Photonic Crystals: Shaping the Flow of Thermal Radiation

Ivan Čelanović
Massachusetts Institute of Technology
Cambridge, MA 02139

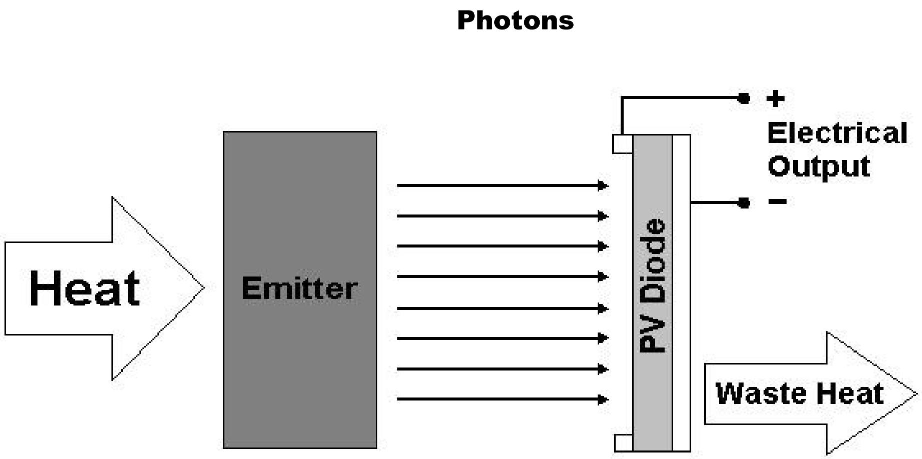
Overview:

- Thermophotovoltaic (TPV) power generation
- Photonic crystals, design through periodicity
- Tailoring electronic- and photonic bandgap properties: a path towards record efficiencies
- Photovoltaic module: design and characterization
- TPV system design challenges
- Quasi-coherent thermal radiation via photonic crystals

Thermophotovoltaic power generation: basic ideas and concepts

Thermo-photo-voltaic conversion

TPV power conversion describes the <u>direct</u> conversion of thermal radiation into electricity.



Brief History

1956 - **Dr. H. Kolm / Dr. P. Aigrain** independently propose TPV power conversion concept

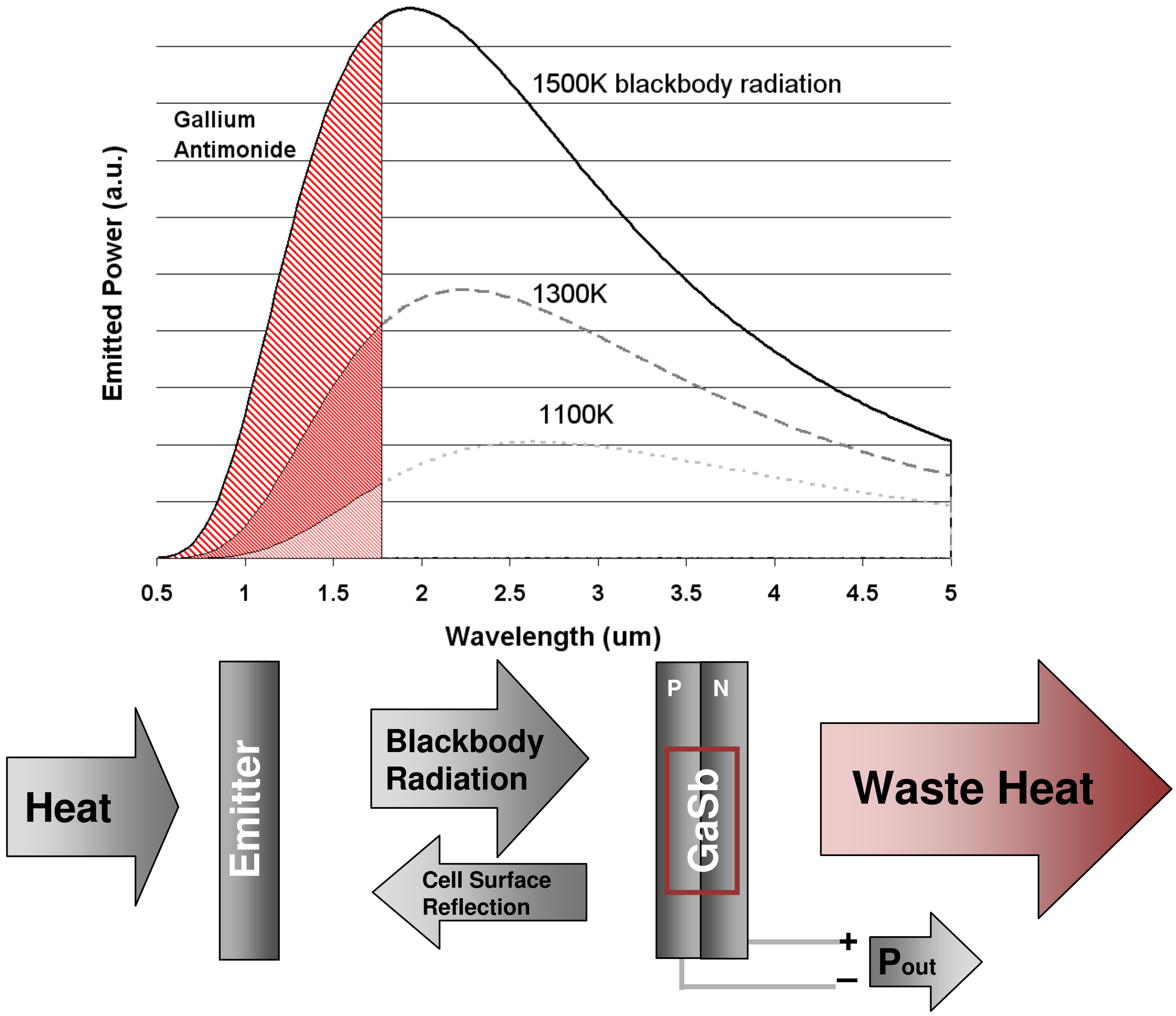
1970's - Loss of interest in TPV due to low efficiencies

1990's - **Advancements in microfabrication technology** allow for production of low-bandgap diodes, opening the door for more efficient TPV

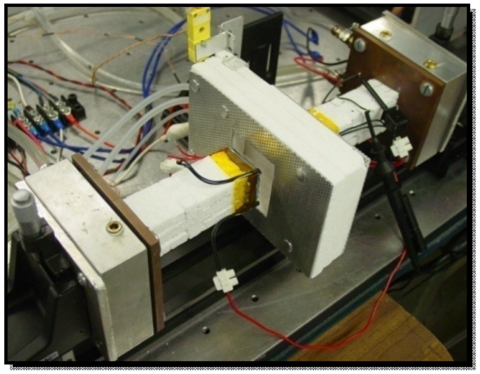
1994 - **First NREL Conference on TPV Generation of Electricity**

2000's **-Photonic crystals for thermal radiation control**

Basic TPV energy conversion diagram



PV vs. TPV

Properties:	PV (Solar Cells) 	TPV 
Sensitivity Range	**Visible and NIR**	**NIR and IR**
Source	**Sun**	**Thermal emitter**
Source Temperature	**Over 5000K (sun's surface)**	**1000-1500K**
Distance from Source	**Over 90 million miles**	**μm to cm**
Energy reflected from cell surface	**Lost to atmosphere**	**Recycled to the emitter**

Courtesy of DOE/NREL, Credit - Beck Energy.

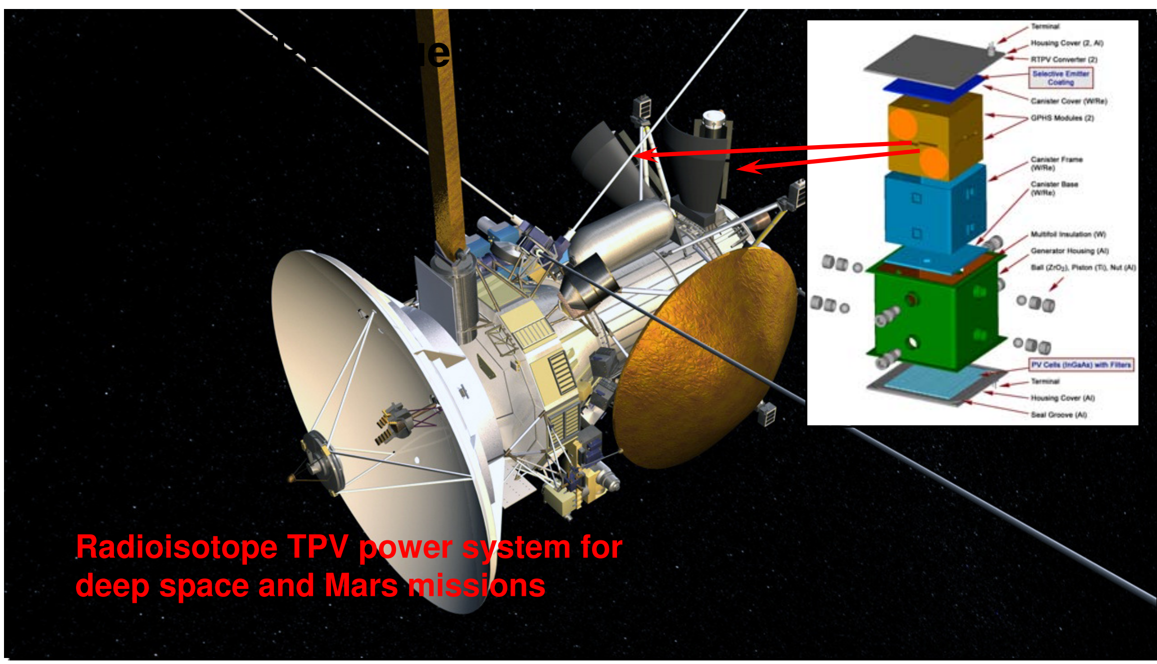
TPV Technologies and applications

AA radioisotope TPV battery:
~10 mWe
30 years life time
24% efficiency

Photo courtesy of LLNL.

micro-TPV power generator (propane/butane operated)

Courtesy of Klavs Jensen. Used with permission.



Images courtesy of NASA.

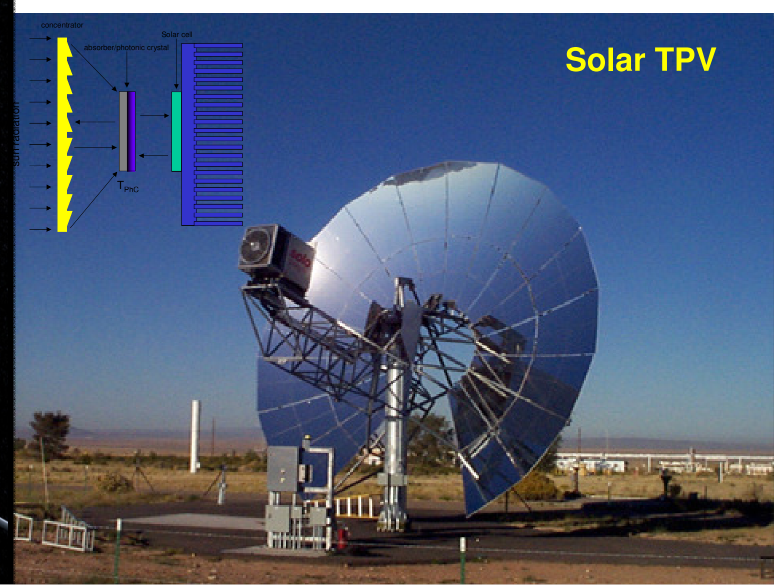
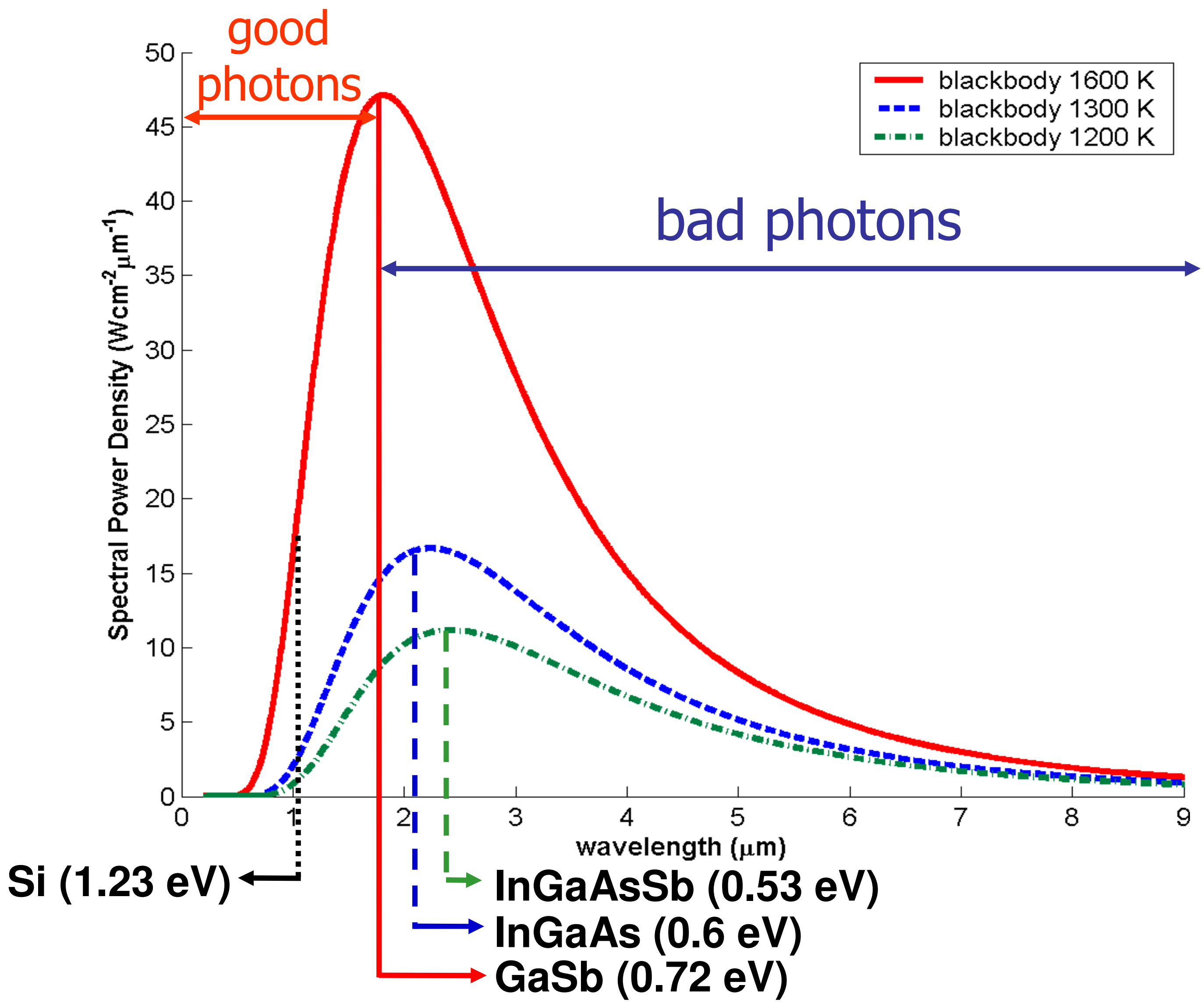
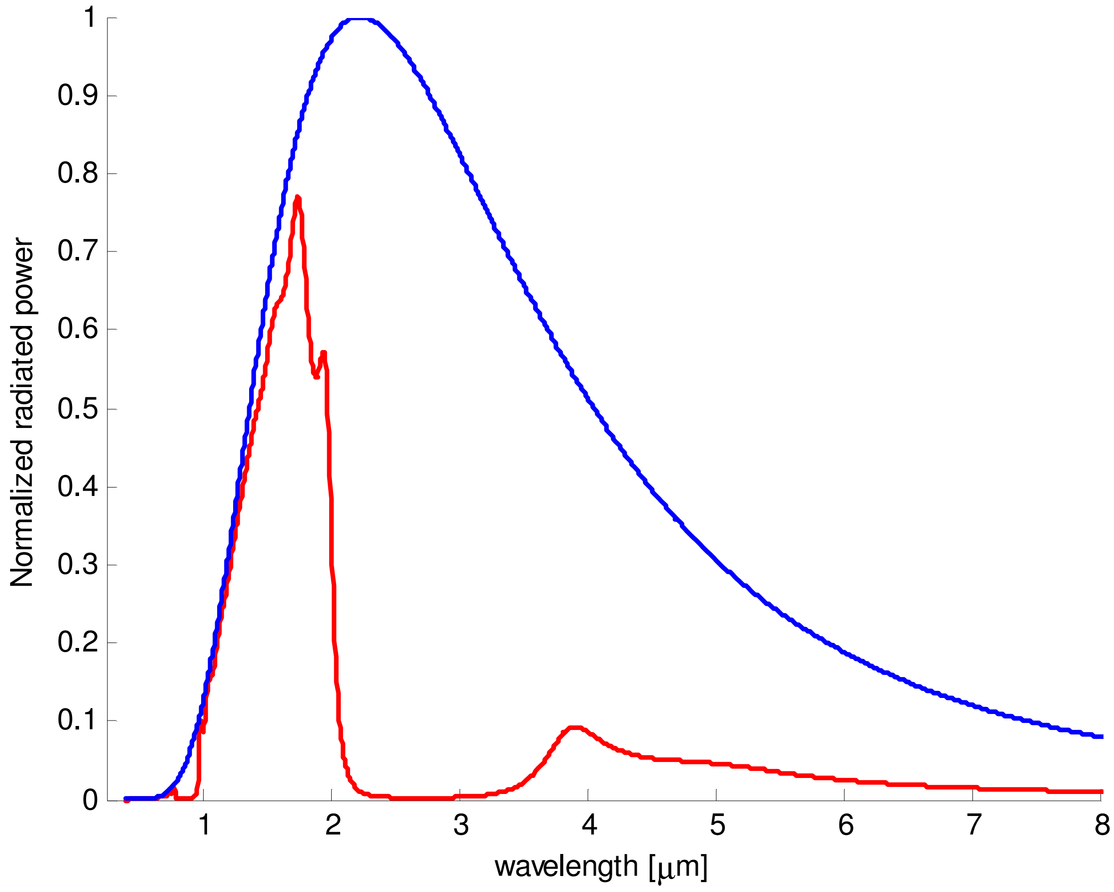


Photo courtesy of Sandia National Labs.

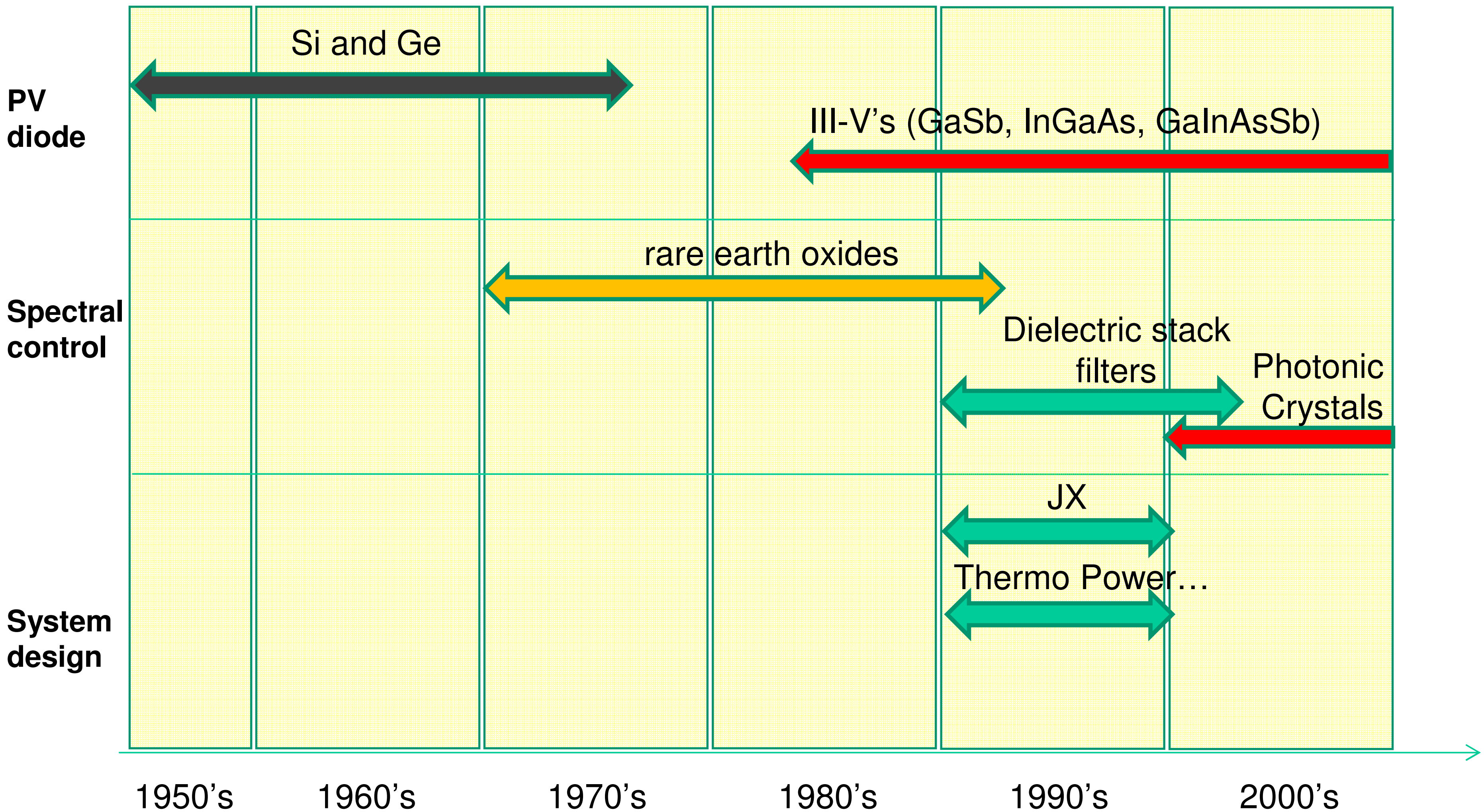
Thermophotovoltaics: converting thermal radiation into electricity, with no moving parts



Photonic Crystals: shaping thermal radiation

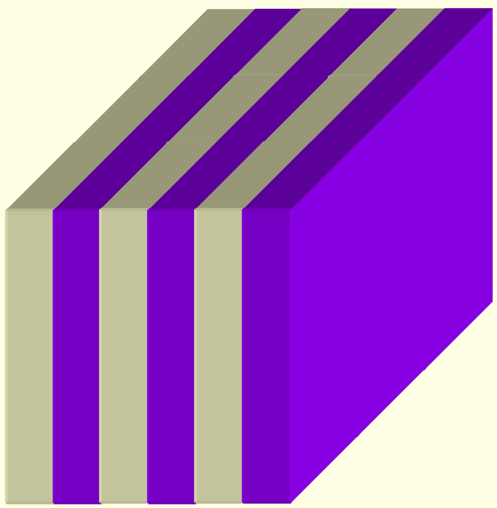


TPV Technology roadmap: the time is now



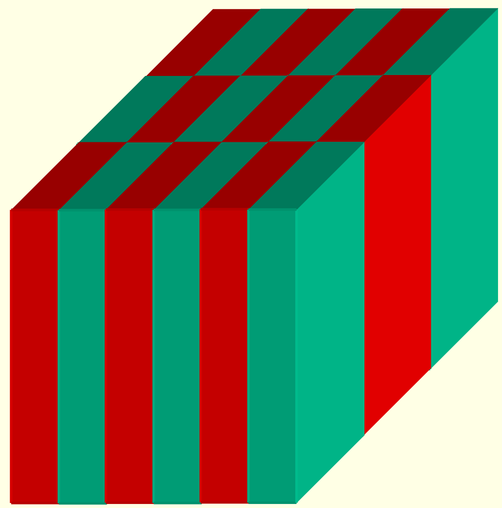
Photonic crystals, design through periodicity

