SAND2010-5397C

Mid-infrared surface plasmon coupled emitters utilizing intersublevel transitions in InAs quantum dots

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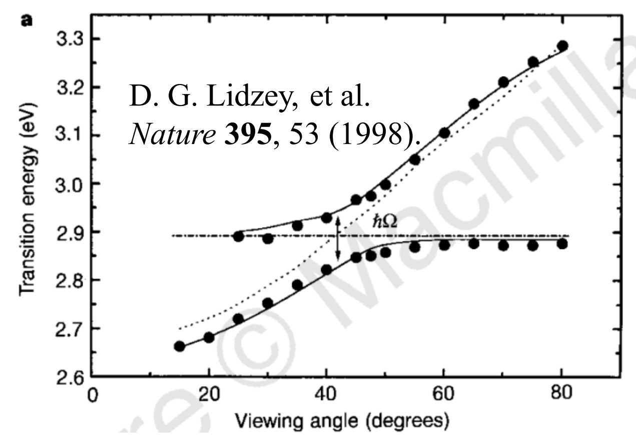
Background to Rabi Splitting

What is Rabi Splitting?

- **evidence of Rabi oscillation which manifests as an anti-crossing behavior from the mixing of exciton and photon modes. (indication of strong coupling)**



Why is Rabi Splitting important?

- **strong coupling between radiation and active media can lead to new functionalities in LEDs, lasers, and photodetectors.**

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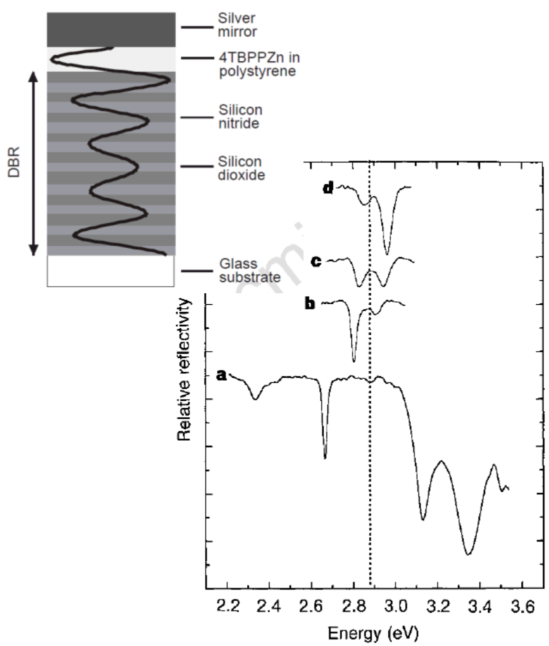
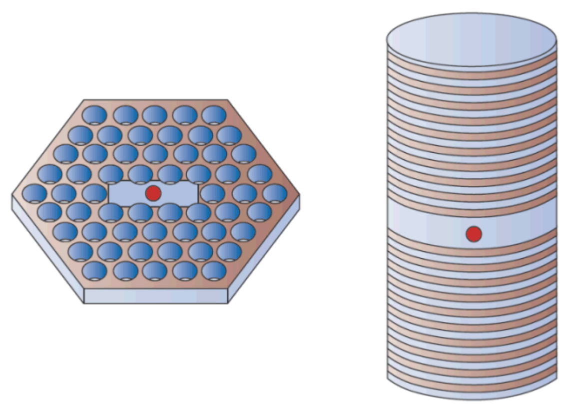
Observation of Rabi Splitting

Organic Semiconductors in Microcavities



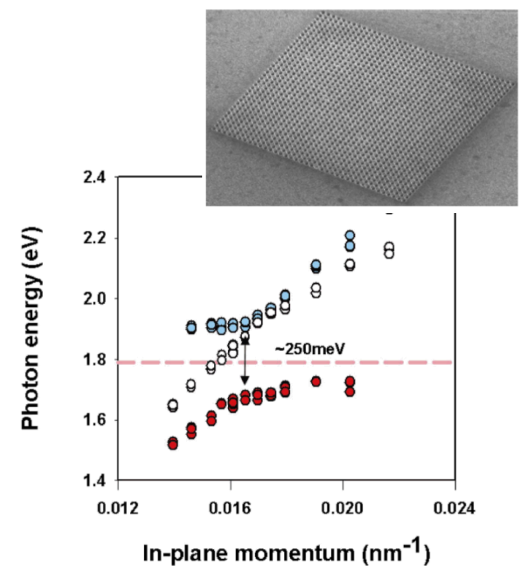
D. G. Lidzey, et al. *Nature* **395**, 53 (1998).

QWs and QDs in Microcavities



G. Khitrova, et al. *Nature Phys* **2**, 81 (2006).

Organic Molecules Interacting with Surface Plasmons



J. Dintinger, *Phys. Rev. B* **71**, 035424 (2005).

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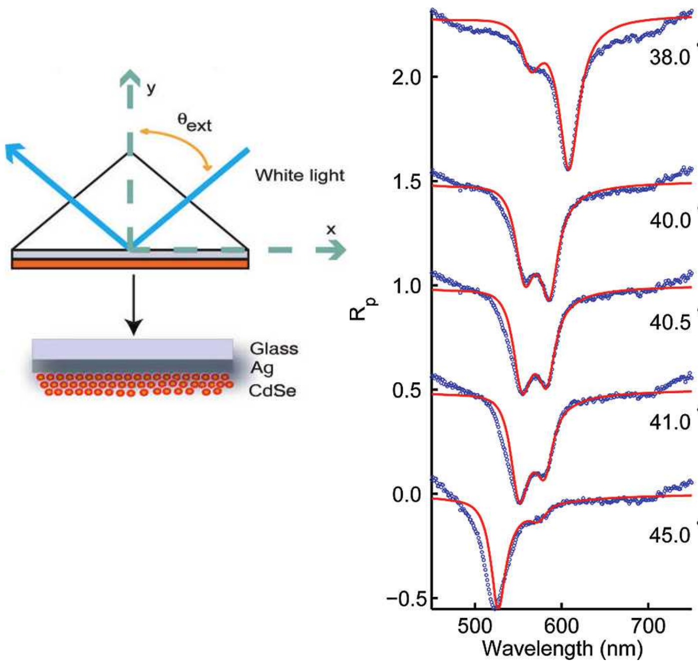
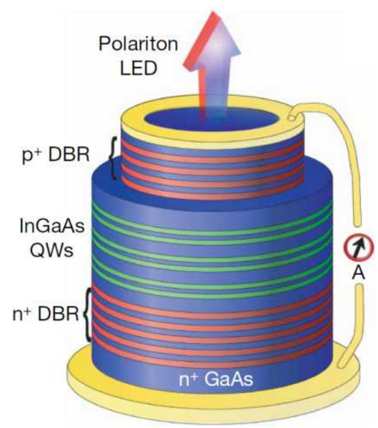
Observation of Rabi Splitting

Surface Plasmons and Nanocrystals



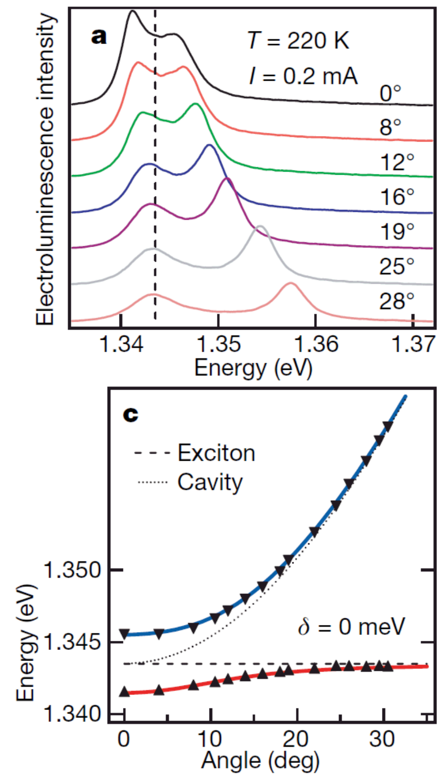
D.E. Gomez, et al. *Nano Letters* **10**, 274 (2010).

Surface Plasmons and Nanocrystals



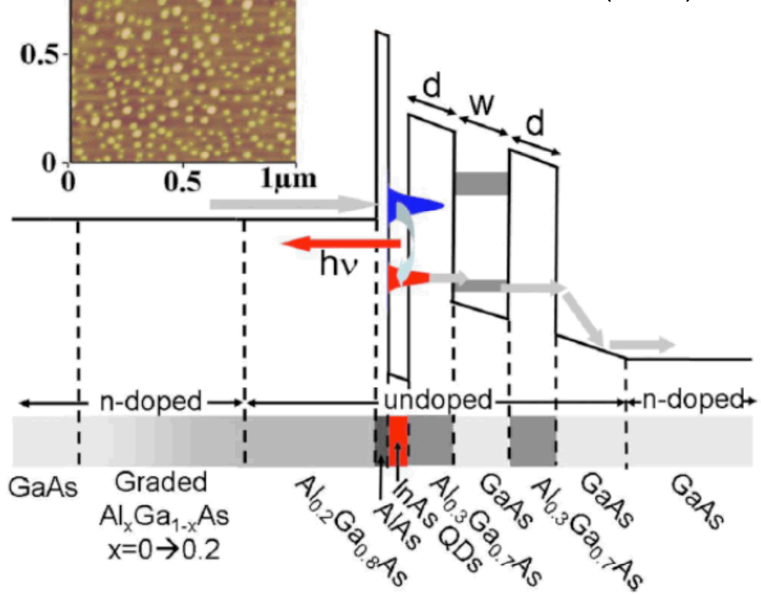
S.I. Tsintzos, et al. *Nature Letters* **453**, 372 (2008).

S.I. Tsintzos, et al. *APL* **94**, 071109 (2009).



