# Refraction and Dispersion in Nonlinear Photonic Crystal Superlattices

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# Outline

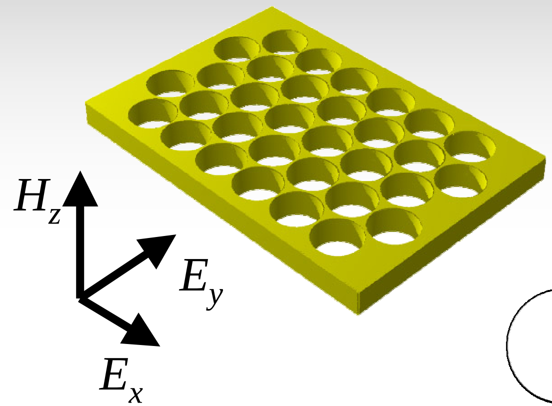
- Introduction to superlattice structure
- Experimental methods
  - Fabrication
  - Optical characterization
- Results
  - Reflectivity spectrum
  - Band structure: Measured and calculated
- Tunable SL PC structures
  - Consequences of index tuning
  - Refraction effects: FDTD and wavevector analyses
- Conclusion

# Motivation

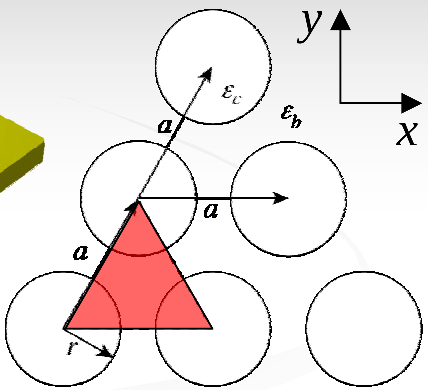
- Fabrication of 2D PCs not as complicated as 3D
- 2D PC offers integration onto opto-electronic systems directly on common substrate
- Superlattice PC structures of this type have not been fabricated or characterized
- Observe band folding effects in PCs
- Improvement of large refraction effects (superprism) for beam steering, signal processing, demultiplexing
- Investigate methods to electro-optically tune these effects, such as 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

