Photonic Band Gap Materials

Engineering
the Fundamental
Properties of
Light

PBG Materials: Engineering the Fundamental Properties of Light

Engineering the Laws of Refraction:

Negative and
Out-of-plane
Refraction

Localization of Light:

Reduction of Optical Pathways
Trapping of Light in Air
2D PBG Hollow core photonic crystal fibers

Engineering Diffraction:

Single mode air-waveguides, micro-cavities, bends etc.
Diffractionless flow of light without "leaky" modes
Light Localization based Integrated Optics in 3+1 Dimensions

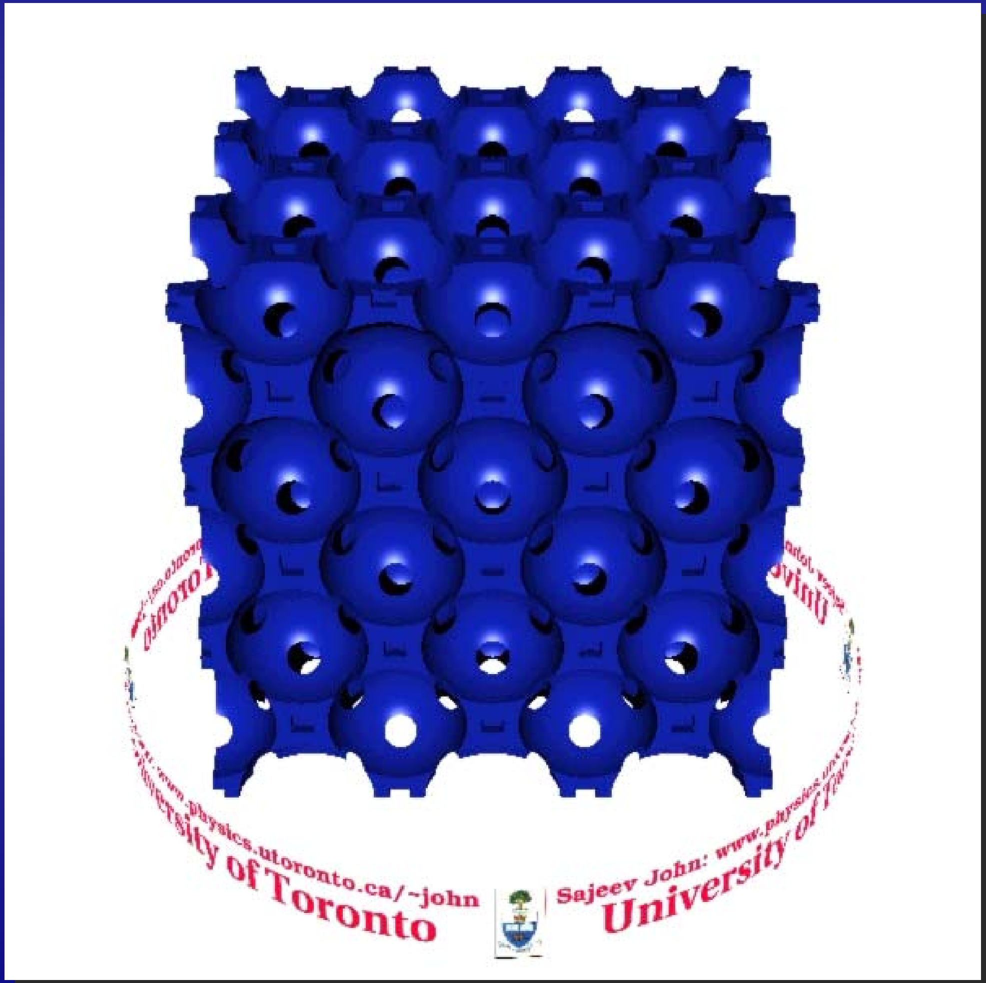
Micro-fabrication of 3D PBG materials:

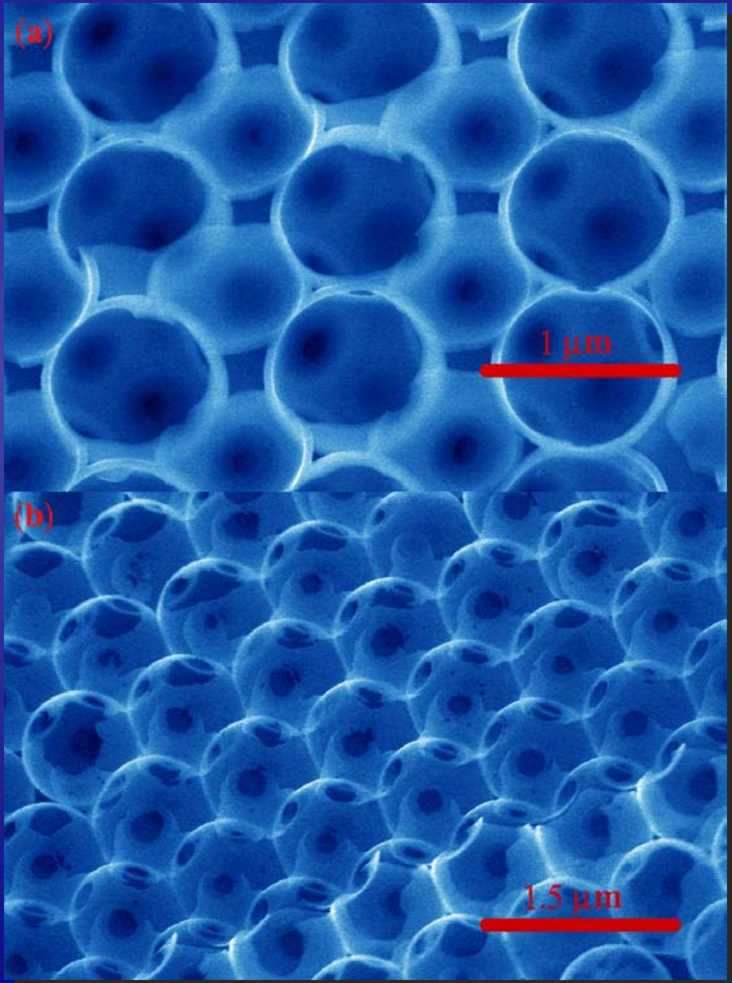
Direct laser writing, plasma tuning, and double inversion to Si

