Novel 2D Photonic Crystals Structures

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Photonic Crystal Programs Overview

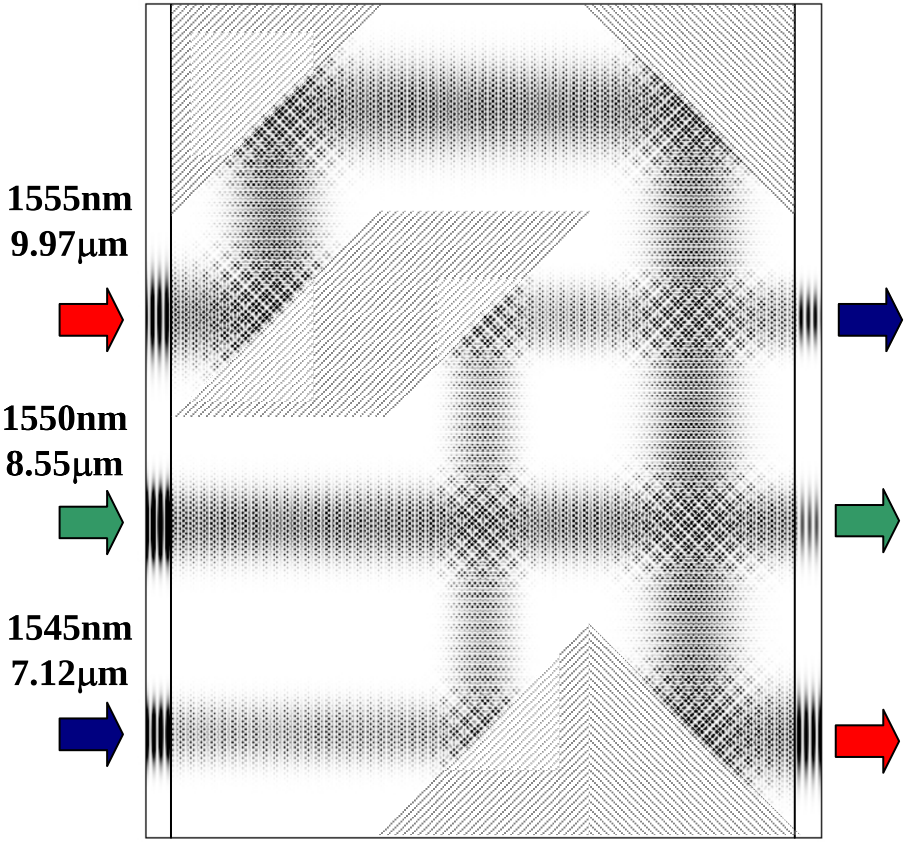
- **3D Photonic Crystal Structures**
  - PC Micro-cavities, Phosphors
  - Atomic Layer Epitaxy: Templating
  - Inverse/Non Close Packed Opals
  - Holographic Templates
- **2D Photonic Crystal Waveguides**
  - Triangular and Square lattices
  - Superlattices – triangular based
  - Non-Linear Structures

2D Photonic Crystal Program

- **2D Photonic Crystal Structures**
  - **"Virtual Waveguides"** Low divergent propagation in slab waveguides
  - **"Fabry-Perot Etalons"** – spectral tuning
- **2D Superlattice Photonic Crystal Waveguide Structures**
  - Superlattices – triangular based
  - Static; Hybrid; E/O superlattice
  - Non-Linear Structures
    - Liquid Crystal Infiltration of 2D PC
    - Non-linear & Electro-Optical (EO) materials
- **Impact of New Structures & Materials**
  - Tunable effects

Virtual Waveguide Interconnect System

- Advantages of free-space optics
  - No coupling
  - Intersections allowed
  - Broadband operation
- Advantages of integrated optics
  - Confined beams
  - No hermetic packaging
  - One lithography step
- Disadvantages
  - Small feature sizes required (beam size ~15a)
  - Compared to 2-3a for line defect PC waveguides
- PC mirrors have lower PBG



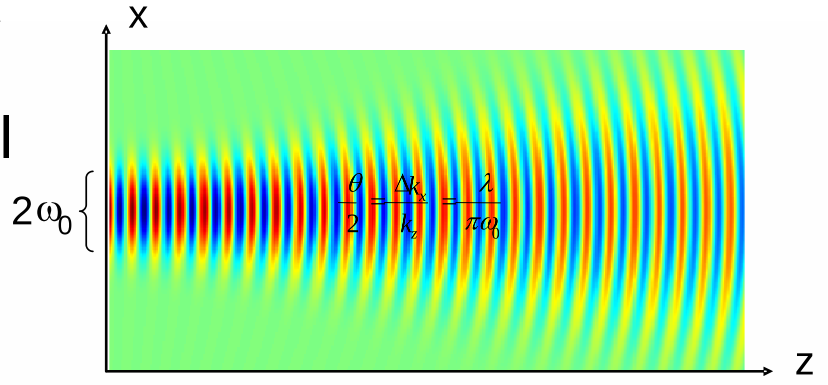
- Collimation exploits same phenomena as sub-wavelength focusing

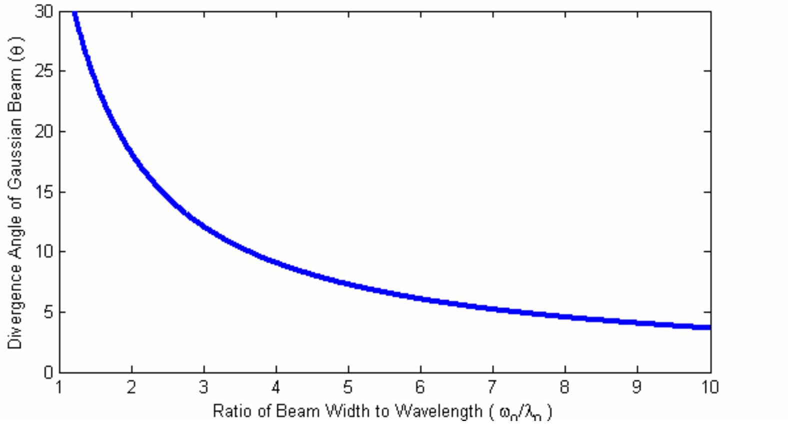
Beam Properties
Divergence Angle of 2D Gaussian Beam

- A Gaussian beam spreads in the paraxial approximation in an isotropic material as:

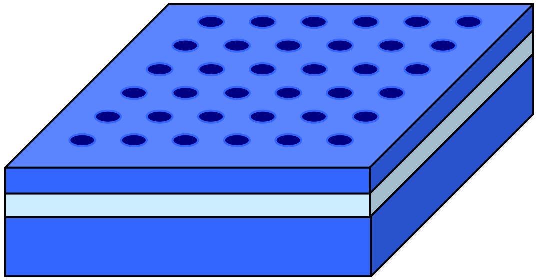
$$\frac{\theta}{2} = \frac{\Delta k_x}{k_z} = \frac{\lambda}{\pi \omega_0}$$

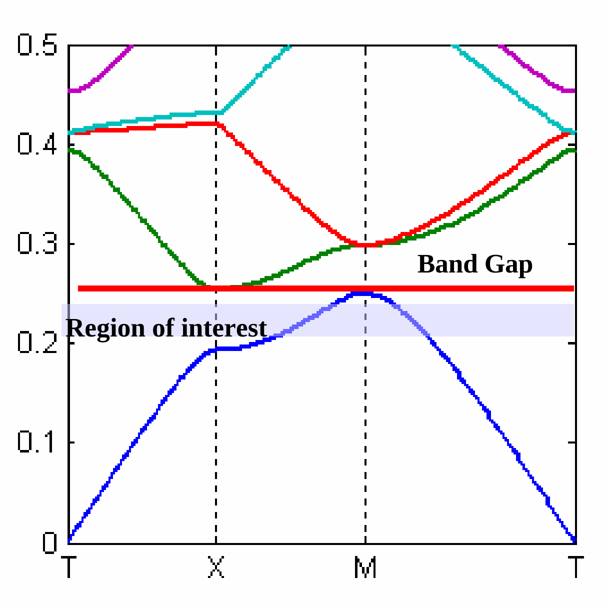
- The divergence determines the coupling efficiency into the photonic crystal

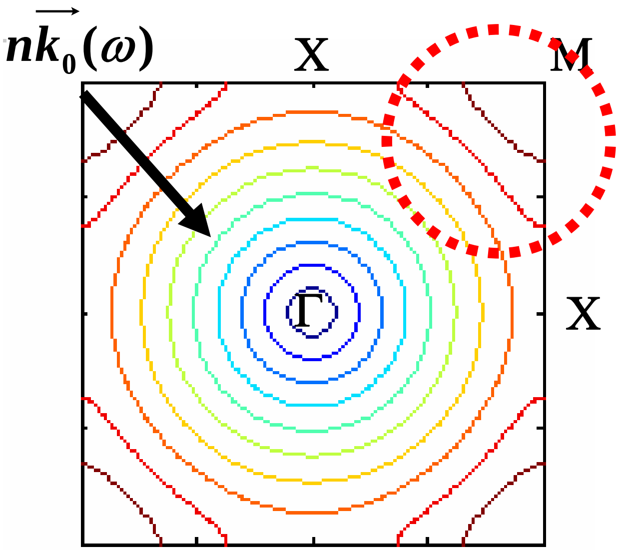




Analysis of 2D Photonic Crystals
Square Lattice







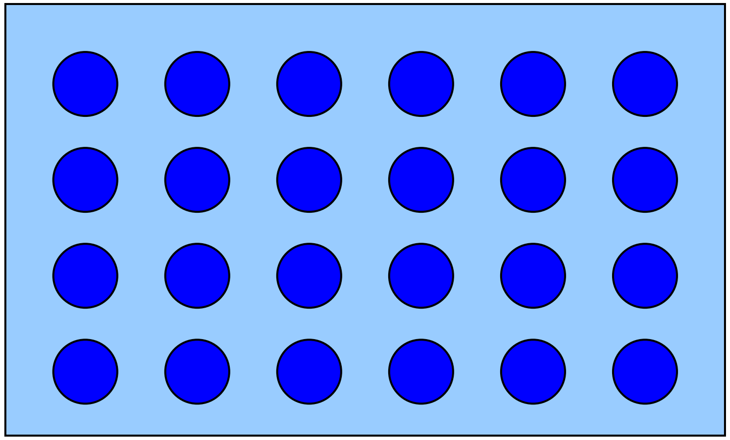
- Square lattice
  - Hole diameter
  - Refractive index

- Band Diagram
  - Boundaries of the band surface
  - Identification of band gaps

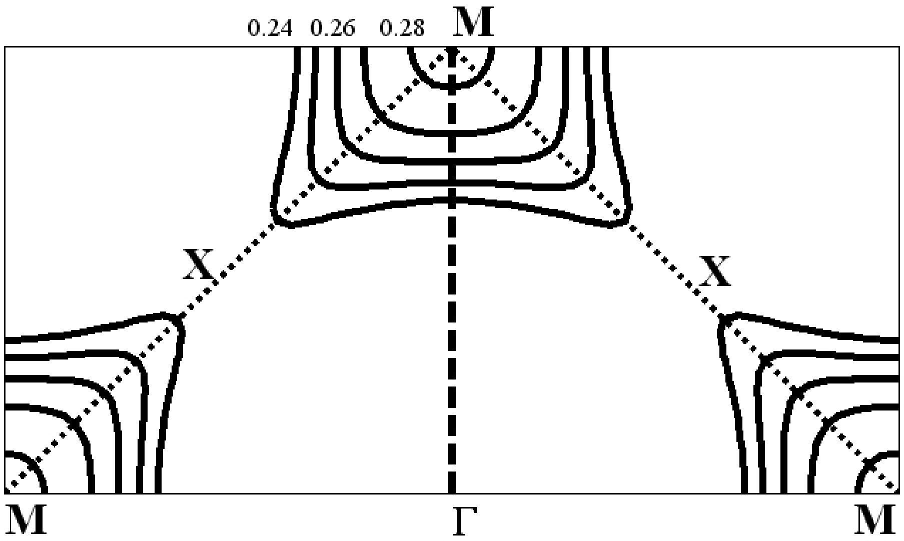
- Allowed Wave Vector Curve
  - Equifrequency curves of the band surface
  - Identification of propagation effects

