SAND2008-5836P

Photonics, Plasmonics and Phononics

Sandia National Laboratories

T.S. Luk

New Mexico Tech Sept. 12, 2008

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Center for Integrated Nanotechnologies

One Scientific Community Focused on Nanoscience Integration

A U.S. DOE Nanoscale Science Research Center

- **96,000-square-foot CINT Core Facility will be a distribution point for researchers best served at smaller "gateways" at LANL and Sandia**
- **$75.8 million Center — one of five funded nationwide by the Office of Science**

Nano-bio-micro Interfaces: Import biological principles and functions into artificial bio-mimetic nano- and microsystems.

Nanophotonics and Nanelectronics: Precise control of electronic and photonic wavefunctions to invoke novel and unique properties.

Complex Functional Nanomaterials: Promote complex and collective interactions between individual components in materials to yield emergent properties and functions.

Nanomechanics: Understanding the underlying mechanisms of mechanical behavior of nanoscale materials and structures is the objective of the nanomechanics theme.

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Outline

- What are photonic crystals?
  - Basics
  - Fabrication
  - Thermal emission control

- Photonics: Radiation control
  - Solar thermal photovoltaic
  - Solar photovoltaic
  - Polariton light source

- Plasmonics: Integration of micro- and nano- photonic device (multi-stage field concentrator

- Phononics: Thermal energy scavenging

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Photonic crystals

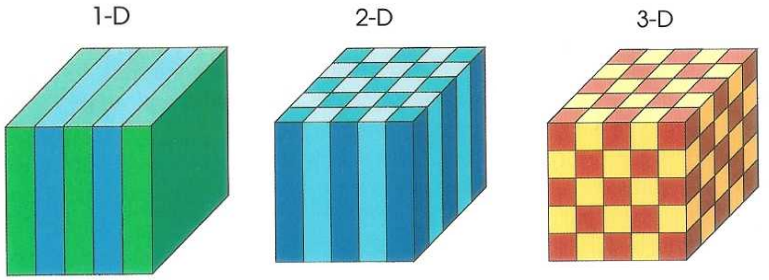
Photonic crystal: a metamaterial

A metamaterial (or meta material) is a material which gains its properties from its structure rather than directly from its composition. To distinguish metamaterials from other composite materials, the *metamaterial* label is usually used for a material which has unusual properties.

In this context: λ~a

Photonic crystal:

- A periodic array of electromagnetic scattering centers which results in the creation of regions of forbidden propagation commonly termed "spectral gaps" or "band-gaps"
- Bragg condition alone is insufficient to create an omni-directional bandgap.
- Threshold value of ε(r) is also needed.



Principle of PBG Operation:

An electromagnetic wave passing throughout an array of periodic scatterers will undergo destructive interference for certain combinations of wave-vectors at certain frequencies, thus forbidding propagation for such wave-vectors at these frequencies.

$$\left[\nabla \times \left(\frac{1}{\varepsilon(\vec{r})}\nabla \times\right)\right]\vec{H}(\vec{r}) = \left(\frac{\omega}{c}\right)^2 \vec{H}(\vec{r})$$

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Photonic Crystal Fabrication at SNL

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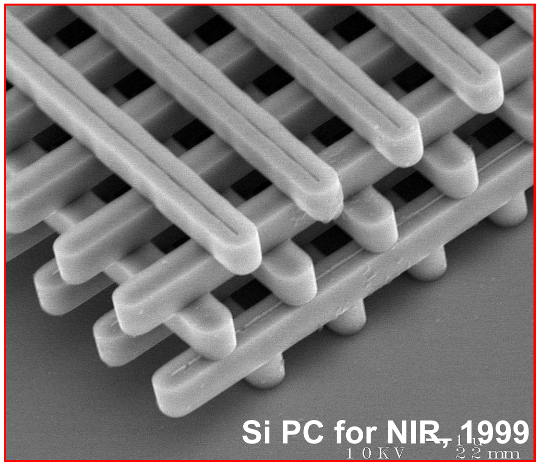
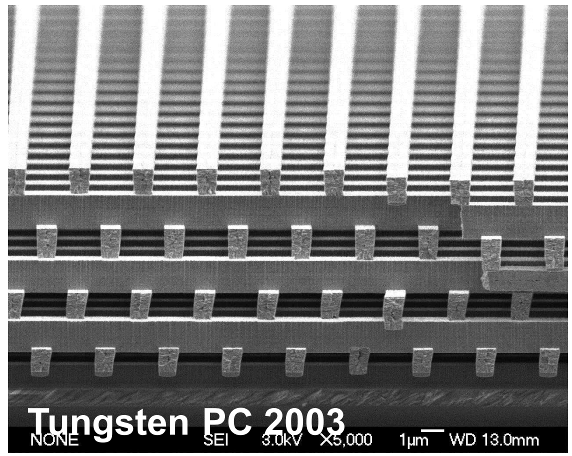
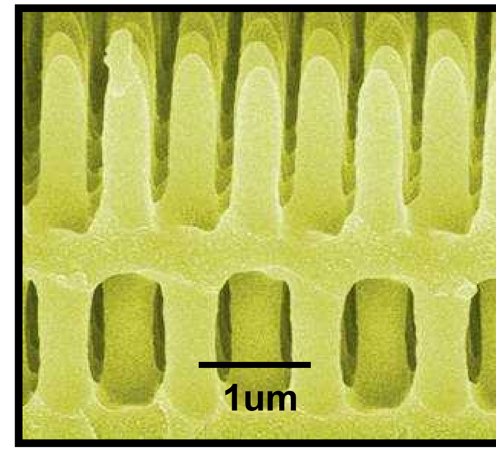
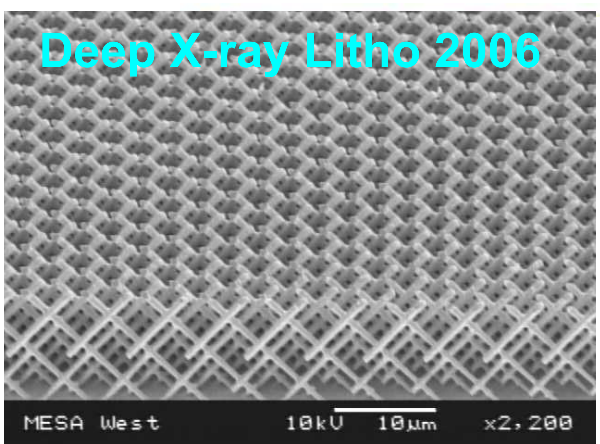
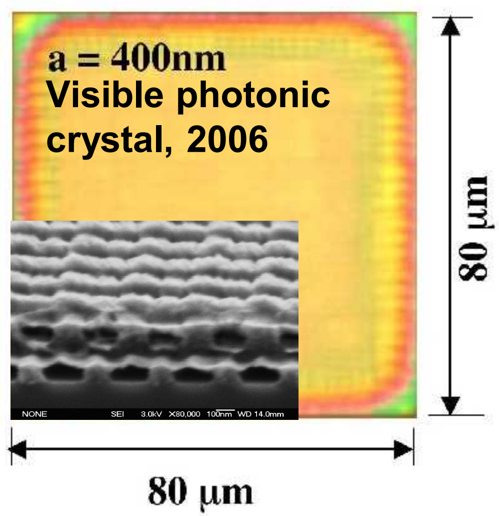
- Enabling fabrication technologies - Low temperature, low stress CMOS compatible and large volume fabrication.
- Other fabrication techniques: proximity field lithography, DXRL, EBL.

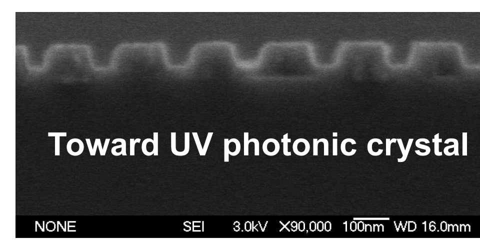












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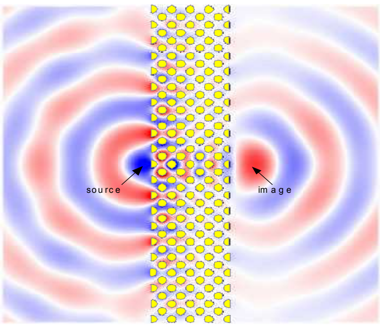
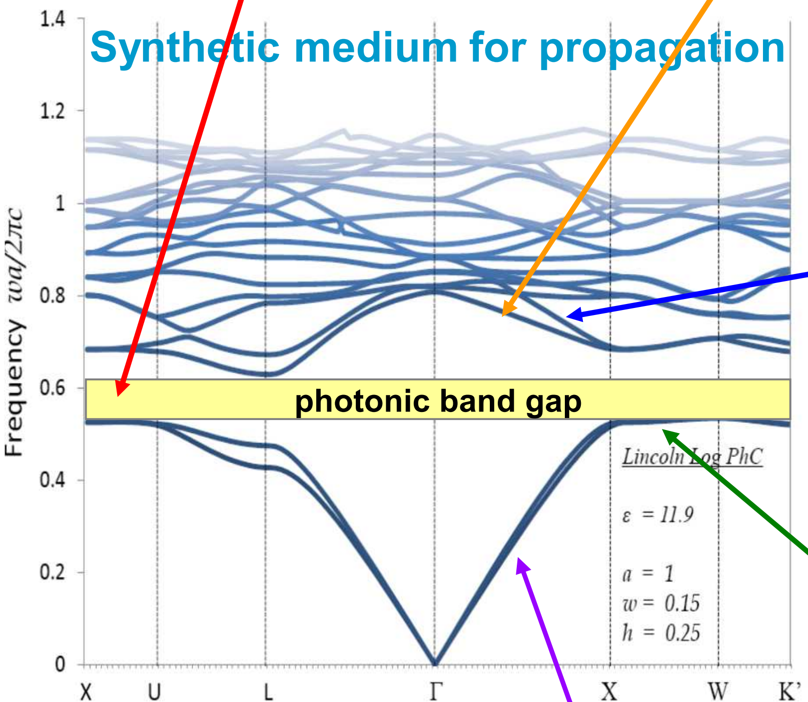
Photonic crystal bandstructure anatomy

Bandgap region
- Inhibit spontaneous emission
- Nanocavity
- Waveguides

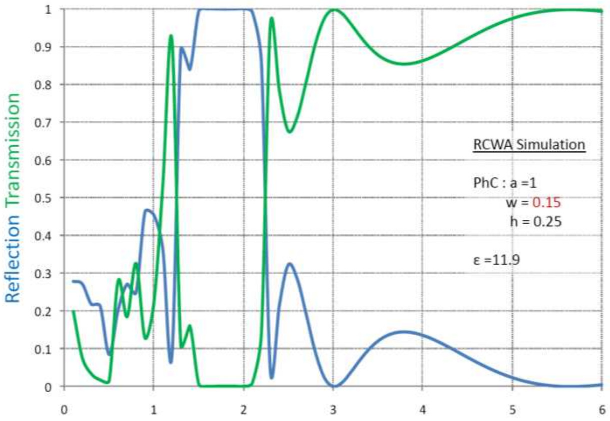
Backwards slope means
- Negative refraction
- Subwavelength imaging



Synthetic medium for propagation



Strong curvature:
- Super-prisms
- Dispersion control



Linear dispersion region
- Optical waveguide and circuits

$d\omega/dk \rightarrow 0$:
- Slow light,
- High photon density of states
- Enhance spontaneous emission

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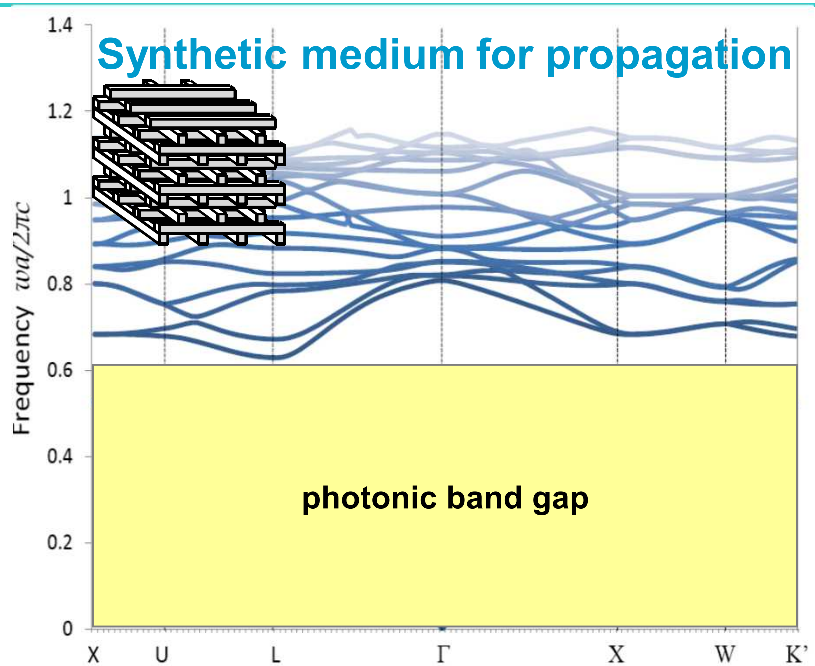
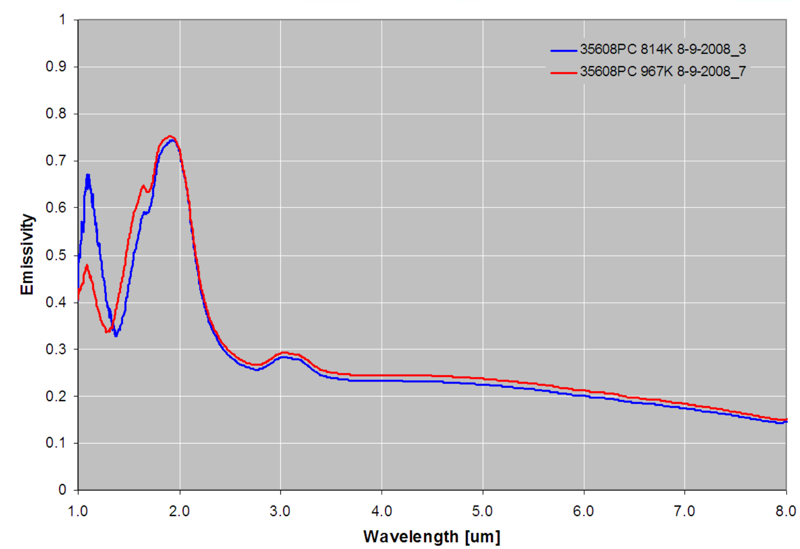
Metallic Photonic crystals