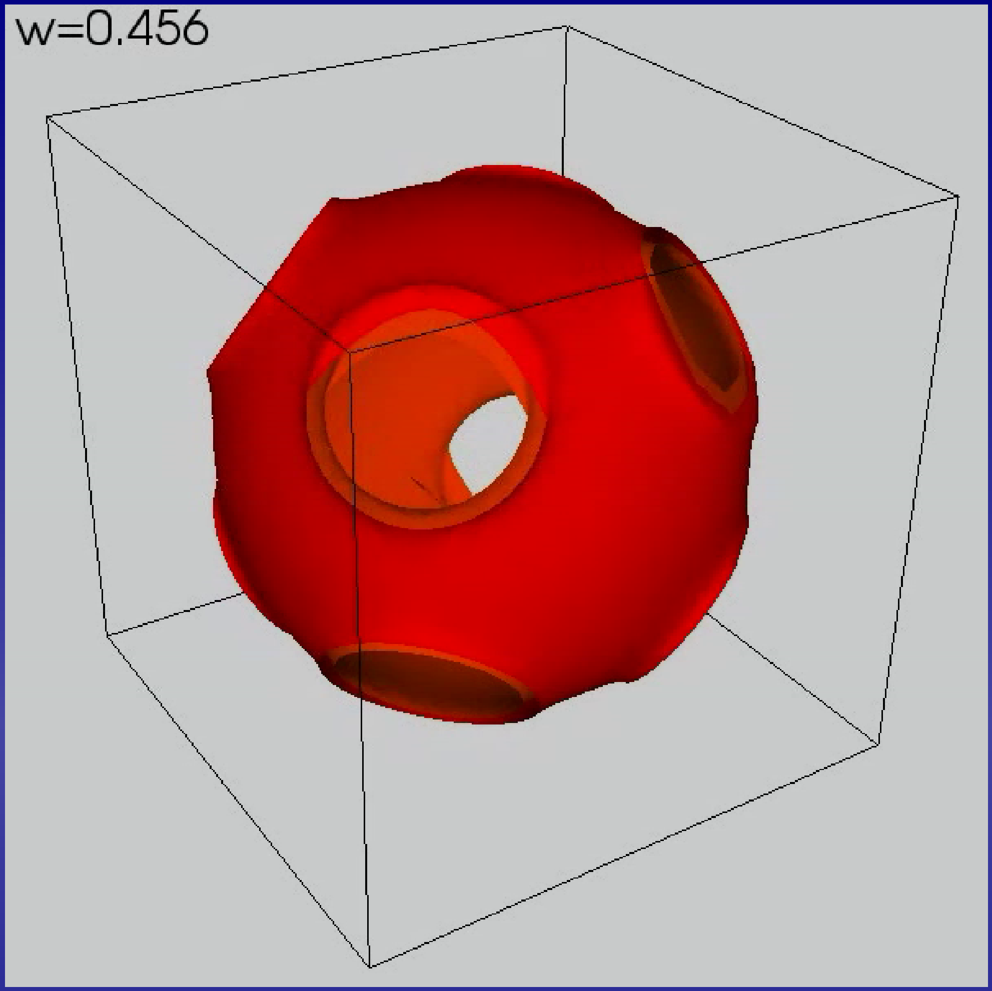
3D Photonic Band Gap Materials

Si Inverted Opal

A. Blanco et. al.
Nature 405, 437 (2000)







Modification of Available Light Paths due to Resonances

Ioffe-Regel: $\ell^* \frac{2\pi}{\lambda} \approx 1$

Resonance Regime Generalized Localization Criterion

$$\left(\ell^*\right)^2 \times \left(\text{phase space}\right) \approx 4\pi$$

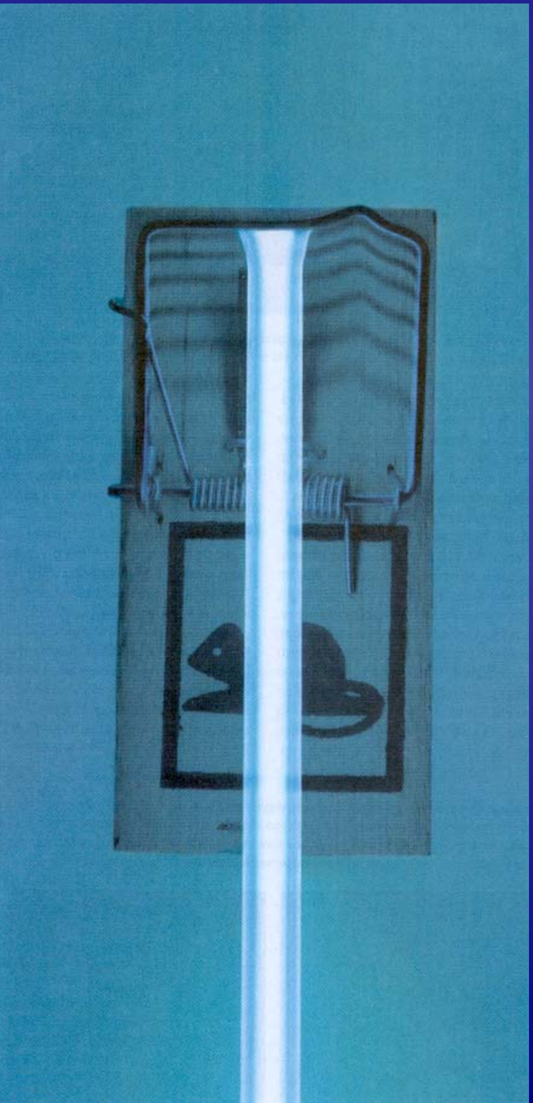
not necessarily $4\pi k^2$

Near Photonic Band Gap

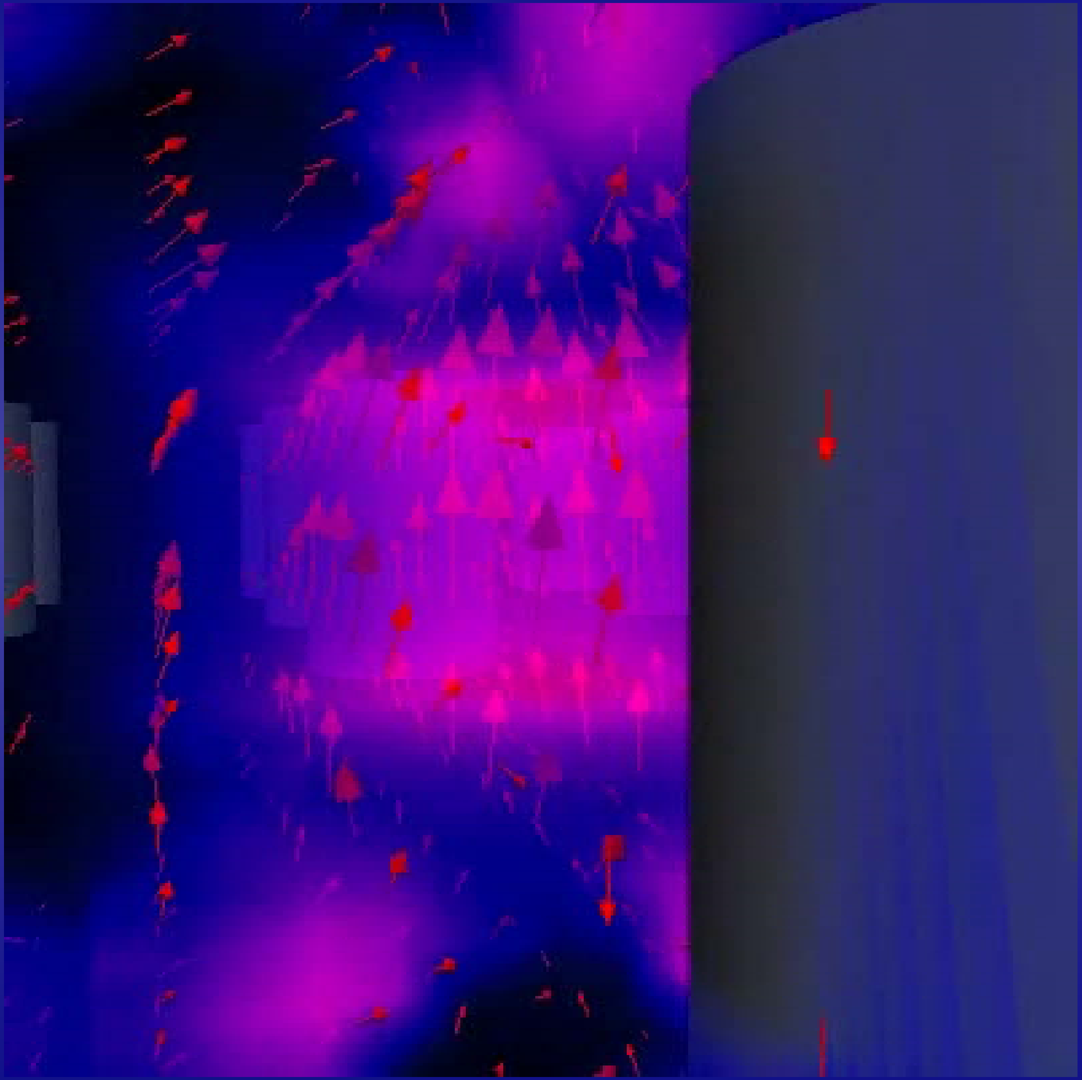
$\rho(\omega) << \rho_0(\omega)$)$=\omega^2/(\pi^2 c^3)$ free space

S. John, Phys. Rev. Lett. 53, 2169 (1984)
S. John, Phys. Rev. Lett. 58, 2486 (1987)
E. Yablonovitch, Phys. Rev. Lett. 2059 (1987)
S.John, R.Rangarajan, Phys.Rev.B. **38**, 10101 (1988)

Localized State of Light in PBG



Electric and Magnetic Fields and Energy Density



Refractive Optics near a Photonic Crystal Surface

(i) Conservation of momentum parallel to interface

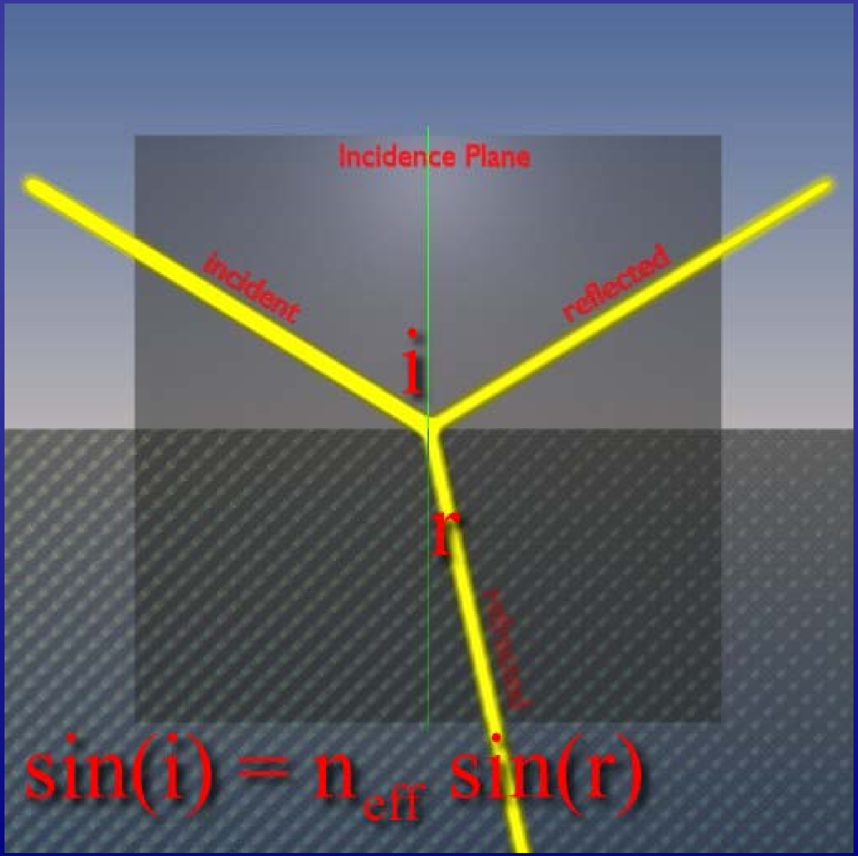
(ii) Refracted ray is normal to iso-frequency surface

k-space picture for uniform dielectric

Snell's Law = Conservation of momentum and energy

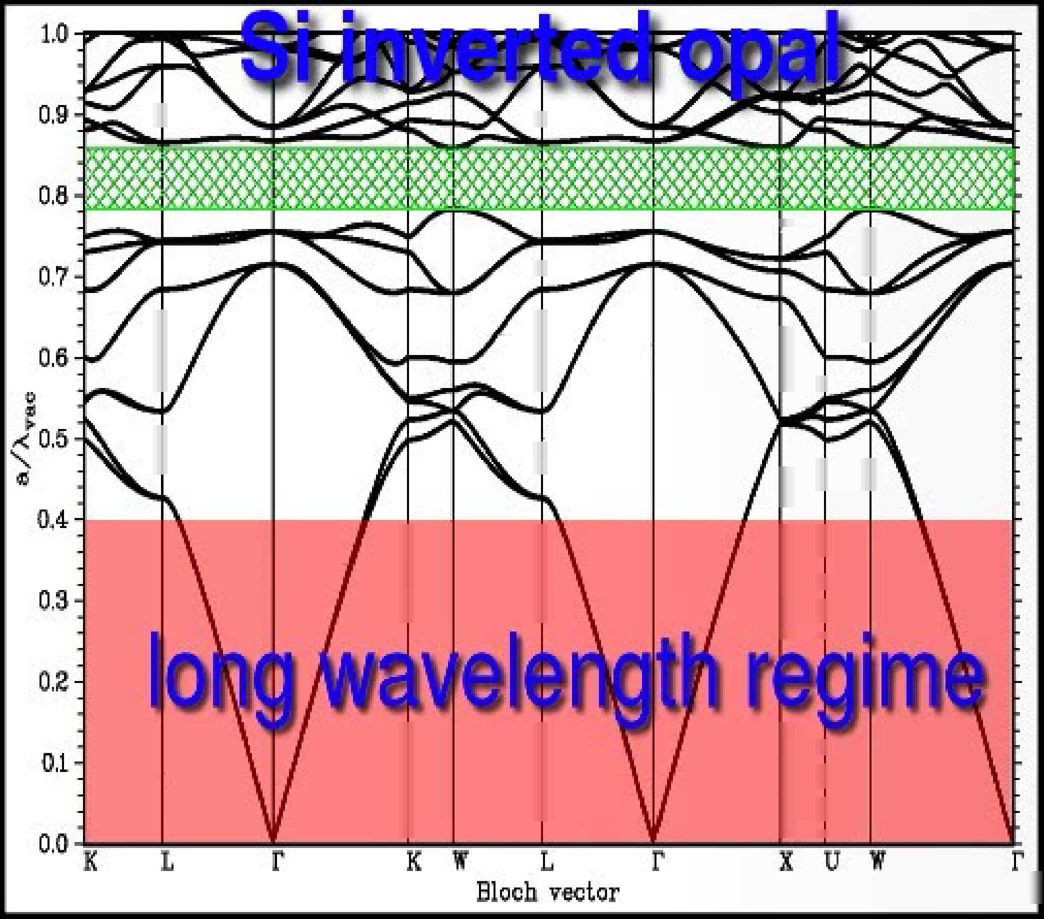
Engineered Refraction

Superprism, Negative Refraction

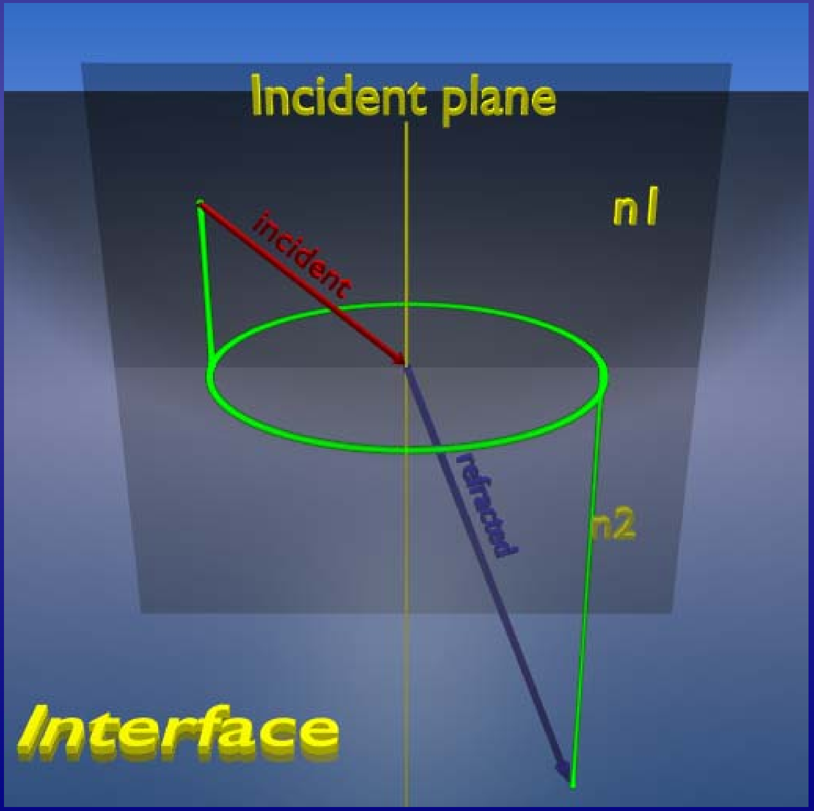


Anomalous Refractive Optics at a Silicon Inverse Opal Surface

Iso-frequency surface curvature yields negative refraction, out-of plane refraction multiple refracted rays, etc…



Azimuthal rotation defines Cylindrical Surface that intersects Iso-freq Surfaces



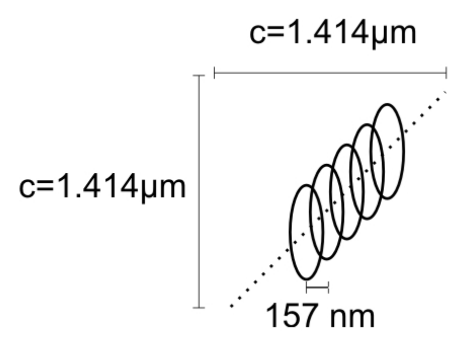
Direct Laser Writing of Photonic Crystals

