Photonic Crystal Superlattices in Electro-Optic Slab Waveguides

Curtis Neff and C. J. Summers

School of Materials Science & Engineering

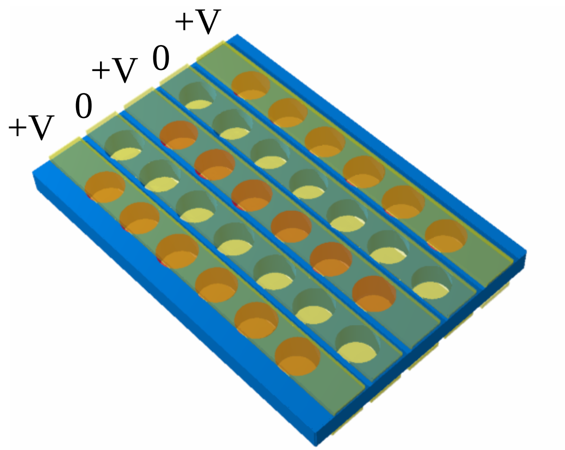
Georgia Institute of Technology

SPIE 49th Annual Meeting
Denver, Colorado
4 August 2004

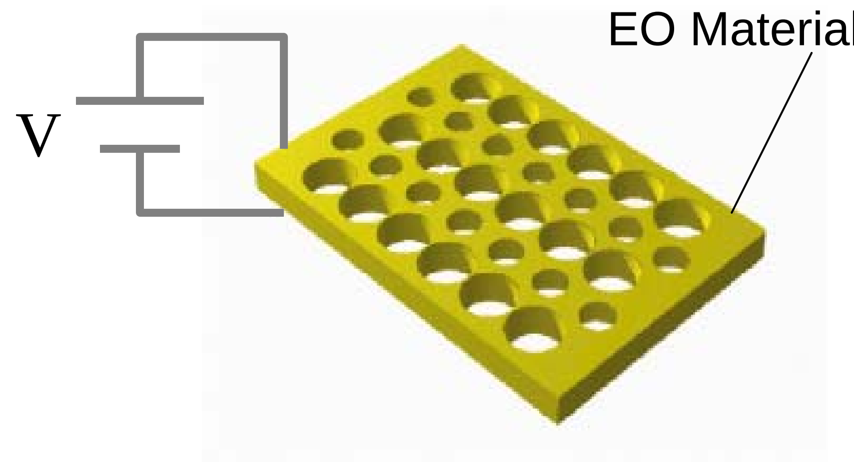
Outline

- Introduction:
  - – PC superlattices
    - 'Dynamic'
    - 'Static'
  - – Consequences of superlattice
- Details of the structure
- Results: Δr and bias/unbias
  - – Band structure
  - – Equifrequency contours
- Refraction effects
- Conclusions

Photonic Crystal Superlattices



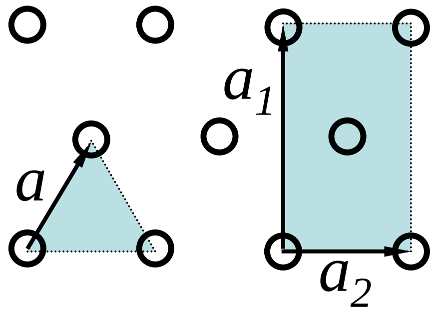
Dynamic Superlattice



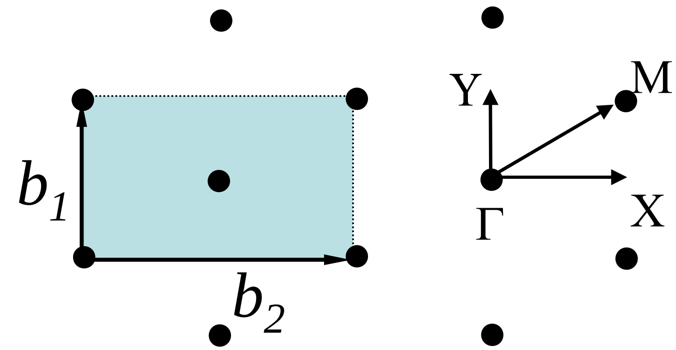
‘Static’/Patterned Superlattice

- Modulations in lattice between rows
  - ‘Dynamic’: Row addressing scheme to modulate n (Park *et al.*, *PECS IV* 2002)
  - ‘Static’: Modulation hardwired into device architecture
- Pattern ‘static’ SL in EO material to introduce tunability of optical properties

