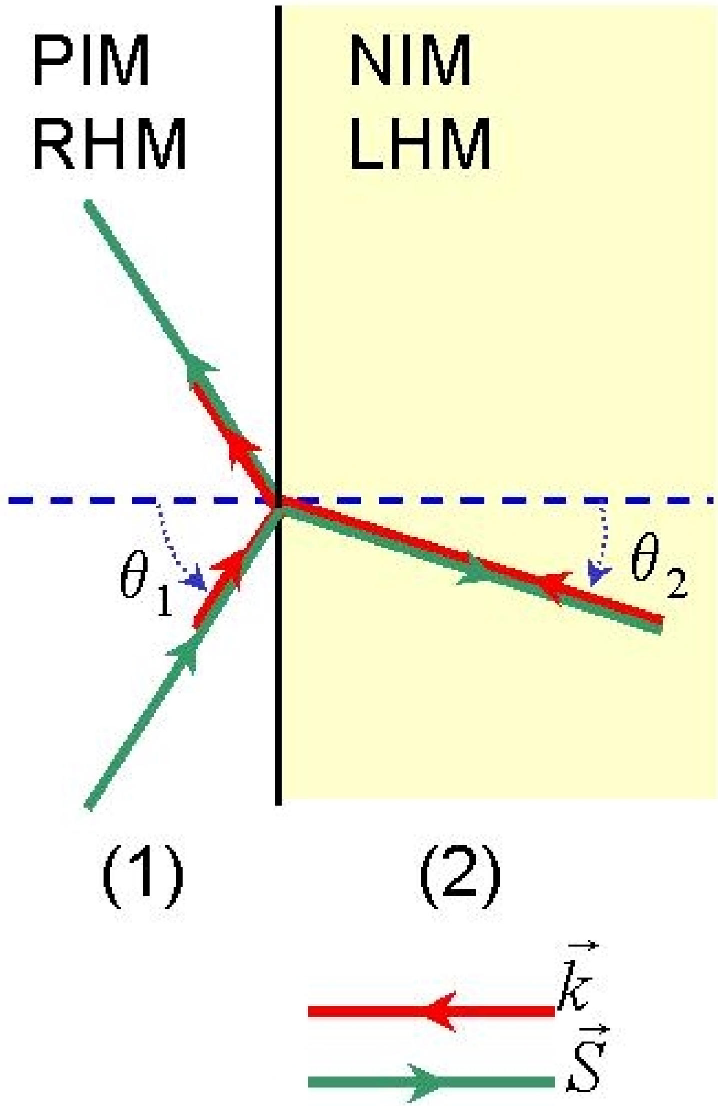
VI. PCs AS NEGATIVE INDEX MATERIALS (NIM)

If $\in < 0$ AND $\mu < 0$ (VESELAGO, 1968)

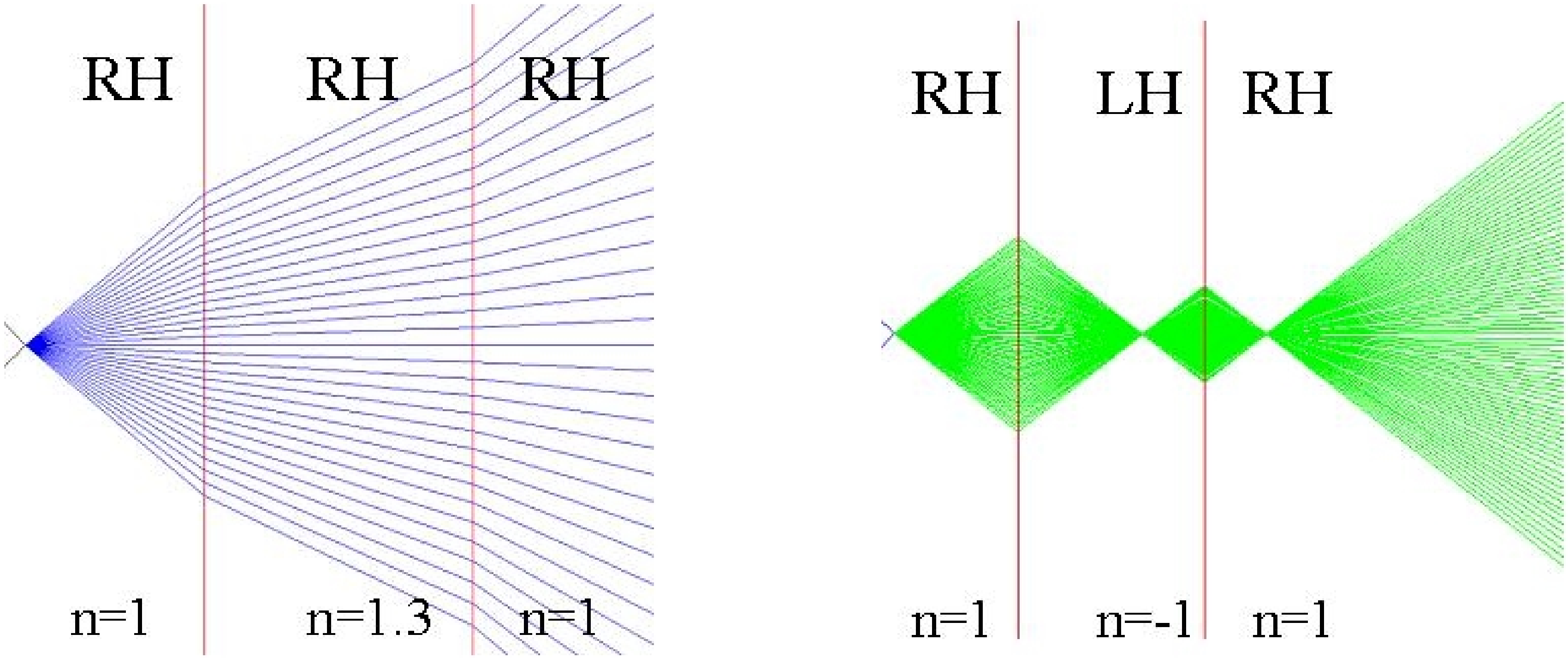
- $\in\mu > 0 \Rightarrow$ **PROPAGATION**
- $\vec{k}, \vec{E}, \vec{H}$ Left Handed (LHM) $\Rightarrow$ **S**=c(**E** x **H**)/4π opposite to $\vec{k}$
- Snell's law with $n \equiv -\sqrt{\in \mu} < 0$ (NIM)
- $\vec{\upsilon}_g$ opposite to $\vec{k}$
- Flat lenses
- Super lenses