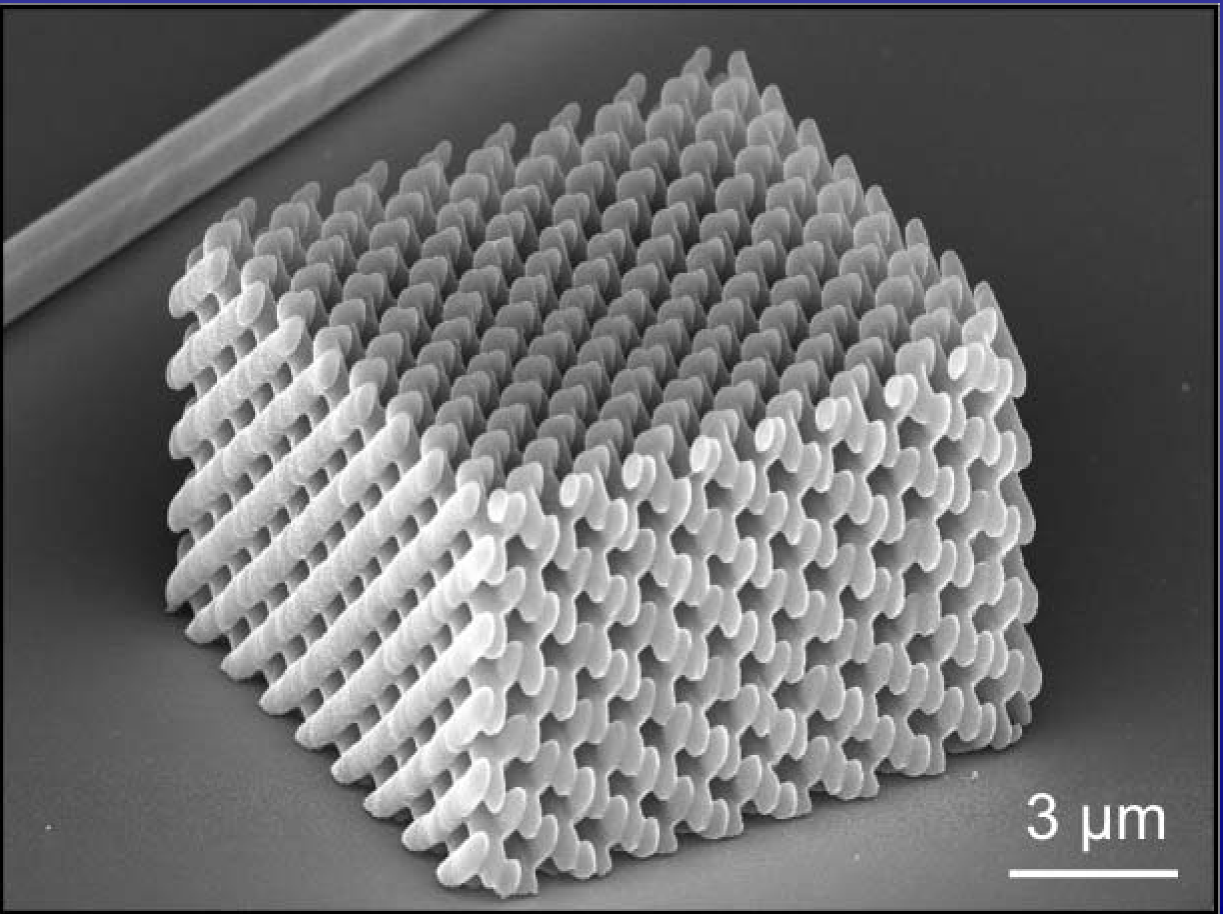
M. Deubel, M. Wegener, A. Kaso, and S. John
Applied Physics Letters 85 (11), 1895 (2004)

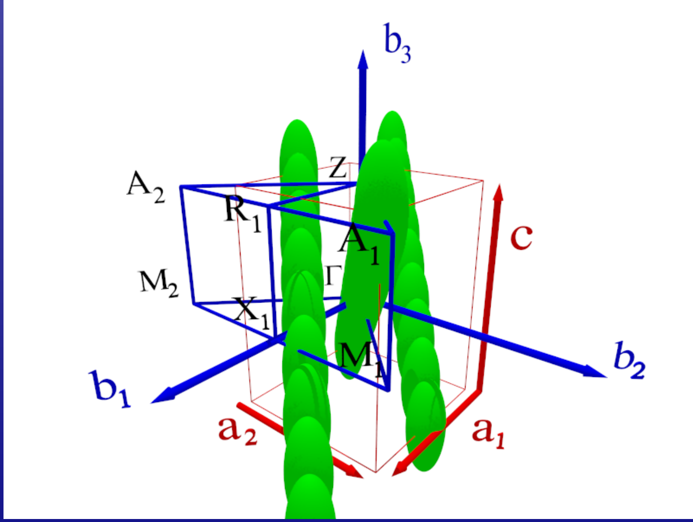
Voxel lateral size as small as 120nm for 780 nm illumination

Two-Photon Absorption

Slanted Pore (SP-2) Architecture





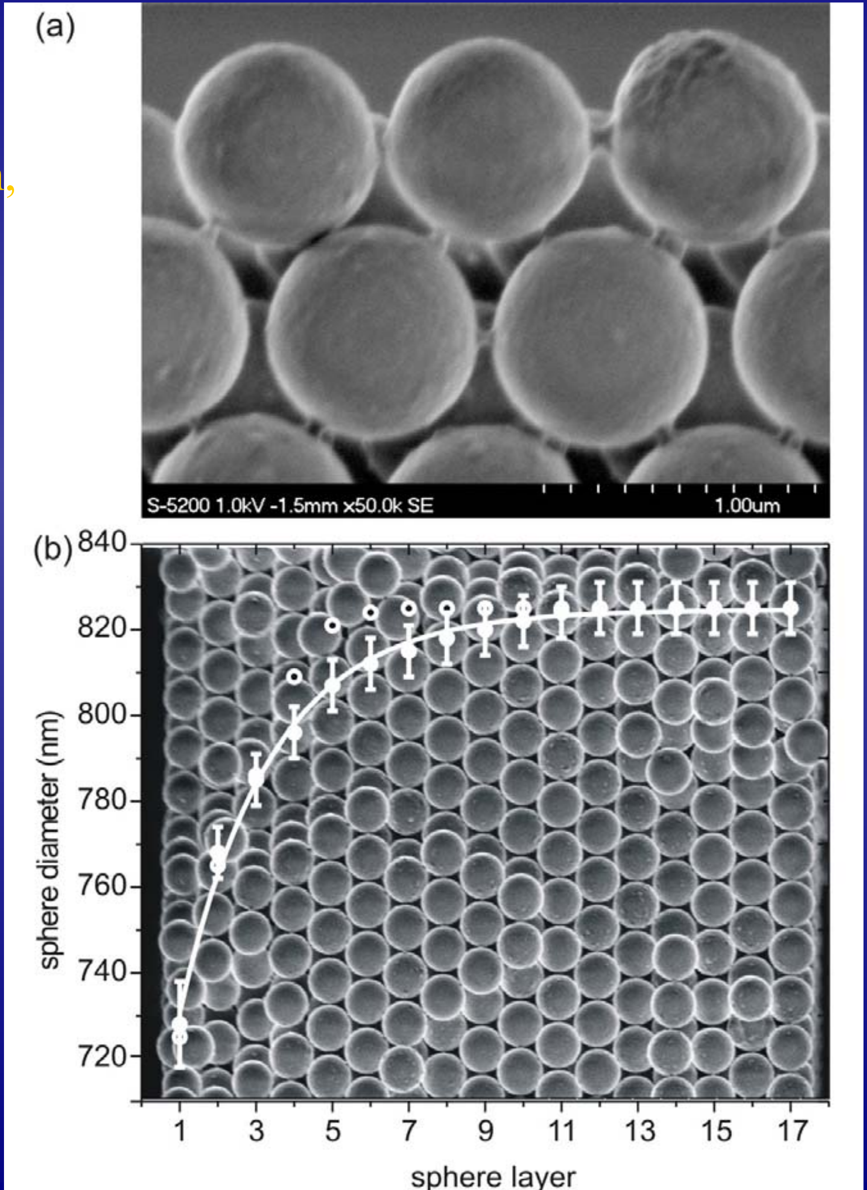


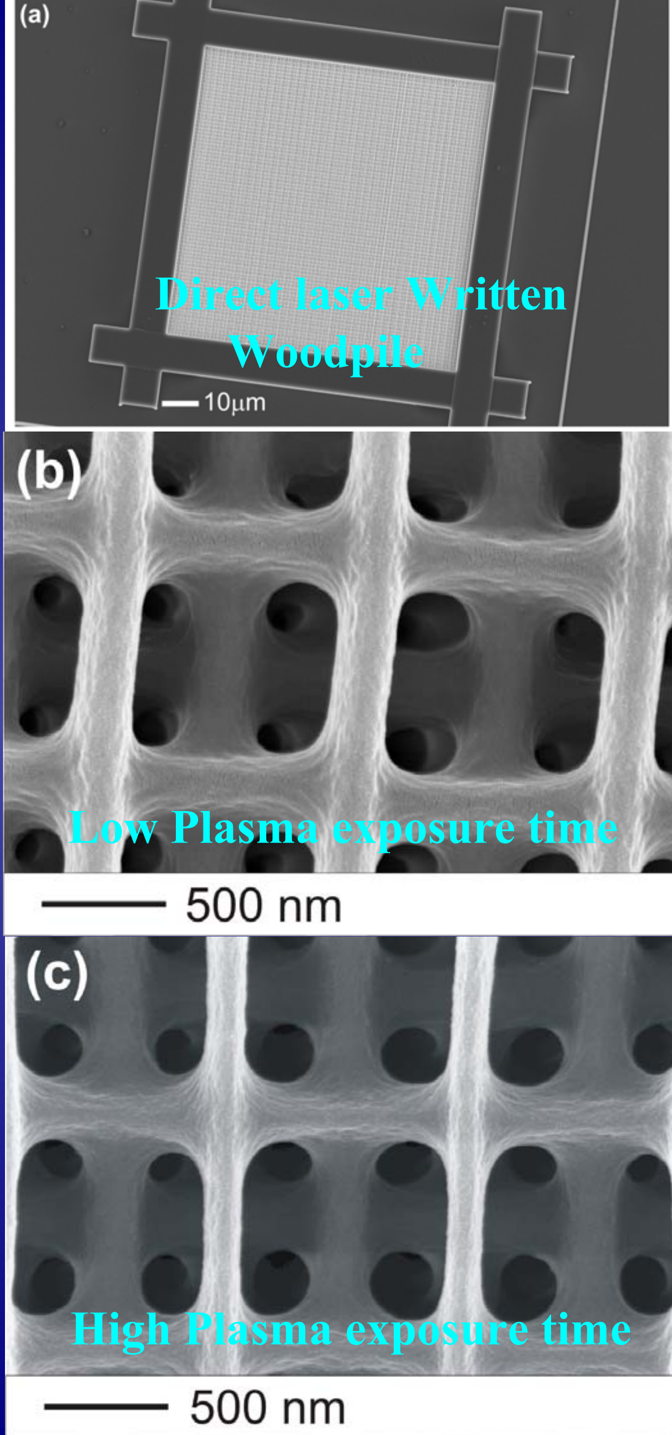
Sub-Nanometer Scale Polishing of Photonic Crystal by Plasma Etching

G. von Freymann,
T. Chan, S. John,
V. Kitaev, G. Ozin,
M. Deubel, and
M. Wegener
Photonics and Nanostructures 2 No. 3, 191 (2004)