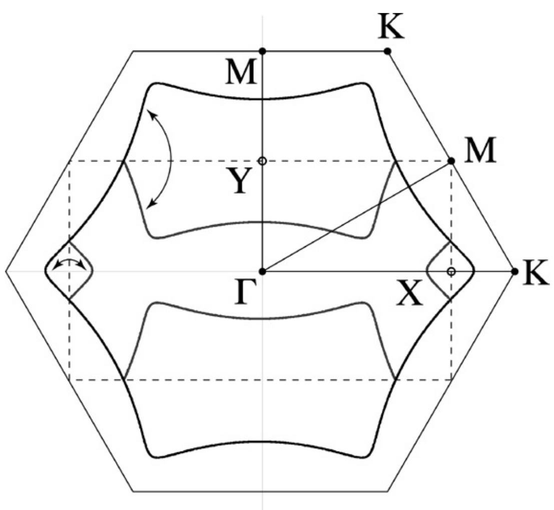
Consequences of Superlattice



Real Space



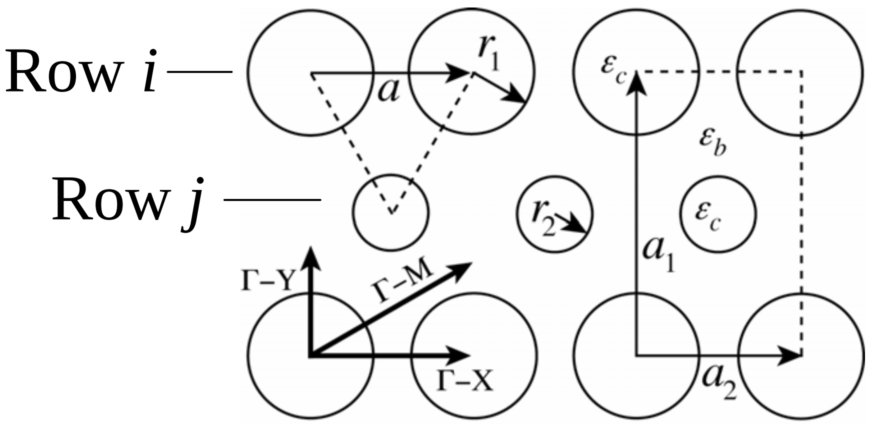
Reciprocal Space

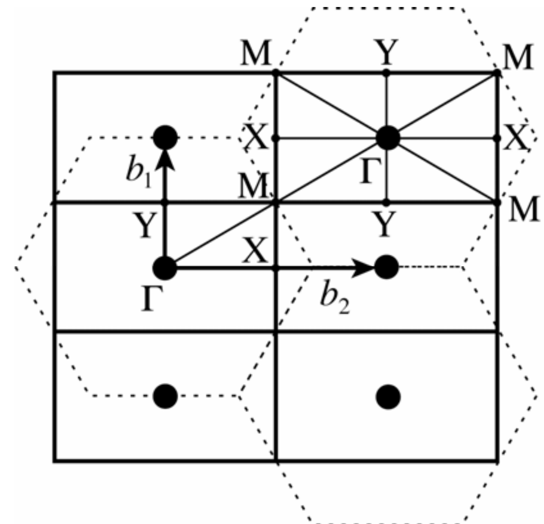


BZ Folding

- New unit cell definition with two holes per lattice point
- New BZ representation: hexagonal becomes rectangular
- BZ folding
- Symmetry reduction