Structure Design

D. Wasserman, et al., APL **94**, 61101 (2009).



- Grown by MBE
- Similar carrier dynamics to a QCL
- Electrons are injected into the conduction band
- Electrons relax and emit photons
- Electrons in the ground state of the QDs tunnel to the adjacent well and are collected

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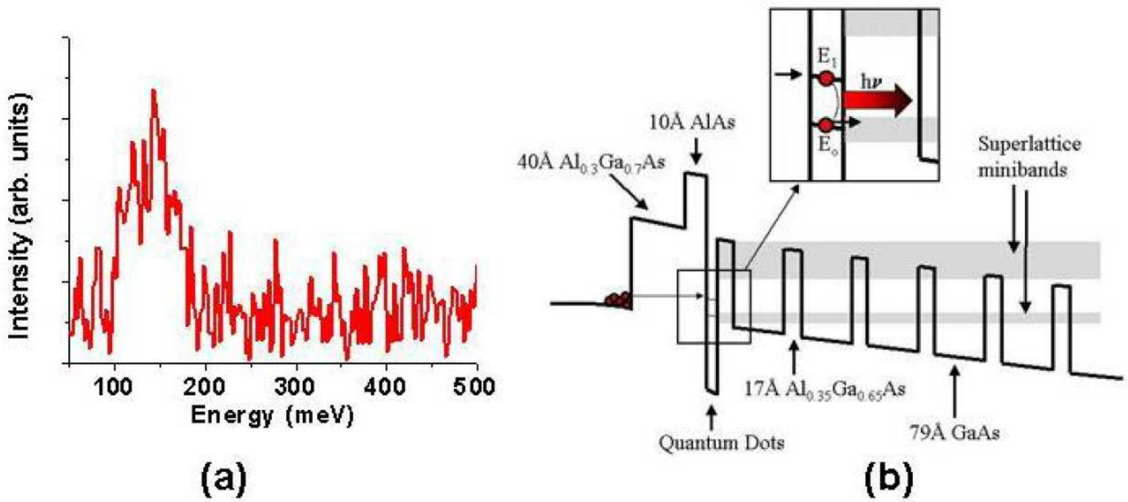
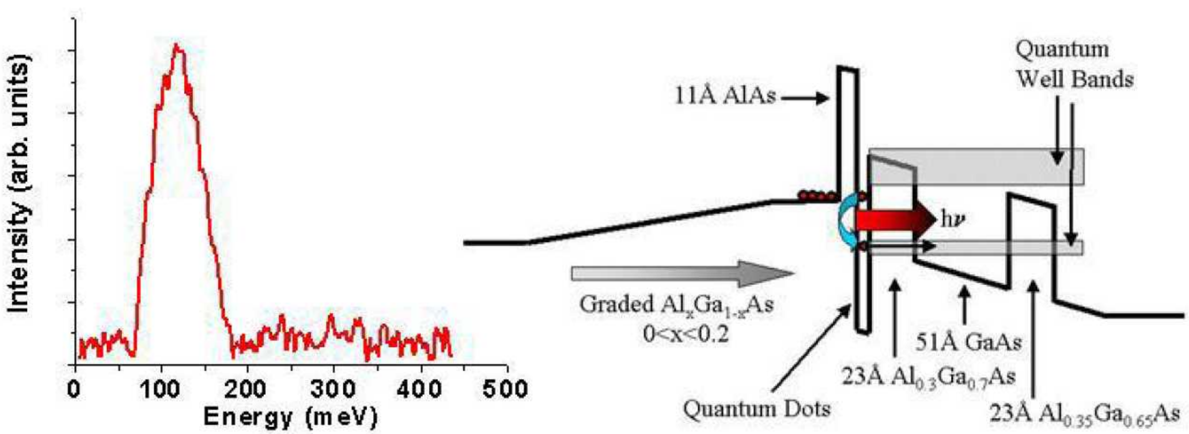
InAs Quantum Dot Active Material

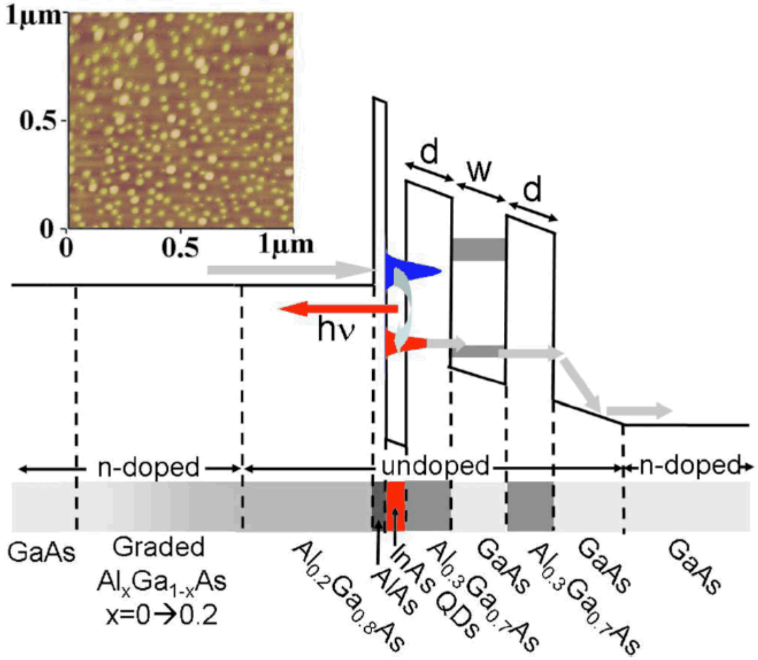


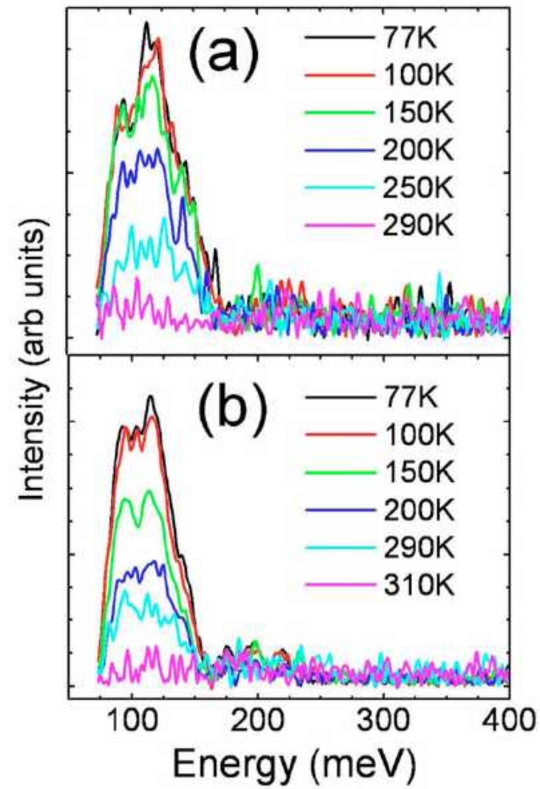
APL 81, 2848, 2002



SPIE 63860E, 2006

InAs Quantum Dot Active Material





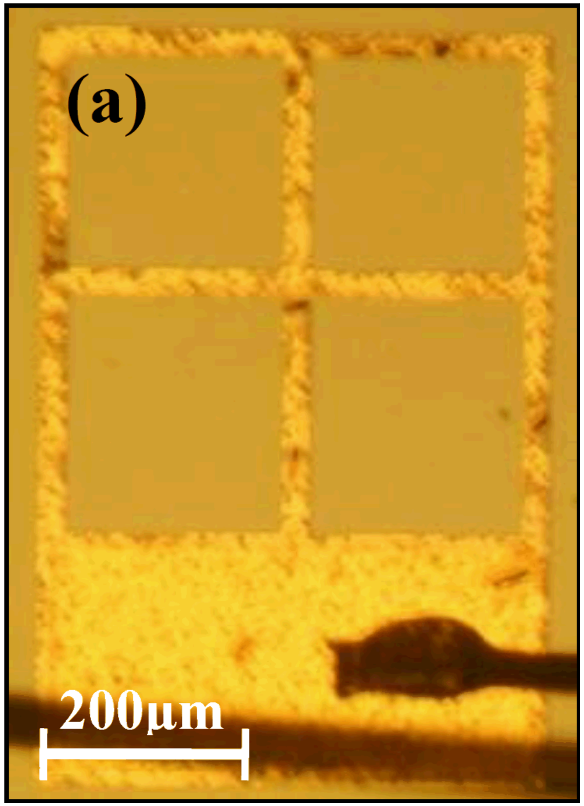
Room temperature midinfrared electroluminescence from InAs quantum dots

D. Wasserman,[1,a)] T. Ribaudo,[1] S. A. Lyon,[2] S. K. Lyo,[3] and E. A. Shaner[3]

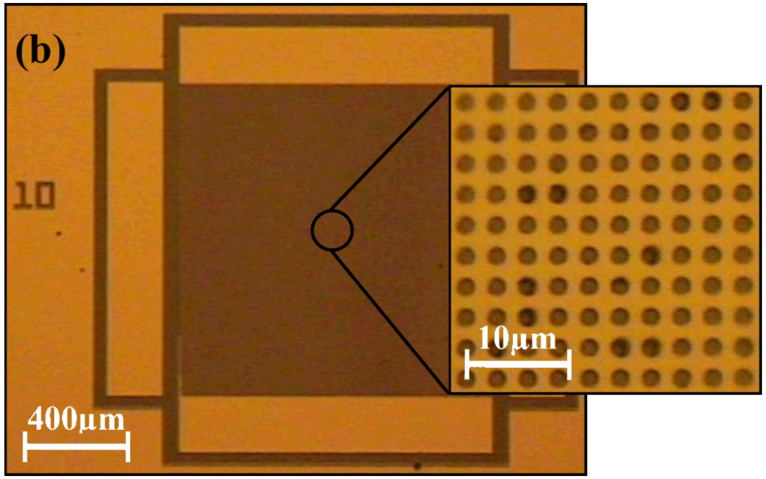
APL 94,061101 (2009)

Plasmonic Mesh Design

Window Contact



Mesh Contact



Resonant Wavelength (µm)	Diameter (µm)	Pitch (µm)
9	1.4	2.8
10	1.5	3.0
11	1.6	3.3
12	1.8	3.6