Spectral compression by photonic crystal



Network topology: ⇒ Metallic sheet reflectivity at long wavelengths

Engineered thermal Emitter

⇒ *Photon states below the band edge are forbidden*

⇒ *PC can only radiate energy within an allowed narrow band*

⇒ *PC narrow emission band can be engineered in frequency and space*

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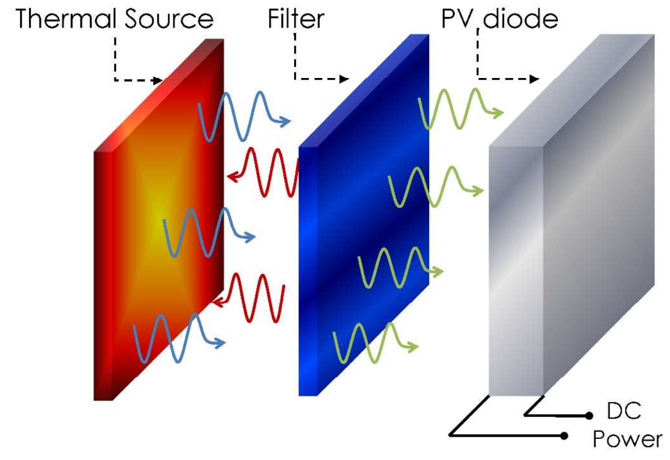
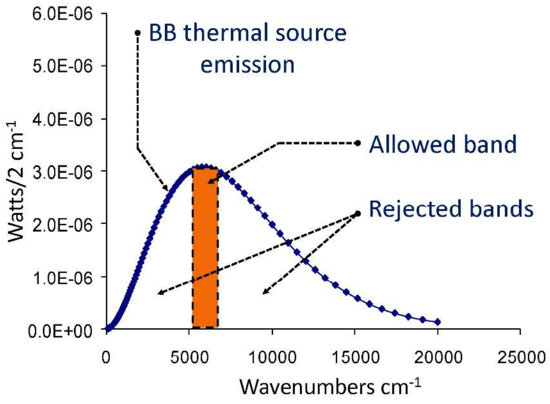
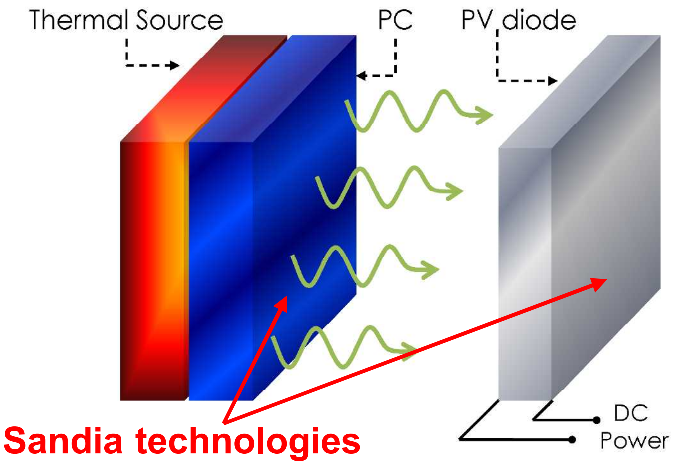
Thermo-photovoltaic application

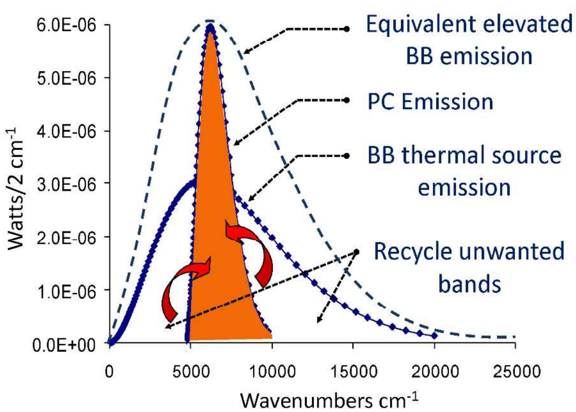




Passive Filtering:

- **Reflect or reject unwanted portion of the spectrum.**
- **Not all the heat are recaptured by the emitter.**
- **Lower emitter temperature.**





Energy Recycling:

- **Lower heat loss to unwanted spectra.**
- **Cause higher emitter temperature.**
- **Higher emission rate and higher Carnot efficiency.**

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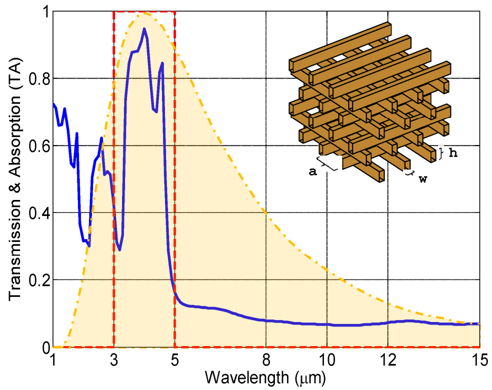
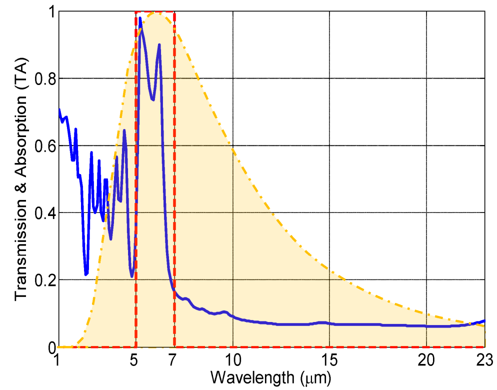
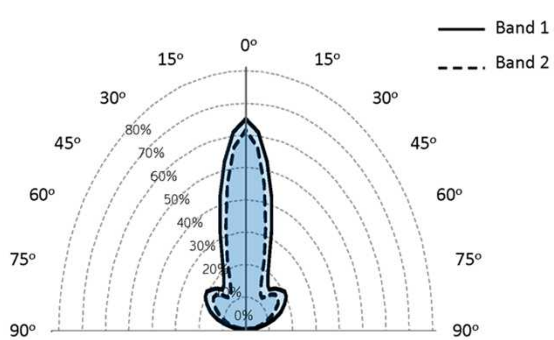
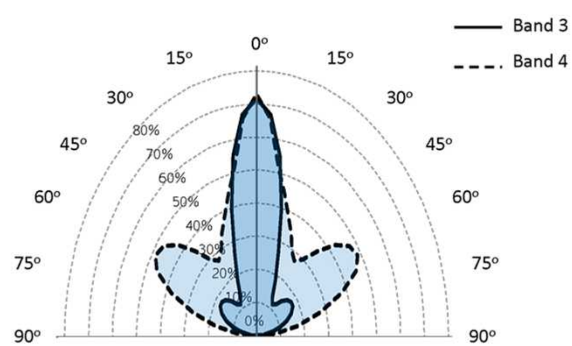
Directional Photonic crystal emitters





	a (μm)	w (μm)	h (μm)	η_{ePhC} %	η_{eBB} %	η_{pPhC} %	T_1 K
Band 1	3.4	0.7	0.8	69.4	35.1	67.1	726
Band 2	5.2	1.0	1.0	56.5	22.9	74.7	460
Band 3	7.0	1.8	1.7	54.0	19.0	74.5	358
Band 4	9.6	3.4	4.5	40.3	14.9	73.7	283





Emitter (power) efficiency

$$\eta_{e-PhC}(\lambda) = \frac{\sum_{\lambda_1}^{\lambda_2} A(\lambda)\, N_E(\lambda)}{\sum_{\lambda_{min}}^{\lambda_{max}} A(\lambda) N_E(\lambda)}$$

$$N_E(\lambda) = \frac{2\pi C^2 h}{\lambda^5 \left(e^{\frac{hc}{\lambda k T}} - 1 \right)}$$

Modified power efficiency

$$\eta_{p-PhC}(\lambda) = 1 - \frac{\sum_{\lambda_{min}}^{\lambda_{max}} A(\lambda)\, N_E(\lambda)}{\sum_{\lambda_{min}}^{\lambda_{max}} N_E(\lambda)}$$

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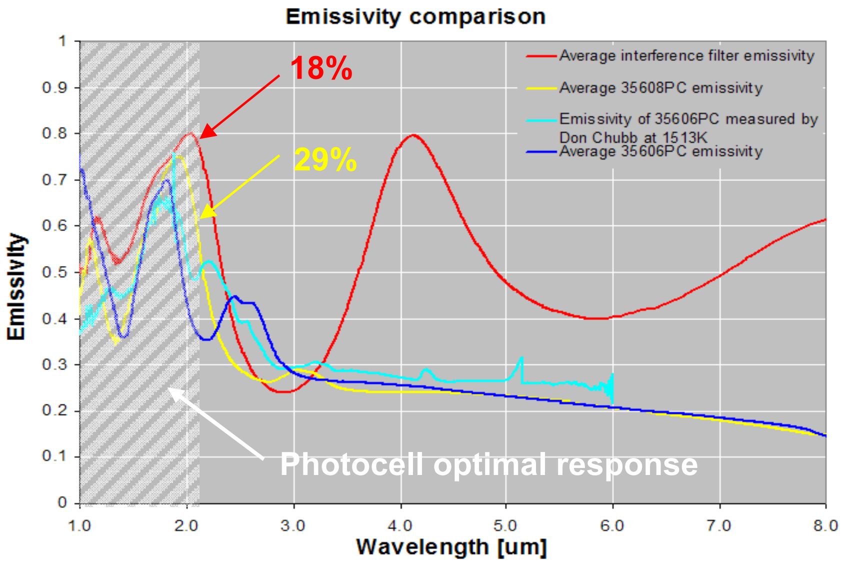
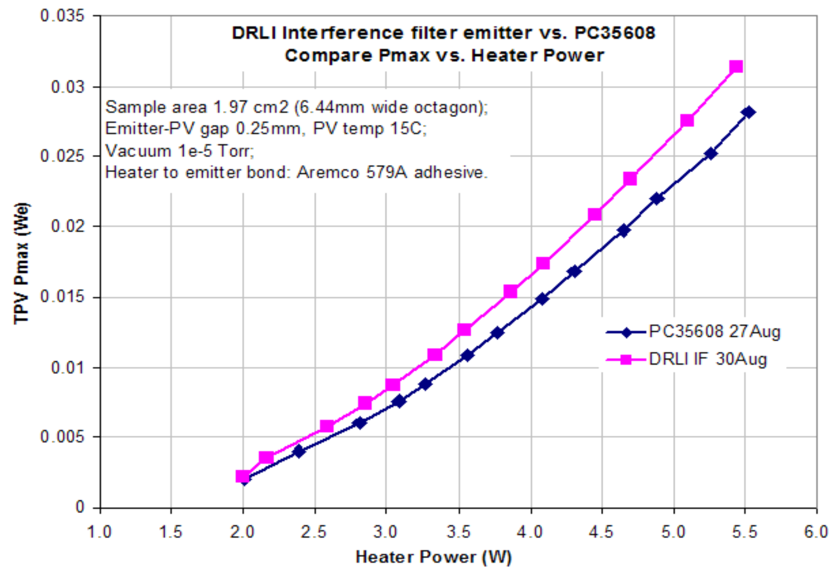
Emitter comparison





PV efficiency

- Maximum TPV Diode Efficiency ~ 45.5% = eQE * VF *FF
- eQE (external quantum efficiency) 'best case' = 90% (typical is 80%)
- VF (voltage factor) 'best case' = 410mV/junction / 0.6eV bandgap = 68.33%
  (typical 390 mV junction -> VF= 65%)
- FF (Fill Factor = diode ideality) 'best case' = 74% (typical =70%)
- Typical TPV Diode Efficiency = 0.8 * 0.65 * 0.7 = 36.4% (45% max.)

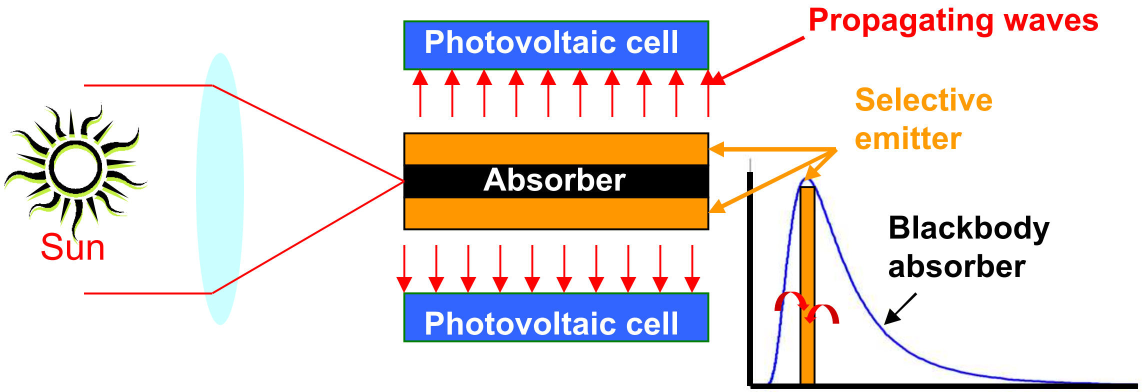
Emitter efficiency 30% (70% is realizable)

TPV efficiency = 14-20% at 1100K demonstrated (31.5% is realizable)

Wernsman, R.R. Siergiej, S.D. Link, R.B. Mahorter, M.N. Palminiano, R.J. Wehrer, R.W. Schultz, G.P. Schmuck, R.L. Messham, S. Murray, C.S. Murray, F. Newman, D. Taylor, D.M. DePoy, T. Rahmlow, "Greater than 20% radiant heat conversion efficiency of a thermophotovoltaic radiator/module system using reflective spectral control", IEEE Trans. Electron Devices, **51**, 512 (2004).