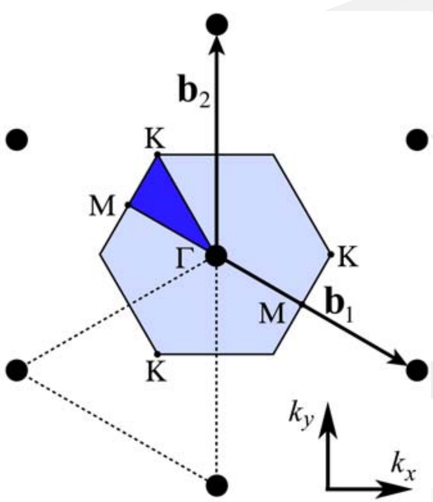


TE polarization

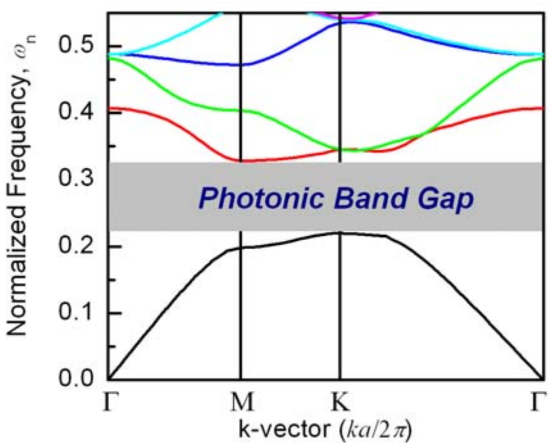


Real Space

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

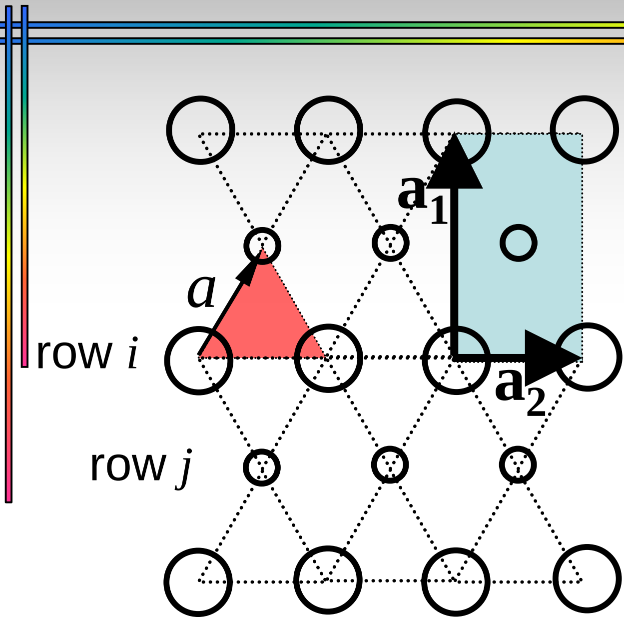


Reciprocal Space

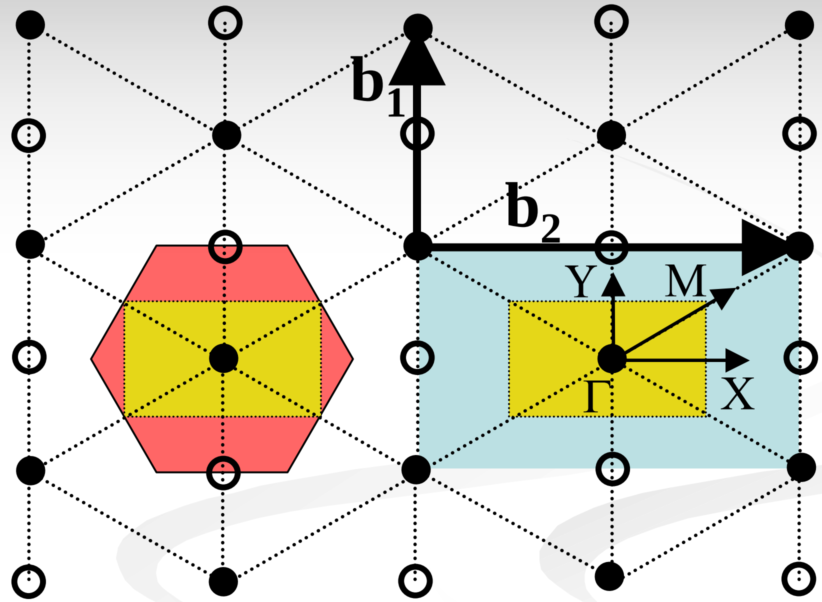


Band Diagram

# Superlattice: Real & Reciprocal Space




Real Space



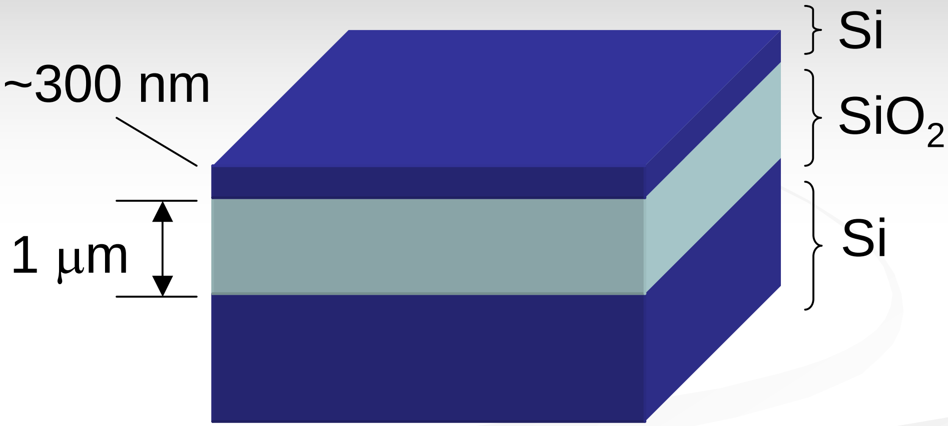

Reciprocal Space

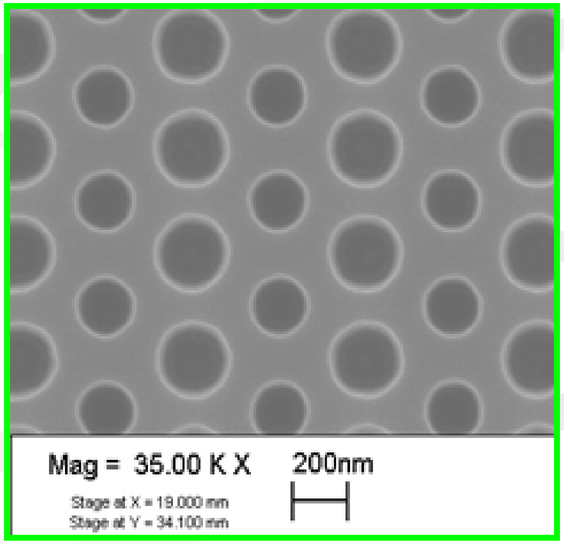
