SAND2011-0067C

# Strong Coupling Between Surface Plasmons and Conduction State Transitions in InAs Quantum Dots

**Eric Shaner[1]**

**David C. Adams[2], Troy Ribaudo[2], Dan Wasserman[2], Stephen Lyon[3], Brandon Passmore, Paul Davids[1], and Weng W. Chow[1]**

[1] Sandia National Laboratories, Albuquerque, NM 87185-1086
[2] Department of Physics and Applied Physics, University of Massachusetts, Lowell, MA 01854
[3] Department of Electric Engineering, Princeton University, Princeton, NJ 08544

This work was supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences through the Energy Frontier Research Center (EFRC) for Solid-State Lighting Science. This work was performed, in part, at the Center for Integrated Nanotechnologies, a U.S. Department of Energy, Office of Basic Energy Sciences user facility. Sandia National Laboratories is a multi-program laboratory operated by Sandia Corporation, a Lockheed-Martin Company, for the U. S. Department of Energy under Contract No. DE-AC04-94AL85000.

UMASS LOWELL Photonics Center

SSLS EFRC

Sandia National Laboratories

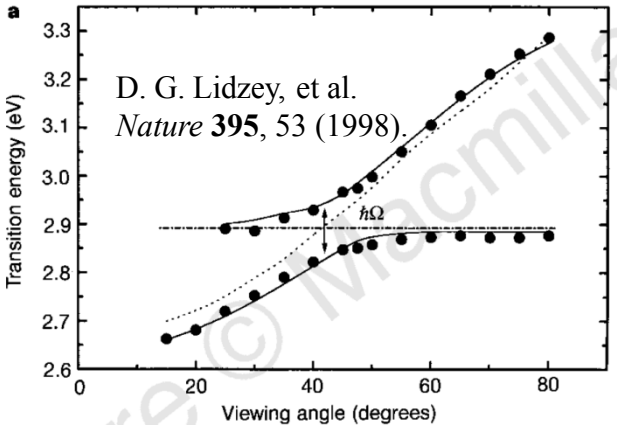
# Background

## 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.





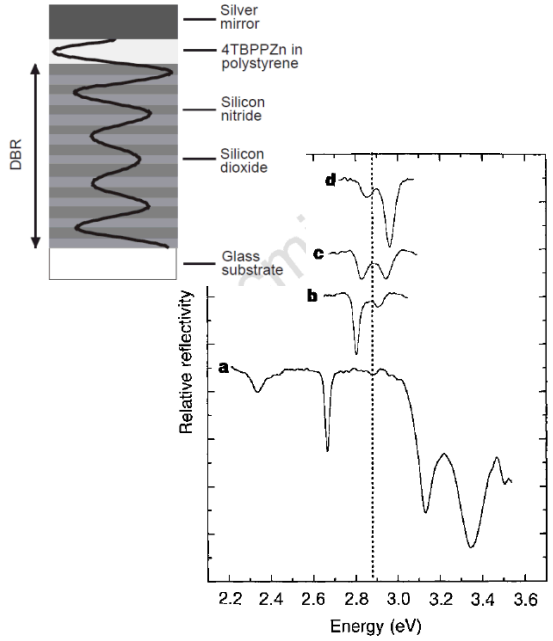

UMASS LOWELL Photonics Center

SSLS EFRC

Sandia National Laboratories

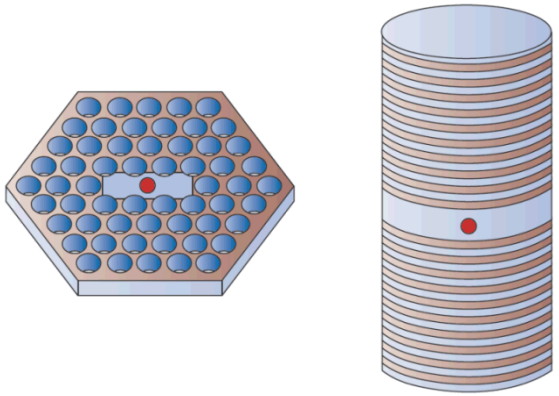
# Observation of Rabi Splitting

## Organic Semiconductors in Microcavities



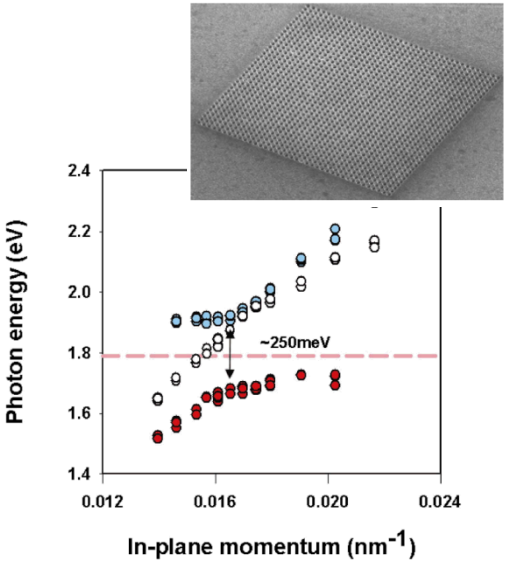

D. G. Lidzey, et al. *Nature* **395**, 53 (1998).

## 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).

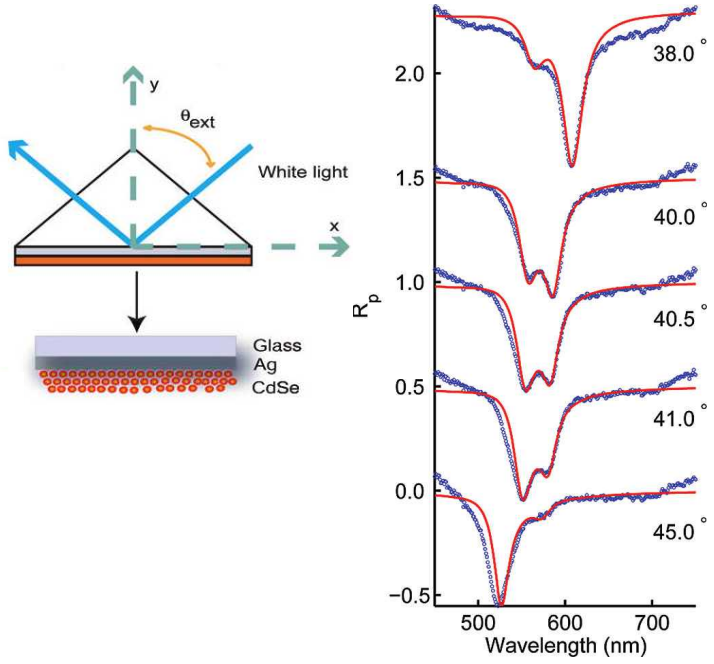
UMASS LOWELL Photonics Center

SSLS EFRC

Sandia National Laboratories

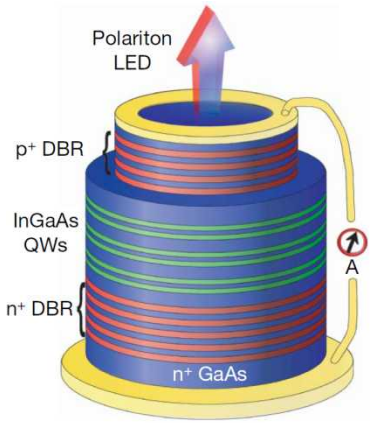
# Observation of Rabi Splitting

## Surface Plasmons and Nanocrystals



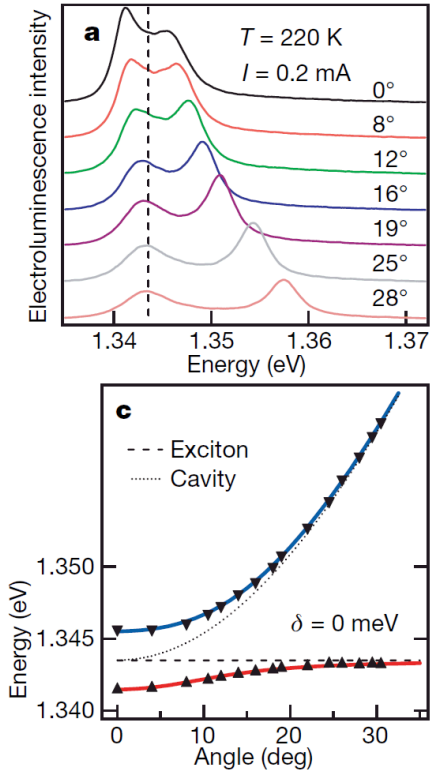

D.E. Gomez, et al. *Nano Letters* **10**, 274 (2010).

