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Metasurfaces and Epsilon-Near-Zero Modes in Semiconductors

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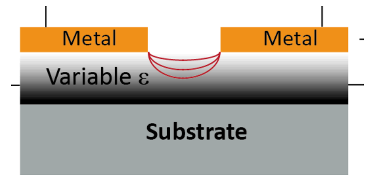
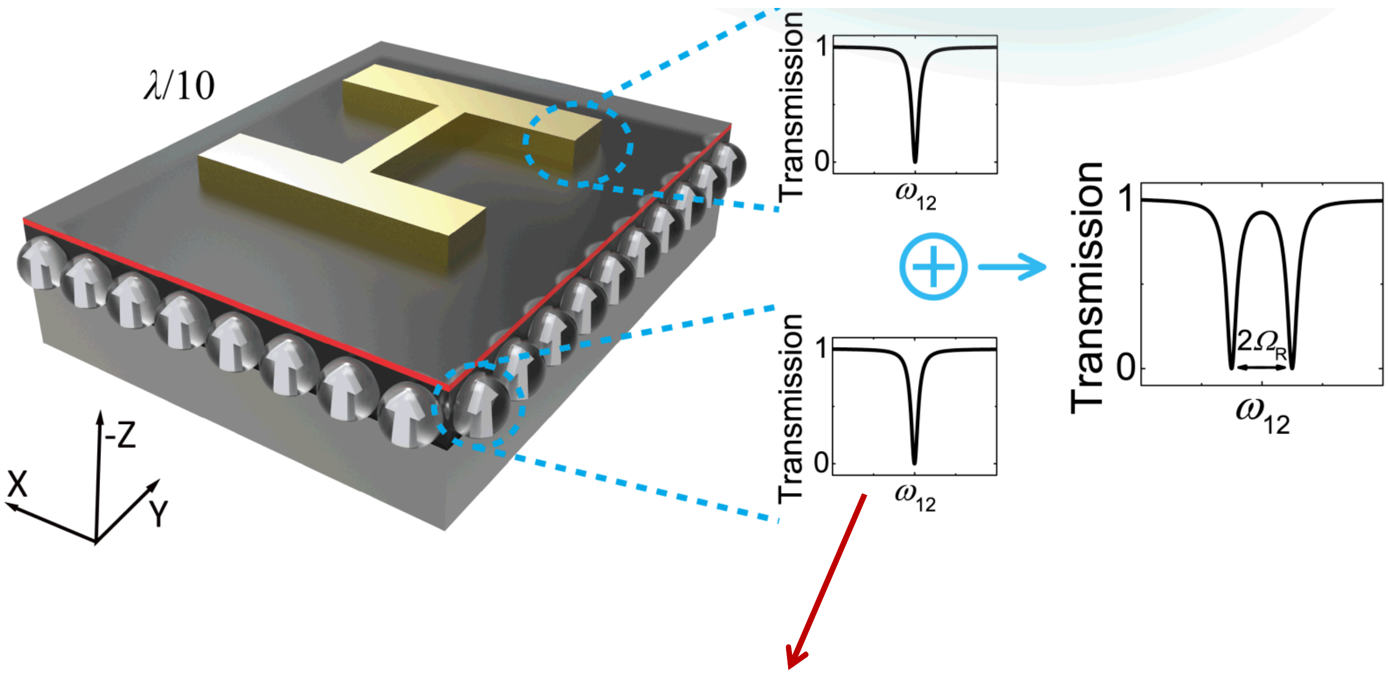
Planar Metamaterials and Strong Coupling