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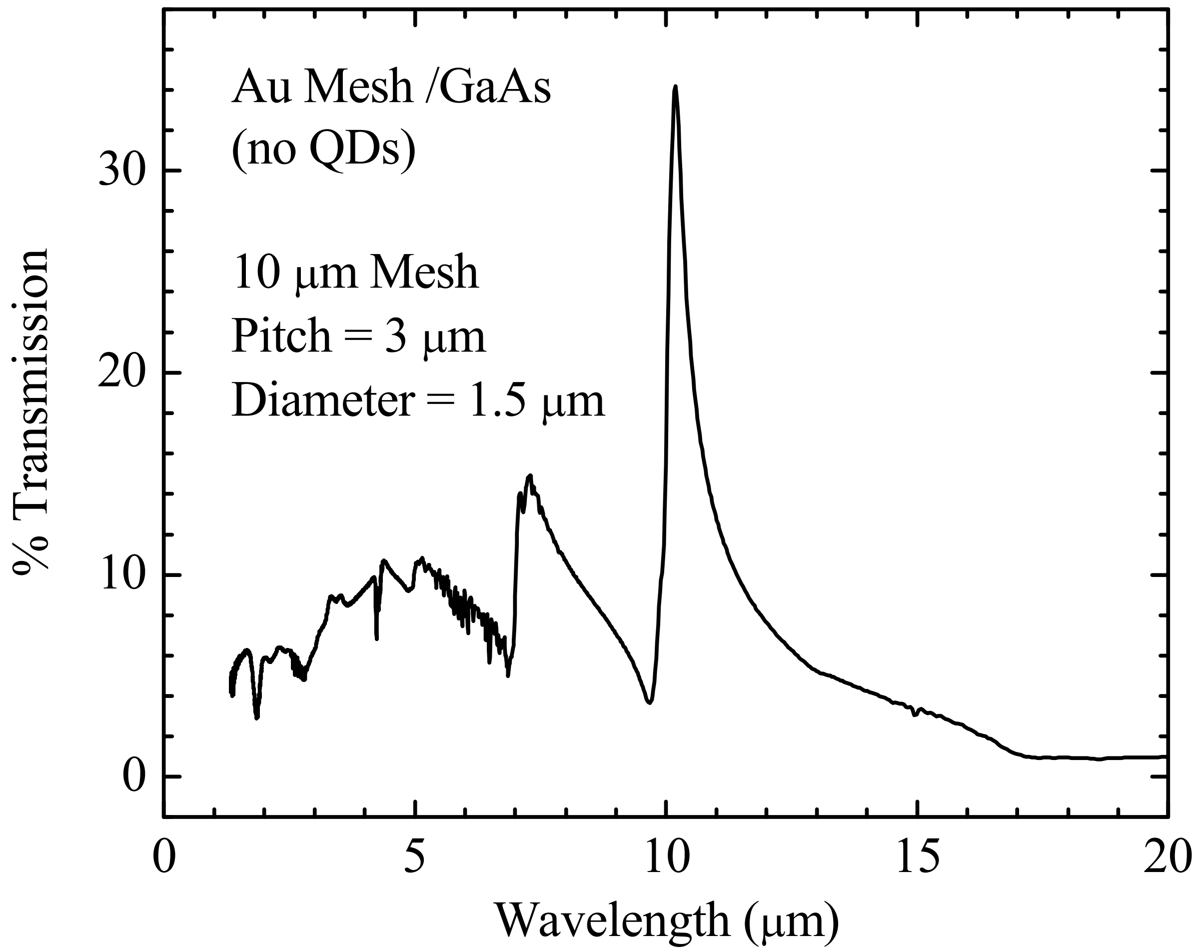
Extraordinary Optical Transmission



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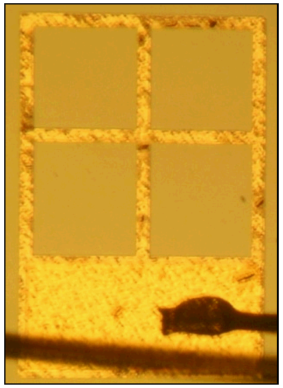
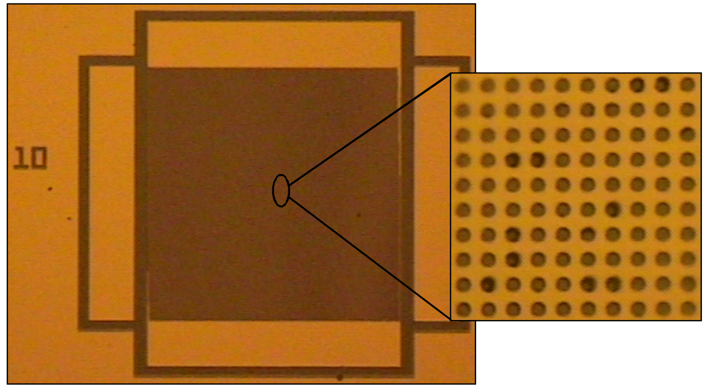
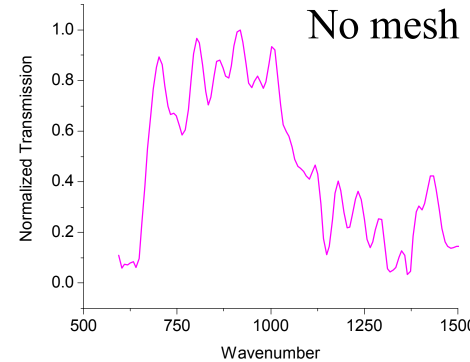
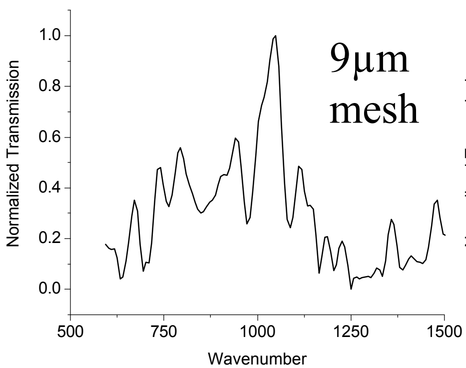
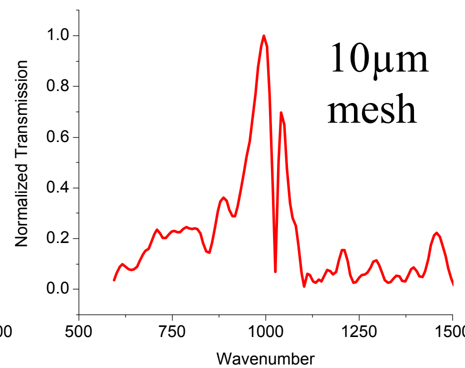
Active mid-IR material + plasmonic structure

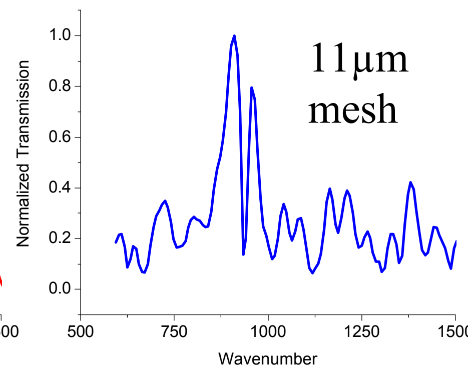


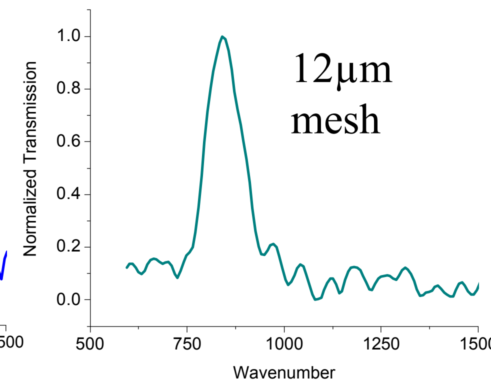






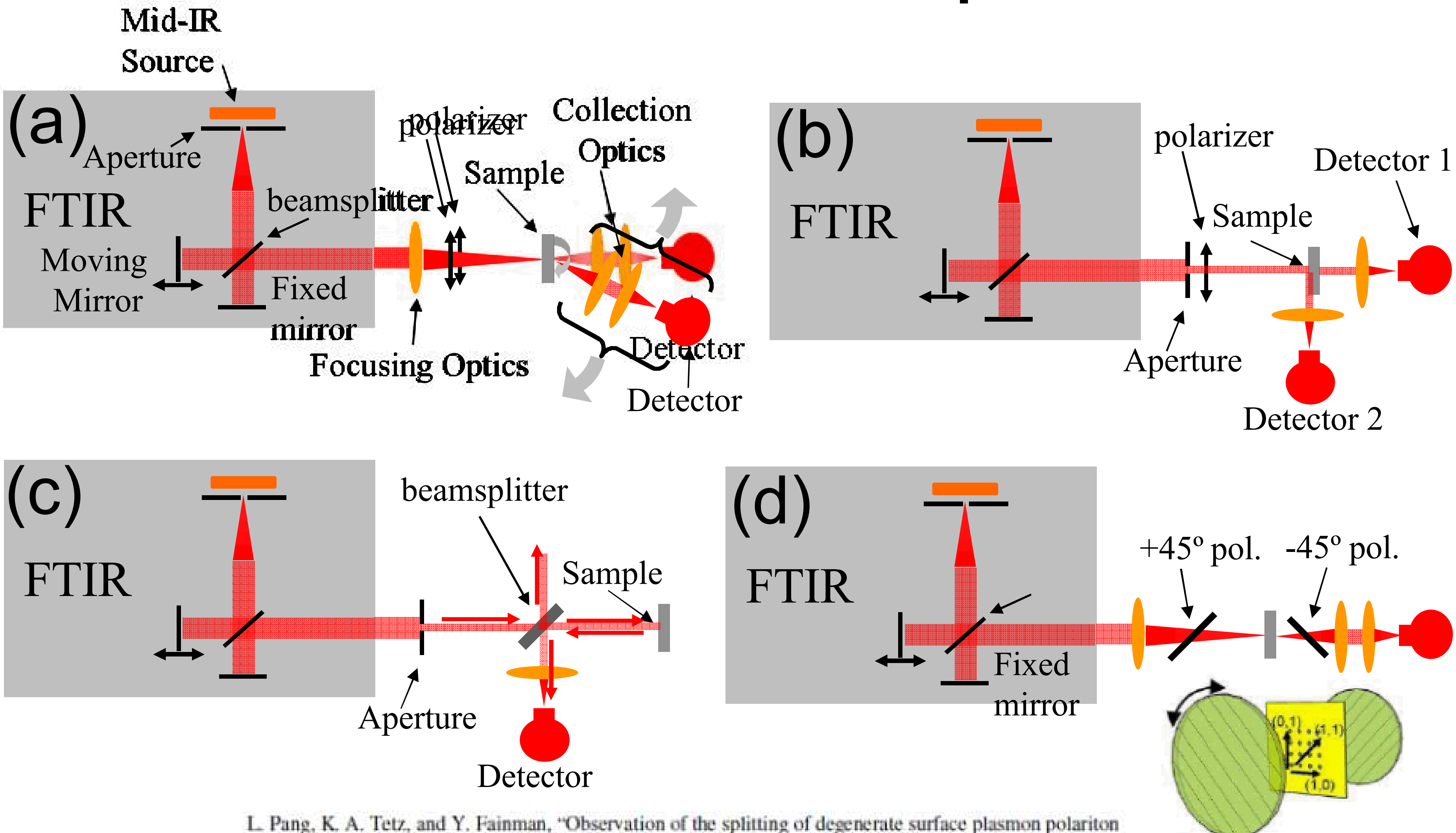






More than just filtering…

Spatial and Spectral Investigations: Experimental Set-Ups



L. Pang, K. A. Tetz, and Y. Fainman, "Observation of the splitting of degenerate surface plasmon polariton modes in a two-dimensional metallic nanohole array," Appl. Phys. Lett. 90, 111103 (2007).