- Alternating rows posses different property ($\Delta r$, $\Delta n$, or both)
- Unit cell definition with two holes per lattice point

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

# Fabrication

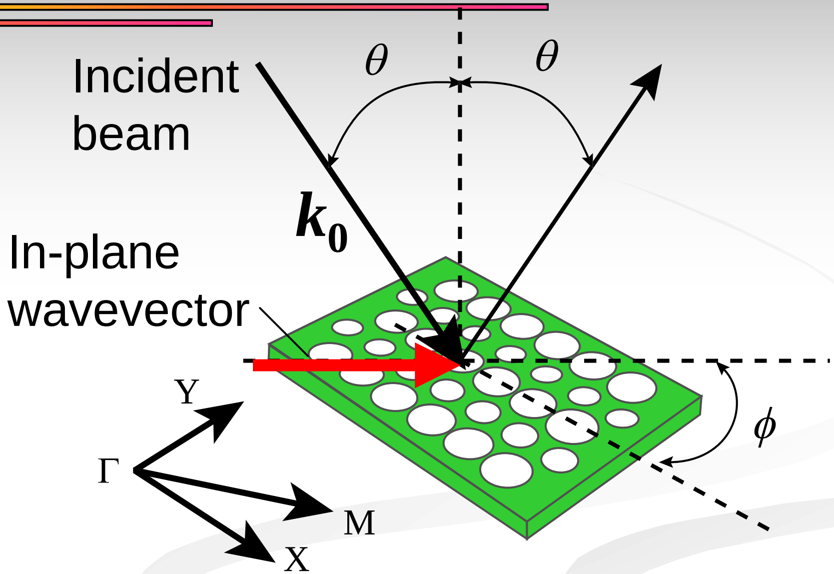
- E-beam lithography
- ICP dry etching with Chlorine/$C_4F_6$ recipe
- 1 $mm^2$ area written using smaller unit patterns
- Lattice constant: $a$=358 nm
- Silicon slab waveguide (SWG)