"Reversal" of Snell's Law





Focusing in a Left-Handed Medium



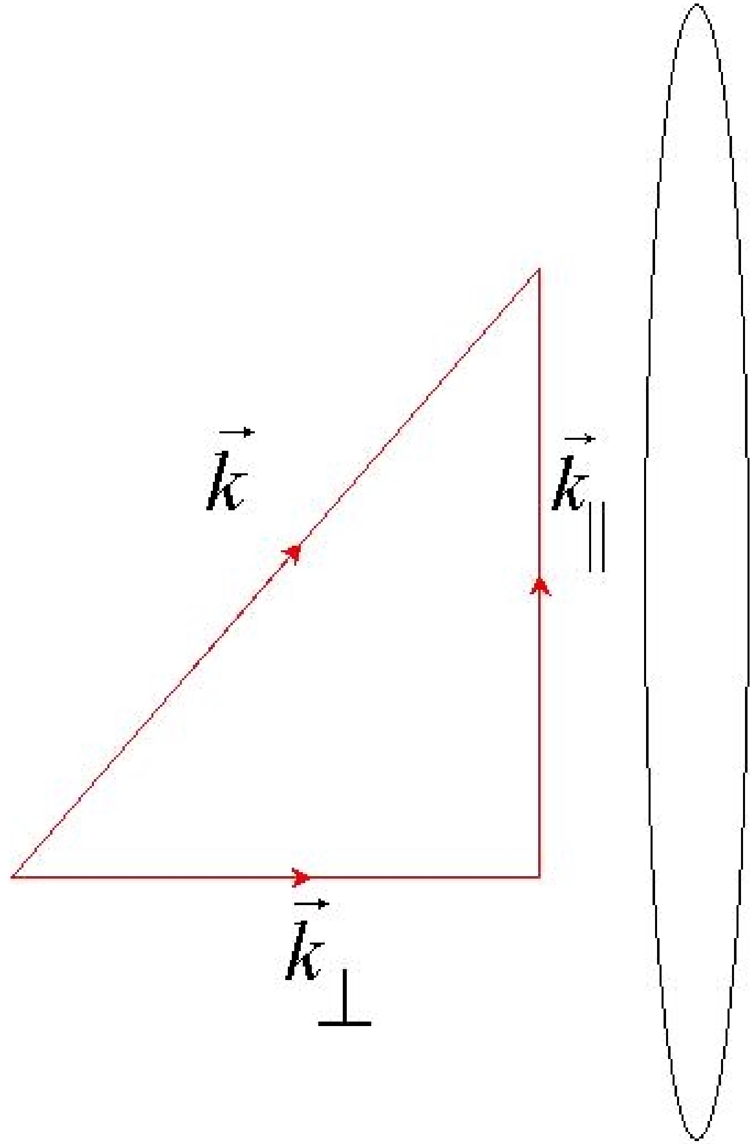
Super lenses

$$\omega^2 = c^2\left(k_{\parallel}^2 + k_{\perp}^2\right) \Rightarrow \quad IF \quad k_{\parallel} > \omega/c \Rightarrow$$

$k_{\perp}$ **IMAGINARY** $\quad e^{ik_{\perp} r_{\perp}} \sim e^{-|k_{\perp}| r_{\perp}}$

$\Rightarrow$ **Wave components with decay, i.e. are lost** ,

then $\Delta_{max} \approx \lambda$



IF n < 0, PHASE CHANGES SIGN

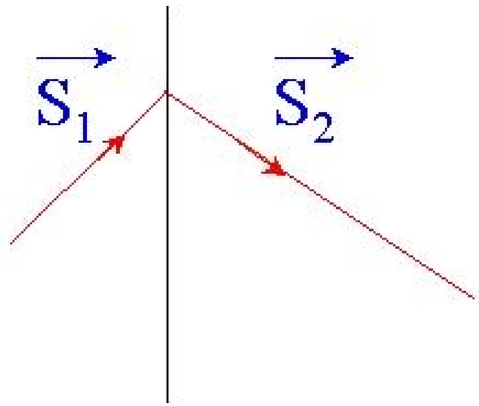
$$e^{ik_\perp k_\parallel} \sim e^{|k_\perp| r_\perp}$$

IF $k_\perp$ **IMAGINARY**

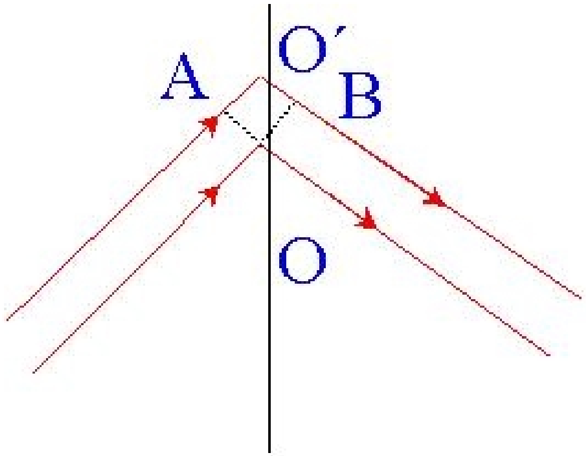
THUS $k_\parallel > \omega / c$ **ARE NOT LOST !!!**