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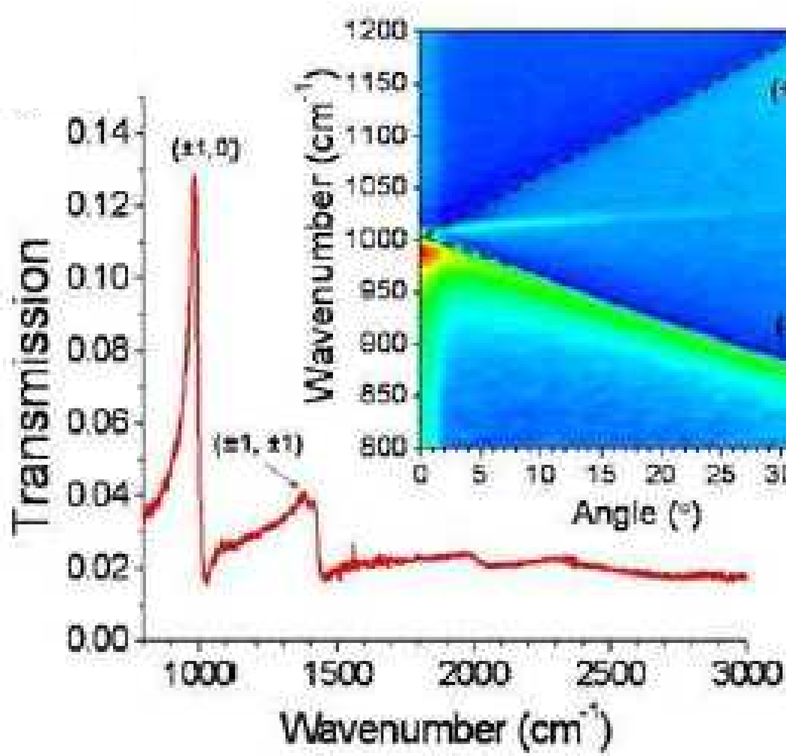
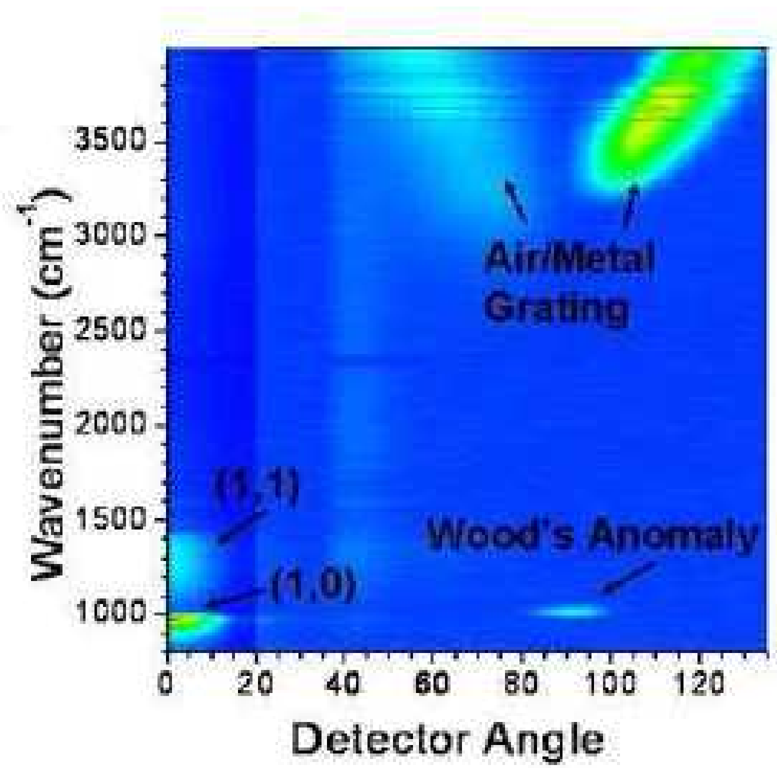
Spatial and Spectral Investigations: Doped EOT samples





Optics express 17(2):666-75, **2009**

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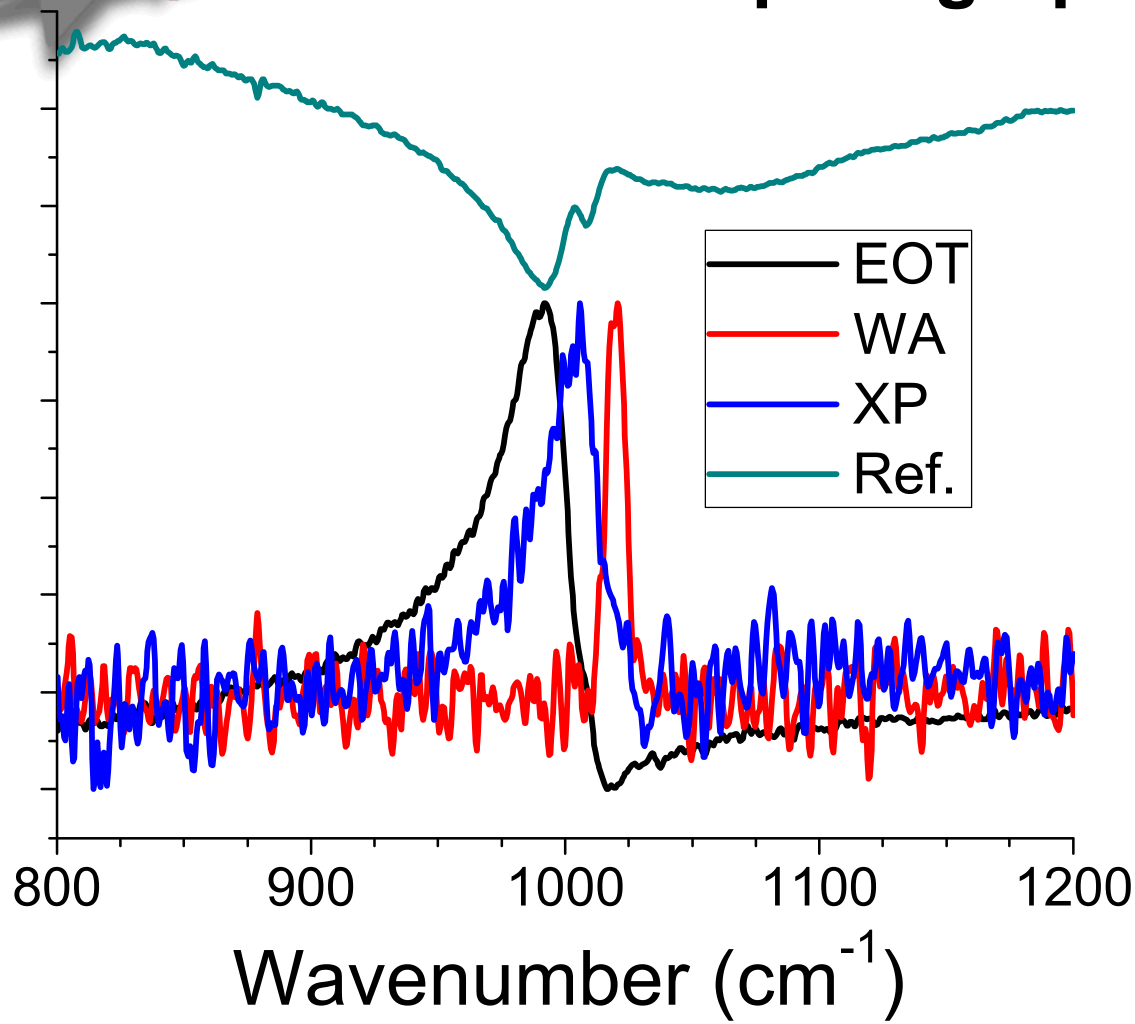
Comparing Spectra



"Loss mechanisms in mid-infrared extraordinary optical transmission gratings", T. Ribaudo, E.A. Shaner, K. Freitas, J.G. Cederberg, D. Wasserman, *Opt. Express* **17** 666 (2009).

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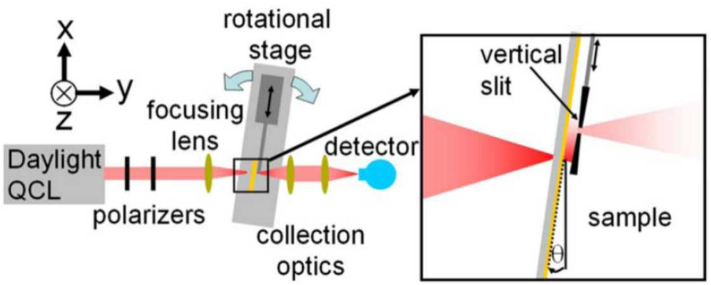
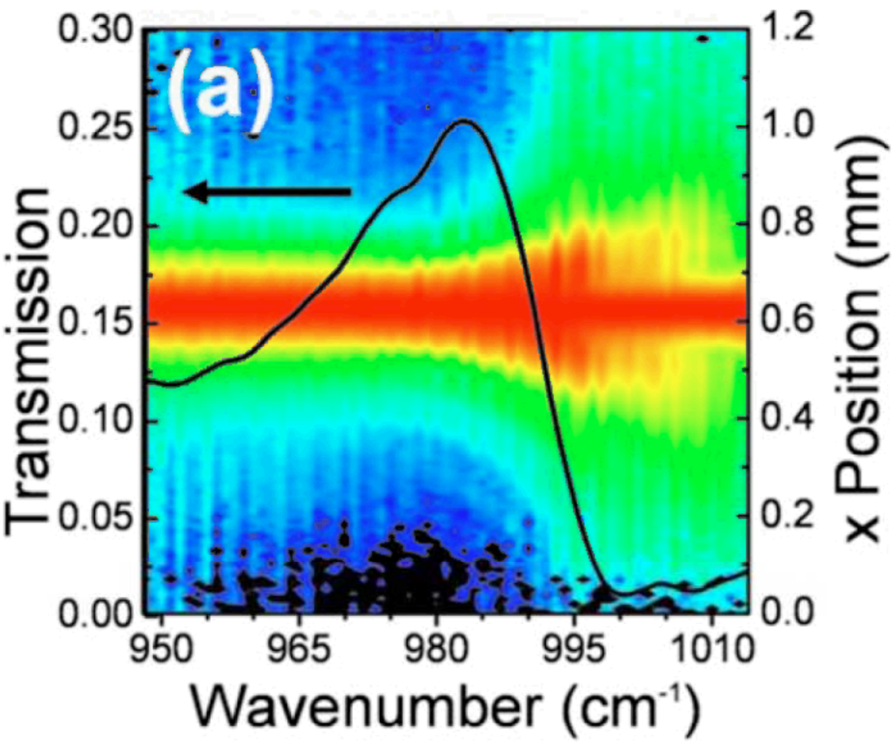
Surface Wave Propagation

Experimental setup for spatially and spectrally resolved transmission



T. Ribaudo, D. Adams, B. Passmore, E. Shaner, D. Wasserman, APL **94**, 201109 (2009).



A contour plot of transmitted/scattered light intensity as a function of position and wavelength for horizontally polarized normally incident radiation. The black curve represents the normal incident transmission for the plasmonic mesh.

