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Visible Three-Dimensional Photonic using Silicon

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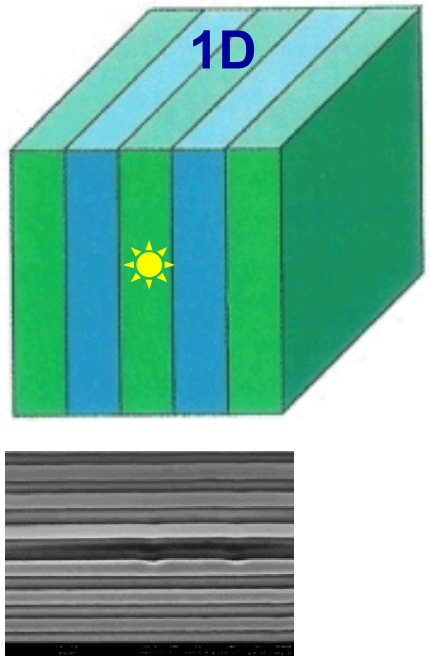
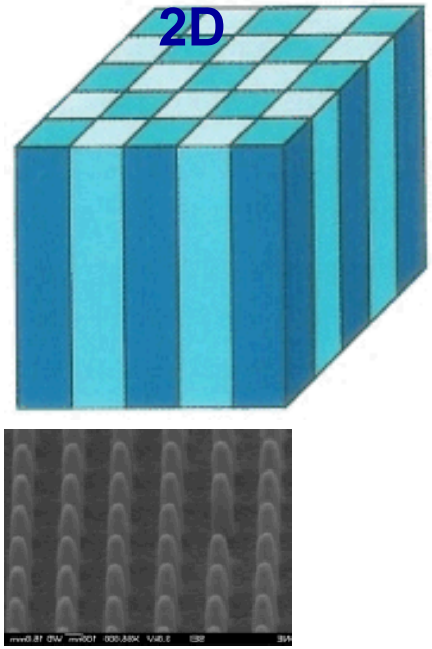
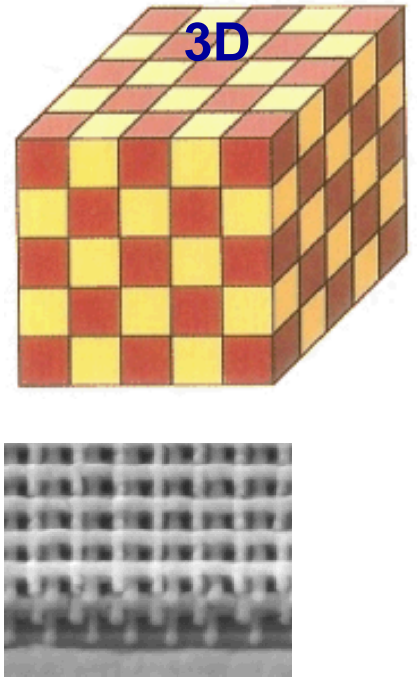
Photonic Crystals (PC)- A Brief Intro







- Characterized by a 'Photonic Bandgap': a range of frequencies where electromagnetic modes are forbidden.
- Can be used to confine, guide or direct light efficiently with a small device 'footprint'
- Can control and modify emission and absorption

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Three dimensional PCs are ideal as they can offer ultimate light control.

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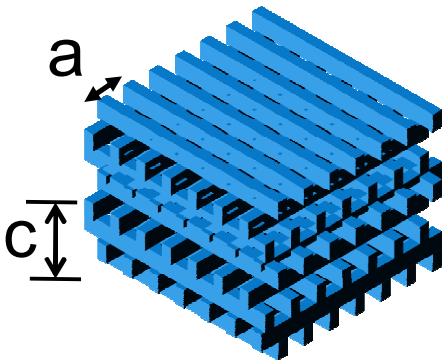
Three-dimensional Photonic Crystal