MM resonators create strong optical fields that lead to strong coupling



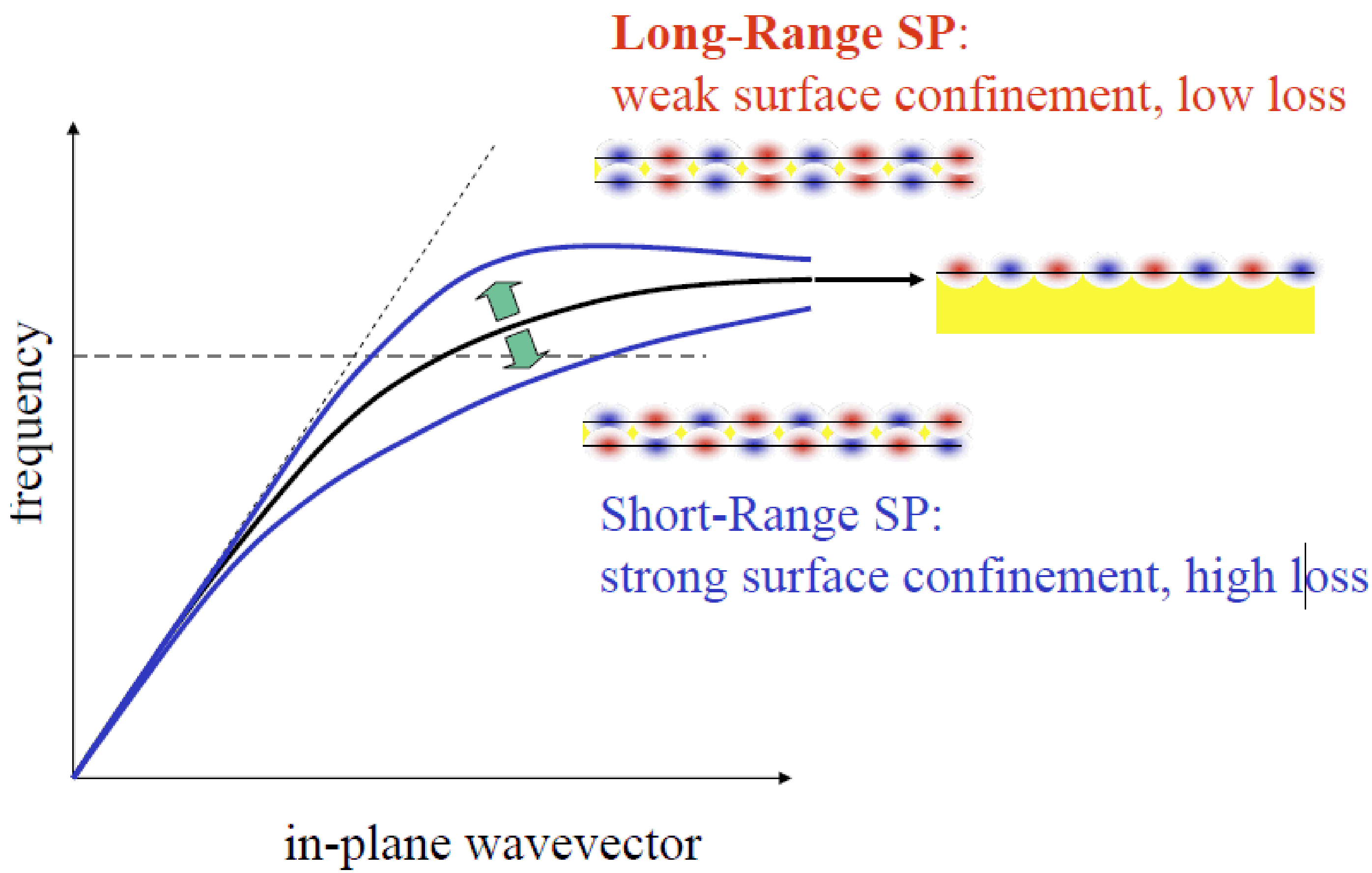


Optical Phonons: Nano Letters 11, 2104 (2011)
Intersubband Transitions: Nature Communications 4, (2013)
Epsilon Near Zero modes: Nano Letters **13**, 5391 (2013)

Outline

- Epsilon Near Zero and Berreman Modes
  - Fundamentals
  - Berreman modes: Thermal emission
  - ENZ modes: coupling to metamaterial resonators
- Epsilon Near Zero modes coupled to both, metamaterials and dipole transitions
  - Optical Phonons
  - Intersubband transitions