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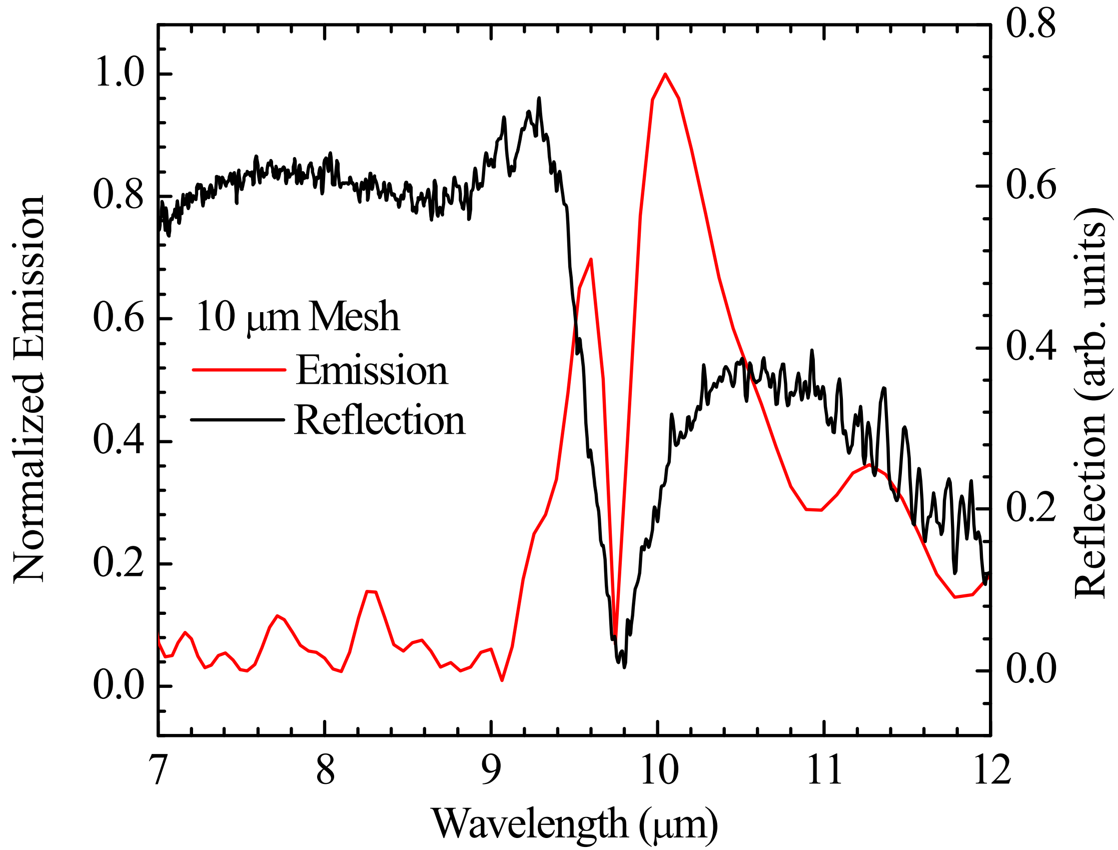
Reflection and Emission for 10 μm Mesh



The normalized emission and reflection for the 10 μm mesh design measured at 77 K. The reflection from the metal hole array was referenced to the gold surrounding the mesh.

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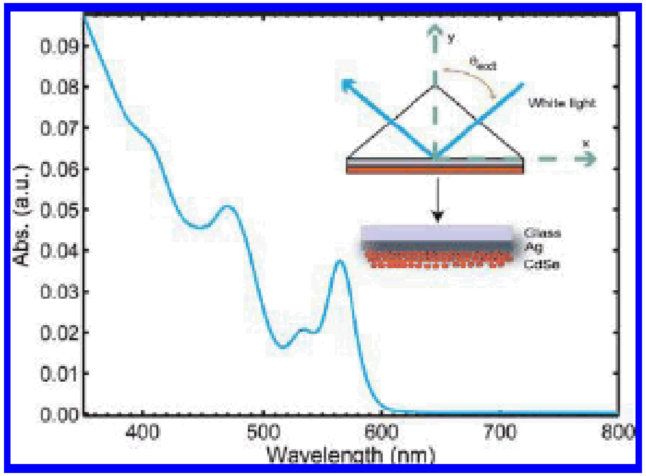
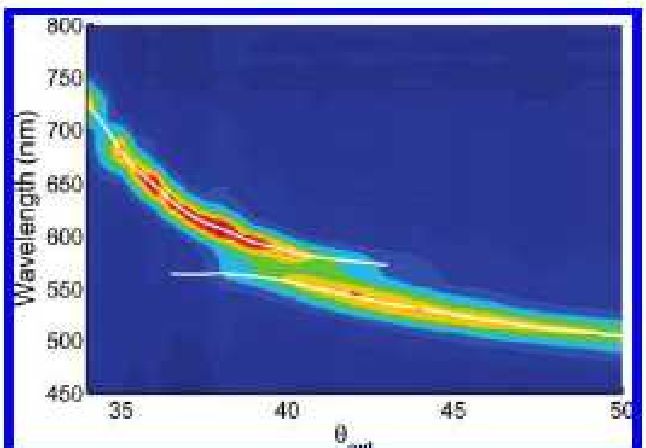
Plasmon coupling to nanocrystals

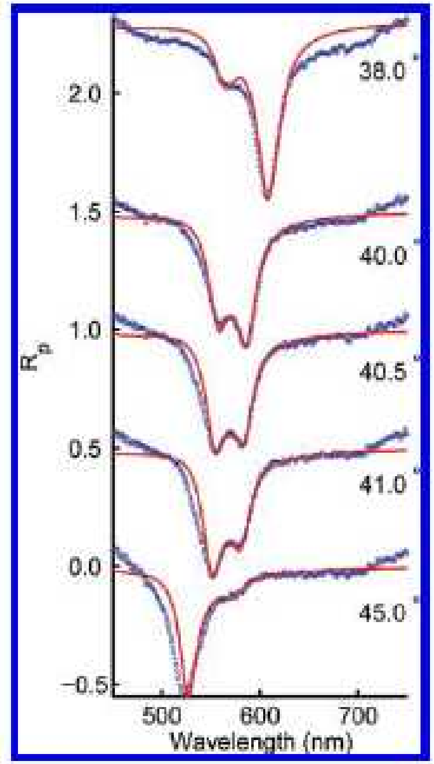
Surface Plasmon Mediated Strong Exciton−Photon Coupling in Semiconductor Nanocrystals

D. E. Gómez,[*,†,‡] K. C. Vernon,[†,‡] P. Mulvaney,[§] and T. J. Davis[†,‡]

Nanoletters 10, 274, 2010







Look at changes in reflection (absorption) as a function of angle

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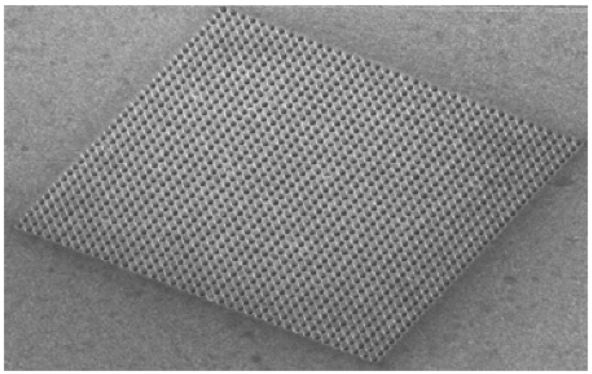
Plasmon coupling to J-aggregate

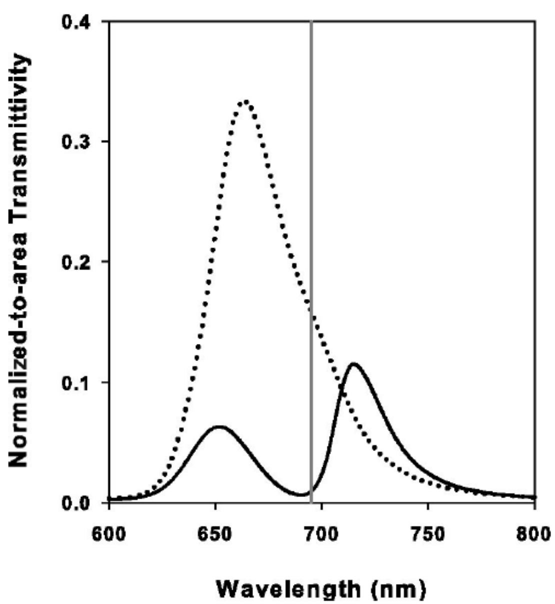
Strong coupling between surface plasmon-polaritons and organic molecules in subwavelength hole arrays

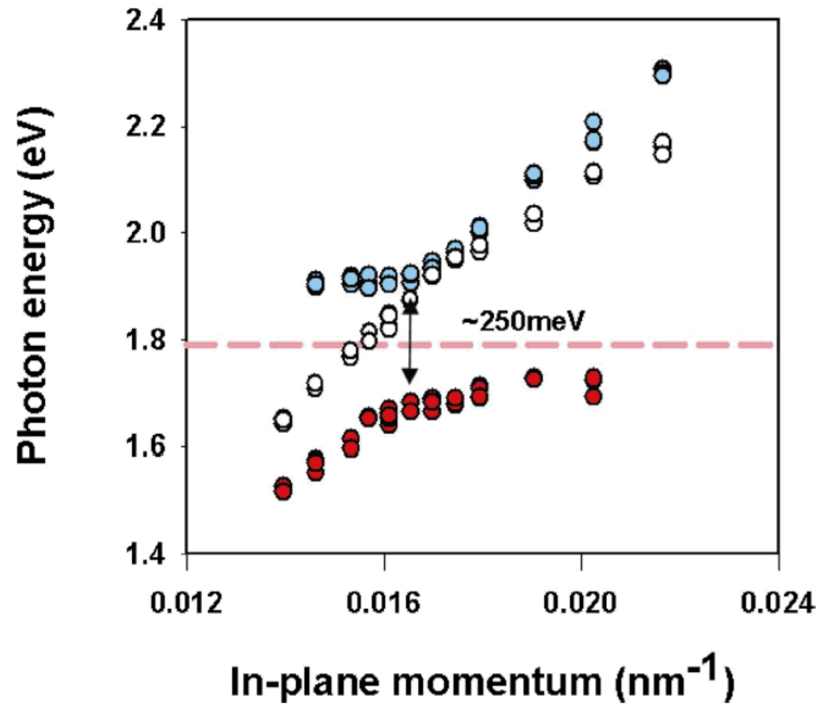
J. Dintinger,[1] S. Klein,[1,*] F. Bustos,[1,†] W. L. Barnes,[2] and T. W. Ebbesen[1,‡]