Goals

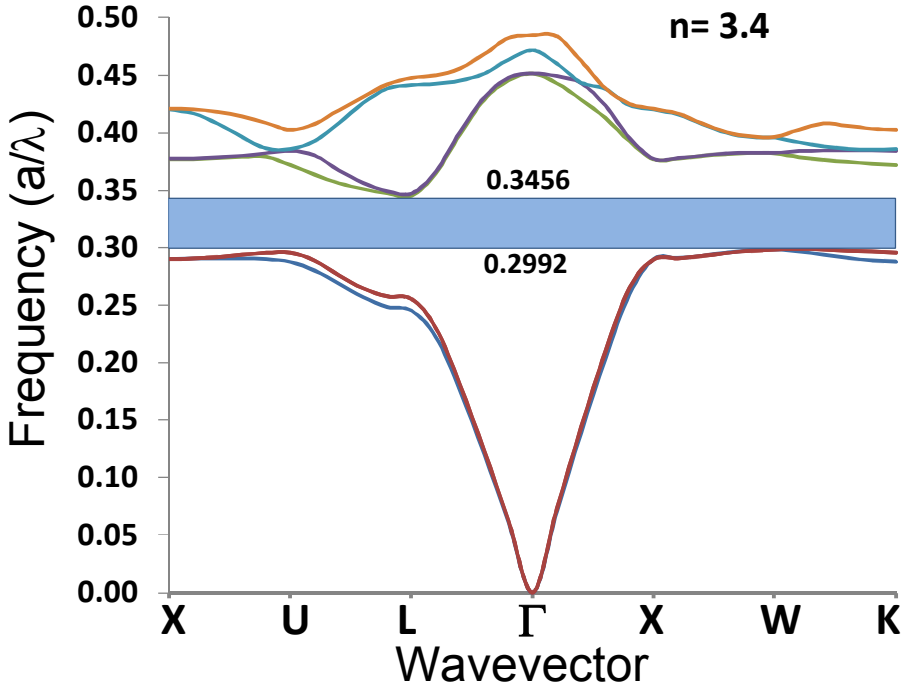
- Achieve complete three-dimensional photonic bandgap
- Maximize the spectral width of the bandgap

✓ Desired lattice structure (diamond-like) ✓ Large refractive index contrast

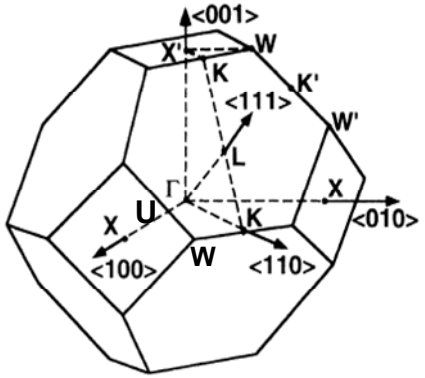
Logpile PC



Photonic Band Structure



First Brillouin Zone



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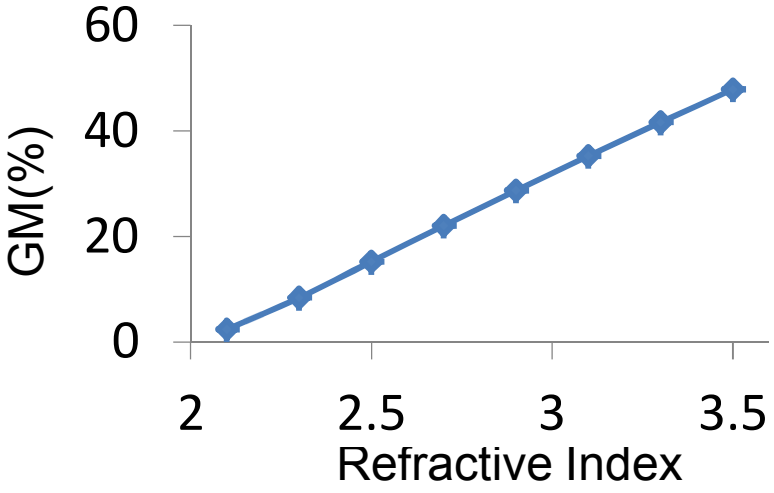
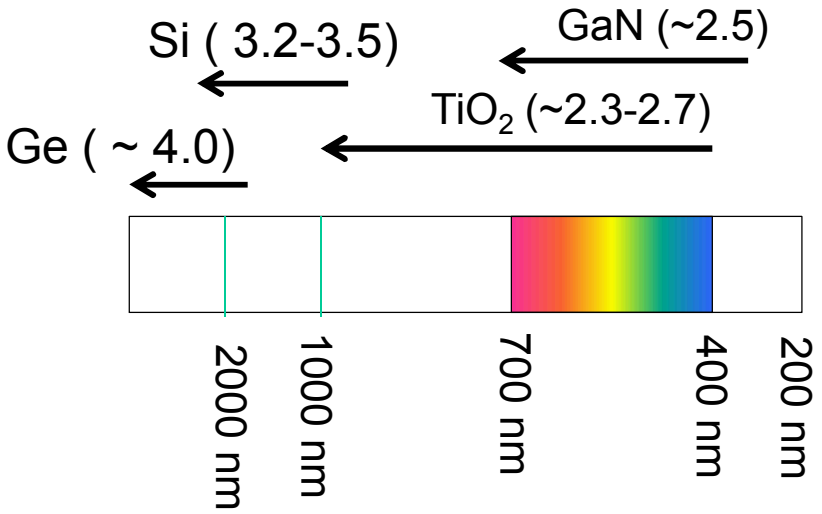
Optimizing 3D Photonic Bandgap

