Photonic Crystals with Tunable Refraction and Dispersion

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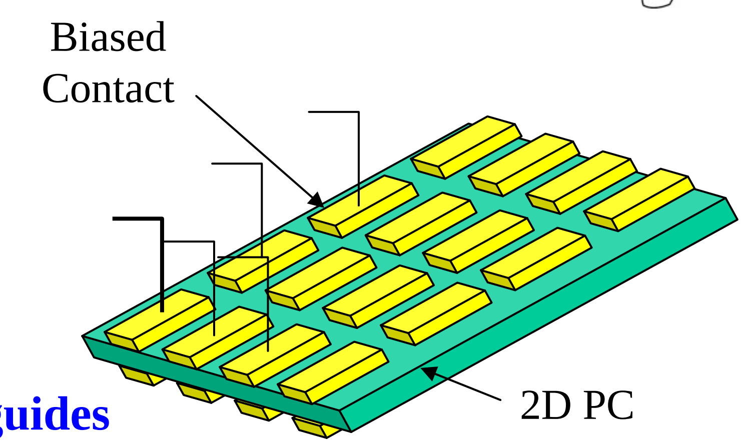
Outline

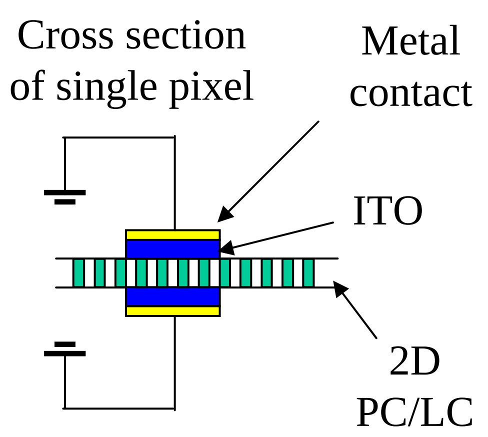
- **Motivation**
  - New ways to control beam propagation in slab waveguides
  - Modify Dispersion Contours thru impact of new structures & tunable materials
- **2D Photonic Crystal Band Structures**
  - Triangular and Square lattices
  - Superlattices
  - Non-Linear Structures
    - Liquid Crystal Infiltration of 2D PC
    - Electro-Optical (EO) materials
- **2D Superlattice Photonic Crystal Waveguides**
  - Static; Hybrid and E/O superlattice structures;
- **Summary**

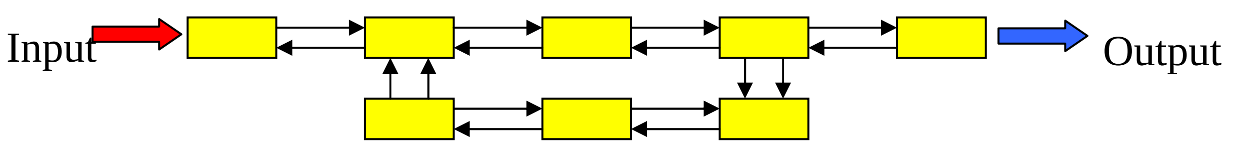
Optical Routing Using Photonic Crystals

- **Conventional waveguide challenges**
  - Cross coupling between adjacent waveguides
  - Difficulties in alignment from outside sources
  - Large bend radii necessary for lossless bends
- **Properties of ideal waveguides**
  - Sharp, lossless 90 degree bends
  - No coupling between adjacent or crossing waveguides



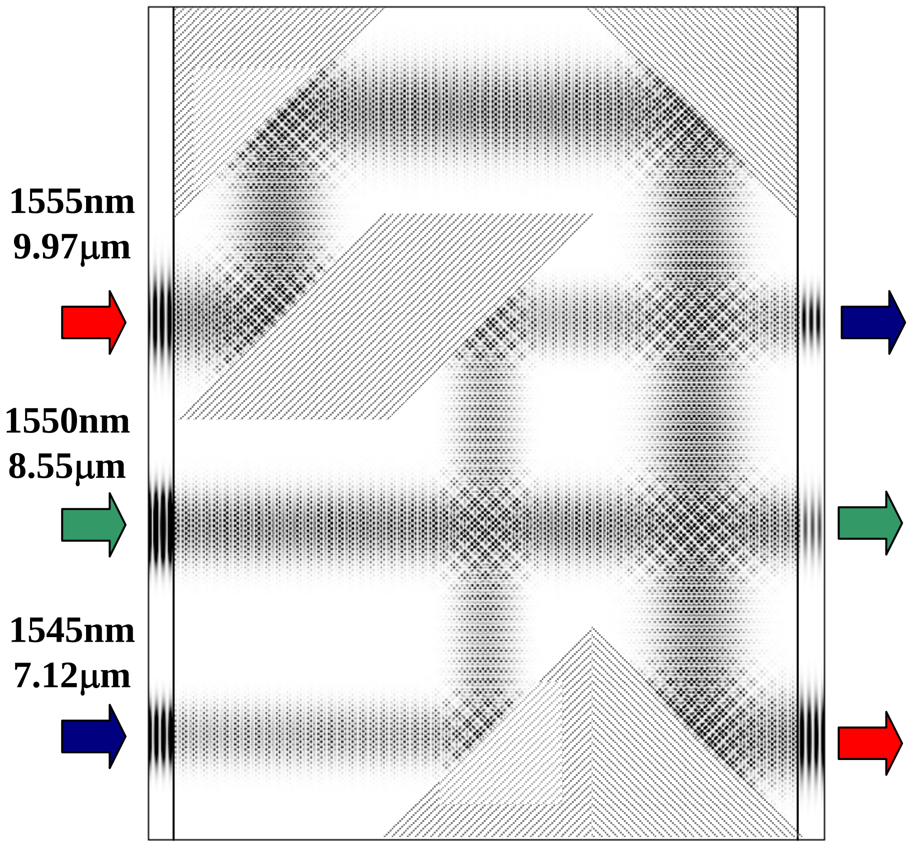
- **Photonic crystal based on line defects**
  - Many systems, guiding, resonators, drop line filters, etc
- **Free-Space Guiding**
  - Virtual waveguiding
    - Low divergence waveguides: "Virtual Waveguides"
  - Free space beam steering
    - Refraction based dynamic tuning





Virtual Waveguide Interconnect System

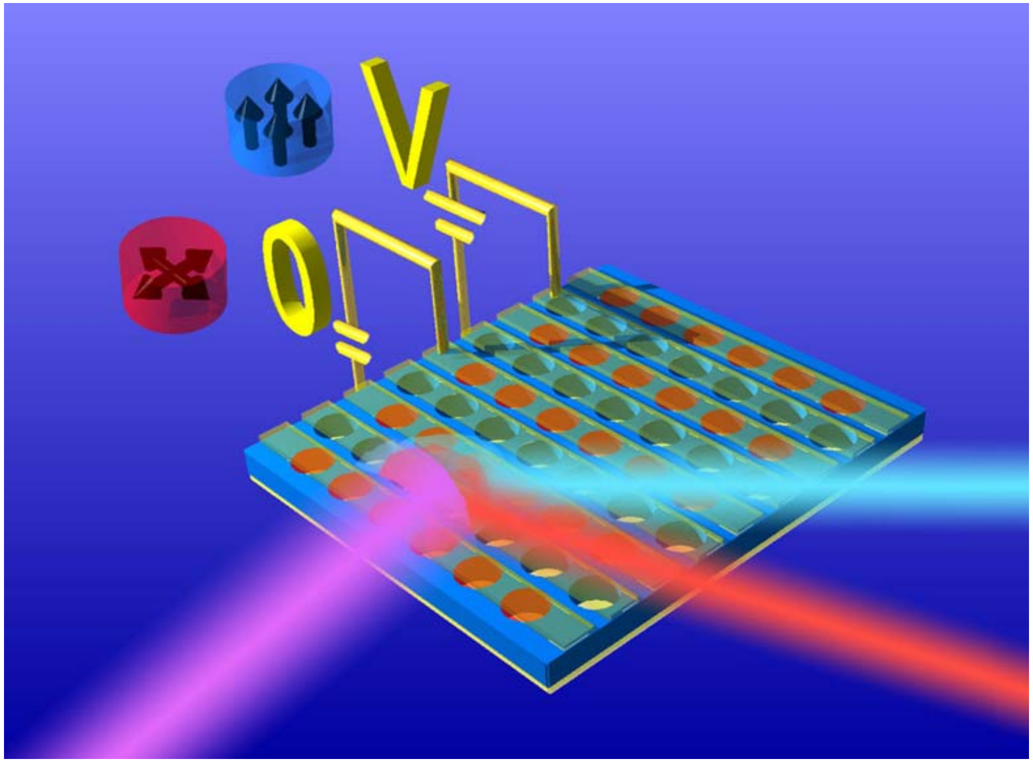
- **Advantages of "free-space" optics**
  - **No coupling**
  - **Intersections allowed**
  - **Broadband operation**
- **Advantages of integrated optics**
  - **Confined beams**
  - **No hermetic packaging**
  - **One lithography step**
- **Disadvantages**
  - **Small feature sizes required (beam size ~15a)**



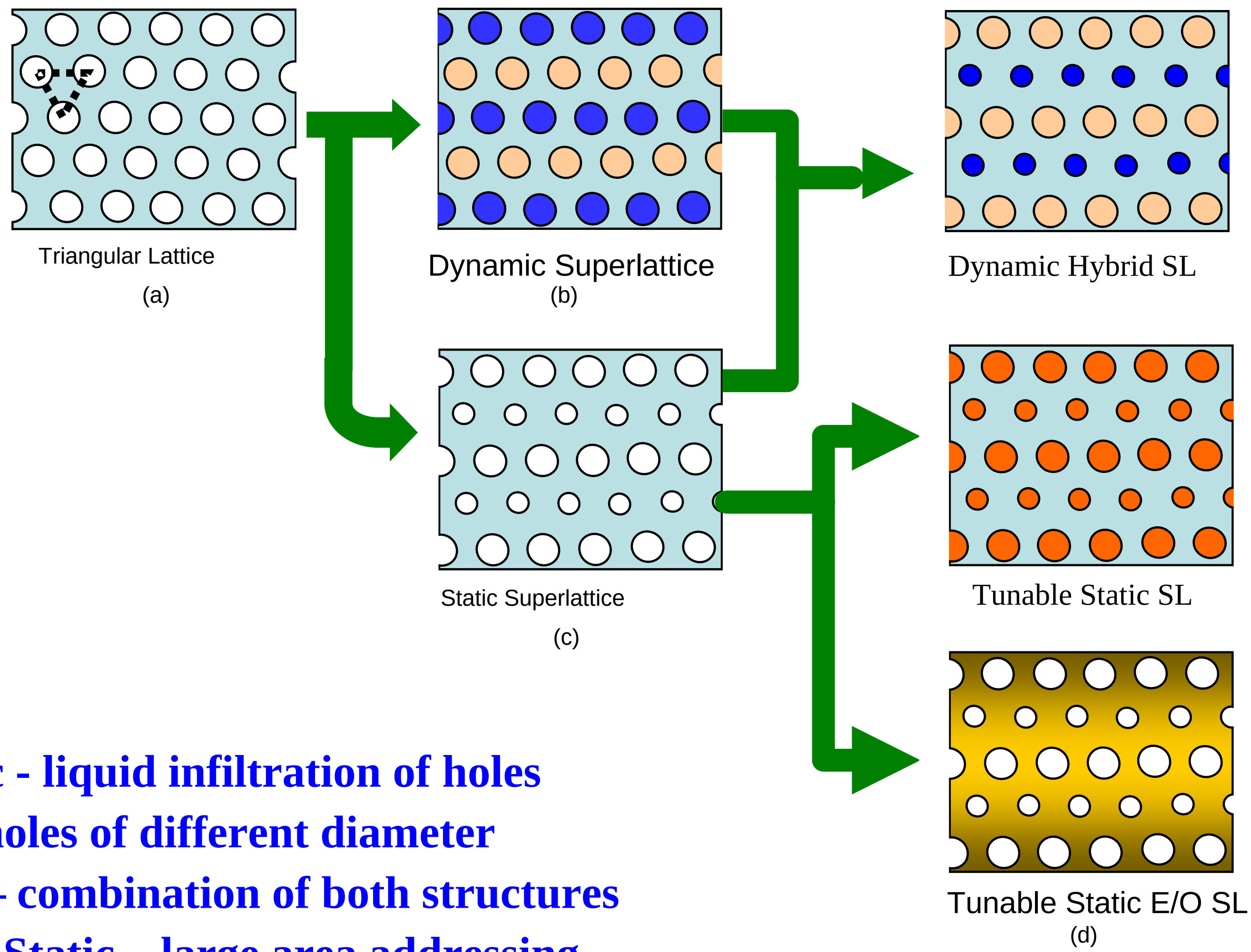
- Tunability in these structures will allow fully reconfigurable circuits
  - PBG modulation introduces mirrors and wavelength tuning