Concavity Reversal Near Brillouin Zone Boundaries

- First band concavity reverses near the M point in a square lattice
- Dispersion curve approximately linear and normal to the Γ-M direction near the concavity reversal
- Robust to small fluctuations in λ and r
- Provides orthogonal grid of propagation for ease of design
- First band guarantees confinement along the thickness of the waveguide

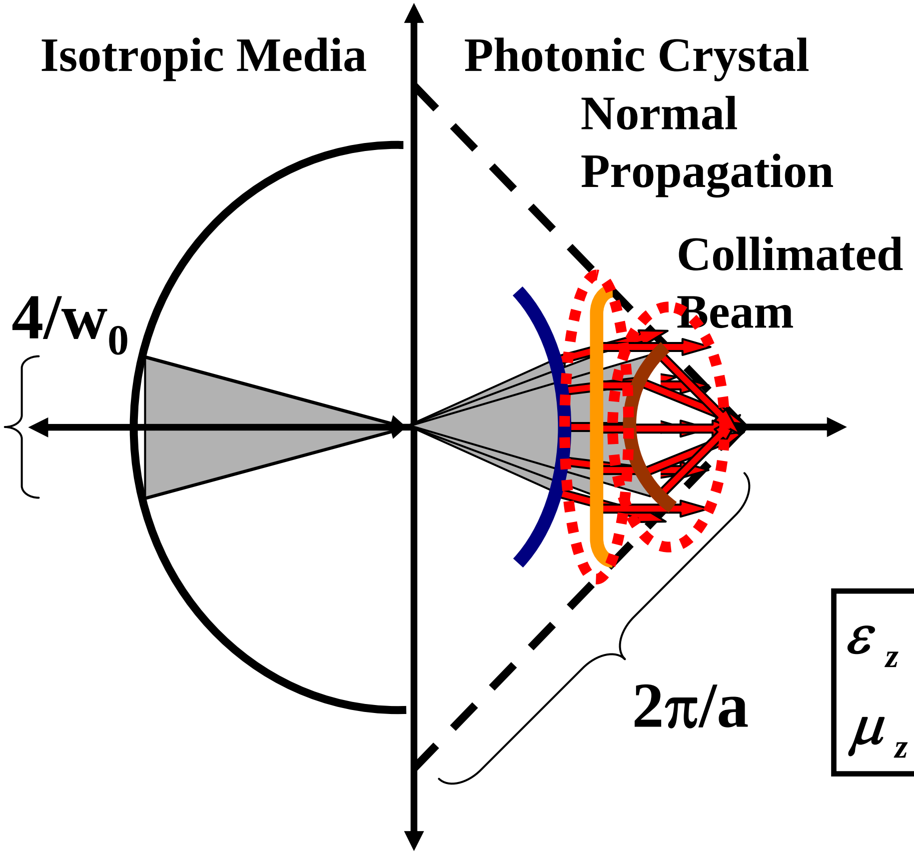


r=0.2a, ε_{matrix}=2, $\varepsilon_{pillars}$=11



Dispersion Curve Analysis of Square Lattice PC

- PC lattice designed to produce dispersion contours with a wide range of curvatures
  - Concave – normal propagation -- defocusing
  - Straight – collimated beam guiding
  - Convex – negative index for sub-wavelength focusing

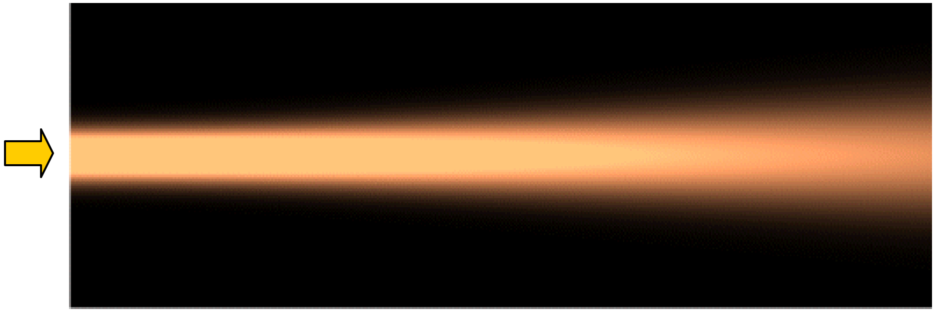


$\varepsilon_z = \infty$ $\mu_z = \infty$	$\varepsilon_z = \textit{negative}$ $\mu_z = \textit{negative}$

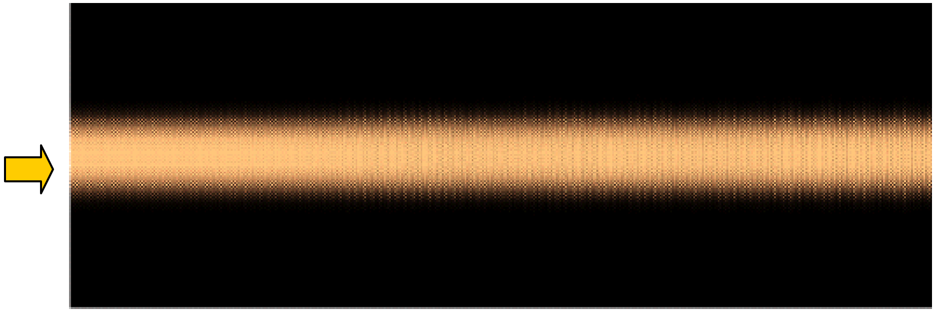
- **Canceling of Z-component leads to self-collimation**
- **Effective negative index for the energy propagation obtained**

Self-Collimated Beams in FDTD Simulation

- FDTD simulation of self-collimation
  - $\omega_n = 0.26$
  - $\lambda = 1.55$mm
- Clear intensity confinement in photonic crystal
  - ~25x longer propagation possible than in air
  - No discernable beam spread for 120µm of propagation of a 8.5µm wide beam
- Beam spread decreased by an order of magnitude or more with beam sizes as small as 5-10 λ_0
- Applications include:
  - Virtual waveguide interconnect system
  - Miniaturization of conventional optical components for small beams

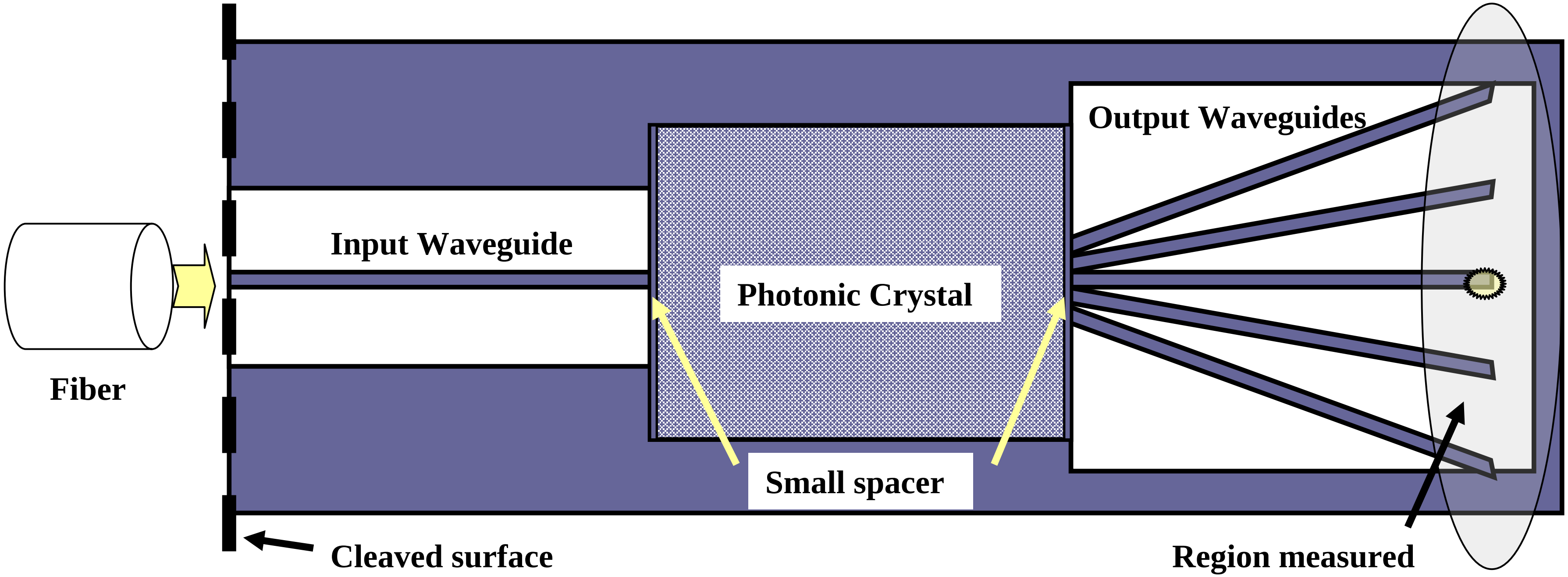


Air



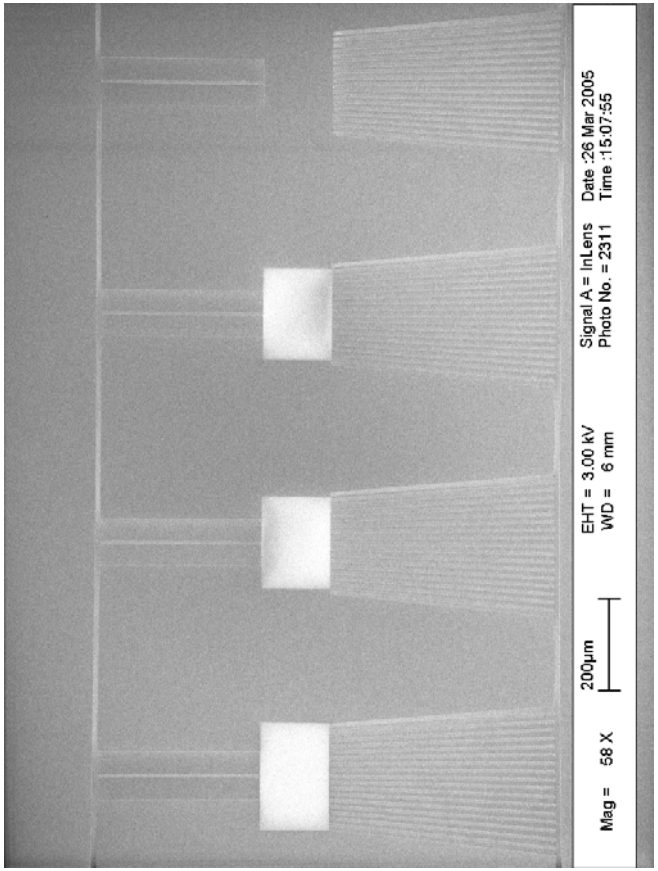
Photonic Crystal

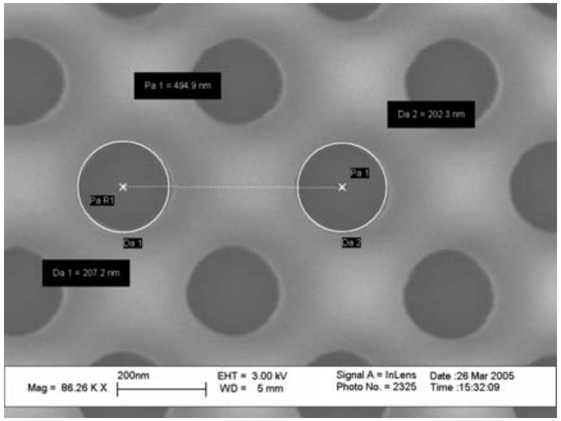
Test Structure Design for Collimation

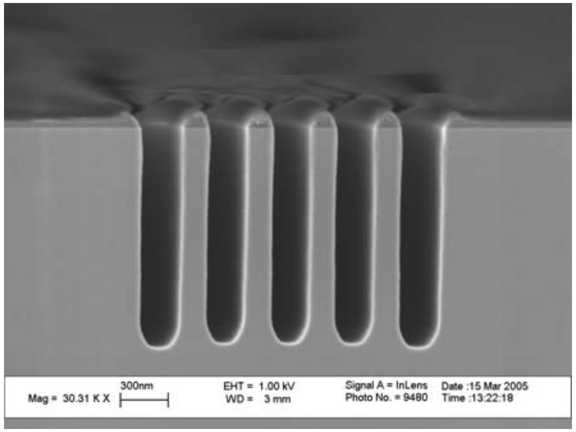


- Principle of operation
  - Gaussian like input from input waveguide
  - Beam spread observable from number of lit output waveguides
- Quality requirement
  - Smooth surfaces (<L_s/20)
  - Anisotropic sidewalls (<5°)
  - Uniform hole sizes in photonic crystal (<5% locally)
  - Large area ~ 150 μm^2