$$\text{Gap to Midgap Ratio (GM)} = \frac{\text{Gap center Frequency}}{\text{Bandgap width}}$$





- Refractive index for non-absorbing materials is small in the visible regime
- Silicon has a number of useful properties:
  - Larger refractive index (n ~ 3.4).
  - Compatible with large scale fabrication and easy integration with electronics.
  - Applications : Photovoltaics, light emission, detection, sensing and communications.

Can we use silicon for 3DPC in the visible, beyond its absorption edge?

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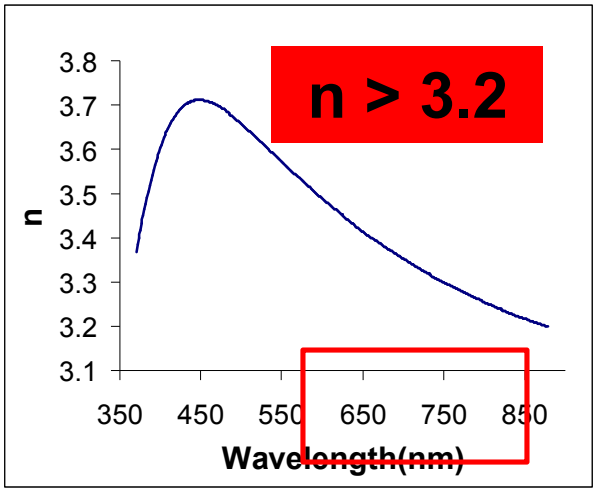
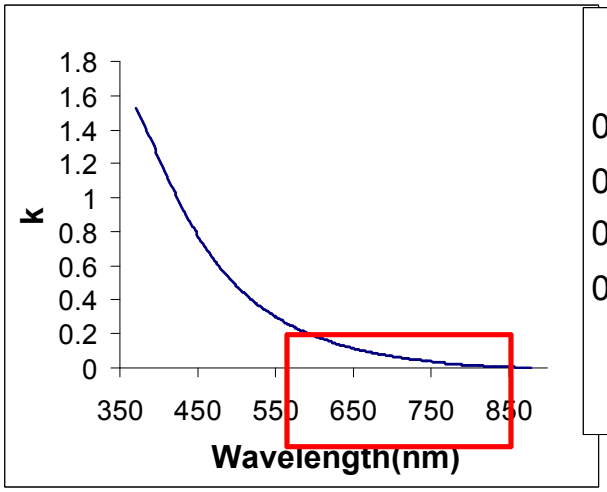
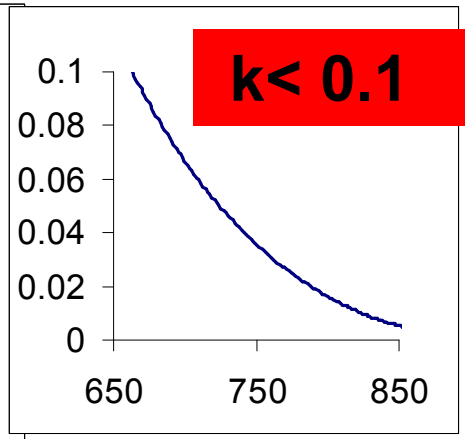
Properties of Silicon in the Visible

Ellipsometric data from electron beam evaporated silicon







Silicon is an indirect bandgap semiconductor, so its imaginary part of the refractive index (k) increases slowly.