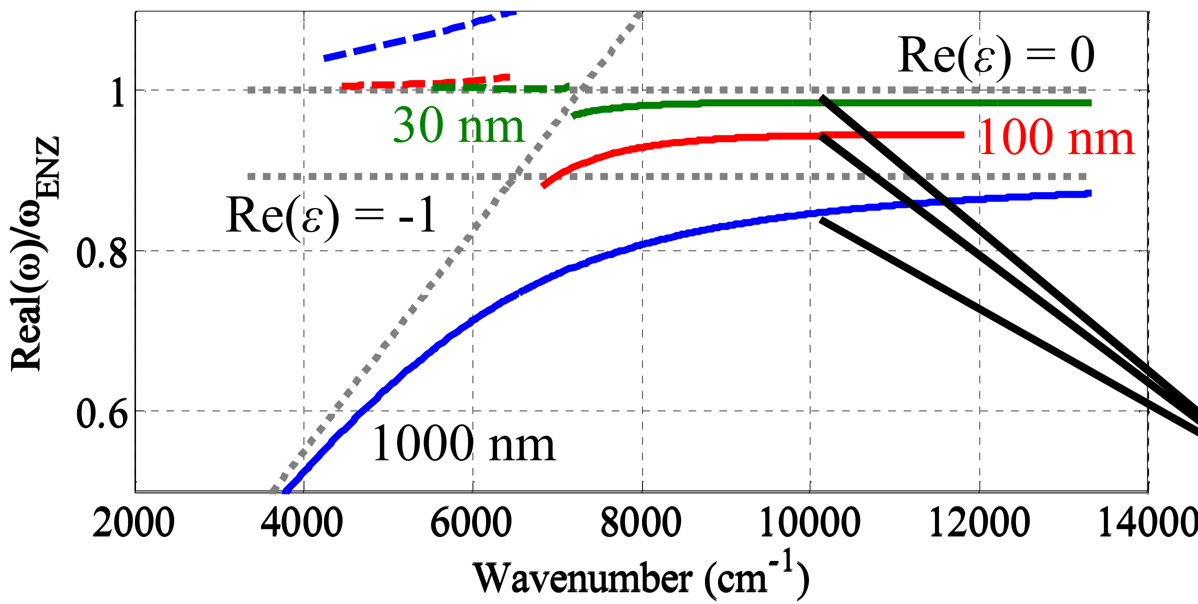
Plasmon Modes of a Thin Film

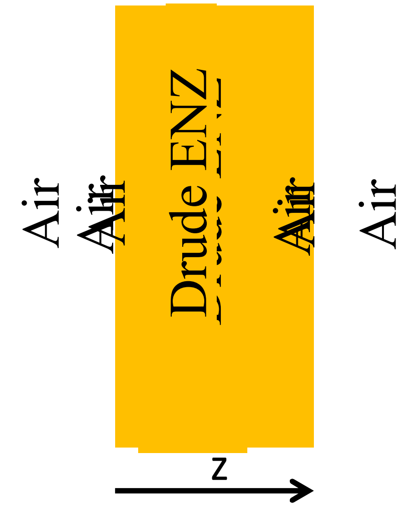


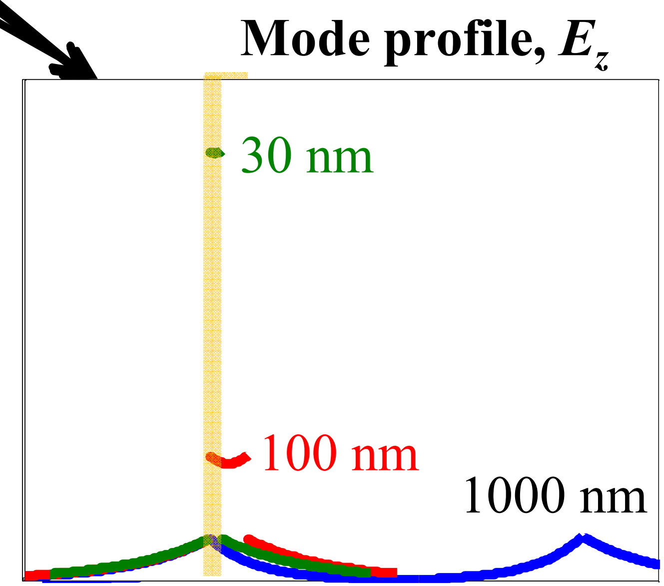
(courtesy, Dept. of Physics, Hanyang Univ.)