Test Structures of “Virtual Waveguide”

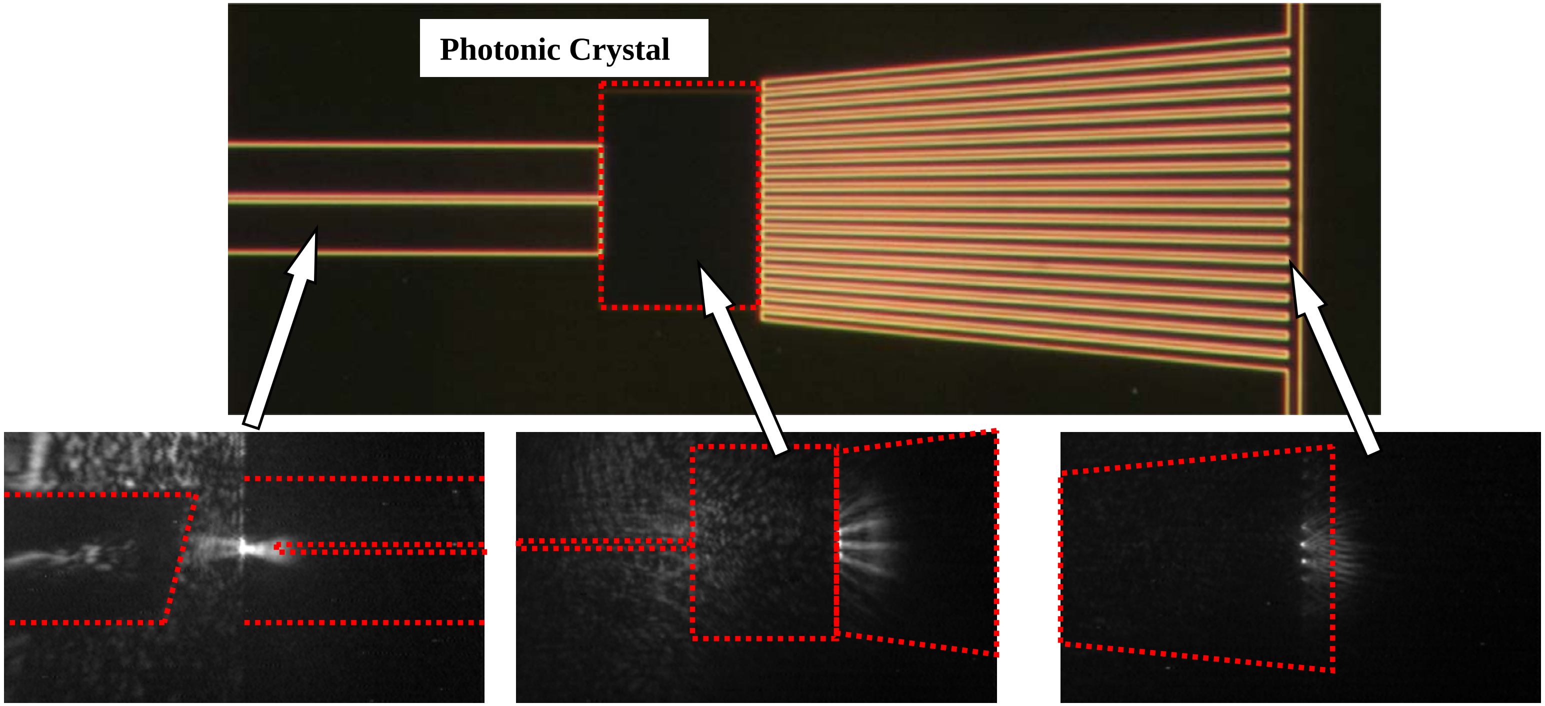






- Input waveguide, photonic crystal, fan of waveguides for analysis
- Examples of photonic crystal fabrication.

Direct Top-View Measurements



Input from the fiber

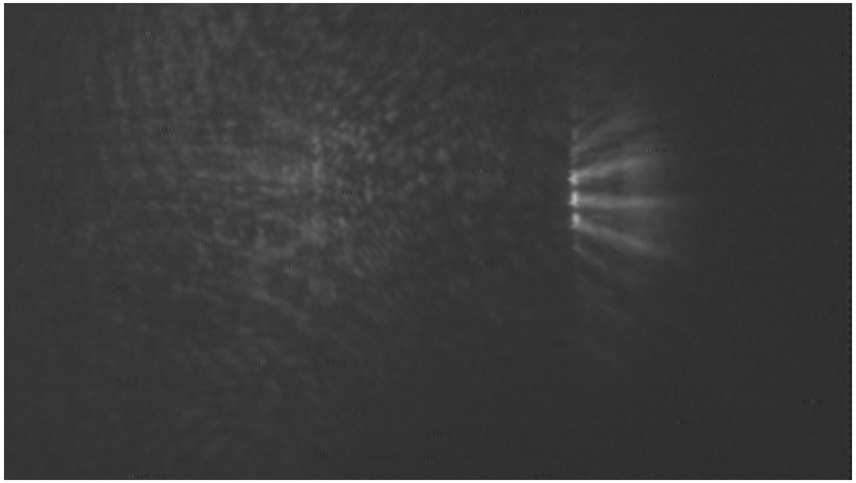
Propagation thru the photonic crystal

Output from the waveguides

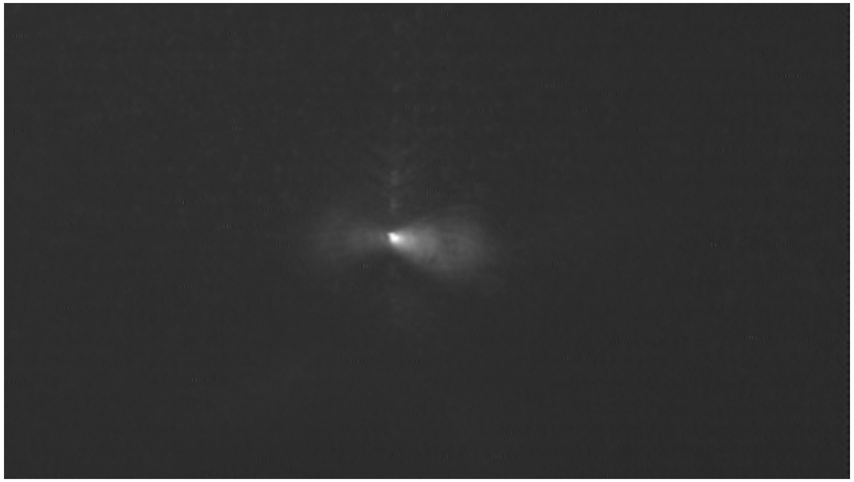
- Infrared camera utilized to view scattered light from the device

Measurements of Virtual Waveguide Effect

- Test structure with no photonic crystal:
  - Approximately 8 WGs lit up



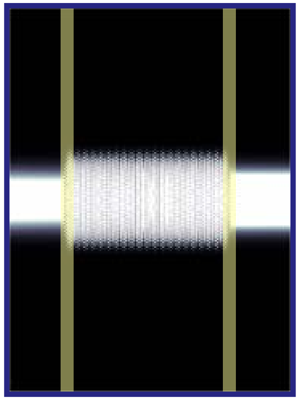
- Test structure with "virtual waveguide" photonic crystal:
  - Only central waveguide lit up



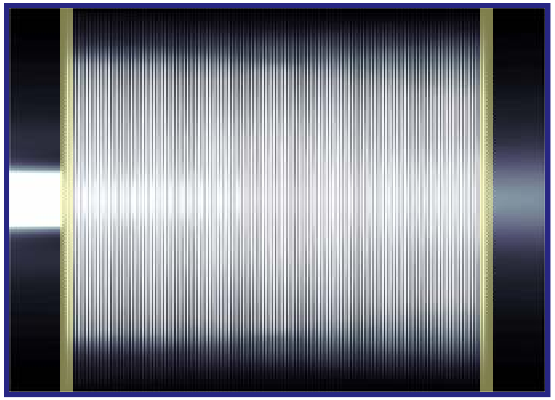
- Very good beam collimation in PC

Applications:
Fabry-Perot Interferometer

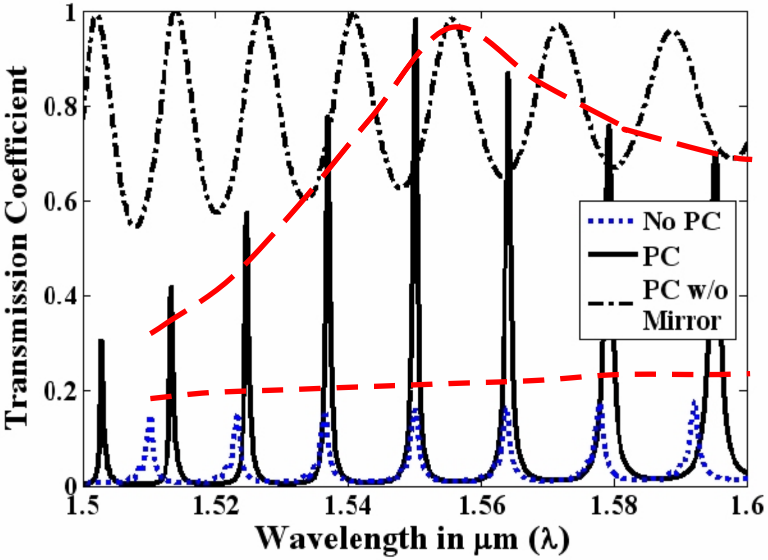
- Beam spread degrades performance
  - Beam size
  - Intensity leaks backward (<16% center intensity)
- Photonic crystal confines beam
  - >98% transmitted center intensity for mode near self-collimation
  - Can control bandwidth for selecting number and intensity of transmitted beams
- Concept extends to other interferometers and bulk optical devices