Photonic crystals are periodical structures with 1D, 2D or 3D periodicity



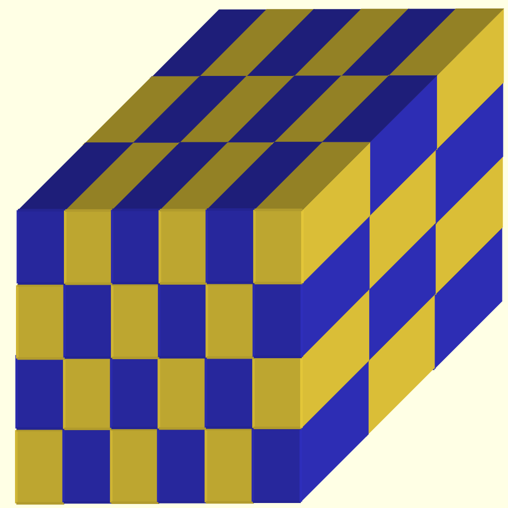
1-D Periodicity

$$\varepsilon(x, y, z) = \varepsilon(x + \lambda_x, y, z)$$



2-D Periodicity

$$\varepsilon(x, y, z) = \varepsilon(x + \lambda_x, y + \lambda_y, z)$$

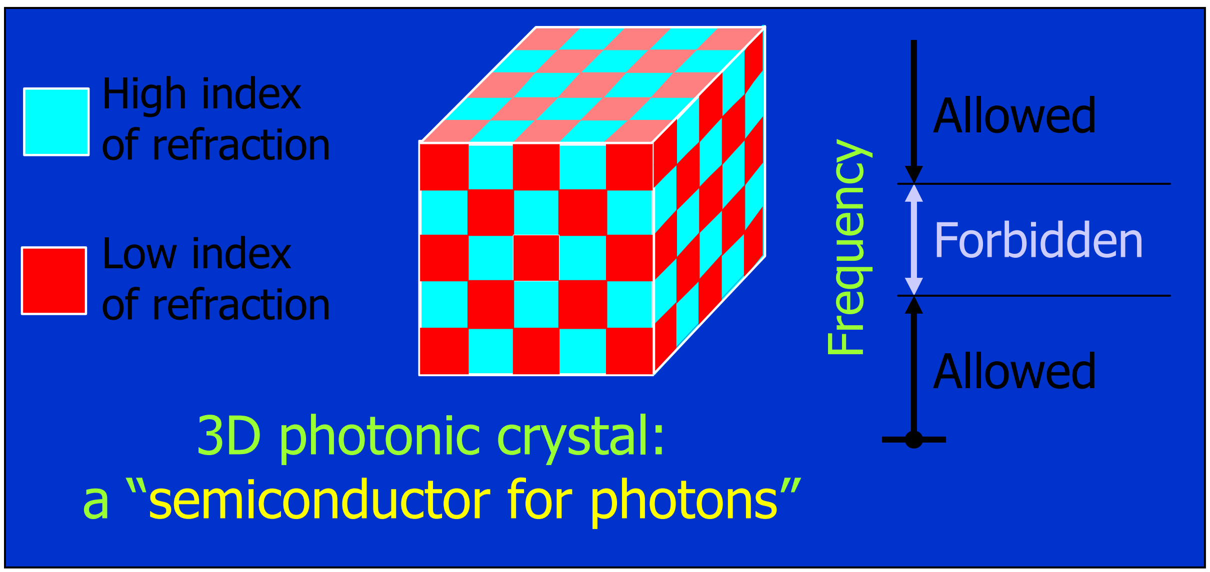


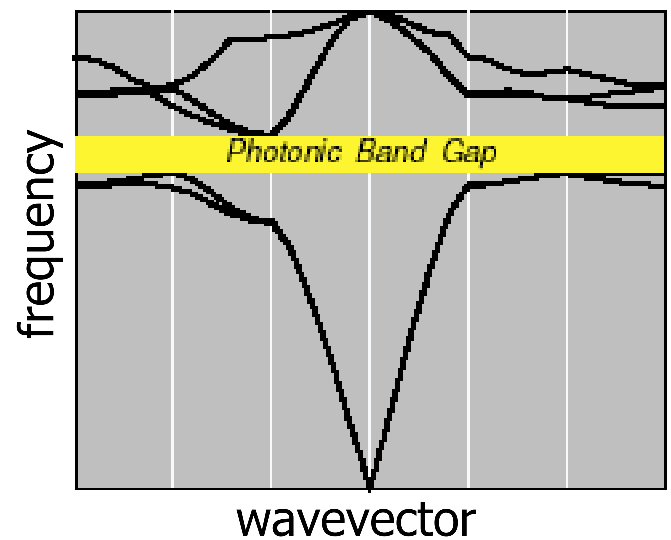
3-D Periodicity

$$\varepsilon(x, y, z) = \varepsilon(x + \lambda_x, y + \lambda_y, z + \lambda_z)$$

Metamaterial:

optical properties determined from its nano-structure
(rather than its composition)





Refs: E.Yablonovitch, Phys. Rev. Lett. **58**, 2059, (1987).
S.John, Phys. Rev. Lett. **58**, 2486, (1987).

Controlling density of photonic states

⇓

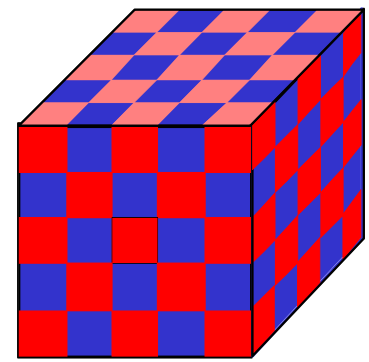
controlling thermal emission spectrum

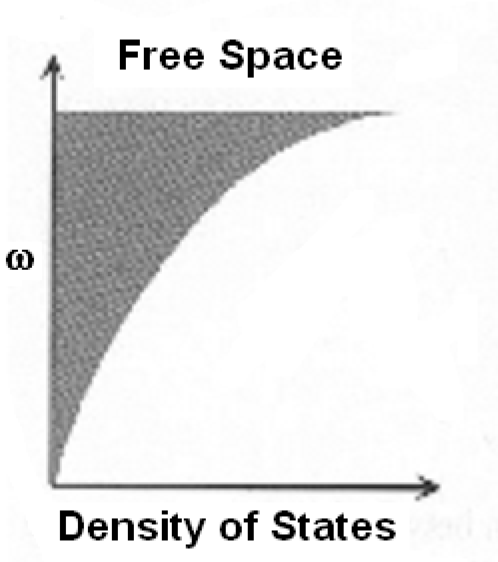
$$u(\omega, T) = N(\omega) * \left[\frac{\hbar\omega}{e^{\frac{\hbar\omega}{k_B T}} - 1} \right]$$

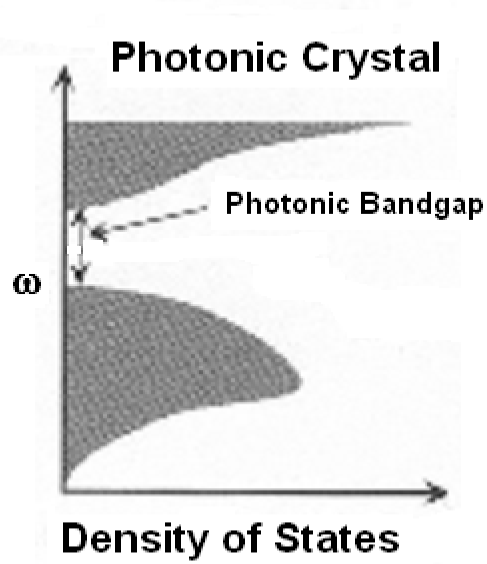
energy density

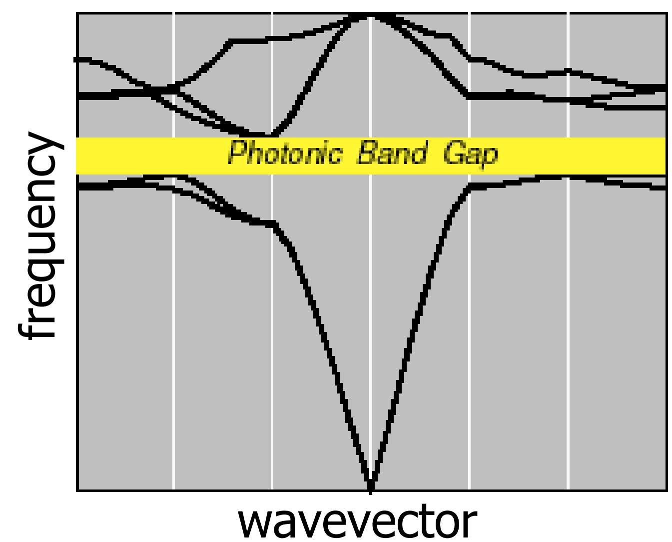
density of photonic modes

energy in each photonic mode

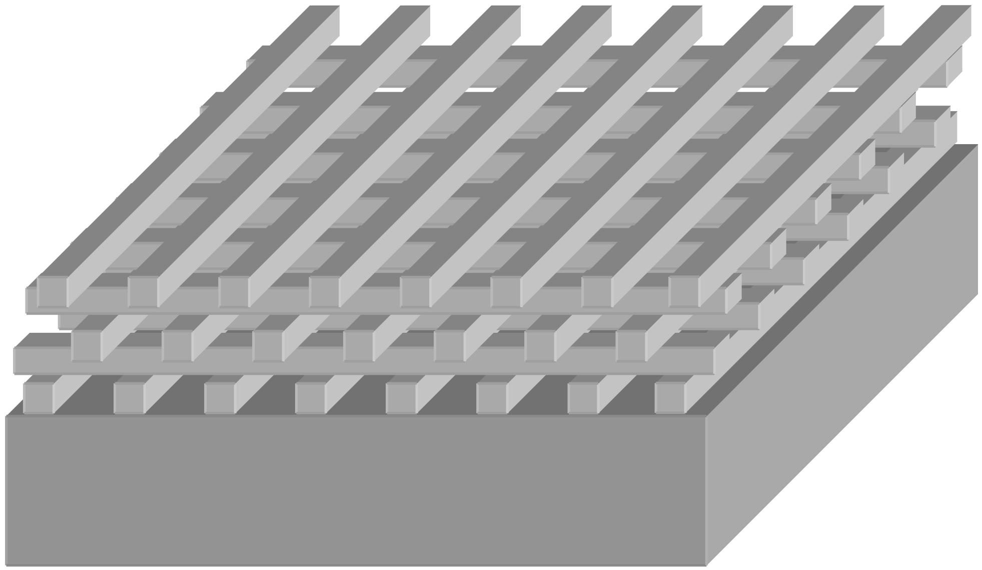


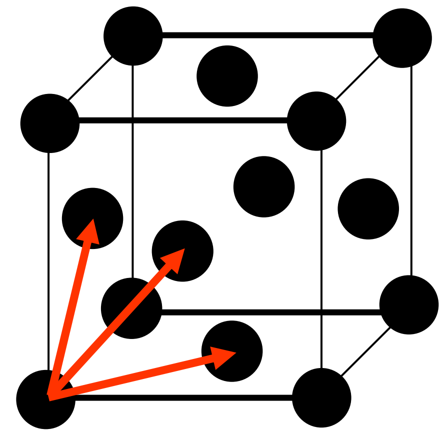




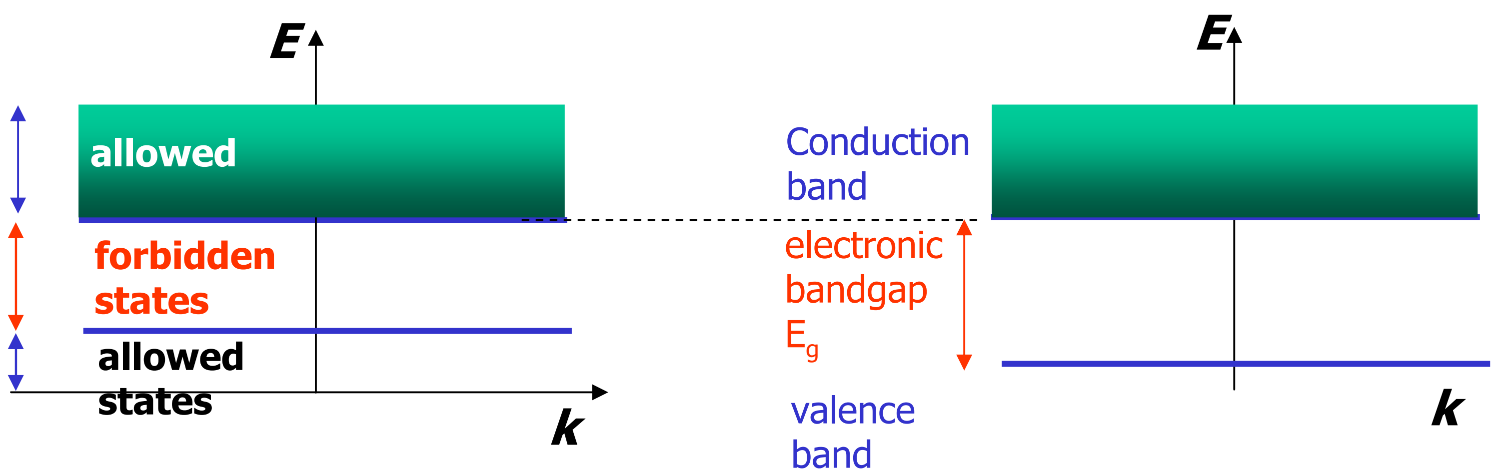


Photonic crystals are analogous to semiconductors





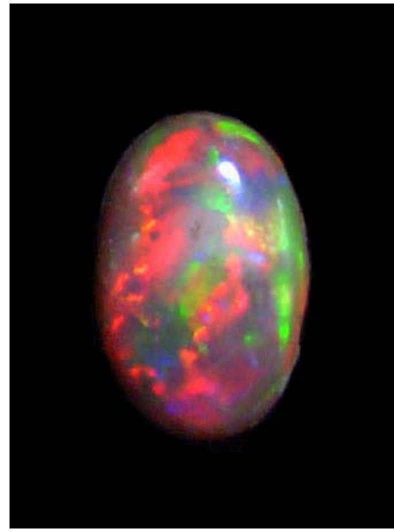
Face center cubic lattice



Naturally occurring photonic crystals:

Butterfly wings

Opal



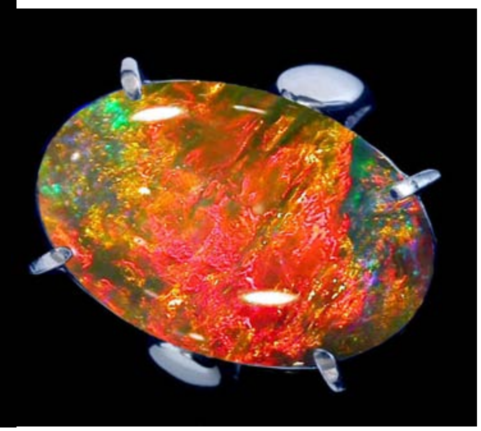


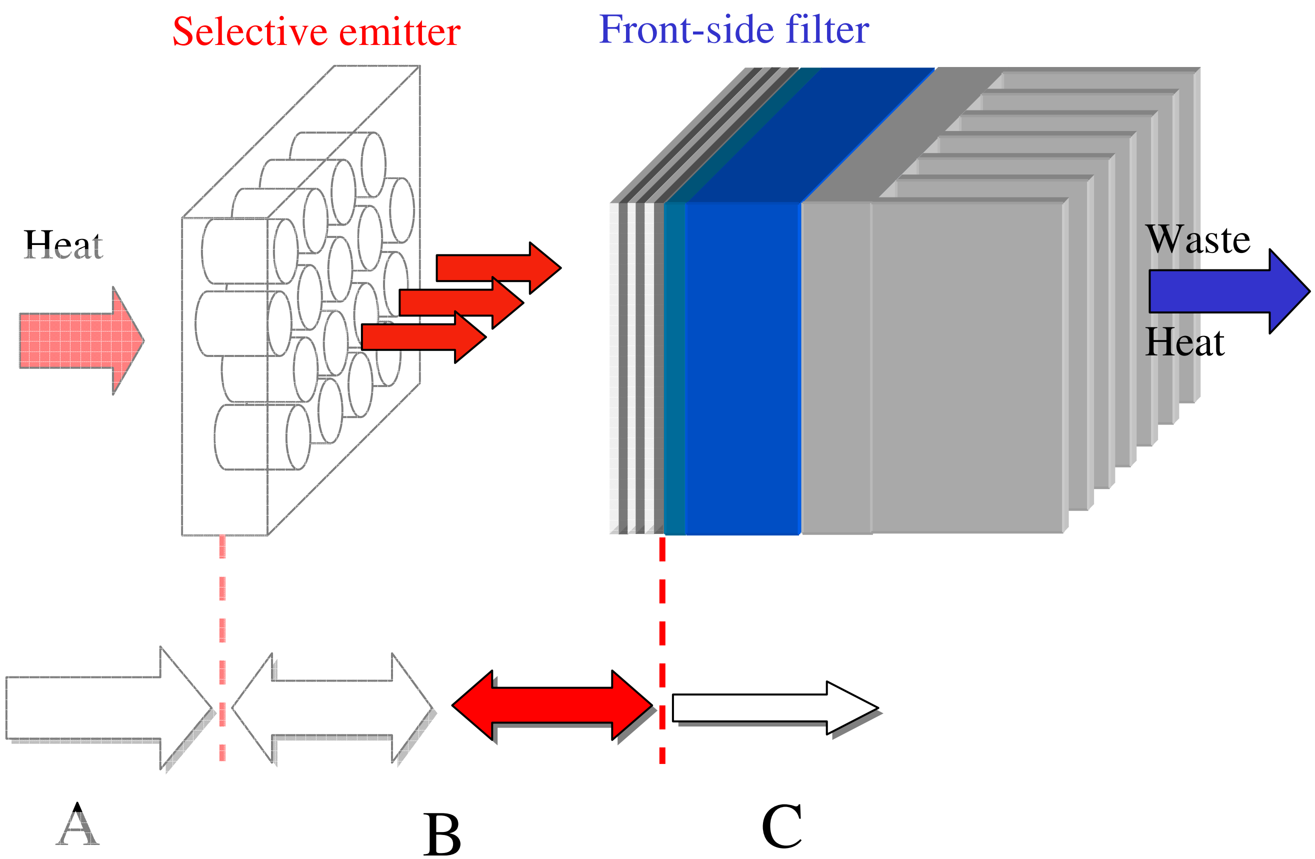
Photo by Megan McCarty at Wikimedia Commons.
Images removed due to copyright restrictions.
Please see: http://www.tils-ttr.org/photos/Mitoura-gryMDneo.jpg
http://www.tils-ttr.org/photos/Mitoura-gryMVneo.jpg

Fig. 11 in Ghiradella, Helen. "Light and Color on the Wing: Structural Colors in Butterflies and Moths." *Applied Optics* 30 (1991): 3492-3500.
Fig. S1a, S2, and S4a in Vukusic, Pete, and Ian Hooper. "Directionally Controlled Fluorescence Emission in Butterflies." *Science* 310 (November 18, 2005): 1151.
Fig. 3 in Pendry, J. B. "Photonic Gap Materials." *Current Science* 76 (May 25, 1999): 1311-1316.

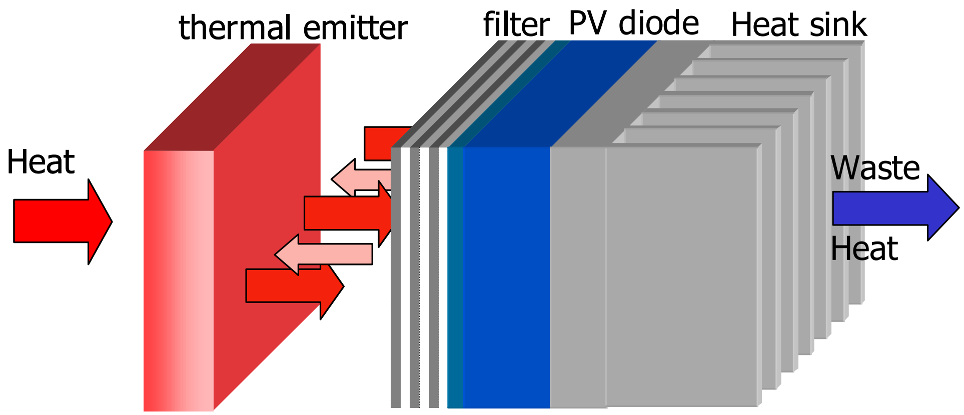
P. Vukusic, I. Hooper, "Directionally controlled fluorescence emission in butterflies," Science, vol. 310, pp. 1151

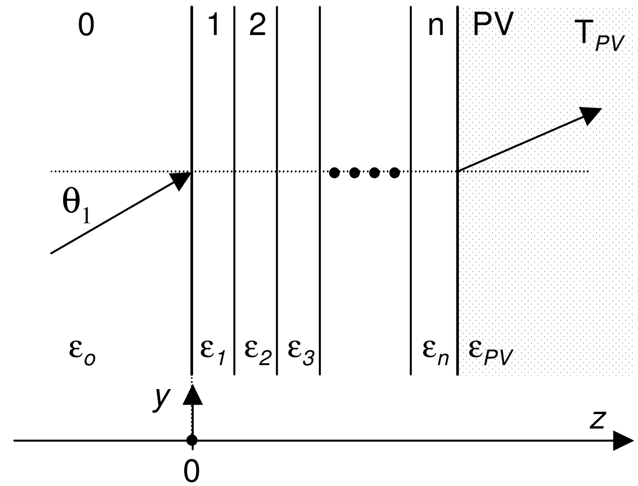
Tailoring electronic- and photonic bandgap properties: a path towards record efficiencies

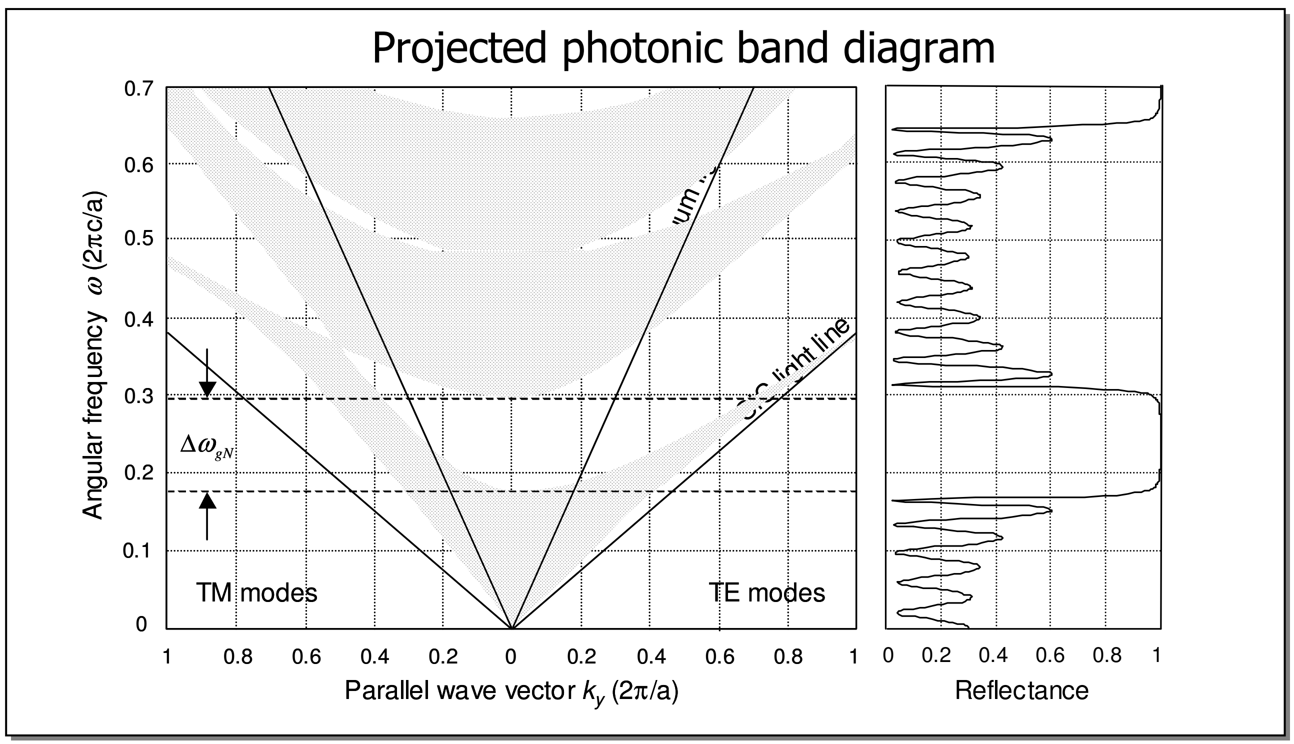
Photonic crystal as omnidirectional mirror