Econoumou, 1969
Burke 1986
etc

Plasmon Modes of a Thin Film: “ENZ mode”





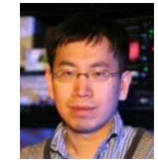


The smaller the thickness, the larger E_z

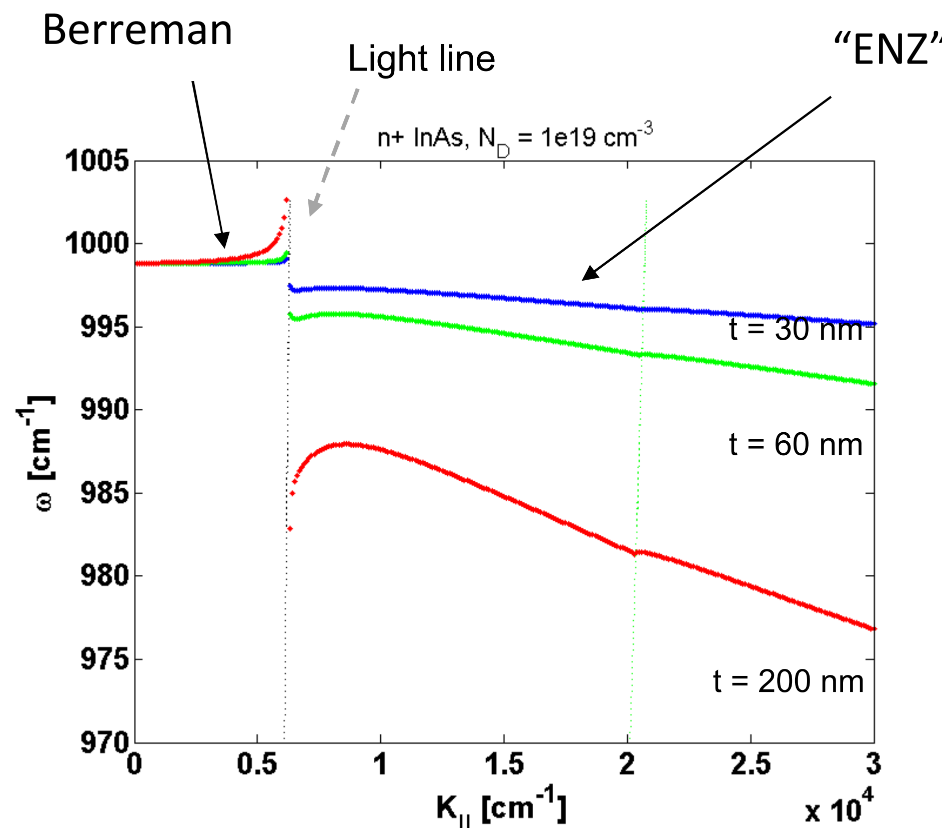
This mode is the ENZ mode

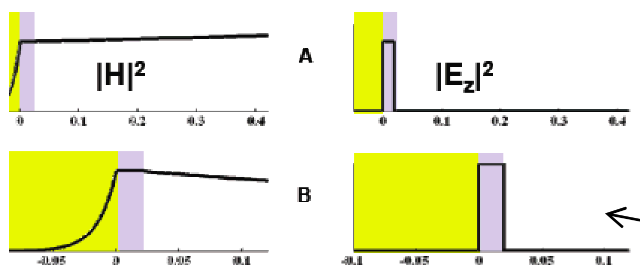
The mode is the surface plasmon polariton