Variables:
Plasma flow rate
Exposure Time
Temperature

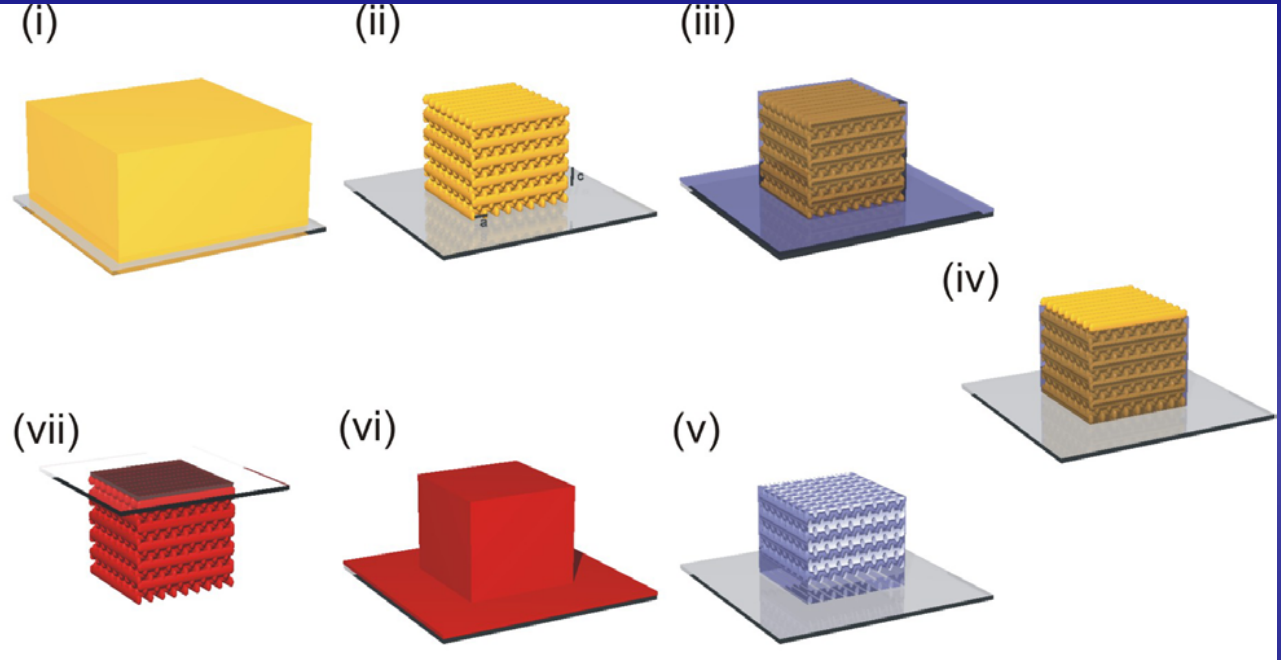
Polystyrene Opal with Engineered Sphere Diameter Gradient near Surface



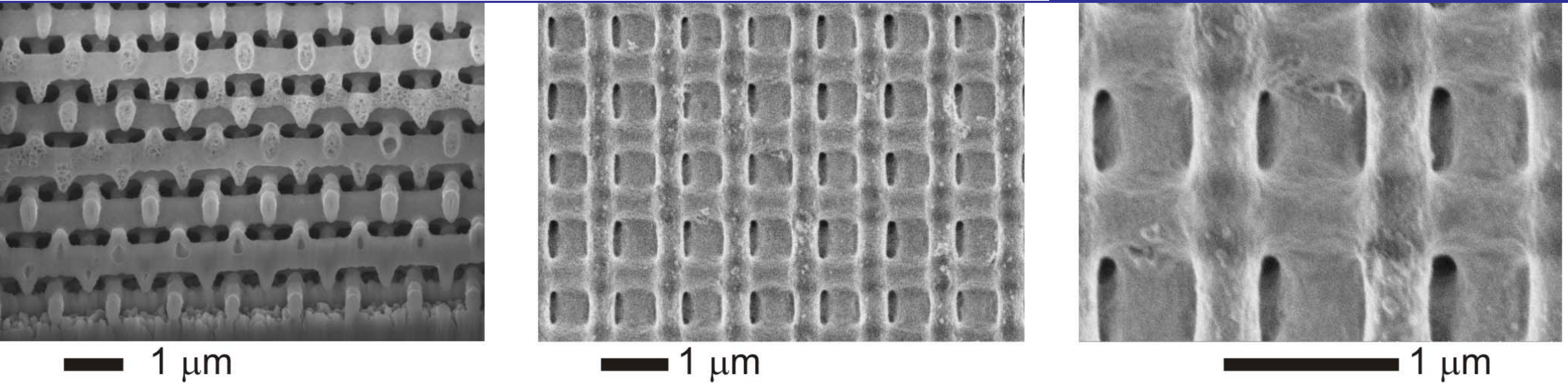


Synthesis of Silicon PBG materials from Polymer Photoresist by Direct Laser Writing and Double Inversion

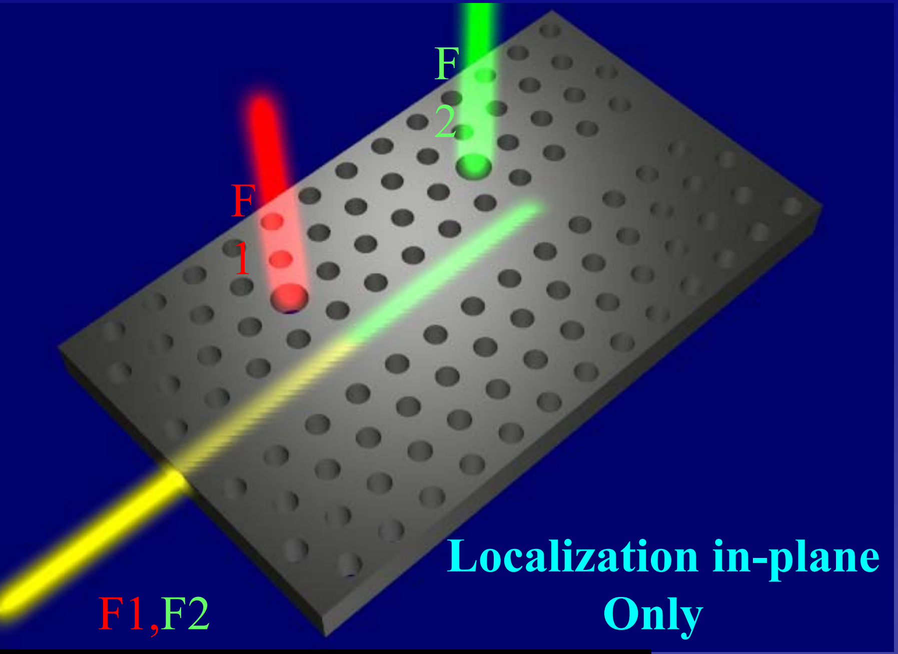
Toronto-Karlsruhe collaboration



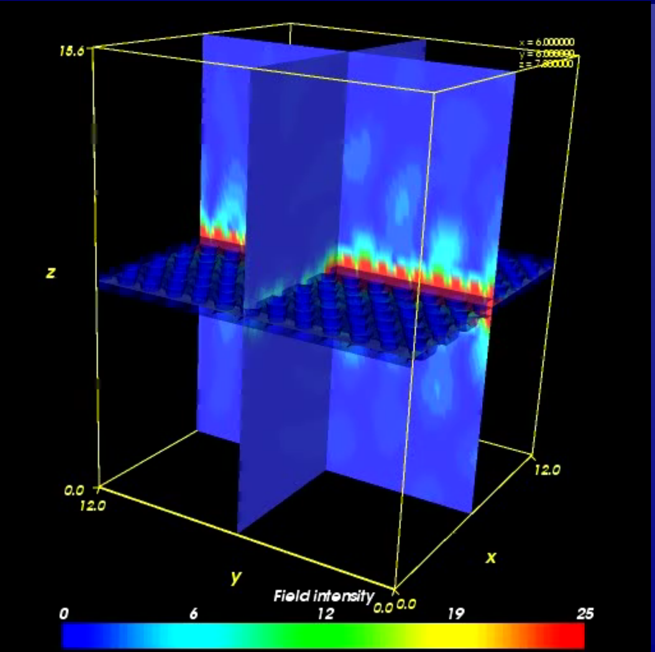
(i) Spin coat SU8
(ii) Direct Laser Write and Develop
(iii) Room Temp CVD of SiO2
(iv) Remove excess SiO2 by RIE to expose SU8
(v) Remove SU8 by oxygen plasma etch and combustion
(vi) Disilane CVD
(vii) Selective etch of SiO2 to yield silicon PBG



Dielectric Wave-guide in 2D Photonic Crystal Membrane



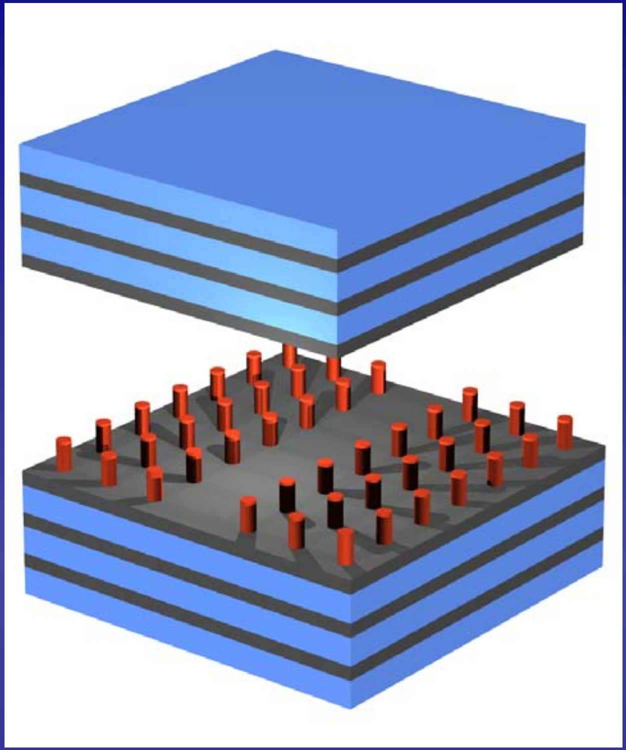
Localization in-plane Only



Disorder:

25 nm diameter randomness

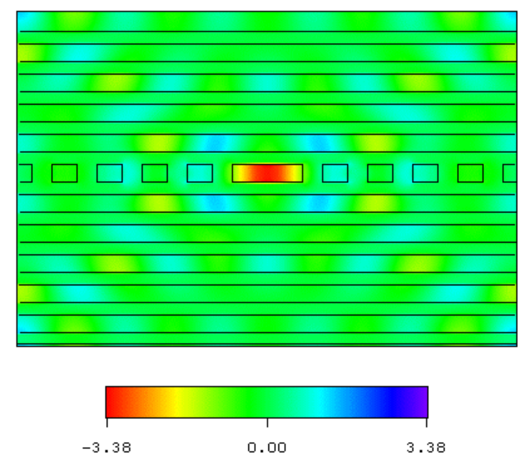
Air-Waveguide Omni-Reflector Cladding ?