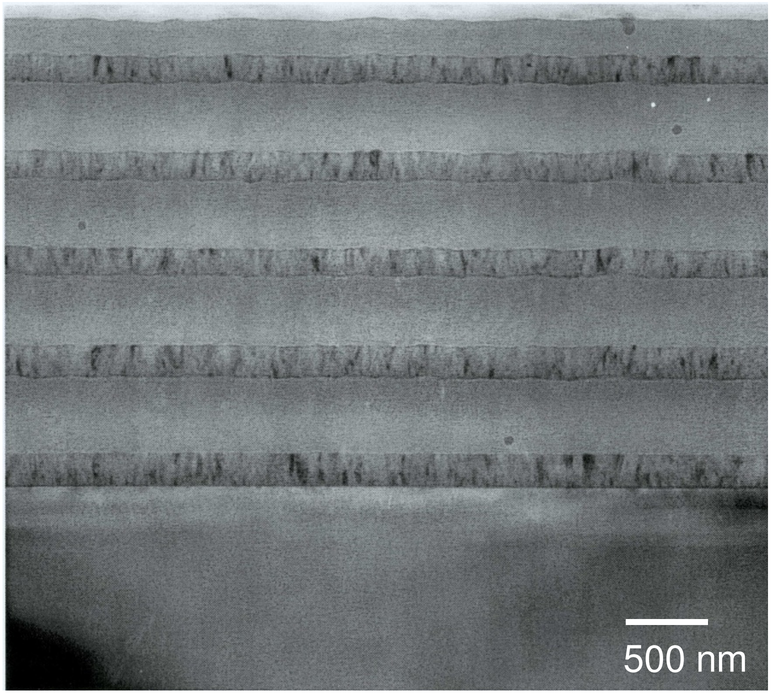
1D Si/SiO_2 photonic crystals exhibit omni-directional bandgap



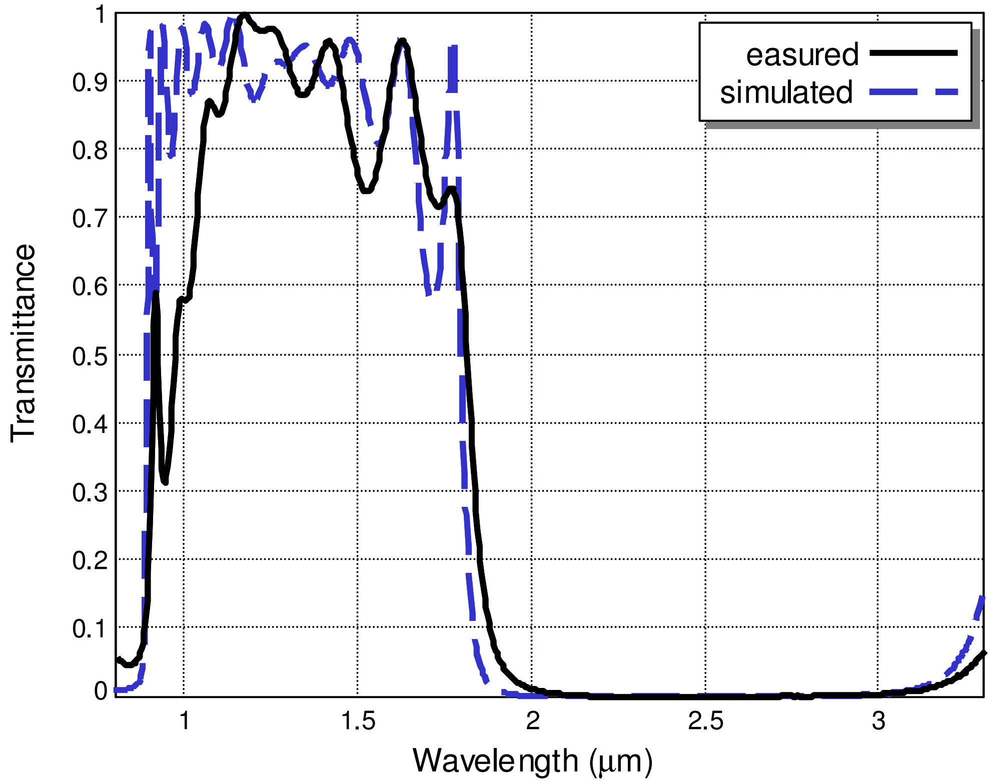




Spectral characterization of 1D photonic crystal



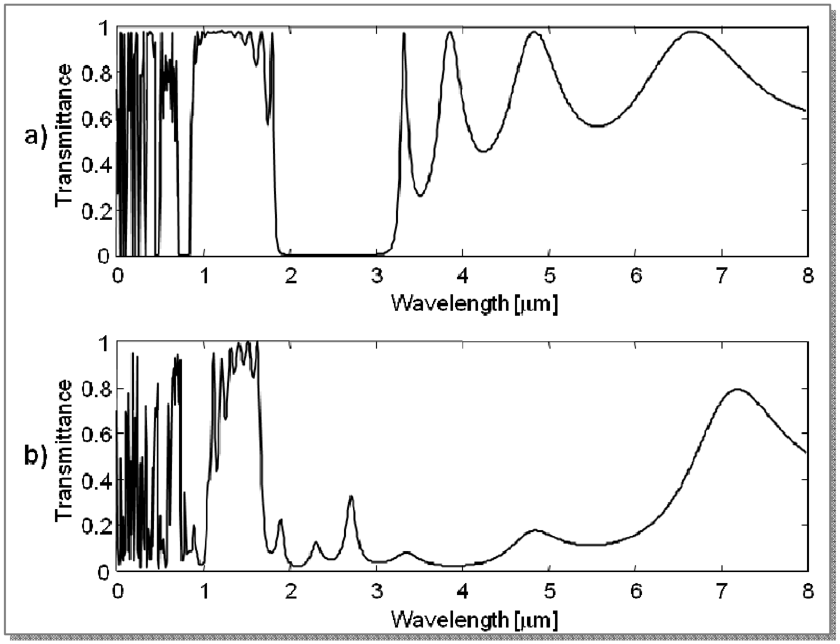
TEM cross section of LPCVD* grown
quarter-wave stack filter with half-layer at the top

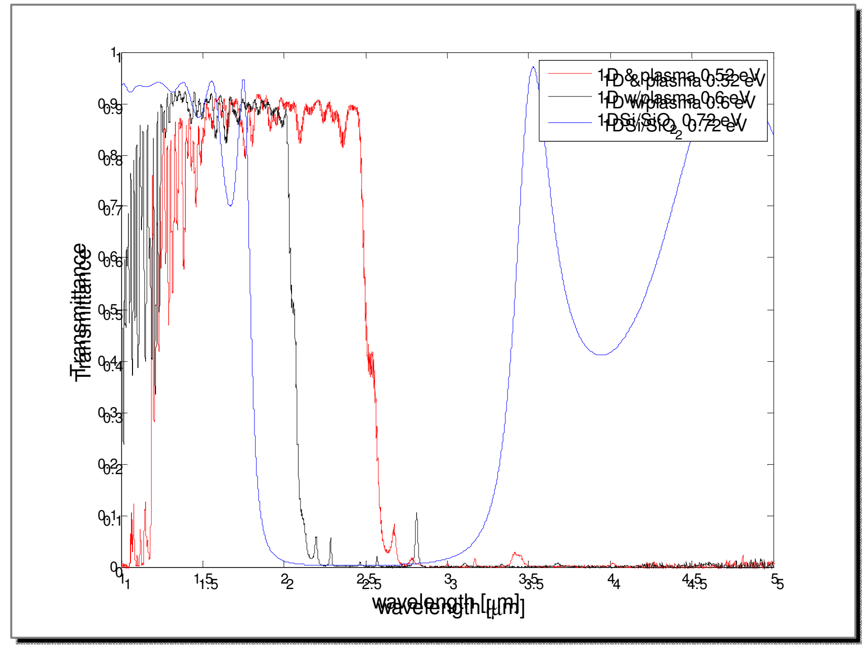


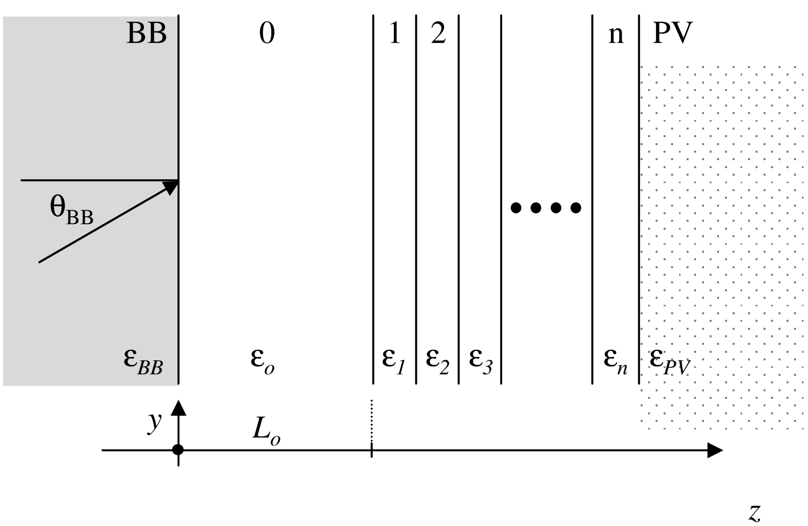
Si = lighter layers (170nm)
SiO_2 = darker layers (390nm)

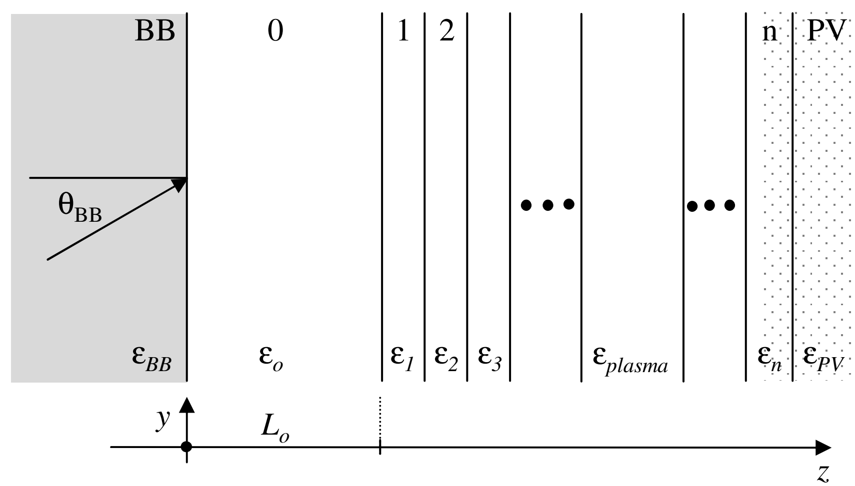
Image removed due to copyright restrictions.
Please see Fig. S2 in Vukusic, Pete, and Ian Hooper. "Directionally Controlled Fluorescence Emission in Butterflies." *Science* 310 (November 18, 2005): 1151.

Front side PhC designs, 0.72 eV, 0.6 eV, 0.52 eV

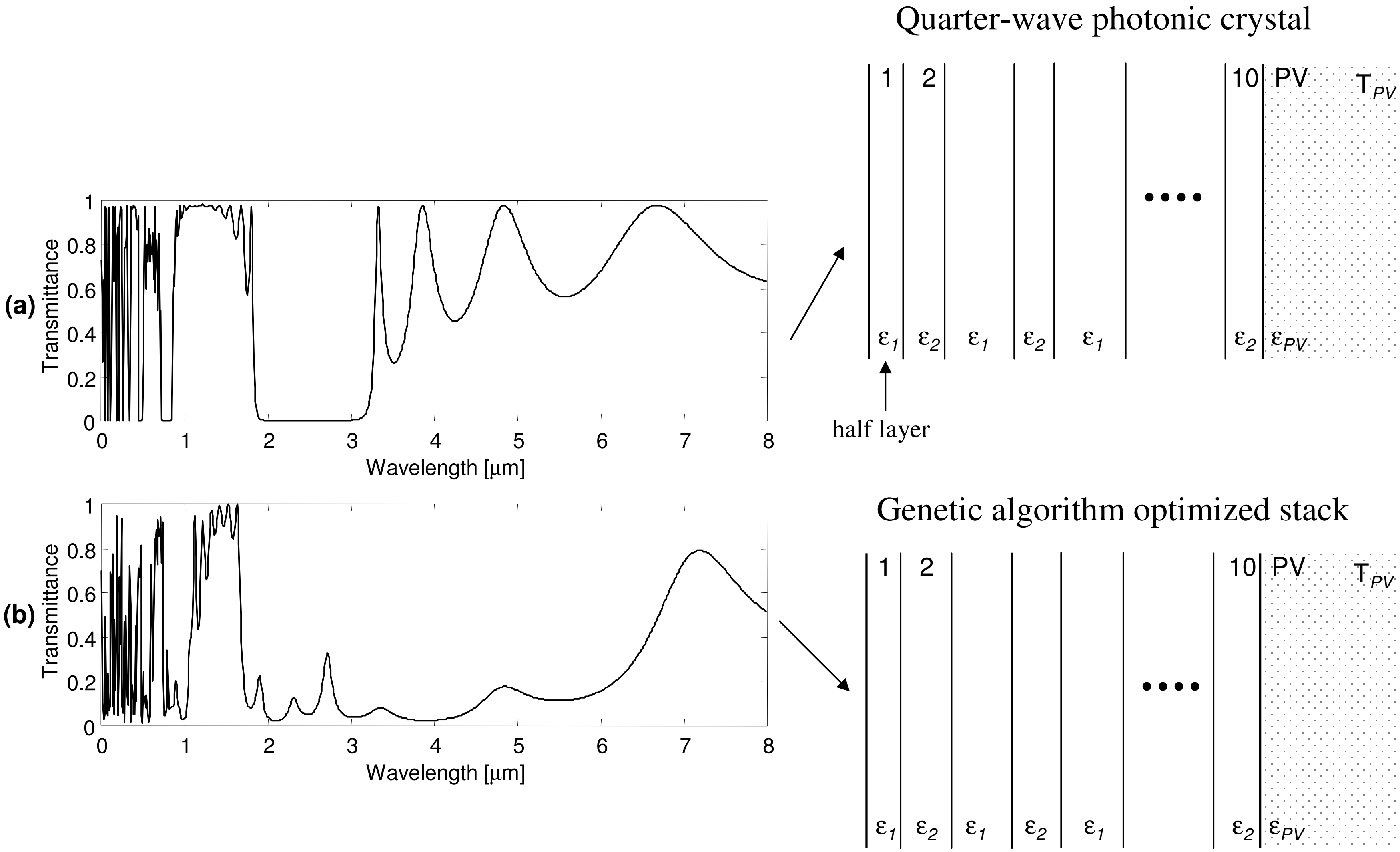




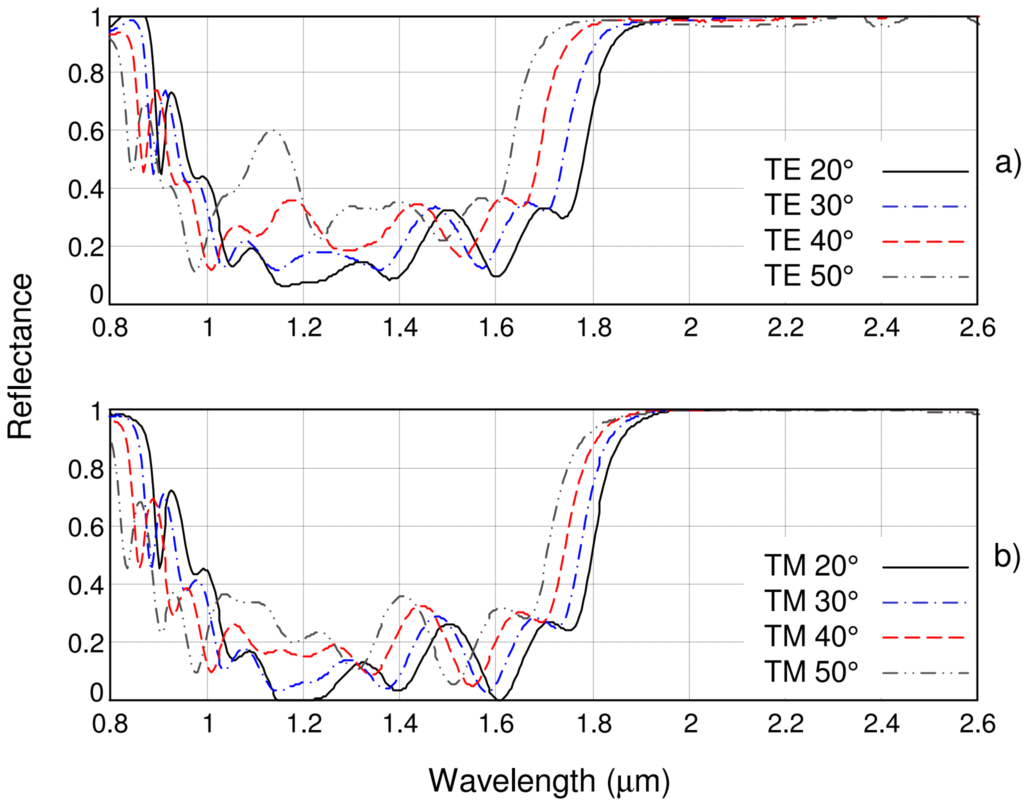




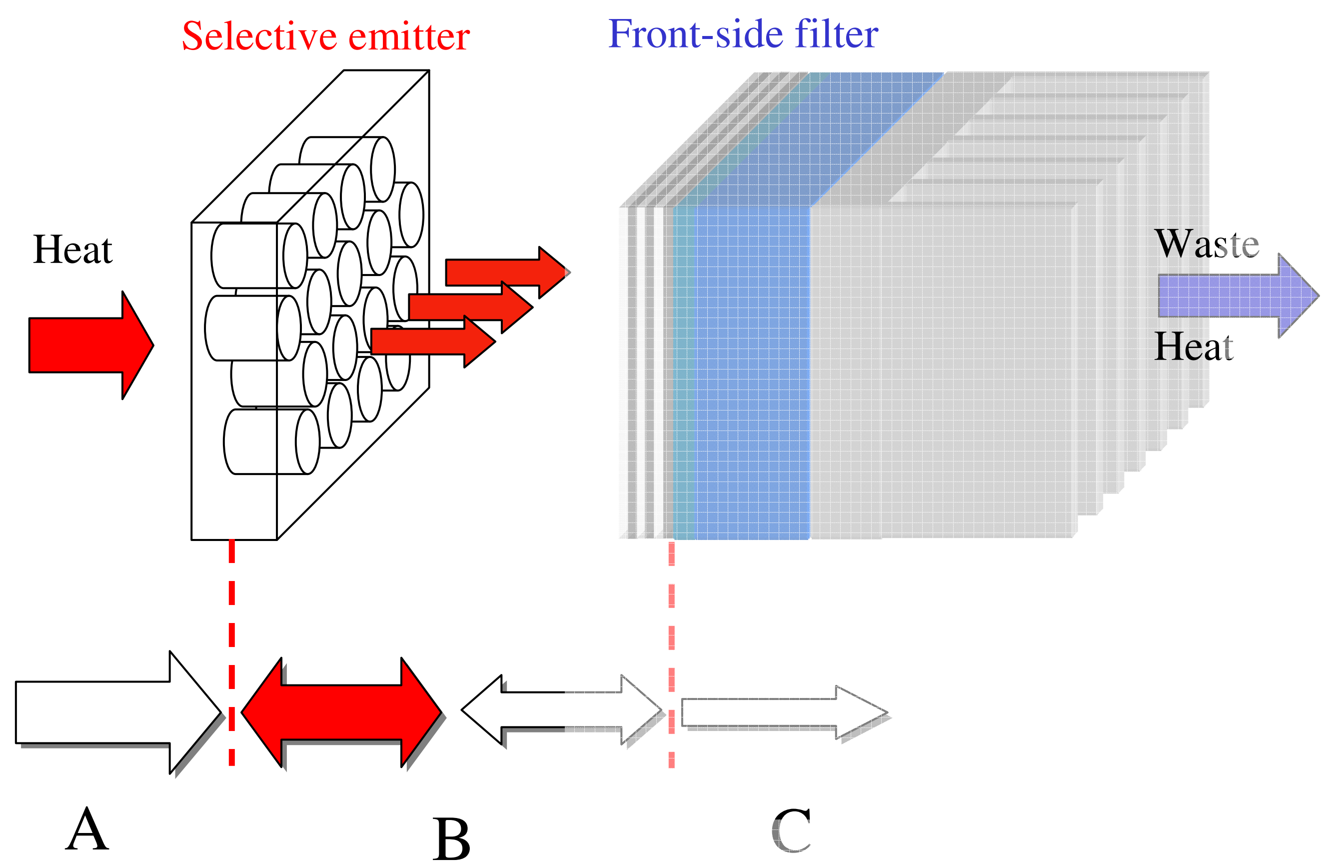
1D Si/SiO_2 photonic crystals: quarter-wave based stack and genetic algorithm optimized stack as a spectral control tool



Spectral characterization of fabricated 1D photonic crystal



Improving the spectral efficiency via selective thermal emission



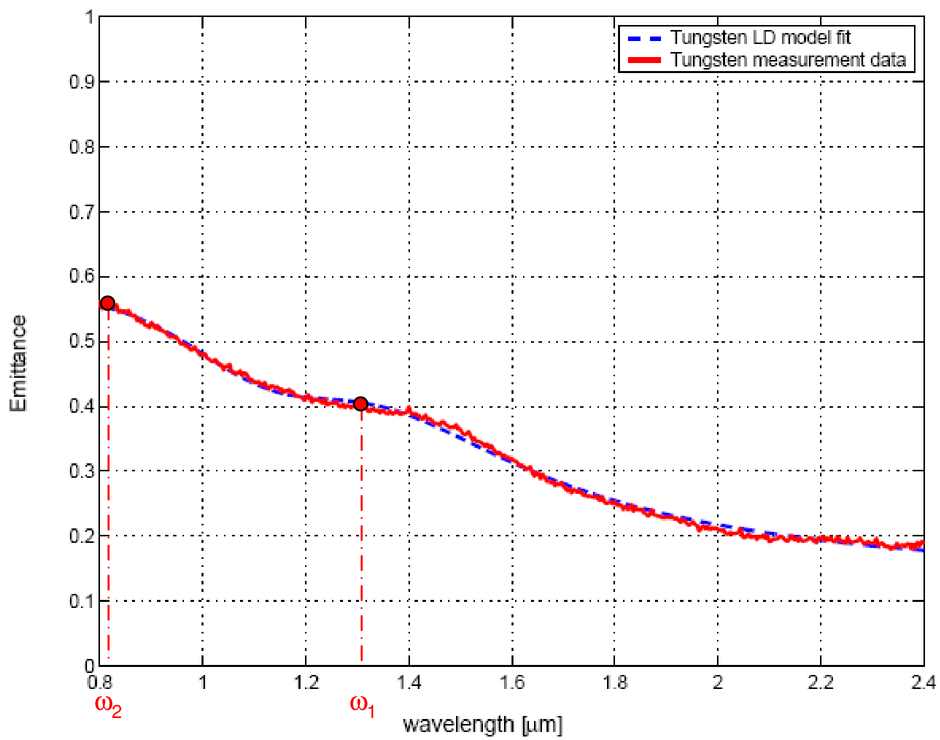
But remember thermal emitter is really hot! (up to 1500K)

Refractory metals have high melting temperature, especially *tungsten*, and that is why it has been used for incandescent light bulbs ever since