## Surface Plasmons and Nanocrystals




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

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

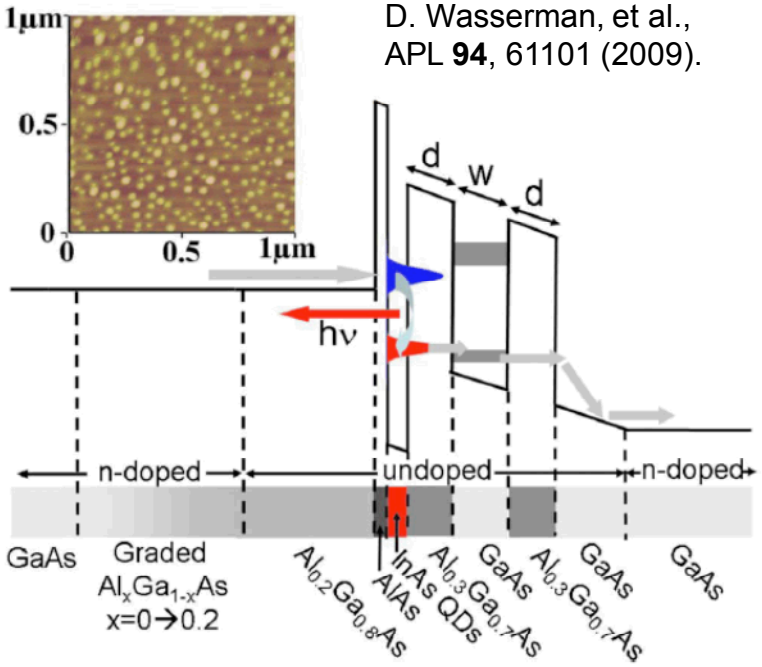



UMASS LOWELL Photonics Center

SSLS EFRC

Sandia National Laboratories

# Structure Design




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

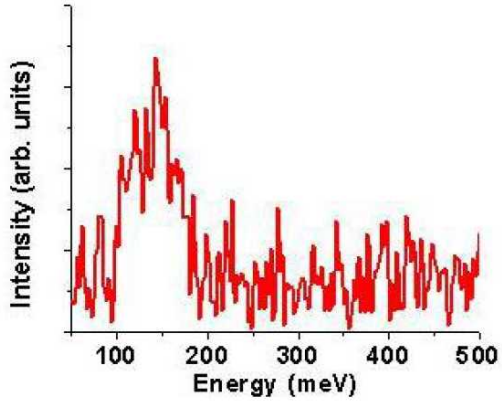
- Grown by MBE
- Similar carrier dynamics to a QCL
- Electrons are injected into the conduction band
- Electrons relax and emit photons
- Electrons in the ground state of the QDs tunnel to the adjacent well and are collected

UMASS LOWELL Photonics Center

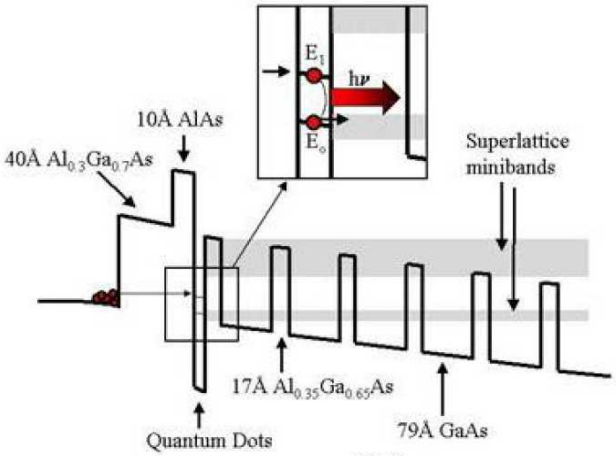
SSLS EFRC

Sandia National Laboratories

# InAs Quantum Dot Active Material

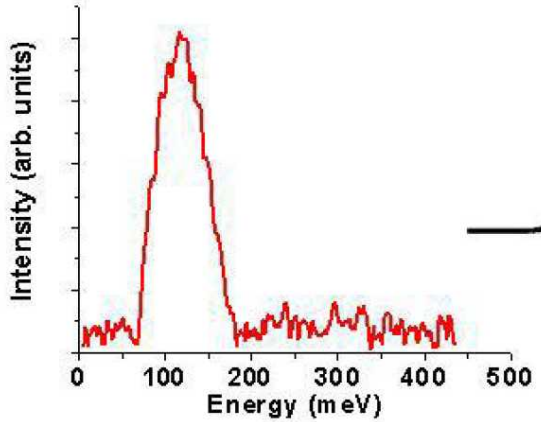


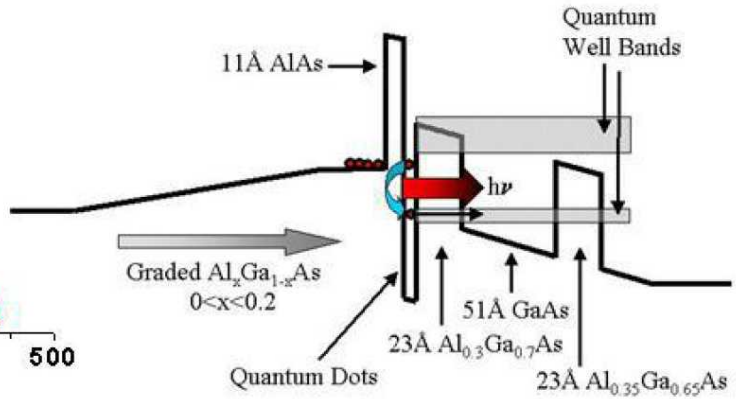

(a)




(b)