Device Structure

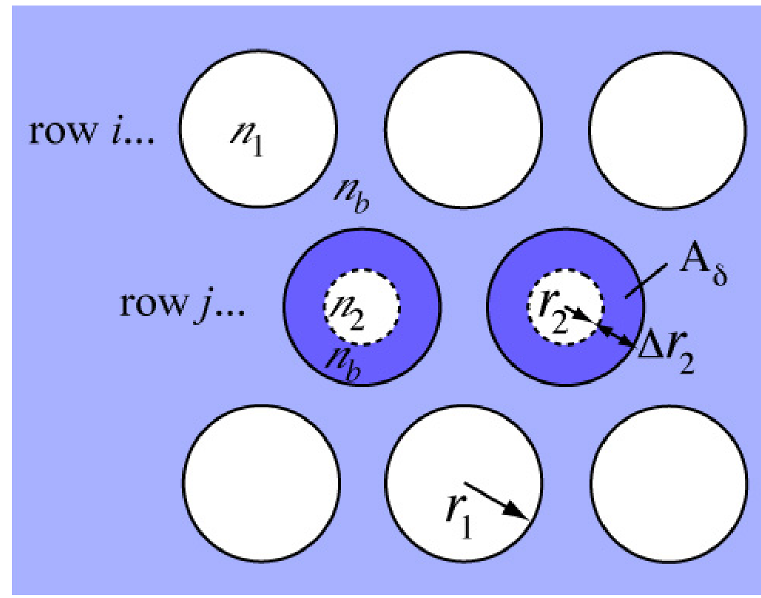




- Triangular photonic crystal patterned in EO material, i.e. PLZT, to introduce tunable properties. (Scrymgeour *et al. APL,* 2003, Xiong *et al*. *JQE* 2002)
- A different idea: Pattern a static superlattice into PLZT
- Row i, row j holes have radius r_1, r_2 respectively
- r_1 held constant while r_2 decreased
- Superlattice ‘strength’ increases as ratio r_2/r_1 decreases

Superlattice Strength: Effective Index of Row *j* Holes

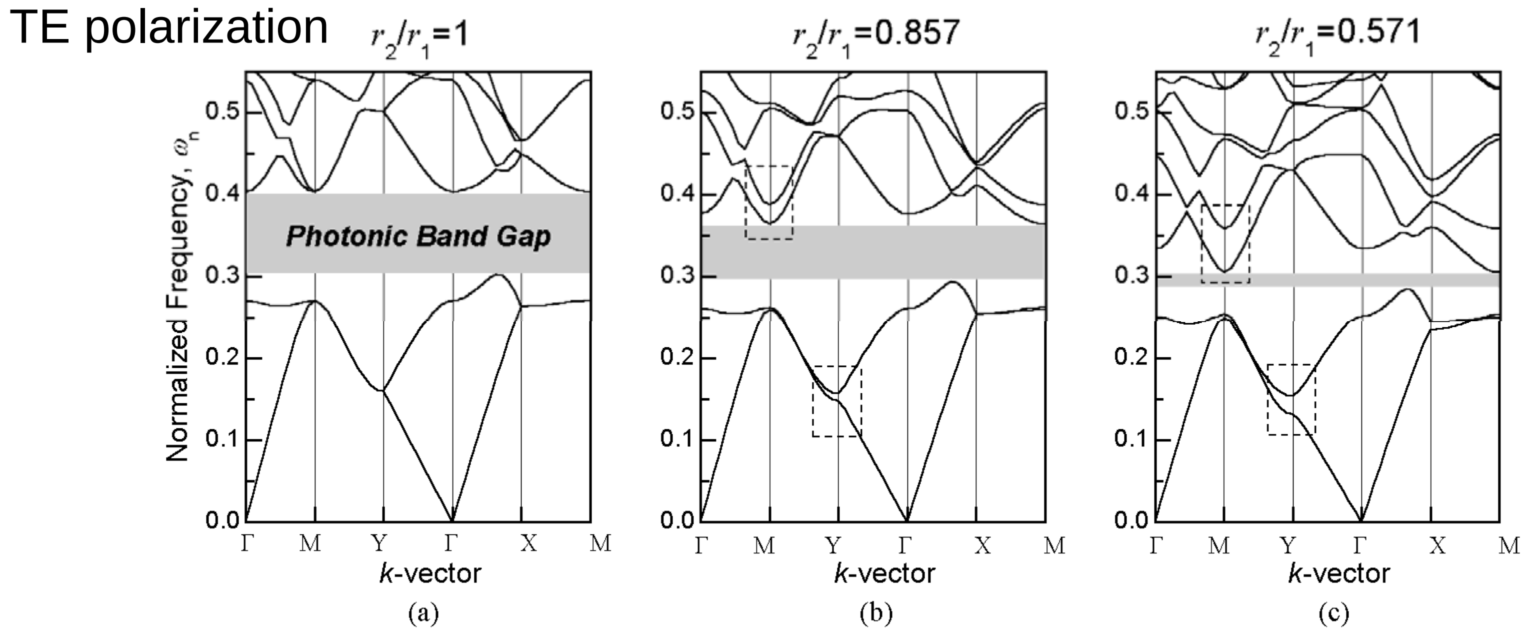
- Consider index of hole weighted by the area of the hole
- Average amount of material added to structure by reducing r_2 hole over the area of r_1 hole
- Result is the 'effective index' of the hole
- Quantitative value of superlattice strength for comparison with dynamic superlattice
- For r_2/r_1=0.857, n_{eff}=1.395 which is Δn=0.395 between rows of holes