William D. Coolidge, invented the process for producing the ductile tungsten in 1909 that revolutionized light bulbs and X-ray tubes. His first light bulb was named “Mazda”

http://www.harvardsquarelibrary.org/unitarians/coolidge.html

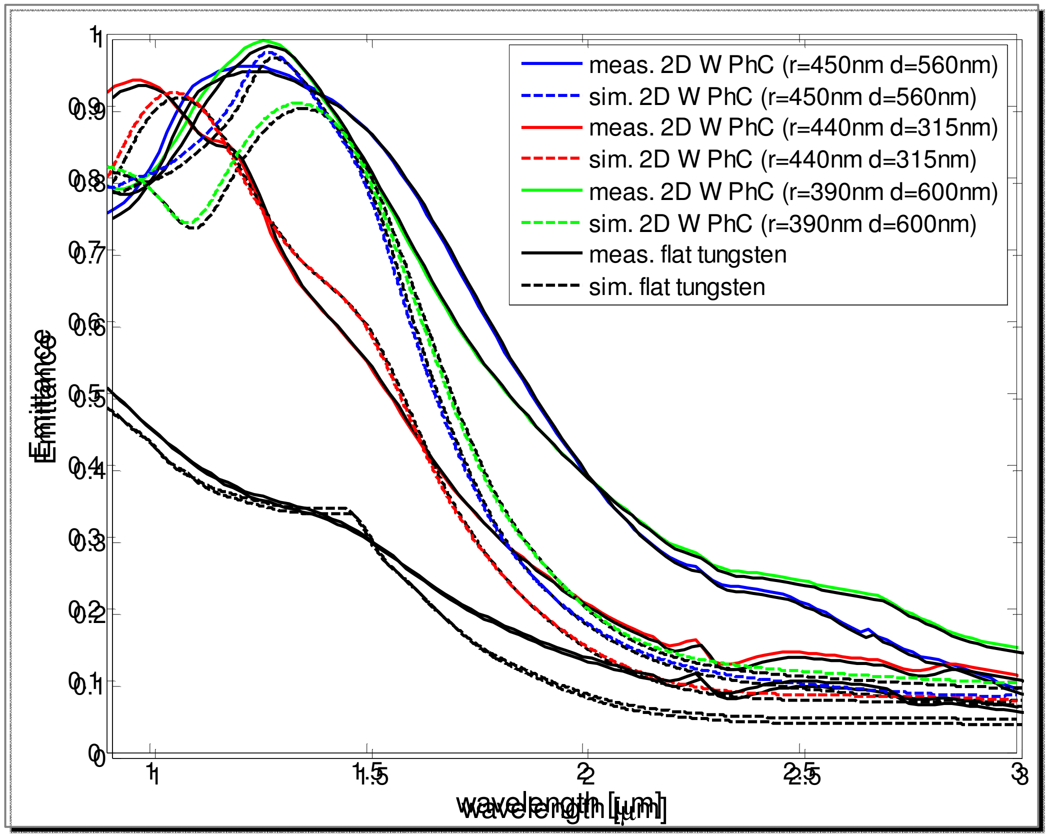
Adding an array of resonant cavities in tungsten can help us tailor the emittance

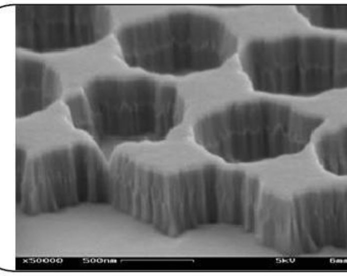


Lorentz-Drude model for tungsten

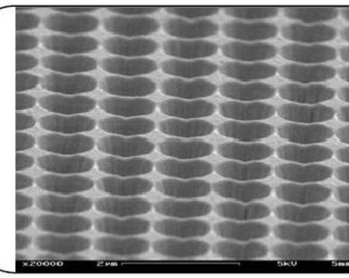
$$\varepsilon(\omega) = 1 + \sum_j \frac{\omega_{pj}^2}{\omega_j^2 - \omega^2 + i\Gamma_j \omega}$$

2D W PhC as selective thermal emitter:

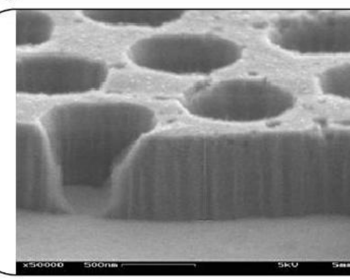




Prototype 1
Sample area: ~175mm²
Period: 1000nm
Hole diameter: 910nm
Hole depth: 550nm
Wall aspect ratio: 0.05

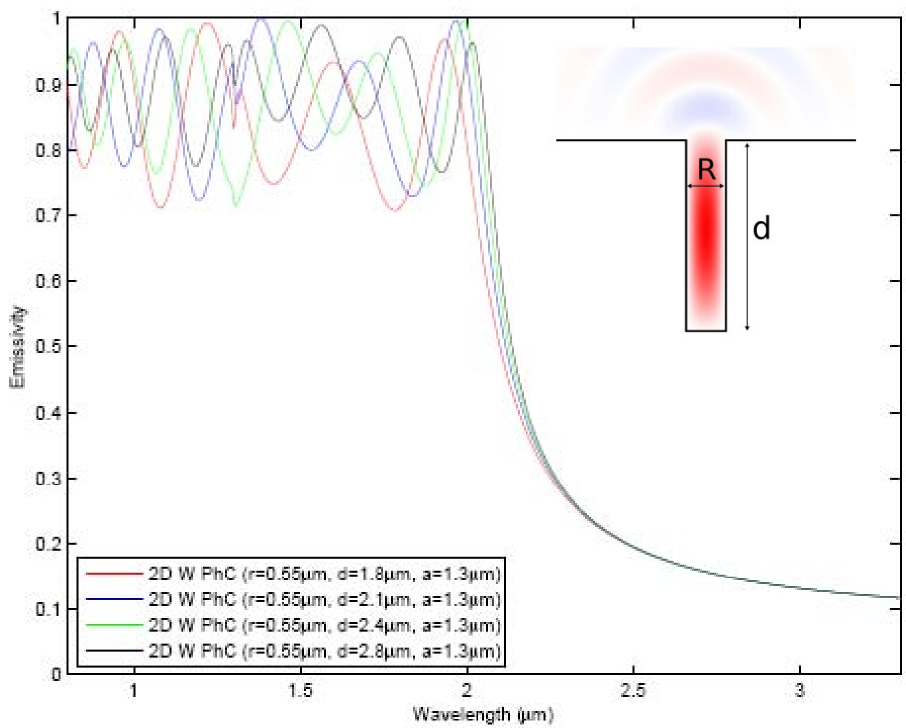


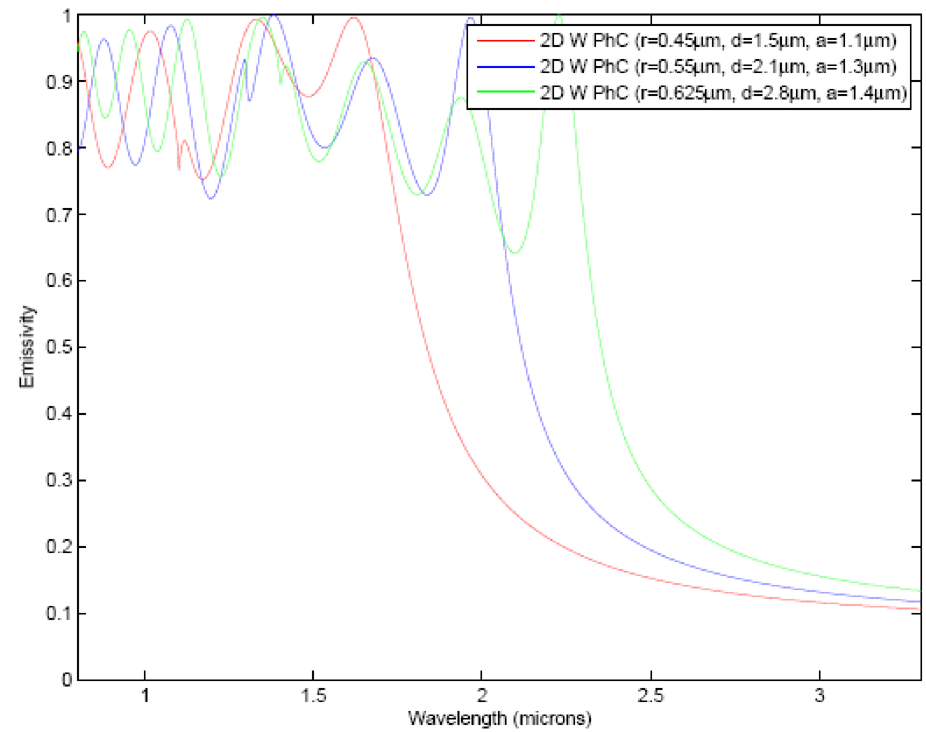
Prototype 2
Sample area: ~175mm²
Period: 1000nm
Hole diameter: 820nm
Hole depth: 315nm
Wall aspect ratio: 0.09



Prototype 3
Sample area: ~225mm²
Period: 1000nm
Hole diameter: 720nm
Hole depth: 600nm
Wall aspect ratio: 0.04

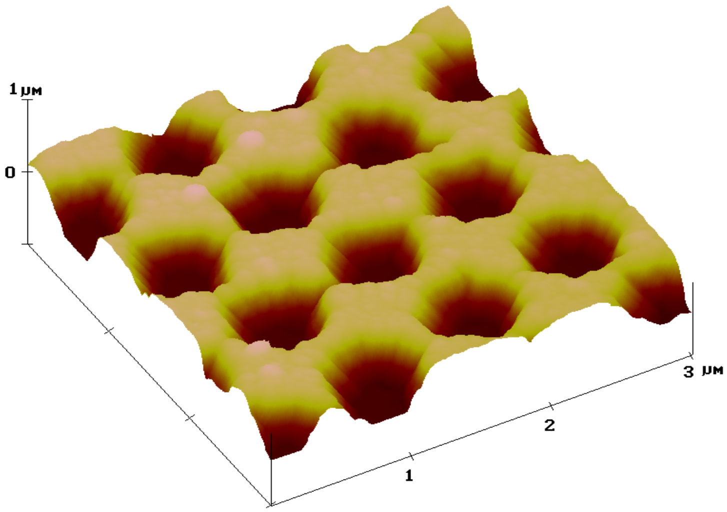
2D W PhC exhibits tunable cut-off and resonant enhancement

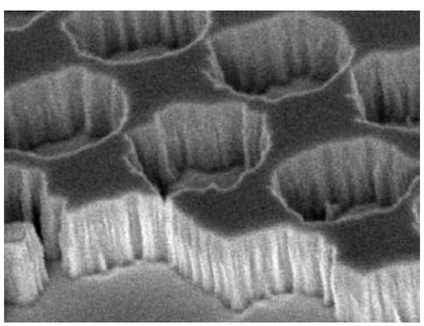




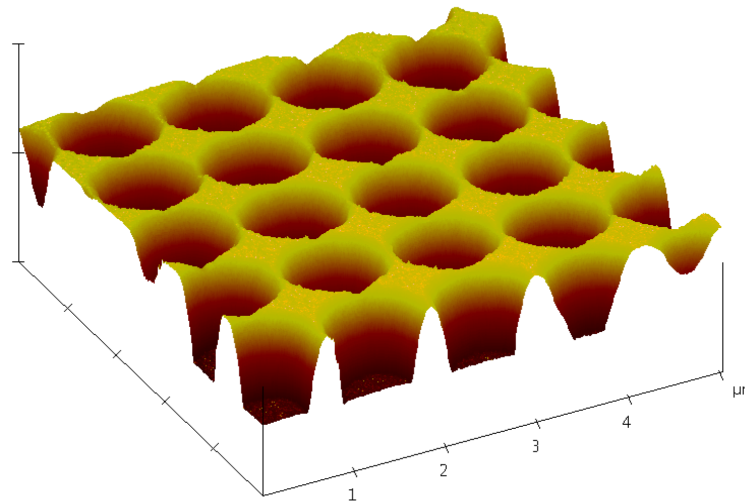
Fabrication process improvements

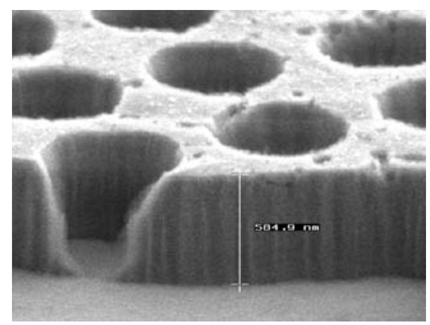
- Old



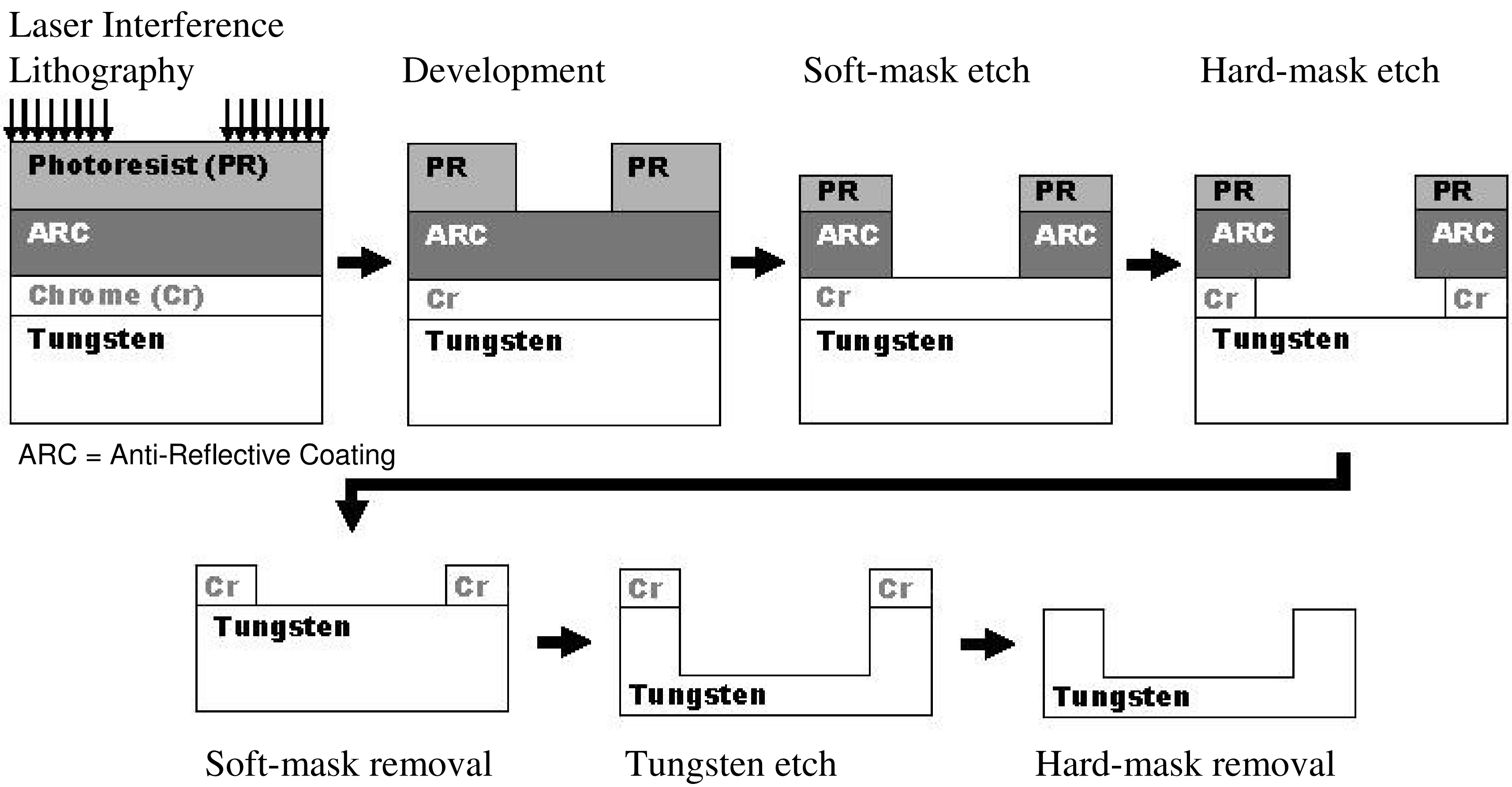


- New



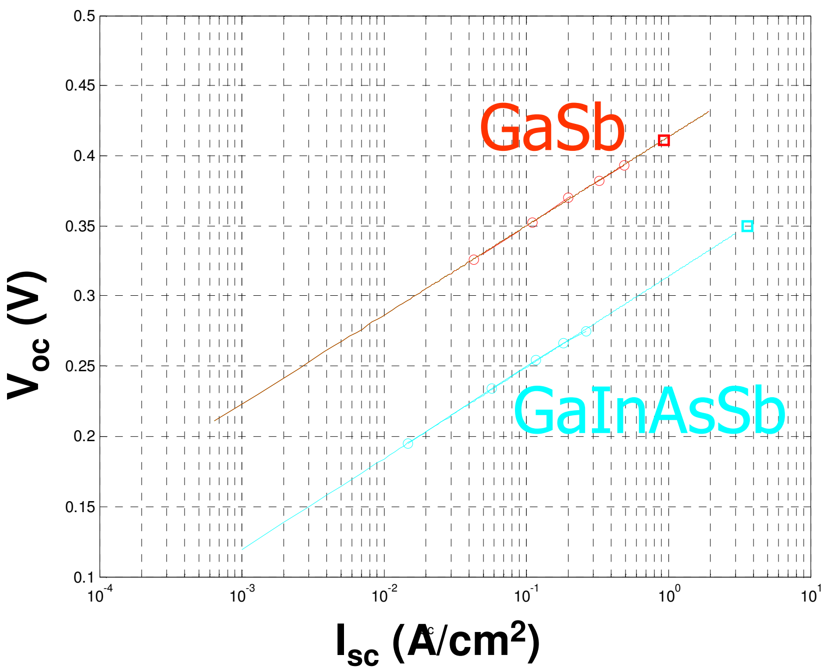


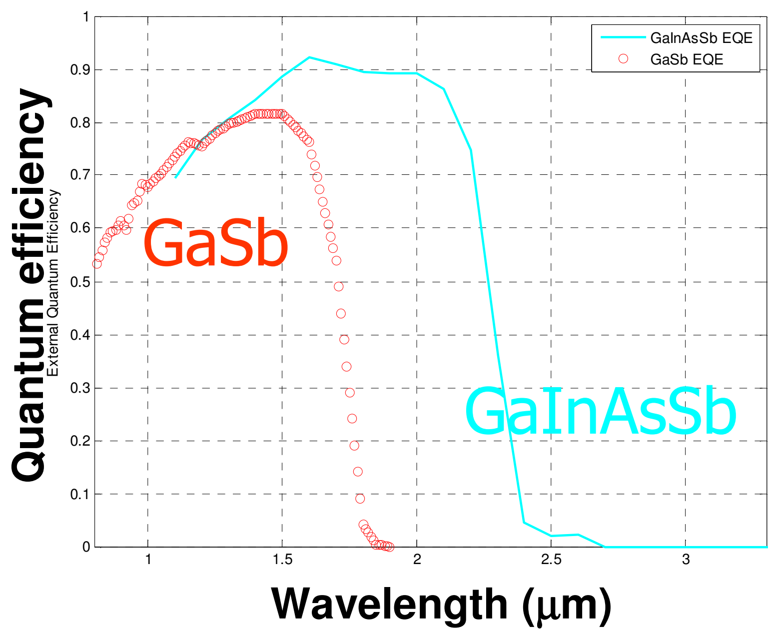
Fabrication Process

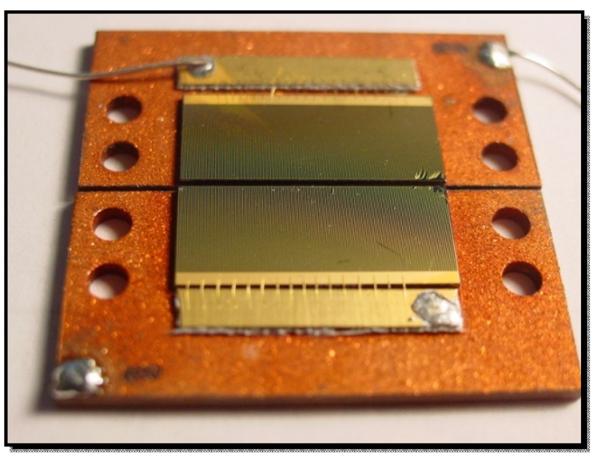


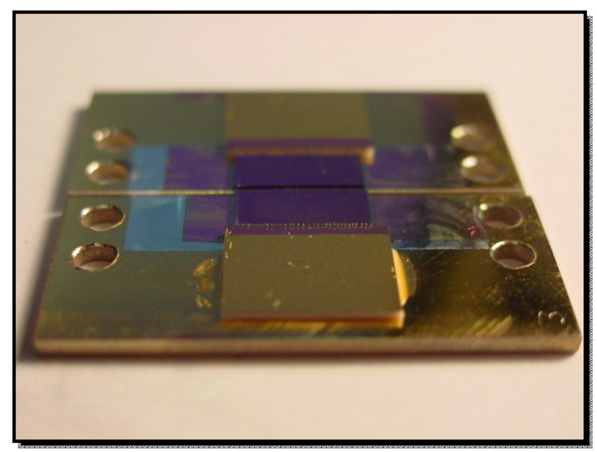
Tailoring electronic- and photonic bandgap properties: a path towards record efficiencies

GaSb and GaInAsSb diode comparison



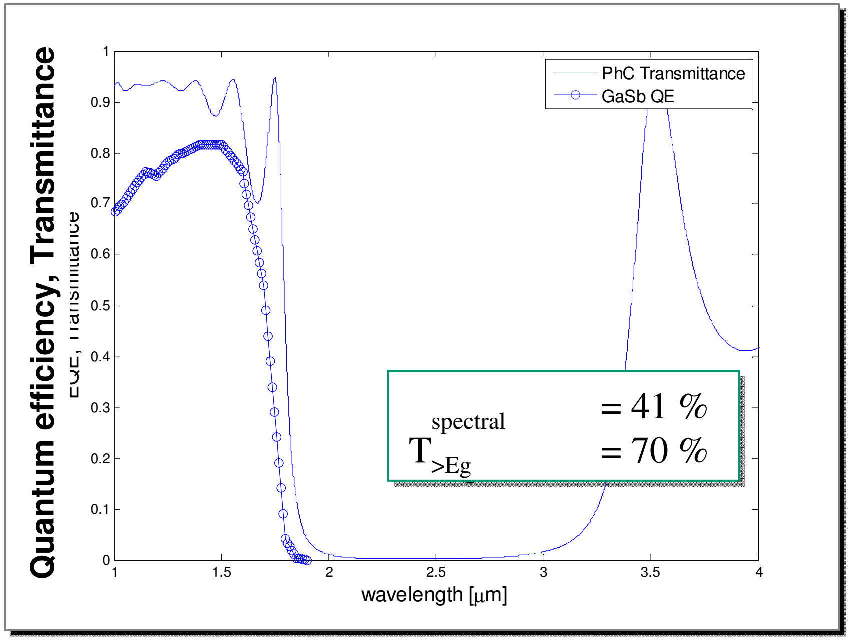


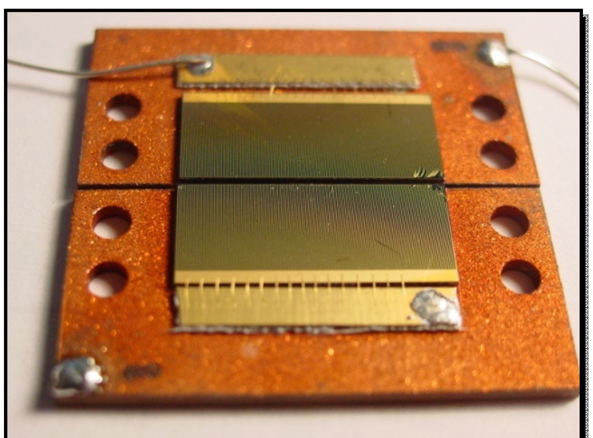




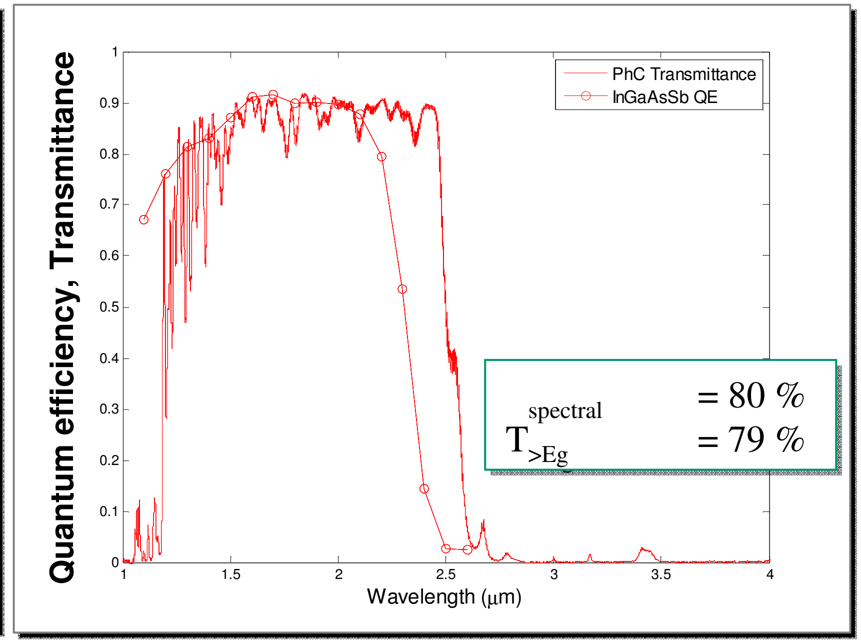
Tuning the PhC and PV diode bandgaps: GaSb (0.72 eV) and GaInAsSb (0.52 eV)