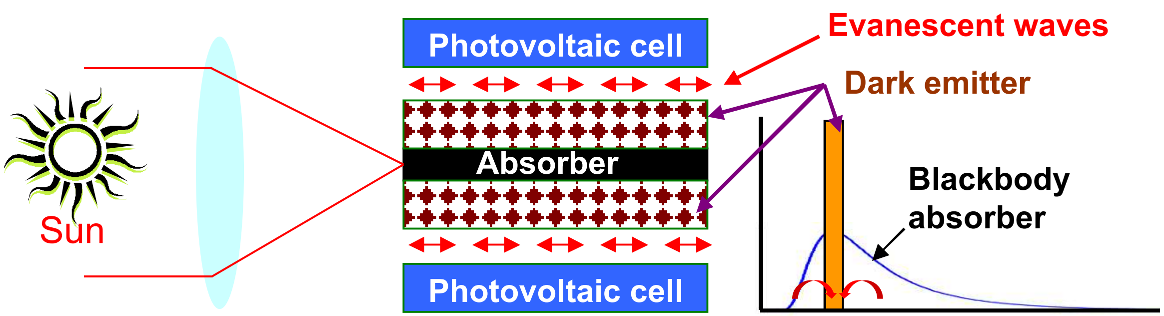
How to do better?

Conventional solar-TPV: selective emitter



Issues:
Energy transfer rate limited to BB rate.
When include detector efficiency and imperfect emitter, system efficiency 10-30%

Proposed solar-TPV: evanescent coupled dark emitter



Features:
Harvested power is limited by the supplied power (KW/cm^2 demonstrated with near field probe).

Challenges:
Emitter to detector spacing is very small, sub-100nm.

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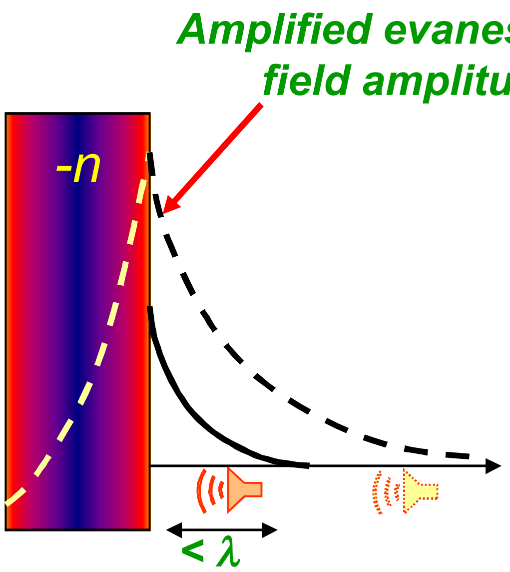
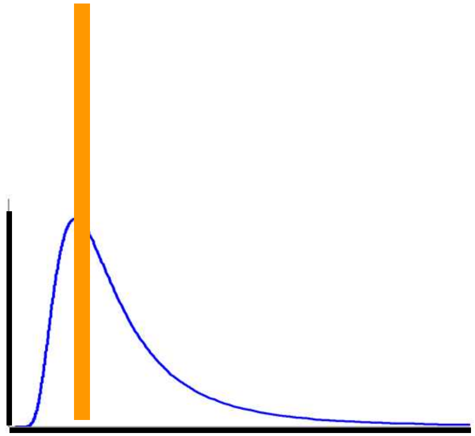
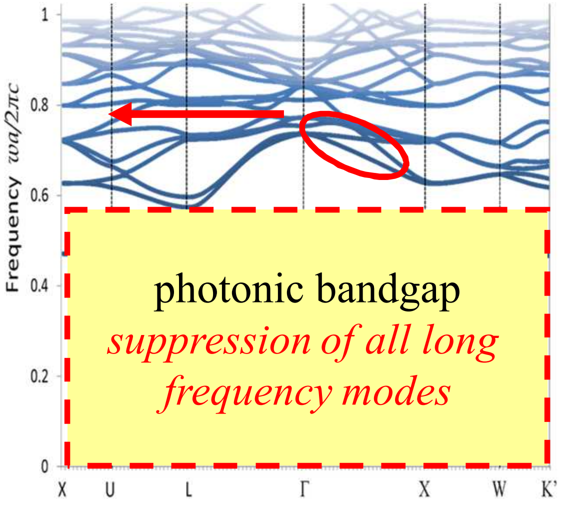
Dark emitter







- Non-radiating surface state to spectrally compress blackbody spectrum into narrow band to match PV cell absorption.

- Negative index material to extend evanescence field.

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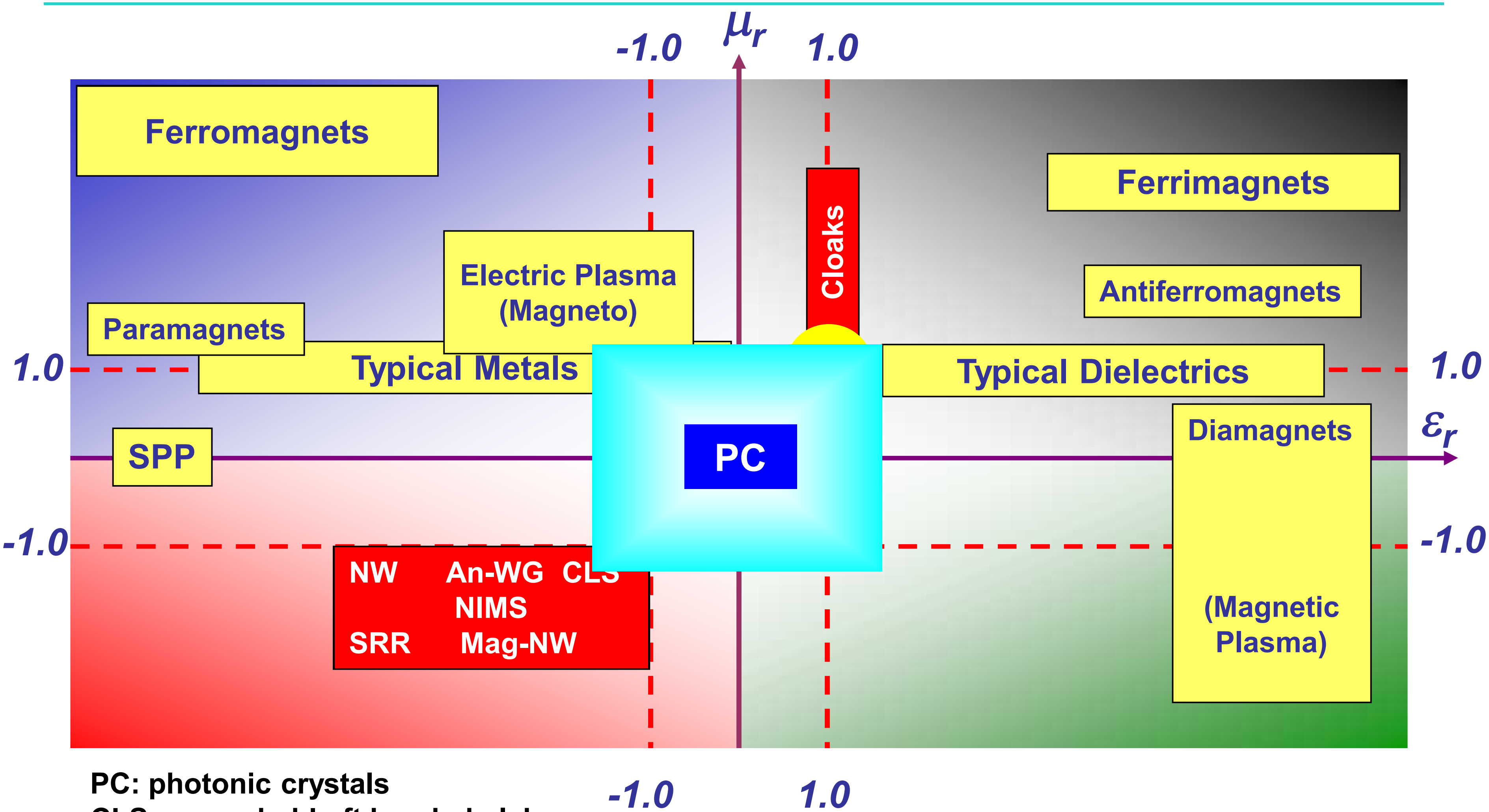
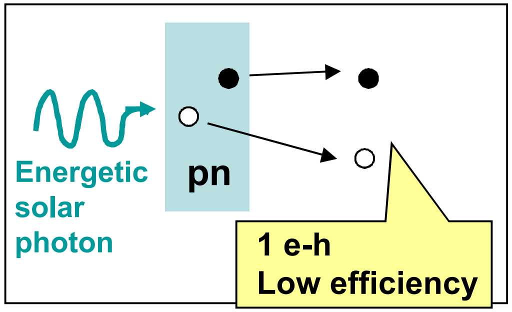
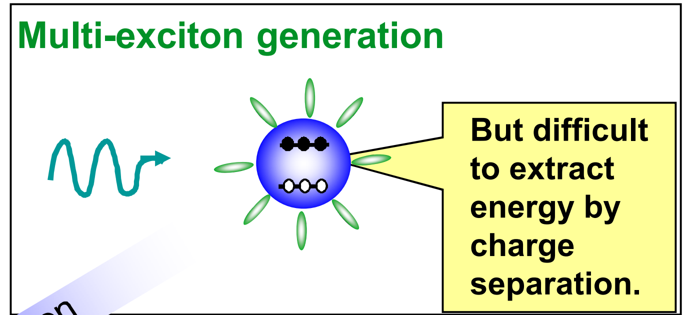
Metamaterial landscape

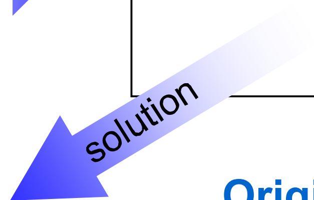


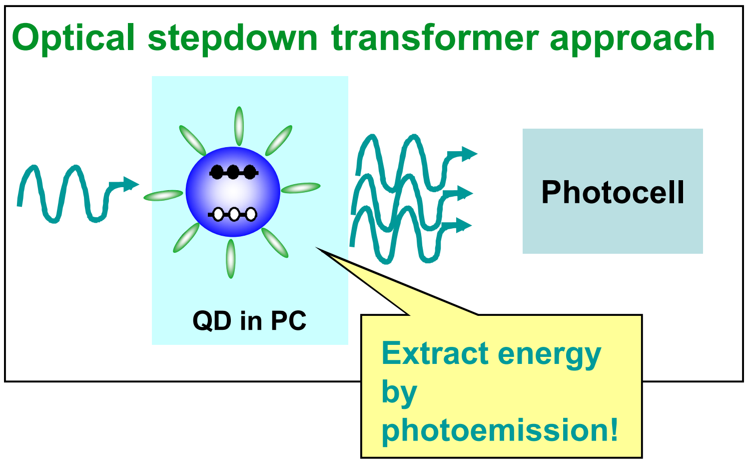
PC: photonic crystals
CLS: cascaded Left handed slabs
MO: Magneto-optical.
NW: nanowire
AN-WG: anisotropic waveguide

Photonic crystal solution to energy extraction from quantum dots









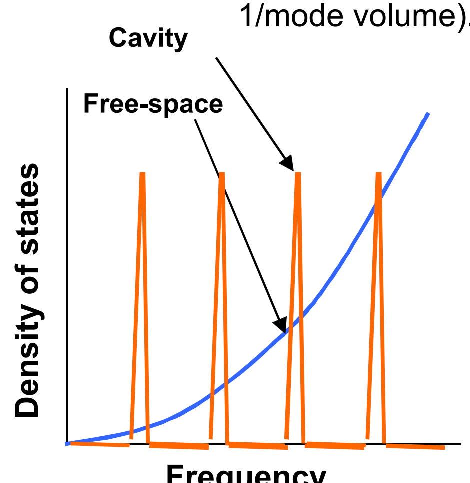
Origin of radiative lifetime

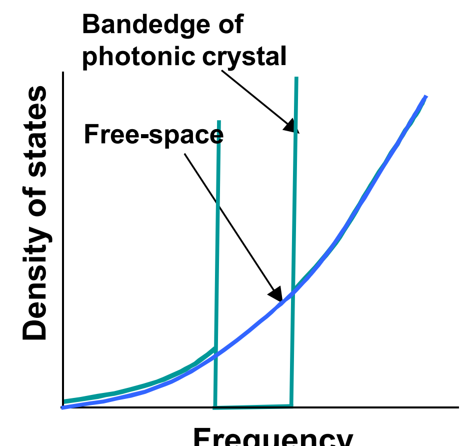
Radiative rate is governed by the interaction of the emitter to the vacuum field, this quantity depends on:

1. Dipole moment of the radiative transition (material intrinsic property).
2. Number of final states available (related to density of states, free space density of states.
3. Electric intensity of the vacuum mode (proportional 1/mode volume).

How to change radiative rate?

- Increase density of states using cavity or photonic crystal engineering.
- Increase vacuum field intensity by shrinking the mode volume.





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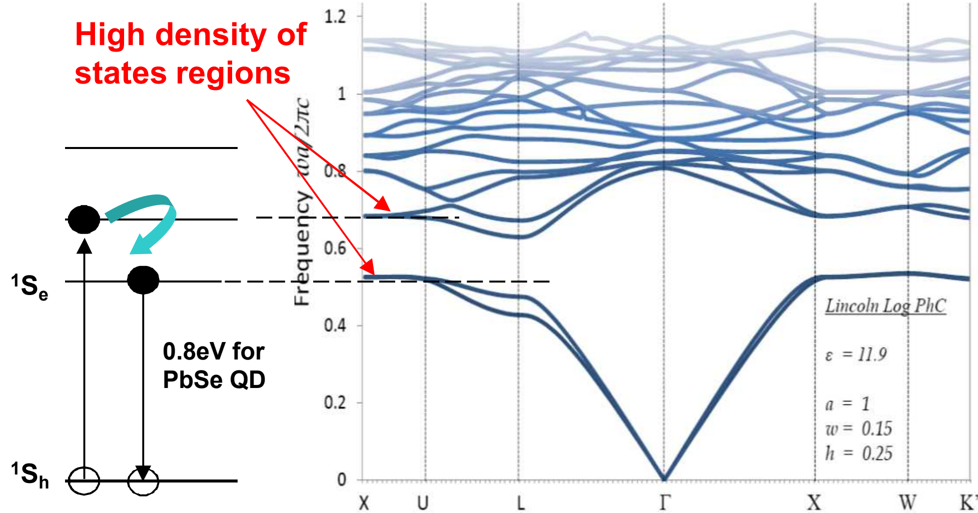
Radiative properties control by photonic crystals: Band edge effect

Band edge effect

Slower group velocity means high density of states which increases absorption coefficient.