G. Subramania, Y-J Lee, and A.J. Fischer, Advanced Materials **22**, 4180-4185 (2010)

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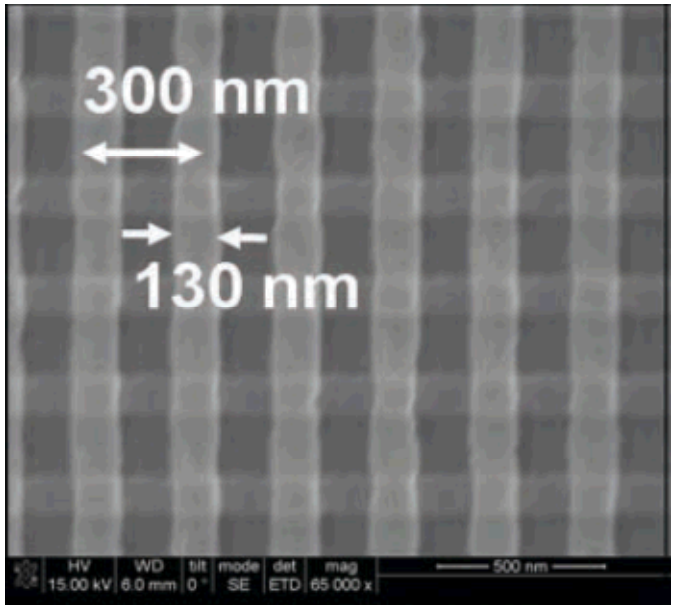
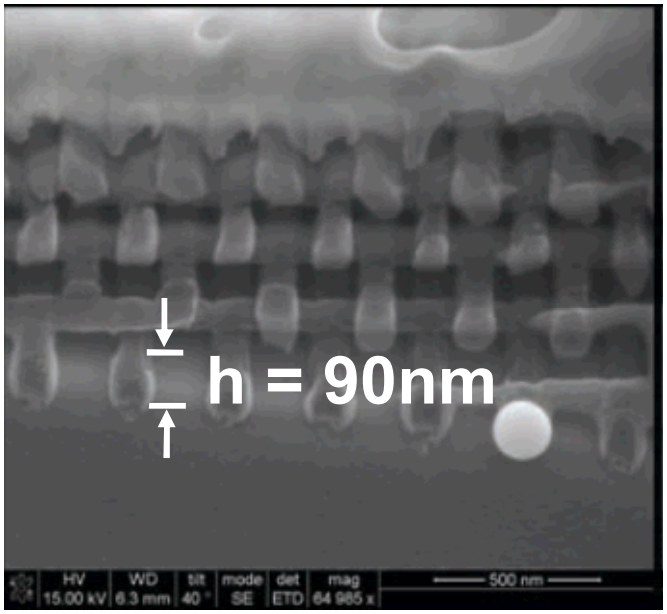
Nine Layer Silicon Logpile

- Fabricated using a multilayer electron beam direct write.
- Nine layers (~ 2 unit cells) with three different lattice constants : of a =220nm, 250nm and 300nm is fabricated
- The width of each rod is approximately 0.3-0.4*a with the height of each rod approximately 90nm.