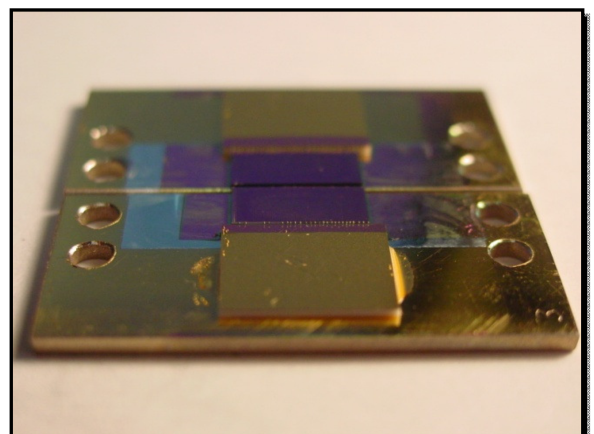
GaSb



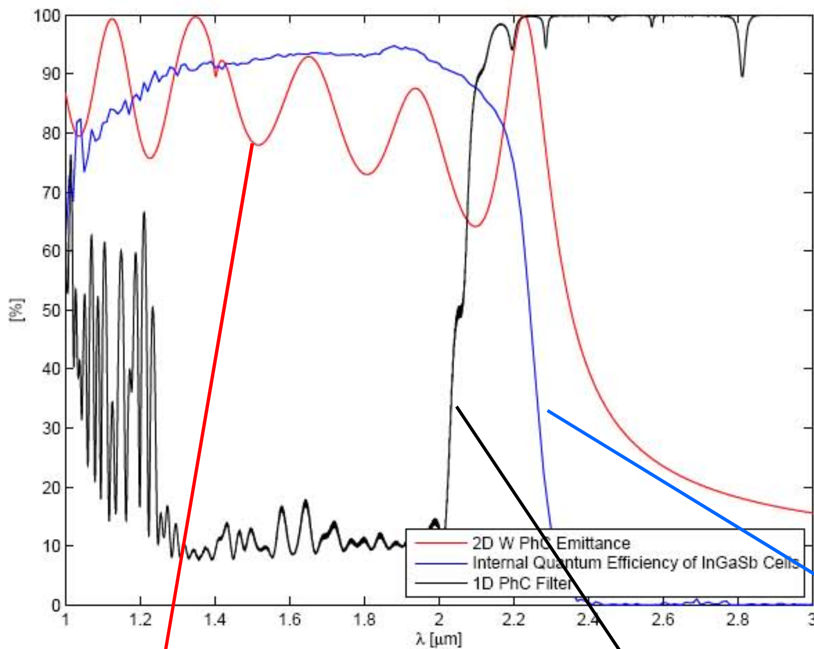


GaInAsSb

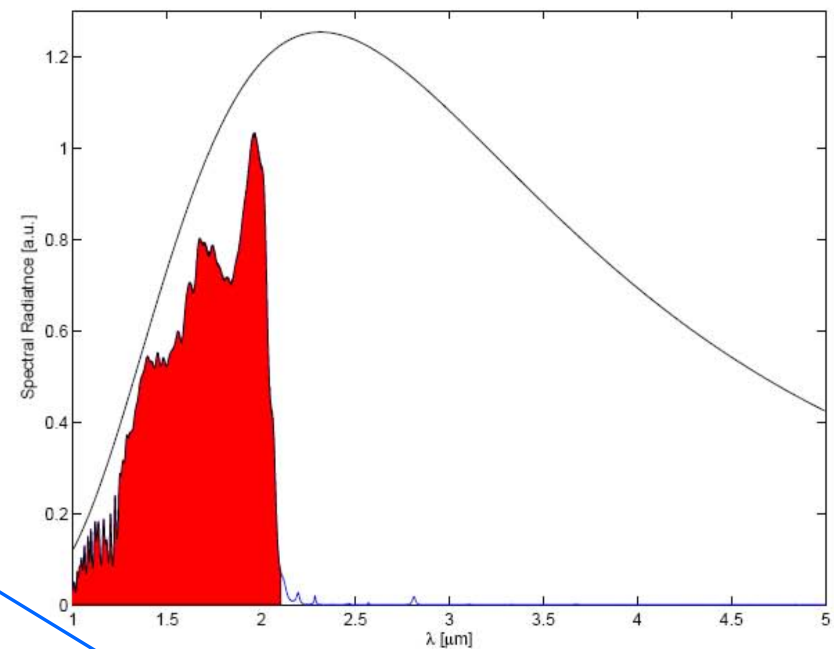




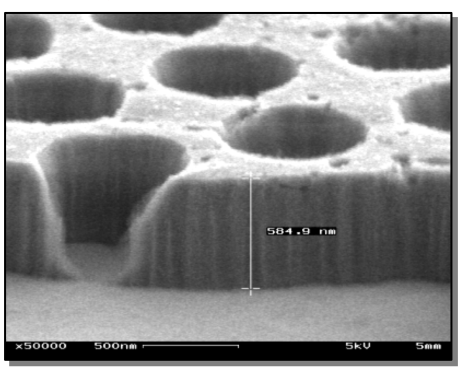
Photonic crystals tailoring photonic- and electronic bandgaps

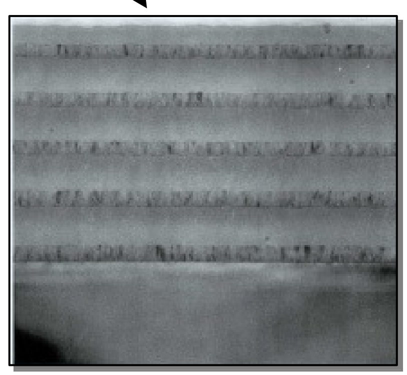


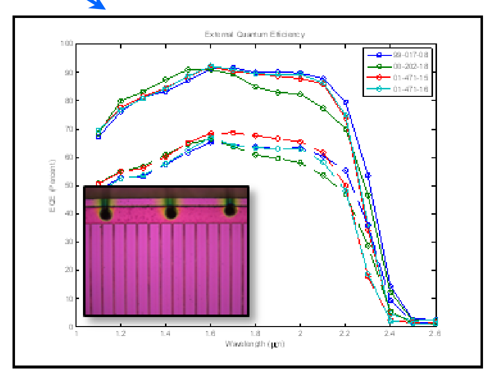
(a) Bandgap tuning



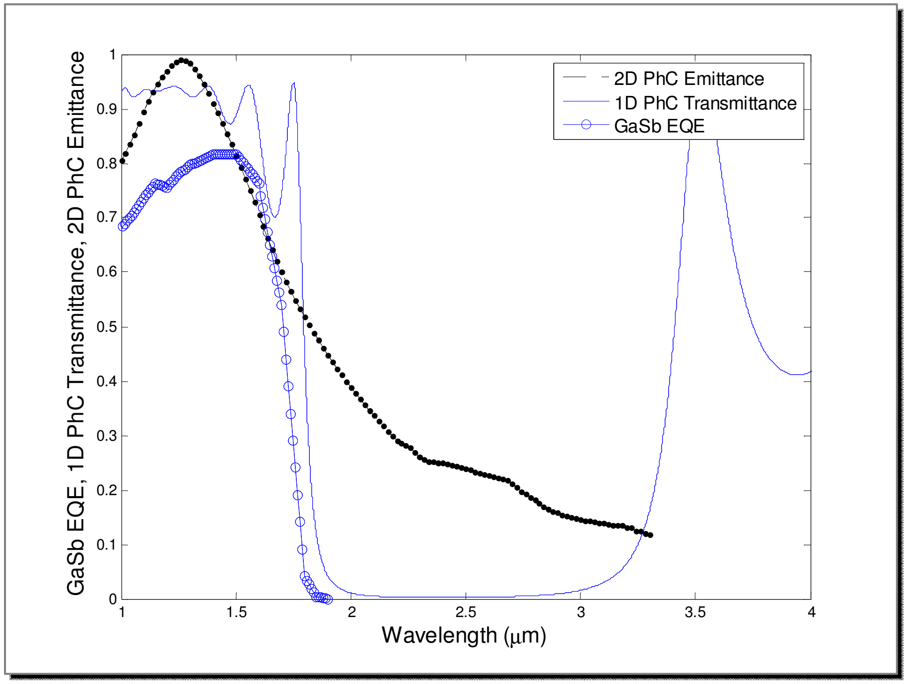
(b) Emittance tailoring

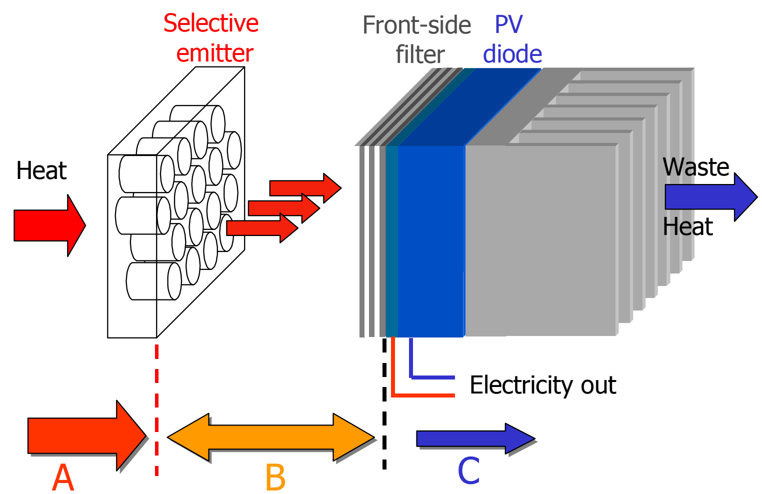






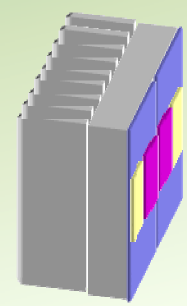
Tuning the PhC and PV diode bandgaps: GaSb (0.72 eV)



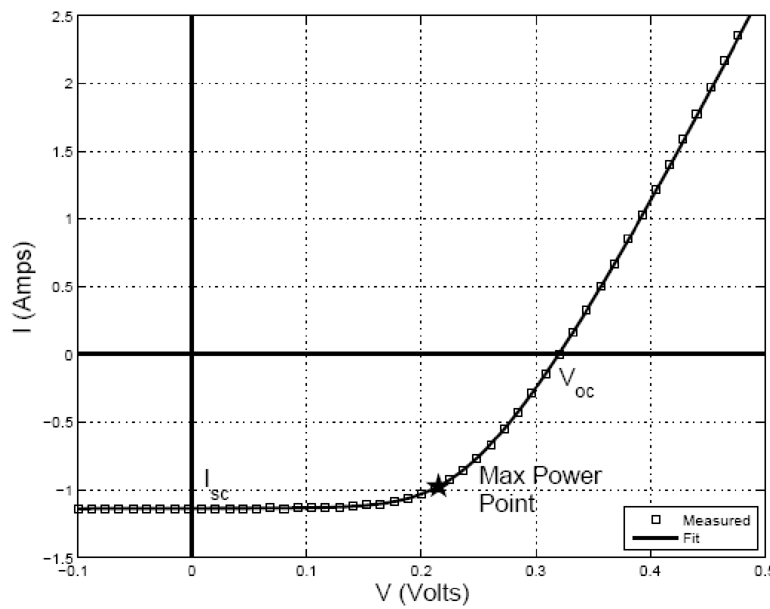


	Spectral efficiency	Above bandgap transmittance
1D PhC and 2D W PhC	93 %	70 %

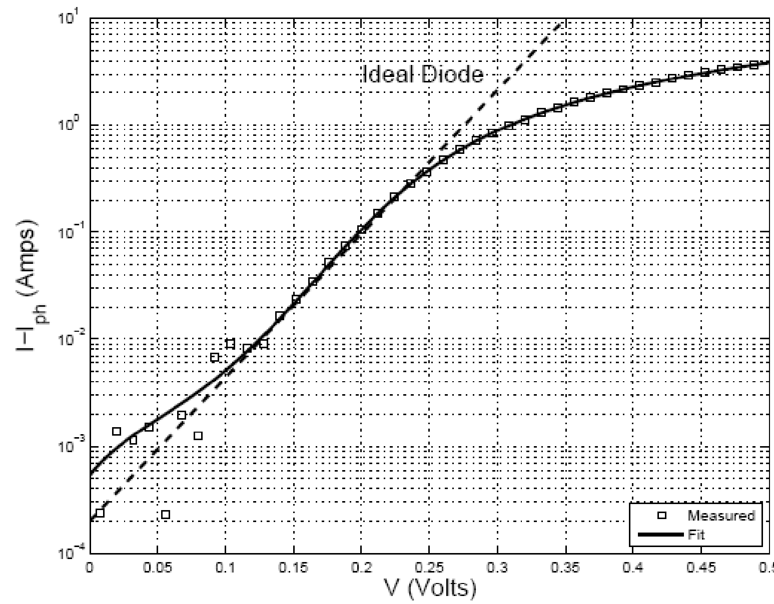
Photovoltaic module:
design and characterization



Simple TPV diode model



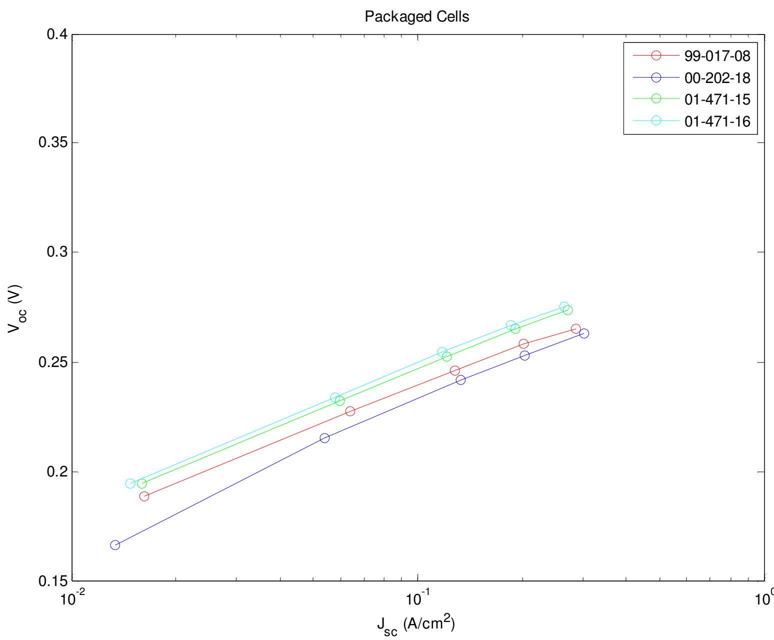
(a) Terminal IV curve

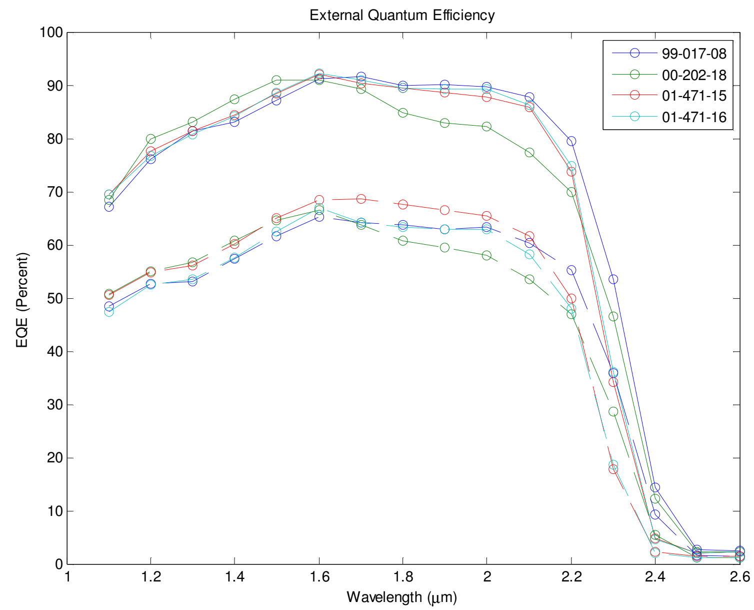


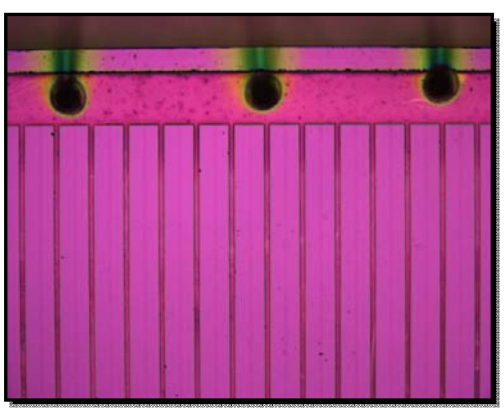
(b) Diode IV curve

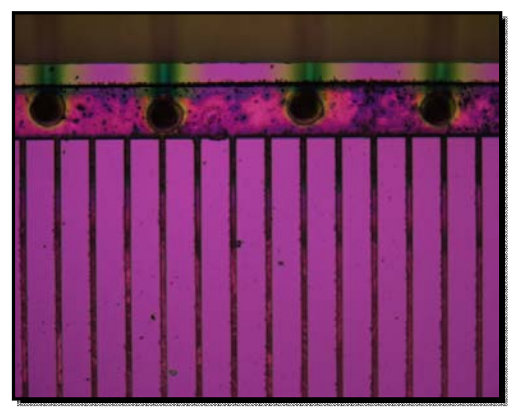
$$I = I_{ph} - I_0 \left(\exp \left[\frac{q}{n k_B T_j} (V + I R_s) \right] - 1 \right) - \frac{V + I R_s}{R_{sh}},$$