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

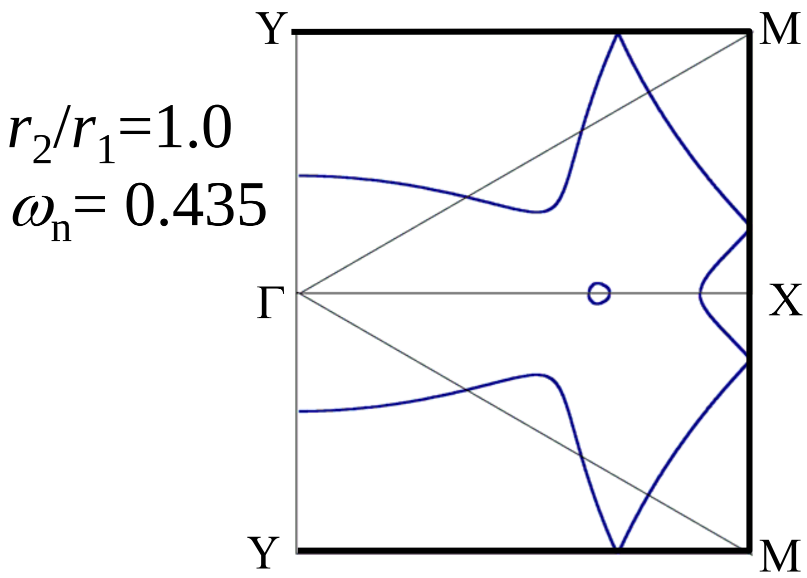
$$= n_b \left(1 - \left(\frac{r_2}{r_1}\right)^2\right) + n_2 \left(\frac{r_2}{r_1}\right)^2$$

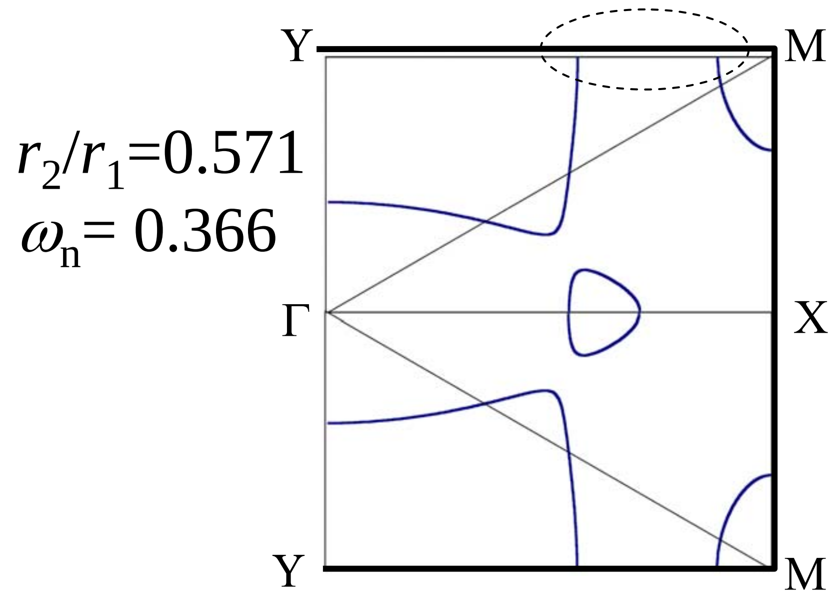
Band Structure: Δr Effects



- Decreasing r_2 increases amount of material in structure
- Stronger effect on air bands than dielectric bands
- Shifts bands to lower frequencies
- Decreases width of PBG
- Increases band splitting at high symmetry points