OBJECTIONS

- ABSORPTION INVALIDATES CONCLUSIONS
- PARALLEL MOMENTUM IS NOT CONSERVED



- CAUSALITY IS VIOLATED



- **FERMAT's PRINCIPLE**

$$\int n\,dl \quad \text{minimum (?)}$$

- **SUPERLENSING IS NOT POSSIBLE**

Materials with ε < 0 and μ <0	Photonic Crystals
$\vec{\upsilon}_g$ **opposite to** $\vec{k}$	$\vec{\upsilon}_g$ **opposite to** $\vec{k}$
$\langle \vec{S} \rangle = \langle u \rangle \vec{\upsilon}_g$	$\langle\langle \vec{S} \rangle\rangle = \langle\langle u \rangle\rangle \vec{\upsilon}_g$
$\langle \vec{S} \rangle$ **opposite to** $\vec{k}$	$\langle\langle \vec{S} \rangle\rangle$ **opposite to** $\vec{k}$
$\alpha \equiv 1 + \frac{d \ell n \lvert n \rvert}{d\omega}$	$\alpha \equiv 1 + \frac{d \ell n \lvert n \rvert}{d\omega}, \quad \lvert n \rvert = \frac{c \lvert \vec{k} \rvert}{\omega}$
$n\alpha > 0$	$n\alpha > 0 \Rightarrow n = \pm \lvert n \rvert, \begin{matrix} +, \alpha > 0 \\ -, \alpha < 0 \end{matrix}$
$\vec{\upsilon}_g = \frac{\vec{\upsilon}_p}{\alpha}, \vec{\upsilon}_p = \frac{c}{\lvert n \rvert} \vec{k}_0$	$\vec{\upsilon}_g = \frac{\vec{\upsilon}_p}{\alpha}, \vec{\upsilon}_p = \frac{c}{\lvert n \rvert} \vec{k}_0$

$$\langle \vec{p} \rangle = \frac{\in \mu}{c^2} \langle \vec{S} \rangle + \frac{\vec{k}}{8\pi} \left[\frac{\partial \in}{\partial \omega} \langle \vec{E}^2 \rangle + \frac{\partial \mu}{\partial \omega} \langle \vec{H}^2 \rangle \right] \qquad \langle \vec{p} \rangle = \frac{\langle u \rangle}{\omega} \vec{k}$$

REPLY TO THE OBJECTIONS

- **PCs HAVE PRACTICALLY ZERO ABSORPTION**
- **MOMENTUM CONSERVATION IS NOT VIOLATED**
- **FERMAT's PRINCIPLE is OK**

$$\int ndl \quad \text{extremum}$$

- **CAUSALITY IS NOT VIOLATED**
- **SUPERLENSING POSSIBLE BUT LIMITED TO A CUTOFF k_c OR 1/L**

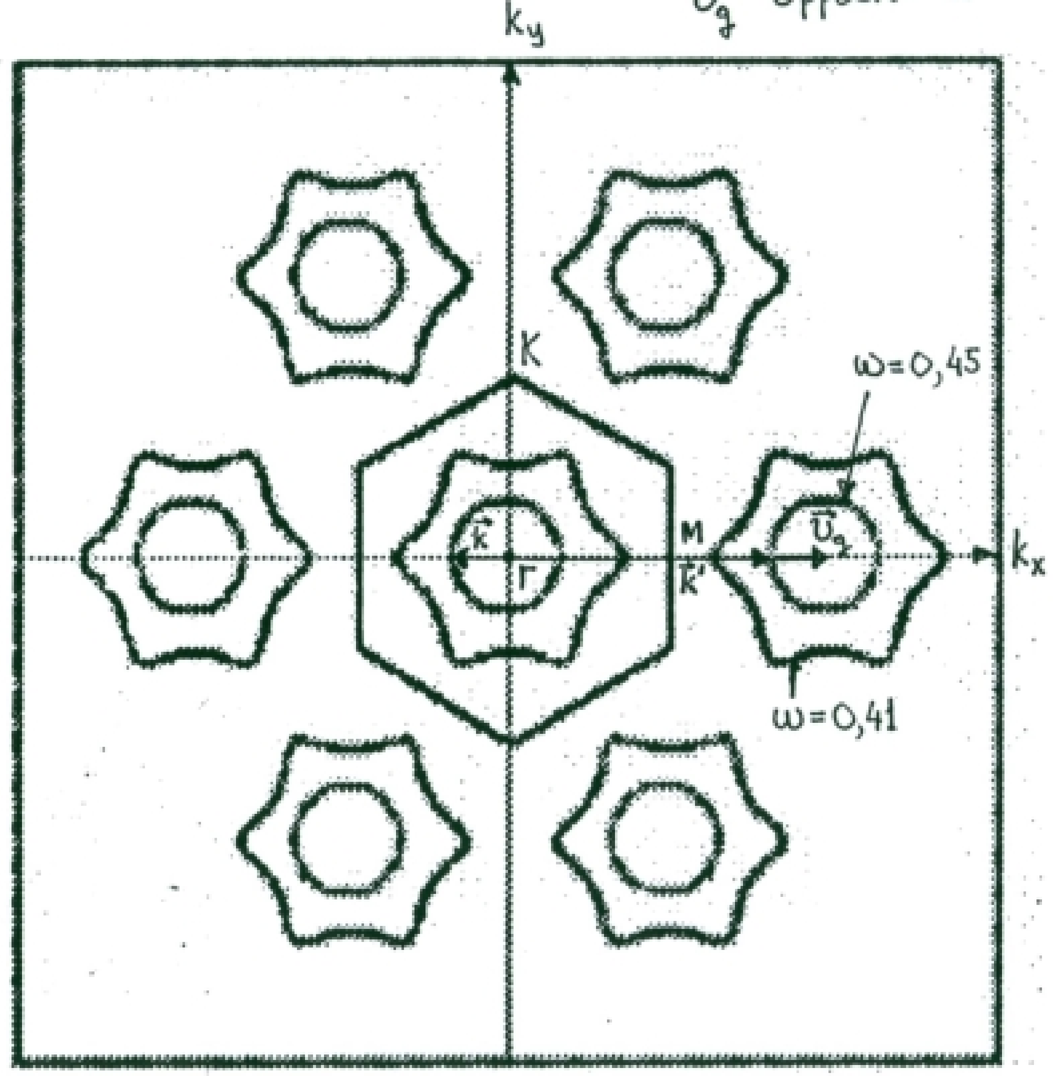
M. Notomi, PRB $\underline{62}$, 10696 (2000)