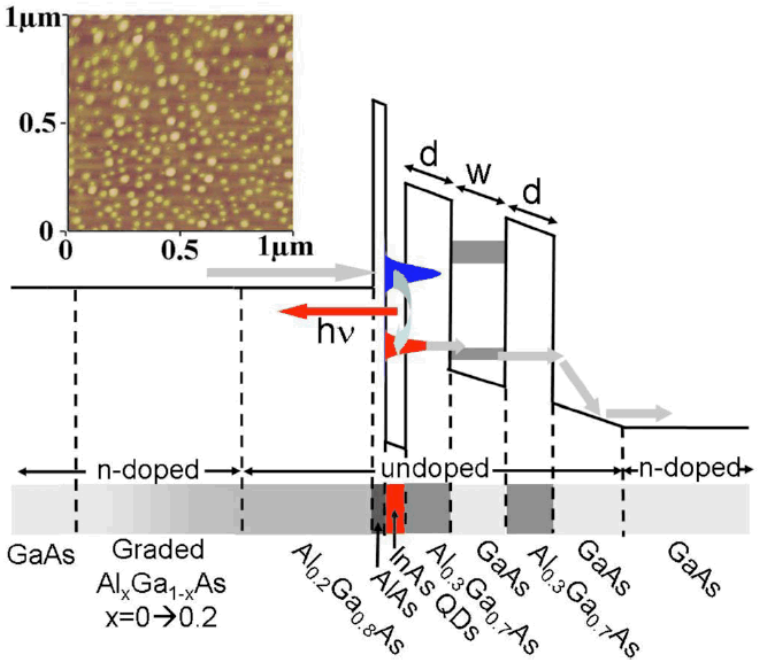
APL 81, 2848, 2002

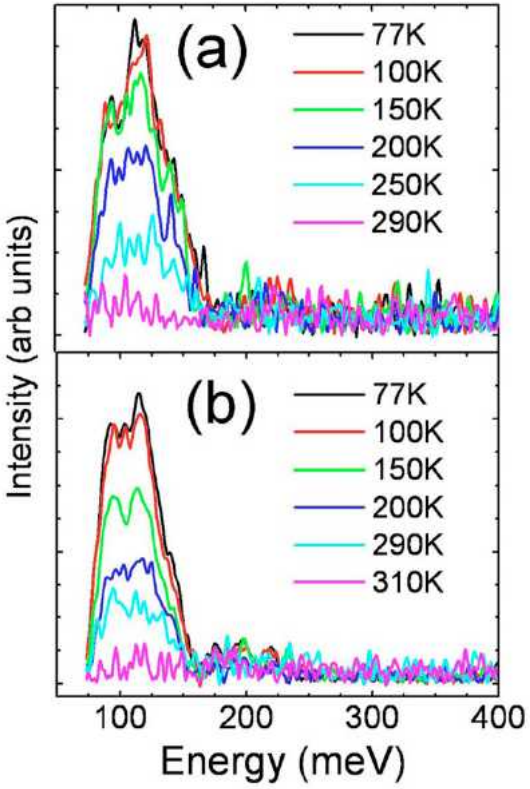



SPIE 63860E, 2006

# 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)

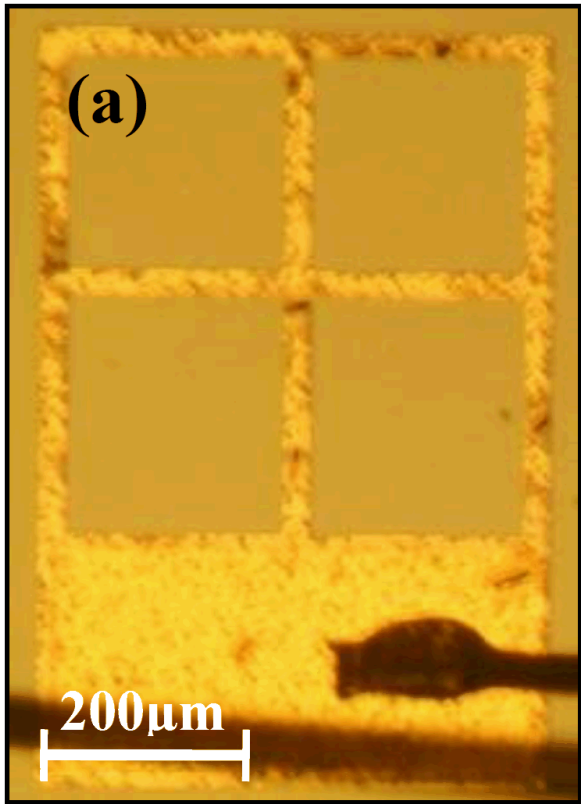
UMASS LOWELL Photonics Center

SSLS EFRC

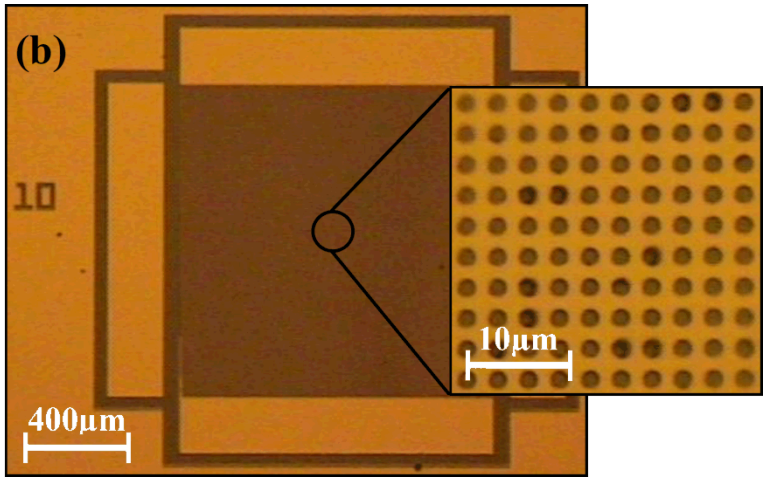
Sandia National Laboratories

# Plasmonic Mesh Design

Window Contact




Mesh Contact



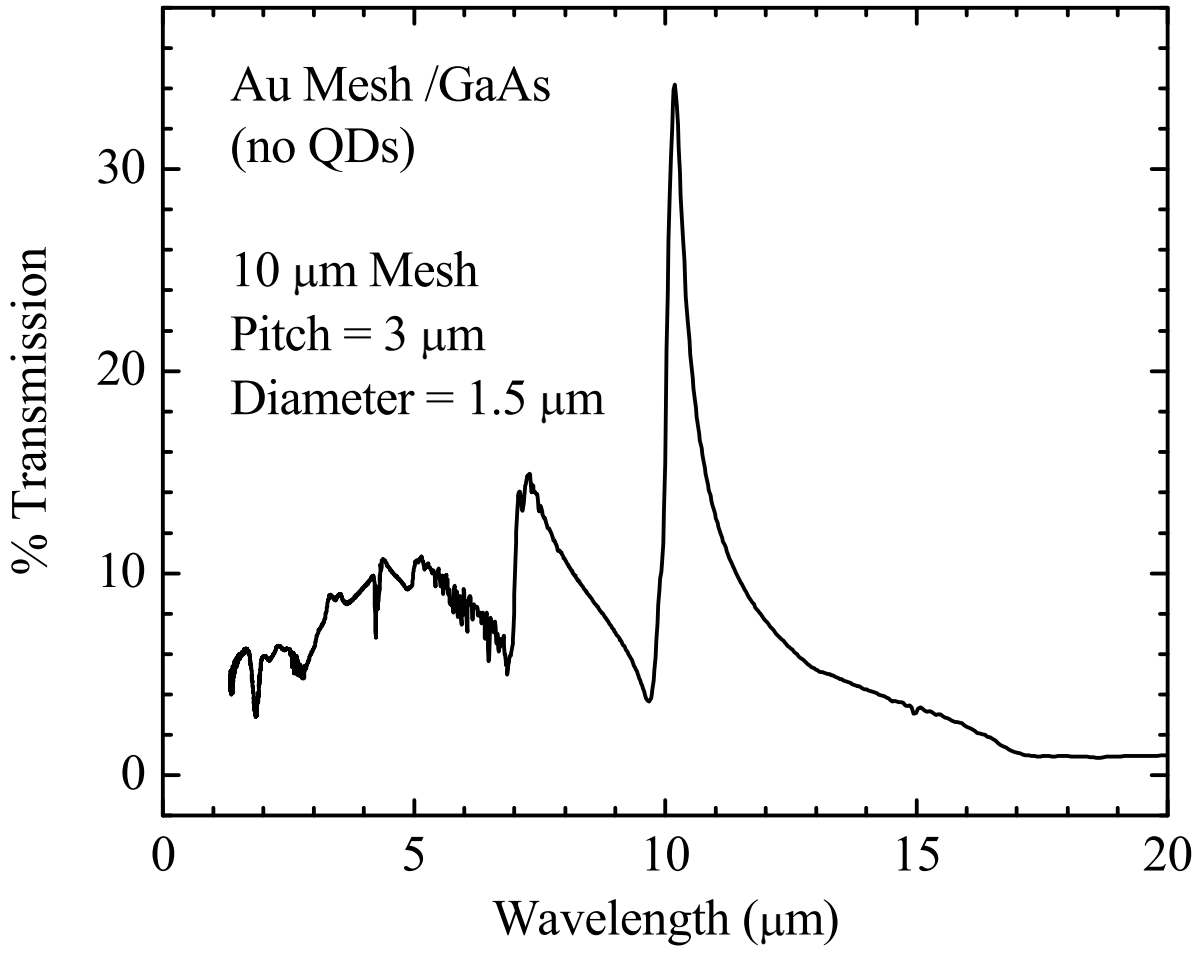

| Resonant Wavelength (µm) | Diameter (µm) | Pitch (µm) |
|---|---|---|
| 9 | 1.4 | 2.8 |
| 10 | 1.5 | 3.0 |
| 11 | 1.6 | 3.3 |
| 12 | 1.8 | 3.6 |

UMASS LOWELL Photonics Center

SSLS EFRC

Sandia National Laboratories

# Extraordinary Optical Transmission

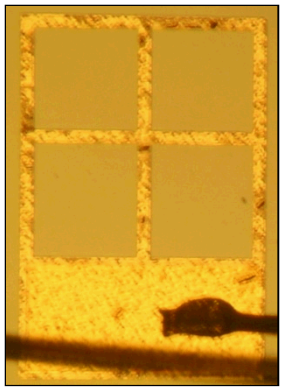


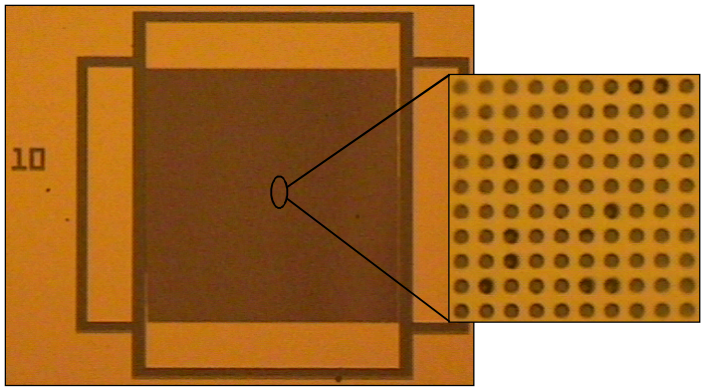

UMASS LOWELL Photonics Center

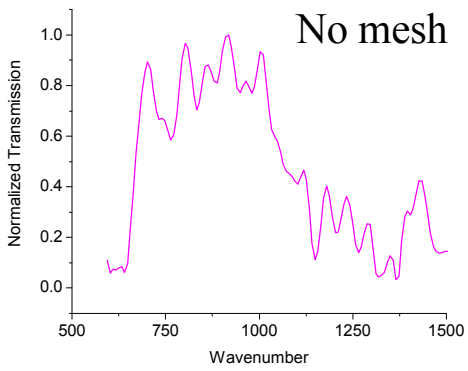
SSLS EFRC

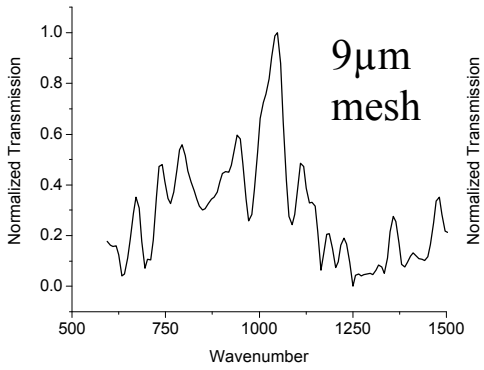
Sandia National Laboratories

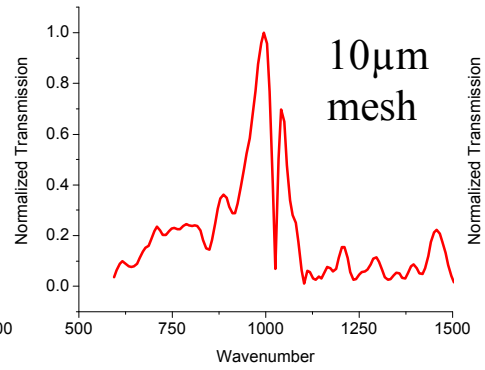
# Active mid-IR material + plasmonic structure