Equifrequency Contours: Δr

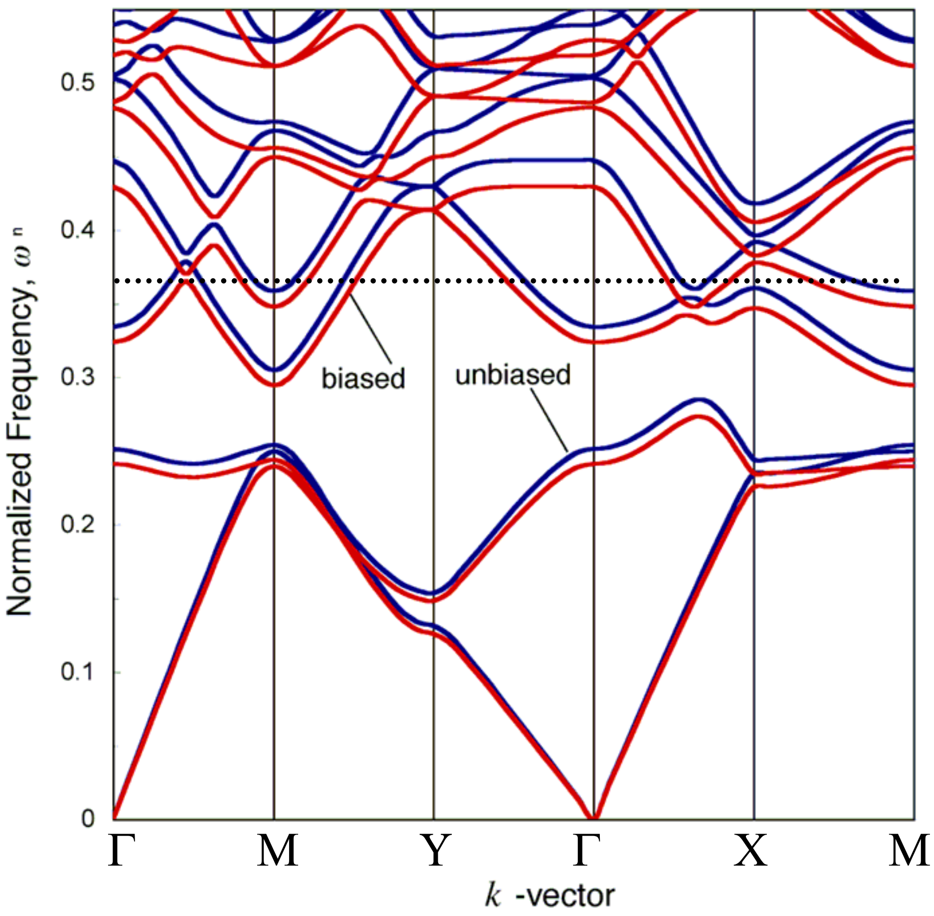




- For no radius difference, BZ folding scheme is straight forward and curves converge to a single point at BZ boundaries.
- Radius modulation causes curves to diverge/repel at BZ boundaries -- ‘MQW effect’.
- Net result: relatively flat curvature in center of BZ with high curvature near BZ boundaries