Enhanced radiative process may out-compete non-radiative process so that they become un-important.



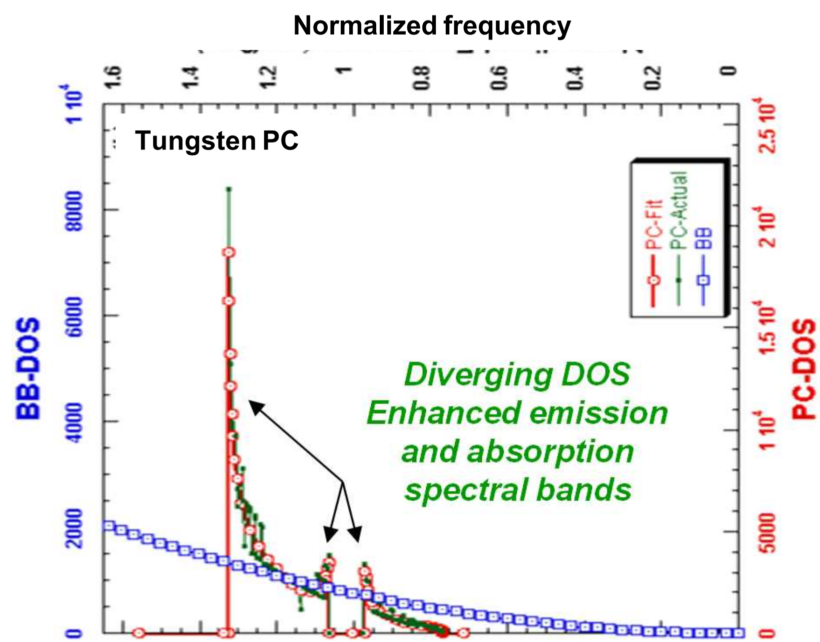
Radiative transition rate

$$\Gamma_{eg} = \frac{2\pi}{\hbar^2}\sum_{k,n}\left|\left\langle g,1_{k,n}\left|\vec{d}\cdot\vec{E}(\vec{x}_0)\right|e,vac\right\rangle\right|^2\delta\left(\omega_{k,n}-\omega_0\right)$$

$$\Gamma_{eg} = \frac{\pi\omega_0\,|\vec{d}\,|^2}{\varepsilon_0\hbar}\rho\left(\vec{x}_0,\frac{\vec{d}}{|\vec{d}\,|},\omega_0\right)$$

Photonic density of states engineering

$$\hat{\vec{E}}(\vec{x}_0) = \sum_{k,n}\sqrt{\frac{\hbar\omega_{k,n}}{2\varepsilon_0 V}}\left(\vec{E}_{\vec{k},n}(\vec{x}_0)\,\hat{a}_{\vec{k},n} + h.c.\right)$$



I. El-Kady et. al. "Emission from an active photonic crystal", Phys. Rev. B, vol. 72, 195110 (2005)

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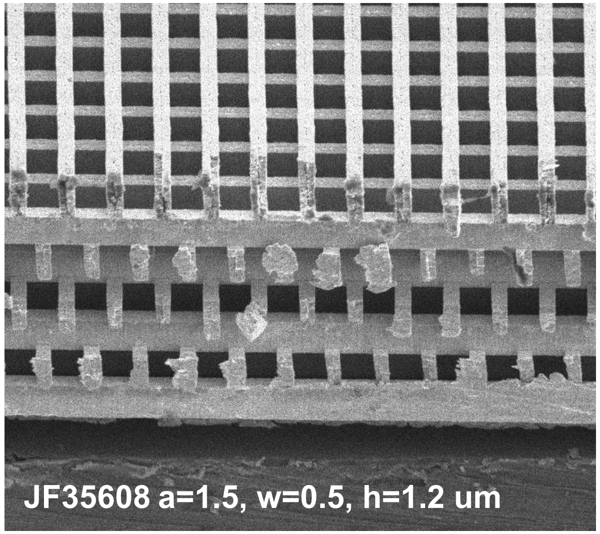
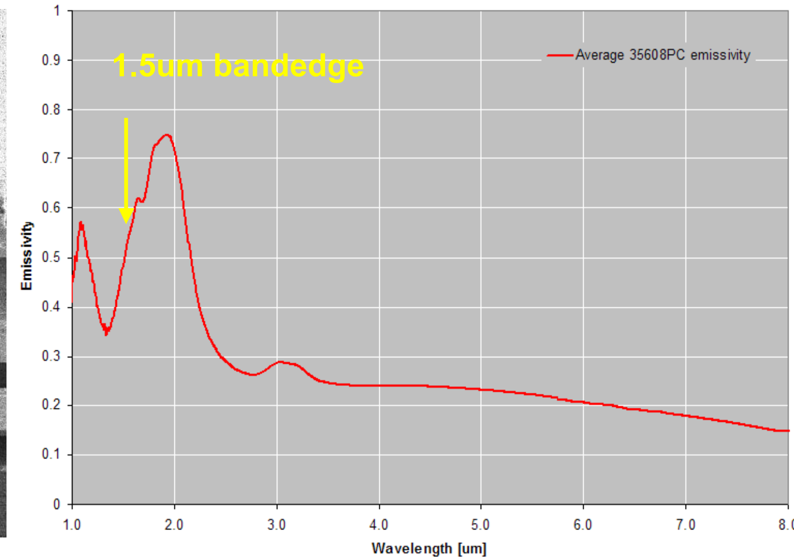
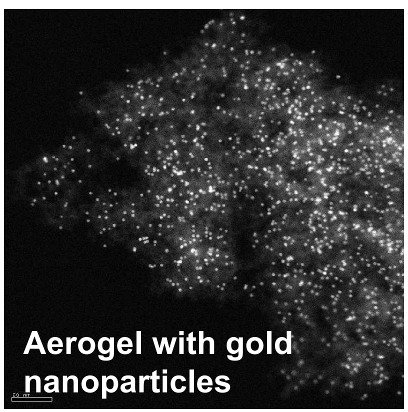
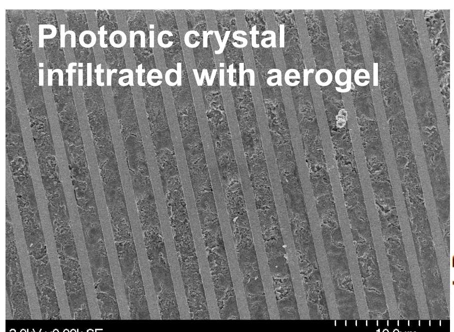
Radiative properties control by photonic crystals: Band edge effect (cont'd)

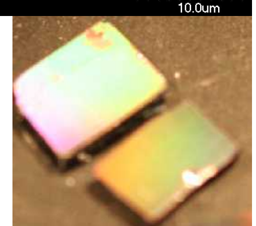
Photonic crystal with the bandedge at the right place

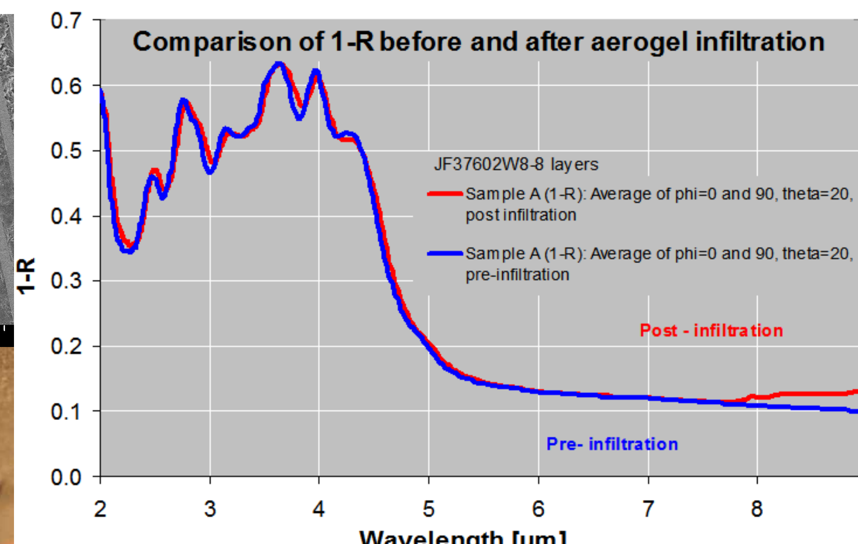












Infiltration of aerogel does not affect photonic crystal reflectivity

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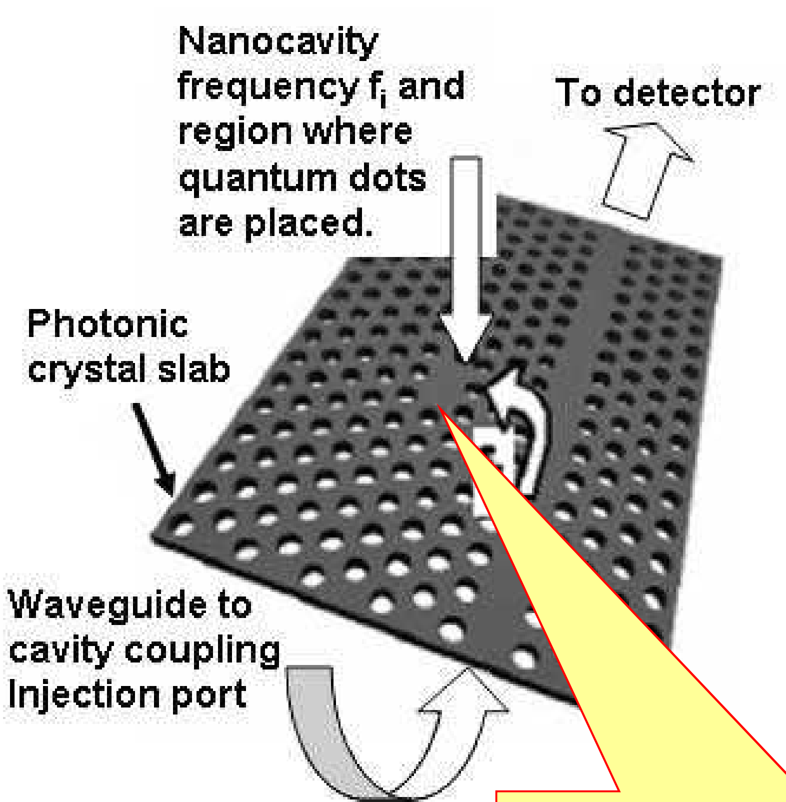
Radiative properties control by photonic crystals: Purcell effect



Purcell enhancement factor

$$P = \frac{3}{4\pi^2}\left(\frac{\lambda}{n}\right)^3 \frac{Q}{V}$$

Spontaneous emission enhancement factor

$$\frac{\Gamma}{\Gamma_0} = \left(\frac{3\lambda_C^3 Q}{4\pi^2 n^3 V_m}\right) \times \zeta_r \times \left(\frac{\Delta\lambda_C^2}{\Delta\lambda_C^2 + 4(\lambda_C - \lambda_X)^2}\right) + f,$$

Enhancement factor

Purcell factor (interaction strength with vacuum field in a small confined volume)

Cavity resonance effect

- **Mode volume is less than $(\lambda/n)^3$.**
- **Q = 10^6 demonstrated.**
- **Q of 10^9 is possible.**
- **Purcell factor of 10^5.**

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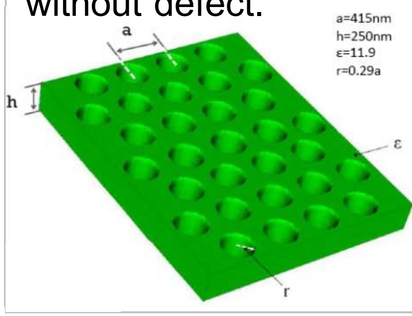
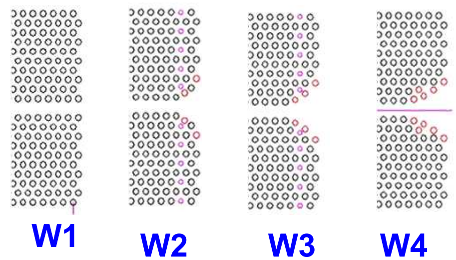
Radiative control using photonic crystals Nanocavities : challenges

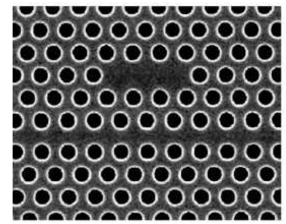
Modeling 2D Photonic crystal bandstructure without defect.



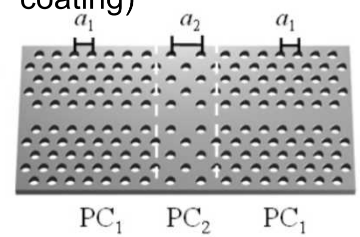
Efficient light coupling into photonic crystal waveguide.