Beam Steering and Dispersion

- **Beam Steering**
  - Tunable refraction
    - Liquid crystal infiltration
    - EO material waveguide
  - Intersections allowed
  - Limited Bandwidth operation
- **Dispersion**
  - Same phenomena as refraction
  - Tunable sweeping of light
  - Mini-spectrometer!
- **Advantages of integrated optics**
  - Confined beams
  - No hermetic packaging
  - One lithography step
- **Disadvantages**
  - Small feature sizes required (beam size ~15a)

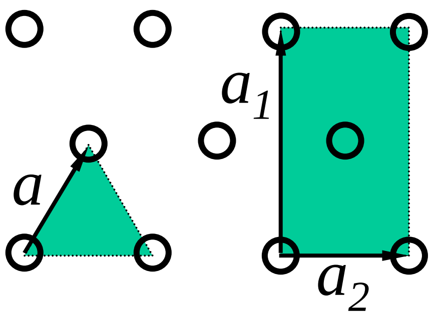


Superlattice Photonic Crystal Structures Based on Triangular Lattice

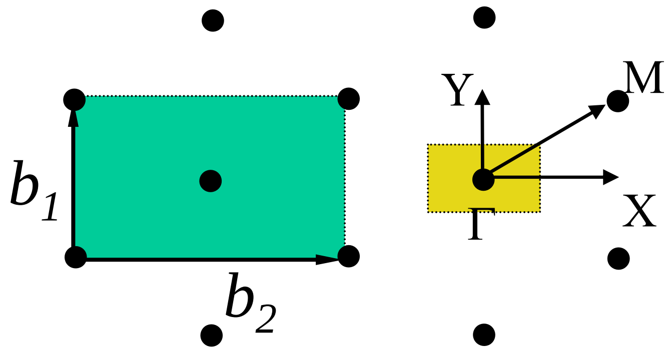


- **Dynamic - liquid infiltration of holes**
- **Static - holes of different diameter**
- **Hybrid – combination of both structures**
- **Tunable Static – large area addressing**
- **Tunable EO Static SL – large area addressing**

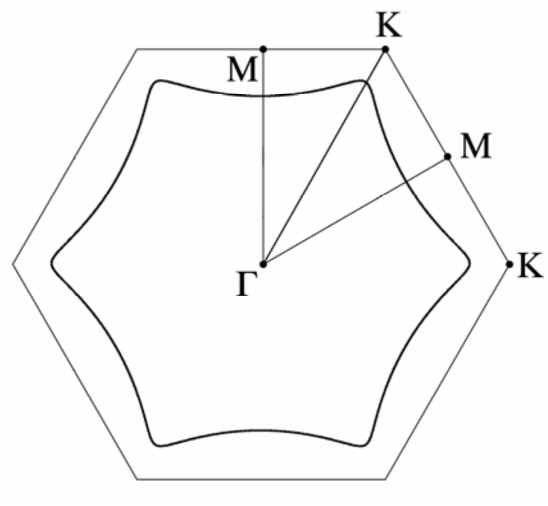
Relationship Between Real & Reciprocal Space for SL

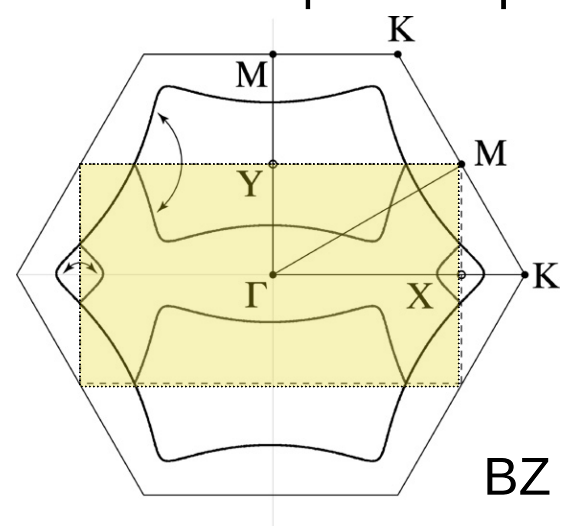


Real Space



Reciprocal Space

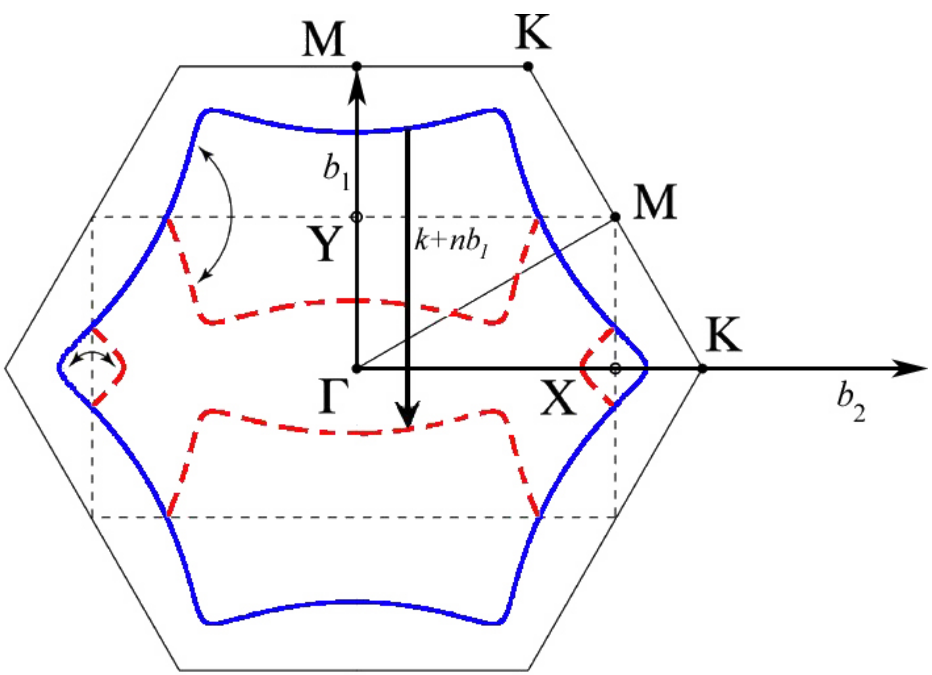


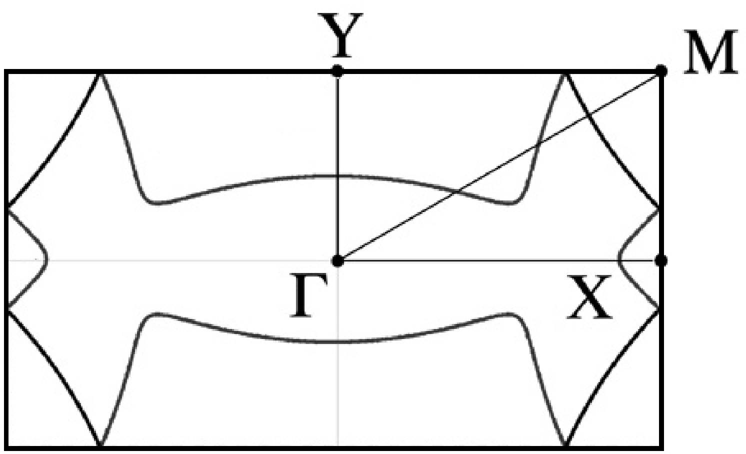


BZ Folding

- Alternating rows posses different property (Δr, Δn, or both)
- New unit cell definition with two holes per lattice point
- New BZ representation: symmetry reduction, hexagonal becomes rectangular: BZ folding

BZ folding in Reciprocal Space

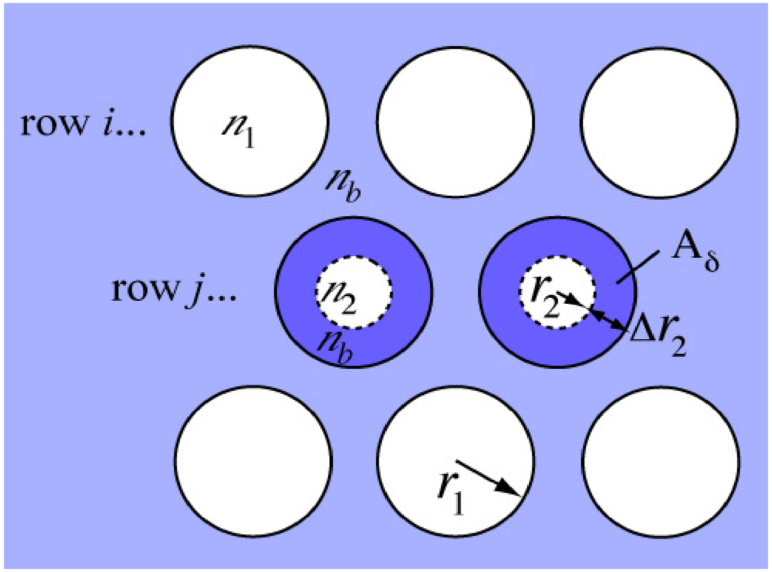




- Hexagonal BZ representation becomes rectangular due to BZ folding

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 Δr
- Thus, r_2 decreased relative to r_1.



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

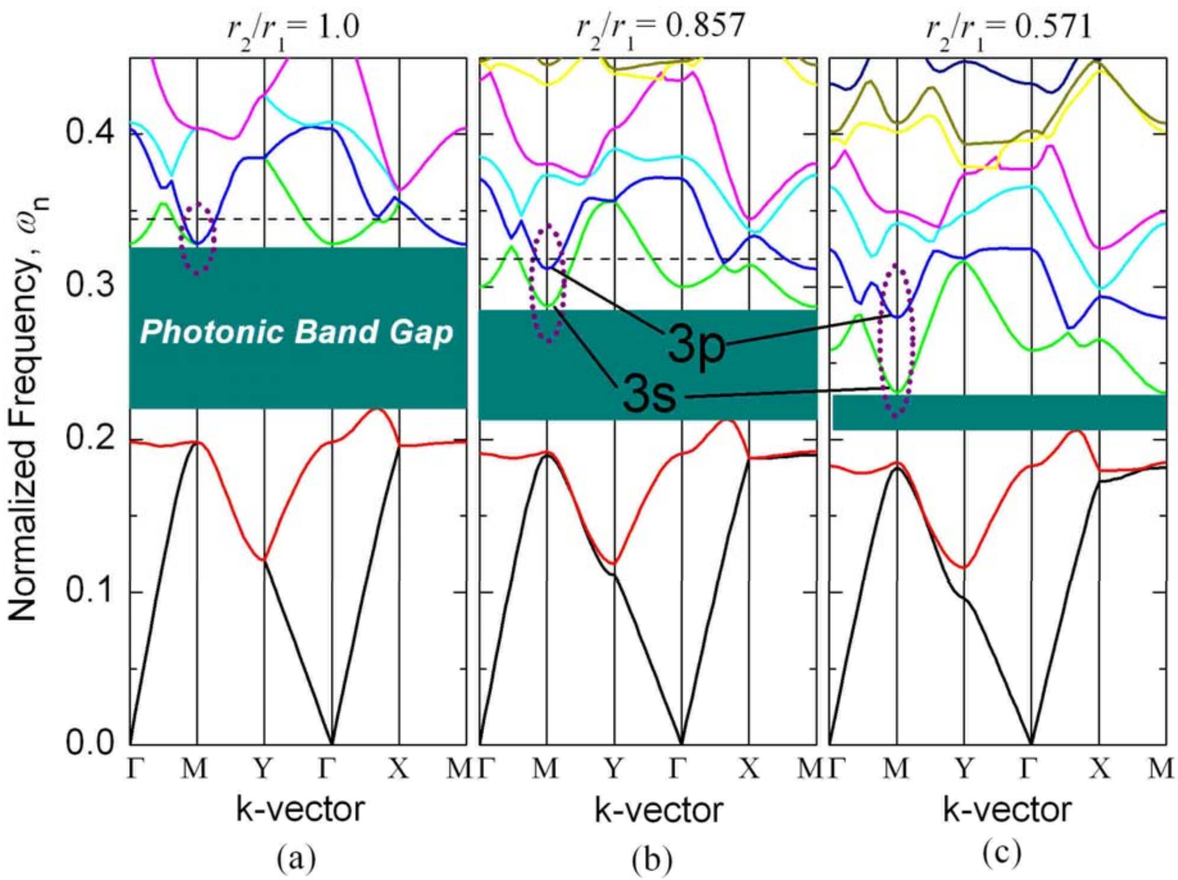
$$n_{eff} = \frac{n_b A_\delta + n_2 A_2}{A_1}$$