PHYSICAL REVIEW B **71**, 035424 (2005)



380 nm pitch silver hole array on quartz



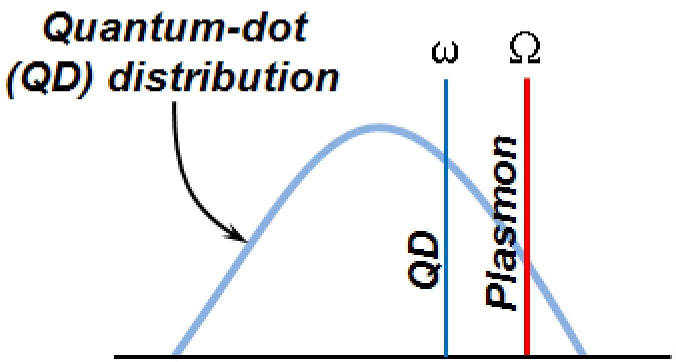


Again, varying angle allows probing of anti-crossing

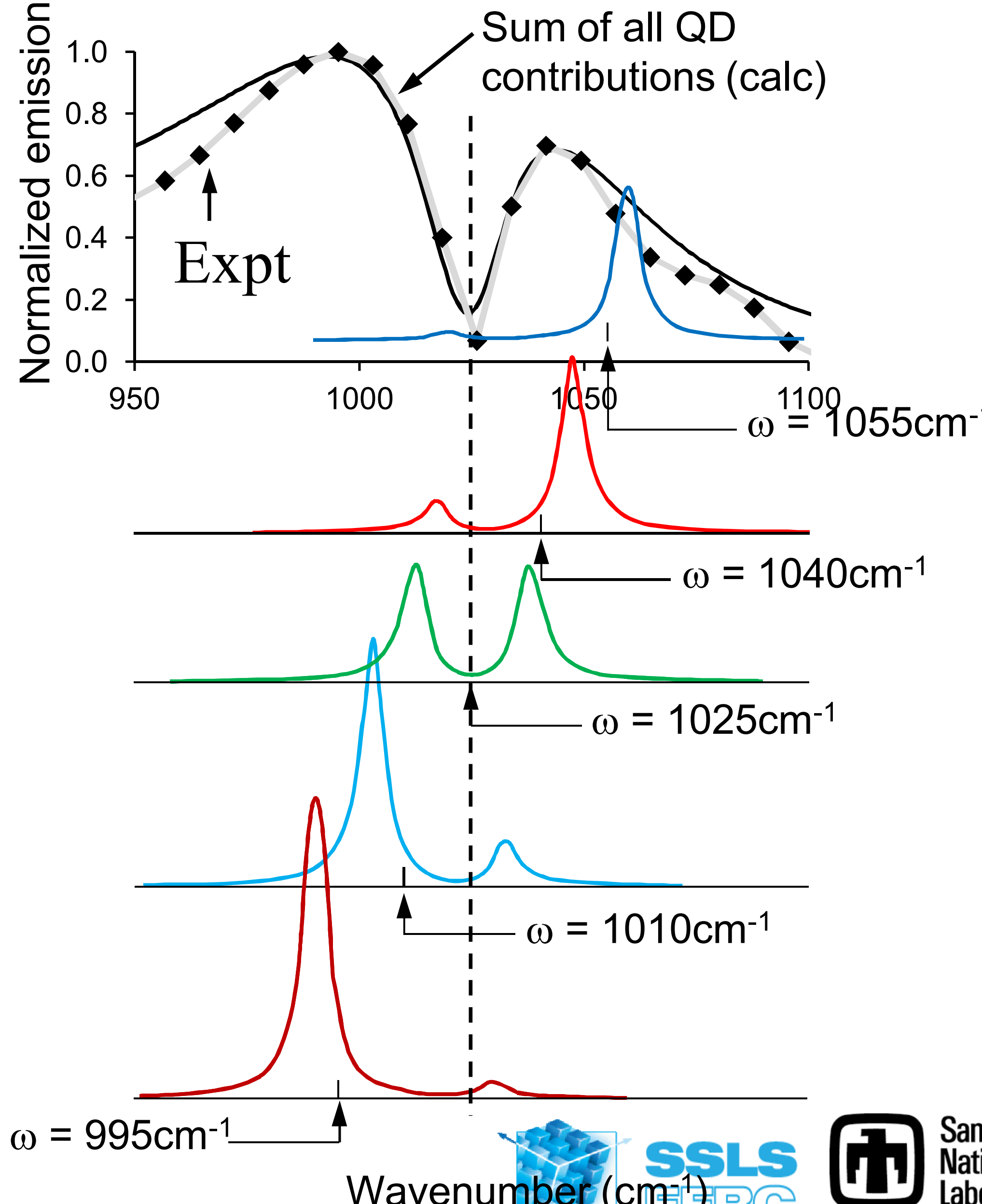
Dealing with an inhomogeneous distribution

- In emission mode, we cannot vary angle of incidence (we do not observe off-normal emission)
- Due to large inhomogenous broadened system, we cannot temperature tune to scan dot energy level through the SP state
- <u>We can model the situation and compare with experiment</u>

Quantum dot contributions to electroluminescence



$$\Omega'_R = \sqrt{\left(\wp E_p/\hbar\right)^2 + (\Omega-\omega)^2}$$



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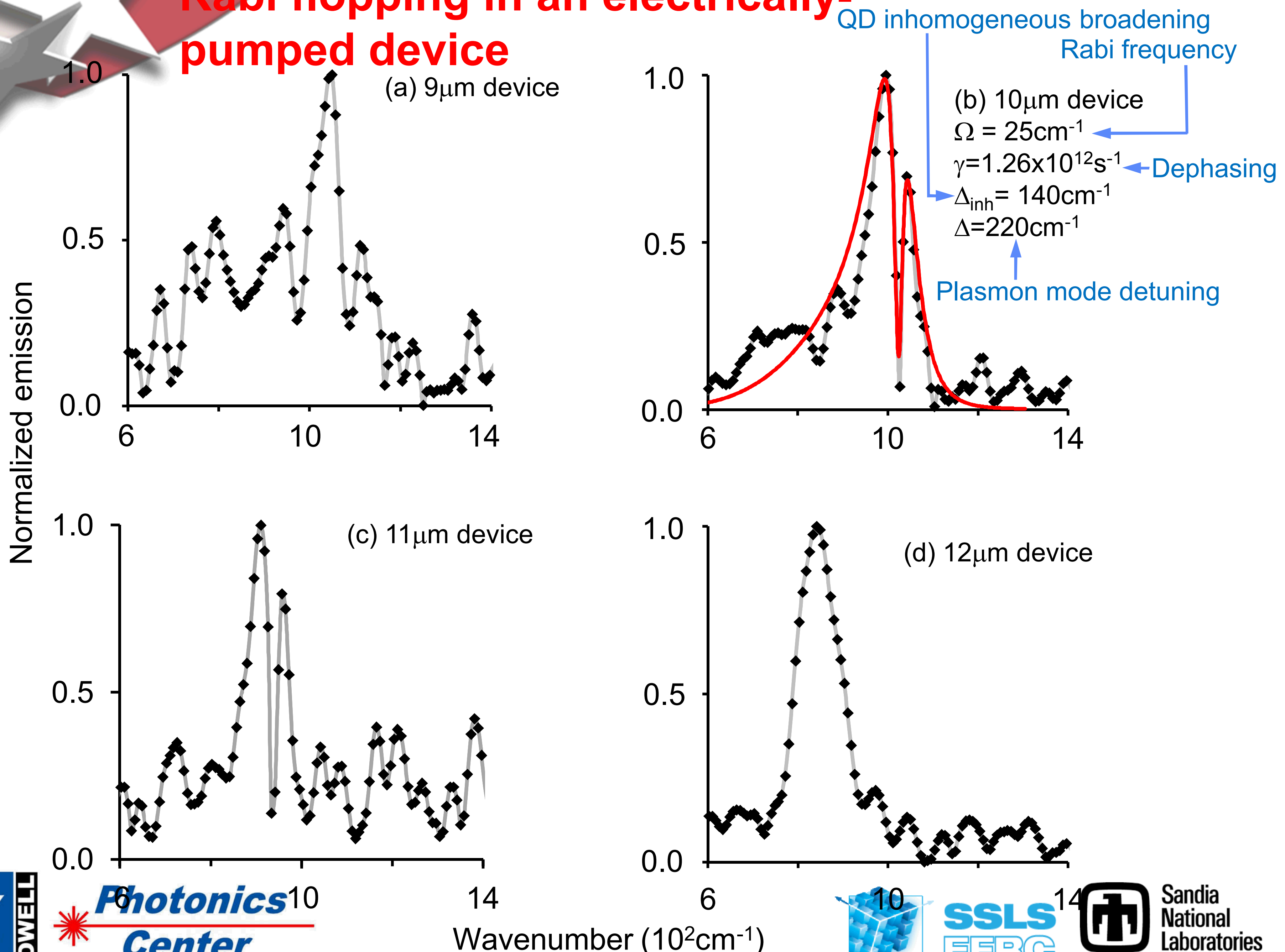
Rabi flopping in an electrically-pumped device