Photonic crystal

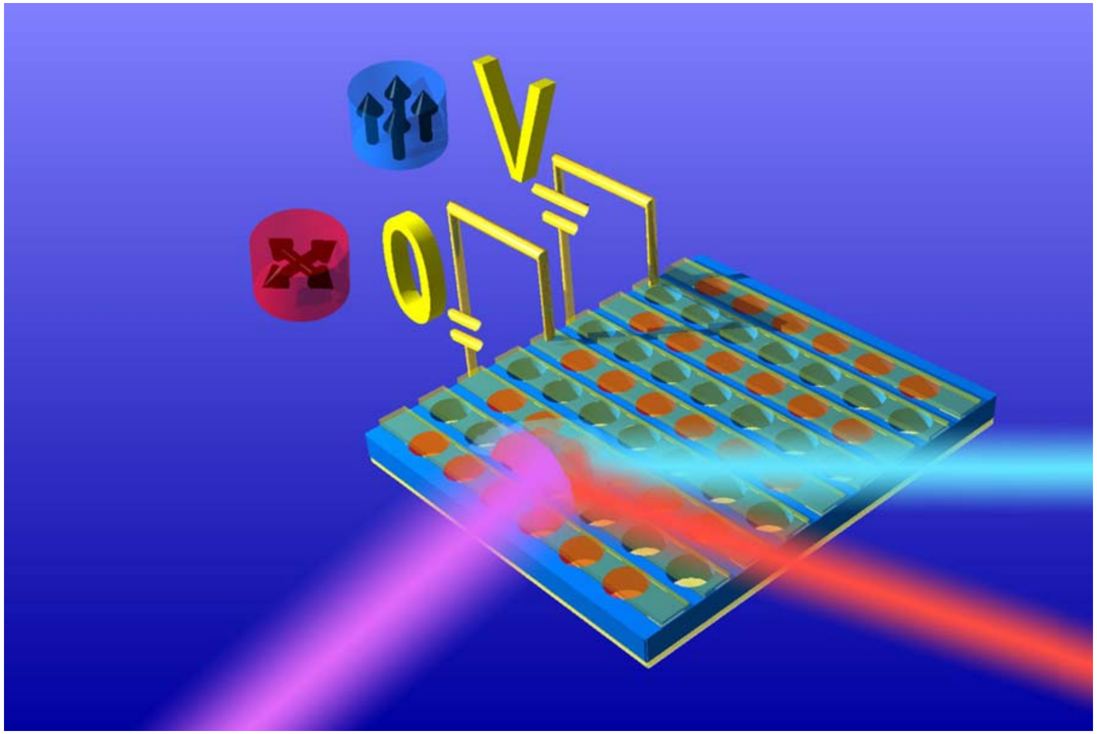


No photonic crystal



Transmitted intensity at center of beam

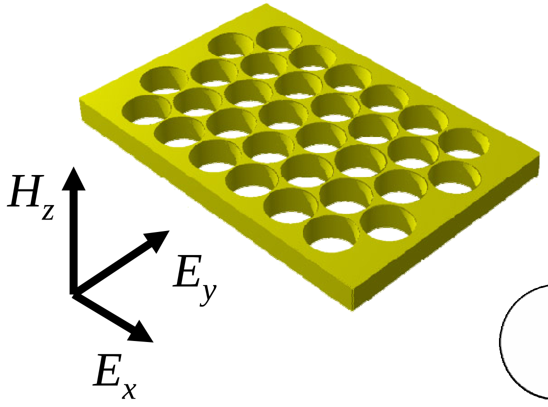
Propagation Effects in Superlattice PCs



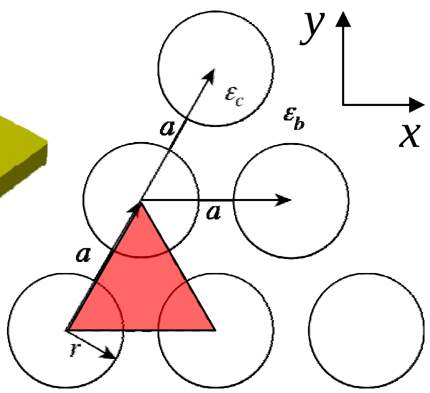
- **Giant refraction**
- **Superprism**
- **Tunable refraction**

Two Dimensional PC: Triangular Lattice

- Simpler structure than 3D
- Top-down fabrication
- Integration with planar circuits
- Simpler analysis of optical properties than 3D
- Can have full PBG (light in plane of PC)
- Giant refraction effects
- *Superprism* effects

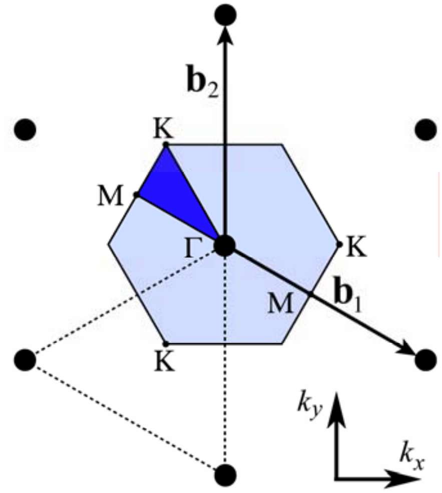


TE polarization

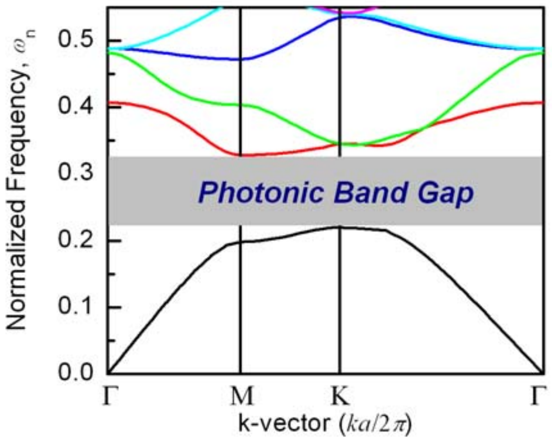


Real Space

- Band diagram: Plot of dispersion relationship, $\omega(k)$, along irreducible BZ boundary

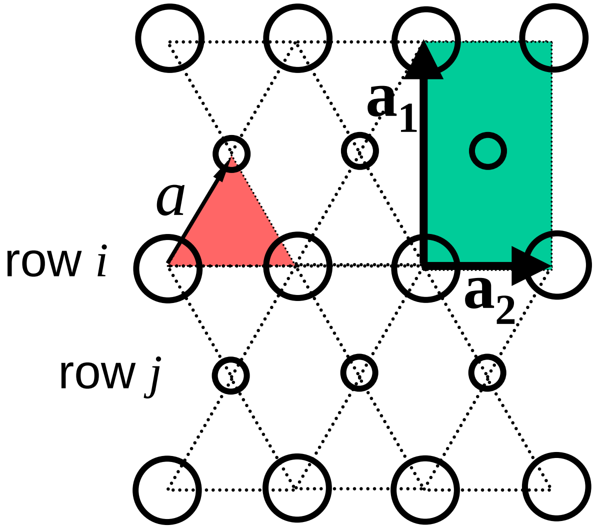


Reciprocal Space

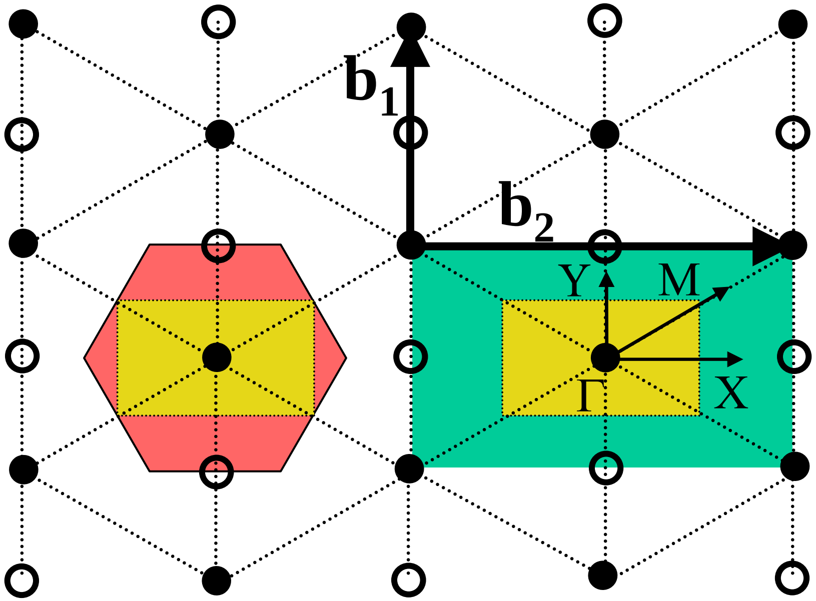


Band Diagram

Superlattice: Real & Reciprocal Space



Real Space



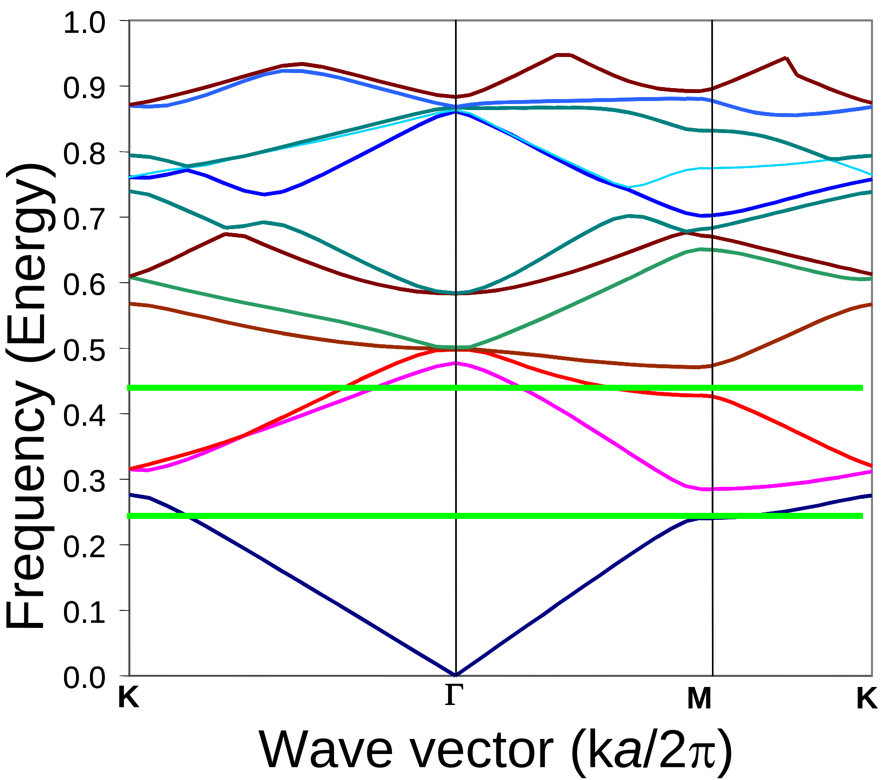
Reciprocal Space

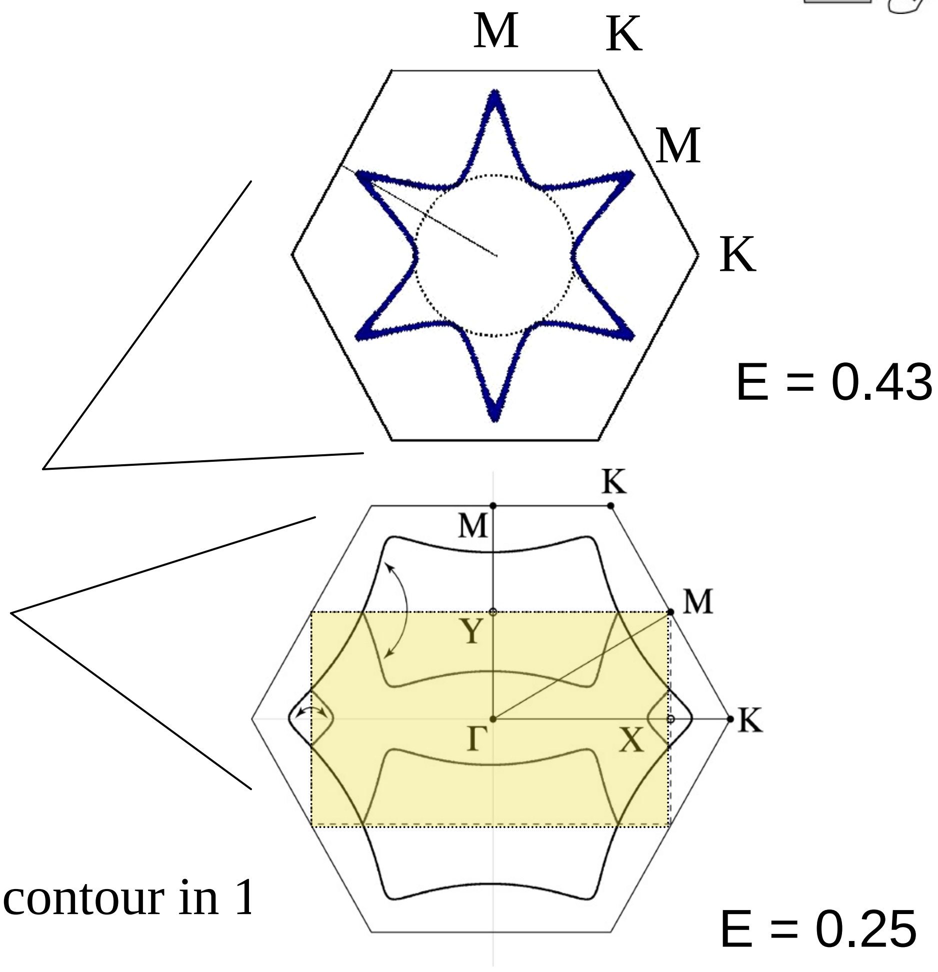
- Alternating rows posses different property (Δr, Δn, or both)
- Unit cell definition with two holes per lattice point

- New BZ representation: hexagonal becomes rectangular
- BZ folding
- Symmetry reduction: six-fold to two-fold