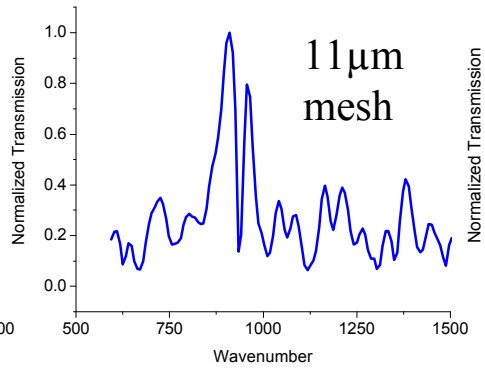


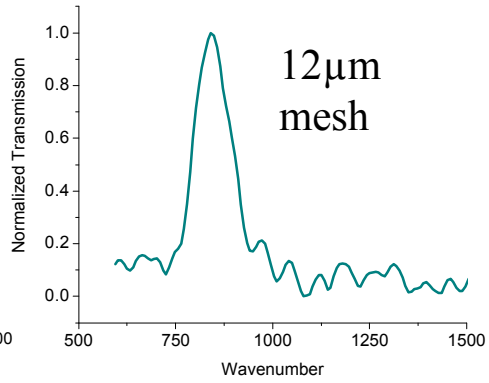


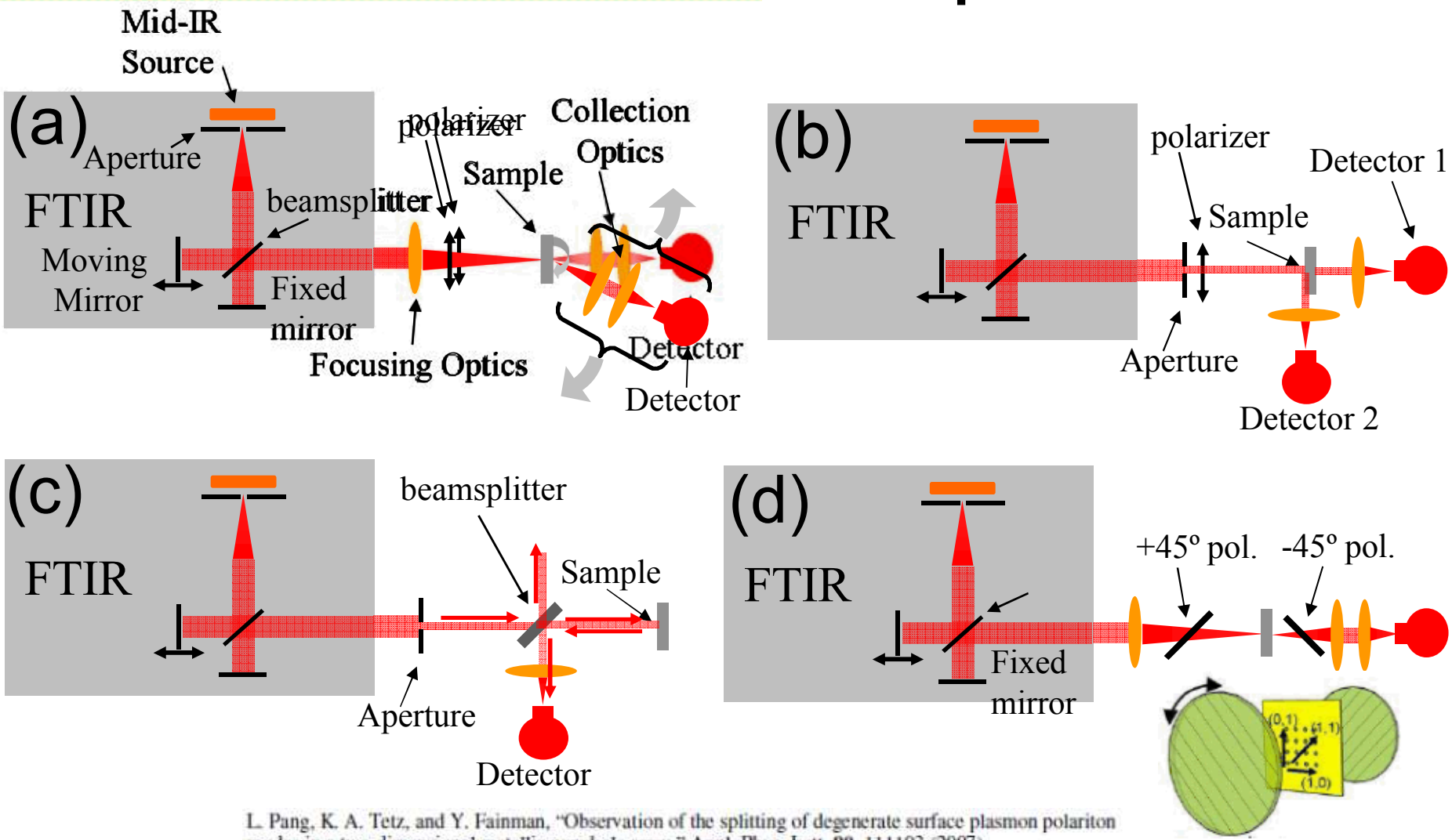




More than just filtering…

# 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).

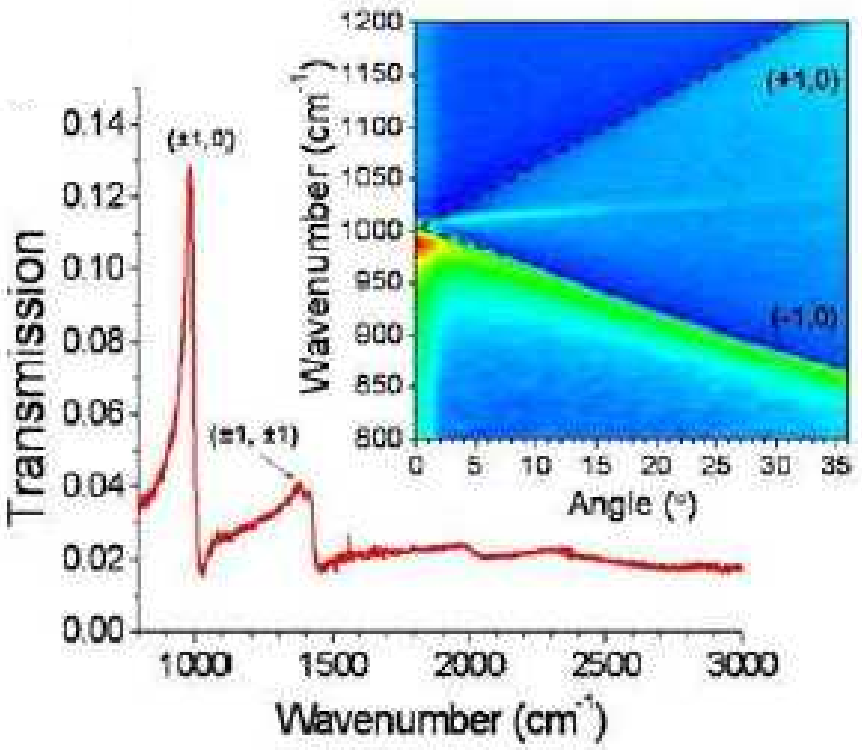


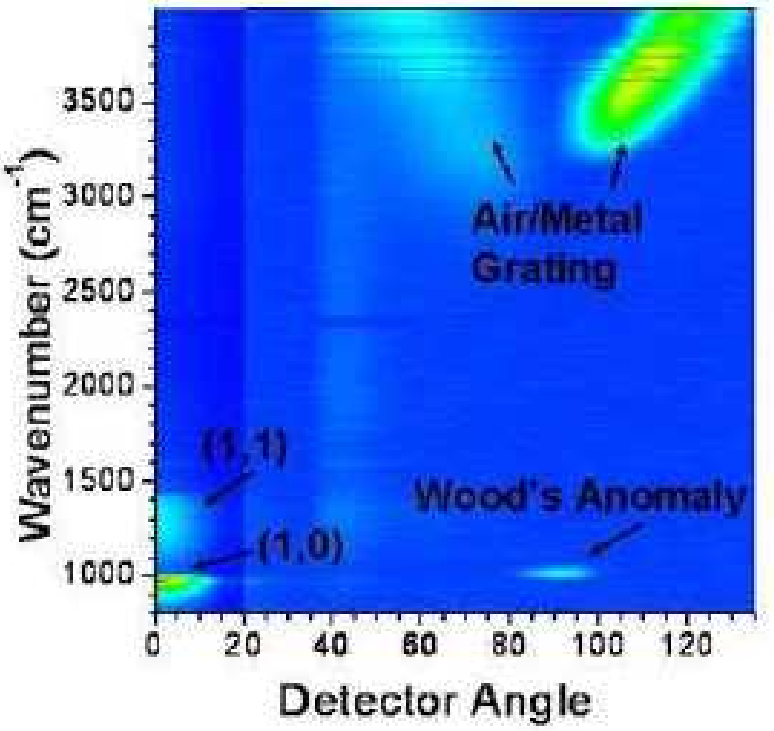
UMASS LOWELL Photonics Center

SSLS EFRC

Sandia National Laboratories

# Spatial and Spectral Investigations: Doped EOT samples



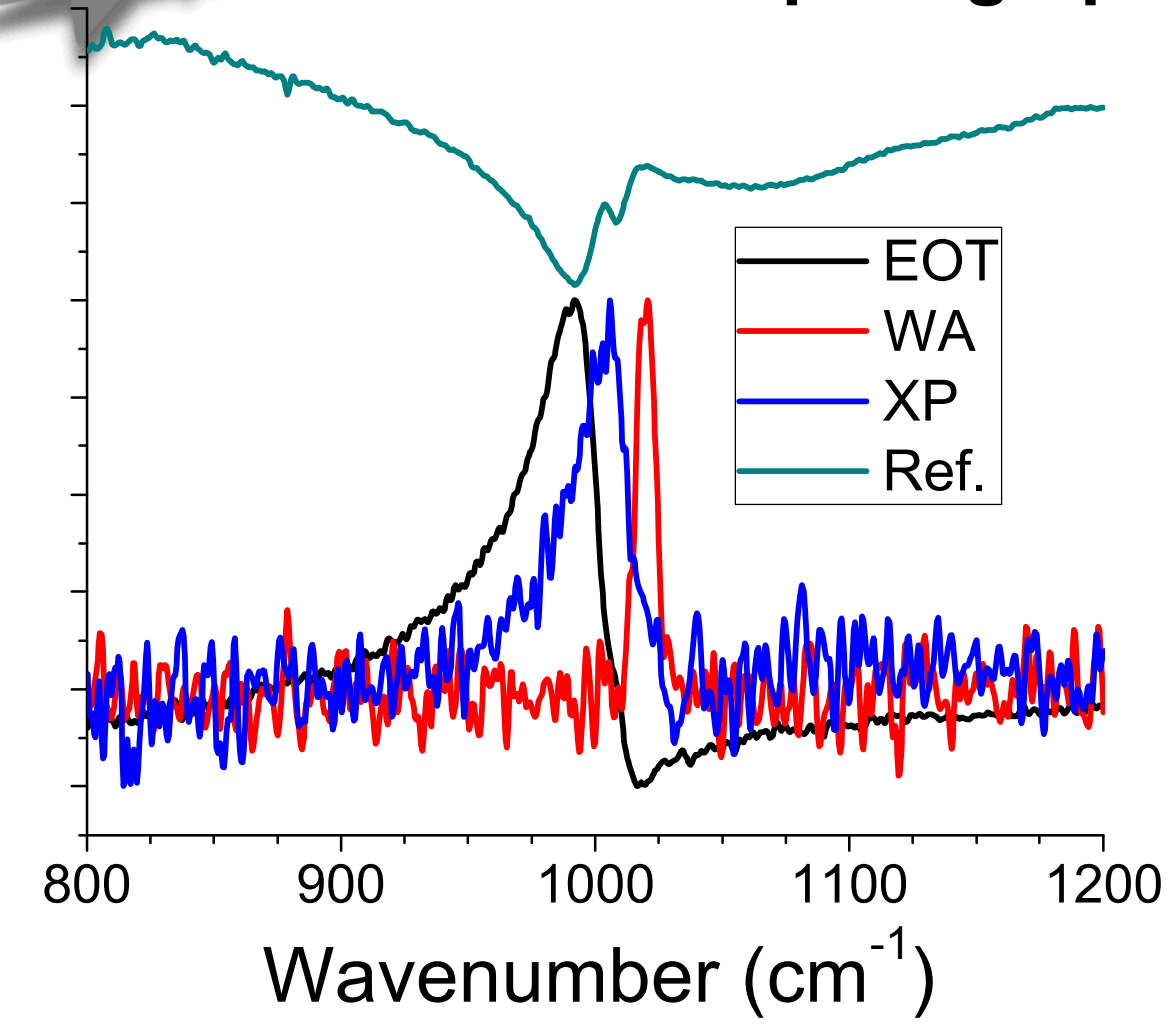

Optics express 17(2):666-75, **2009**

UMASS LOWELL Photonics Center

SSLS EFRC

Sandia National Laboratories

# 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).



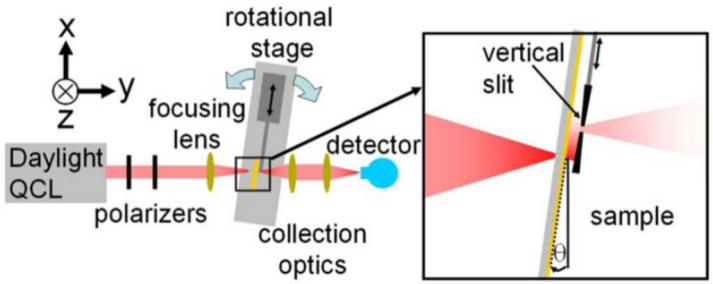
UMASS LOWELL Photonics Center