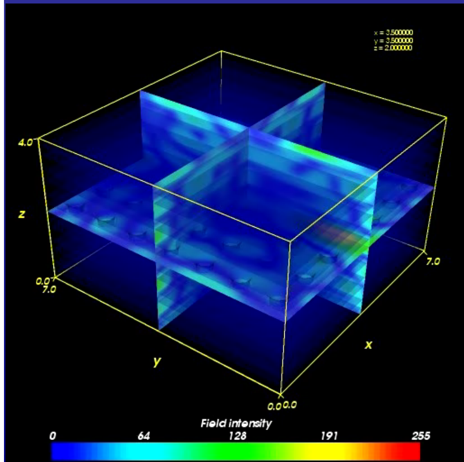


Attempt to optimize Confinement
n1=3.5
n2=1.56

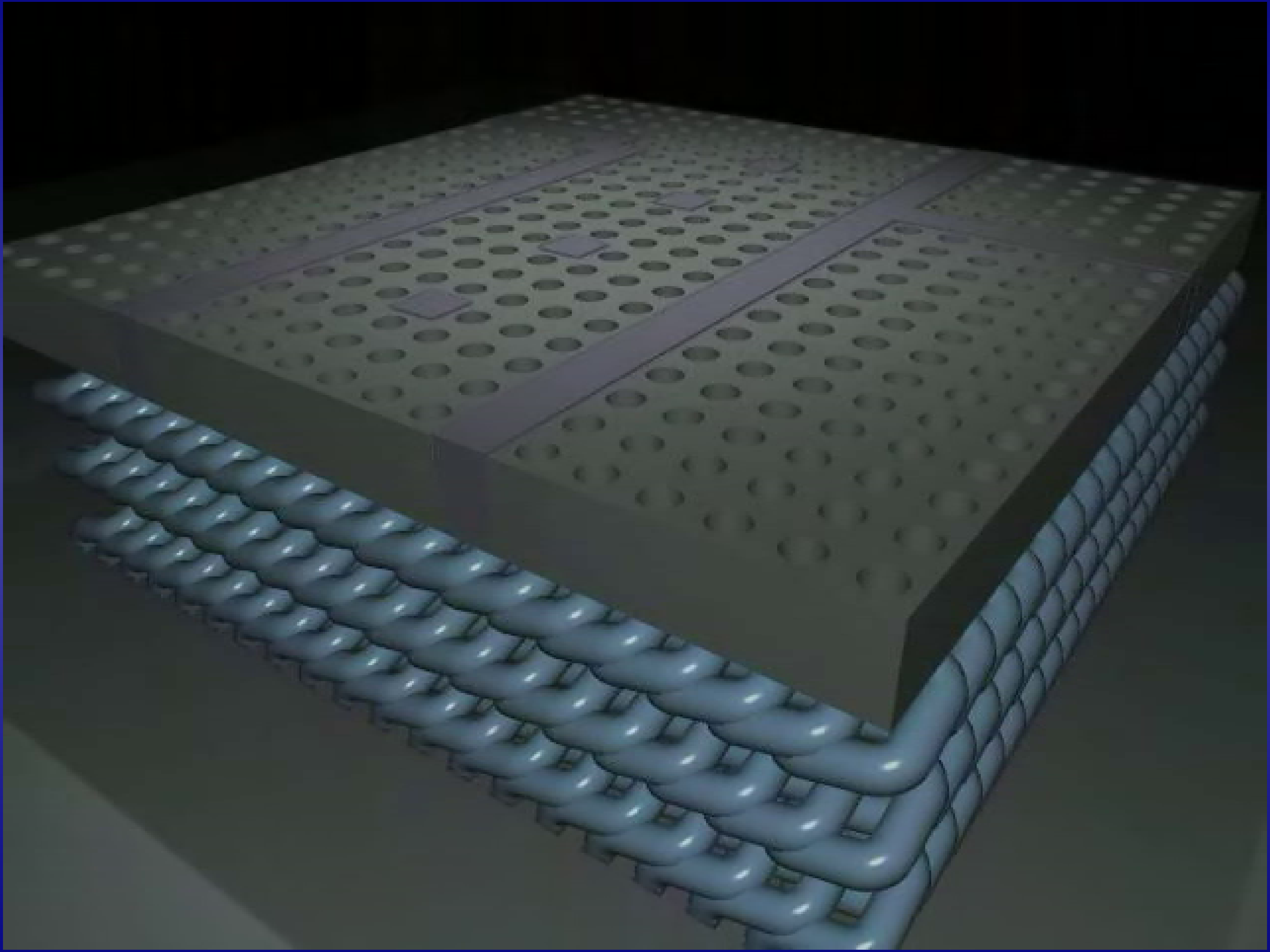
No Disorder:

Rapid leakage into 3rd dimension
Attenuation ~ 2dB /micron



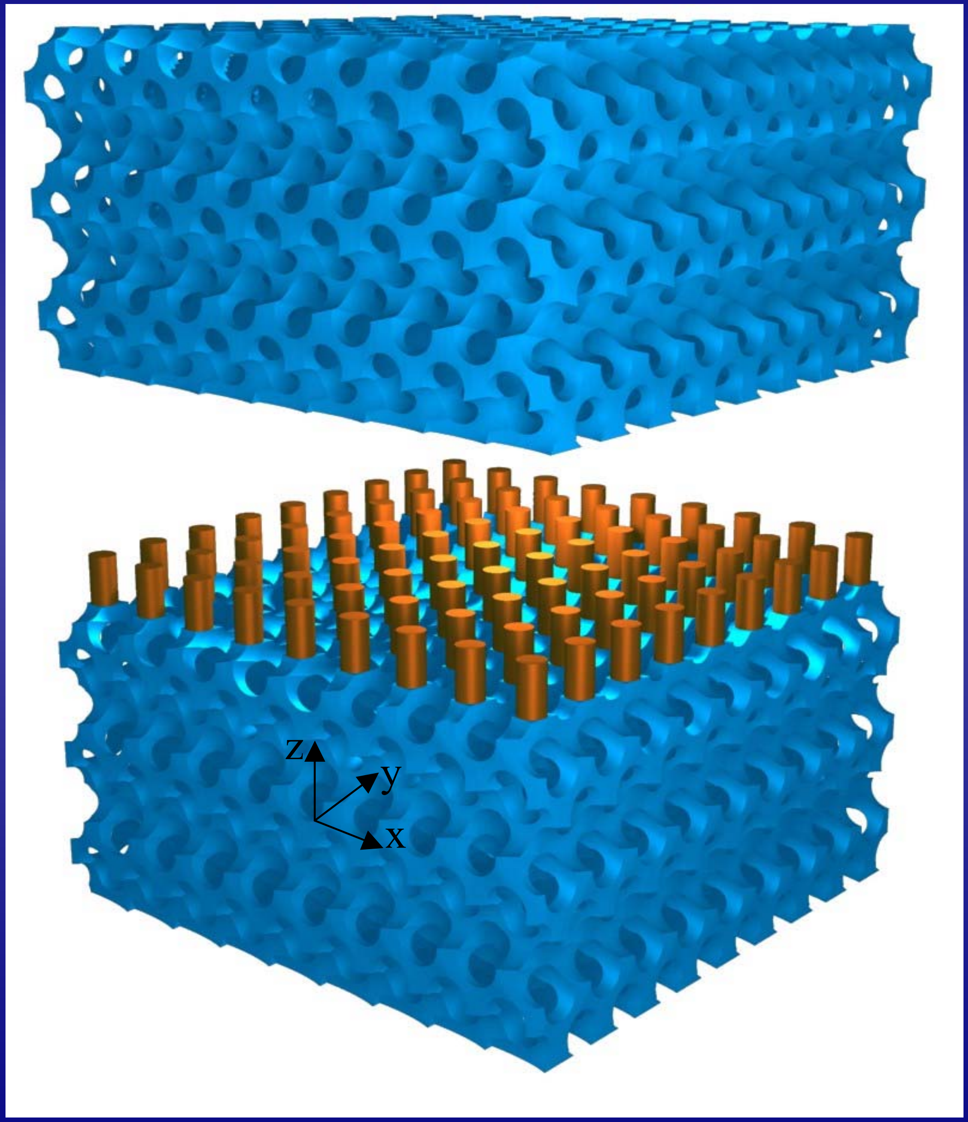


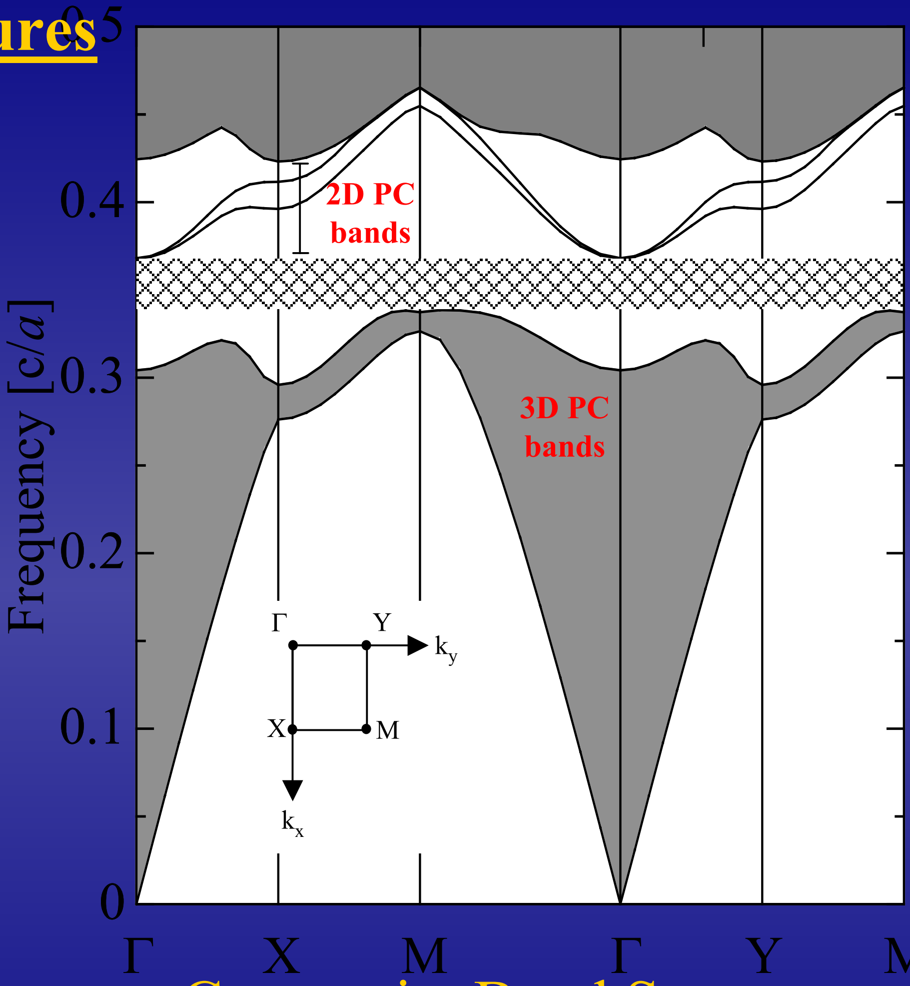
Optical Micro-Chip based on 2D-3D Hetero-structure Design



Optical Micro-Chips based on Dielectric 2D-3D PBG Heterostructures

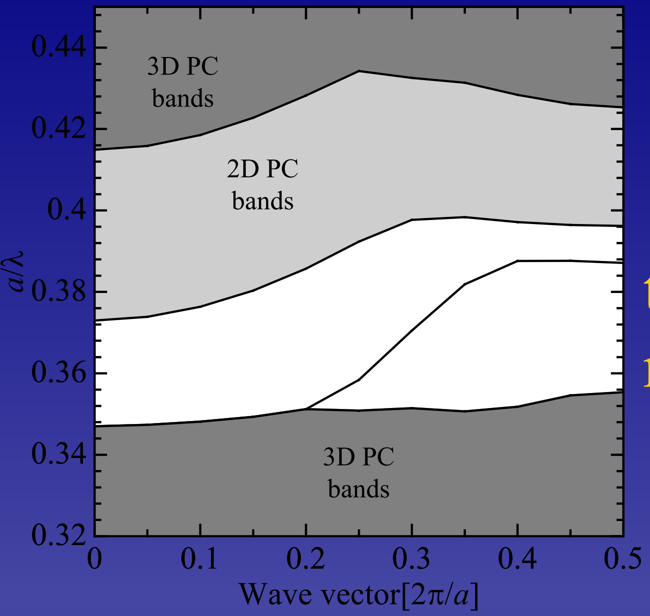
A. Chutinan, S. John, O.Toader
PRL 90, 123901 (2003)



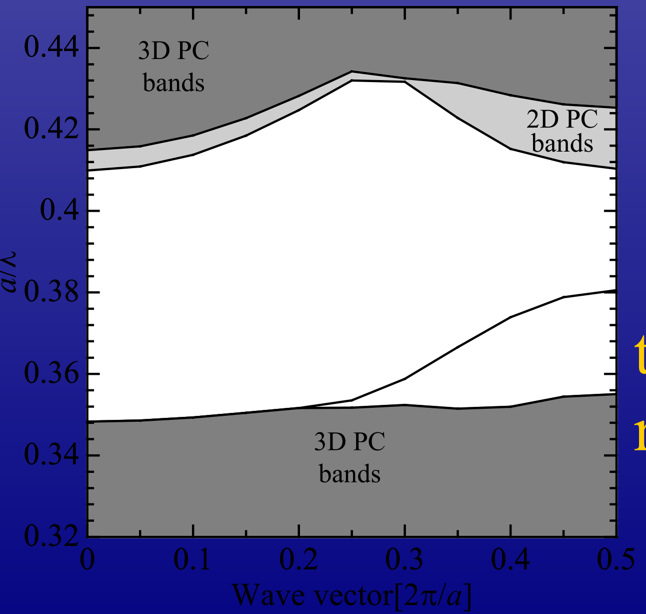


Composite Band Structure for 2-D array of rods Sandwiched between 3-D Inverse Square Spirals

Variation of Gap Modes with Thickness "t" of Micro-chip Layer and Radius "r" of Rods in 2D lattice