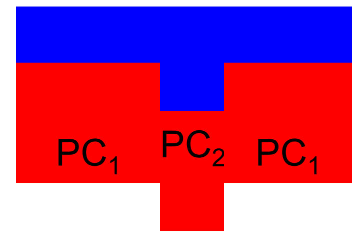


L3 defect (low Q, low risk)

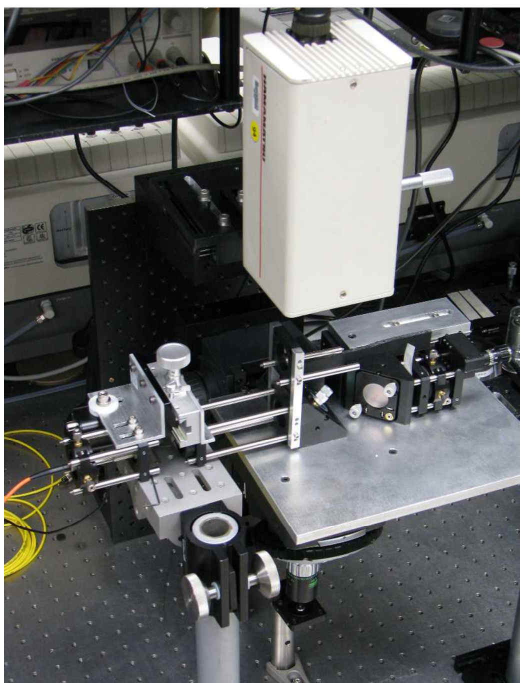


Double heterostructure (mode gap idea, high Q, compatible to QD coating)

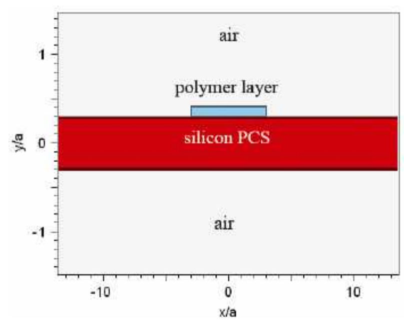


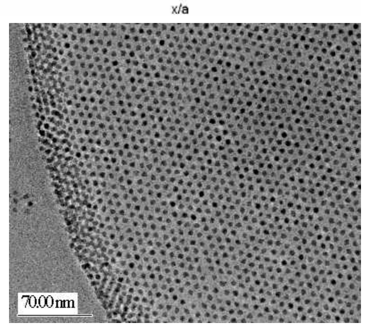


Ultra-sensitive NIR μPL

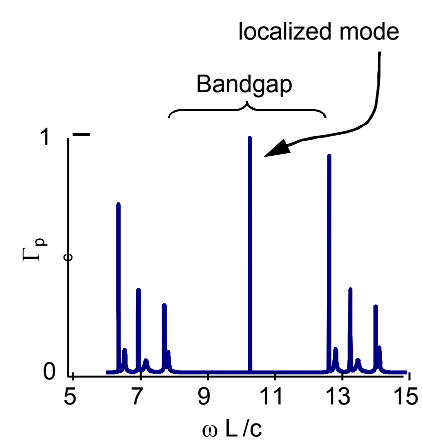


Putting QD on PC

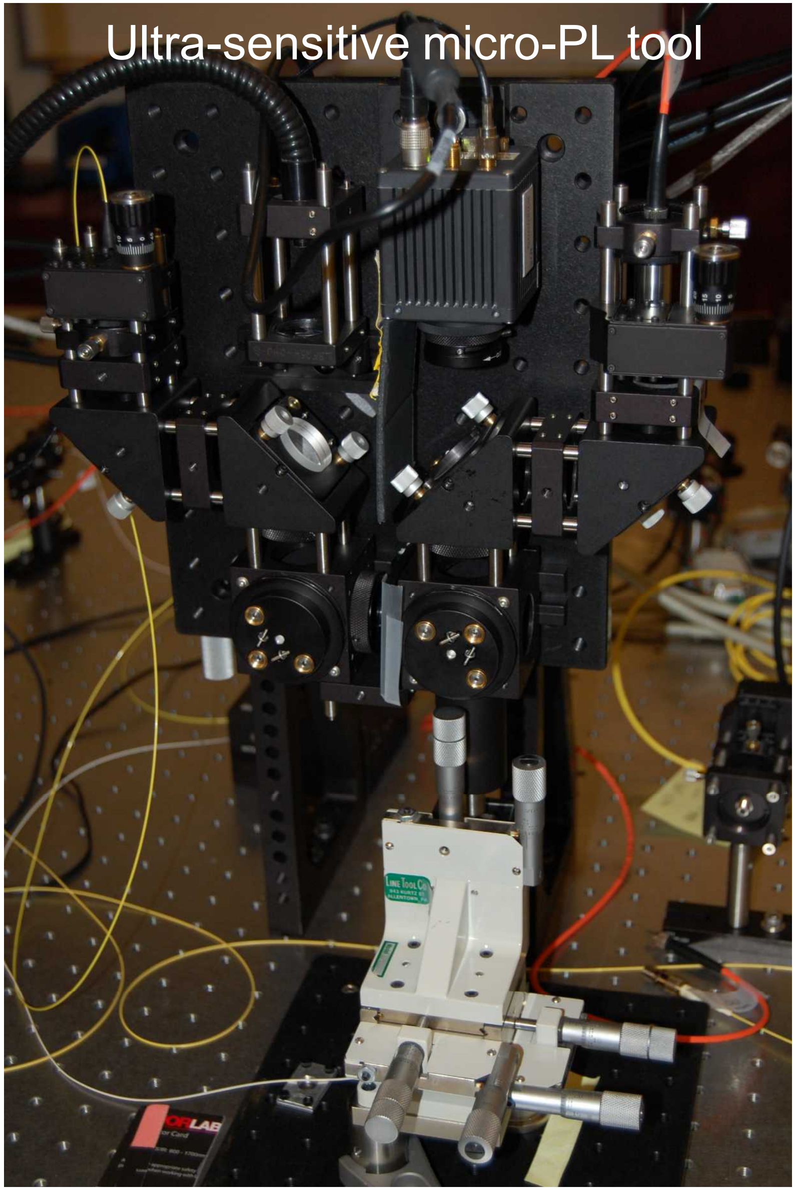


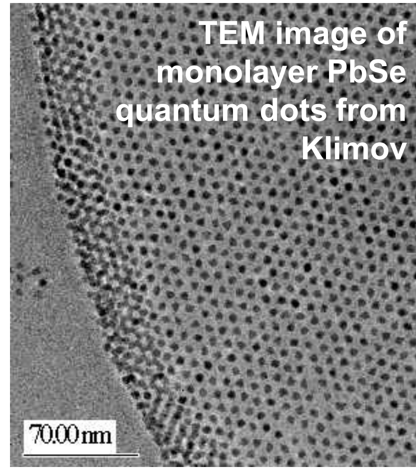


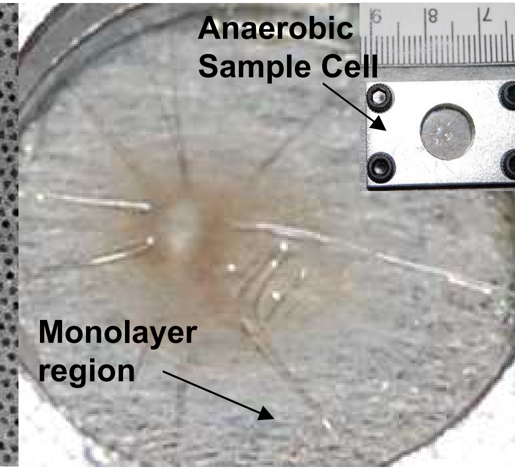
Modeling interaction of QD with a nanocavity

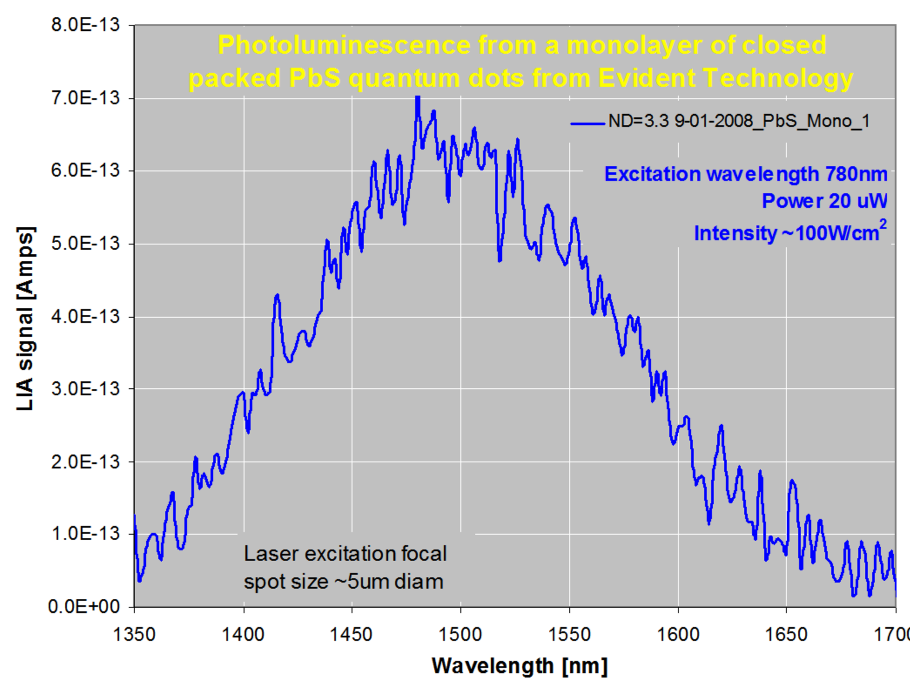


Photoluminescence of monolayer PbS quantum dots









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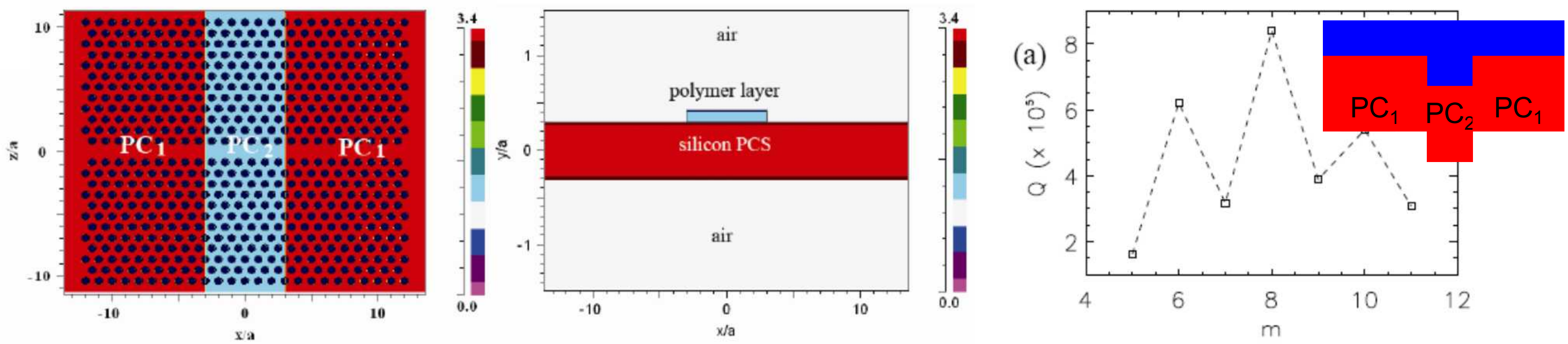
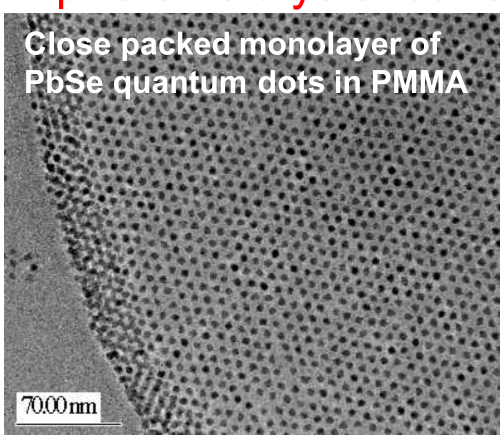
Methodology of integrating nanoparticles with photonic crystals

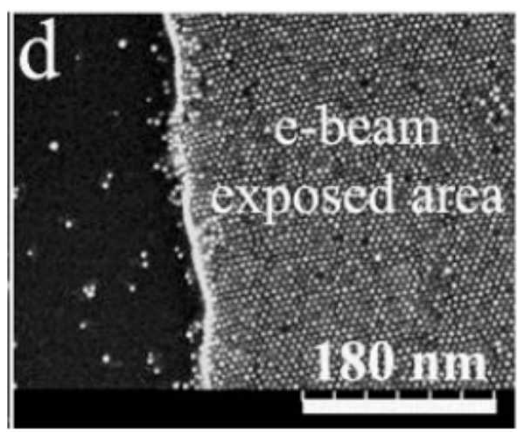
Nanocavities designed are compatible with post-process coating of QDs.

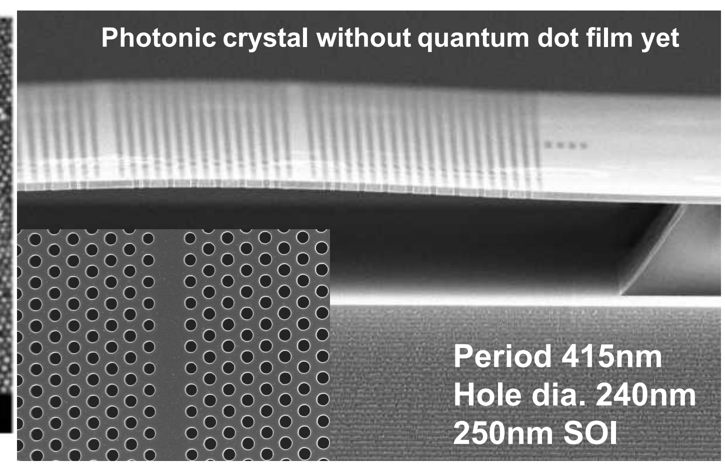


Tomljenovic-Hanic et. al., “High-Q cavities in multilayer photonic crystal slabs”, Opt. Exp. Vol. 15, 17248 (2007)

Close packed monolayer of quantum dots in PMMA can be coated on photonic crystal surface







J. Pang, S. Xiong, F. Jaeckel, Z. Sun, D. Dunphy, and C.J. Brinker, “Free-standing, Patternable Nanoparticle/Polymer Monolayer Arrays Formed by Evaporation Induced Self-Assembly at a Fluid Interface”, JACS, vol. 130, 3284 (2008).