SSLS EFRC

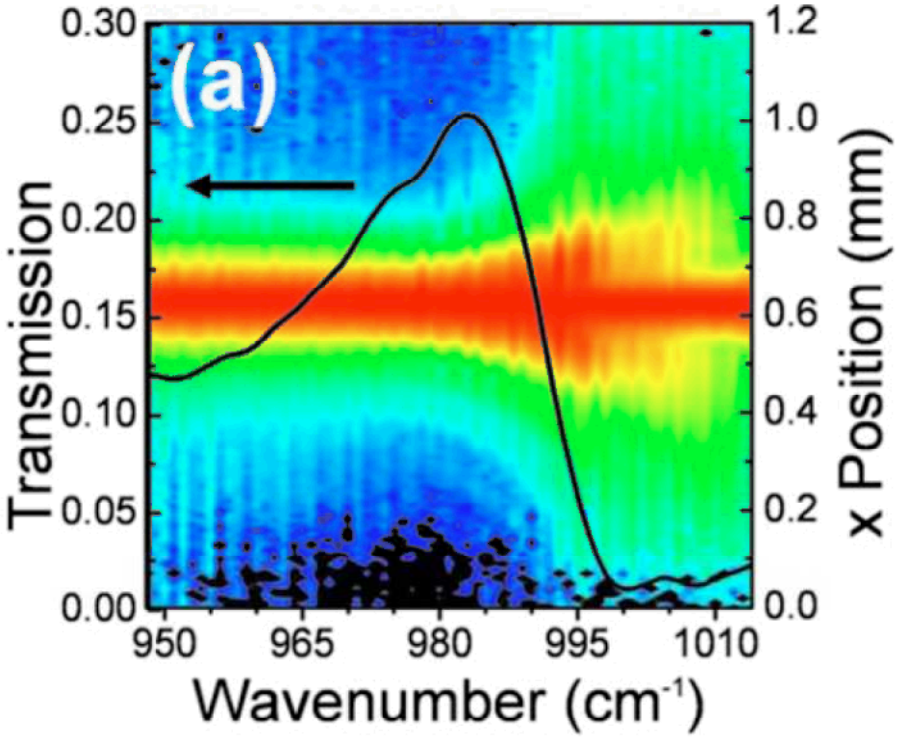
Sandia National Laboratories

# 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).



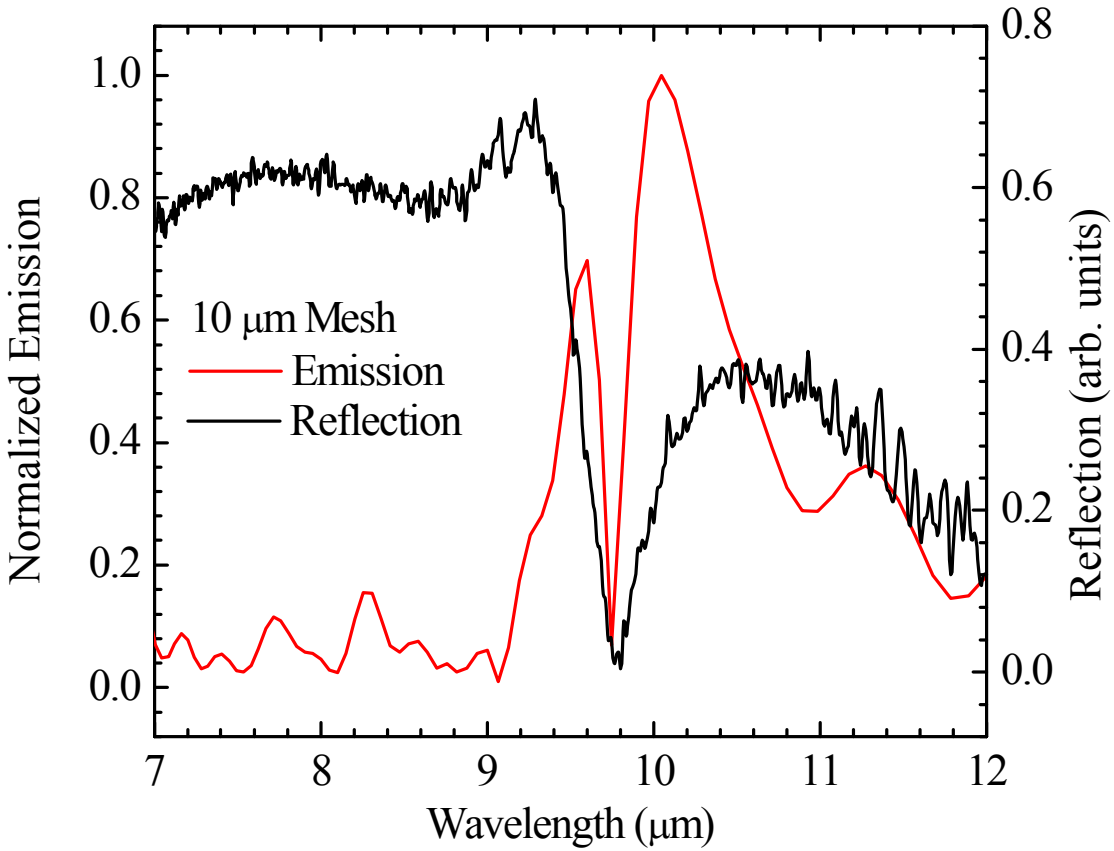

A contour plot of transmitted/scattered light intensity as a function of position and wavelength for horizontally polarized normally incident radiation. The black curve represents the normal incident transmission for the plasmonic mesh.

UMASS LOWELL Photonics Center

SSLS EFRC

Sandia National Laboratories

# 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.

UMASS LOWELL Photonics Center

SSLS EFRC

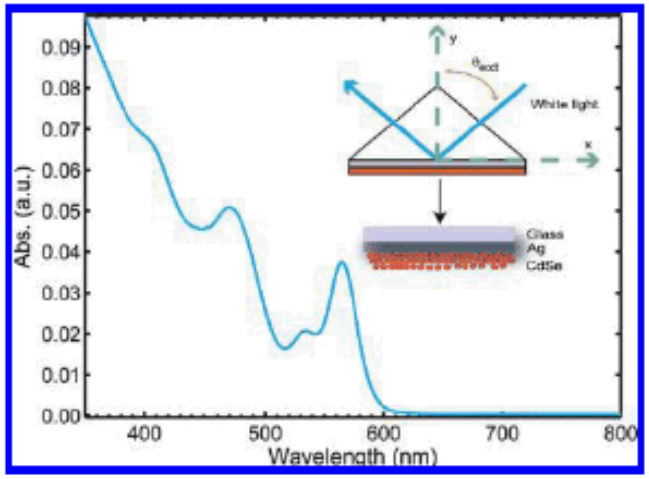
Sandia National Laboratories

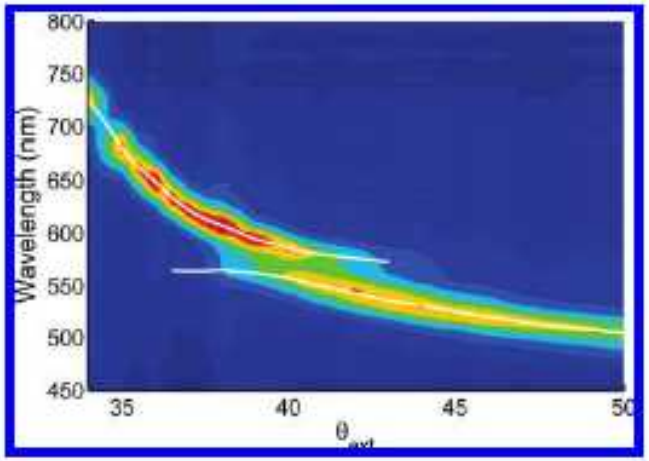