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

- In Si, for r_2/r_1=0.857, n_{eff} = 1.654 which is Δn = 0.654 between rows of holes

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

TE polarization

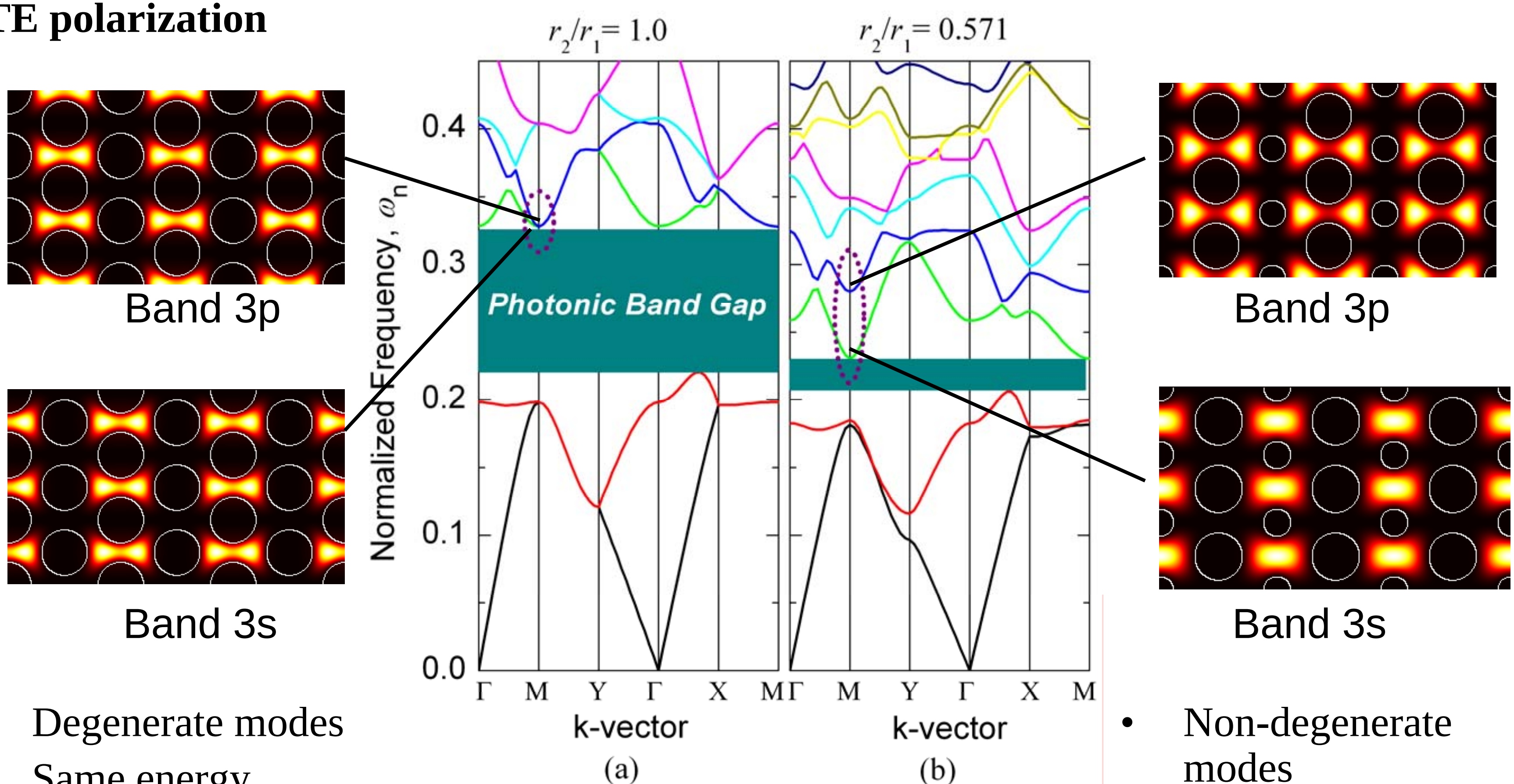


- Decreasing r_2 increases dielectric material in structure
- Stronger effect on air bands than dielectric bands
- Shifts bands to lower frequencies
- Decreases width of PBG
- Increases band splitting
- Similar effect in dynamic superlattice when changing Δn

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

Magnetic Field Power Distribution

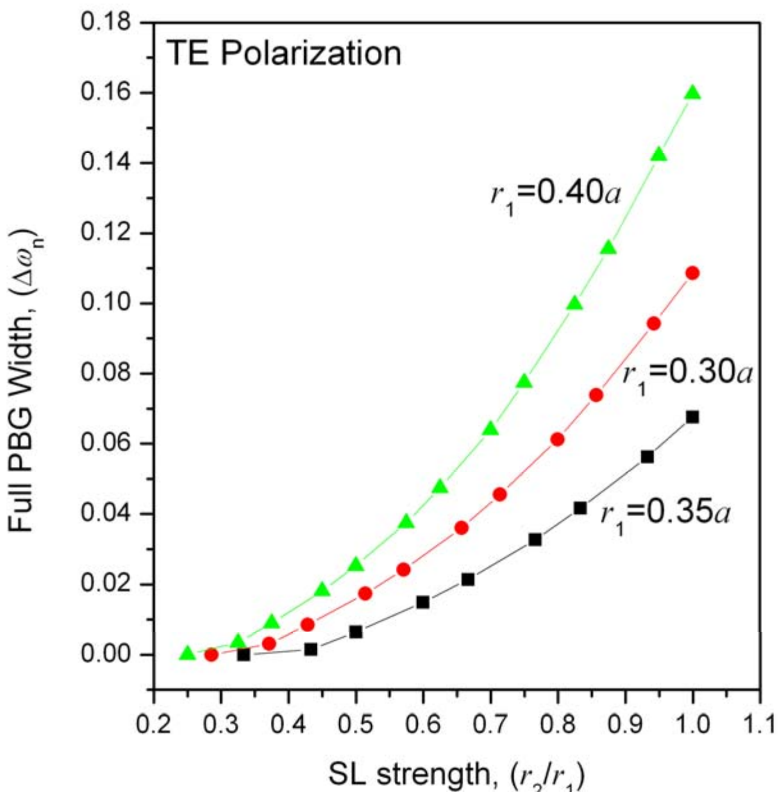
TE polarization

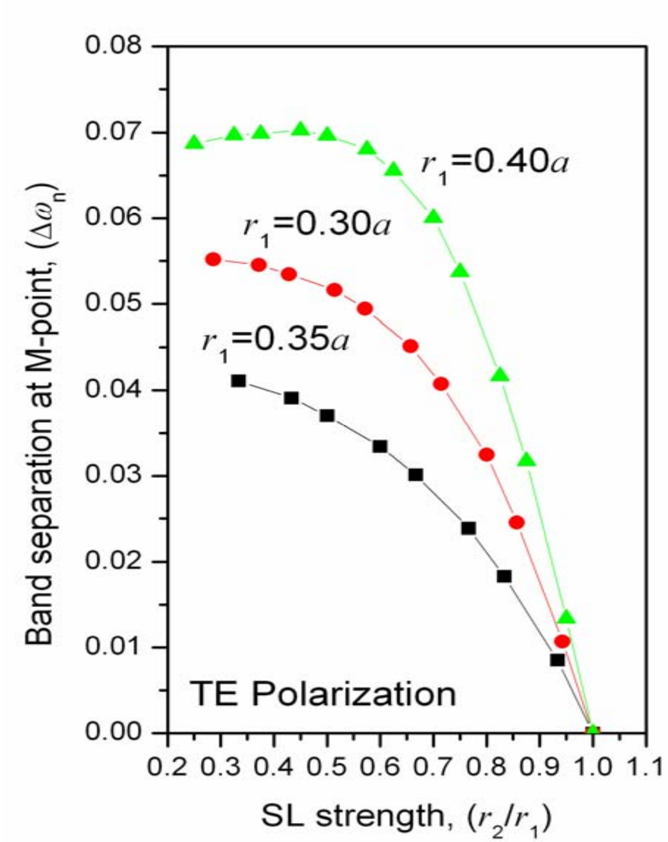


- Degenerate modes
- Same energy density in each mode

- Non-degenerate modes
- Band 3p power > 2X Band 3s

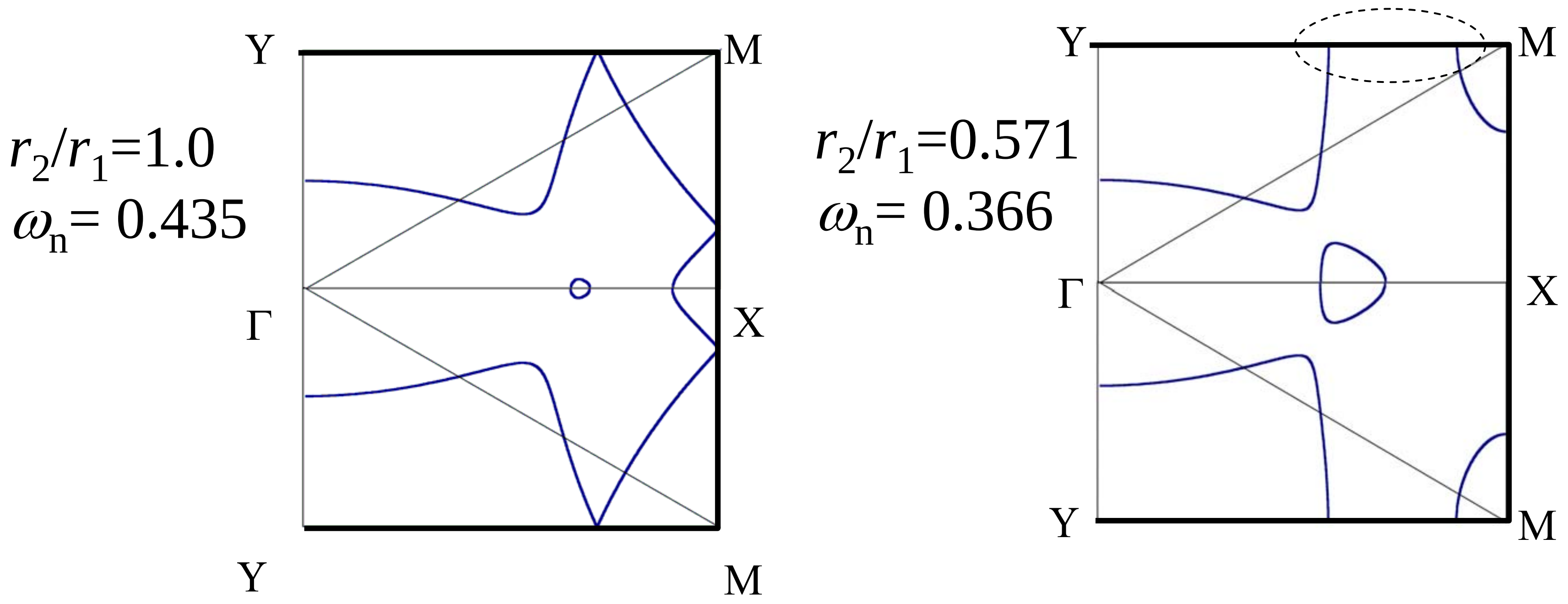
Static Superlattice PC: Dependence of PBG & BS on Hole Radii Ratio