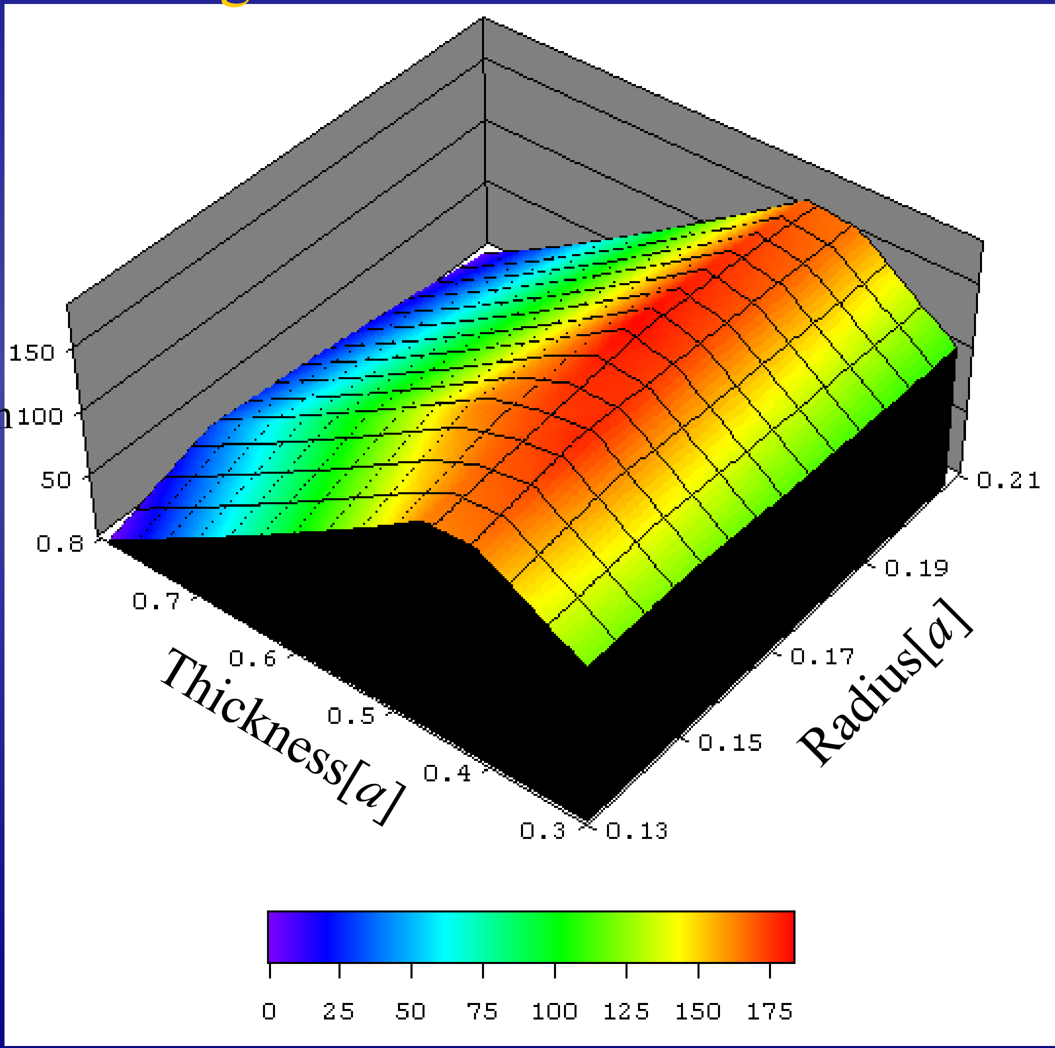


t=0.8a
r=0.15a



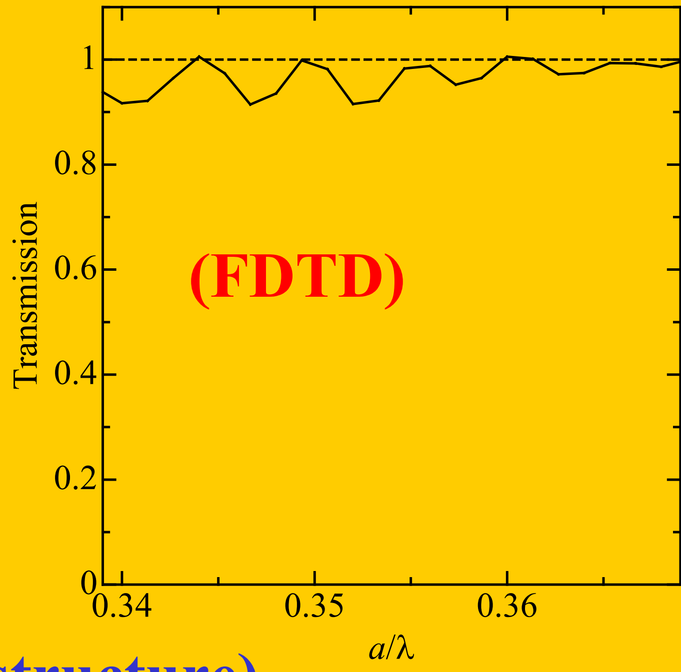
t=0.3a
r=0.15a

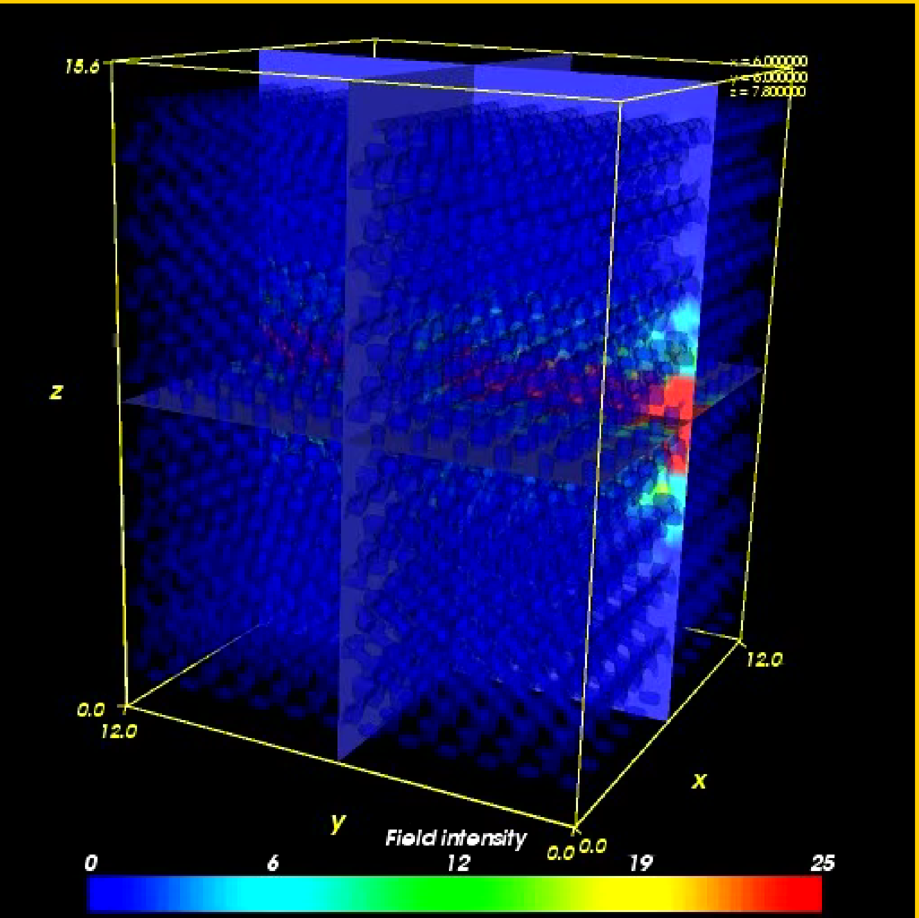
Direct Square Spiral 5: Single Mode Air-Waveguide Bandwidth at 1.5 microns



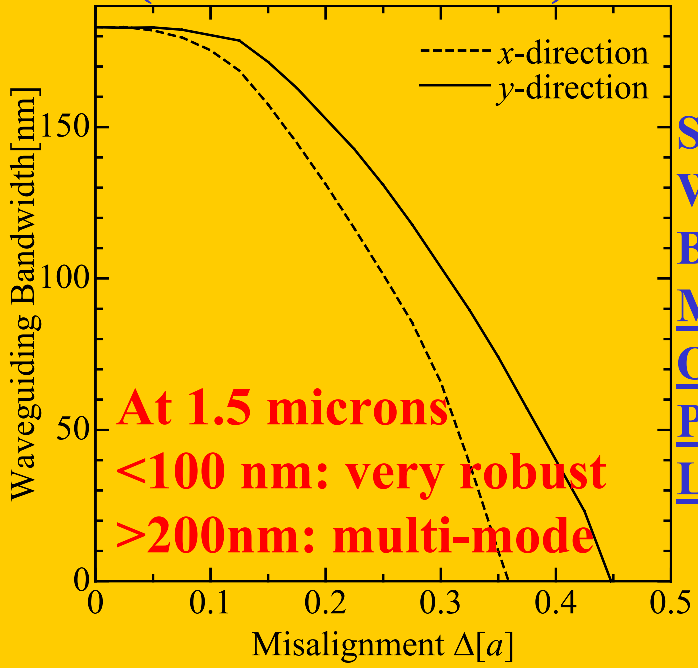
Effect of Disorder on Single-mode Air-waveguide Bandwidth (1.5 microns)

Random rod diameter variation with 20% FWHM fluctuation (48 nm) causes about 5% backscattering over 50 unit cells along waveguide.





(Bandstructure)

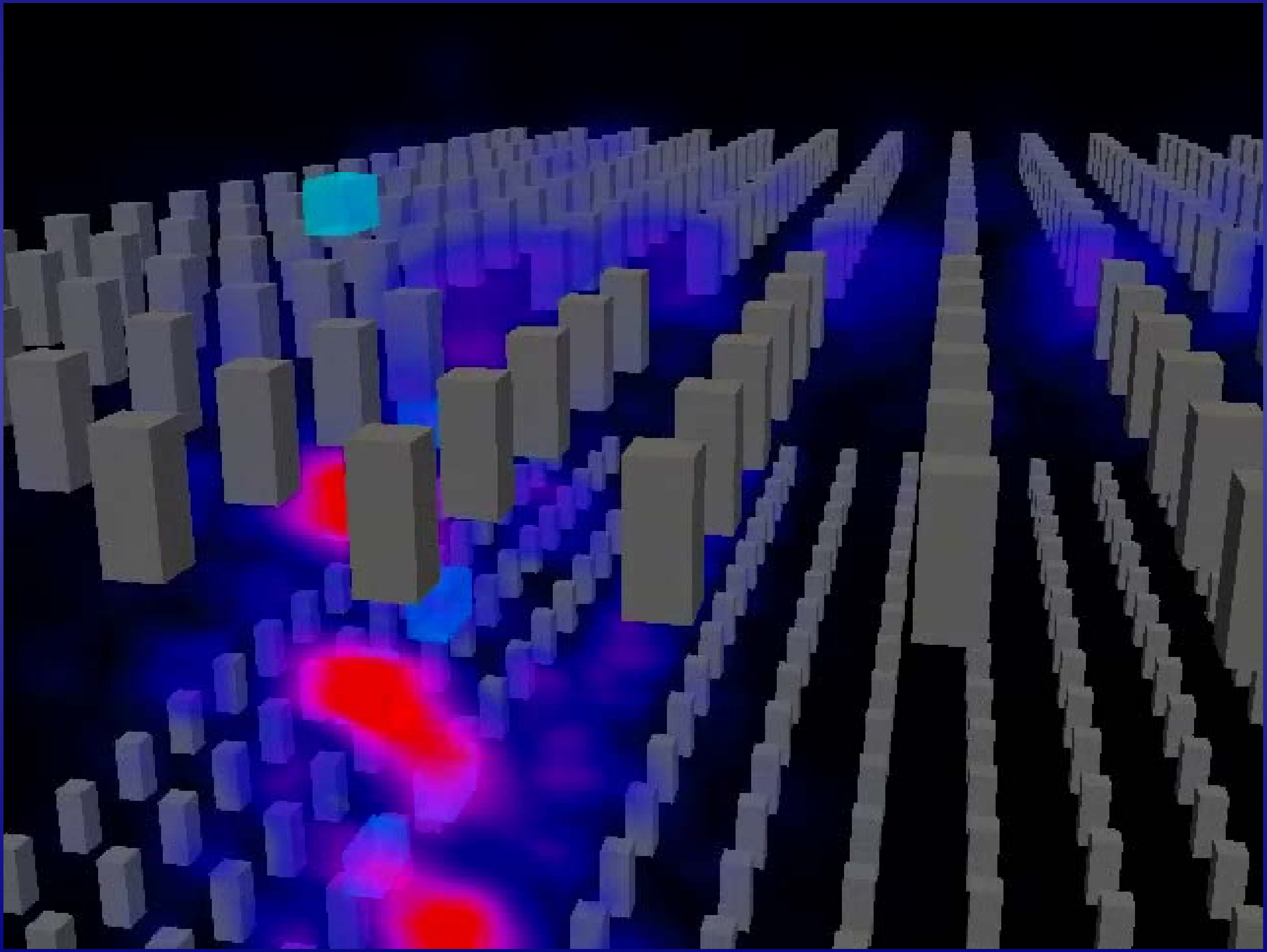


At 1.5 microns
<100 nm: very robust
>200nm: multi-mode

Single Mode Wave-Guiding Bandwidth vs. Misalignment Of Upper 3D PBG Cladding Layer