Top View



Cross-section



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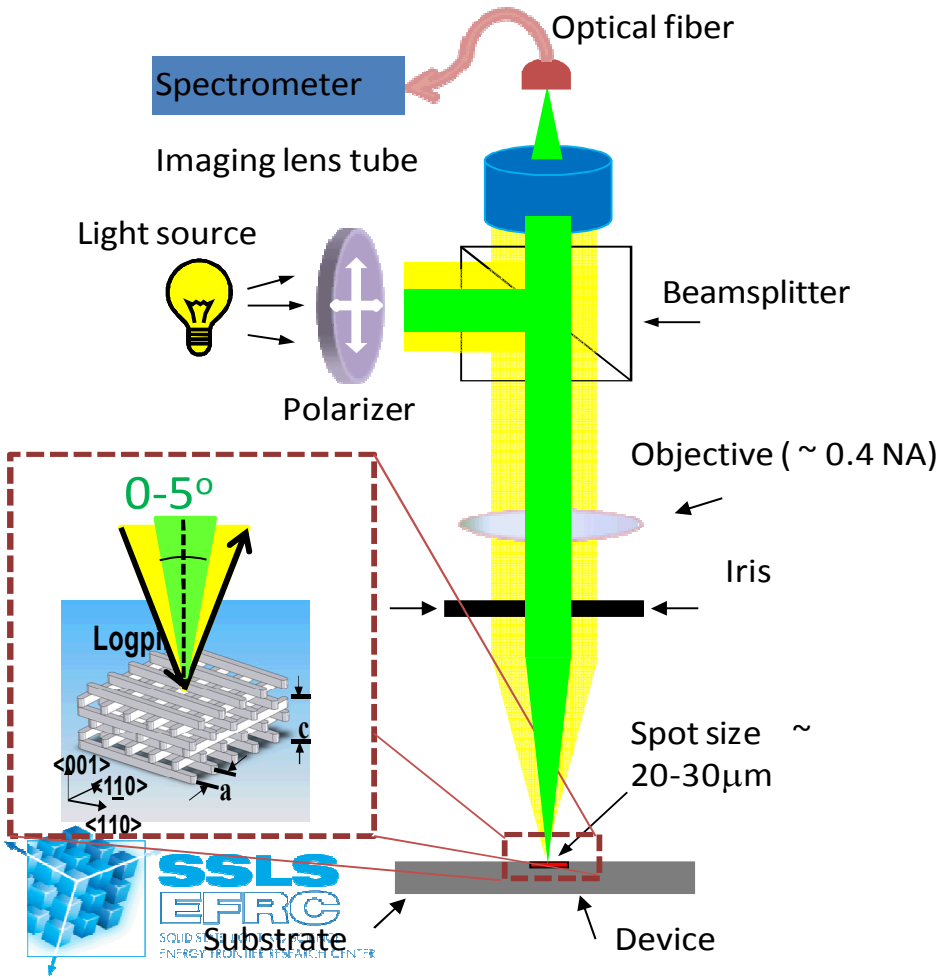
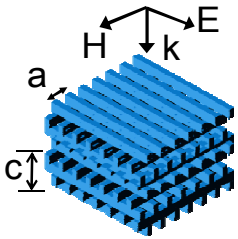
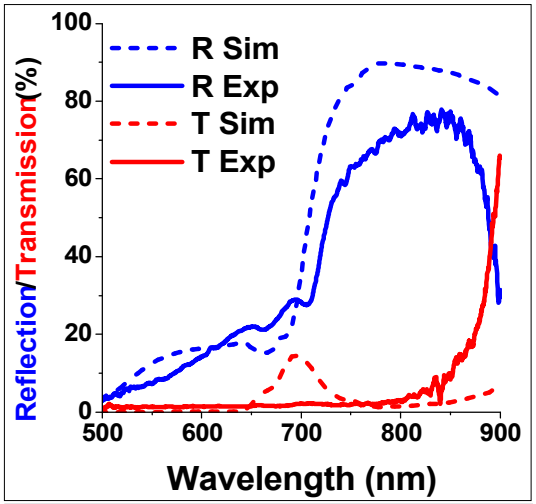
Optical Characterization

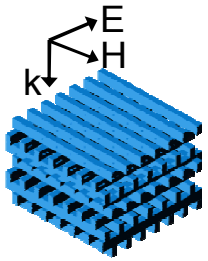
Near-normal incidence (0-5° half angle) is achieved using an objective iris allowing a 25μm spot to be imaged for spectral collection.

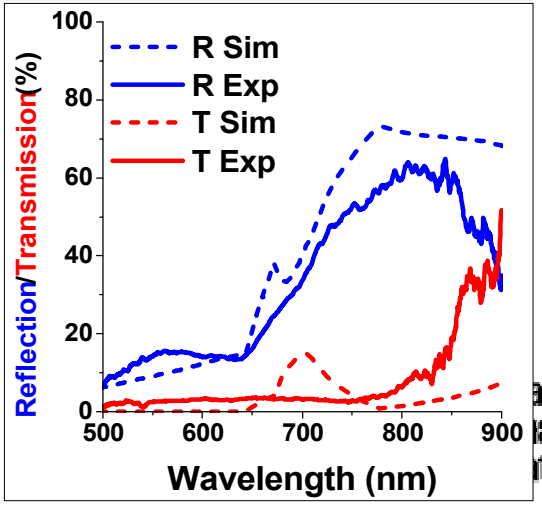
- Reflectance and transmission response is measured for input light polarization parallel and perpendicular to the top layer rods.
- Optical response is compared to finite difference time domain simulation.