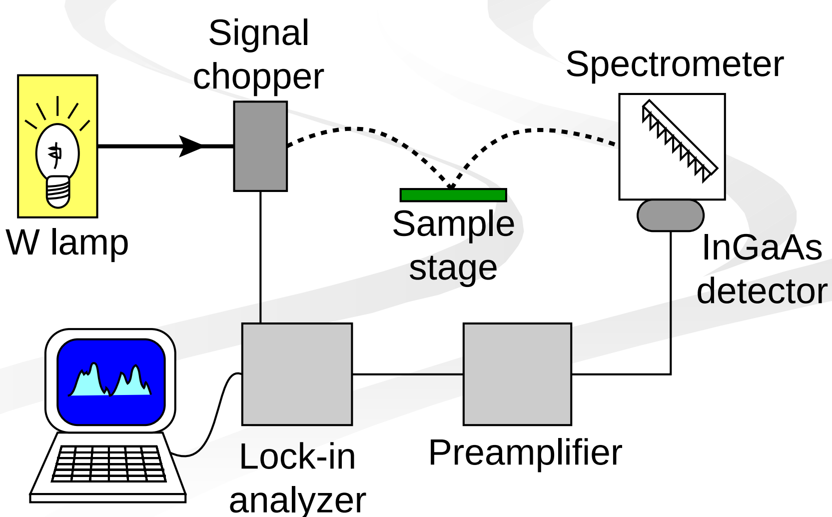


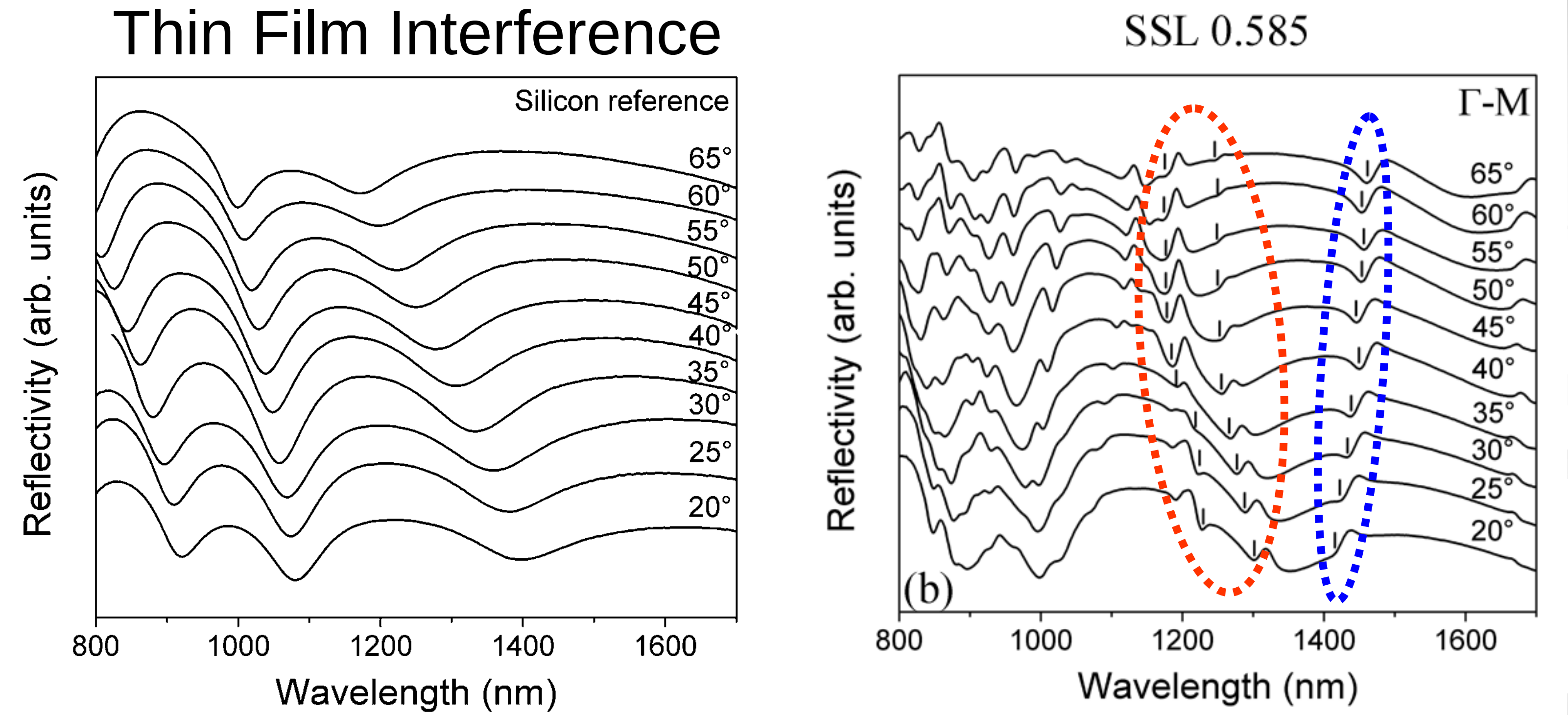
# Optical Characterization

- Resonant band coupling technique (Astratov *et al.* PRB '99)
- Light with in-plane wavevector matching wavevector of a band in PC couples with SWG, causing dip in reflectivity spectrum
- Effective for bands outside of guiding regime of SWG (*light cone*).