# Plasmon coupling to nanocrystals

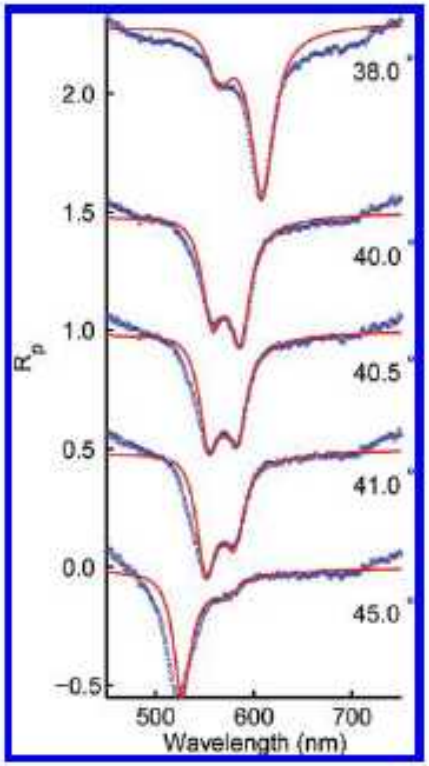
## Surface Plasmon Mediated Strong Exciton–Photon Coupling in Semiconductor Nanocrystals

Nanoletters 10, 274, 2010

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




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

Photonics Center

SSLS EFRC

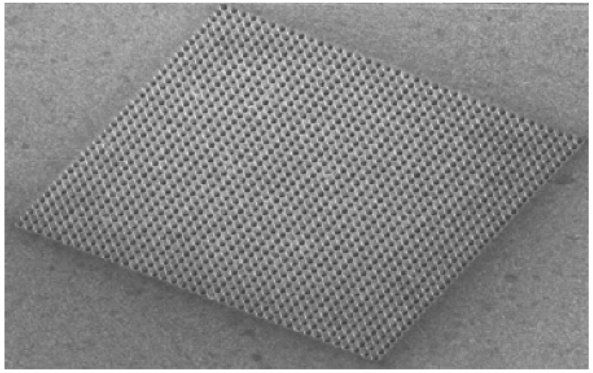
Sandia National Laboratories

# Plasmon coupling to J-aggregate

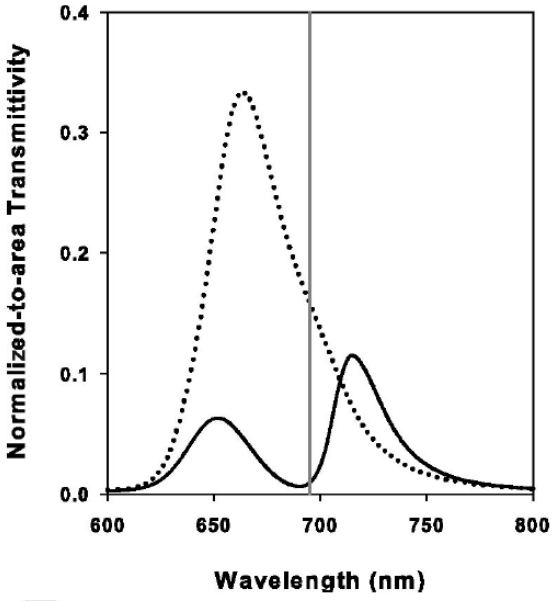
**Strong coupling between surface plasmon-polaritons and organic molecules in subwavelength hole arrays**

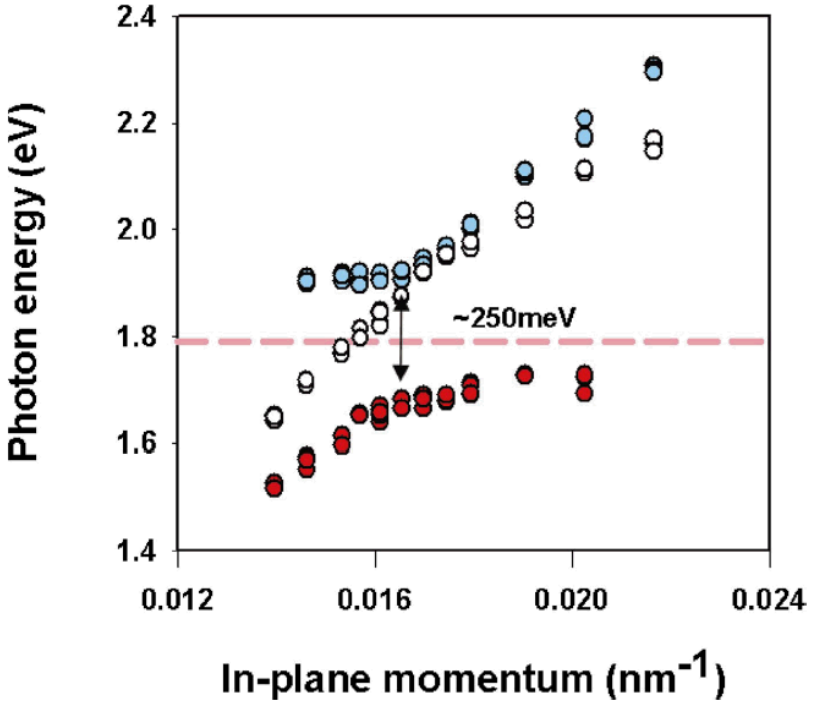
J. Dintinger,[1] S. Klein,[1,*] F. Bustos,[1,†] W. L. Barnes,[2] and T. W. Ebbesen[1,‡]