Dispersion Diagram Energy Dependence

ZnS/Air Triangular Lattice

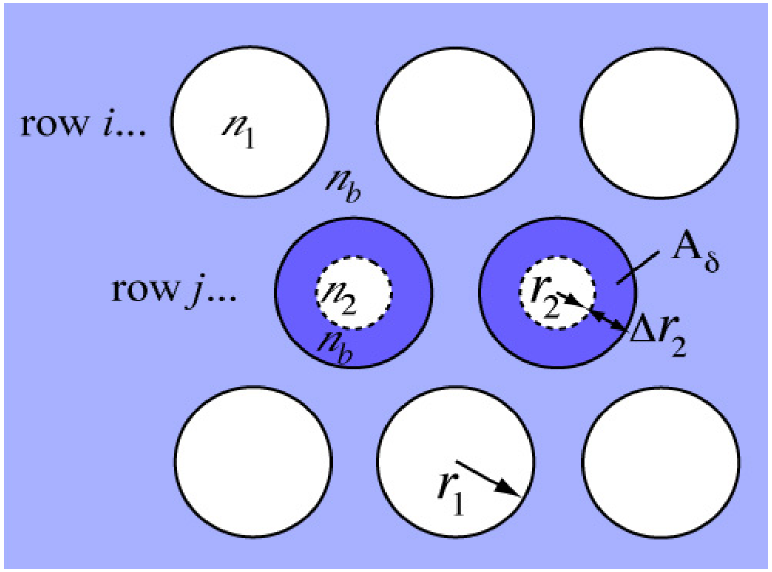




- Dispersion diagram: constant energy contour in 1
- Homogeneous medium → circle
- Photonic crystal → complex in shape
- Propagation of light normal to the dispersion curve, in direction of energy flow

Static Superlattice Photonic Crystal
Superlattice Strength: r_2/r_1

- Superlattice: hole radii, r_1 & r_2, in adjacent rows [*i*, *j*], respectively, Lattice vector *a*
- Increasing superlattice strength accomplished by increasing Δn or Δr between rows



- Strength of superlattice defined as: extra dielectric added when r_2 made smaller, $\mathbf{r_2/r_1}$ ratio

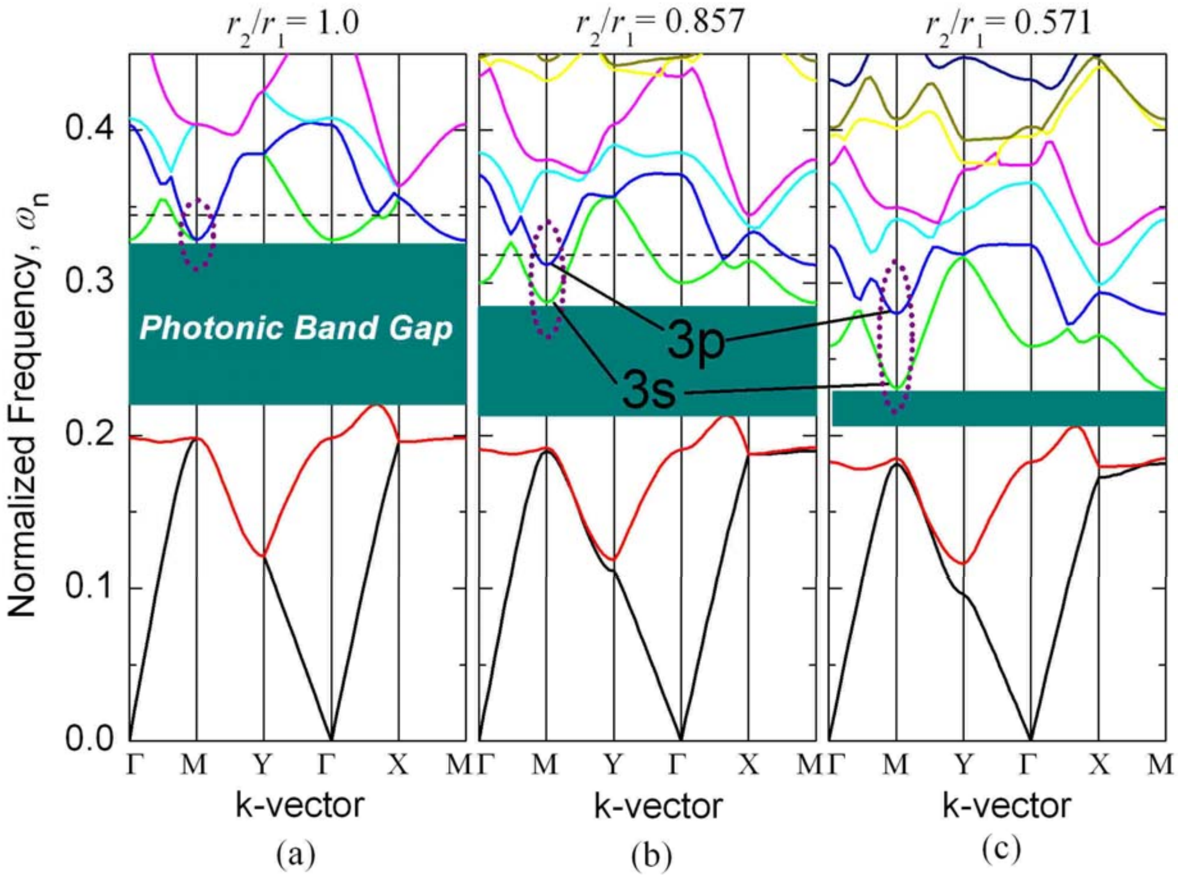
$$n_{eff} = \frac{n_b A_\delta + n_2 A_2}{A_1}$$

$$= n_b \left(1 - \left(\frac{r_2}{r_1}\right)^2\right) + n_2 \left(\frac{r_2}{r_1}\right)^2$$

- In Si, for $r_2/r_1=0.857$, $n_{eff}=1.654$ which is $\Delta n=0.654$ between rows of holes
- To increase the strength of the superlattice. The radius of the columns of row *j* is decreased down to $\Delta r_2=0.15a$ while r_1 is kept constant

Effect of SL Strength (r_2/r_1) on Band Structure (Δr)

TE polarization



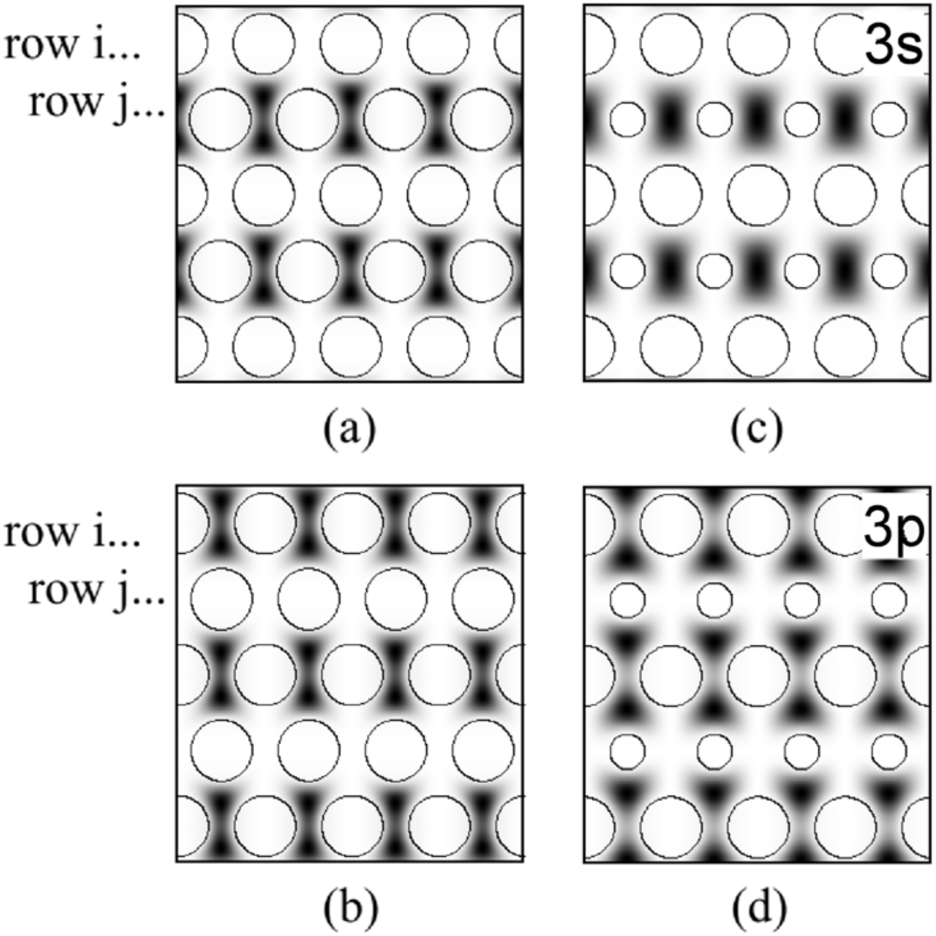
- **Decreasing *r*$_2$ increases dielectric material in structure**
- **Stronger effect on air bands than dielectric bands**
- **Shifts bands to lower frequencies**
- **Decreases width of PBG**
- **Increases band splitting**
- **Similar effect in dynamic superlattice when changing Δn**

- **Evolution of a static superlattice band structure with radius ratio (a) $r_2/r_1 = 1$, (b) $r_2/r_1 = 0.857$, (c) $r_2/r_1 = 0.571$**

Energy Density of Static Superlattice

Δ–lattice

M–point



(a) (c)

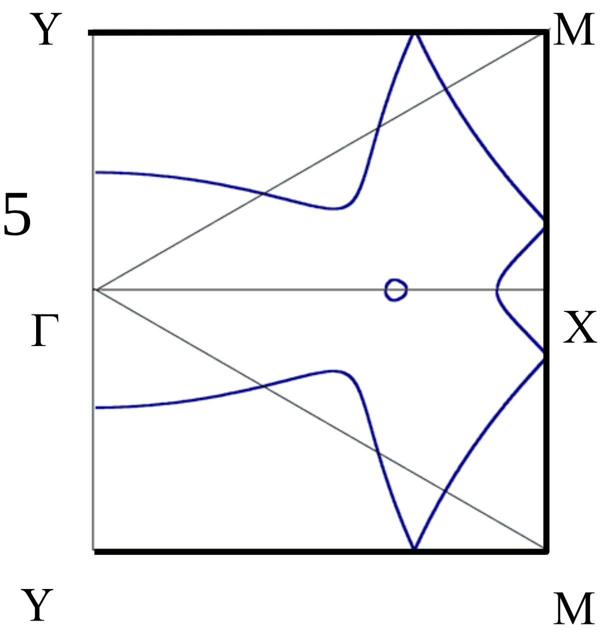
(b) (d)

2D PC-SL with strength 0.571

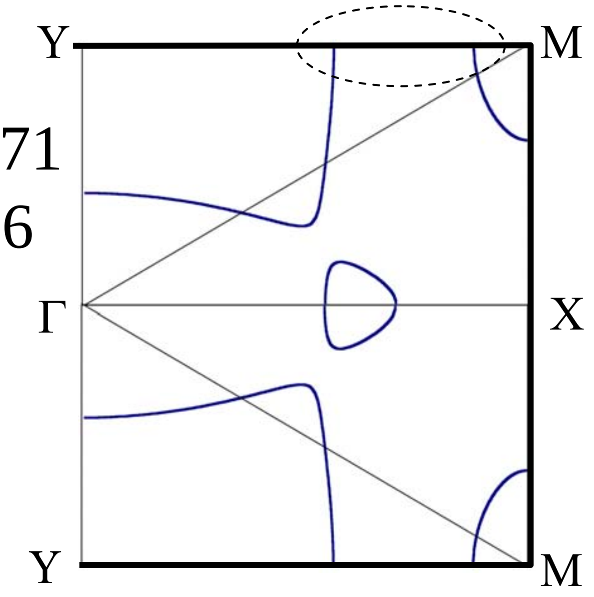
- a & b --- Degenerate states at bottom of air band at M-point Δ-lattice
- c & d --- 3s and 3p states of the 2D PC-SL with strength 0.571