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Summary of accomplishments and challenges

Accomplishments

- Successfully aerogel infiltration into a 3D photonic crystal.
- Successfully fabrication on monolayer of close packed quantum dots in PMMA film.
- Sensitive micro-PL instrumentation capable of measuring PL from a monolayer quantum dot film in a 5 um diameter spot.
- Successful fabrication of 2D photonic crystal nanocavities (optical characterization remained to be done).

Remaining work

- Integrating quantum dots in aerogel.
- Integrating quantum dots and aerogel with 3D photonic crystals.
- Integrating quantum dot film with 2D photonic crystals.

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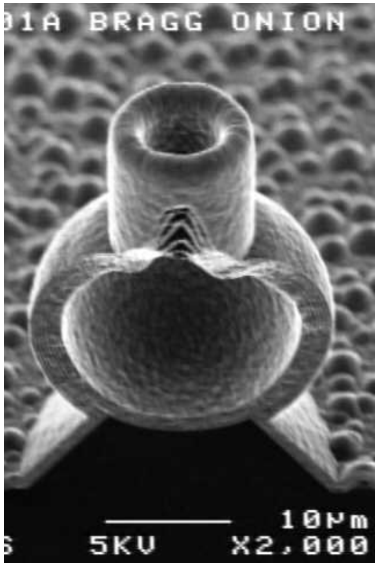
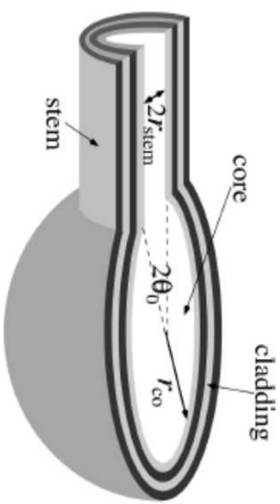
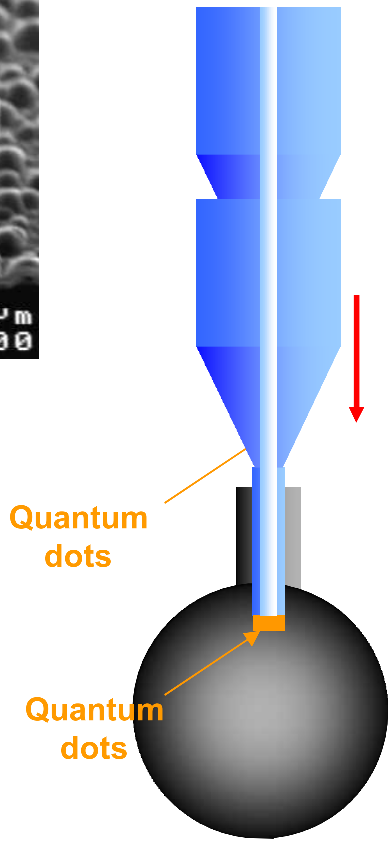
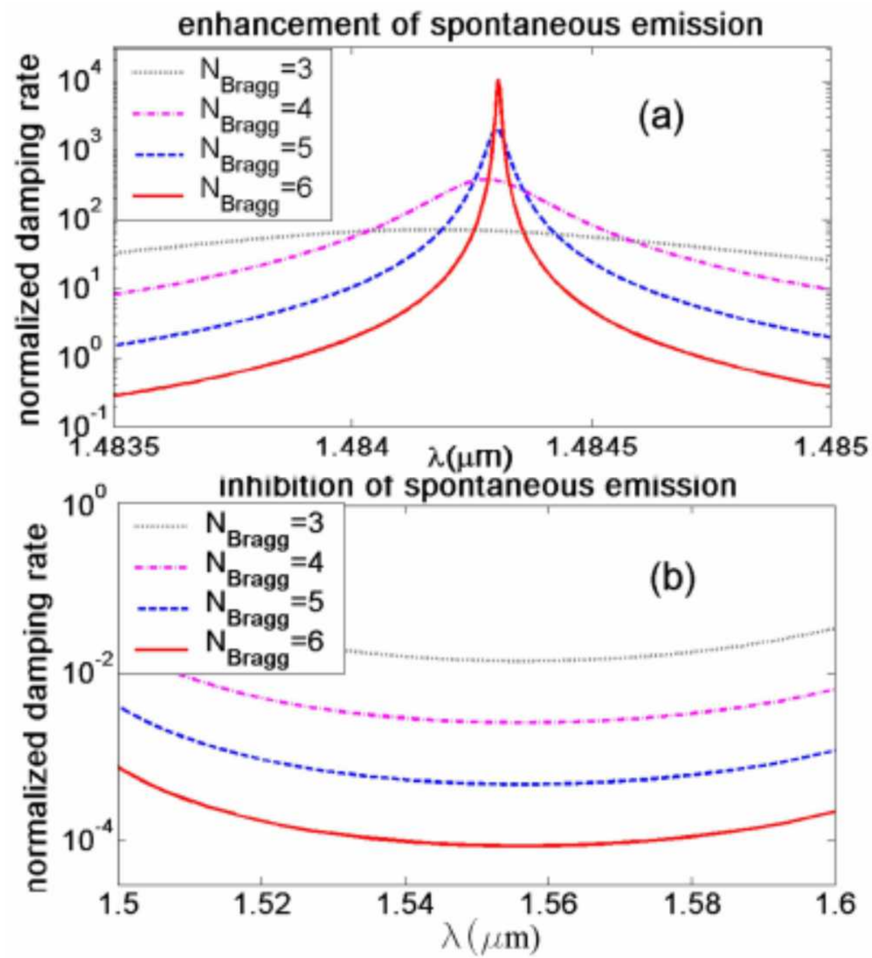
Bragg Onion photonic cavity









W. Liang et. al. "Modification of spontaneous emission in Bragg Onion resonators", Opt. Exp. Vol. 14, 7398 (2004).

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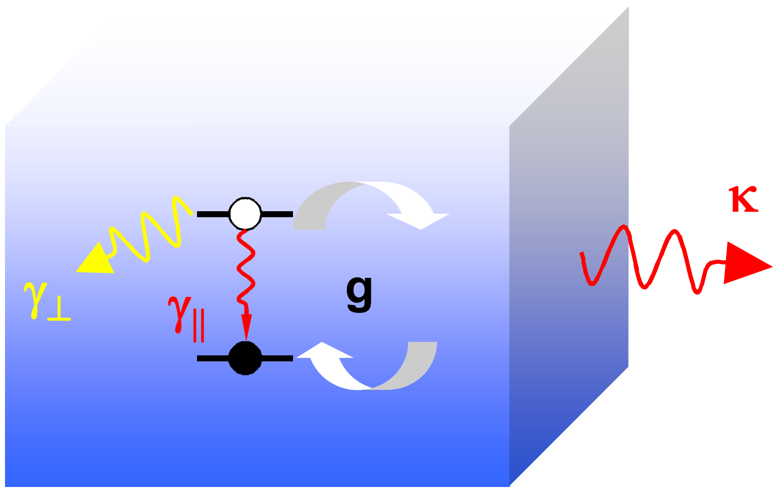
Purcell effect: strong coupling regime



Interaction Hamiltonian ~ hg

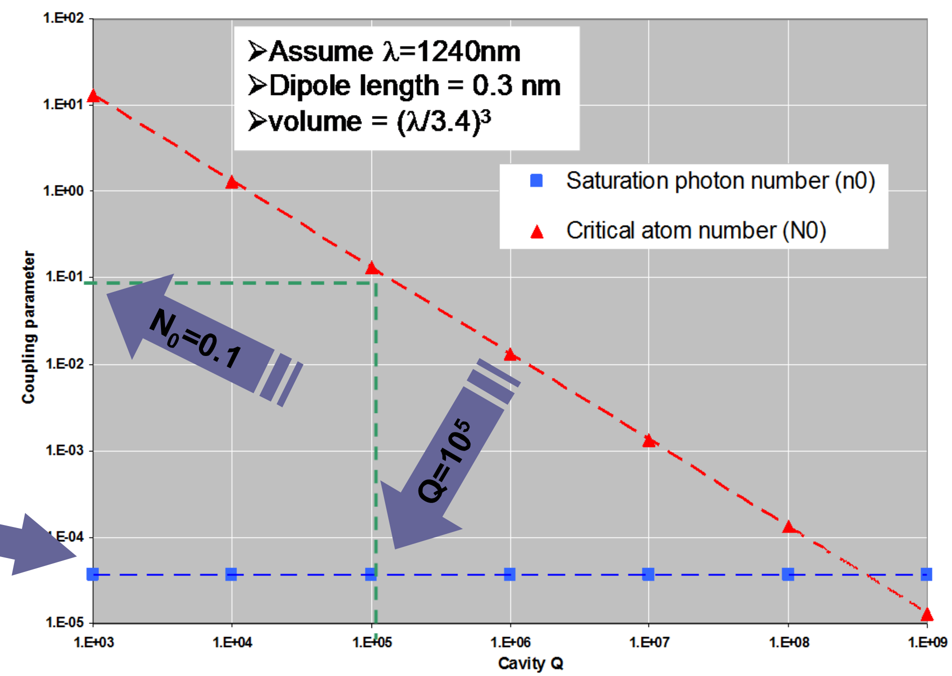
Coupling strength $$g_0^2 = \left(\frac{\mu^2\omega_c}{2\hbar\varepsilon_0 V}\right)$$

Saturation photon number (atom-cavity interaction) $$n_0 = \frac{\gamma_\perp\gamma_\parallel}{g_0^2} \propto V$$

Critical atom number (inverse proportional to atom cooperativity) $$N_0 = \frac{2\gamma_\perp\kappa}{g_0^2} \propto \frac{V}{Q}$$

Applications

- Sensing.
- Single photon source.
- Entangled photons.
- Coupled resonators effects.
- Study decoherence effects of QD.
- Single photon transport.
- Nonlinear optics of single photon.



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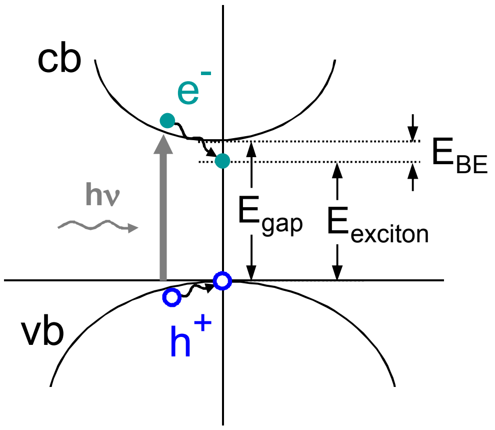
Semiconductor emitter: exciton

What is an exciton?



1.) Incident photon creates and electron-hole pair

2.) Coulomb attraction between electron and hole forms the exciton at slightly lower energy

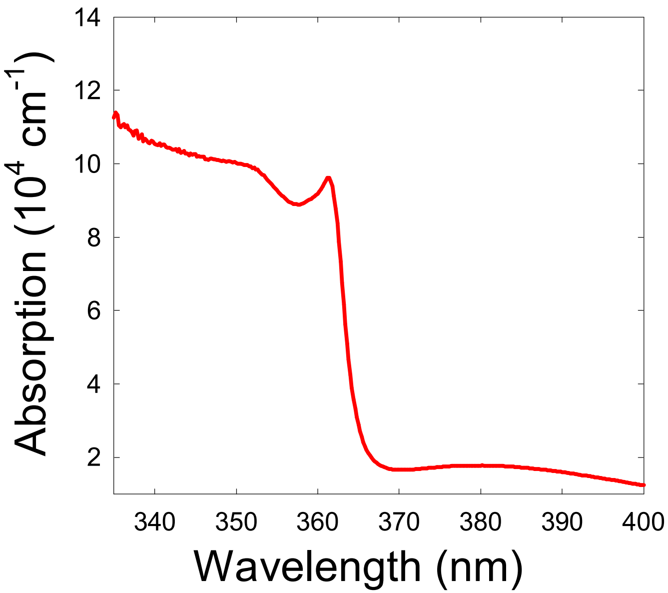
→ Exciton binding energy,

$E_{BE} = E_{gap} - E_{exciton}$

→ $E_{BE,GaN}$ ~ 28 meV (above RT exciton)