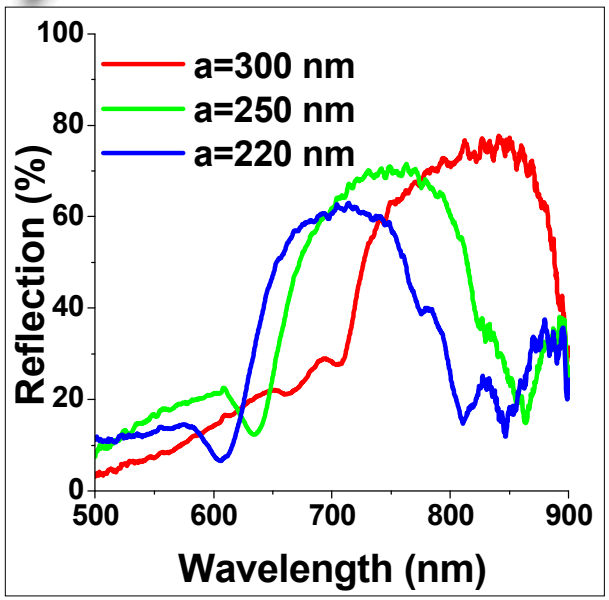


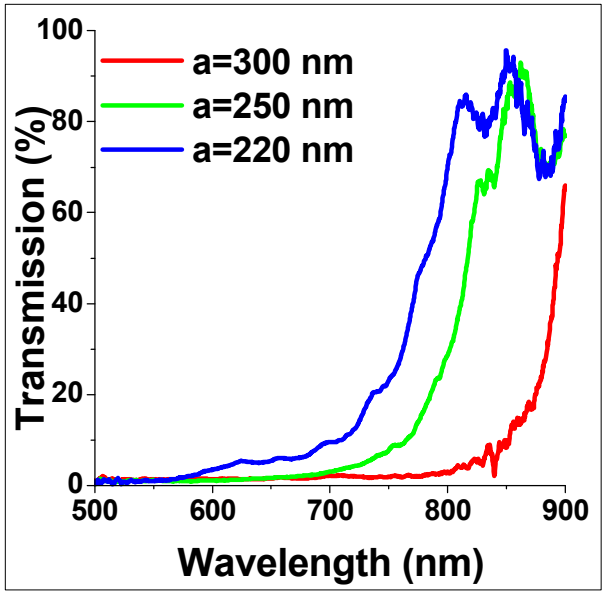


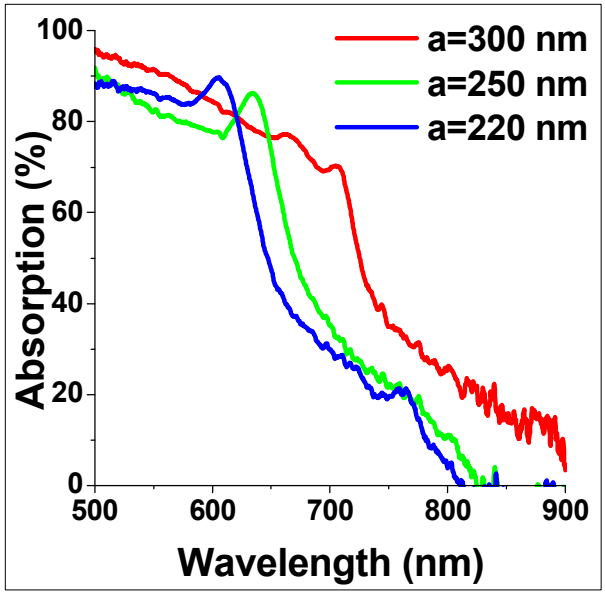




Optical Response: Different Lattice Constants







- Strong Photonic bandgap observed even down to 700nm
- Over 80% transmission at ~ 800nm for a = 220nm and 250nm
- Negligible absorption beyond ~ 800nm for a = 220nm and 250nm