Dispersion Contours: Dependence on r_2/r_1

r_2/r_1=1.0
ω_n= 0.435



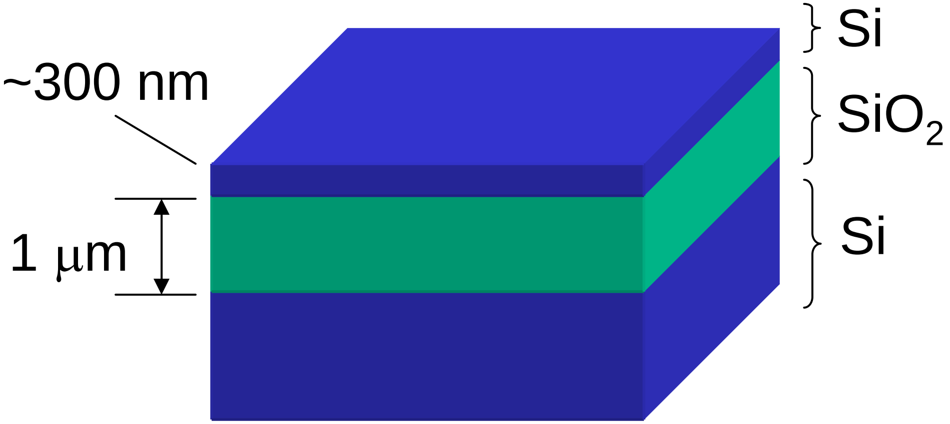
r_2/r_1=0.571
ω_n= 0.366



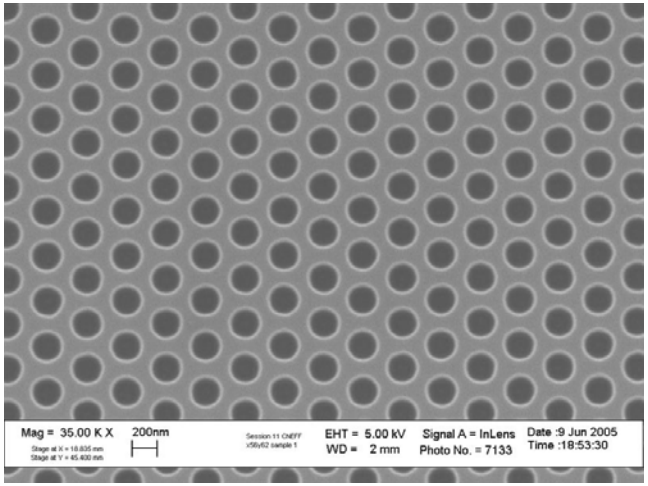
- For Δr = 0, **(r_2/r_1=1)**, BZ folding scheme straight forward: curves converge to a single point at BZ boundaries.
- Radius modulation **(r_2/r_1<1)**: curves diverge/repel at BZ boundaries
- Net result: relatively flat curvature in center of BZ with high curvature near BZ boundaries

Fabrication

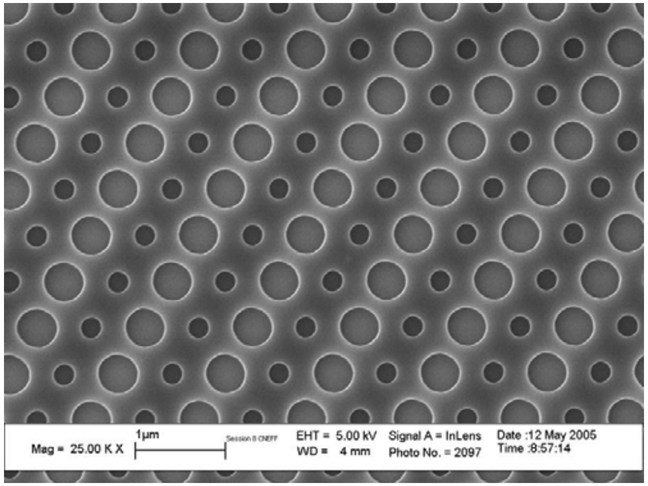
- E-beam lithography
- ICP dry etching with Chlorine/C_4F_6 recipe
- 1 mm^2 area written using smaller unit patterns
- Lattice constant: a=358 nm
- Silicon slab waveguide (SWG)



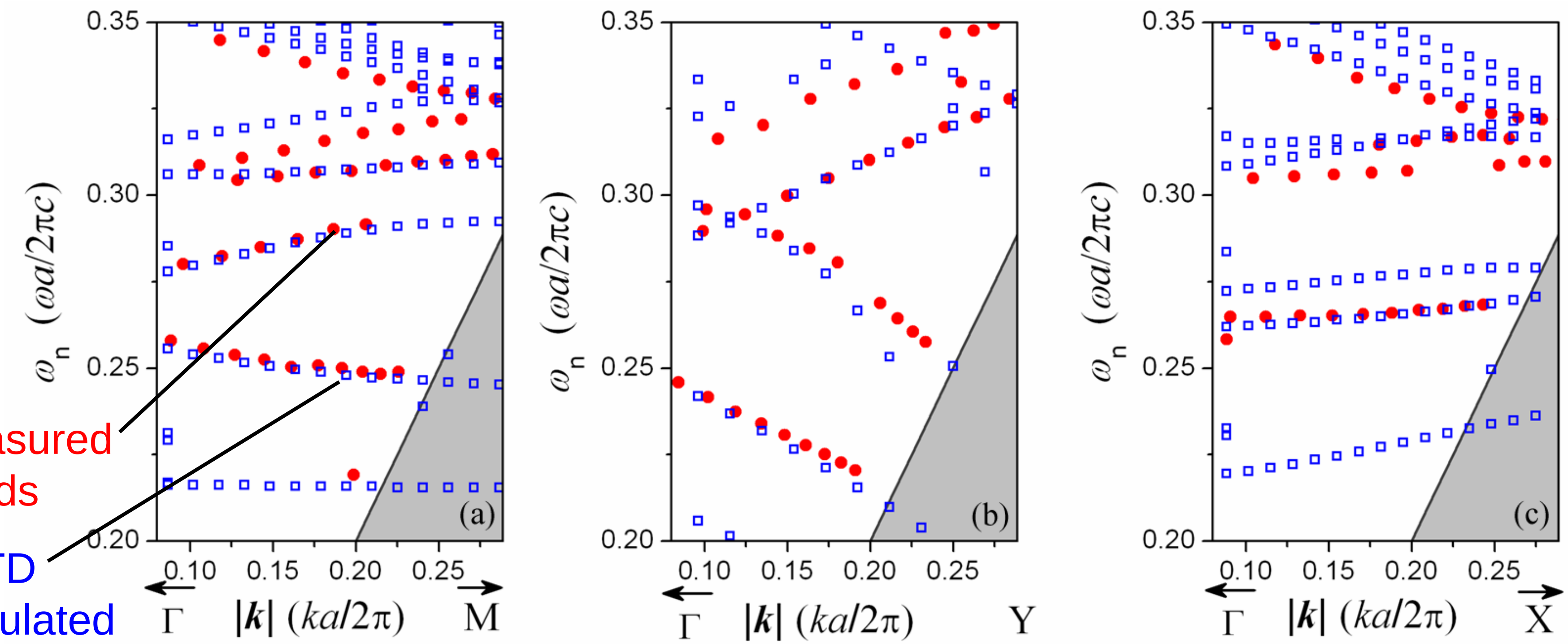
Triangular Lattice



SL Lattice

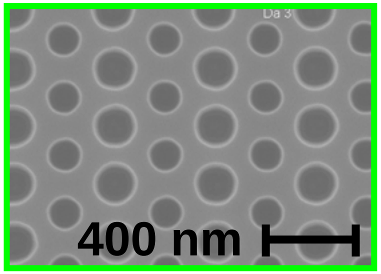


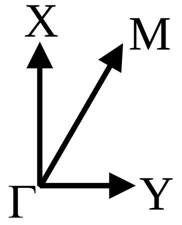
Superlattice: Measured & Calculated Bands



Measured bands

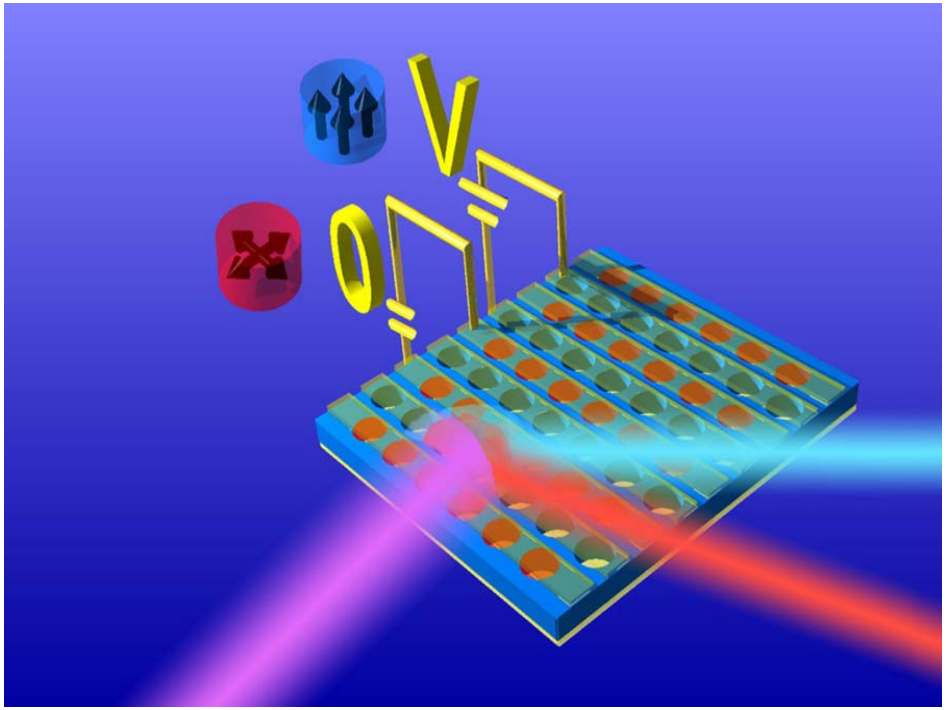
FDTD calculated bands





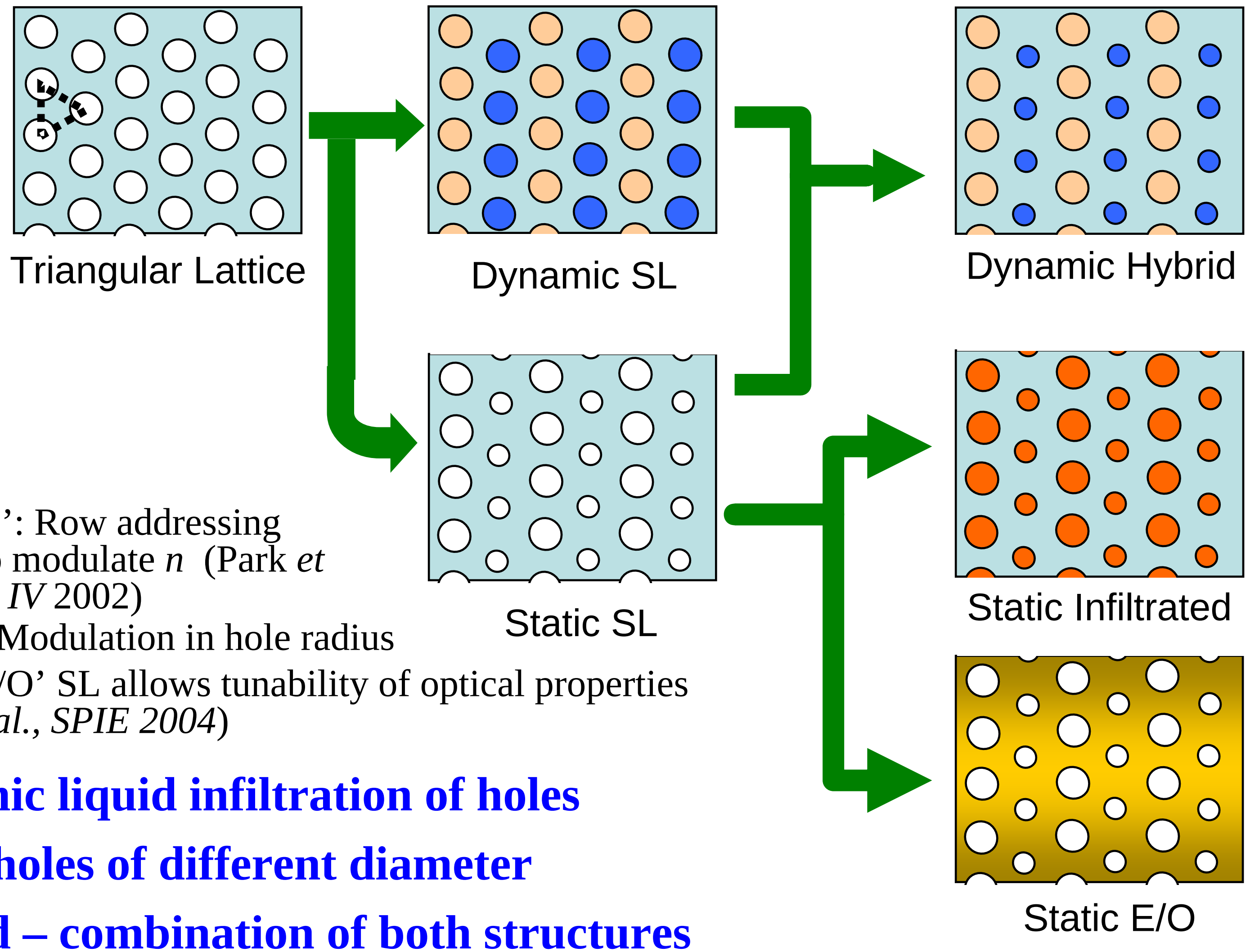
- Dips in spectrum filtered and plotted as *ω* vs. *k*
- Full 3D FDTD calculations to match structure