3.) Exciton polariton is a coupled state between an exciton and a photon

GaN absorption data



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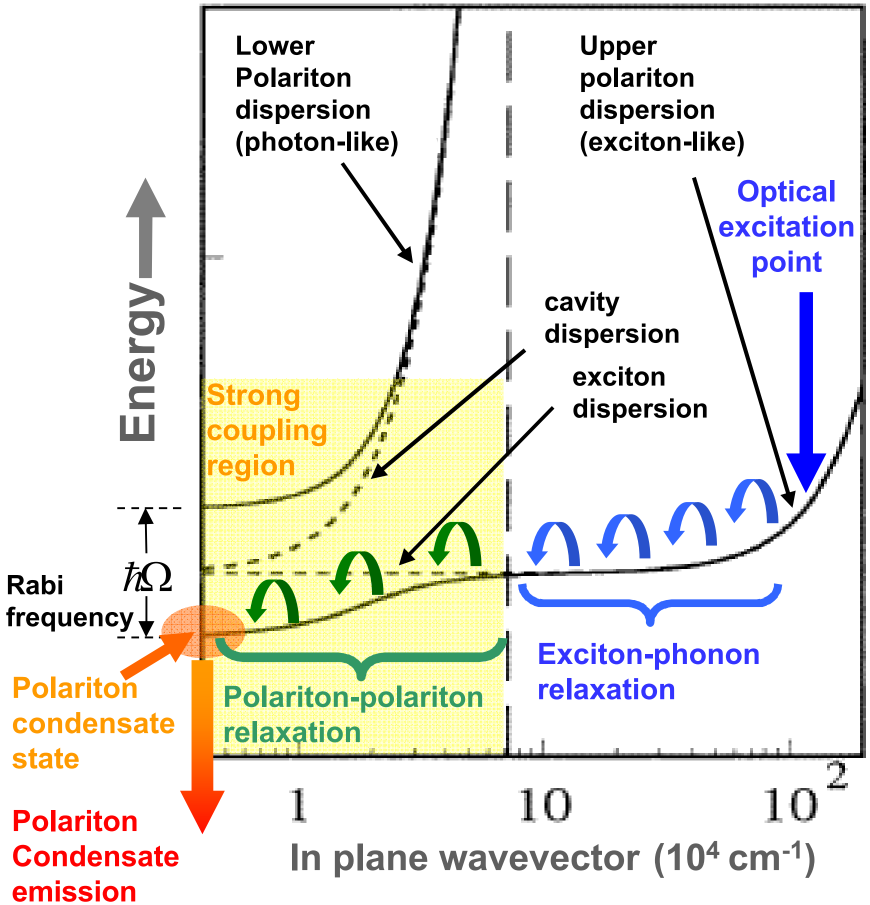
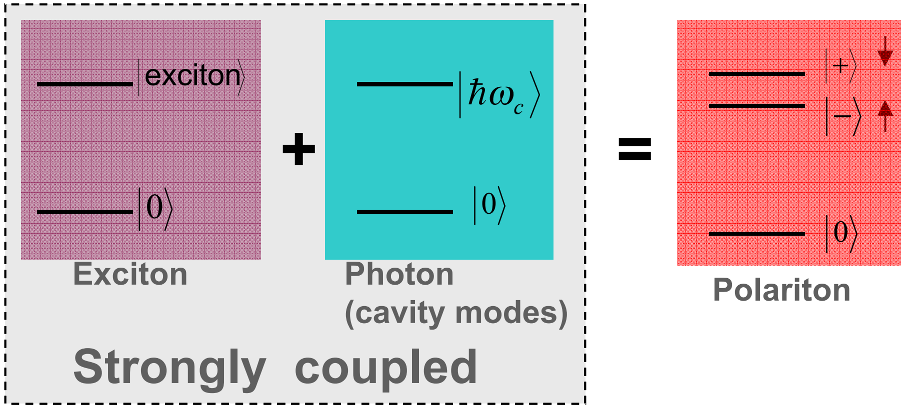
Radiative properties control by photonic crystals: coherent many body effect





splitting $\hbar\Omega = 2d\sqrt{\frac{\hbar\omega_c}{2\varepsilon_0 V}}$

$$\varepsilon_{\pm} = \frac{1}{2}\left(\varepsilon_{exciton} + \hbar\omega_c\right) \pm \sqrt{(\hbar\Omega)^2 + \left(\varepsilon_{exciton} - \hbar\omega_c\right)^2}$$

$$|+\rangle = \frac{1}{\sqrt{2}}\left(|exciton,0\rangle + |0,1\rangle\right)$$

$$|-\rangle = \frac{1}{\sqrt{2}}\left(|exciton,0\rangle - |0,1\rangle\right)$$

Exciton-polariton is bosonic

Polariton source has all the laser properties but no inversion requirement

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Comparison of Polariton and atomic condensates

Atomic BEC		Polariton condensate
❖ Very low density, many body effect less important.	→	❖ High polariton density, many body effect is very important.
❖ Micro-kelvin transition temperatures.	→	❖ High transition temperatures (RT) due to small mass and high density.
❖ Long lived equilibrium state.	→	❖ Equilibrium state is short lived.
❖ Compact applications difficult to achieve.	→	❖ Compact and practical light source is more feasible.

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Room temperature condensate in GaN system

GaN system

❖ Large exciton binding energy (28meV)
    ❖ stable polariton at room temperature.

❖ Large dipole moment leads to large Rabi frequency (50meV).

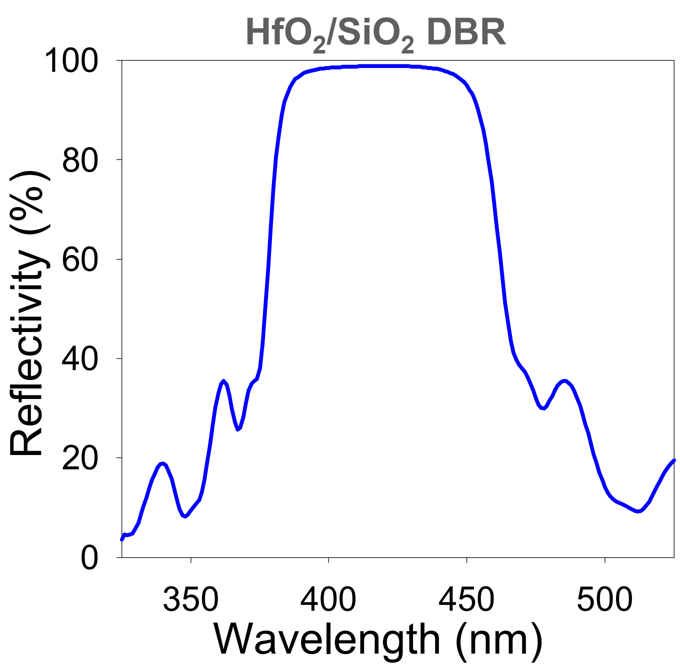
❖ High Mott density (2×10^{19} cm^{-3}).

❖ Sandia has considerable GaN research experience
    ❖ three GaN MOCVD reactors
    ❖ experience with visible and UV device fabrication

❖ Previous Nitride Device work involving cavities
    ❖ HfO_2/SiO_2 DBR development for near UV reflectors (350 – 450nm)
    ❖ InGaN photonic crystal LED program

$$T_c = \left(\frac{n}{\zeta(3/2)} \right)^{2/3} \frac{h^2}{2\pi m k_B}$$

n is the particle density
m is the mass of boson
h is the Planck's constant
k_B is the Boltzmann constant
ζ is the Rieman zeta function $\zeta(3/2)$~2.6124



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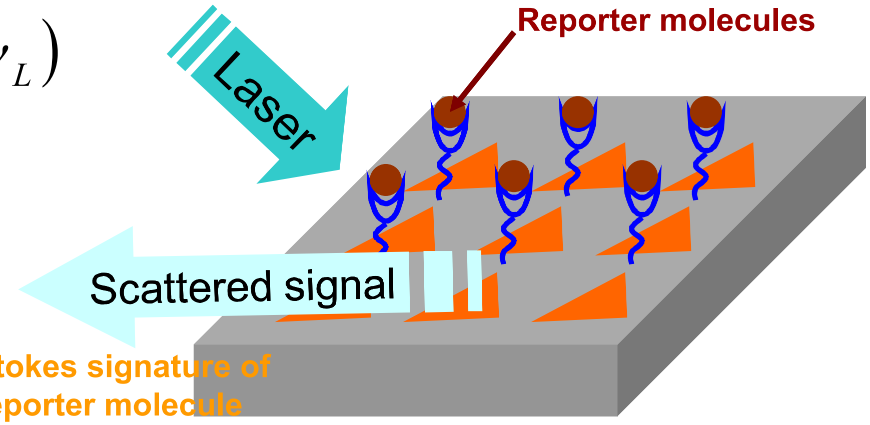
Plasmonics: SERS

Plasmonics:
Electromagnetic field concentrator free-space to nano-scales (not limited by diffraction)

$$S_{Raman}(\nu_s) = N\sigma_{Raman}\left|A(\nu_L)\right|^2\left|A(\nu_S)\right|^2 I(\nu_L)$$

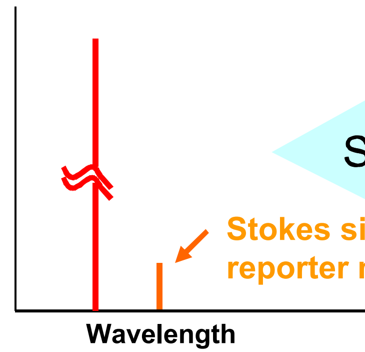


Standard Raman

$A(\nu_L) = A(\nu_S) = 1$

$\sigma_{Raman} = 10^{-31} cm^2$

$S_{Raman} = 1$ au



Giant plasmonic enhancement effect

- Local field enhancement from LSPR.
- Chemical effect also can contribute to enhancement.

$$A(\nu_L) = \frac{E_M}{E_0} = \frac{\varepsilon(\nu_L) - \varepsilon_m}{\varepsilon(\nu_L) + 2\varepsilon_m}\left(\frac{r}{r+d}\right)^3$$

$$A(\nu_L) \sim 10^4$$

Enhanced Raman

$A(\nu_L) = A(\nu_S) = 10^4$

$\sigma_{Raman} = 10^{-31} cm^2$

$S_{Raman} = 10^{16}$ au

Single molecule detection enhancement factor of 10^{14} is required.

Issues:

Reproducible preparation.
Optimized metallic particle array and geometry.
Low fabrication cost and scaleable to volume production.

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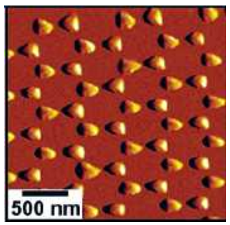
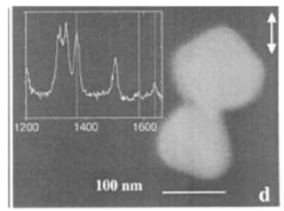
Plasmonics particle design

Status quo:

- Large enhancement factor 10^{14} observed only in nanoparticle aggregates.
- Difficult to reproduce results.





- Difficult to achieve high packing density.

Conventional wisdoms:

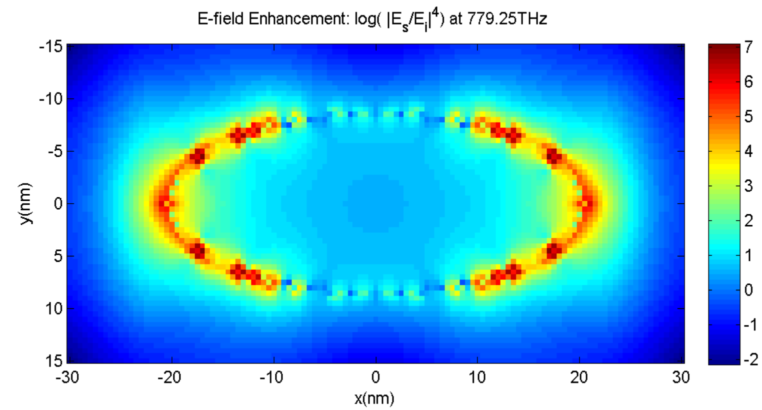
- Particles with sharp points are better.
- Rely on dipole resonance.
- Quest of single particle enhancement of 10^{14}.

Reality:

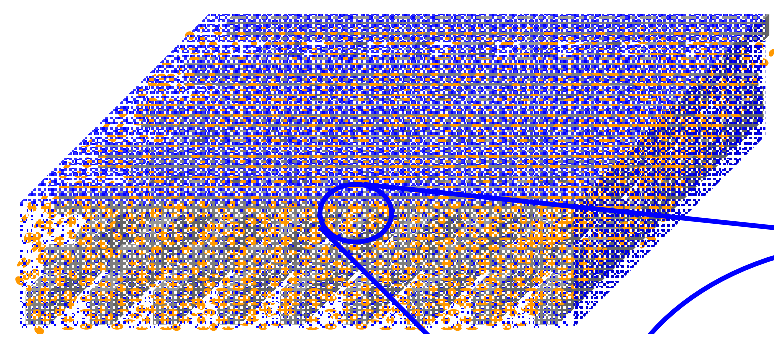
- Space charge limitation prevents high fields.
- Top down fabrication cannot produce particles sharper than few tens nanometers.
- Quest of single particle enhancement of 10^{14} unrealistic, leads to blinking, photochemical degradation.

New approach:

- Use multi-stage field enhancement.
- Use multi-pole field to enlarge high field region and broaden the plasmon resonance.



- Use photonic crystal to increase packing density.



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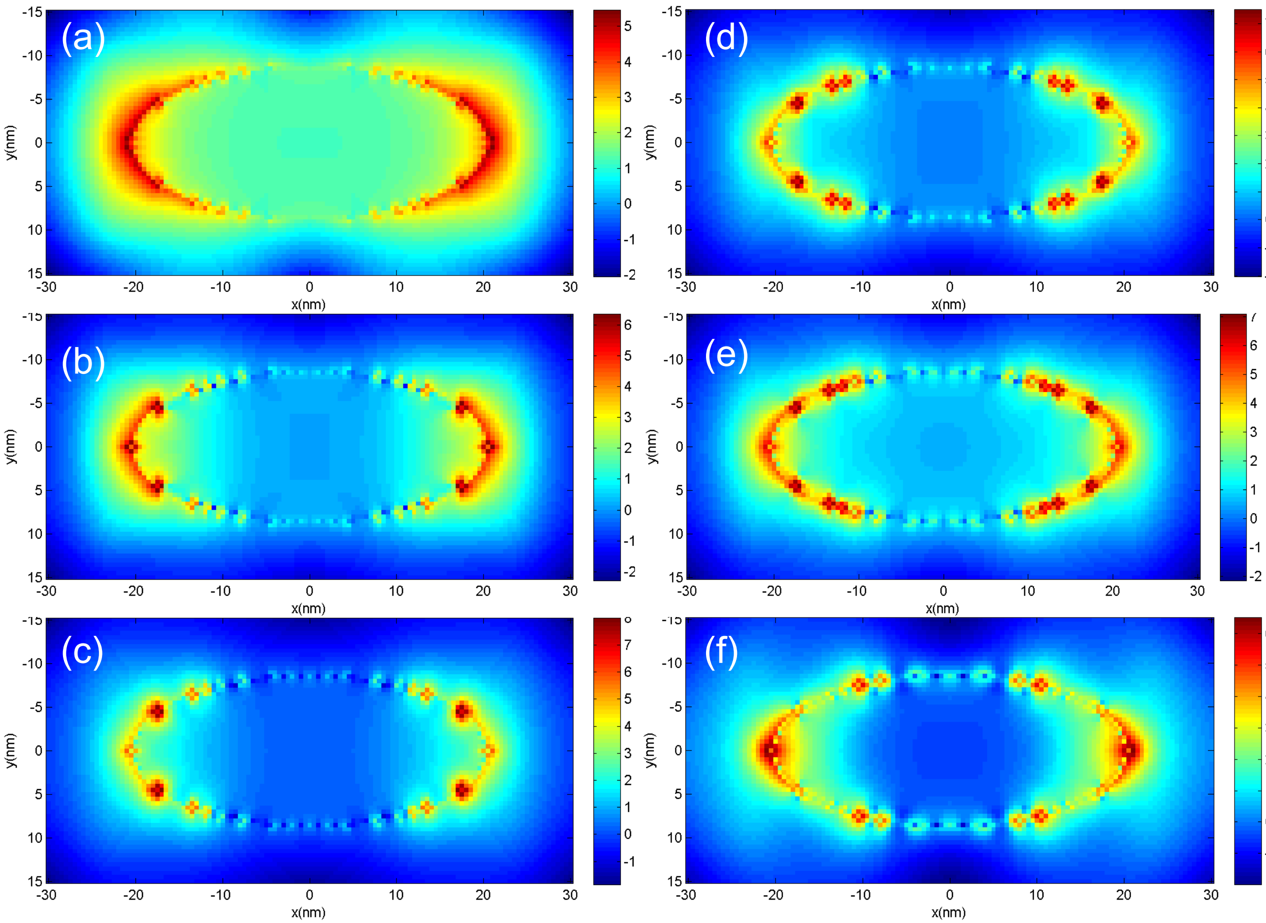
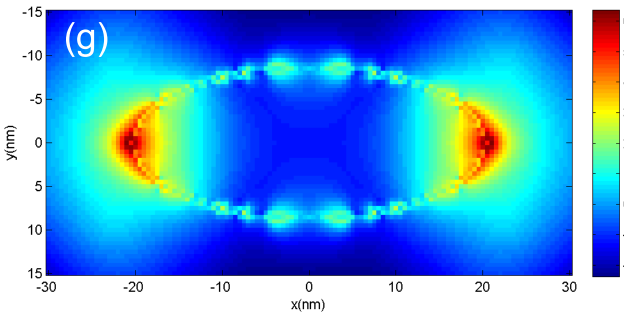
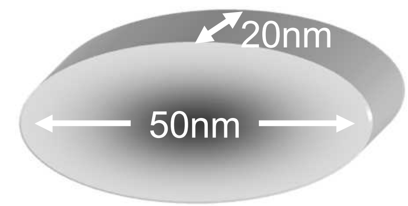
Plasmonics particle design: elliptical particles