Band Structure: Bias Effects

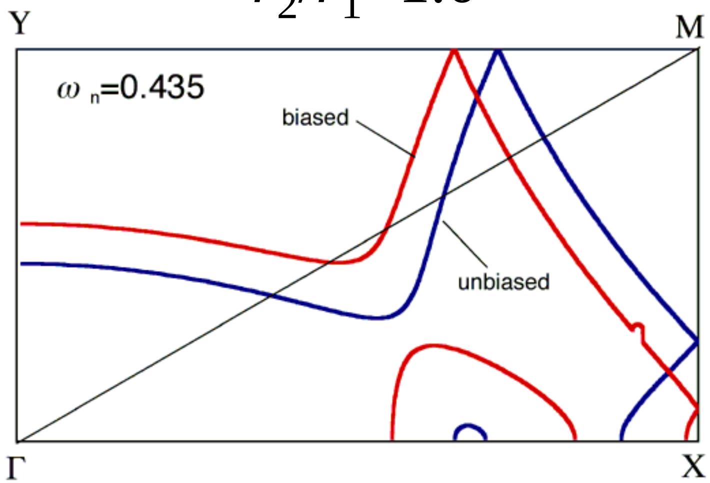
$r_2/r_1=0.571$



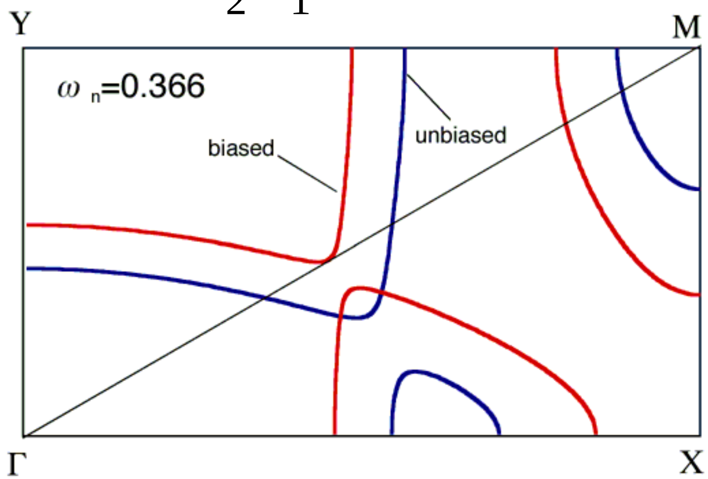
- Bias of 6 V/μm
- Increase n from 2.49 to 2.598 (Δn~ 0.11)
- Moves bands to lower frequencies
- Equifrequency line intersects bands at different points
- Dispersion surface ‘looks’ different for unbiased/biased cases