Tunable Structures



- **Concept:**
  - **Dynamically change lattice property, i.e. refractive index, while under excitation**
- **Consequences:**
  - **Active beam steering**
  - **Tunable filtering**
  - **Signal modulation**

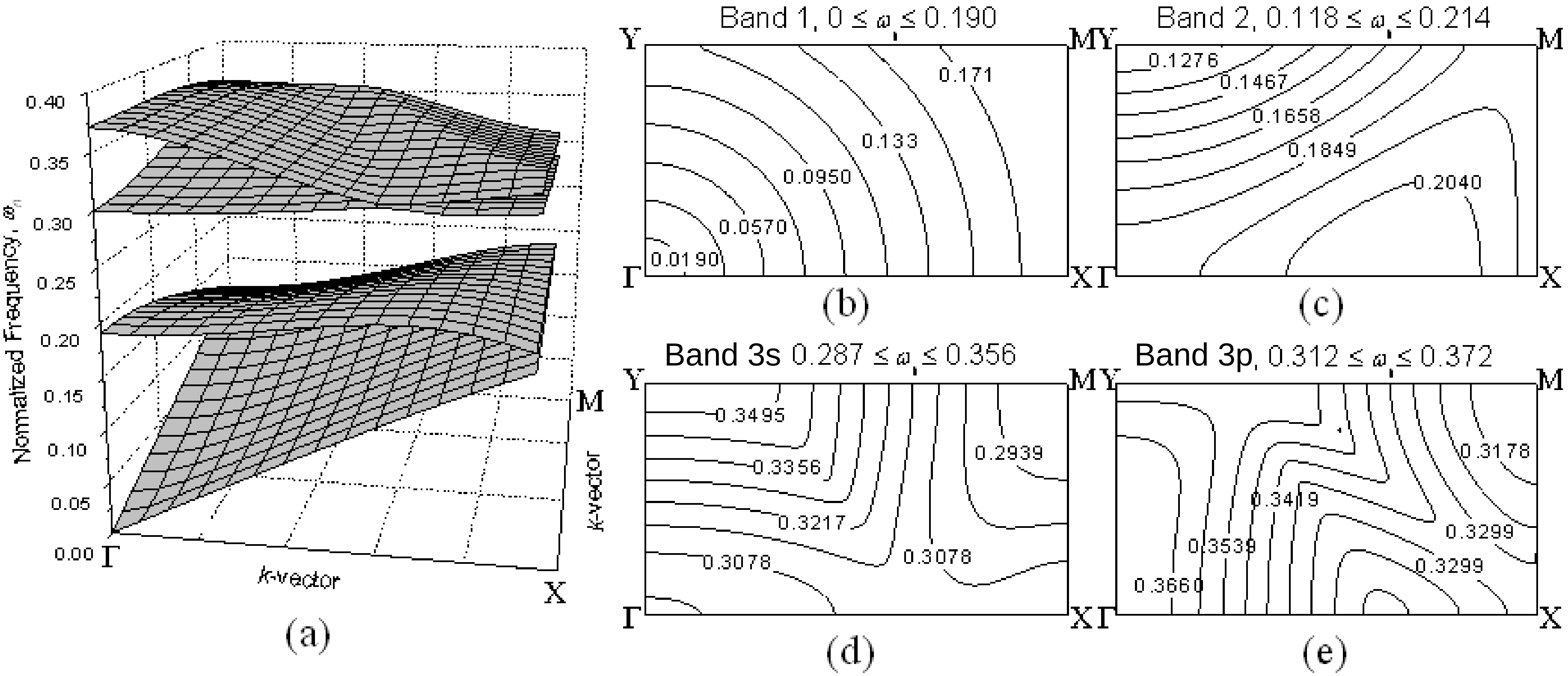
Superlattice Photonic Crystal Structures Based on Triangular Lattice



- ‘Dynamic’: Row addressing scheme to modulate *n* (Park *et al.*, *PECS IV* 2002)
- ‘Static’: Modulation in hole radius
- ‘Static E/O’ SL allows tunability of optical properties (Neff *et al.*, *SPIE 2004*)

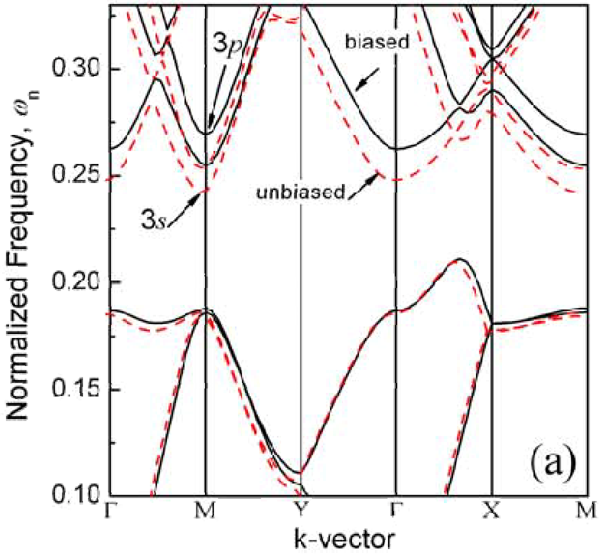
- **Dynamic liquid infiltration of holes**
- **Static holes of different diameter**
- **Hybrid – combination of both structures**

Dispersion Surfaces for First Four Bands of SSL Structures

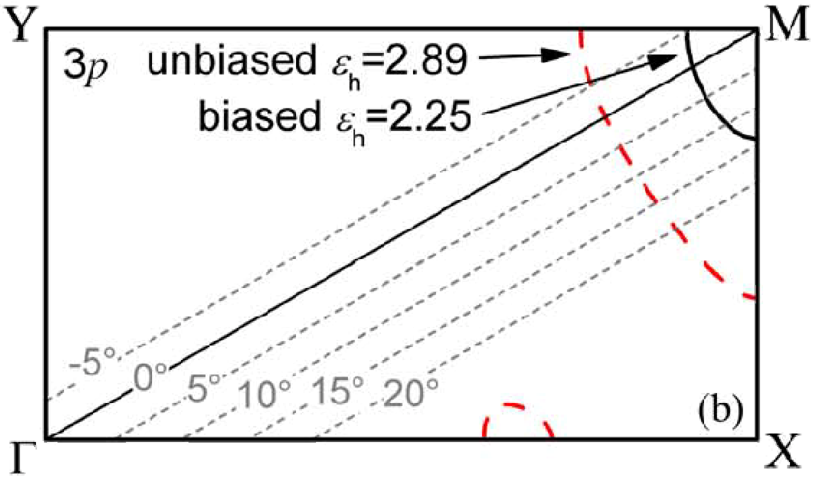


Band Structure and Dispersion
Large Area Addressed Static Infiltrated Superlattice

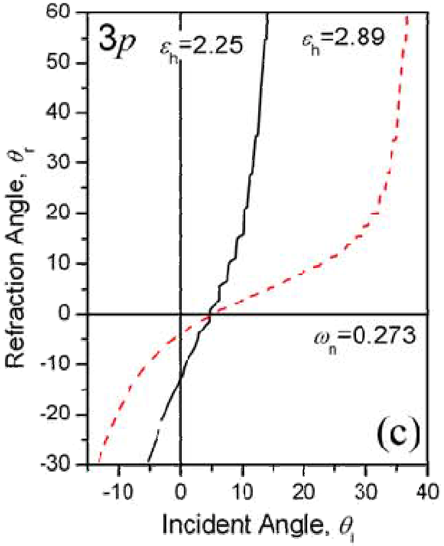
Band Structure

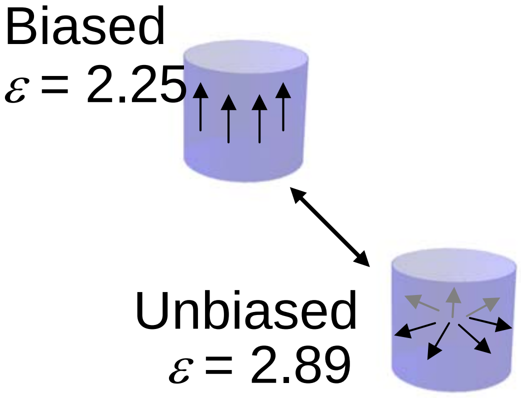


Dispersion Contours



Refraction





Biased
ε = 2.25

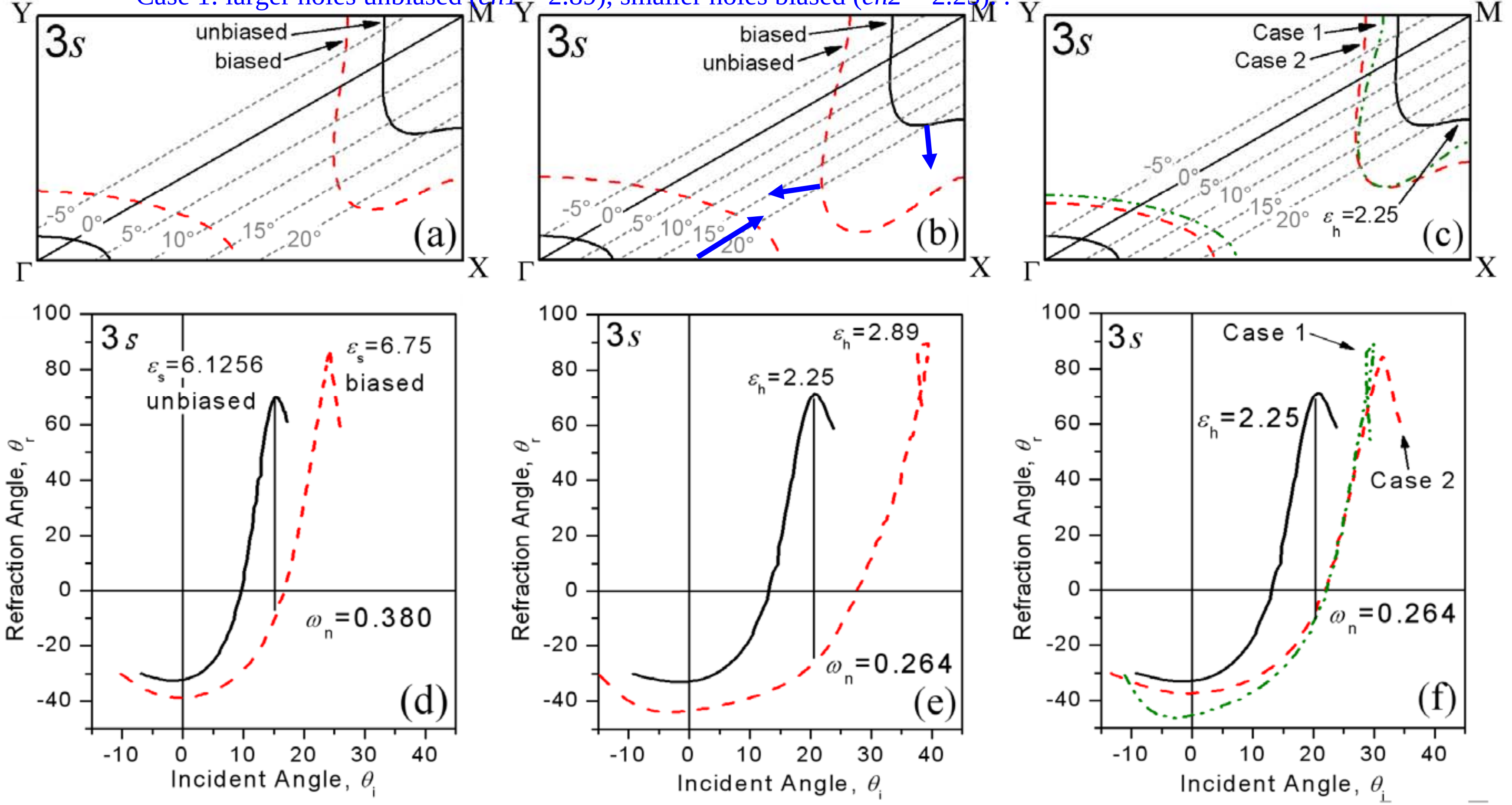
Unbiased
ε = 2.89

- Changing bias/unbias state changes alignment of LC director → changes ε
  - Changes band structure
  - Changes dispersion contours
  - Changes refraction response