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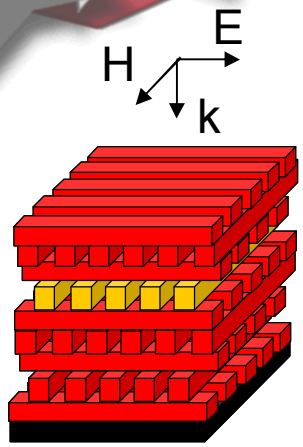
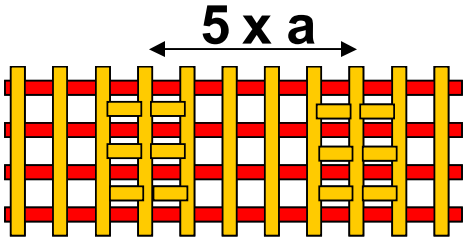
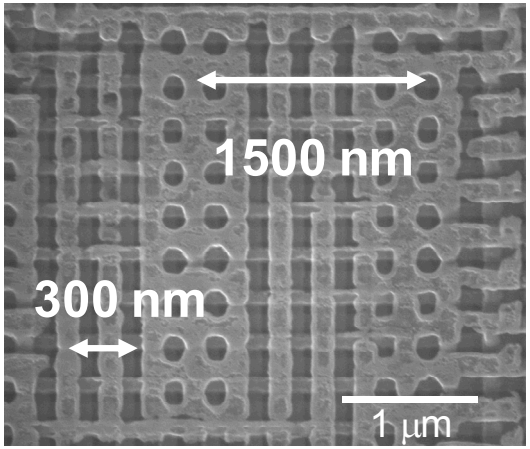
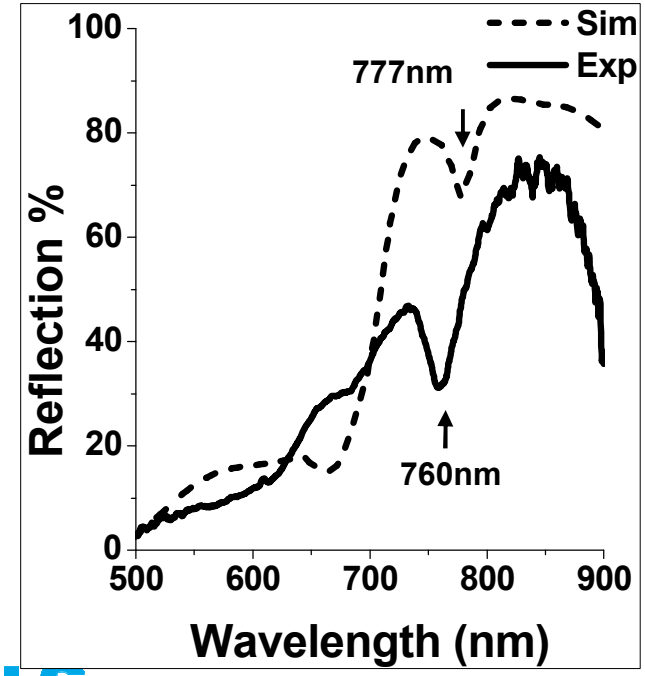
3DPC Cavity in Si logpile