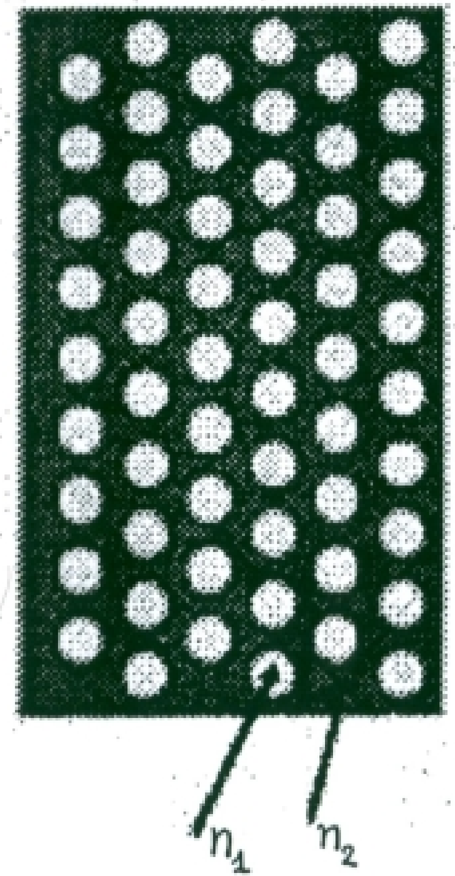
2D GaAs air-hole (d=0,7a)

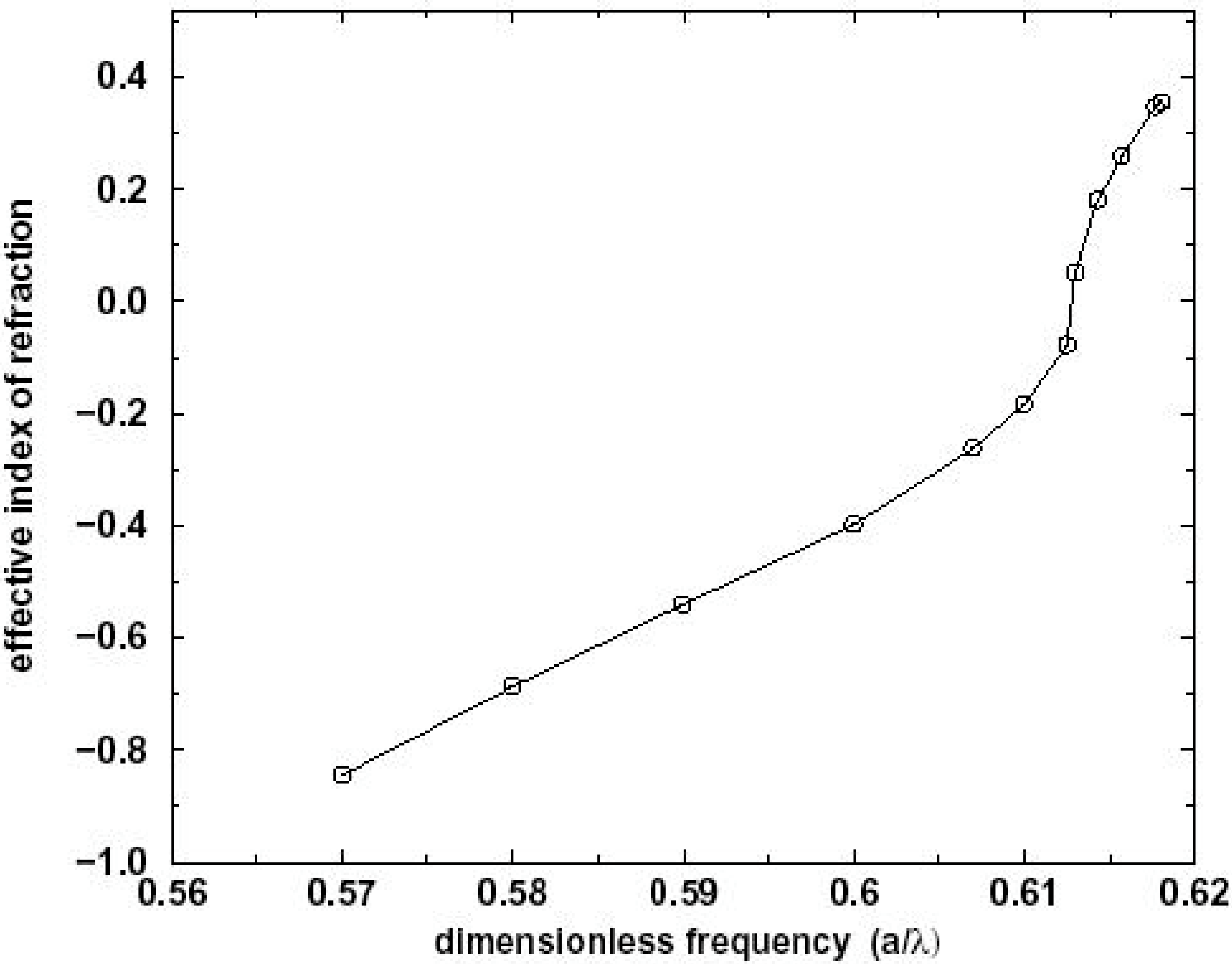
$\vec{k} = \vec{k}' - \vec{G}$

$\vec{v}_g$ opposite $\vec{k}$.