Dispersion Contours and Refraction for Three SSL Devices -3s Band

- (a & d) EO superlattice, (b & e) Hybrid Static superlattice, (c & f) inter-digitated SL

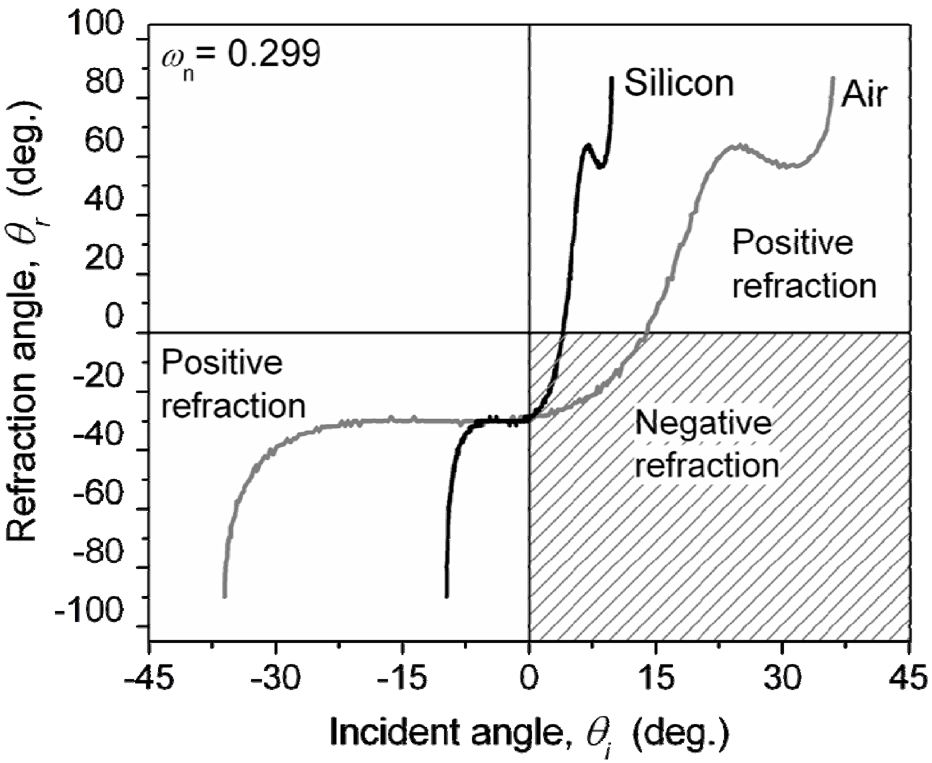
Case 1: larger holes unbiased (*eh1* = 2.89), smaller holes biased (*eh2* = 2.25). .



- For Hybrid Static superlattice, refraction changes from negative to positive with bias

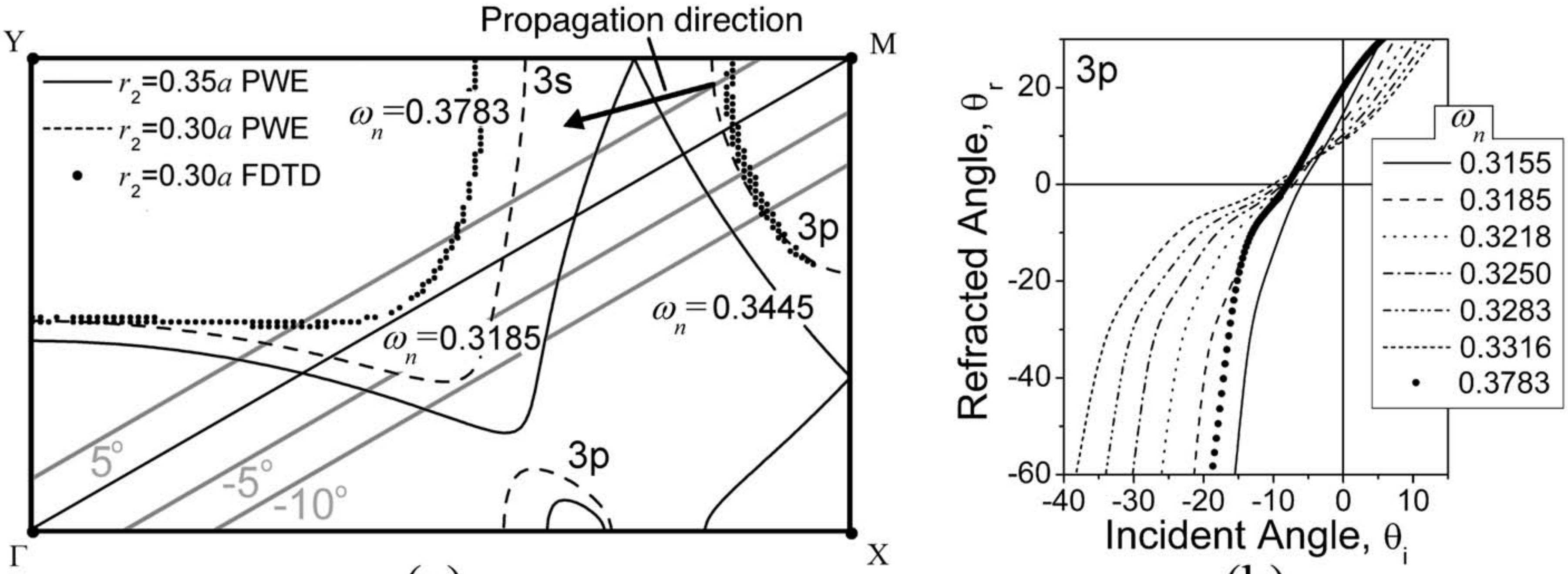
  $\Delta\theta_r = 96^o$ – of the order of 80^o for other structures

Positive & Negative Refraction



- Positive refraction → 'Snell's law' like refraction, *i.e. n* is positive
- Negative refraction → *n* is negative in Snell's law
- Square and Triangular PCs → only negative OR only positive at a fixed frequency
- SL PC → Both regimes at a fixed frequency

Dispersion Contours for SSL-Structures & Spectral Dispersion Properties

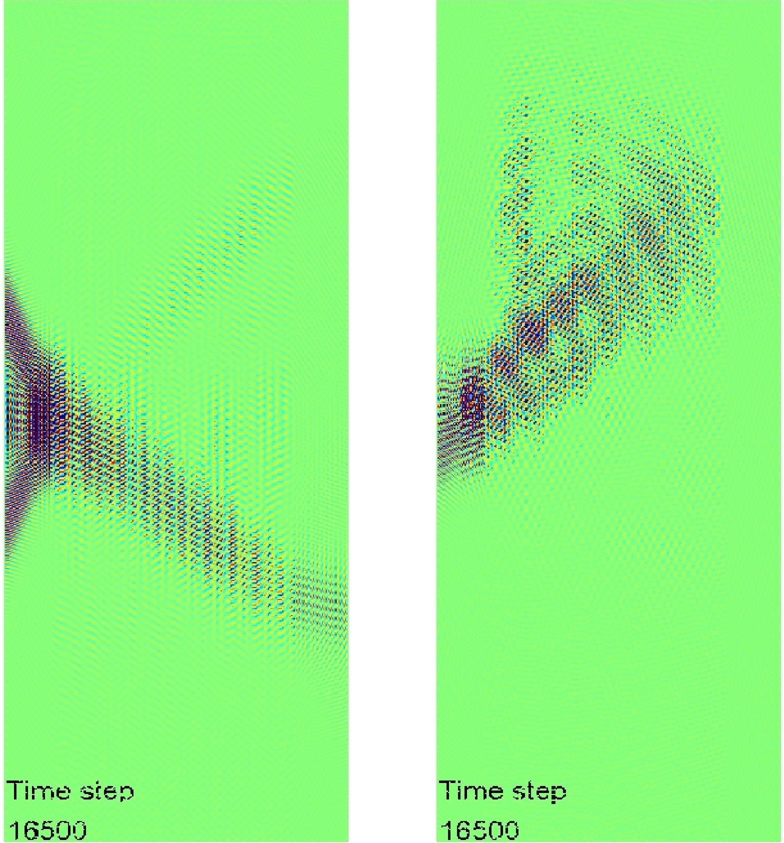


(a) (b)

- TE polarization dispersion contours for SSL structure calculated with PWE method
  - SL strength of 1.0 (solid line) and 0.857 (dashed line)
- FDTD method for SL strength of 0.857 (scattered dots),
- Gray lines show construction lines for a beam of w_n = 0.3185 incident from air
- Spectral Dispersion for r_2/r_1 = 0.857 for range of w_n with 1% spacing between frequencies (group of lines) 2D slab waveguide structure (scattered plot)

FDTD Visualization of Refraction in SSL

- Investigation of effect coherence on refraction



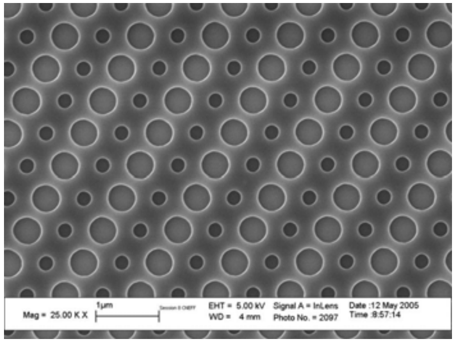
$\theta_i = 0^\circ$

$\theta_i = 12^\circ$

Normalized frequency = 0.309

Static superlattice structure

- Static SL PC surrounded by silicon
- Gaussian beam: launched at incident angles of 0 and 12^o. Width 24a.
- Beam steering:
  - -40.5^o for $\theta_i = 0$
  - 47.15^o for $\theta_i = 12^o$
- SL parameters $r_1=0.35a$ and $r_2=0.3a$
- SL strength: $r_2/r_1 = 0.875$



2D Photonic Crystal Structures

- Control Over Dispersion Surface
  - Low Divergence “virtual waveguides”
    - Beam divergence reduced by factor of ~10
    - Optical interconnects
    - Sensor Technologies
  - Fabry-Perot Interferometer
    - Suitable for wavelength selection, beam width control
    - Chemical and Biological Sensing
  - Negative Index Structures
    - Pendry lens: Refractive Index of -1

2D Superlattice Structures

- **Successfully developed new concept of SL PC**
  - **Experimentally observed 'band folding' effect**
- **Demonstrated that SL significantly enhances tunability, by order of magnitude, for refraction & dispersion**
- **SL introduces unique optical properties and new regimes for beam propagation effects**
  - **Δr or Δn between adjacent rows of holes creates a SL photonic crystal- Greater sensitivity to Δn by optimization of hole size ratio, r_2/r_1**
  - **The superlattice lowers the symmetry of the structure causing:**
    - **BZ folding: Band splitting removal of modal degeneracy**
    - **Highly curved Dispersion Contours near BZ boundaries**
    - **Positive and negative refraction**
    - **Beam steering of > 90 degrees**
- **Hybrid superlattice enhances tunability of optical properties**

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