Equifrequency Contours: Bias Effects

r_2/r_1=1.0

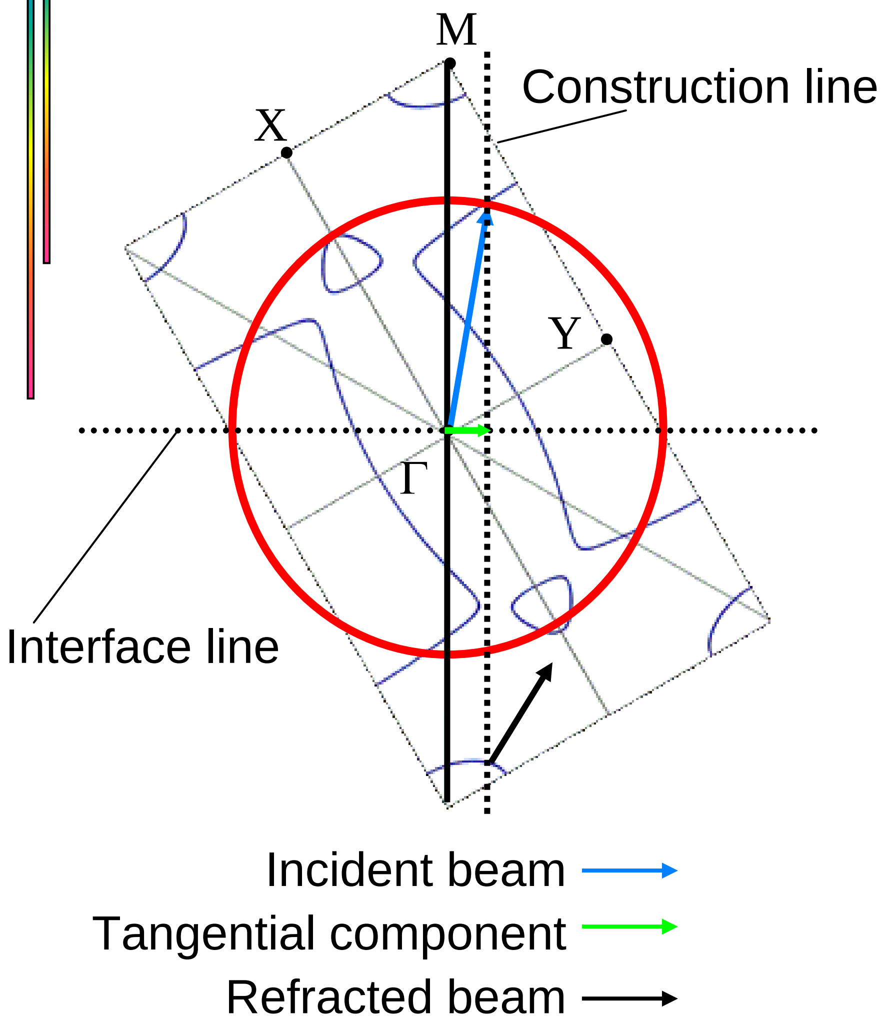


r_2/r_1=0.571



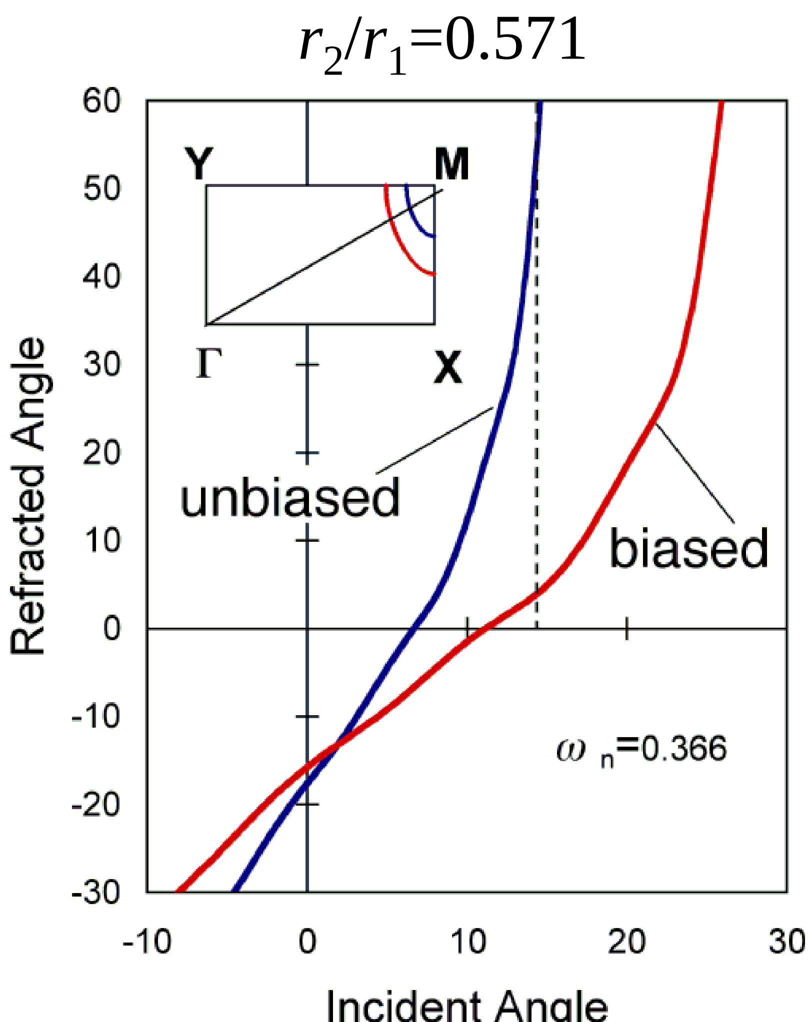
- Equifrequency plane is sectioning two different areas of the dispersion surface
- The different areas have similar contours, but they are shifted.
- Different contours results in different optical responses
  - Refraction/Beam steering
  - Switching/Modulation
  - Dispersion

k-vector Diagrams



- Outlined by Russell *et al.* 1996 and Kosaka *et al. PRB* 1998
- Analysis done in *k*-space
- Tangential component of incident beam conserved at interface
- Conservation condition satisfied at intersection of construction line with EFC
- Refraction angle determined by curvature of EFC
- Final direction of Poynting vector is normal to EFC at point of intersection

Refraction Results



- Bias changes *n* which shifts the EFCs
- At ~14° incident angle, ~55° change in refraction angle
- Increase in effect over triangular lattice
- Refraction occurs at zero incident angle
- Two regimes of refraction: negative and positive

Conclusion

- A modulation in hole radii between adjacent rows of holes creates a superlattice.
- The superlattice lowers the symmetry of the structure causing:
  - BZ folding
  - Band splitting at BZ boundaries
  - Highly curved EFCs near BZ boundaries
- Tunability of refraction >55° with $\Delta n \sim 0.11$
- Greater sensitivity to Δn can be possible through optimization of hole size ratio, r_2/r_1

Acknowledgments

- Professor Wounjhang Park
- Tsuyoshi Yamashita
- Davy Gaillot
- Work supported by MURI sponsored by the Army Research Office under Contract Number DAAD19-01-1-0603