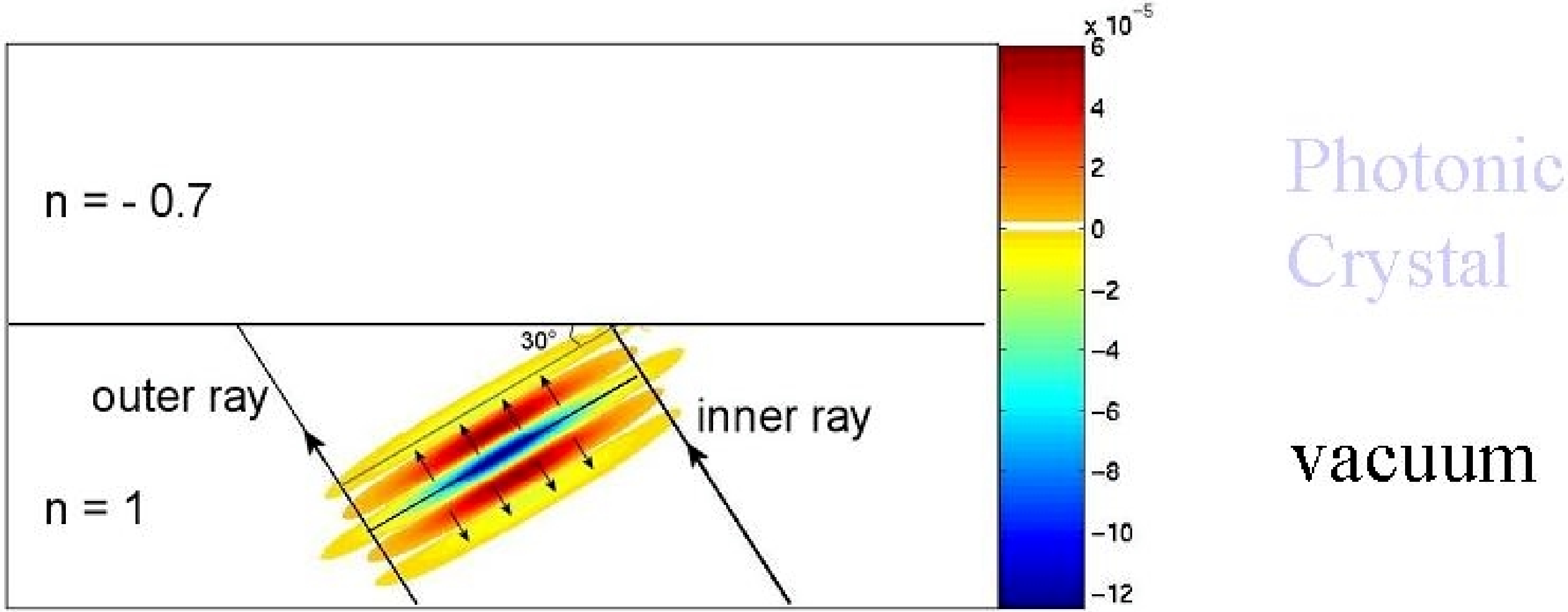
ω in units of ωa/2πc





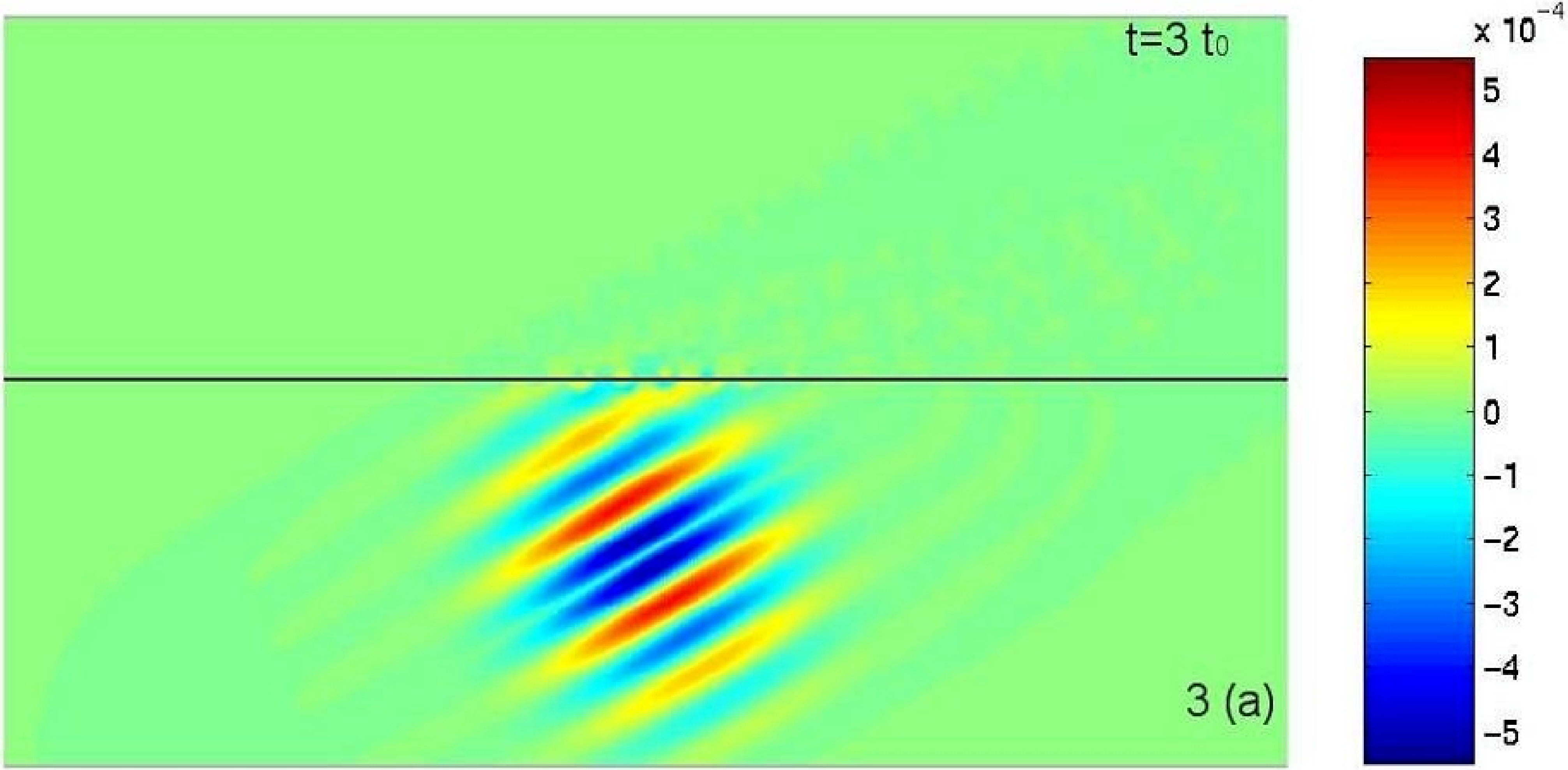

0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
effective index of refraction
0.56
0.57
0.58
0.59
0.6
0.61
0.62
dimensionless frequency (a/λ)

Photonic Crystals with negative refraction.



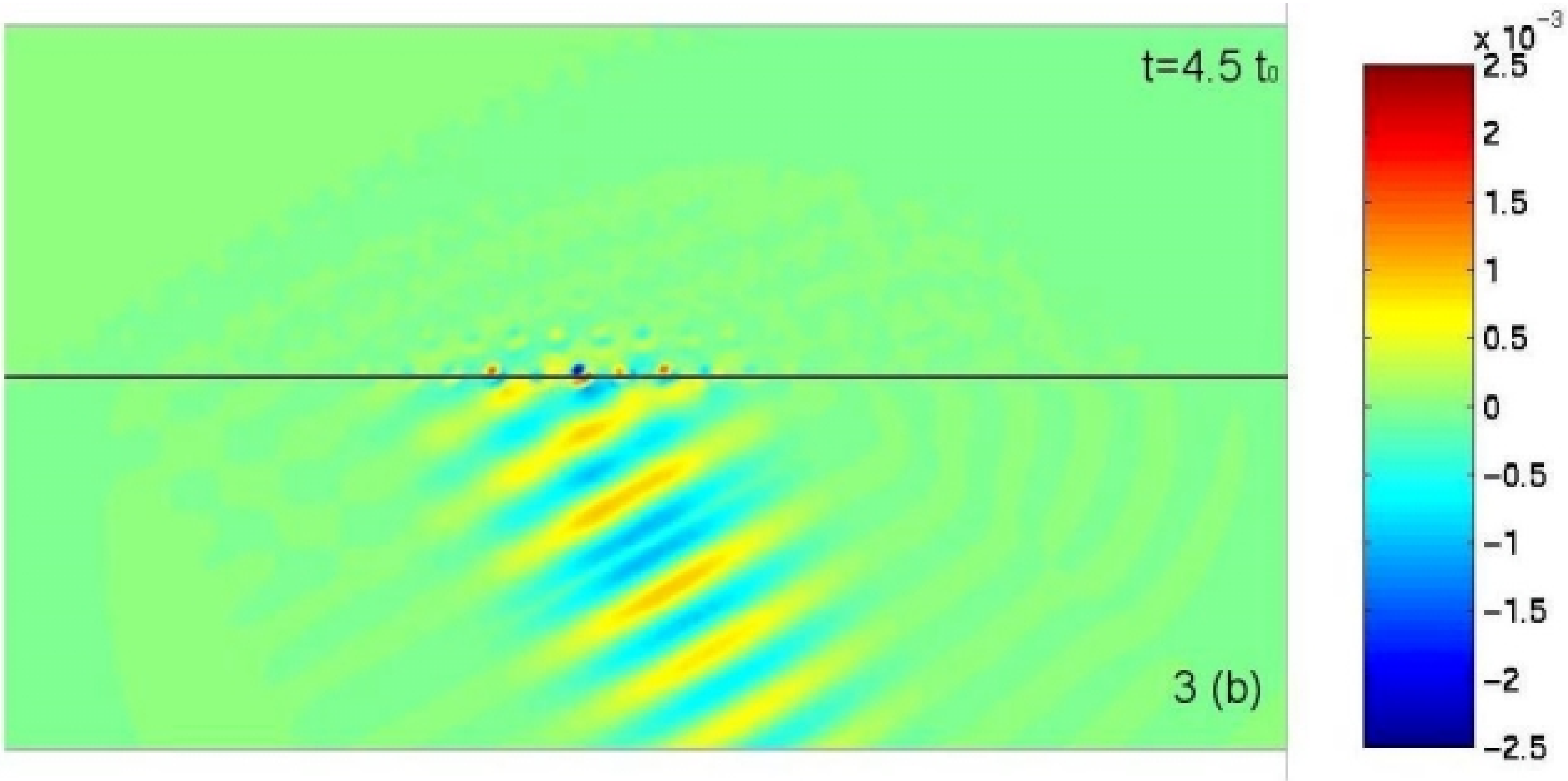
FDTD simulations were used to study the time evolution of an EM wave as it hits the interface vacuum/photonic crystal.
Photonic crystal consists of an hexagonal lattice of dielectric rods with $\varepsilon=12.96$. The radius of rods is $r=0.35a$. a is the lattice constant.

Photonic Crystals with negative refraction.