GaInAsSb diode characterization cont'd



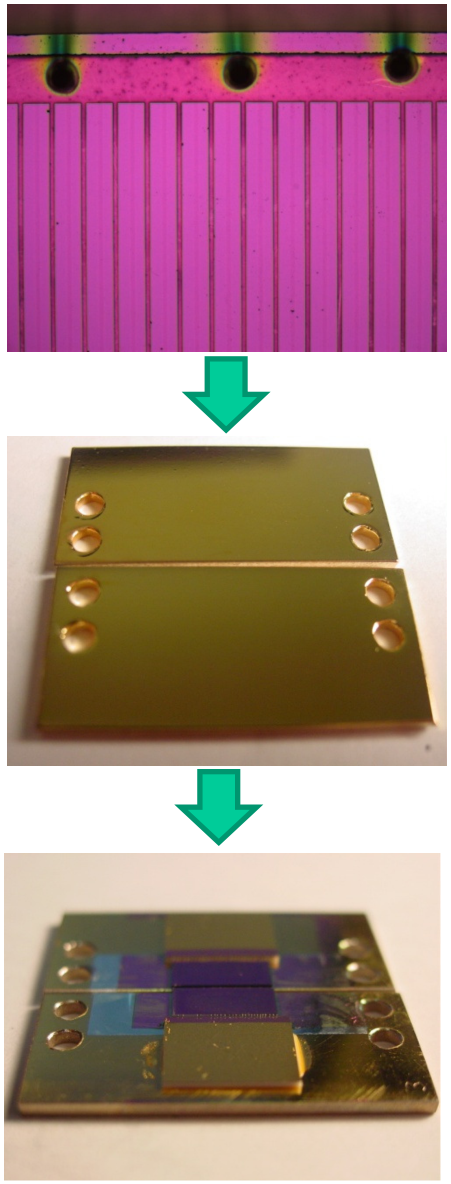


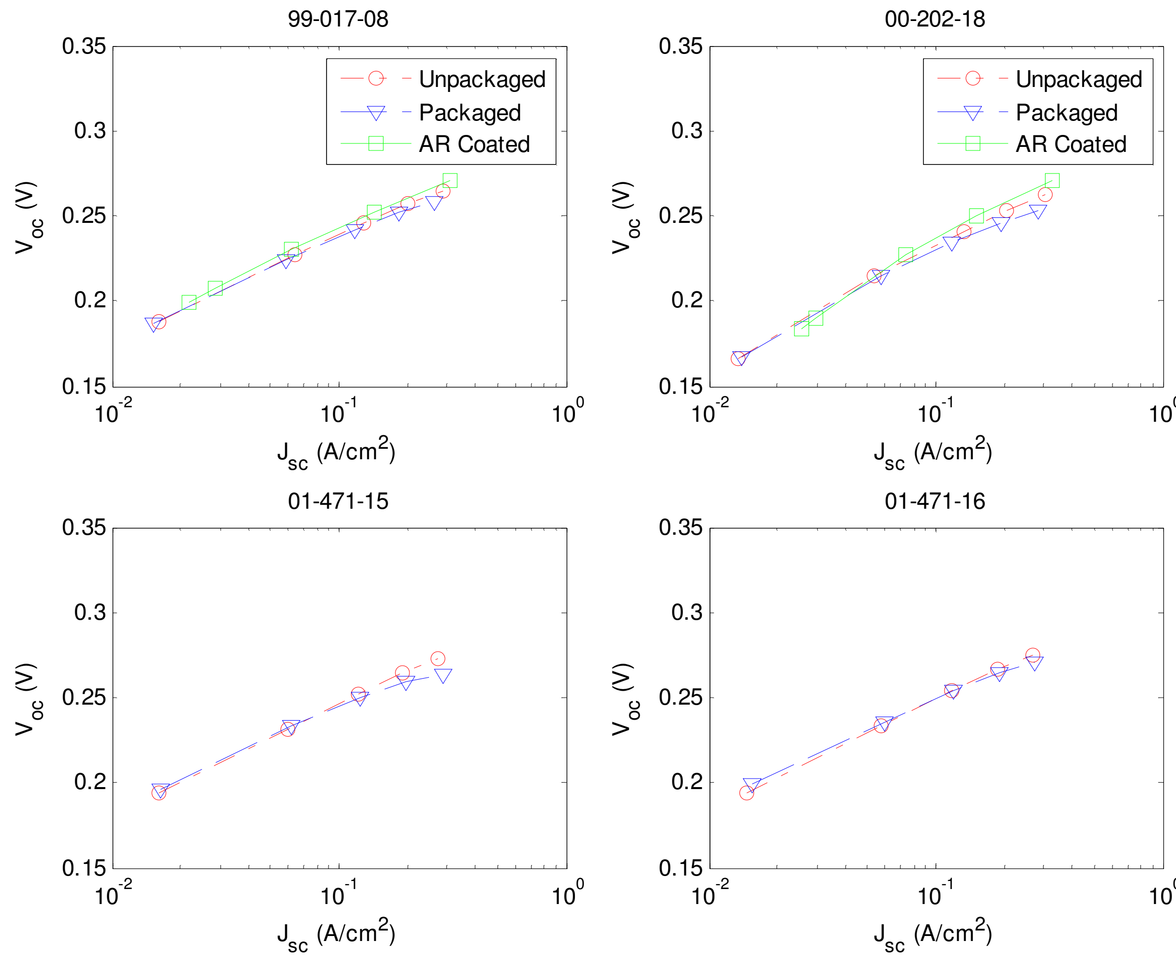


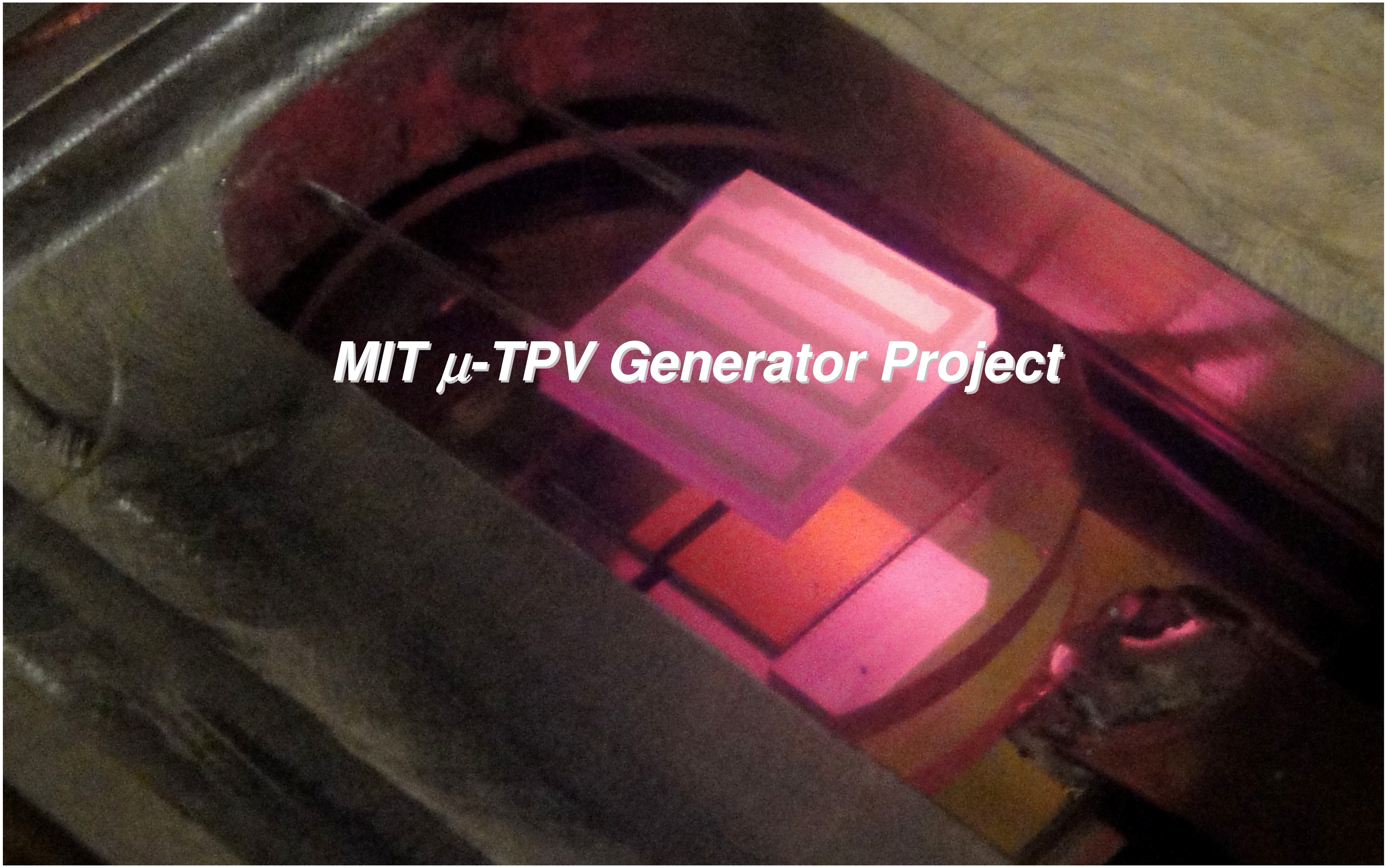


TACONICS

GaInAsSb diode characterization

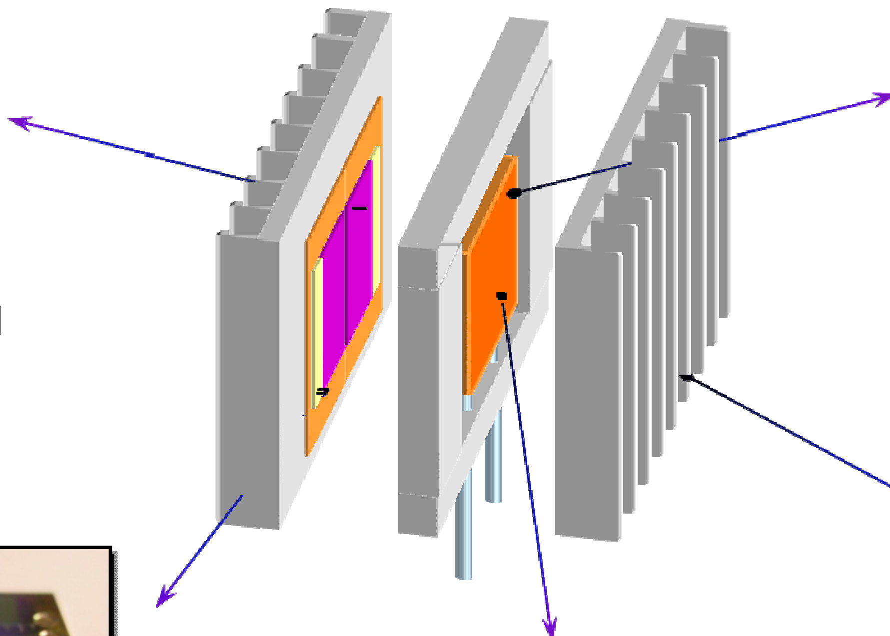


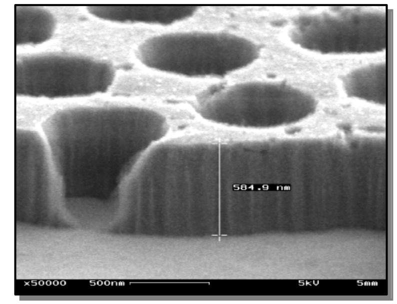



MIT μ-TPV Generator Project

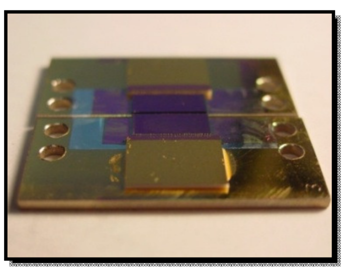
Key innovations in: photonic crystals, MEMs reactors, power electronics, PV

1D photonic crystal

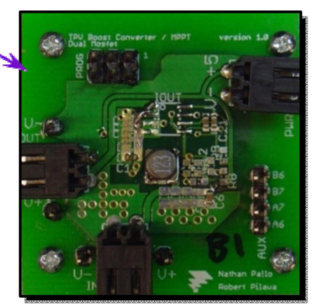




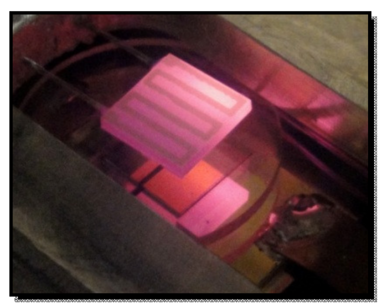
2D tungsten photonic crystal



Low-bandgap PV cells

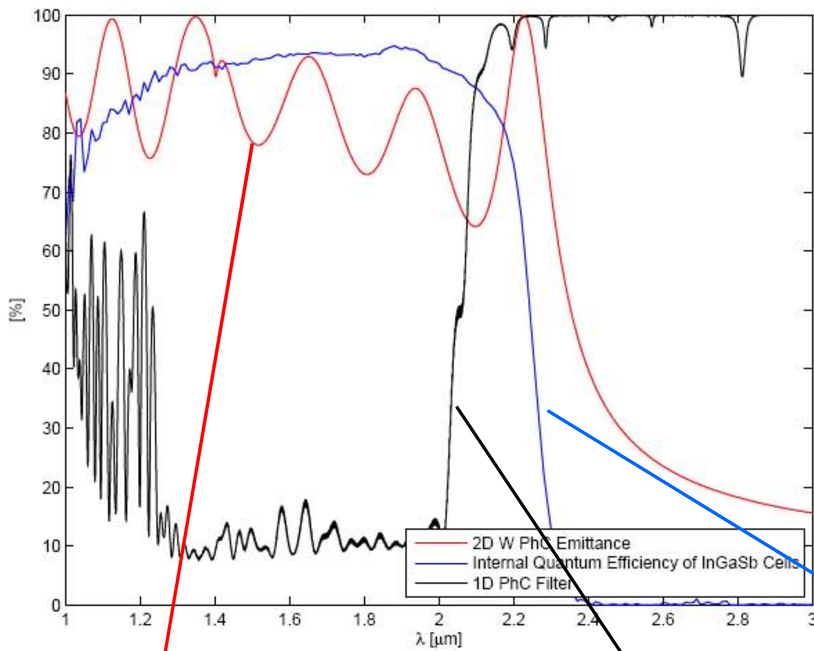


Power electronics

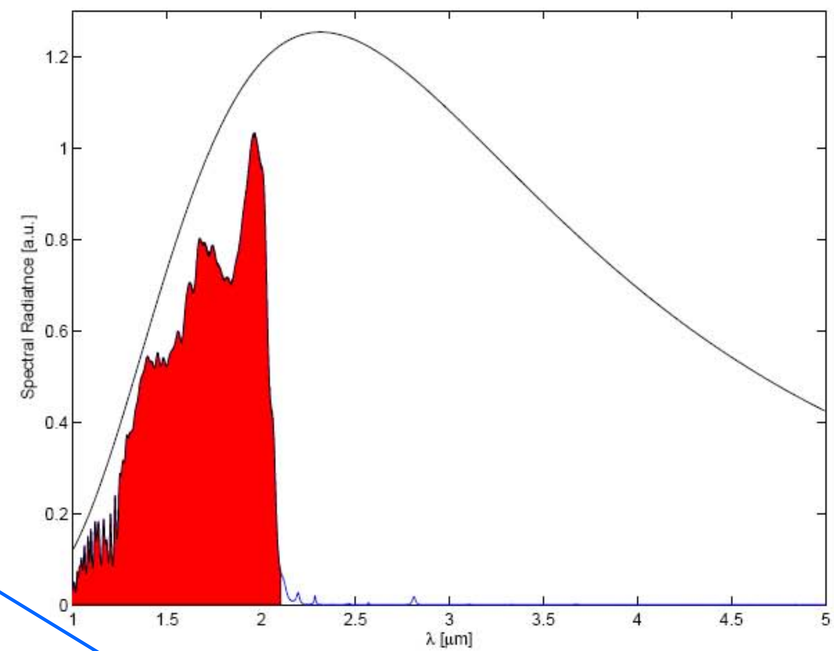


Si micro-fabricated reactor

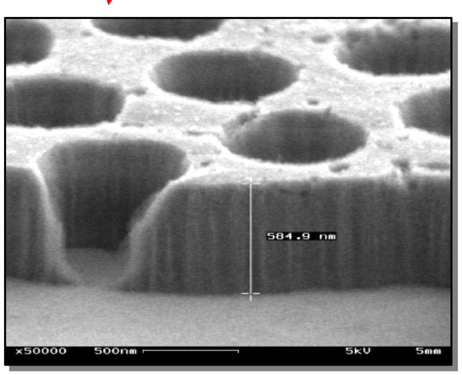
Photonic crystals tailoring photonic- and electronic bandgaps

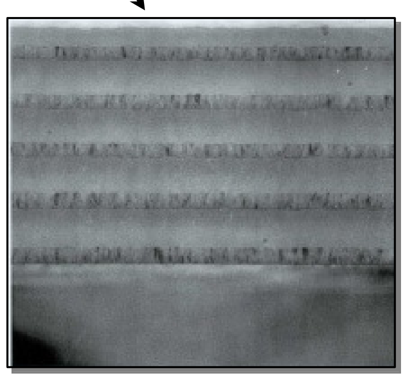


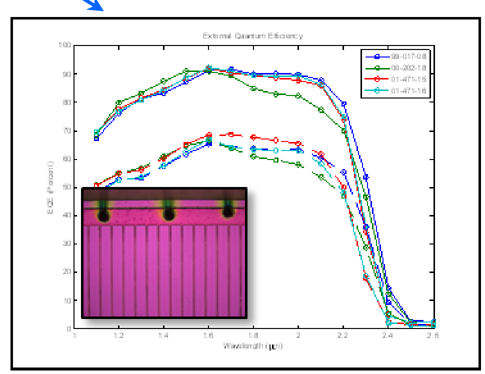
(a) Bandgap tuning



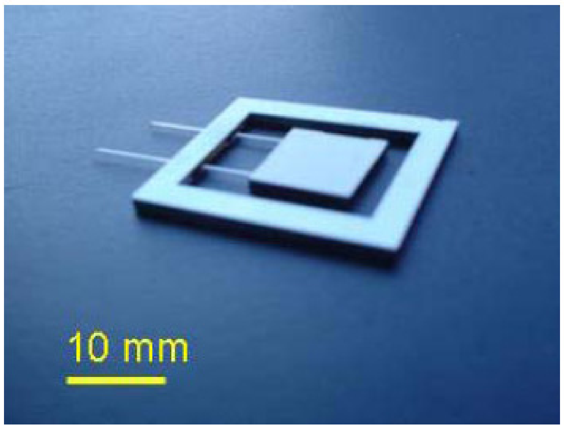
(b) Emittance tailoring

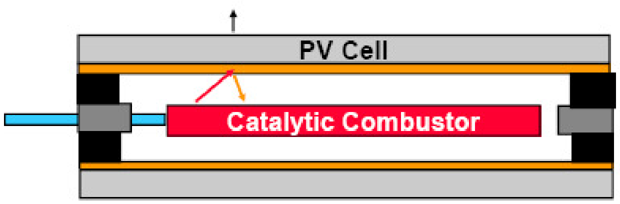


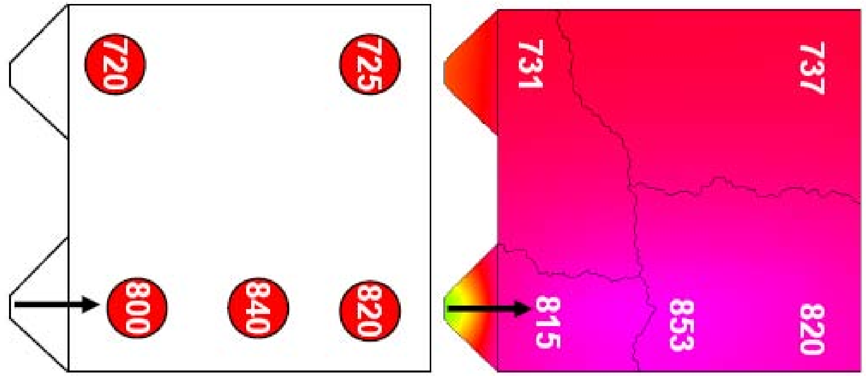


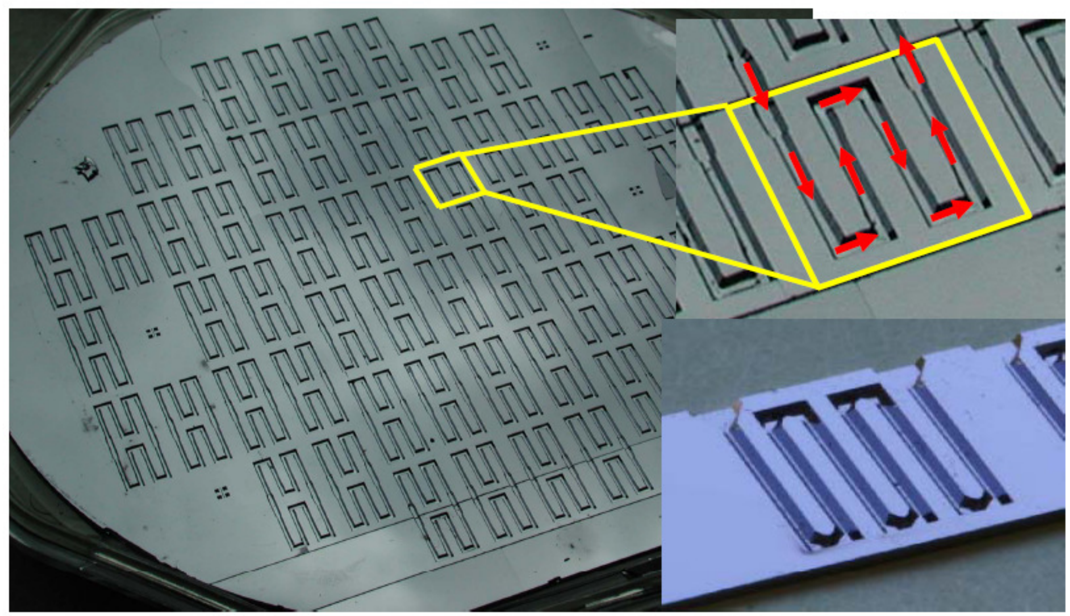


Robust, integrated catalytic micro-reactor design

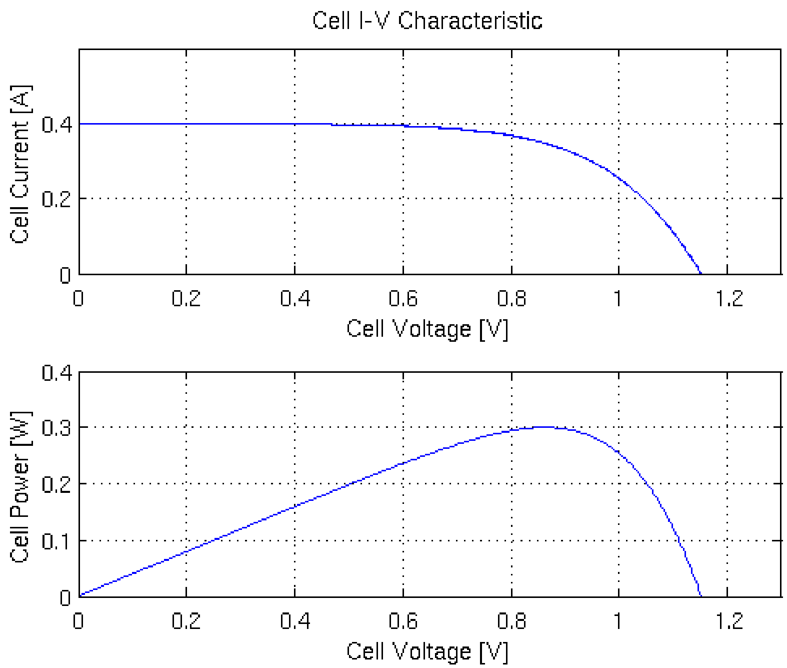


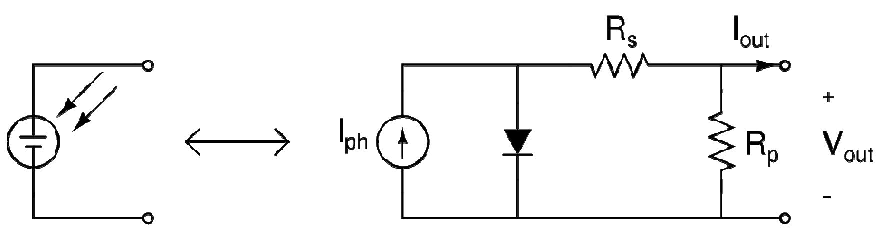


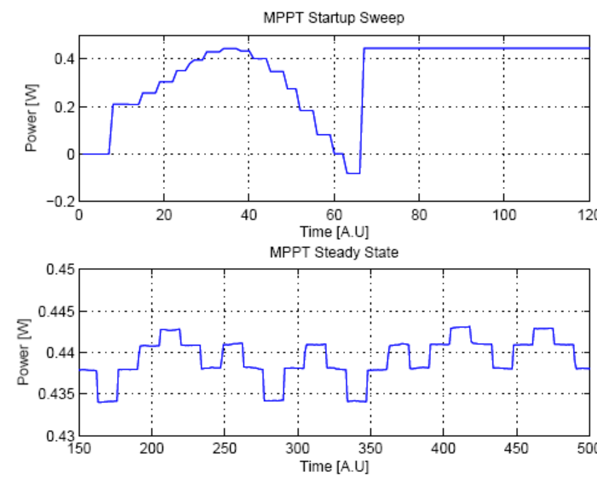


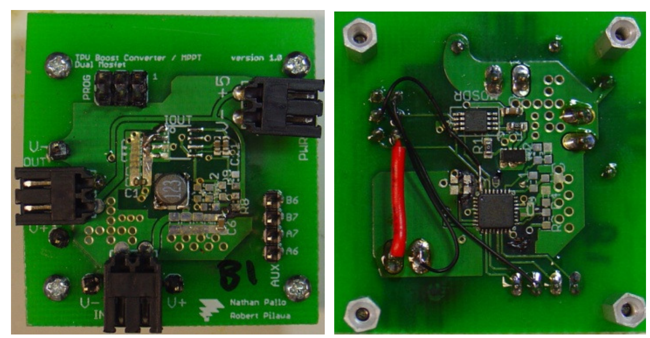


Integrated power electronics controller







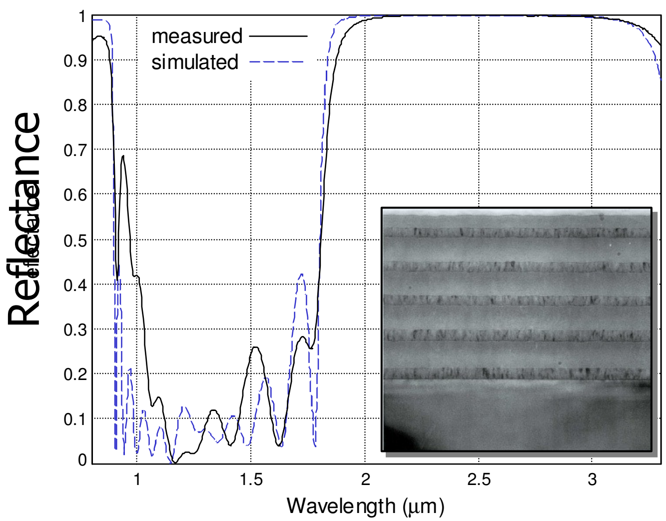


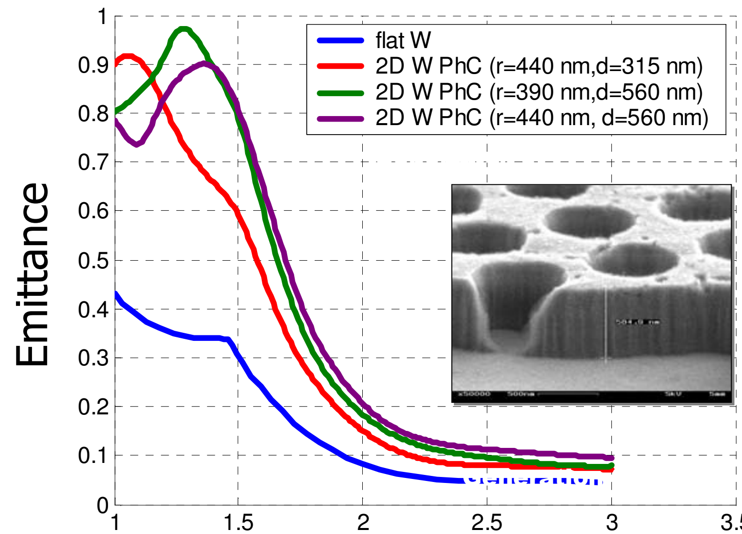
single chip integrated MPPT

Quasi-coherent thermal emission via photonic crystals

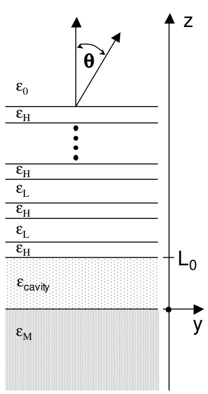
- Vertical-cavity resonant thermal emitter
- 2D PhC slab resonant thermal emission