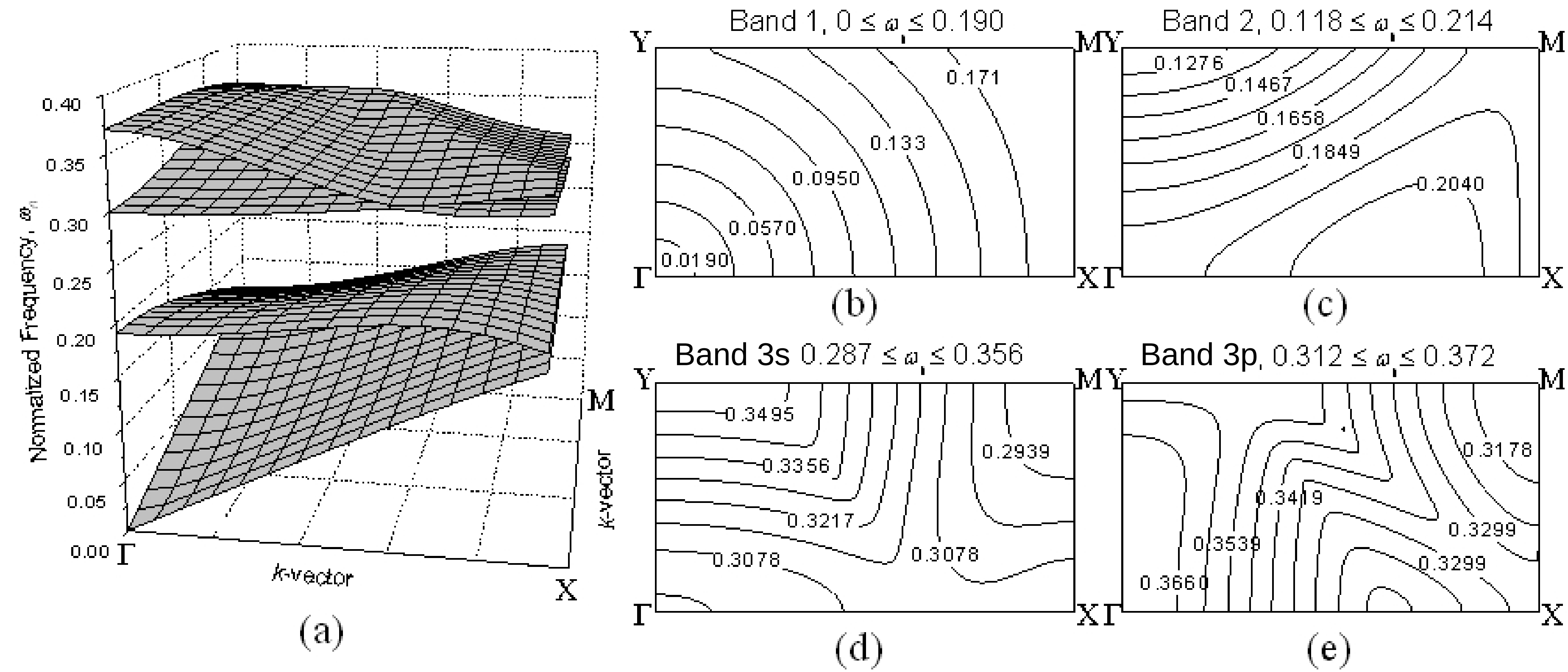
- Dependence of PBG & Band Splitting on radius ratio:
  - For radii of r_1 between 0.30*a* and 0.40*a*
  - Trade off between Gap width and band splitting
  - Band separation strong for r_2/r_1 between 1.0 and 0.55, still have a PBG.

Dispersion Contours: Dependence on r_2/r_1

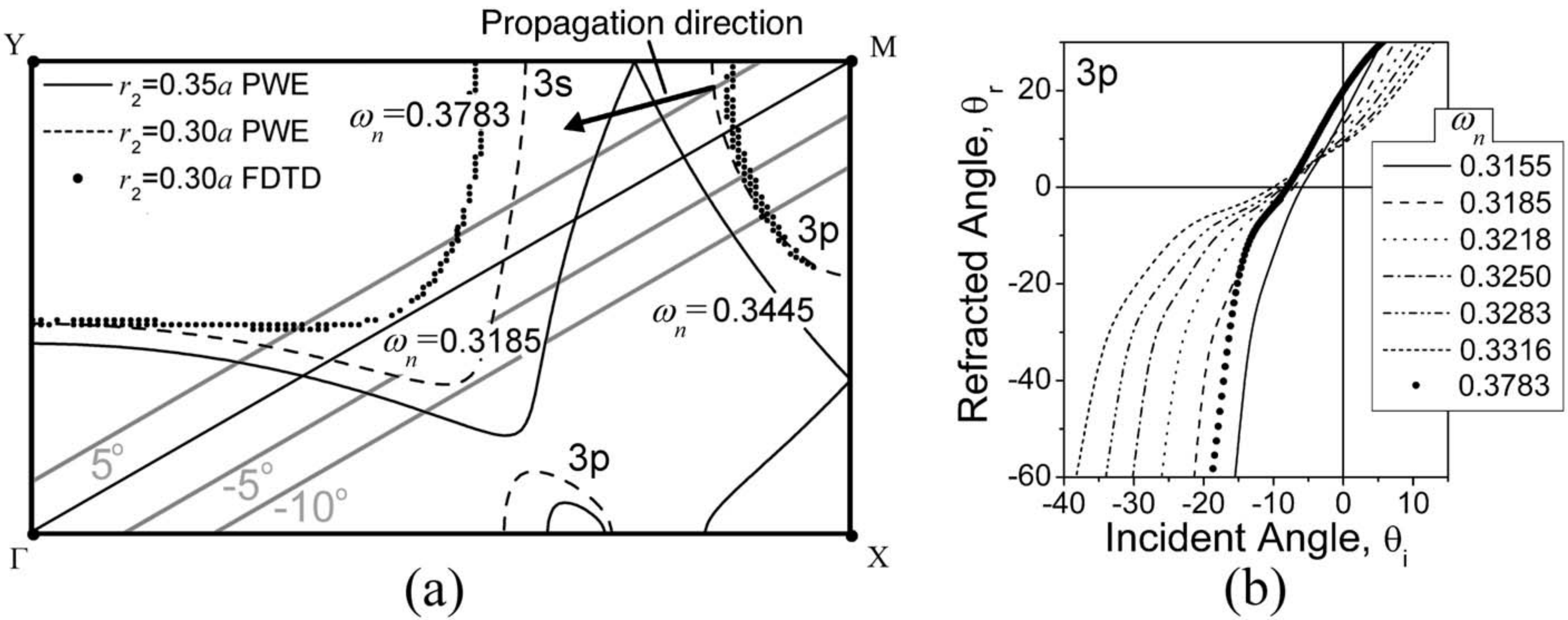


- For Δr = 0, **(r_2/r_1=1)**, BZ folding scheme straight forward: curves converge to a single point at BZ boundaries.
- Radius modulation **(r_2/r_1<1)**: curves diverge/repel at BZ boundaries
- Net result: relatively flat curvature in center of BZ with high curvature near BZ boundaries

Dispersion Surfaces for First Four Bands of SSL Structures



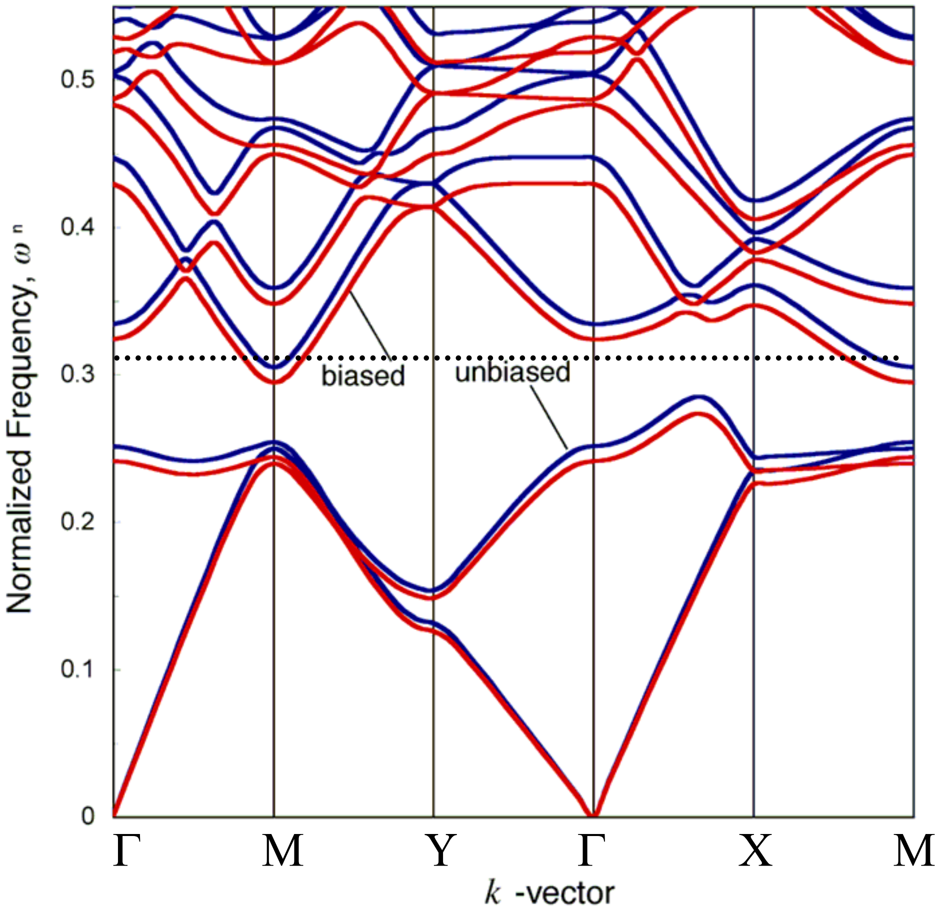
Dispersion Contours for SSL-Structures & Spectral Dispersion Properties



- **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)**

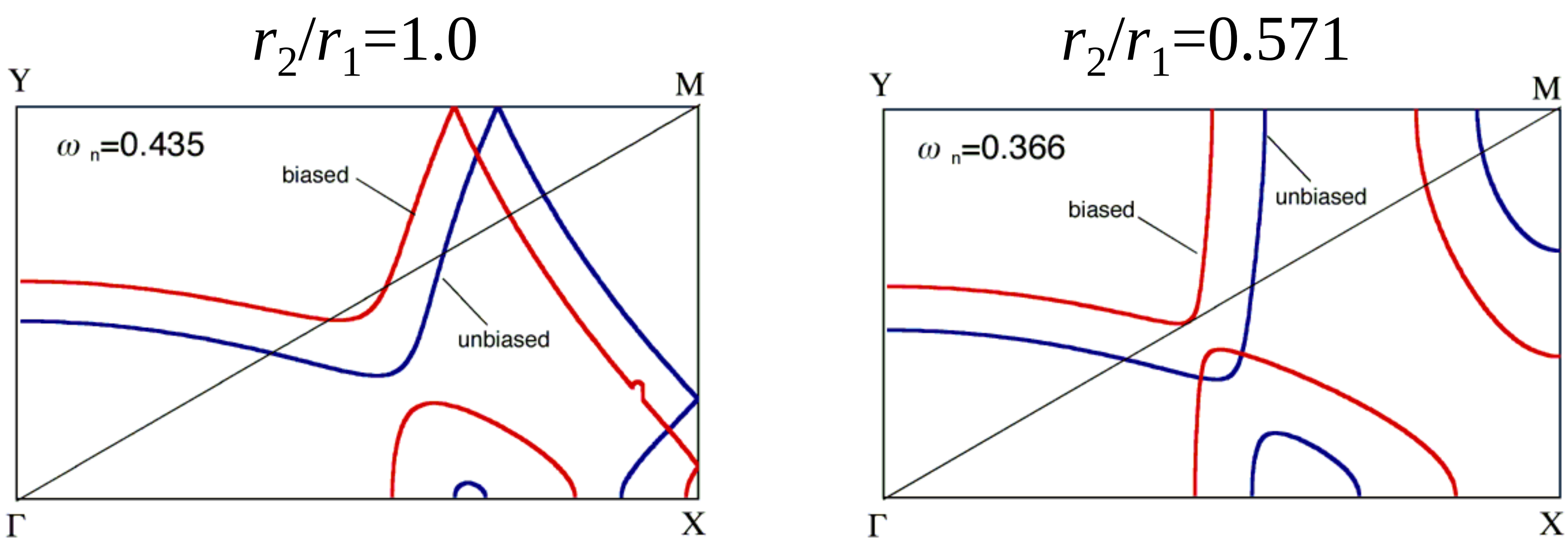
Dynamical Tunability: Voltage Bias Band Structure Effects

r_2/r_1=0.571



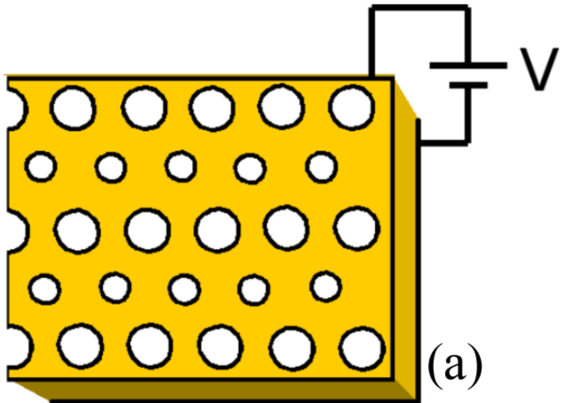
- Bias of 6 V/μm
- Increase n from 2.49 to 2.598 (Δn~ 0.11)
- Moves bands to lower frequencies with bias
- Equifrequency line intersects bands at different points
- Dispersion surface different for unbiased/biased cases