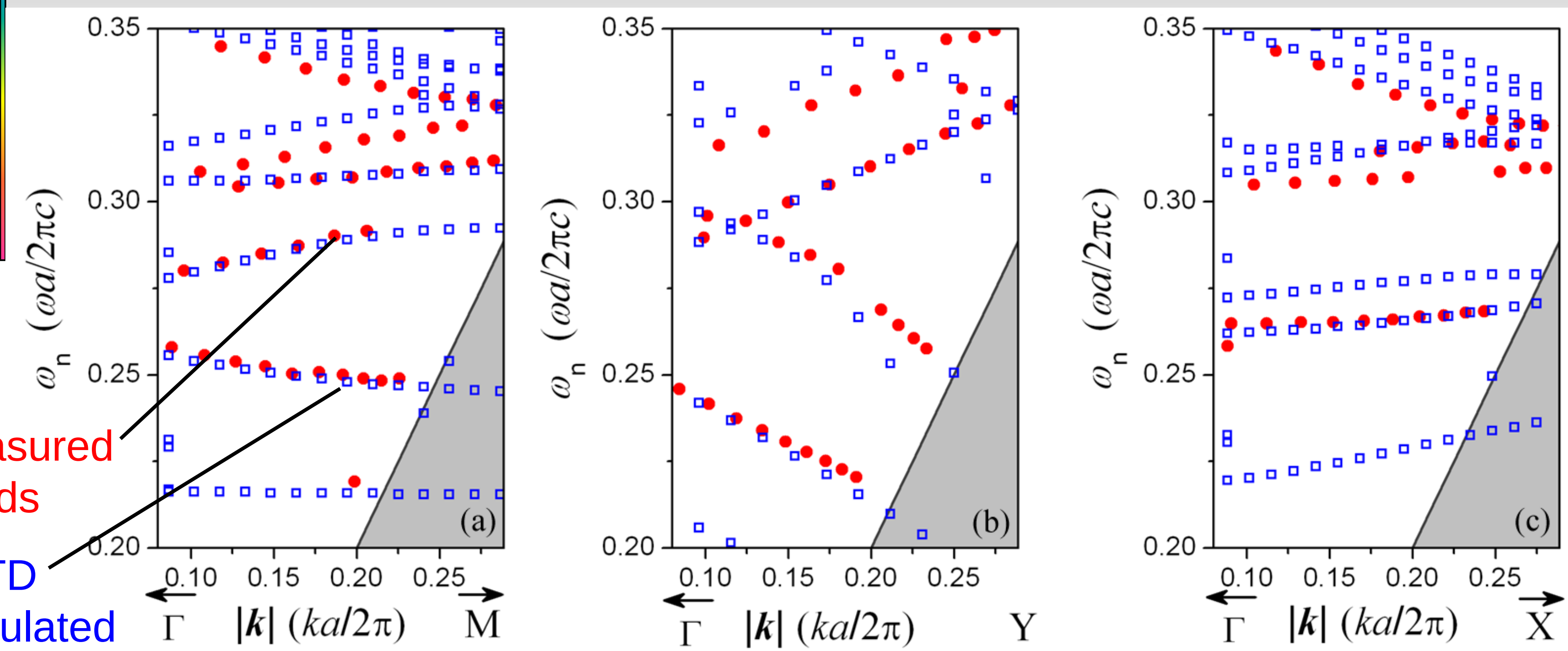



# Reflectivity: Unpatterned vs. Patterned Sol



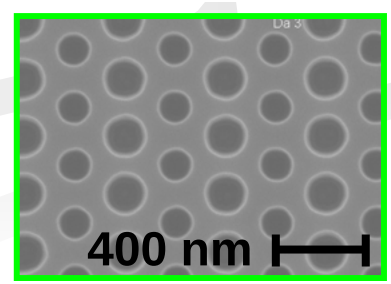

- Gradual dips → thin film interference
- Sharp dips → coupling of light with band of PC
- Repeat measurement for multiple angles, $\theta$, and multiple lattice directions

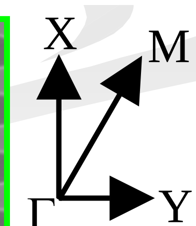
# Superlattice: Measured and Calculated Bands