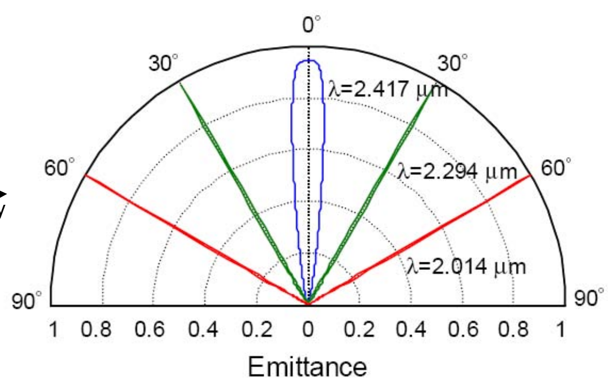
Broad-band spectral control

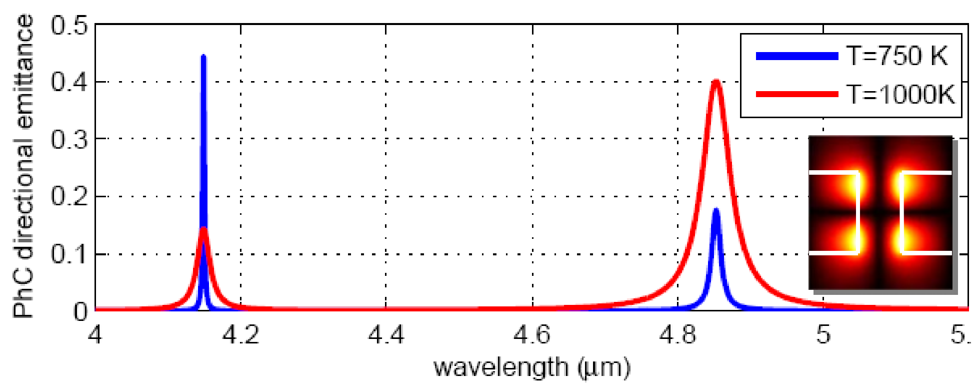




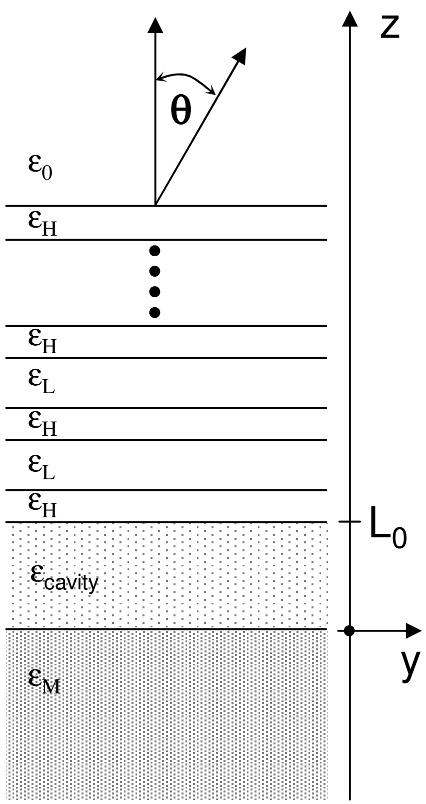
Narrow-band spectral control

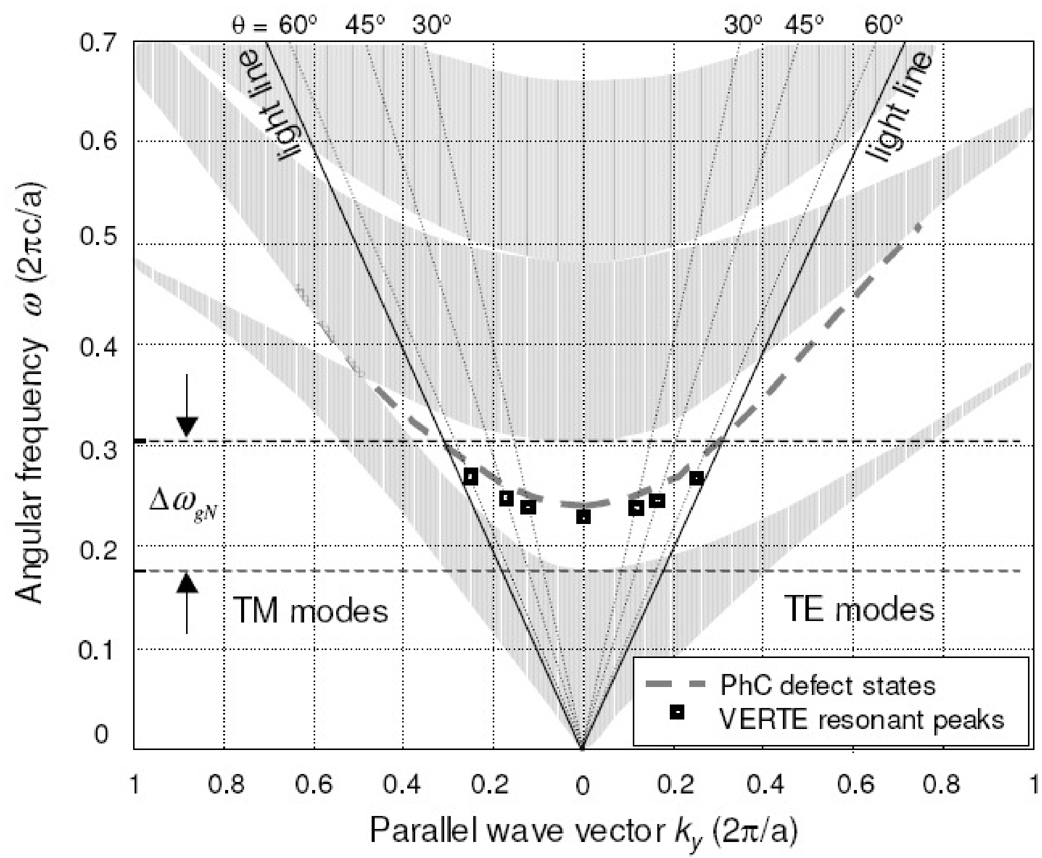




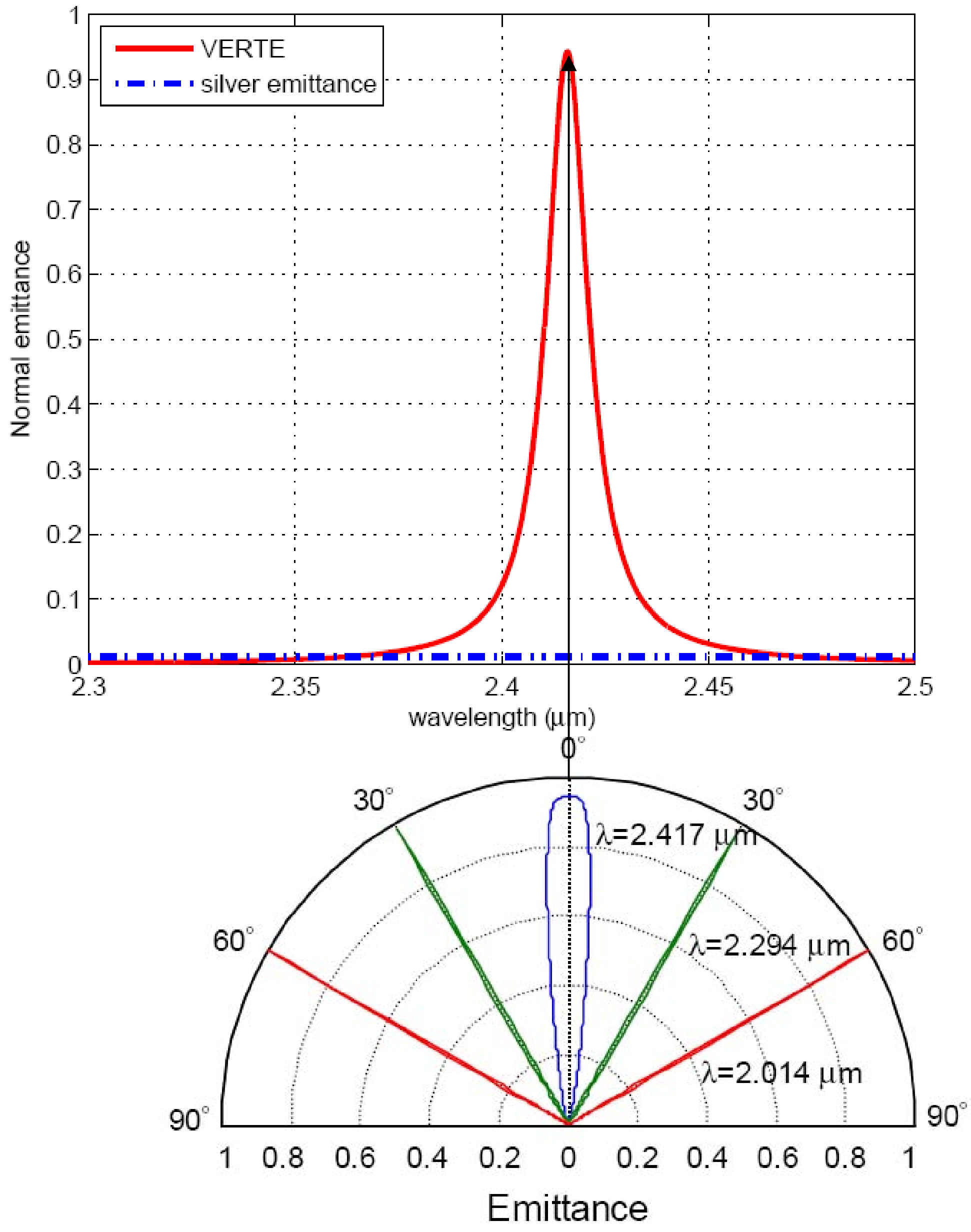


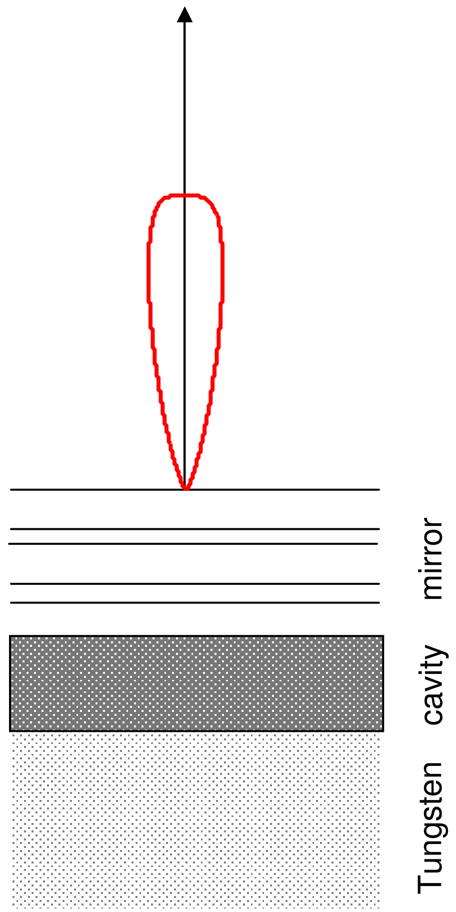
Vertical cavity resonant thermal emitter is highly-directional, quasi-coherent radiation source





Vertical cavity resonant thermal emitter: narrow-band, highly directional and

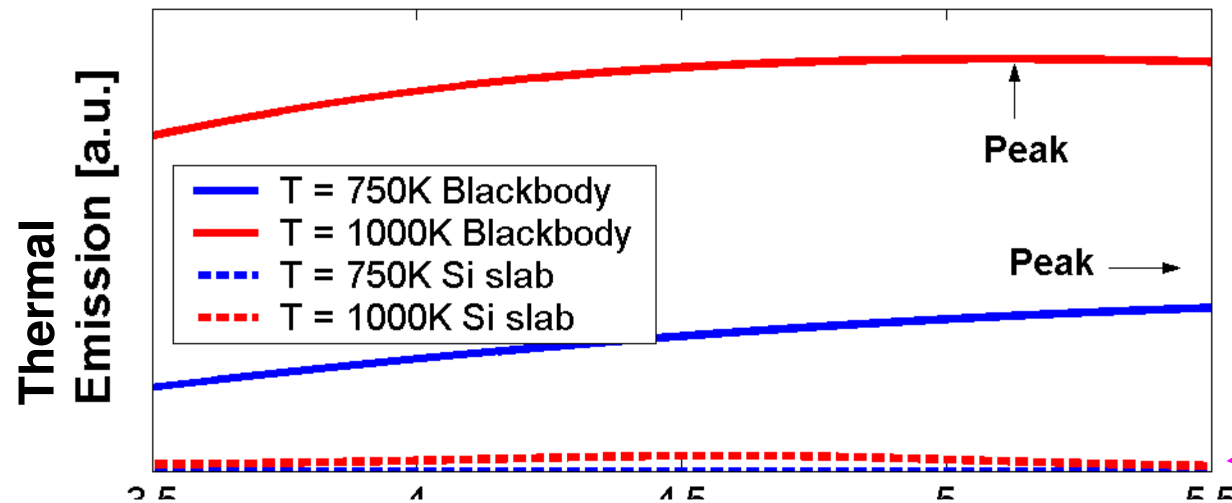


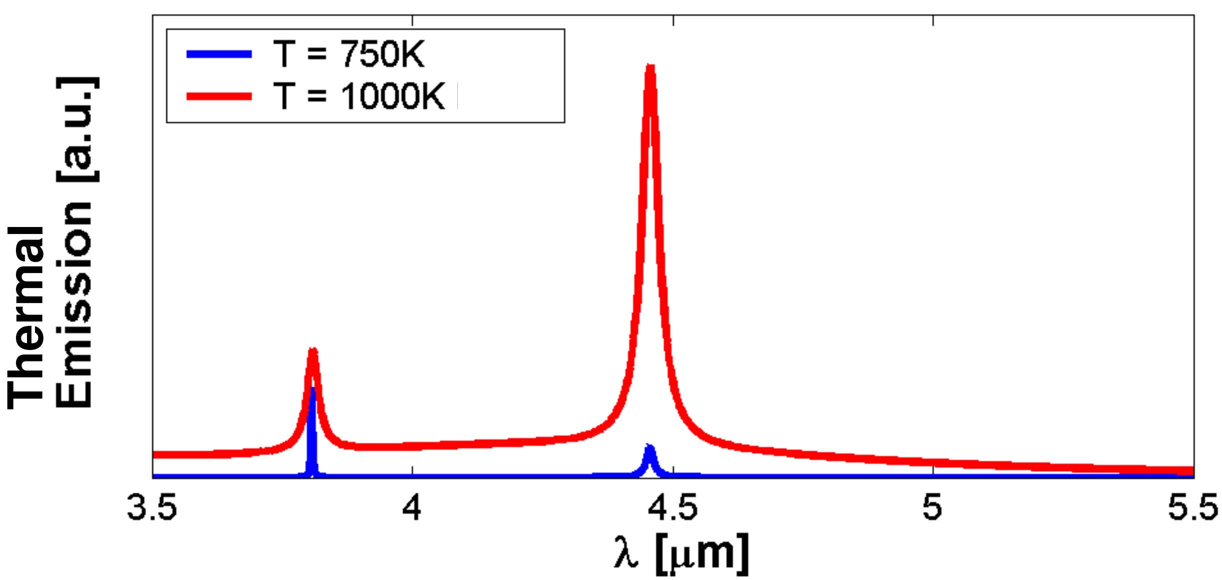


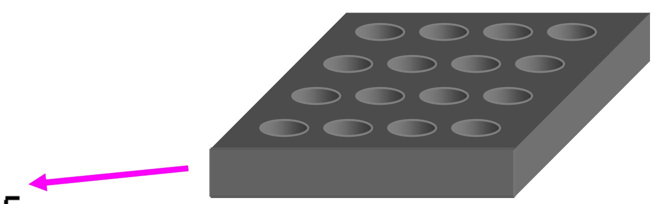
Quasi-coherent thermal emission via photonic crystals

- Vertical-cavity resonant thermal emitter
- 2D PhC slab resonant thermal emission

Black/Gray-Body Physics

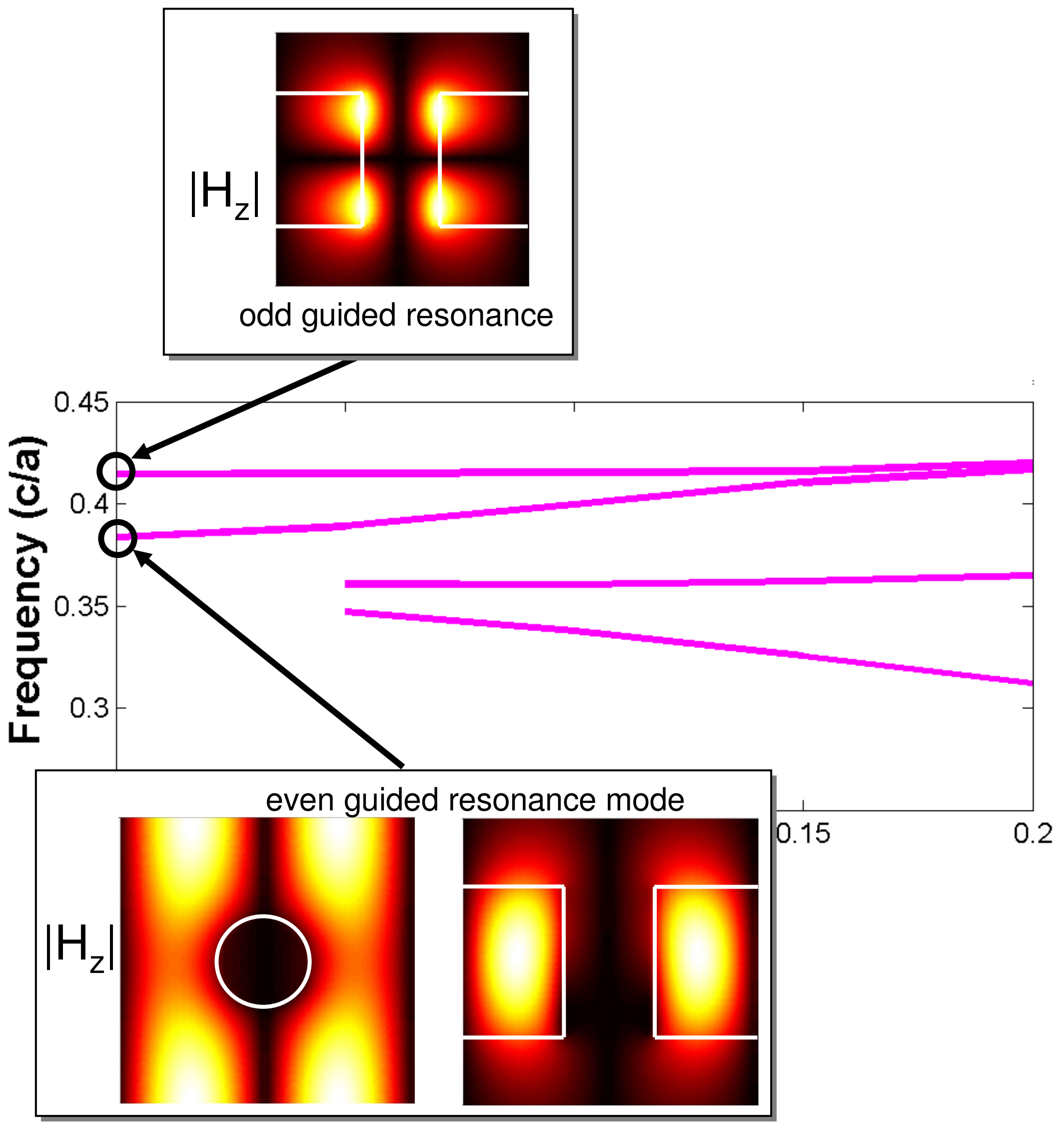


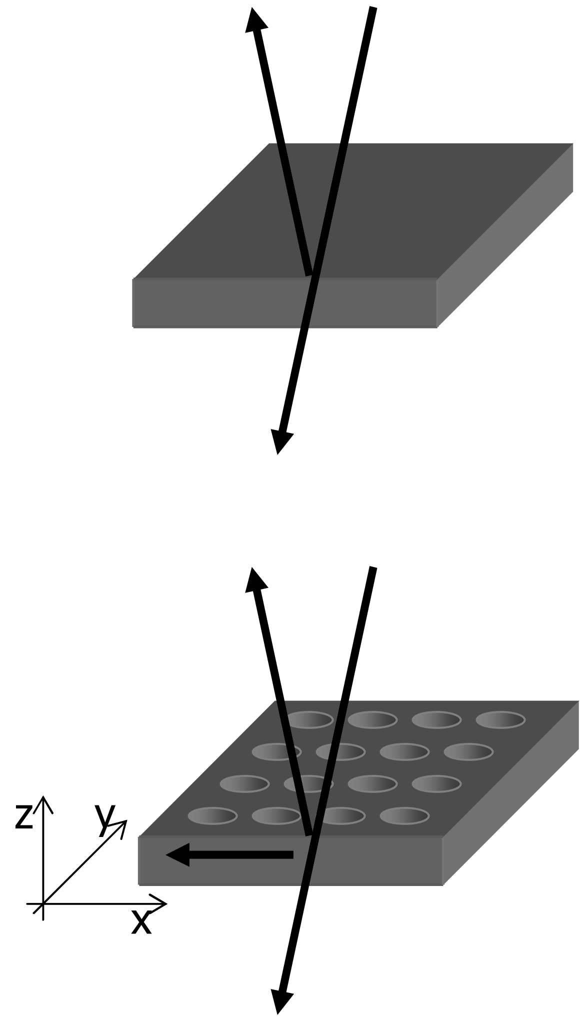




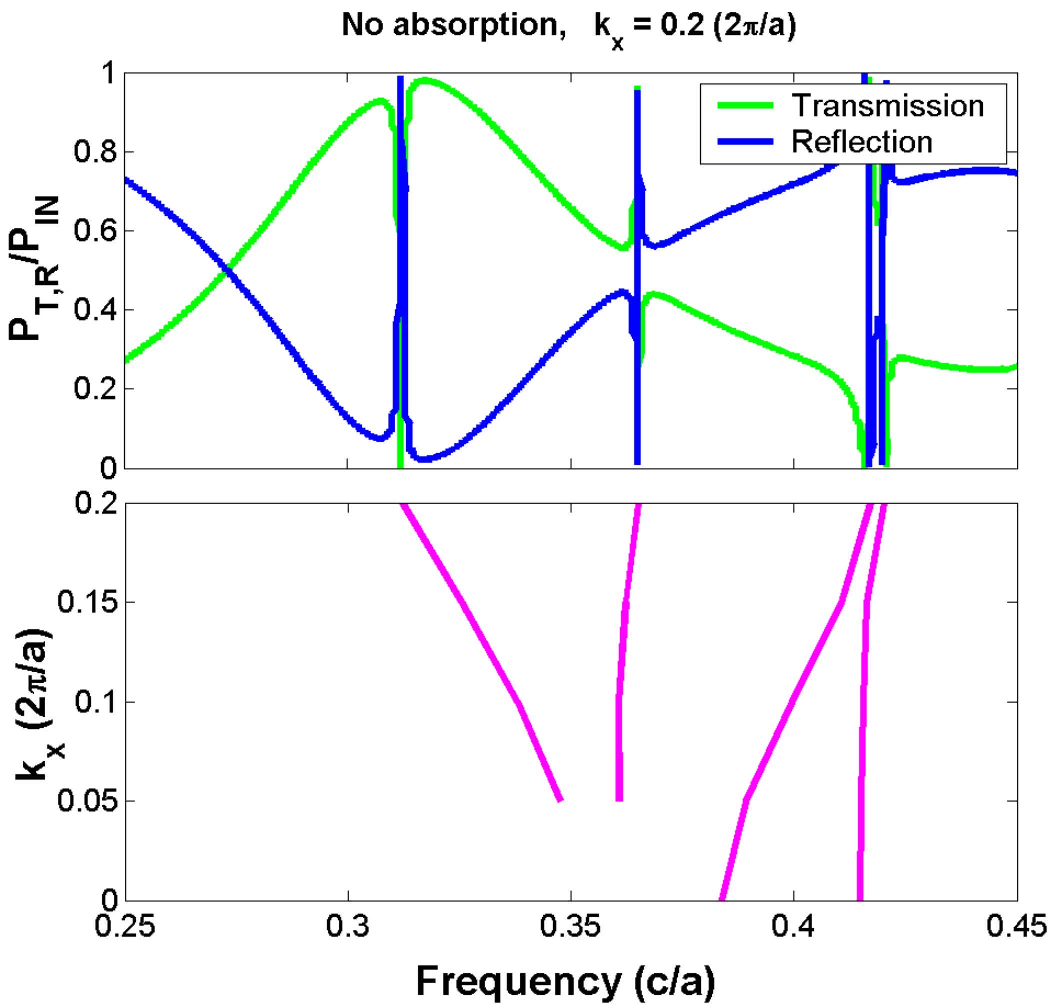
Ref: Max Planck, Annalen der Physik, **4**, 553, (1901).