Dispersion Contours: Bias Effects



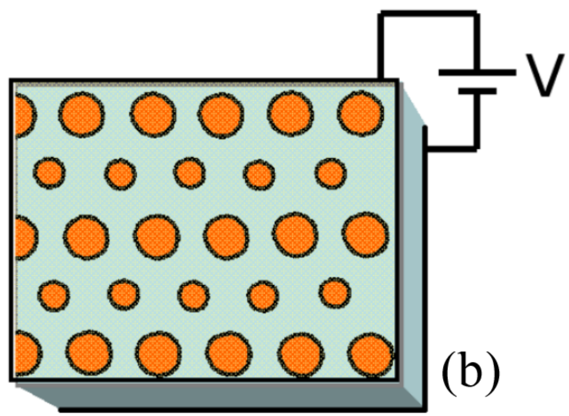
- **Equifrequency plane cuts across two different areas of the dispersion surface**
- **The different areas have similar contours, but they are shifted.**
- **Different contours results in different optical responses**
  - **Refraction/Beam steering**
  - **Switching/Modulation**
  - **Dispersion**

Different Biasing Schemes for Tunable Device Structures



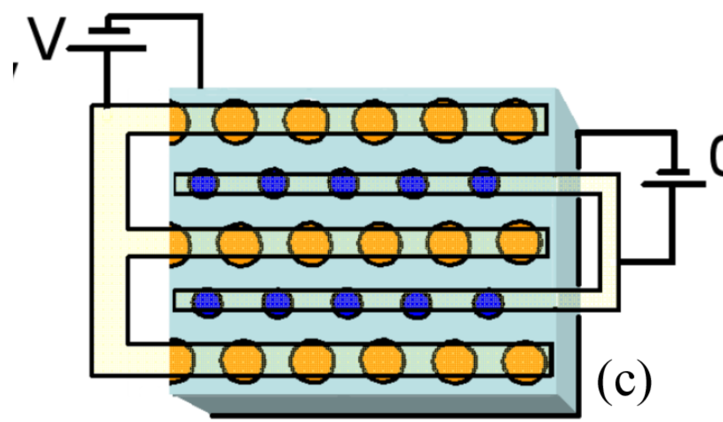
(a)

EO Static SL -- uniform large area bias



(b)

Hybrid (LC infiltrated) SL -- uniform large area bias

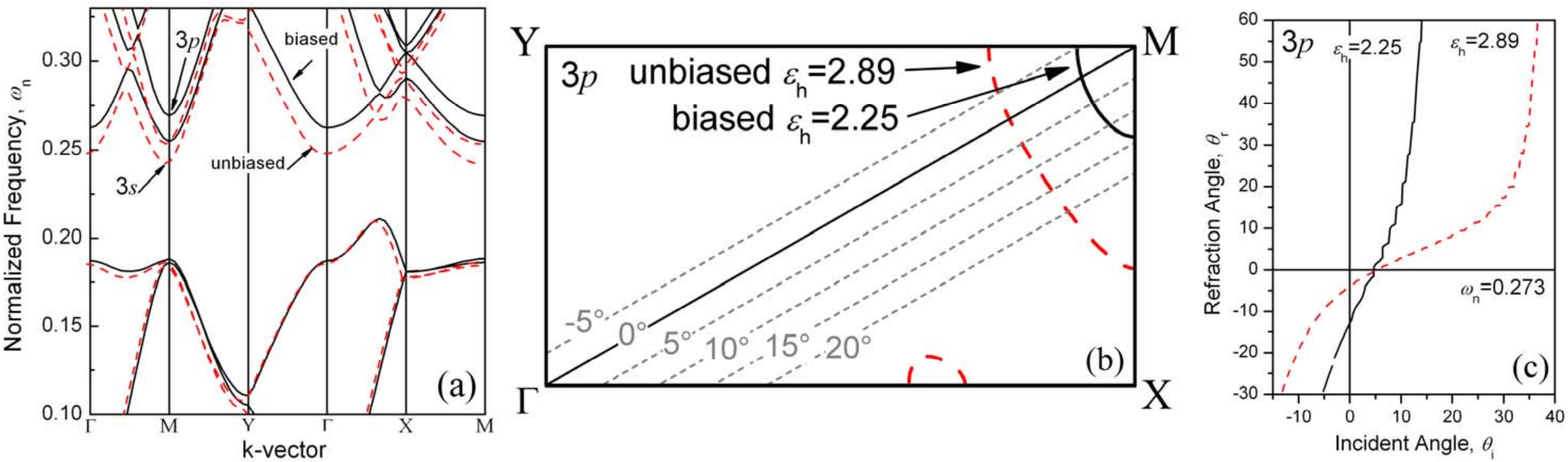


(c)

Inter-digitated SL – row biasing

Band Structure, Dispersion & Refraction for LC Infiltrated Static Superlattice

Band structure, Dispersion contours & Refraction response of 3*p* band (normalized frequency of w_n=0.273)



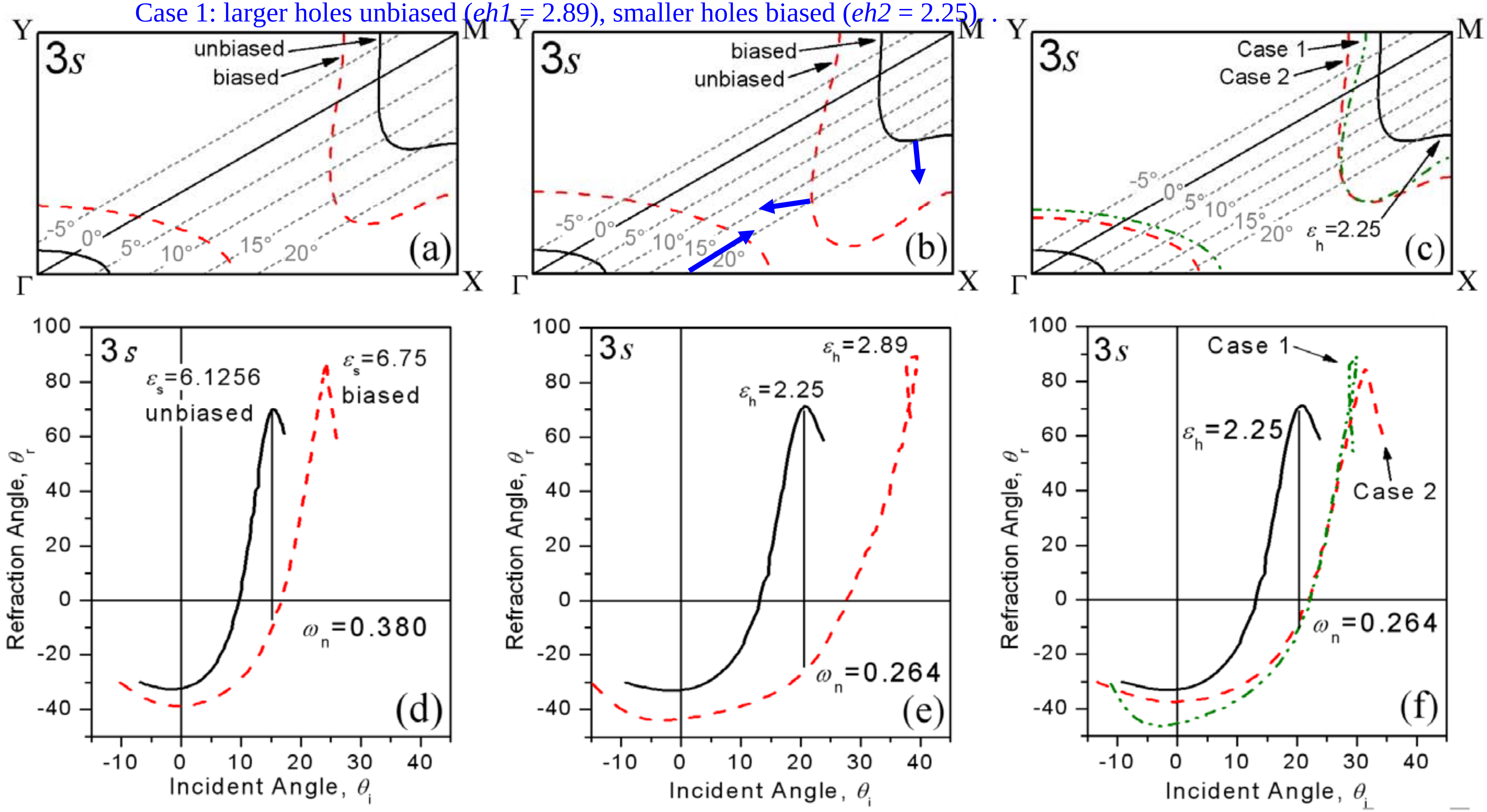
Large Area Addressed SSL
r_2/r_1 = 0.875
w_n=0.273)

Tunability of refraction angle
$\Delta\theta_r \sim 55^o$, EO SSL (10^o)
$\Delta\theta_r \sim 55.3^o$, infiltrated SSL ($14^o$)
$\Delta\theta_r \sim 54.3^o$, for Inter-digitated SSL
Tunability limited by relative flat DC

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

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

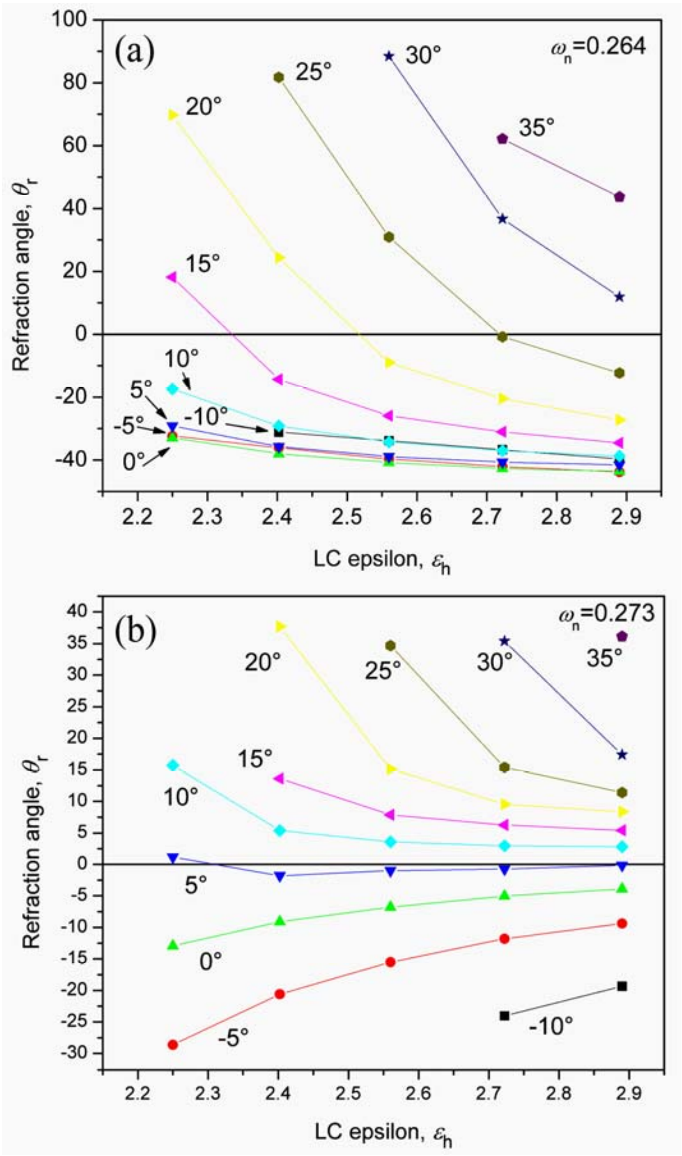
Case 1: larger holes unbiased (*eh1* = 2.89), smaller holes biased (*eh2* = 2.25).