“Epsilon Near Zero” vs Berreman Modes



Young Chul

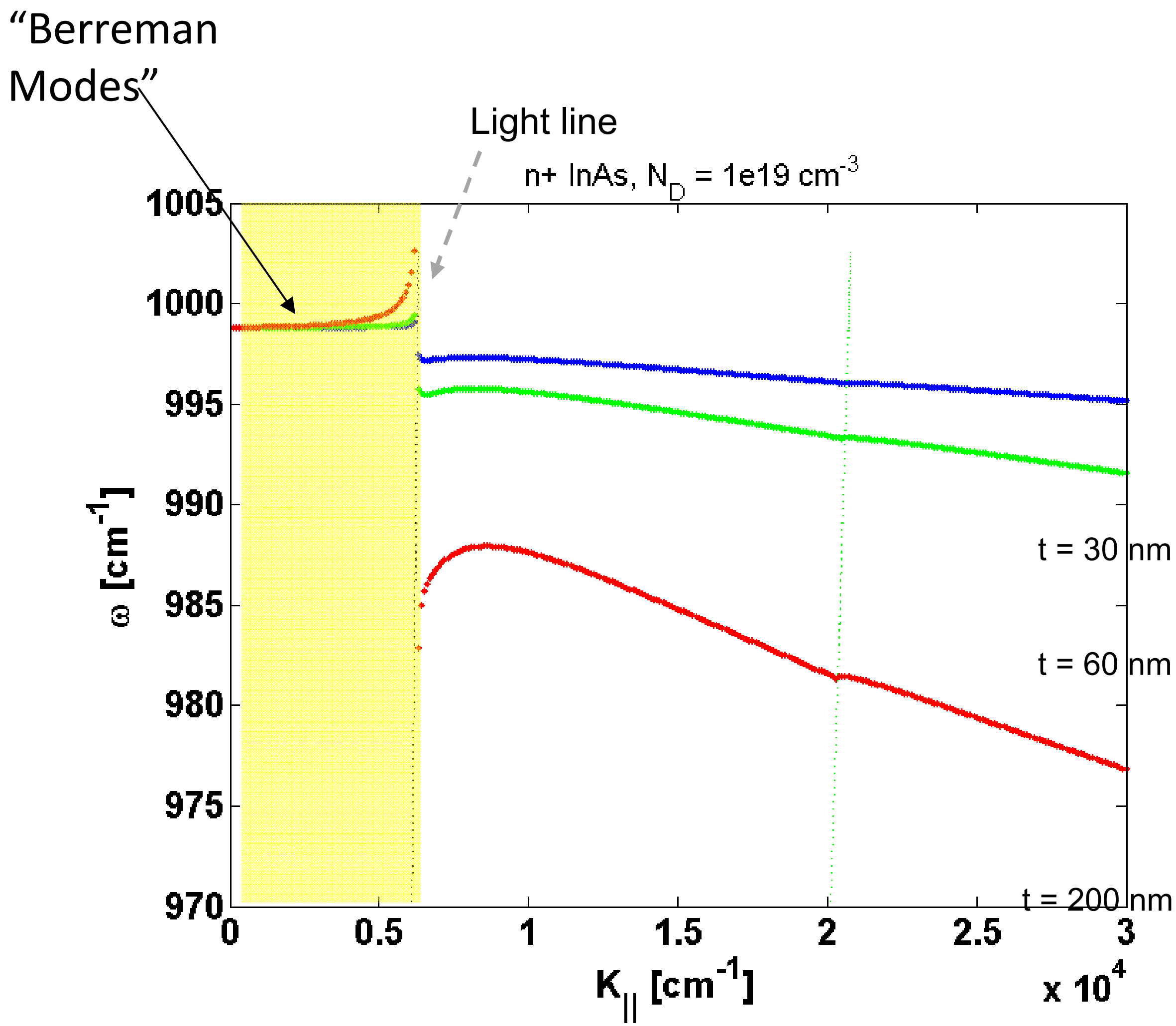




- **Berreman mode (leaky mode),**
- **ENZ mode (bound mode)**
- ENZ mode is a special type of a plasmon polariton