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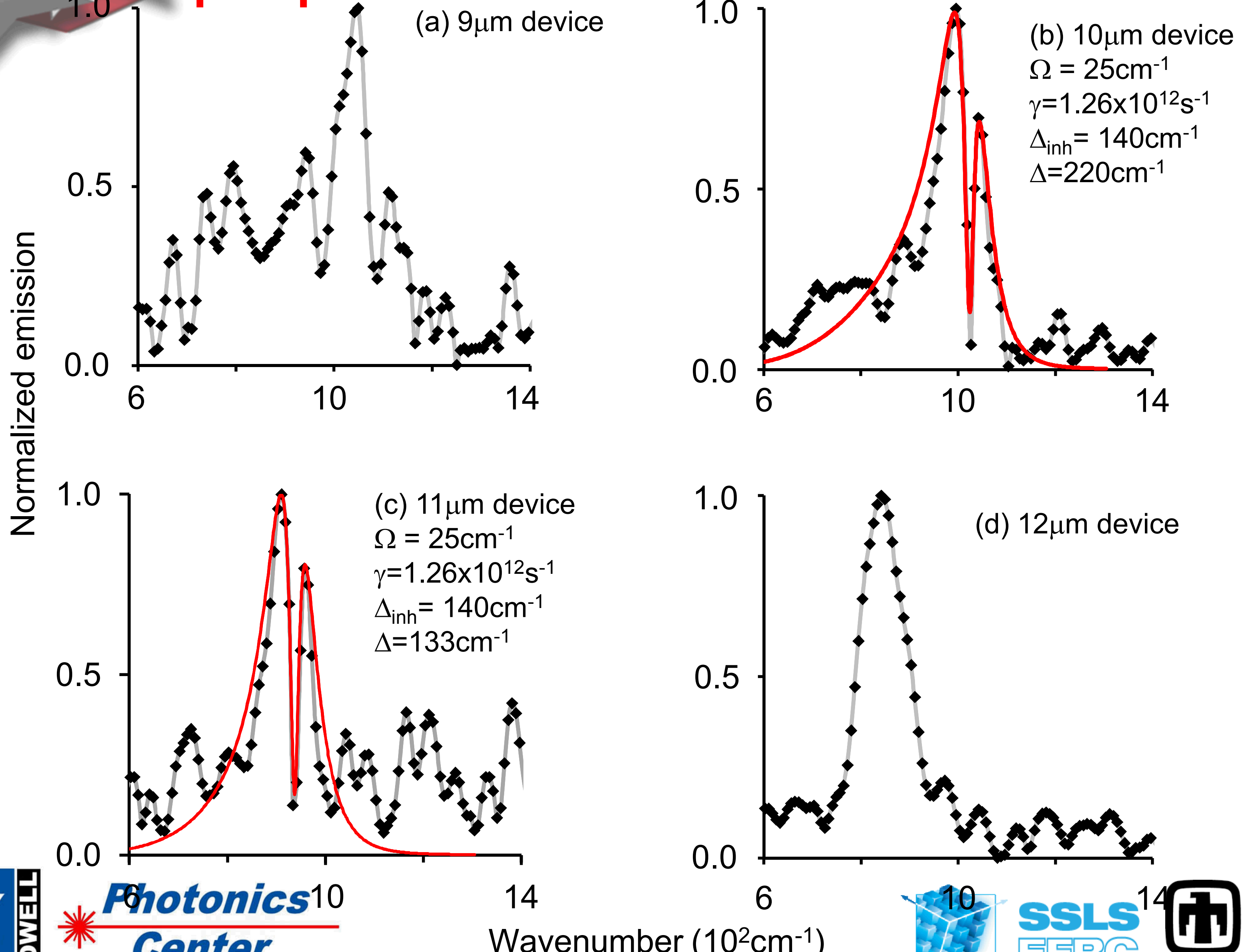
Rabi flopping in an electrically-pumped device



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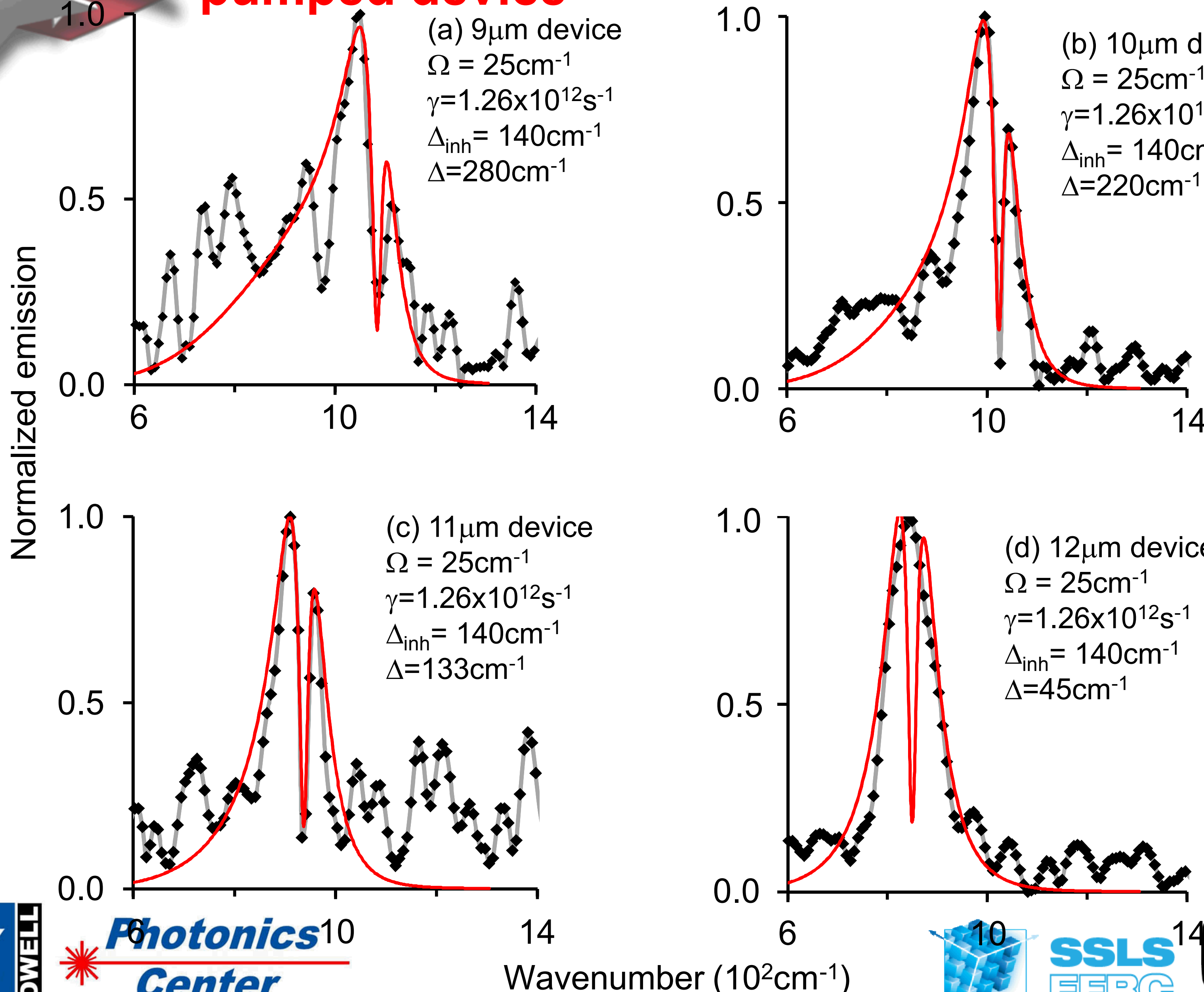
Rabi flopping in an electrically-pumped device



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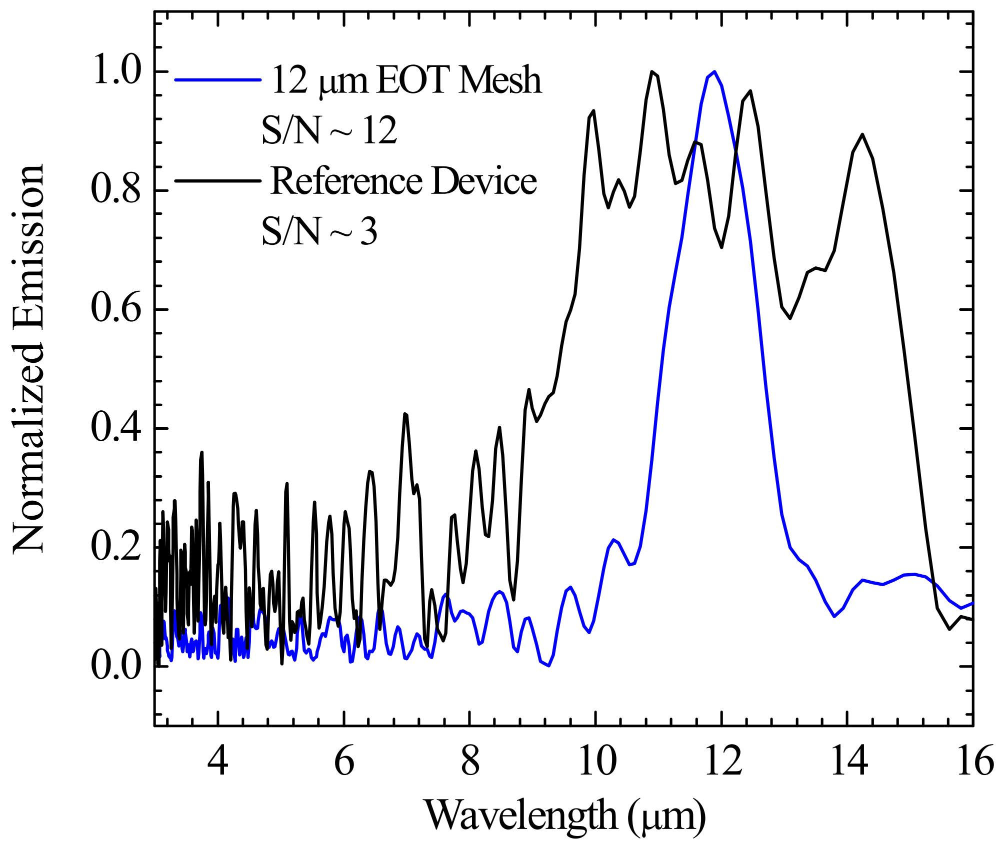
Summary

- Mid-IR emission from a QC-like InAs quantum dot emitter with plasmonic top contact output couplers was demonstrated
- Surface plasmon mechanisms with the devices were confirmed due to the emission null
- Coupling of nanostructures to plasmonic elements offers a path towards enhanced interaction with active media

Extra Slides

Normalized Emission for 12 μm Mesh



The normalized emission from the reference device and the 12 μm mesh design measured at 77 K. The signal-to-noise ratio is higher by a factor of 4 for the mesh compared to the reference device.