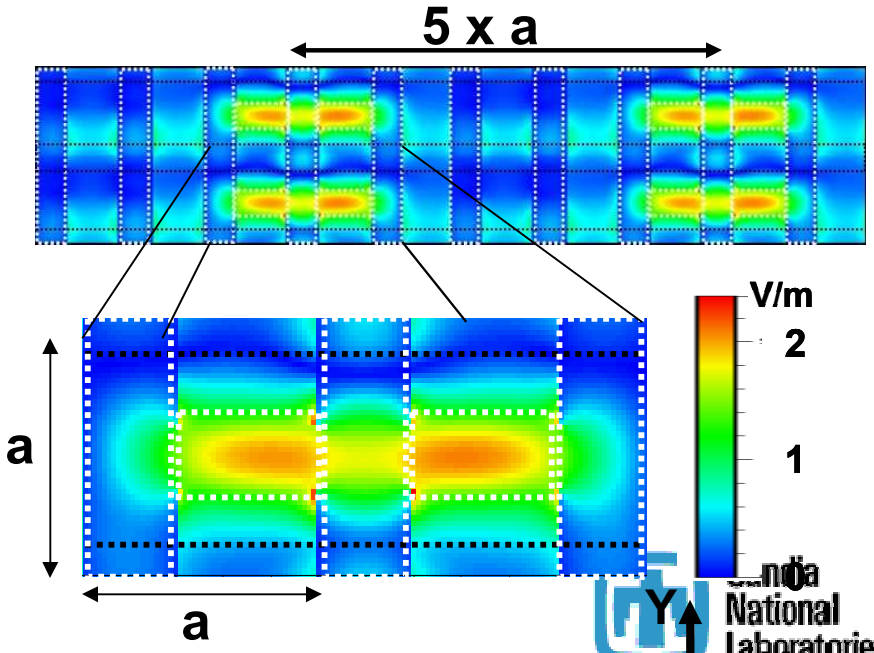








Electric field (E_x) distrubution



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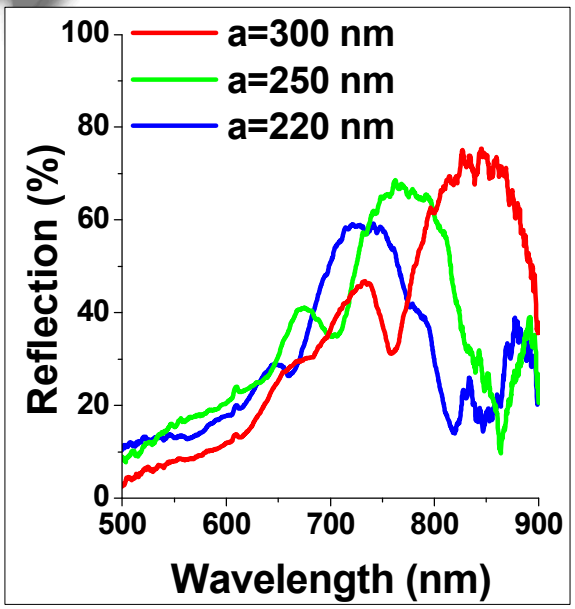
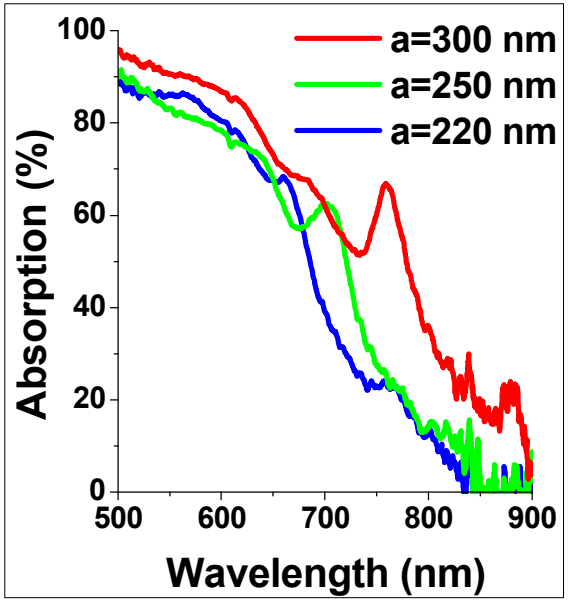
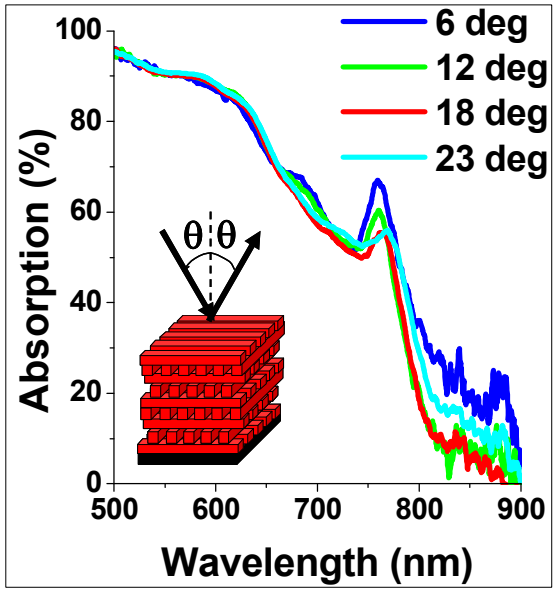
Cavity Response: Absorption Control







- Cavity mode becomes less prominent as lattice constant decreases
- Enhanced absorption at cavity mode : Slow group velocity
- Absorption wavelength relatively constant incidence angles upto 23^{o}

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Summary and Conclusions

- Experimental demonstration with 9 layer logpile PC shows that a large photonic band gap is possible in the visible regime using silicon: ~ 400nm further beyond the electronic bandedge.
- Possible to create functional devices : e.g. defect cavities into the bulk of the 3D PCs.
- Defect cavities creates an absorption mode within the bandgap of the 3DPC that is relatively stable to the incident angle and can be tuned with lattice constant.
- Improved deposition techniques (CVD) can offer higher quality silicon with lower ‘k’ thus, pushing the operational wavelength further into the visible.