3 + 1 Dimensional Integrated Optics

PBG Chip to Chip Interconnects



Diffraction-less
Loss-less flow
over 200 nm
Bandwidth

Hundreds of
WDM channels
No cross-talk

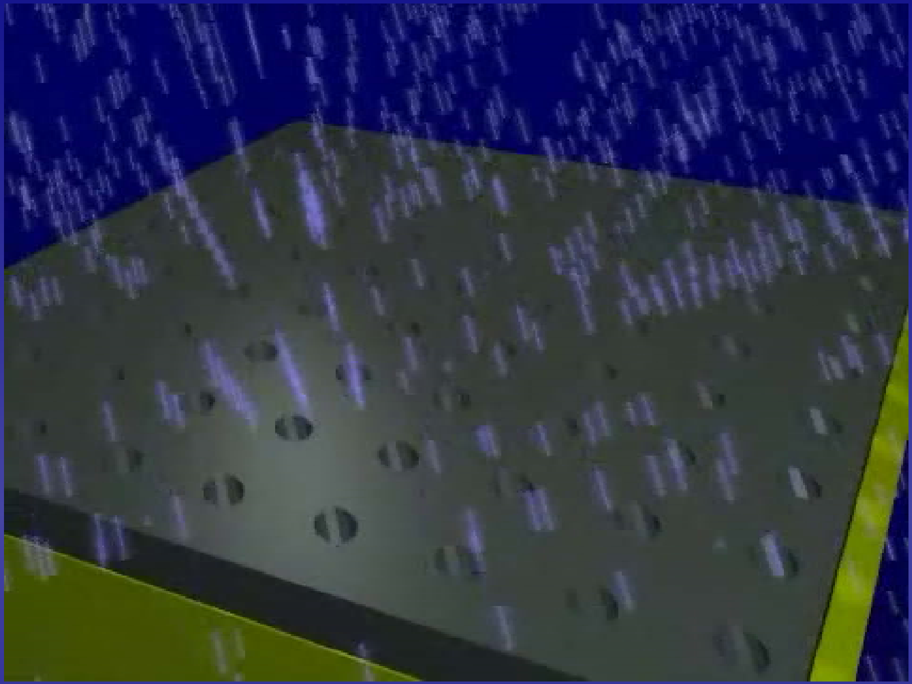
Minimal Heat
Dissipation

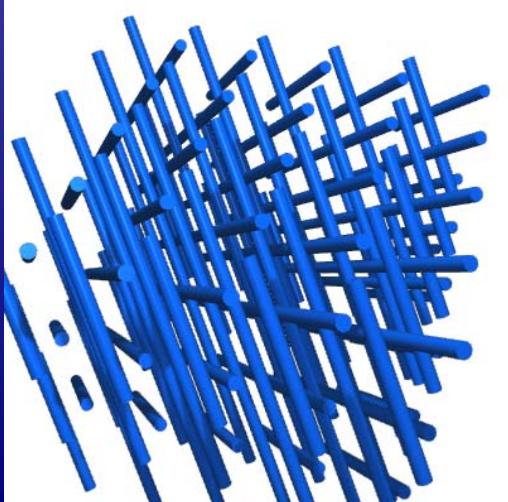
Blue boxes are regions where dielectric is removed to form vertical link

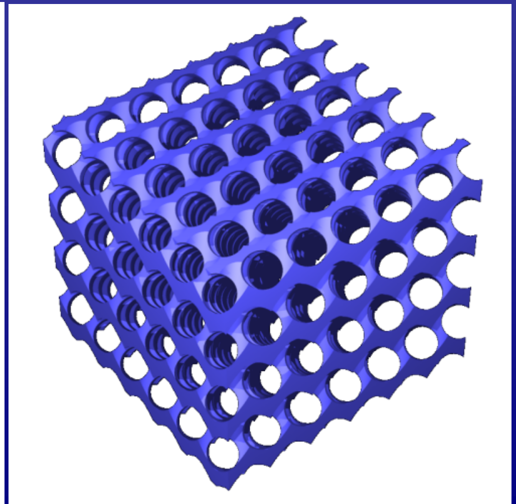
Slanted Pore SP-2 PBG Material
24% 3D PBG

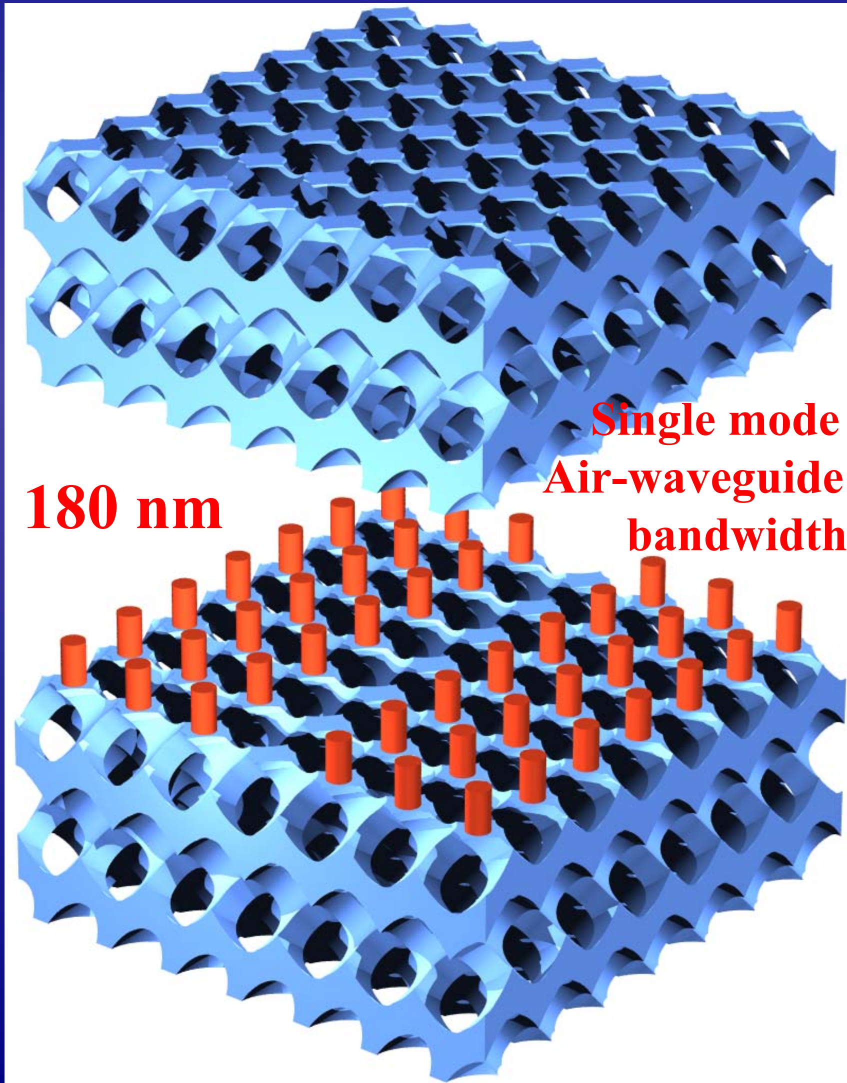
Tetragonal unit cell (a,a,1.4a)
Hole radius 0.345a

Micro-chip layer t=0.6a
Square lattice of circular rods
of diameter 0.3a









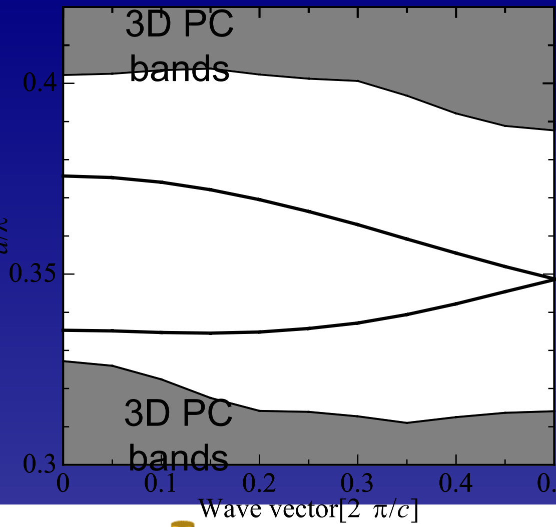
180 nm

Single mode
Air-waveguide
bandwidth

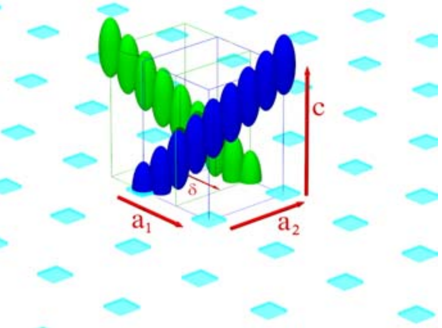
High Bandwidth 3D micro-circuitry in SP2 PBG

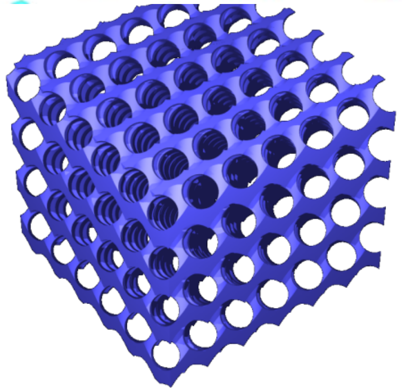
Lattice matched planar micro-chip layers provide 200 nm of single mode bandwidth

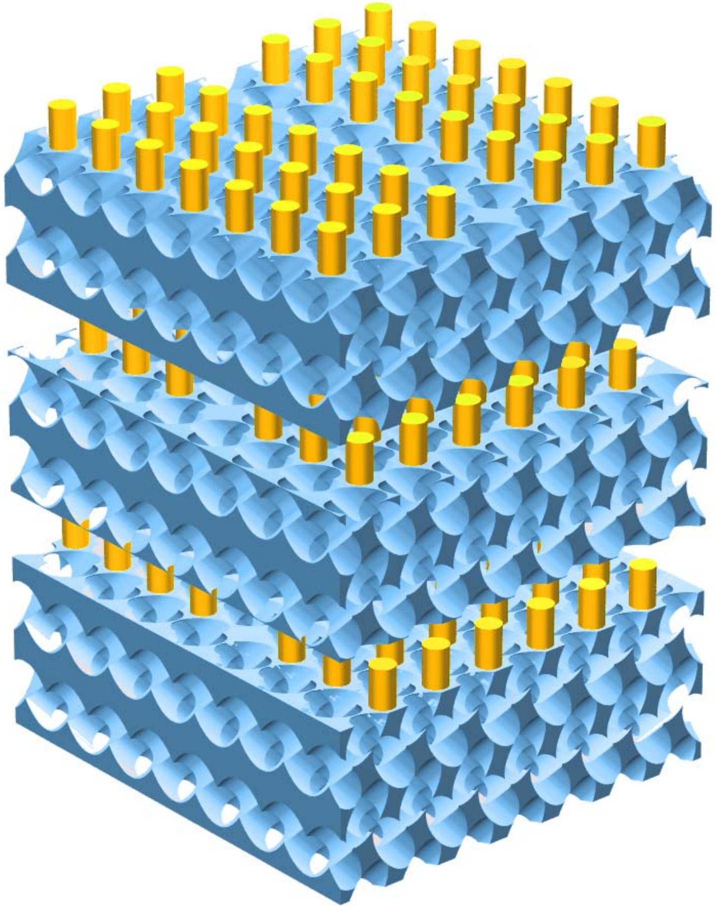
Vertical links act like Fabry-Perot resonators with high transmission bandwidth provided by **couplers**