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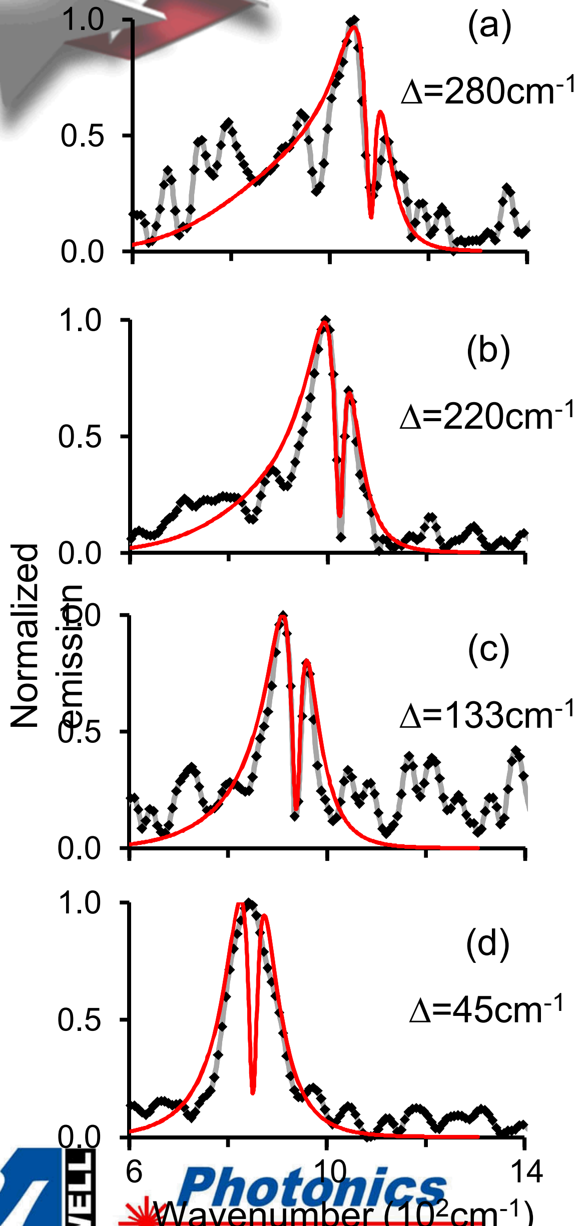
Enabling physics



Rabi frequency

Inter-conduction-band transition

$$\Omega_R = 4.7\times10^{12}\, s^{-1} = \frac{\wp E}{\hbar}$$

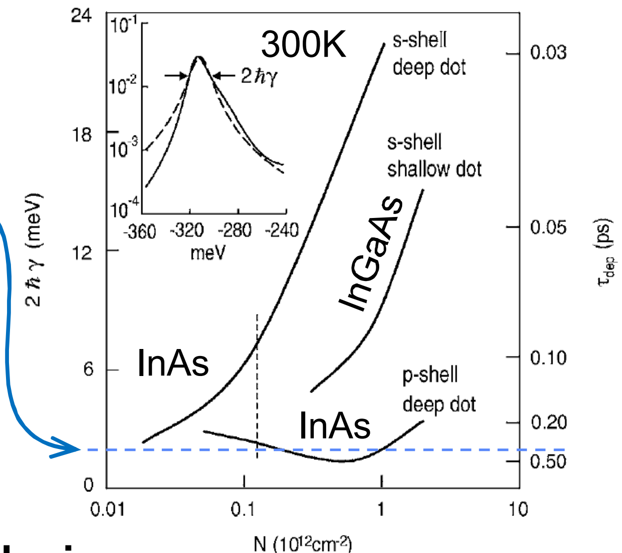
$\wp \rightarrow e\times10nm$

$E \rightarrow 3KV/cm \rightarrow 7\times10^{8}\ photons$

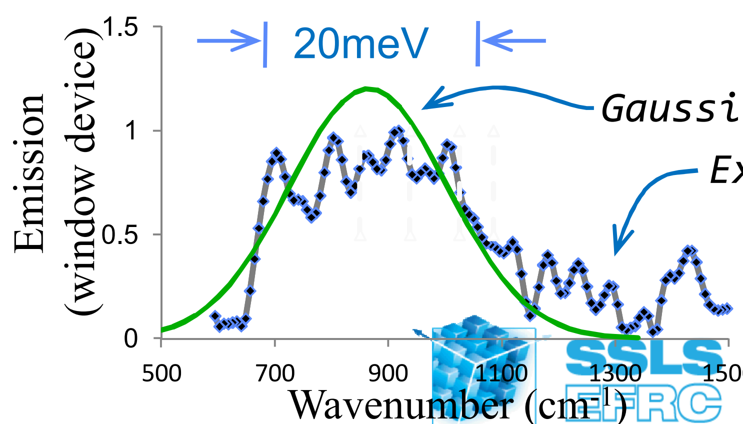
Dephasing

$$\gamma = 1.26\times10^{12}\, s^{-1}$$

Lorke, WWC, Nielsen, Seebeck, Gartner and Jahnke, PRB **74**, 035334, 2006 (with polaron, memory, off-diagonal correlations)



Inhomogeneous broadening



Experimentally demonstrated and theoretically verified: Strong-light-matter interaction in electrically-excited, inter-conduction-state quantum-dot transitions

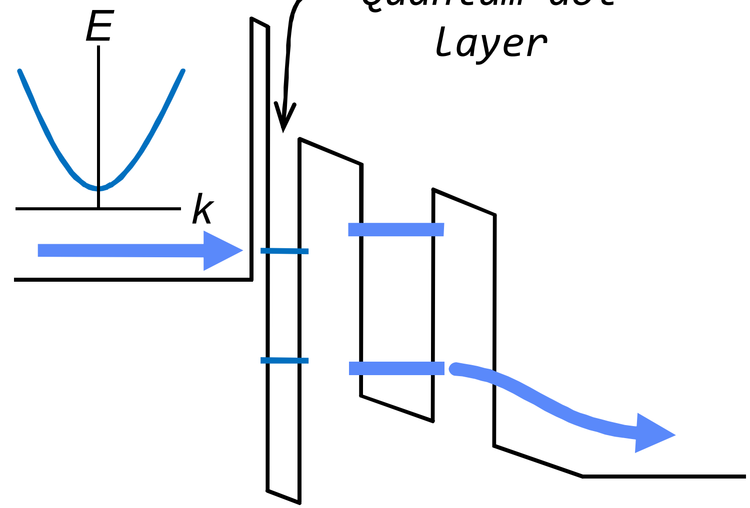
Quantum-coherent electrical excitation!

Advantage of intersubband/level platform for coherent transient and quantum coherence phenomena

	Interband	Intersubband or level
☺ ℘/e	<1nm	10nm
T_1 , T_2	$10^9 s^{-1}$, $10^{13} s^{-1}$	$10^{13} s^{-1}$, $10^{13} s^{-1}$

☹ *for quantum-coherence devices*

☹ *for population-based devices*



when random will lead to a mixed state ☹

$$|\psi\rangle = a|a\rangle + be^{i\phi}|b\rangle$$

2-d to 0-d excitation gives robust pure state ☺

$$|\psi\rangle = a|a\rangle$$

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Our System – Surface Plasmons Coupled to Intersublevel Transitions in QDs

- Electrically excited
- The SP fringing field penetration depth is greater in the mid-IR (~ ½ of λ)
- Based on intersubband transitions so the dipole matrix element is significantly larger
- Dephasing rates are slower due to mismatch of longitudinal optical phonon energy and energy separations of the discrete quantum-dot levels
- Electron-injection scheme populates the upper QD state increasing the likelihood of exciting a pure quantum state

Surface Plasmon Equations

$$\sqrt{i^2 + j^2}\lambda = a_0\sqrt{\frac{\varepsilon_s\varepsilon_m}{\varepsilon_s + \varepsilon_m}} \approx a_0\sqrt{\varepsilon_s} \text{ for } |\varepsilon_m| >> |\varepsilon_s|$$

λ = free space wavelength,
a_0 = the lattice constant,
i , j = integers related to the reciprocal lattice vectors $2\pi/a_0$ **x** and $2\pi/a_0$ **y**, respectively
ε_s = the real part of the dielectric function of the semiconductor and
ε_m = the real part of the dielectric function of the metal

$$k_{sp} = k_x \pm nG_x \pm mG_y$$

k_{sp} = SP wavevector
$k_x = (2\pi/\lambda)\sin\theta$
$G_{x,y} = 2\pi/a_0$

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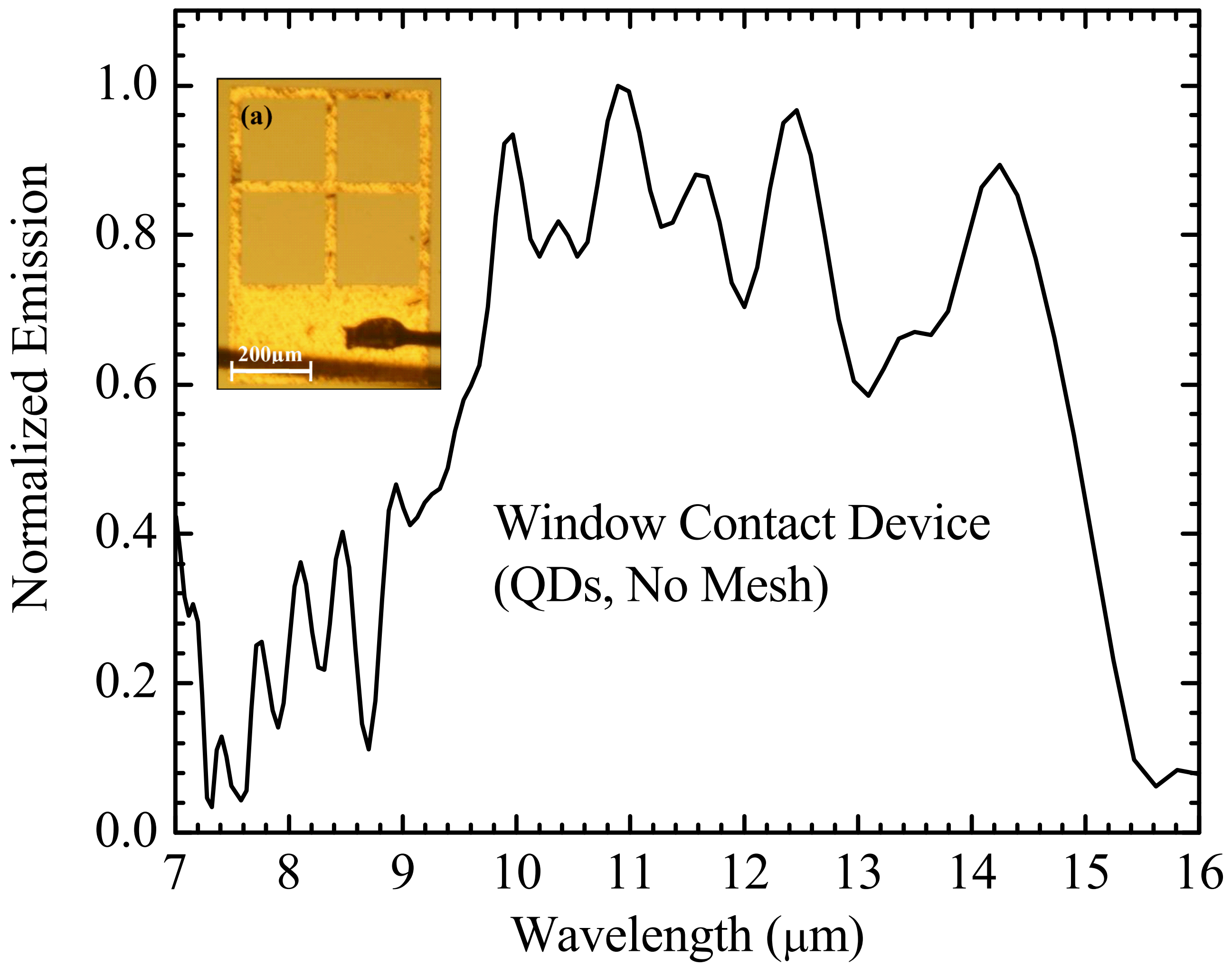
Electroluminescence of Devices



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Electroluminescence of Devices