- 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

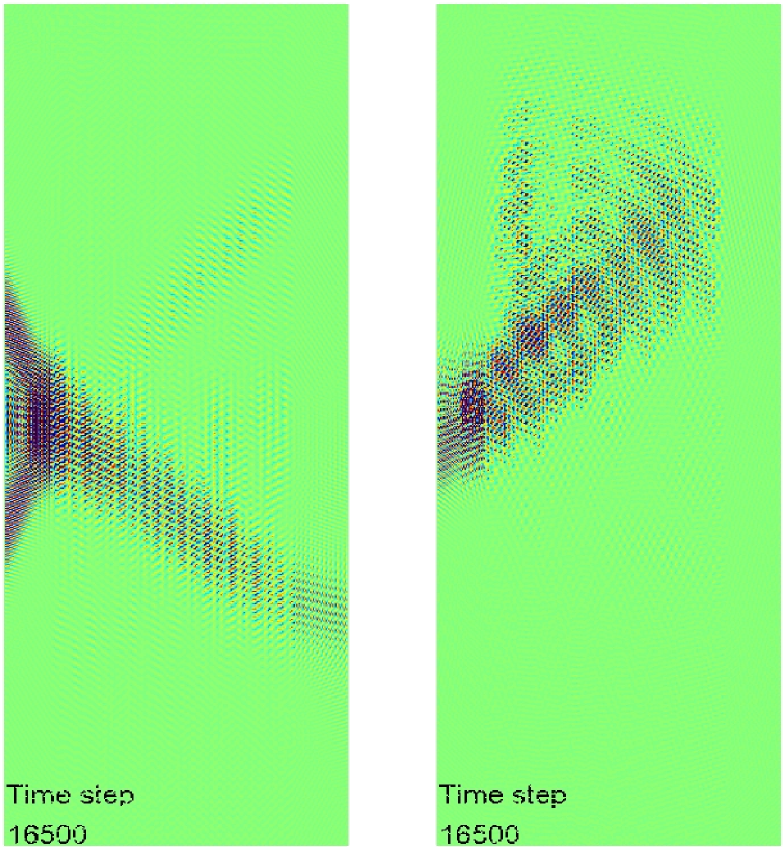
Dependence of Refraction Angle on LC Refractive Index & Angle of Incidence



- Hybrid large area biased SSL structure
- Band 3*s*
  - Normalized frequency of 0.264
  - Incident angles: 0 – 35º.
  - LC index 2.2 to 2.9
  - Dependence of θ_r slower than 3p
  - □ $\Delta\theta_r$ almost twice than in 3p band
- Band 3*p*
  - Normalized frequency of 0.273
  - Incident angles: -10 to 35º.
  - LC index 2.2 to 2.9

FDTD Visualization of Refraction Behavior in SSL

- Investigation of effect coherence on refraction

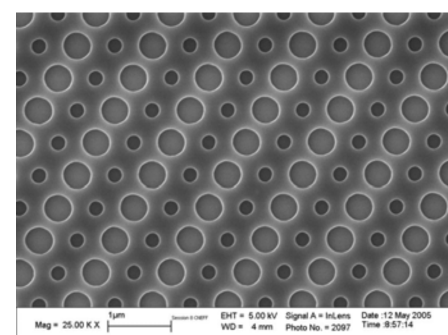


$\theta_i = 0^\circ$ $\theta_i = 12^\circ$

Normalized frequency = 0.309

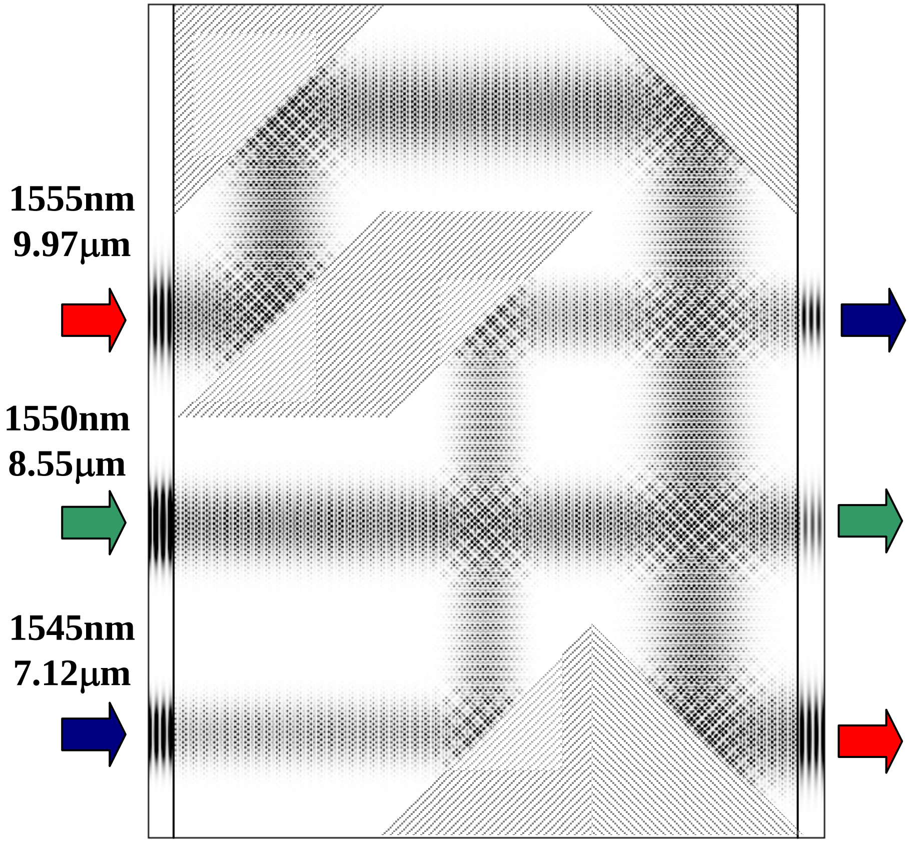
Static superlattice structure

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



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)

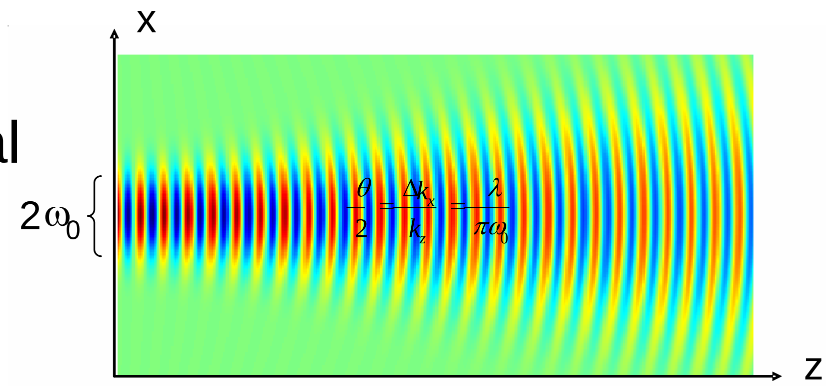


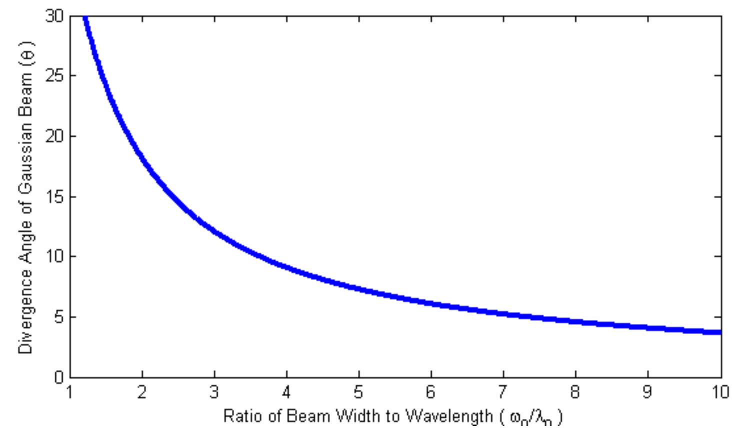
Beam Properties
Divergence Angle of 2D Gaussian Beam

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

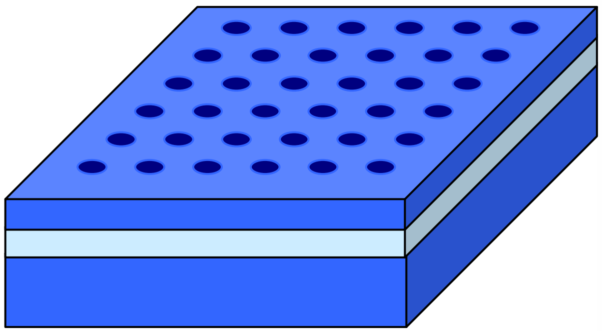
$$\frac{\theta}{2} = \frac{\Delta k_x}{k_z} = \frac{\lambda}{\pi\omega_0}$$

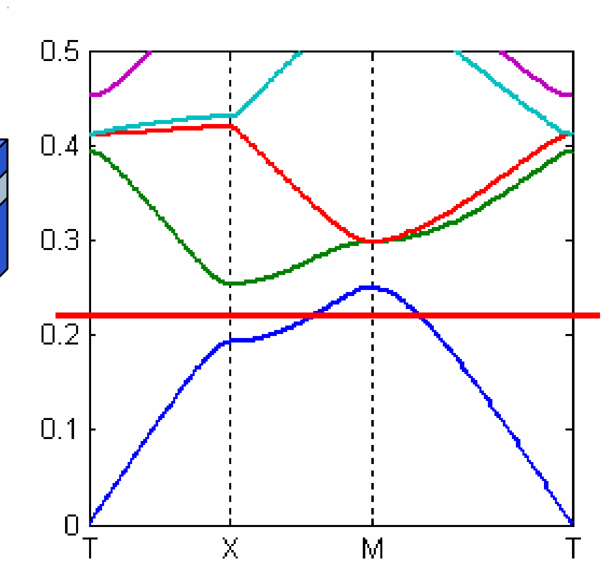
- The divergence determines the coupling efficiency into the photonic crystal