A: 614 THz
B: 719 THz
C: 749 THz
D: 764 THz
E: 779 THz
F: 854 THz
G: 899 THz

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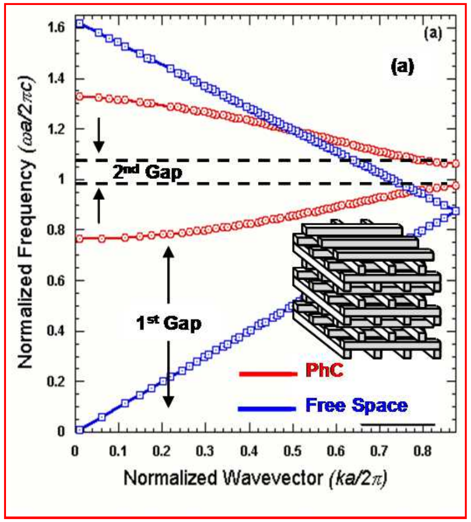
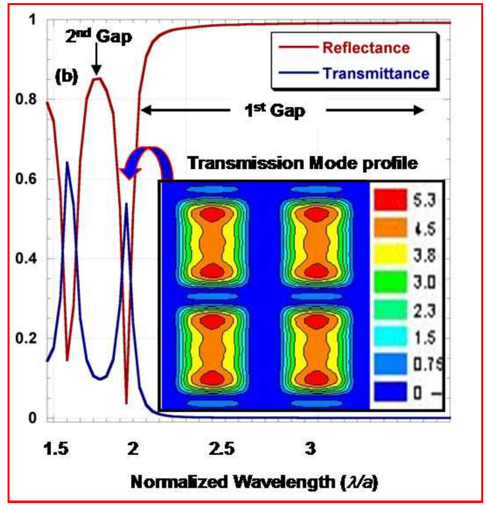
Multi-stage field enhancement

10^2-10^3 gain in enhancement factor due to strong internal field

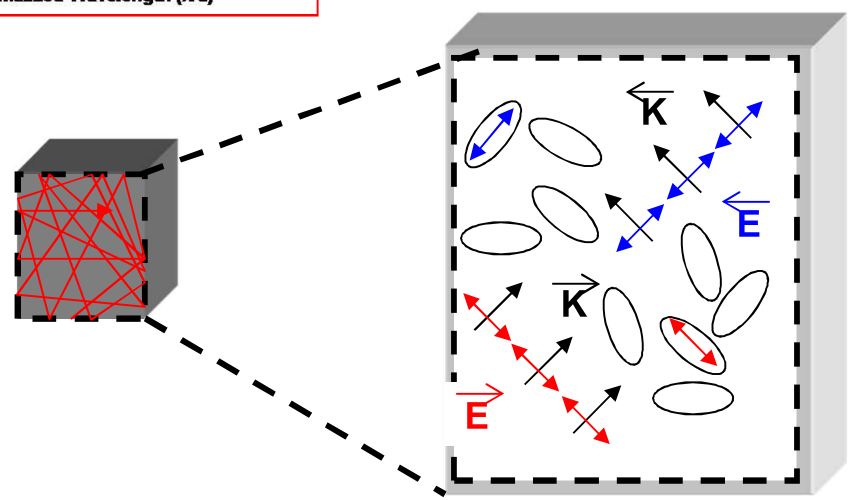




- Electromagnetic radiation is squeezed into the narrow air passages.
- Acts like a metallic cavity.

- The increased photonic DOS amplifies the field at the band-edges.

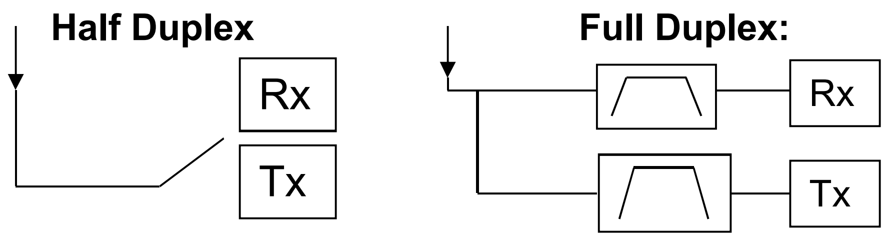
- Aerogel support these particles to achieve areal density of 10^2
- Particle alignment is not necessary.



Total realistic average enhancement factor = $10^7 . 10^3 .10^2 = 10^{12}$

Acoustic Bandgap Crystals:
Why, What, and How?

❖ **Motivation: Telecom (the why):**

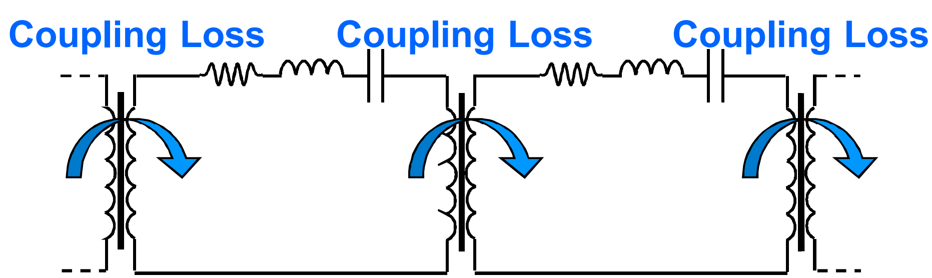


Requires:

⇒ **High resolution steep filtering**

⇒ **High figure of merit Q≈1000-2000**

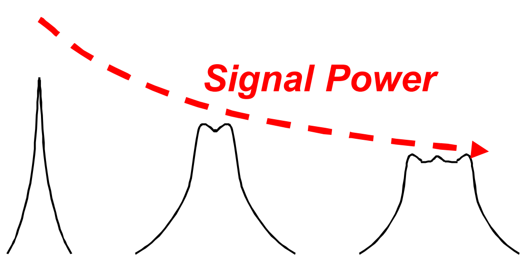
Electro-Acoustic Coupling Losses:



Why not Digital Signal Processing:

Requires high power at high frequencies.

Low resolution ADC



Analogue Signal Processing:

Cascaded insertion losses imply that once we are in the acoustic domain we would like to remain in it!

Acoustic Signal Processing

⇒ ***Phononic Crystals***

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Acoustic Bandgap Crystals Fundamentals

What is a Phononic Crystal?

A phononic crystal is a material which exhibits stop bands for phonons, thus preventing phonons of selected ranges of frequencies from being transmitted through the material.

How does it work?

- Created: by superposing Mie and Bragg resonant scattering by a periodic arrangement in a lattice.
- Requires: sufficient acoustic impedance mismatch.
- Topology: cermet topology (disconnected) of high density inclusions in a low density background matrix.
- Awards: full 3D scalable macro-to-micro control of phonon distribution.

$$\frac{\text{Speed of sound}}{\text{Speed of light}} = \frac{1}{52000}$$

Miniaturization of

- Filters
- Delay Lines
- Phase Shifters
- Acoustic Signal Processing
- Power Combiners/Dividers

Novel applications:

- **Thermal energy harvesting**
- **Johnson Noise Shielding**
- **Rapid accelerated circuitry cooling**
- **Modifying the global heat capacity.**

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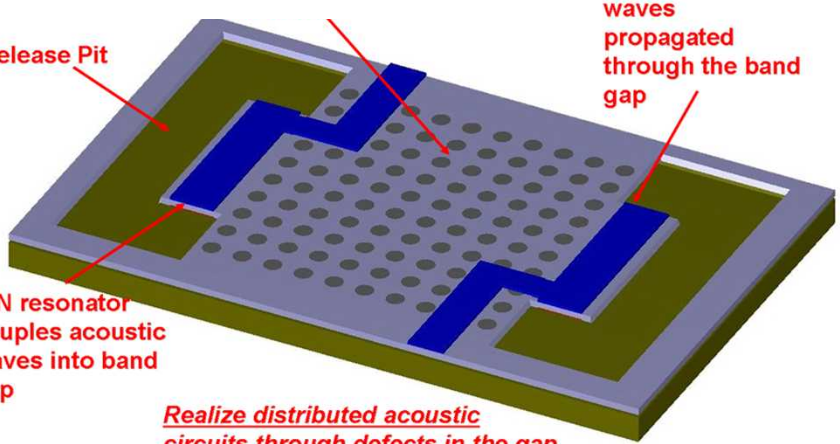
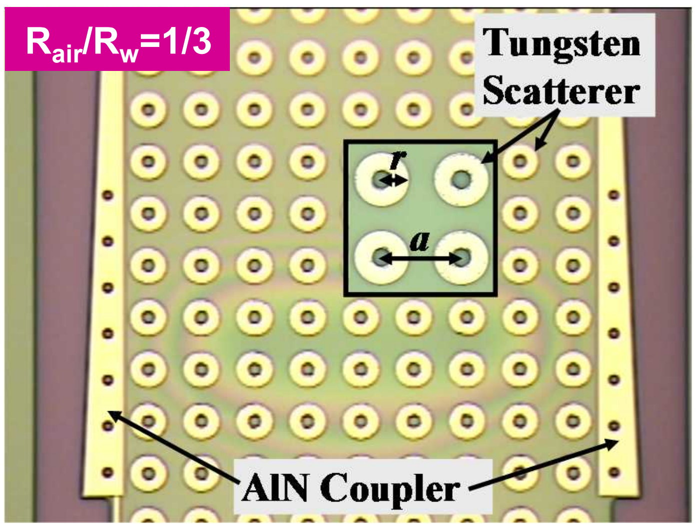
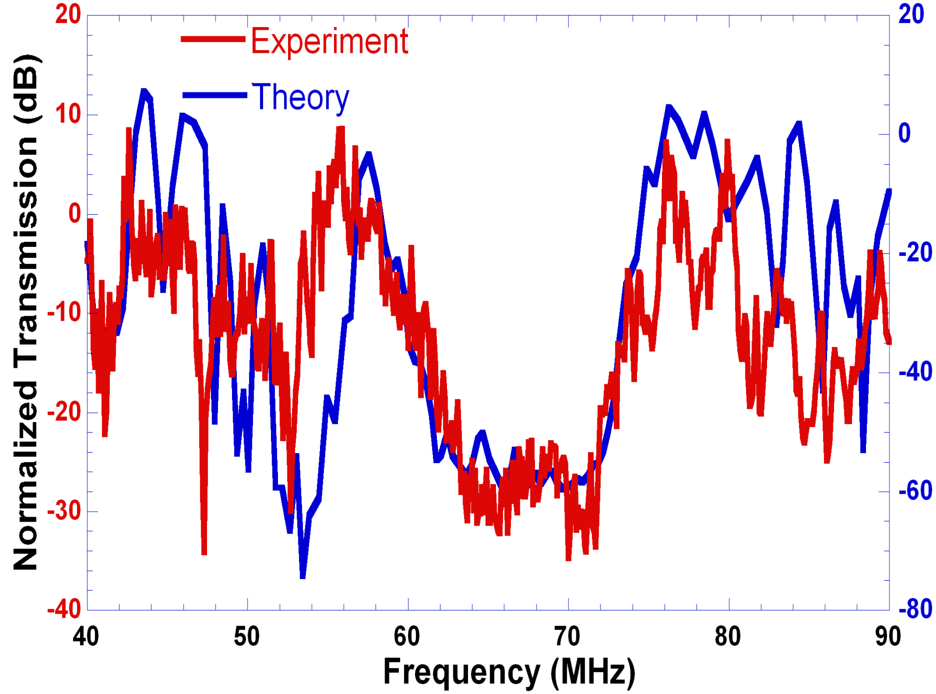
First Acoustic Bandgap Crystals (60-70MHz)





Theory Vs Experiment



Freq	Radius "r"	Pitch "a"	Phonon Temp "T"
10GHz	250nm	500nm	0.5K
100GHz	25nm	50nm	5K
0.5 THz	5nm	10nm	25K
1THz	2.5nm	5nm	50K

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Summary

- Photonic crystal is a good platform to control electromagnetic field.
- Modification of radiative properties of quantum emitters.
- Field concentrate from micro- to nano- scale lengths.
- Knowledge gained lend insights to phonon control.

End

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