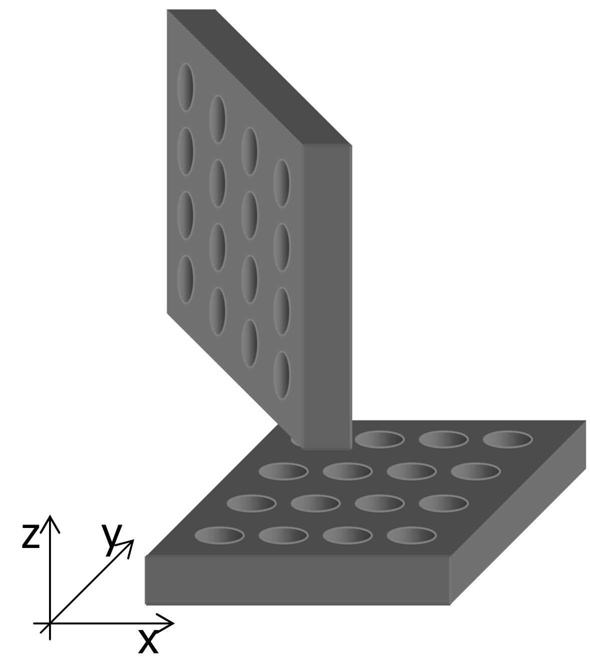
Modes of a 2D PhC slab





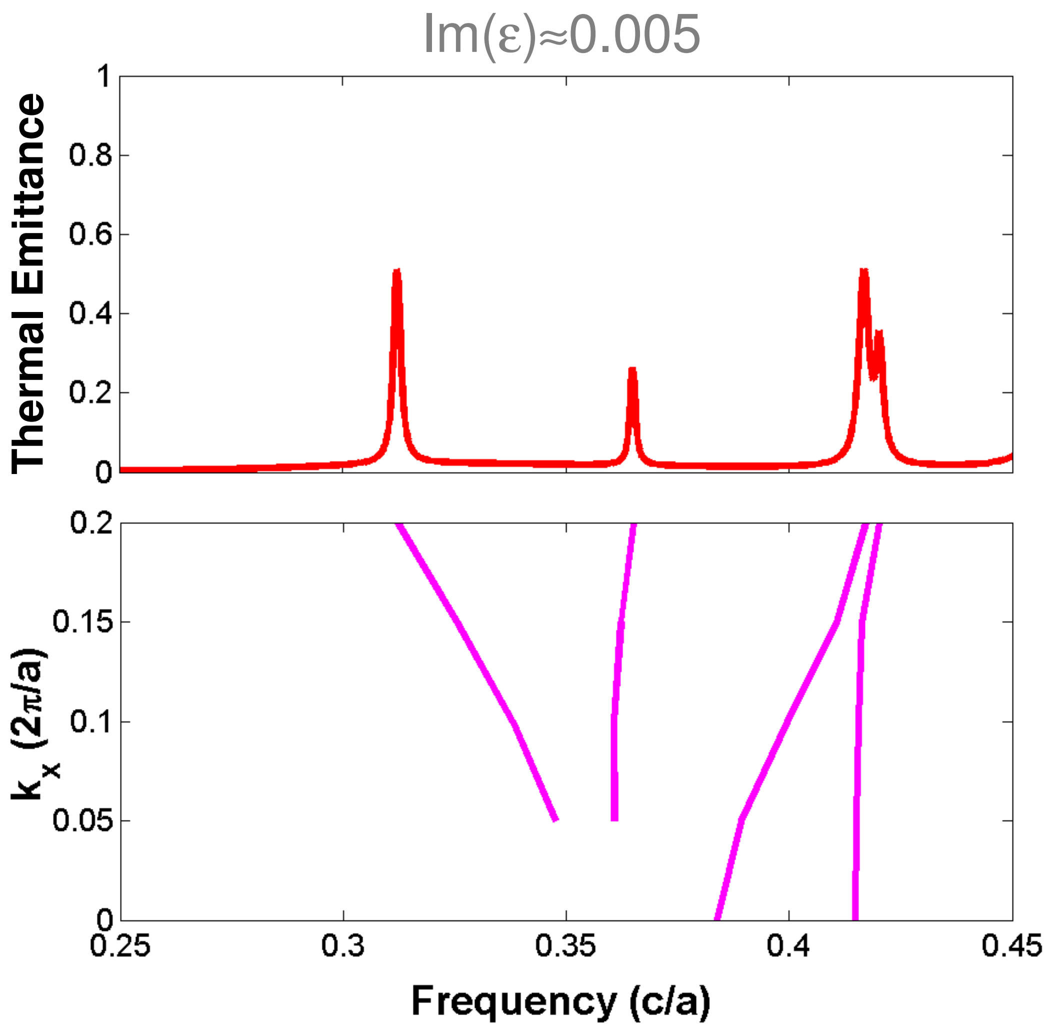
Fano resonances of a 2D PhC slab

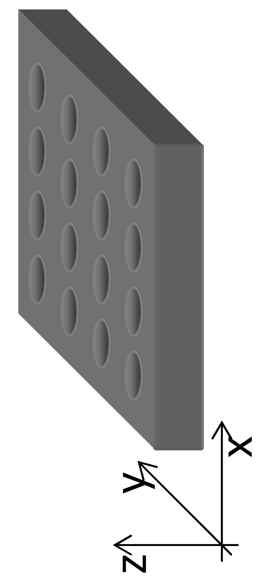




Ref: S. Fan and J. D. Joannopoulos, Phys. Rev. B **65**, 235112 (2002).

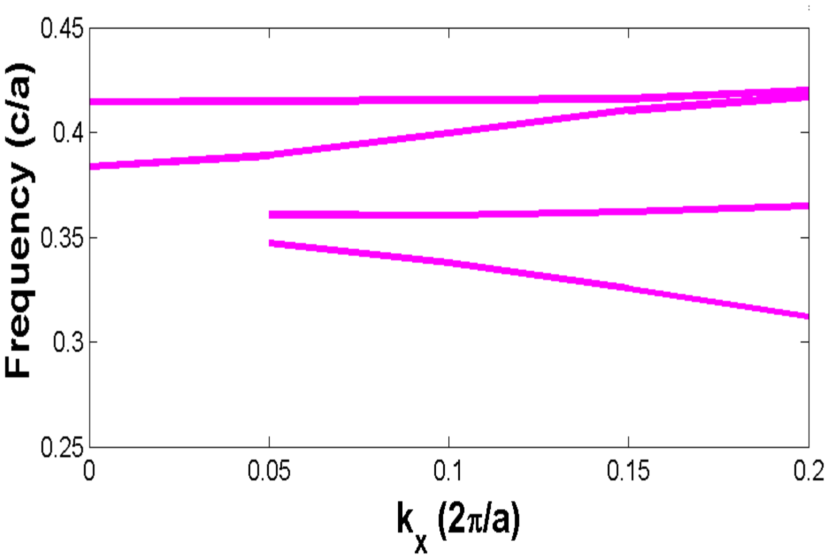
Thermal emittance of a 2D PhC slab

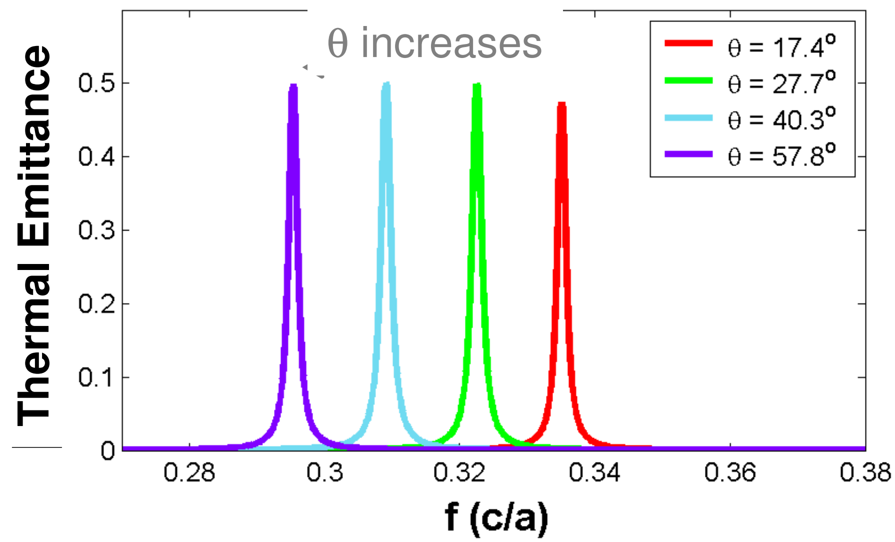


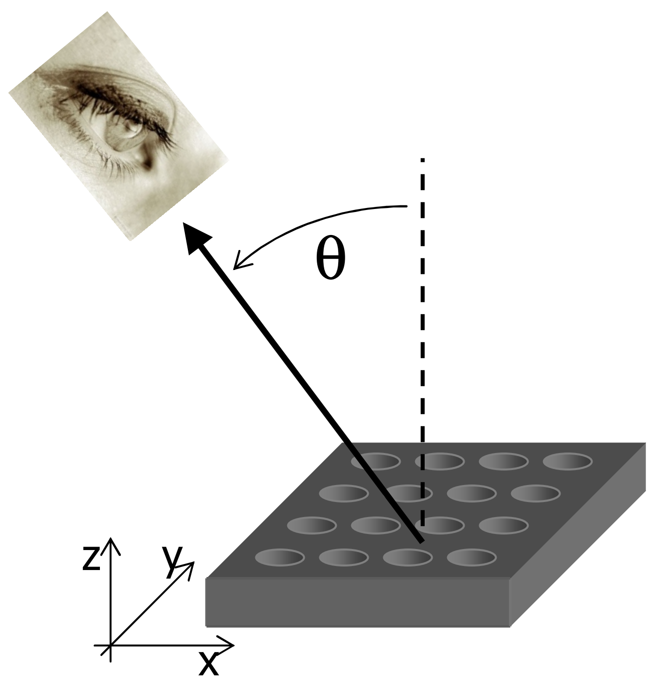


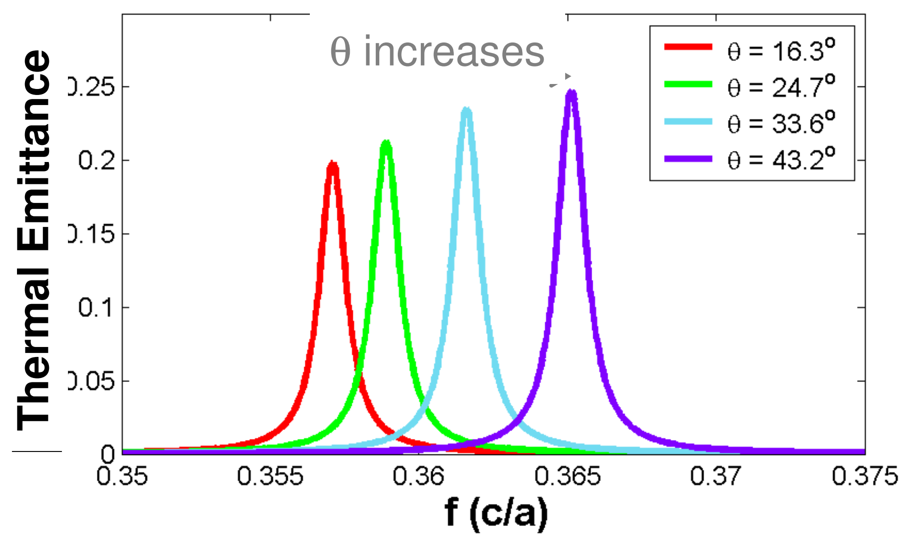
Ref: D.Chan, I.Celanovic, J.D.Joannopoulos, and M.Soljačić, submitted for publication.

Dependence on angle of observation

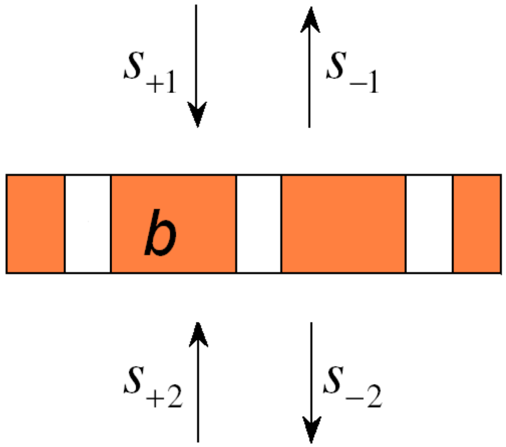








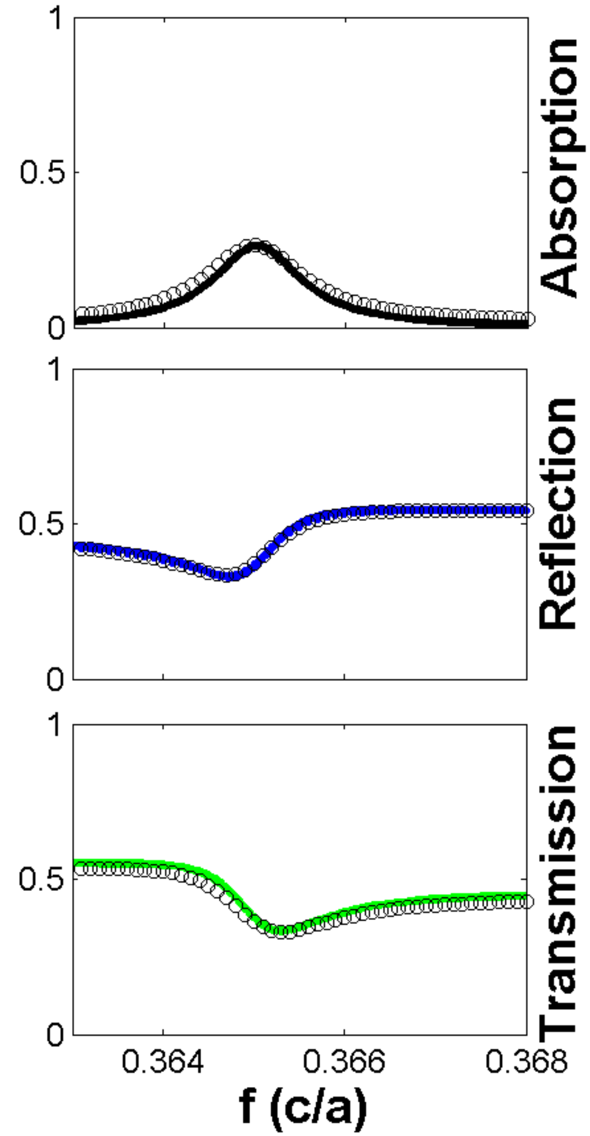
Analytical understanding of Fano resonances



$$\Downarrow$$

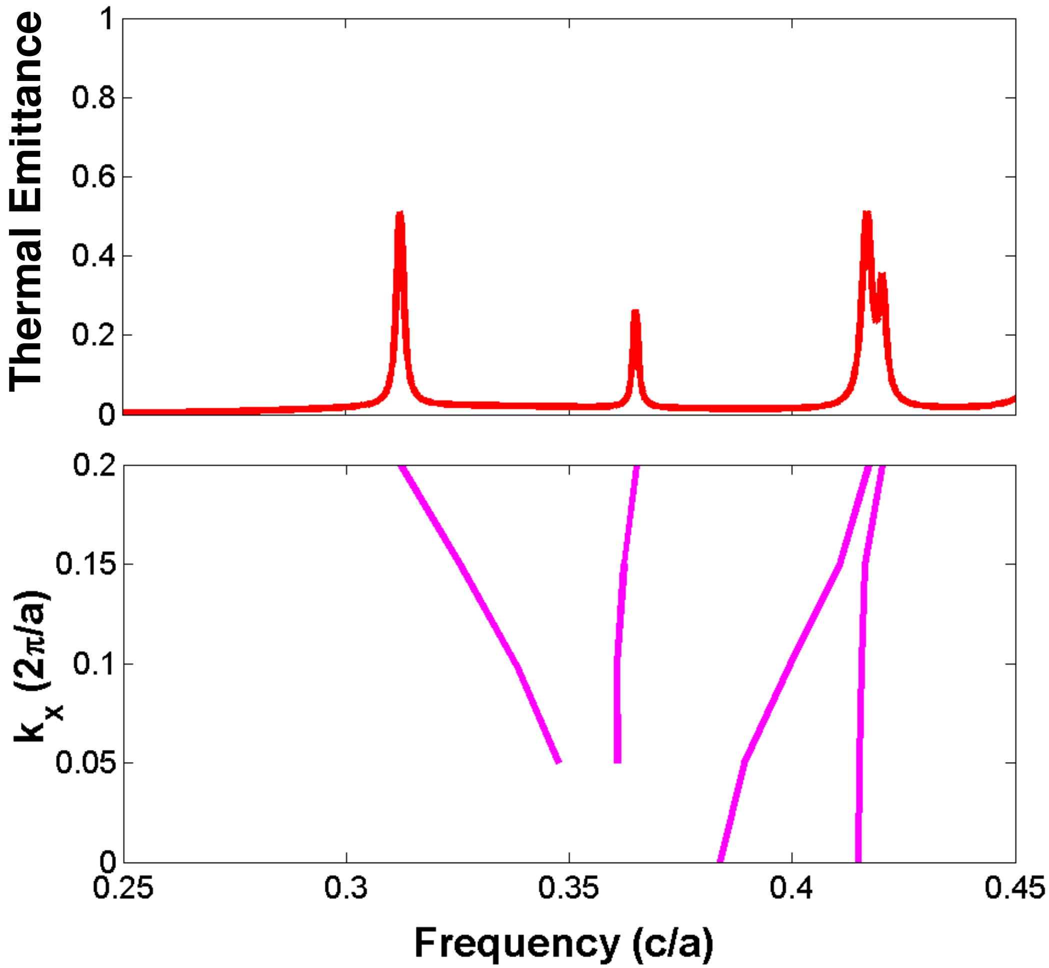
$$|a_{PhC}|^2 = \frac{\frac{2}{Q_{ABS}Q_{RAD}}}{4\left(\frac{\omega}{\omega_{FANO}} - 1\right)^2 + \left(\frac{1}{Q_{RAD}} + \frac{1}{Q_{ABS}}\right)^2}$$

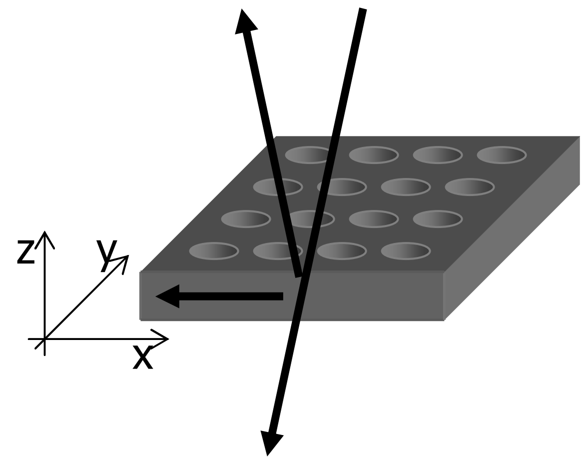
$$Q_{ABS} = \frac{\varepsilon_R}{\sigma \varepsilon_I}$$



$$Q_{ABS} = Q_{RAD} \Rightarrow |a_{PhC}|_{MAX} = 50\%$$

Rules for designing thermal emission





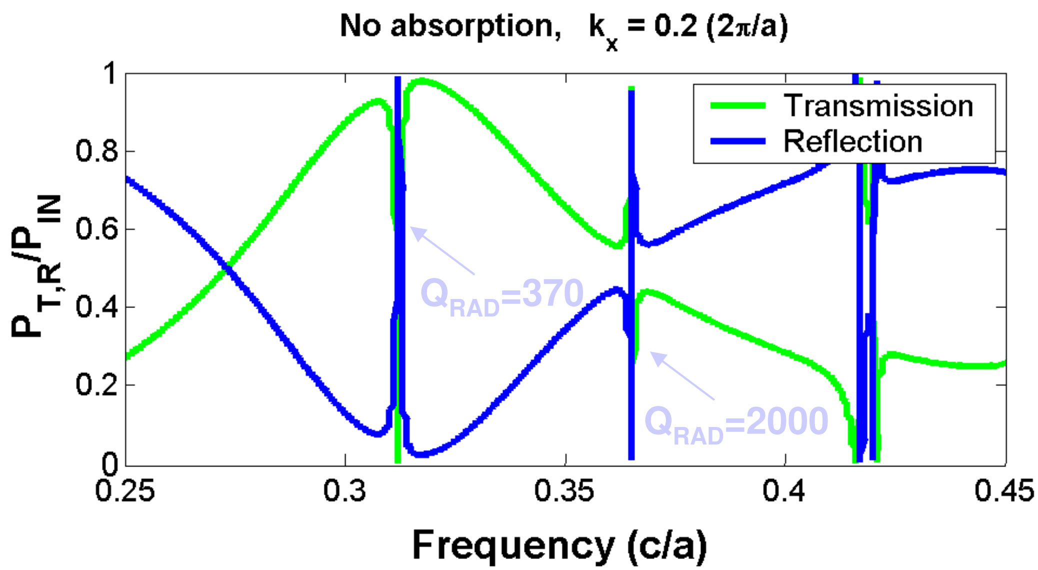
$\omega_{EMIT}(\theta)$:
- slab thickness
- Re(ε)
- lattice constant

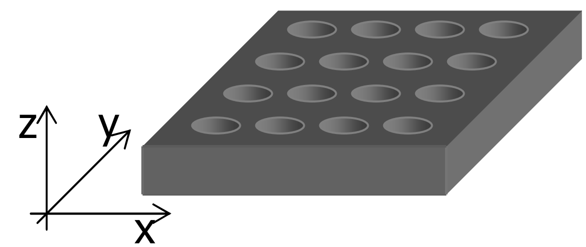
$\Gamma_{EMIT} \Leftrightarrow Q_{RAD}$:
- "size" of holes

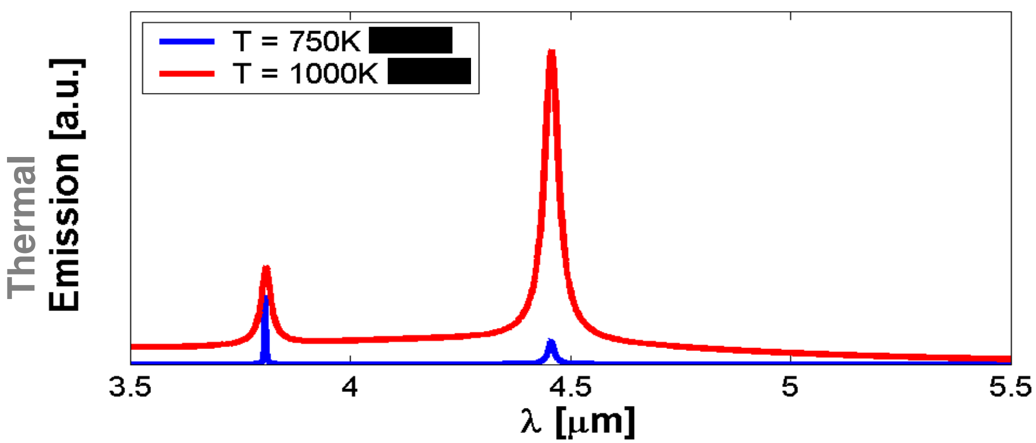
Peak emission $\Leftrightarrow Q_{ABS}$:
- Im(ε)

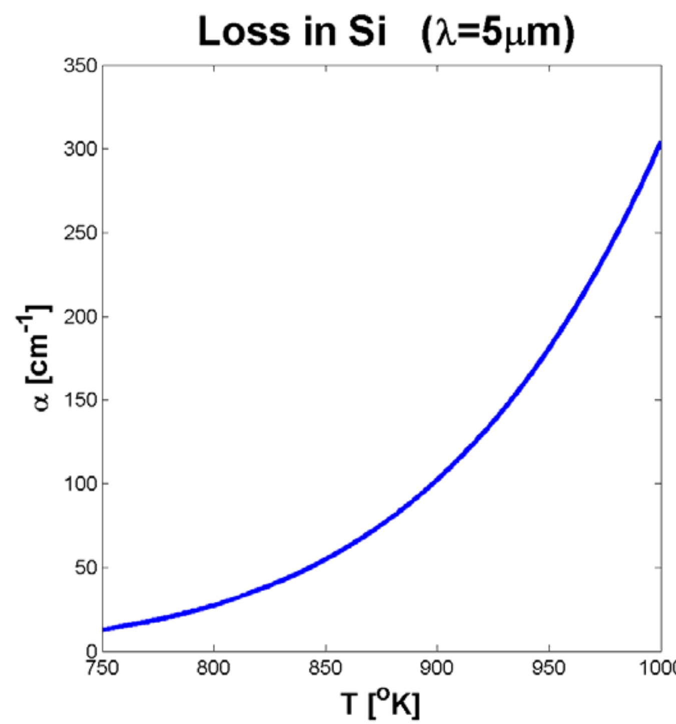
$$|a_{PhC}|^2 = \frac{\frac{2}{Q_{ABS}Q_{RAD}}}{4\left(\frac{\omega}{\omega_{FANO}} - 1\right)^2 + \left(\frac{1}{Q_{RAD}} + \frac{1}{Q_{ABS}}\right)^2}$$

An example of thermal design









Quasi-coherent thermal radiation: summary and opportunities

- PhC's offer unprecedented opportunities for tailoring thermal emission spectra

- Highly anomalous thermal spectra can be obtained

- Even dynamical tuning of spectra is possible

- Research in the combined near-field and quasi-coherent PhC radiation is opening up new frontiers

- Possible applications include: masking thermal targets, coherent thermal sources, high-efficiency TPV generation, chemical sensing, etc.

2.997 Direct Solar/Thermal to Electrical Energy Conversion Technologies
Fall 2009