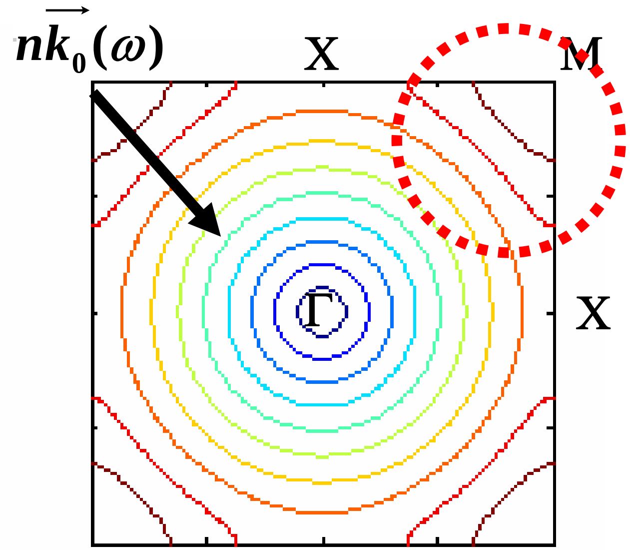




2D Photonic Crystals
Square Lattice

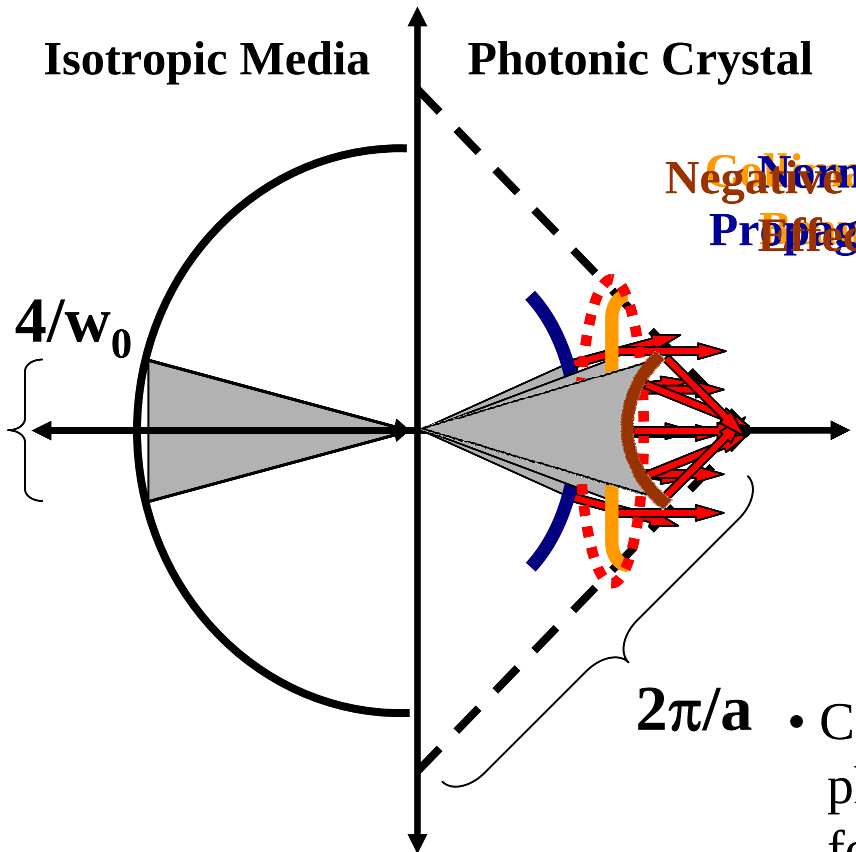






- Square lattice
  - Hole diameter
  - Refractive index
- Band Diagram
  - Boundaries of the band surface
  - Identification of band gaps
- Allowed Wave Vector Curve
  - Equifrequency curves of the band surface
  - Identification of propagation effects

Advantages of Controlling Dispersion Contours



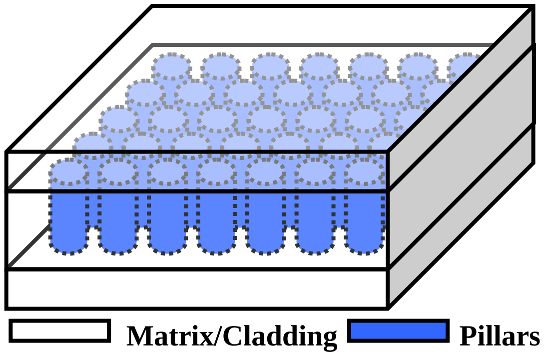
$$\varepsilon_z = negative$$
$$\mu_z = negative$$

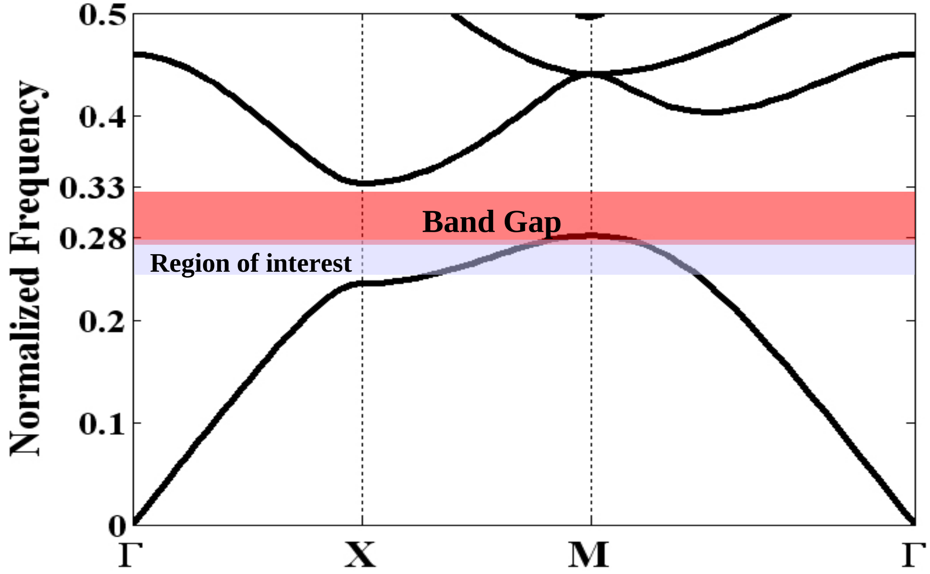
- Collimation exploits same phenomena as sub-wavelength focusing

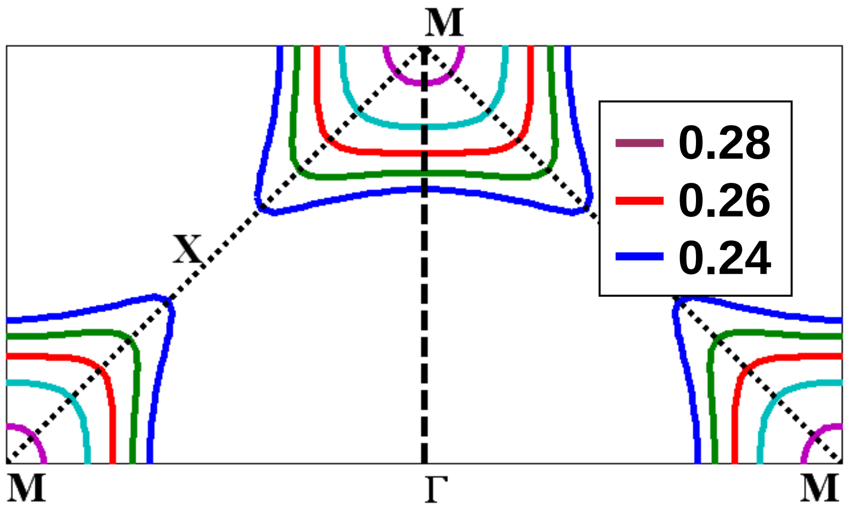
- **Canceling of Z-component leads to self-collimation**
- **Effective negative index for the energy propagation obtained**
- **PC lattice designed to produce dispersion contours with a wide range of curvatures**
  - Concave –produces normal propagation - a defocusing effect
  - Straight – produces a collimated beam guiding
  - Convex – produces a negative index for sub wavelength focusing

Curvature Reversal Near Brillouin Zone Boundaries

- Materials
  - Pillars – ε = 11
  - Matrix – ε = 2
- Square Geometry
  - a = 403nm
  - d = 0.4a = 161nm



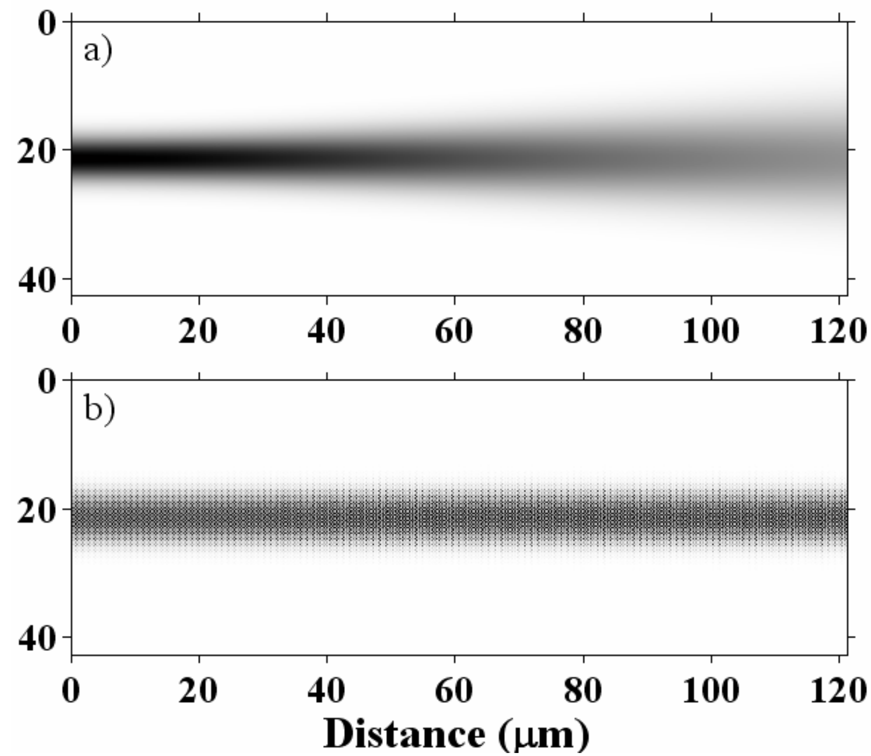




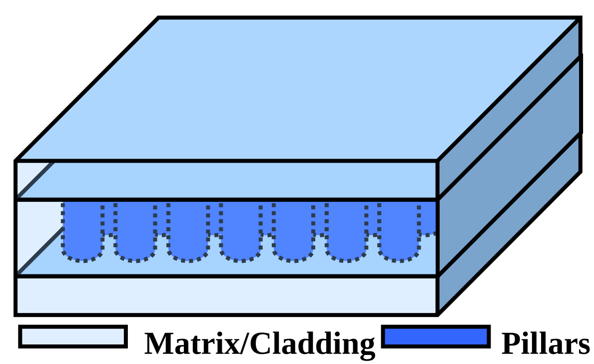
- Evolution from concave to flat to convex dispersion contour with increasing frequency along T - M direction
- Good confinement: Robust design
- Dispersion contours fitted by effective index model

FDTD Simulation of Self-Collimated Beam

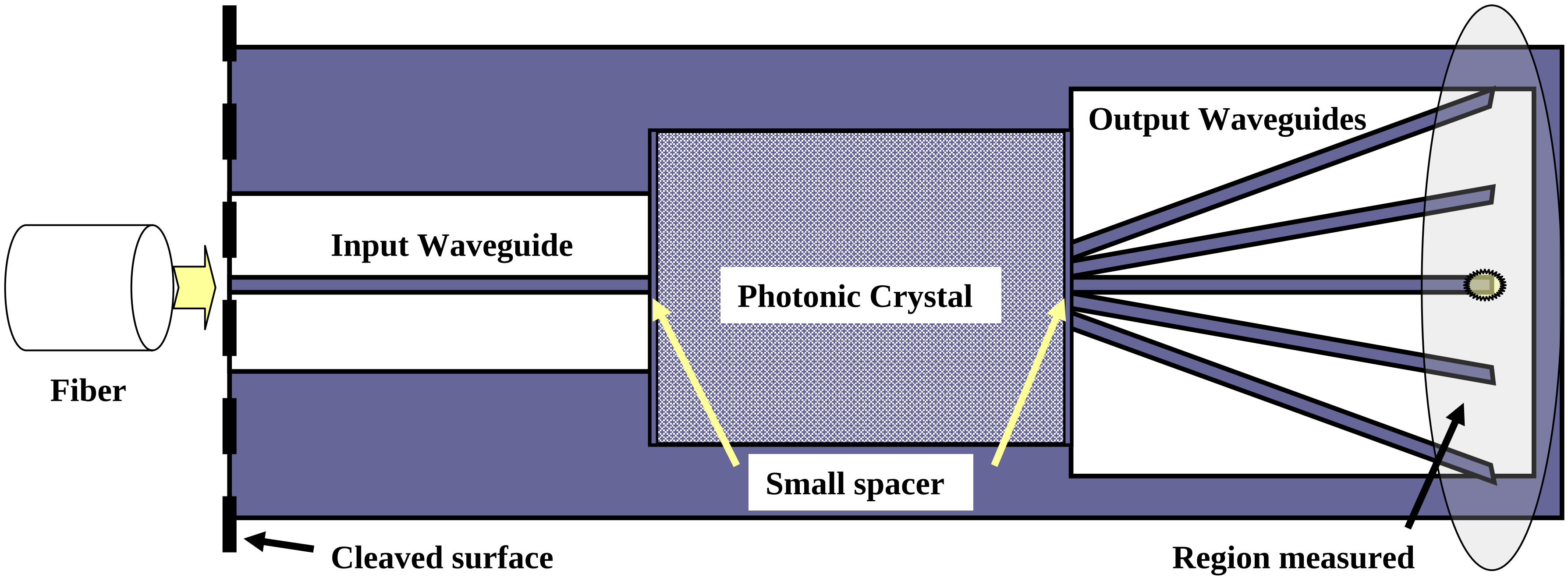
- Good confinement of Gaussian beam
- Beam spread decreased by an order of magnitude or more with beam sizes as small as 5-10 λ_0
- Simulation comparing isotropic silica vs self-collimating photonic crystal
  - Square lattice
  - Silicon pillars (ε=11)
  - Silica matrix (ε=2)
  - r=0.2a; a=403nm; λ=1.55μm