Measured bands

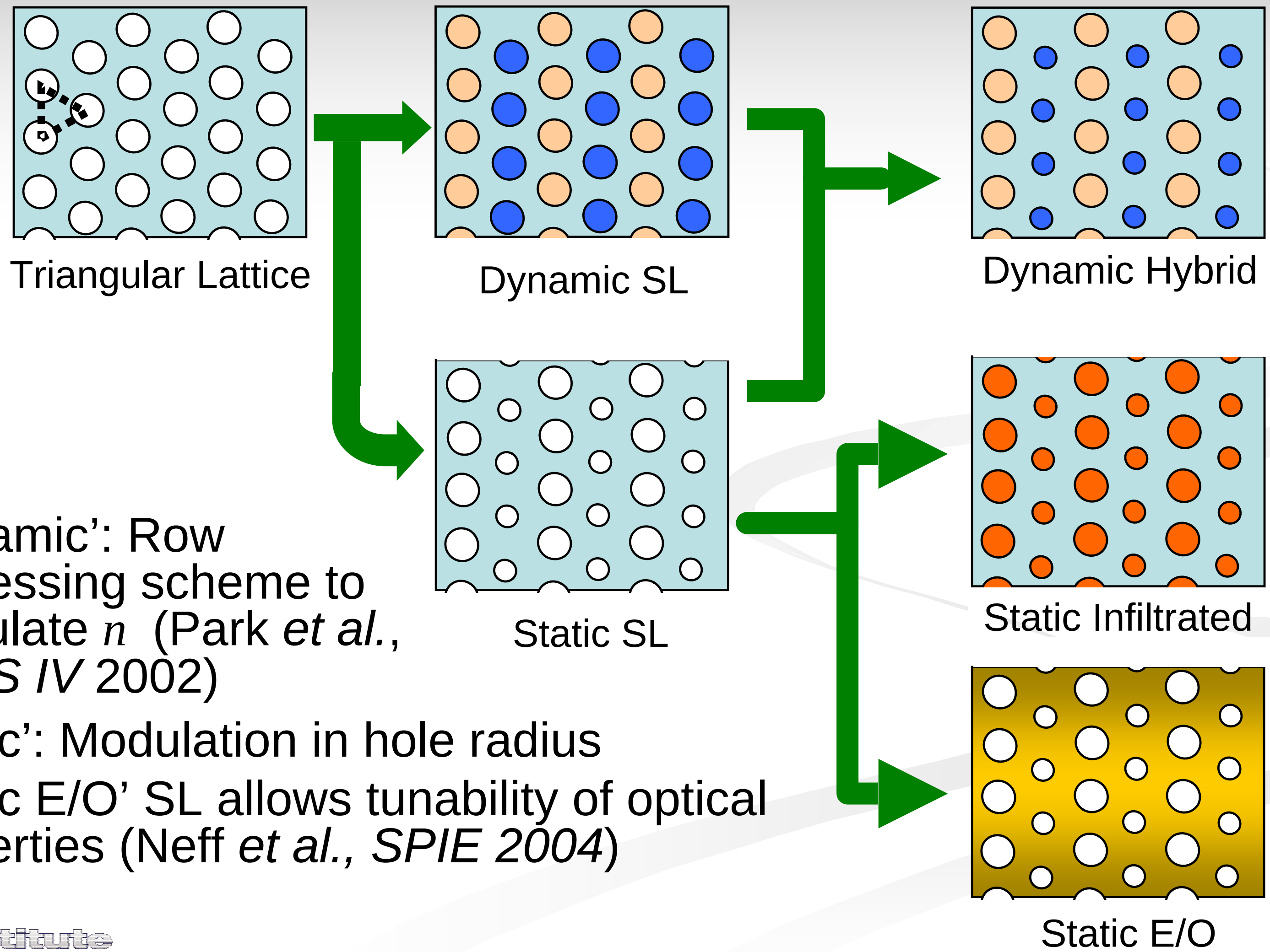
FDTD calculated bands




- Dips in spectrum filtered and plotted as $\omega$ vs. $k$
- Full 3D FDTD calculations to match structure

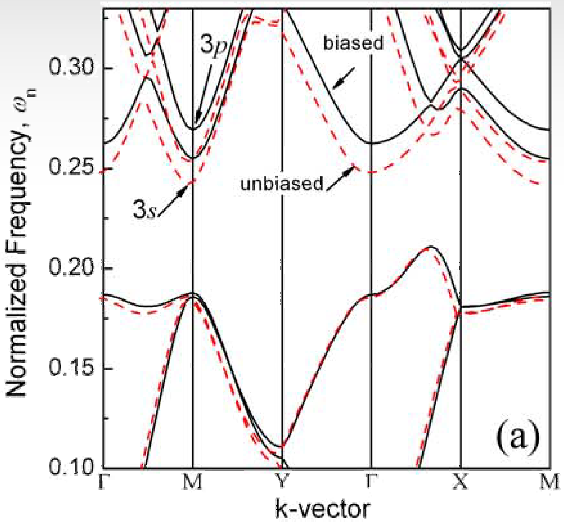
# Tunable Photonic Crystal Superlattices