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



380 nm pitch silver hole array on quartz




Again, varying angle allows probing of anti-crossing

UMAS

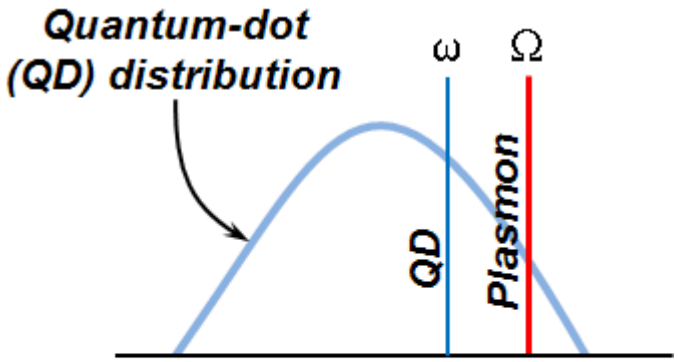
SSLS EFRC

Sandia National Laboratories

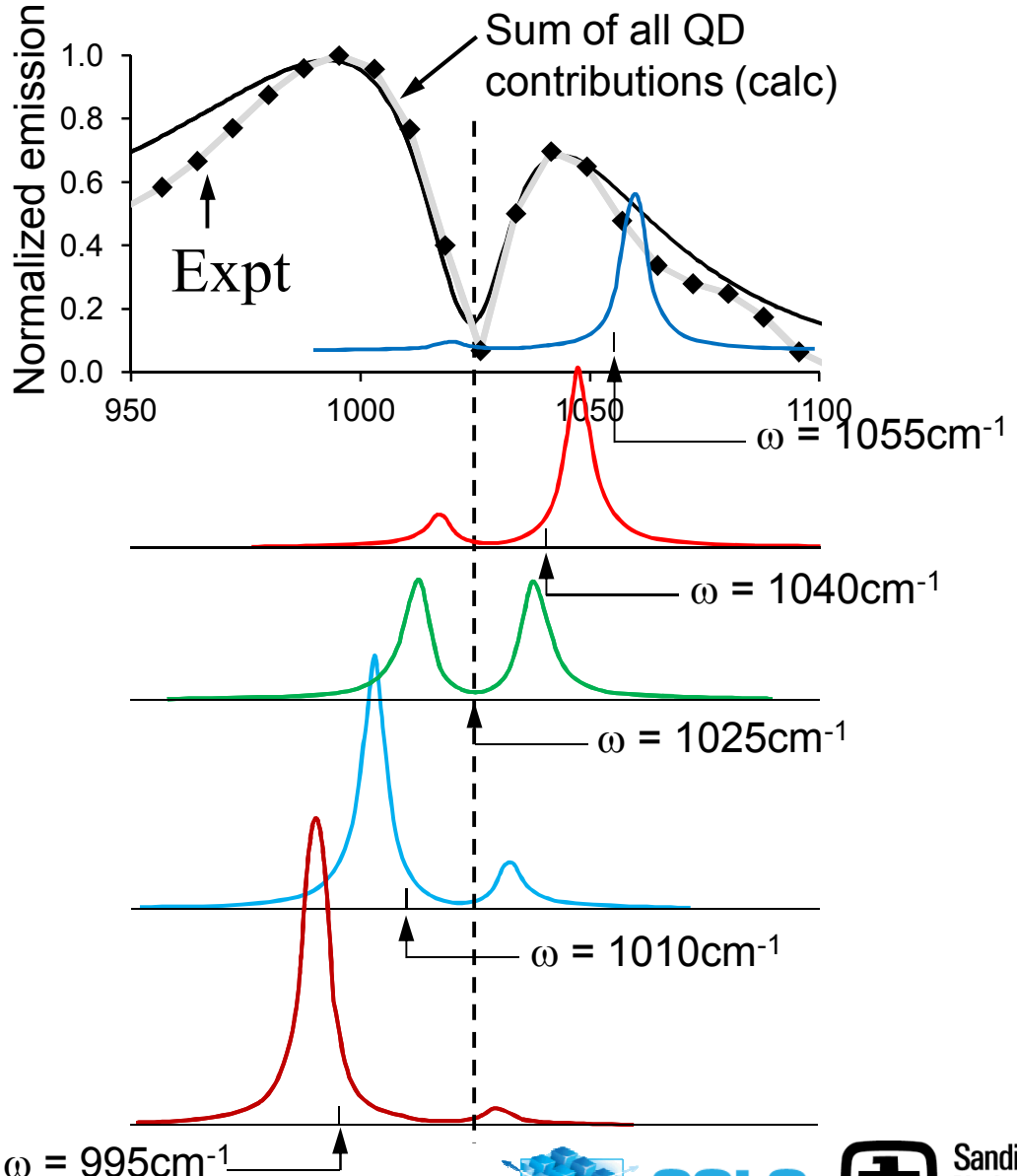
# Dealing with an inhomogeneous distribution

- 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
- We can model the situation and compare with experiment