- Applications include:
  - Virtual waveguide interconnect system
  - Miniaturization of conventional optical components for small beams

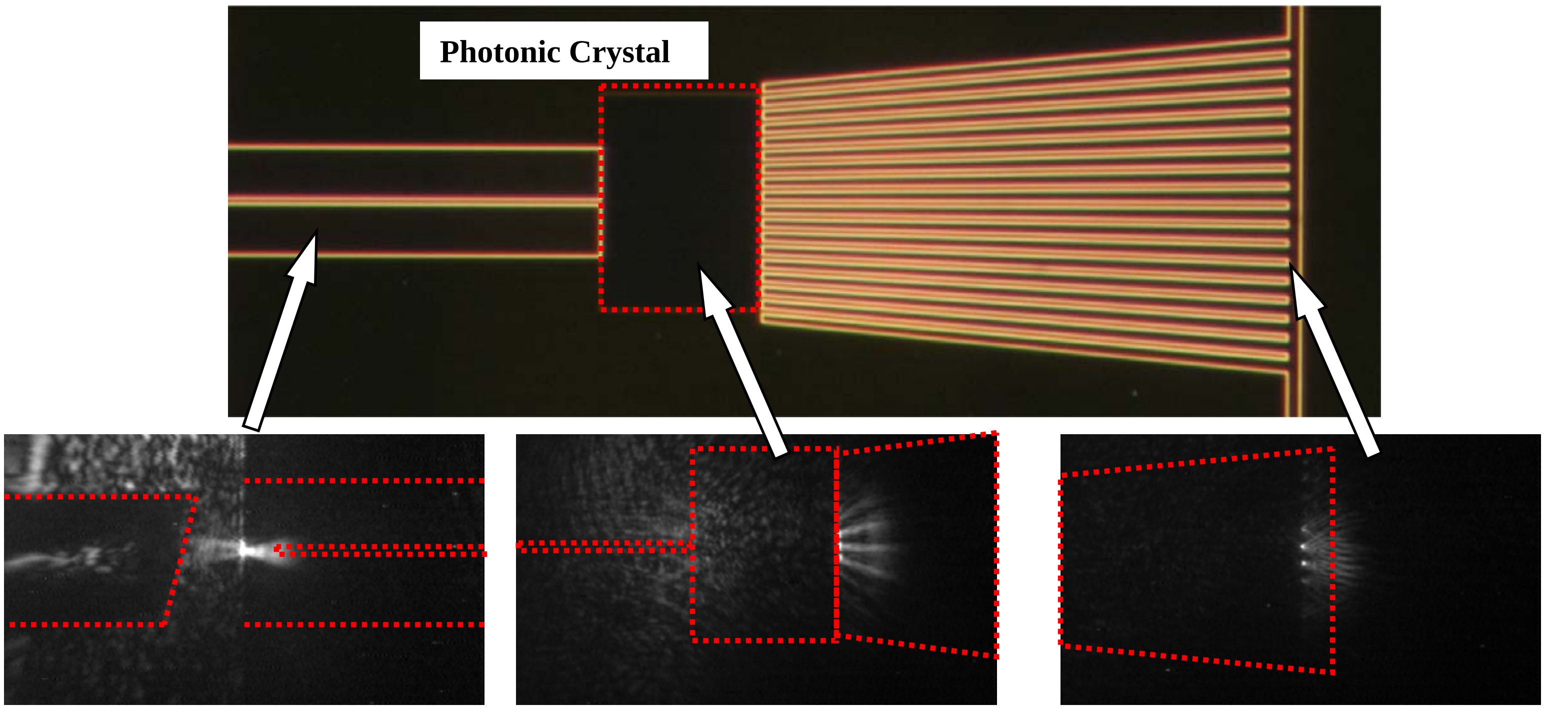


Test Structure Design for Collimation



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

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

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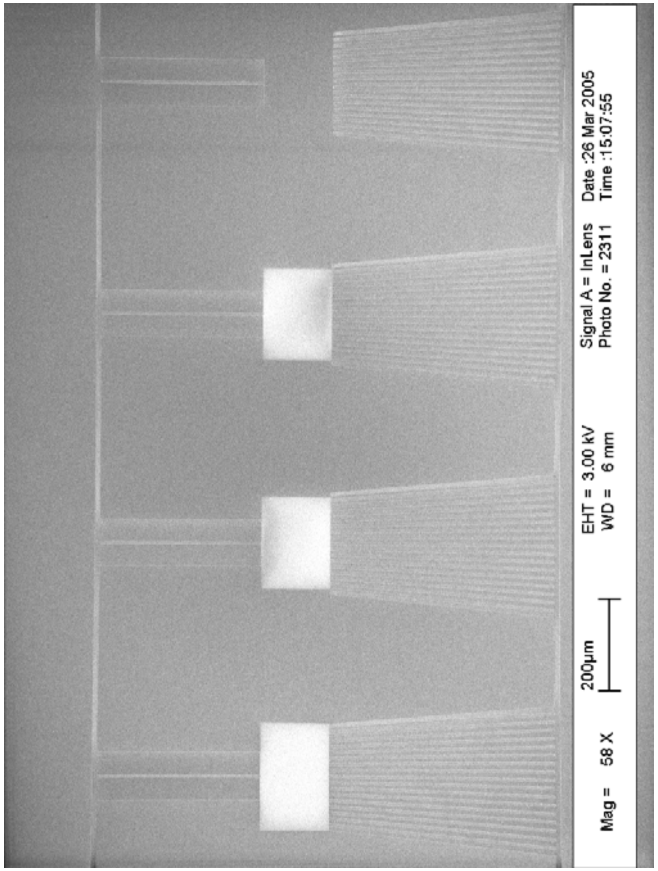
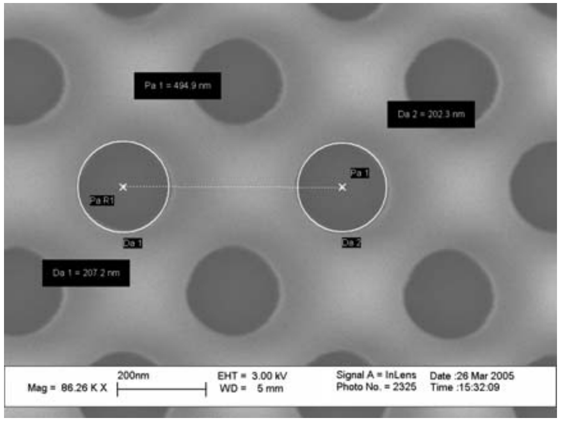
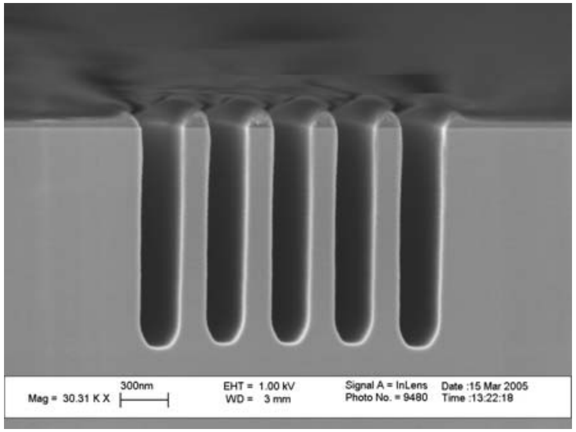
Test Structures of “Virtual Waveguide”



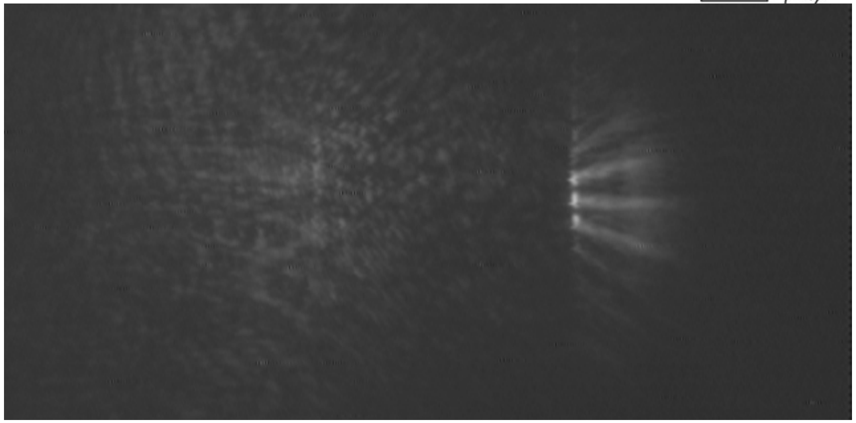




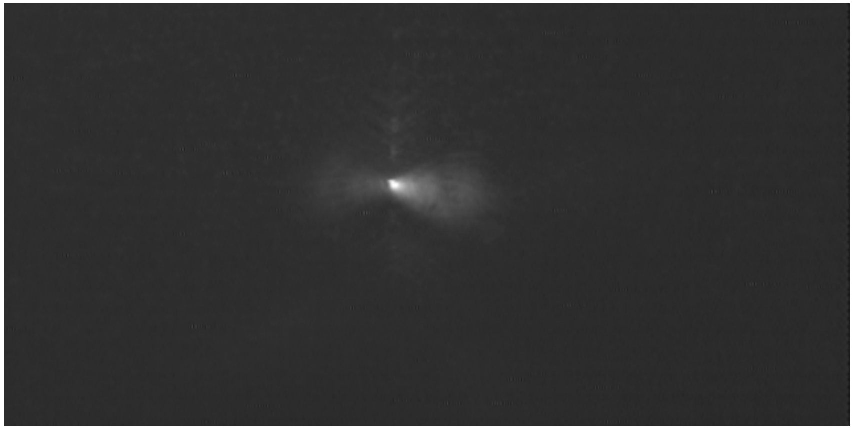
- Input waveguide, photonic crystal, fan of waveguides for analysis
- Examples of photonic crystal fabrication.

Measurements of Virtual Waveguide Effect

- Test structure with no photonic crystal



- Test photonic crystal structure exhibiting “virtual waveguide” effect: with Prof. W. Park, UC



- “Virtual waveguiding” demonstrated
- Recently calculated properties of LC infiltrated structure – negative index focusing effect predicted: ~ -20
- Also tune structure for different wavelengths

Summary

- **Investigated Static and Dynamic Superlattice PC configurations**.
  - Structure and index tuning introduces new modes
    - Drastic changes in band structure and dispersion surface
    - Tunable refraction angle changes over 80^{o}
- **Static Superlattice increases control over optical properties of PCs.**
  - Refraction at normal incidence, negative to positive refraction observed
- **Hybrid superlattice enhances tunability of optical properties of PCs.**
  - Enhances and combines properties of static and dynamic SL PCs
- **Issue is beam divergence – addressed by self-collimation**
- **Low Divergence "virtual waveguides" demonstrated**
  - Focus tuning predicted in these structures
- **Investigating ways to combine self-collimation with tuning**

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Research Group

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Thank You!!