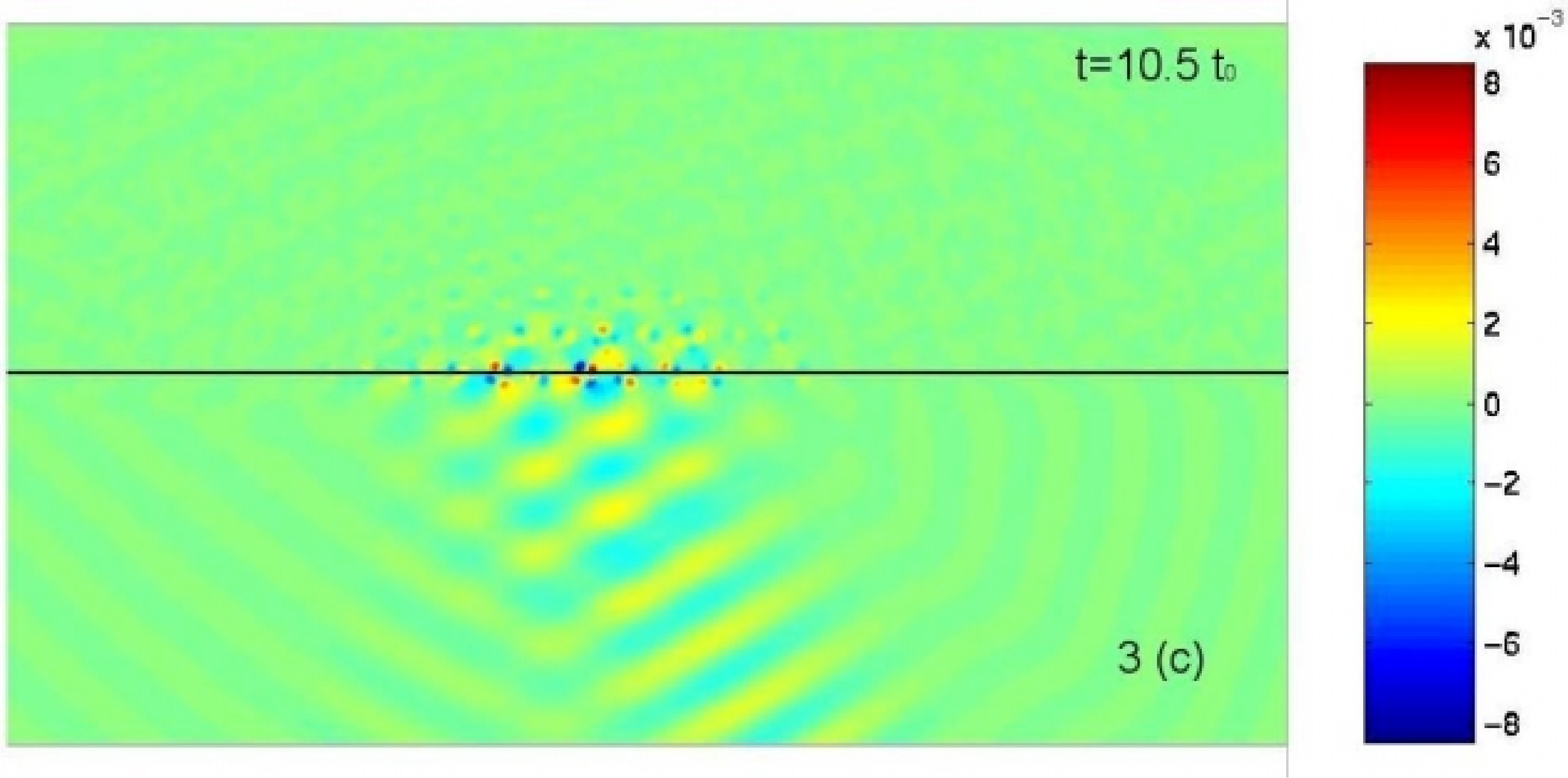


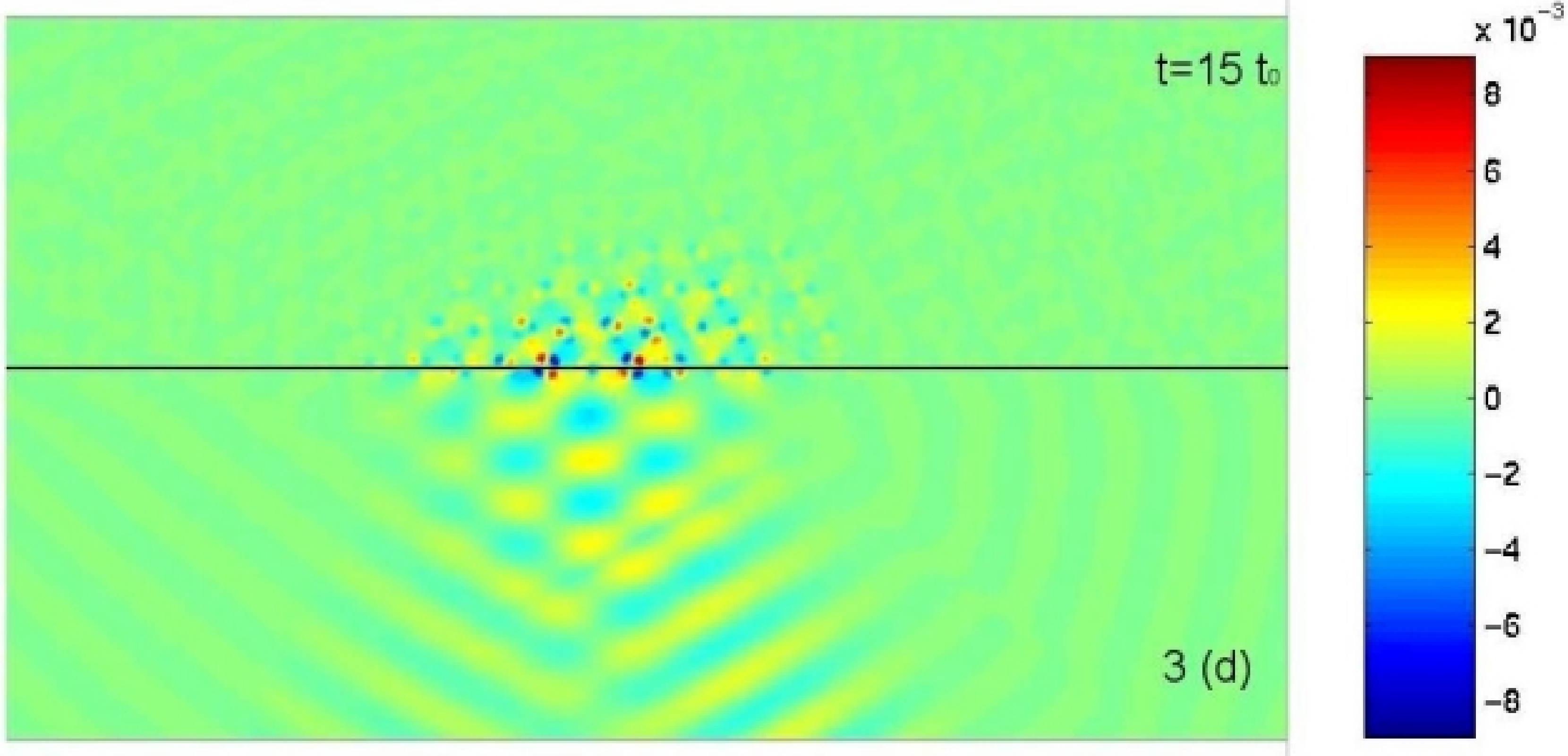
$t_0 = 1.5T$

$T = \lambda / c$

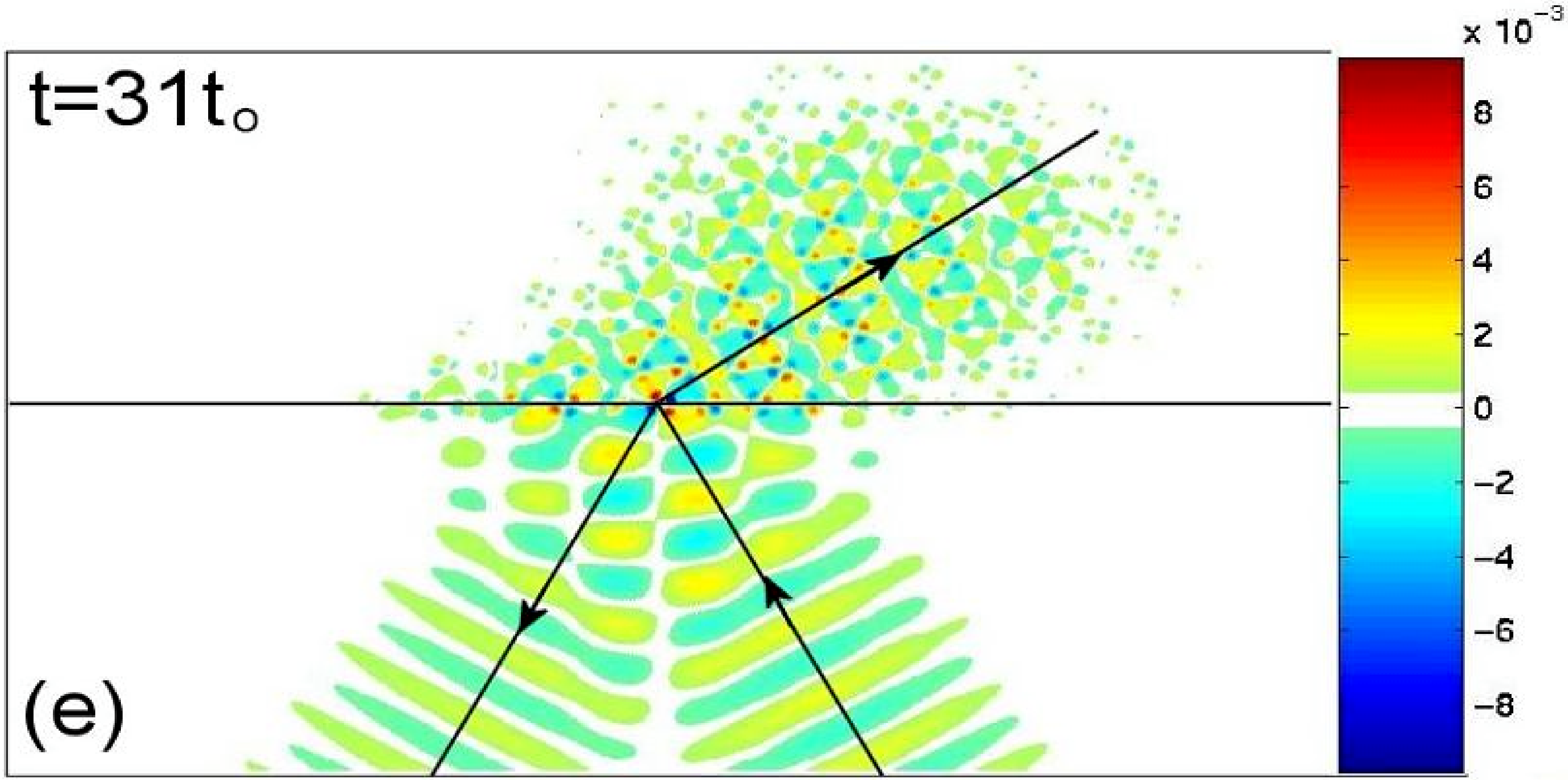


t=4.5 t0
3 (b)
x 10^-3
2.5
2
1.5
1
0.5
0
−0.5
−1
−1.5
−2
−2.5


t=10.5 t0
3 (c)
x 10^-3
8
6
4
2
0
−2
−4
−6
−8


t=15 t0
3 (d)
x 10^-3
8
6
4
2
0
−2
−4
−6
−8

Photonic Crystals: negative refraction



The EM wave is trapped temporarily at the interface and after a long time, the wave front moves eventually in the negative direction.

Negative refraction was observed for wavelength of the EM wave $\lambda = 1.64 - 1.75\ a$ (a is the lattice constant of PC)