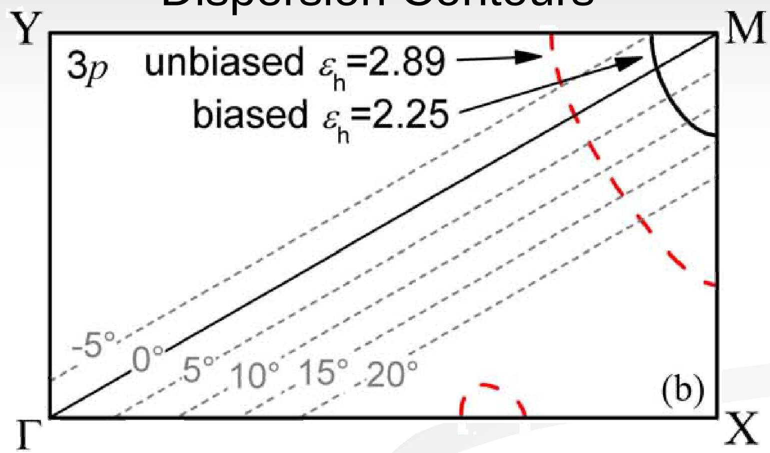

- 'Dynamic': Row addressing scheme to modulate $n$ (Park *et al.*, *PECS IV* 2002)
- 'Static': Modulation in hole radius
- 'Static E/O' SL allows tunability of optical properties (Neff *et al.*, *SPIE 2004*)