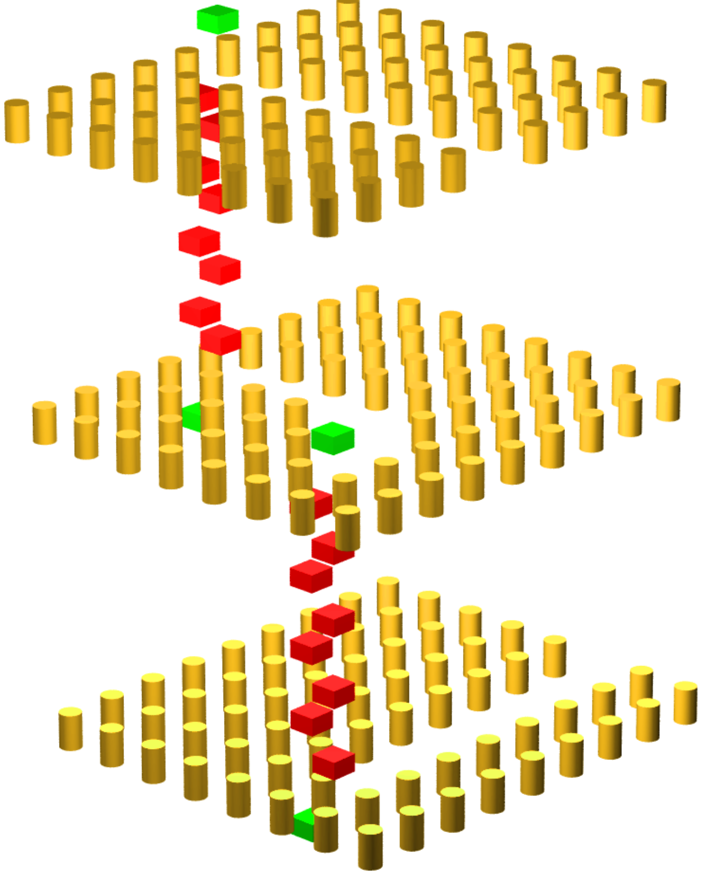


Slanted Pore
3D PBG
Cladding



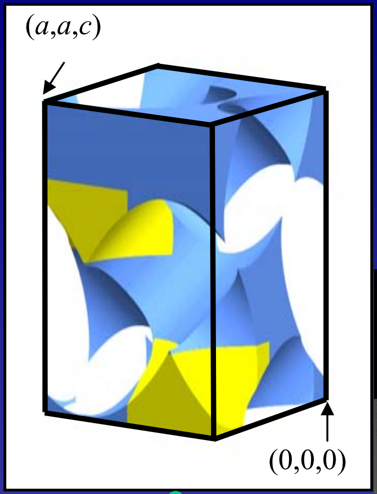


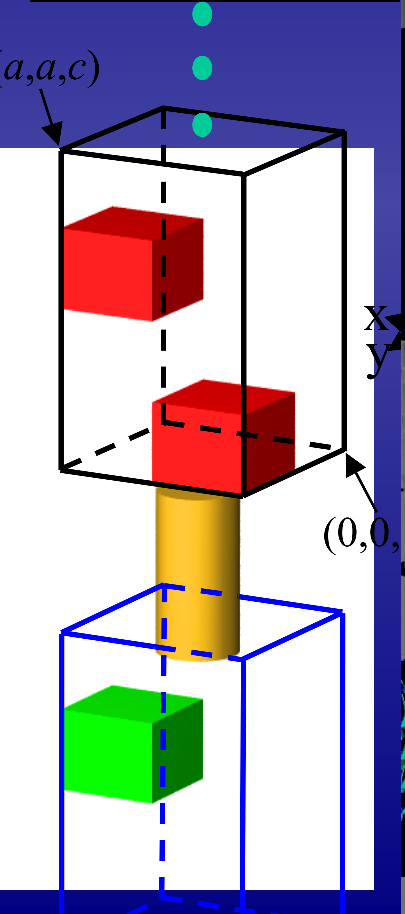


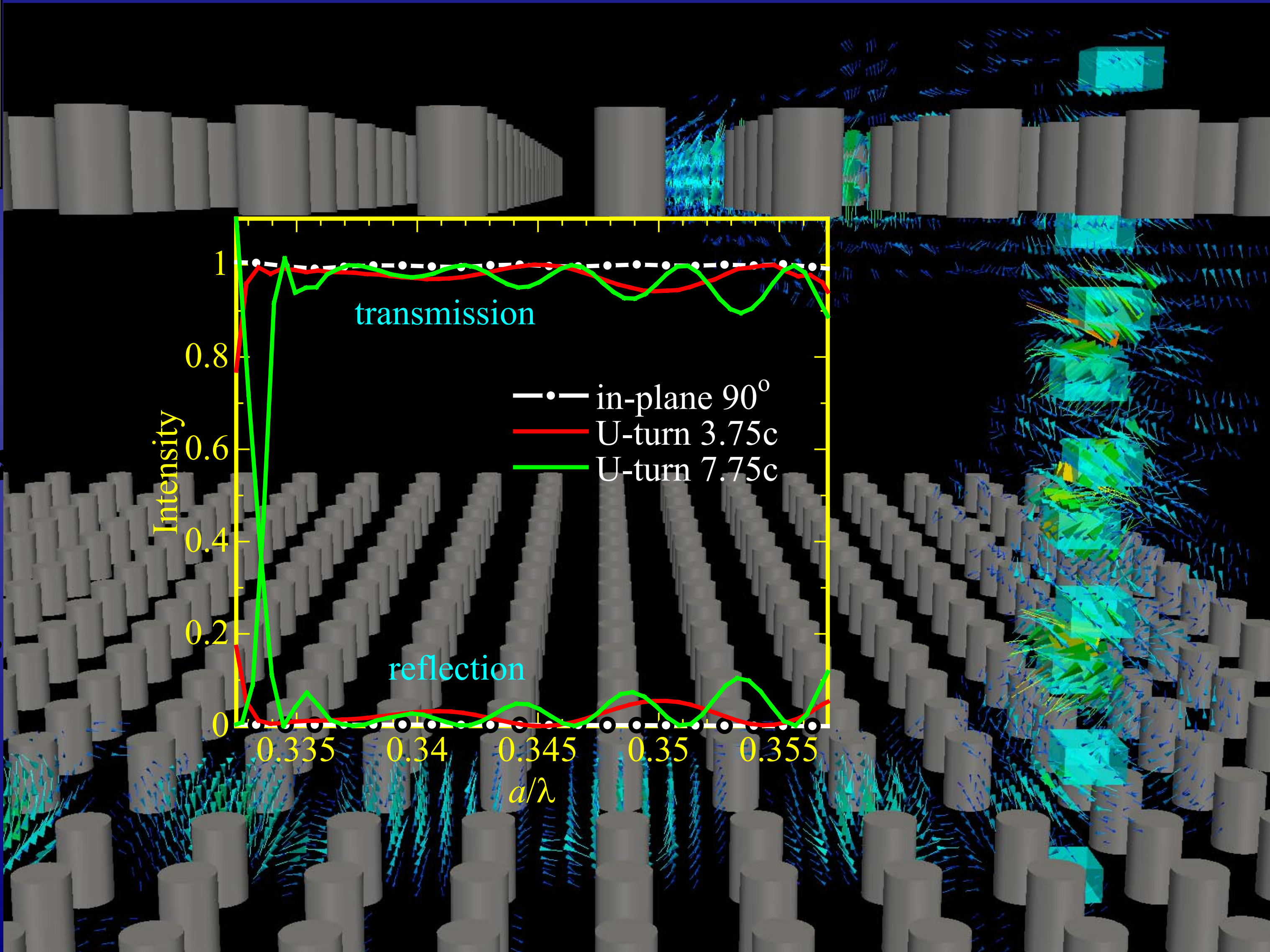


Transmission Characteristics for 3D Circuit Bend

Multiple Fabry-Perot resonances with Q-factor reduced by Coupler (dielectric removed from green box)

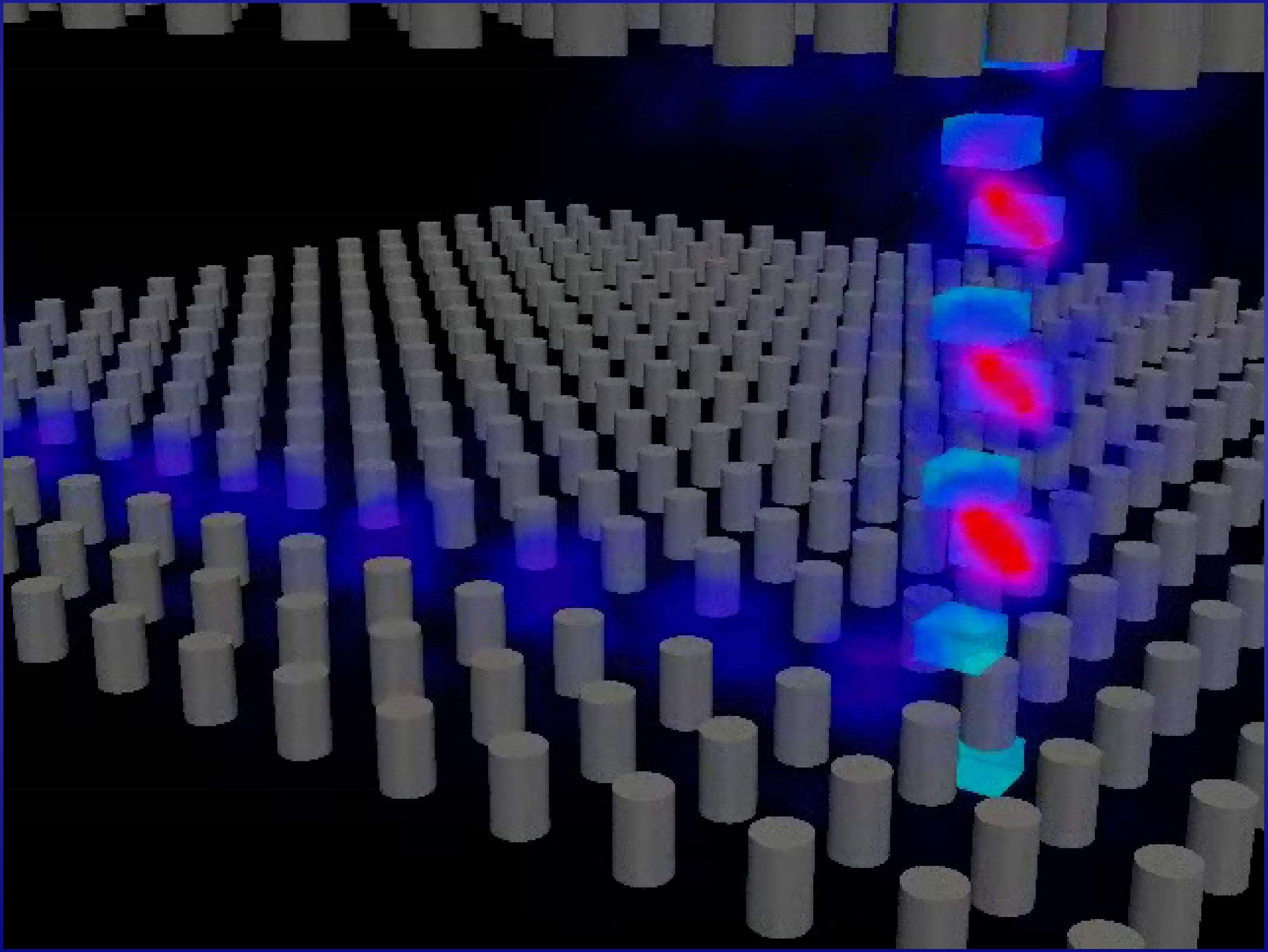






FDTD Simulation of Electric, Magnetic And Poynting Vectors on 3D SP2 Chip

A. Chutinan and S. John
to be published



Diffractionless transmission of Light in Air-guides with sharp 3D bends

Bandwidth:
200 nm on-chip

100 nm overlap between planar and vertical for chip-to-chip interconnection

SUMMARY

Localization of Light in 3D PBG

Diffractionless Flow of Light and Integrated Optics in 3+1 D:

3D air-waveguide circuit paths

100-200 nm single mode bandwidth

Microfabrication:

Direct Laser Writing

Plasma Tuning

Double inversion for Silicon

The Designer EM Vacuum:

Frequency selective control

of spontaneous emission