# Quantum dot contributions to electroluminescence




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

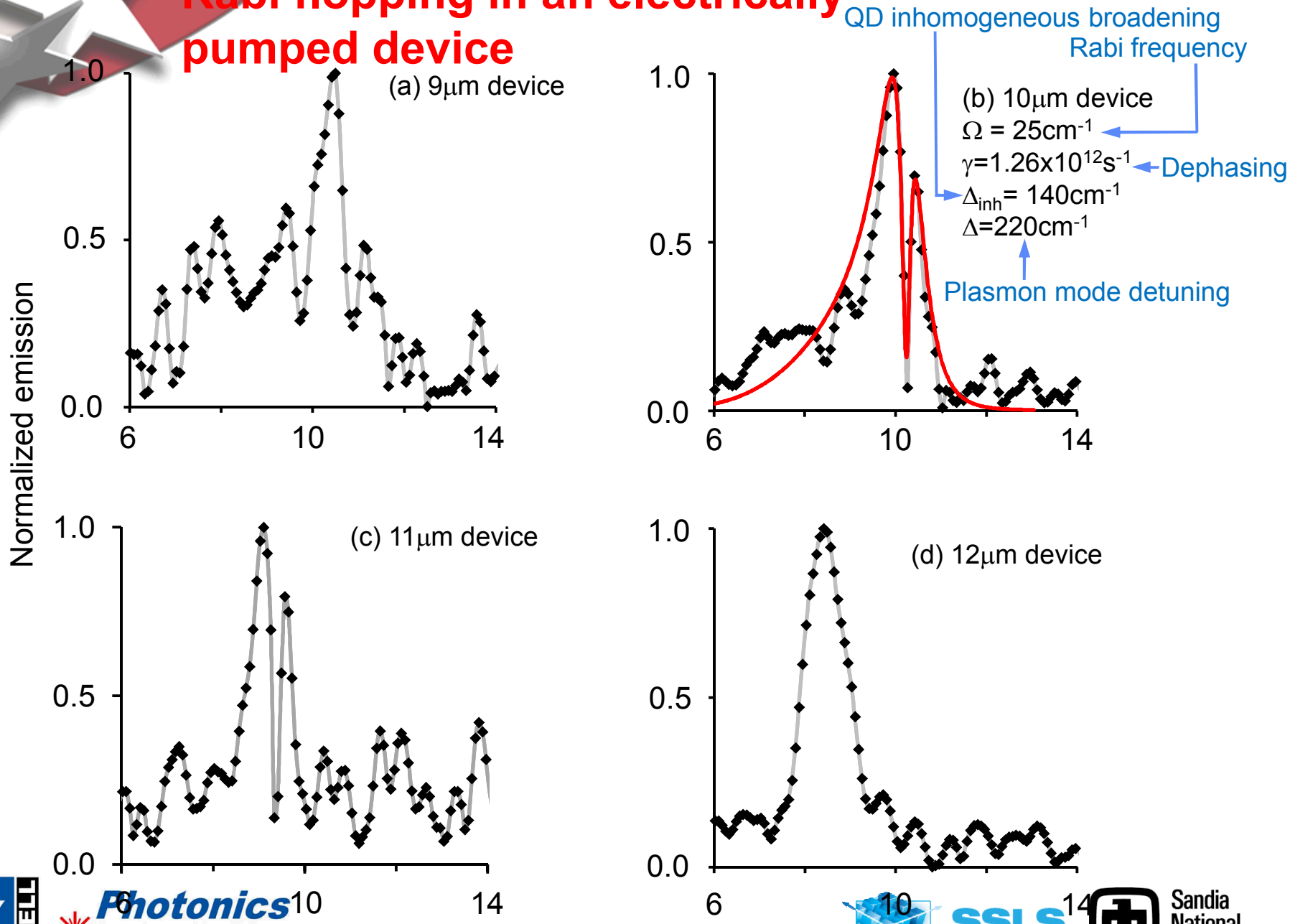



UMASS LOWELL Photonics Center

SSLS ERC

Sandia National Laboratories

# Rabi flopping in an electrically-pumped device



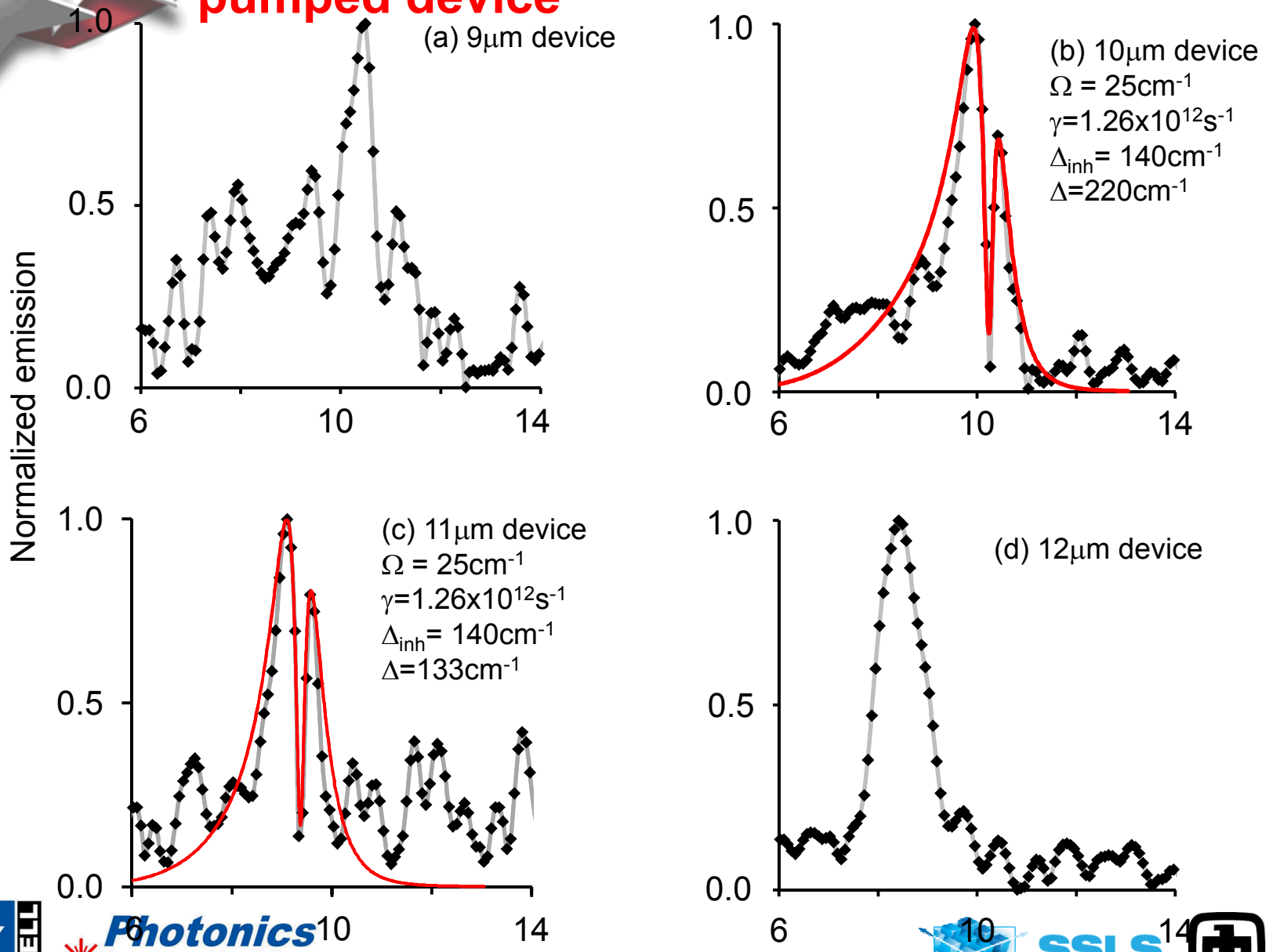

UMASS LOWELL

Photonics Center

SSLS EFRC

Sandia National Laboratories

# Rabi flopping in an electrically-pumped device



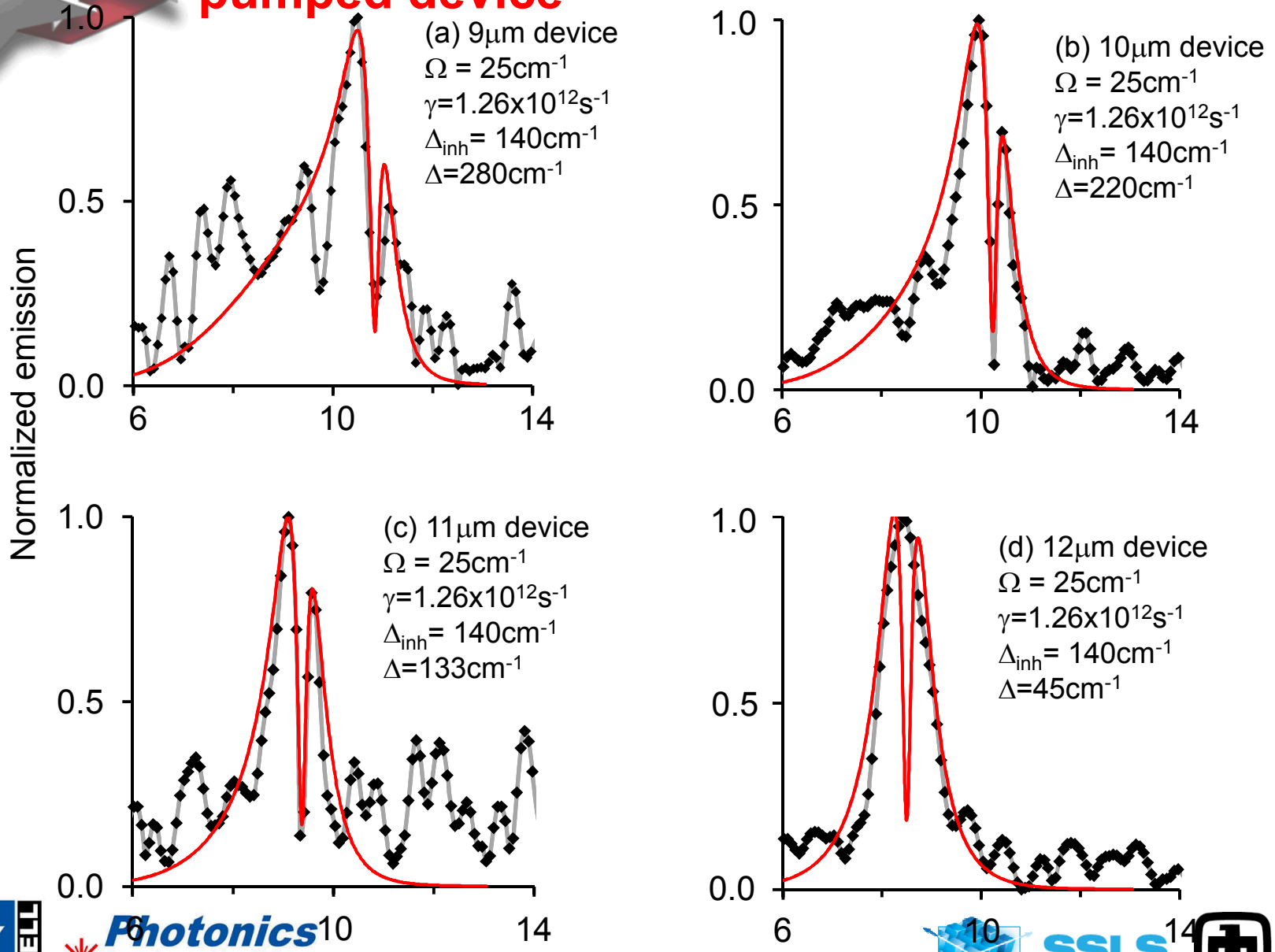

UMASS LOWELL

Photonics Center

SSLS EFRC

Sandia National Laboratories

# Rabi flopping in an electrically-pumped device




UMASS LOWELL

Photonics Center

SSLS EFRC

Sandia National Laboratories

# 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