# Static Infiltrated SL

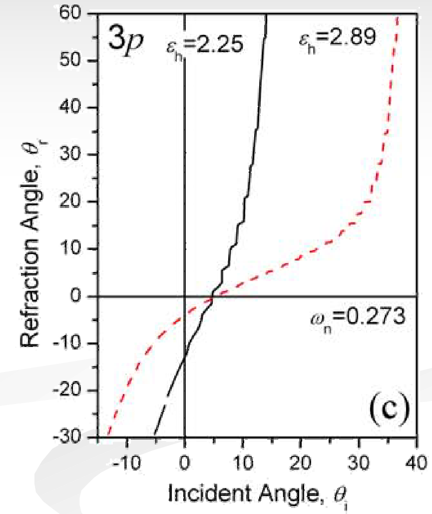
Band Structure



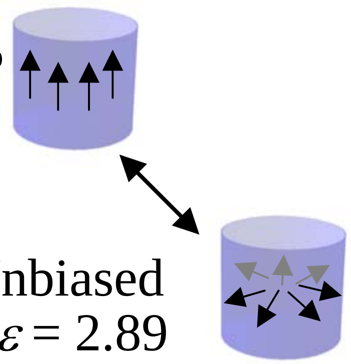

Dispersion Contours




Refraction



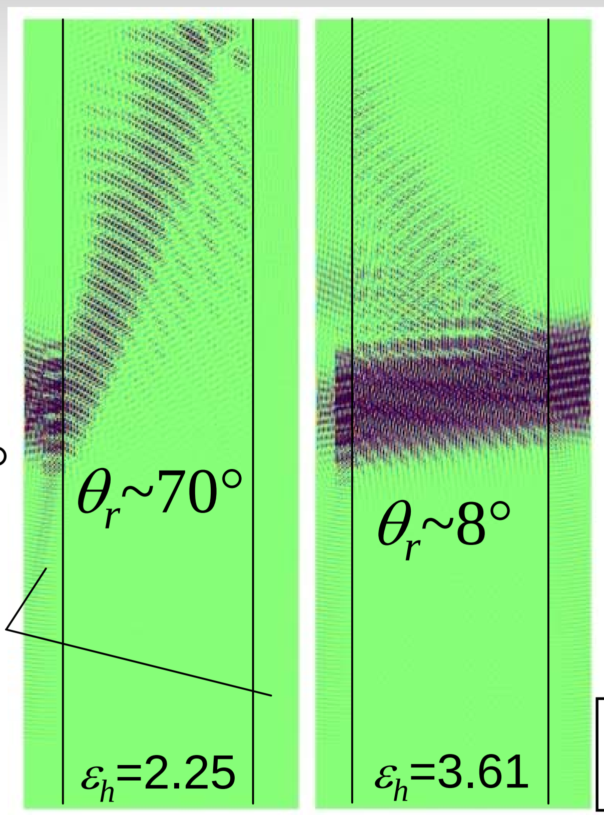

Biased
$\varepsilon = 2.25$

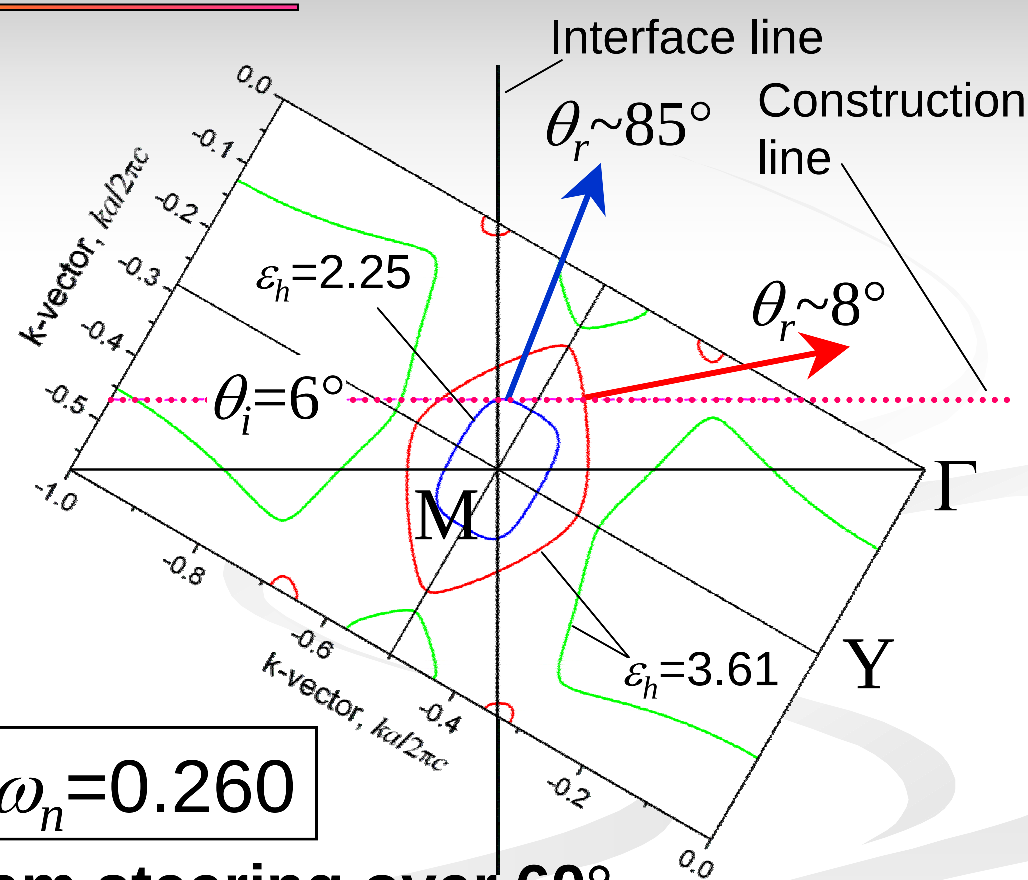


Unbiased
$\varepsilon = 2.89$

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

# Beam Visualization and Wavevector Analysis




$\omega_n$=0.260

**Beam steering over 60°**

- Discrepancies between FDTD and wavevector calculations caused by: Finite beam size in FDTD and inaccurate measurements due to beam spreading

# Conclusion

- Successfully developed new concept of SL PC
- Experimentally observed ‘band folding’ effect
- Demonstrated that SL offers enhancement in tunable refraction effects
- **SL introduces unique optical properties to PCs and creates new regimes for beam propagation effects**

# Acknowledgements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