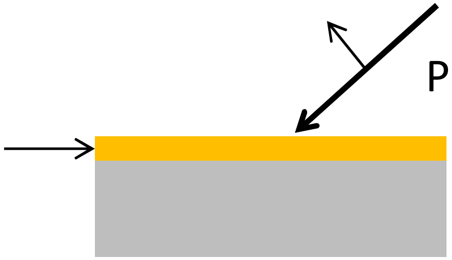
S. Vassant et al., Phys. Rev. Lett. **109**, 237401 (2012)
S. Vassant et al., Opt. Express **20**, 23971 (2012)

Berreman Modes



Leaky modes: can couple from free space

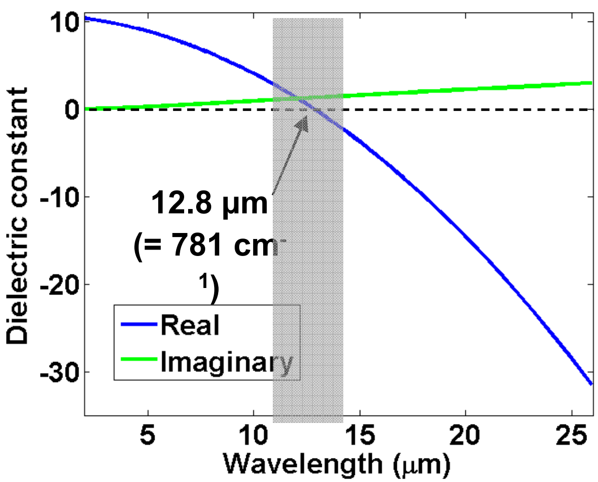
Berreman Modes

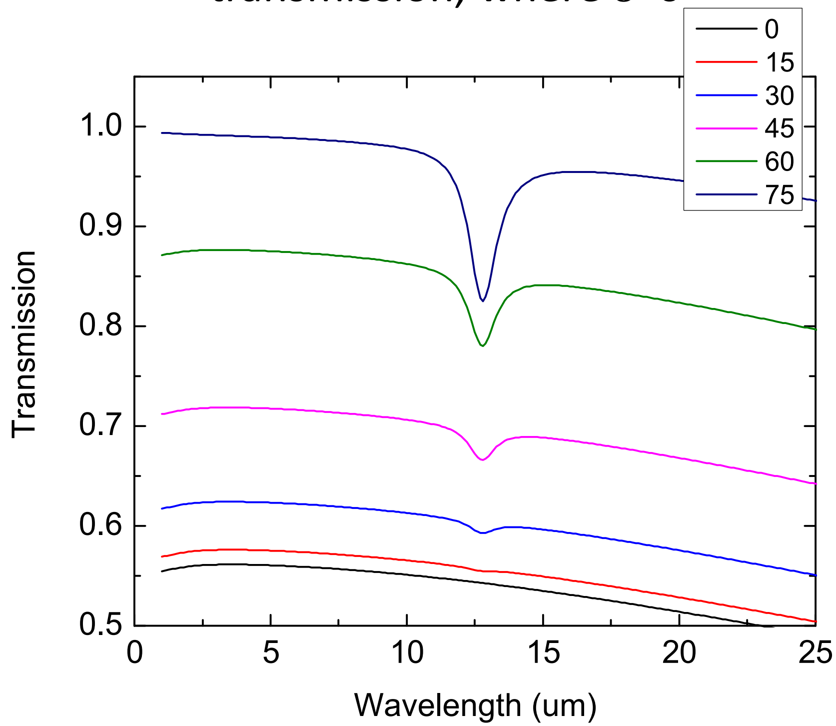


Thin (<<λ) layer where ε crosses 0 (Drude, phonon, etc)

Transmission vs angle (p-pol): A sharp dip is observed in transmission, where ε~0

Example: "Drude" layer

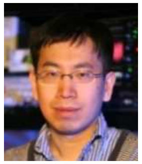




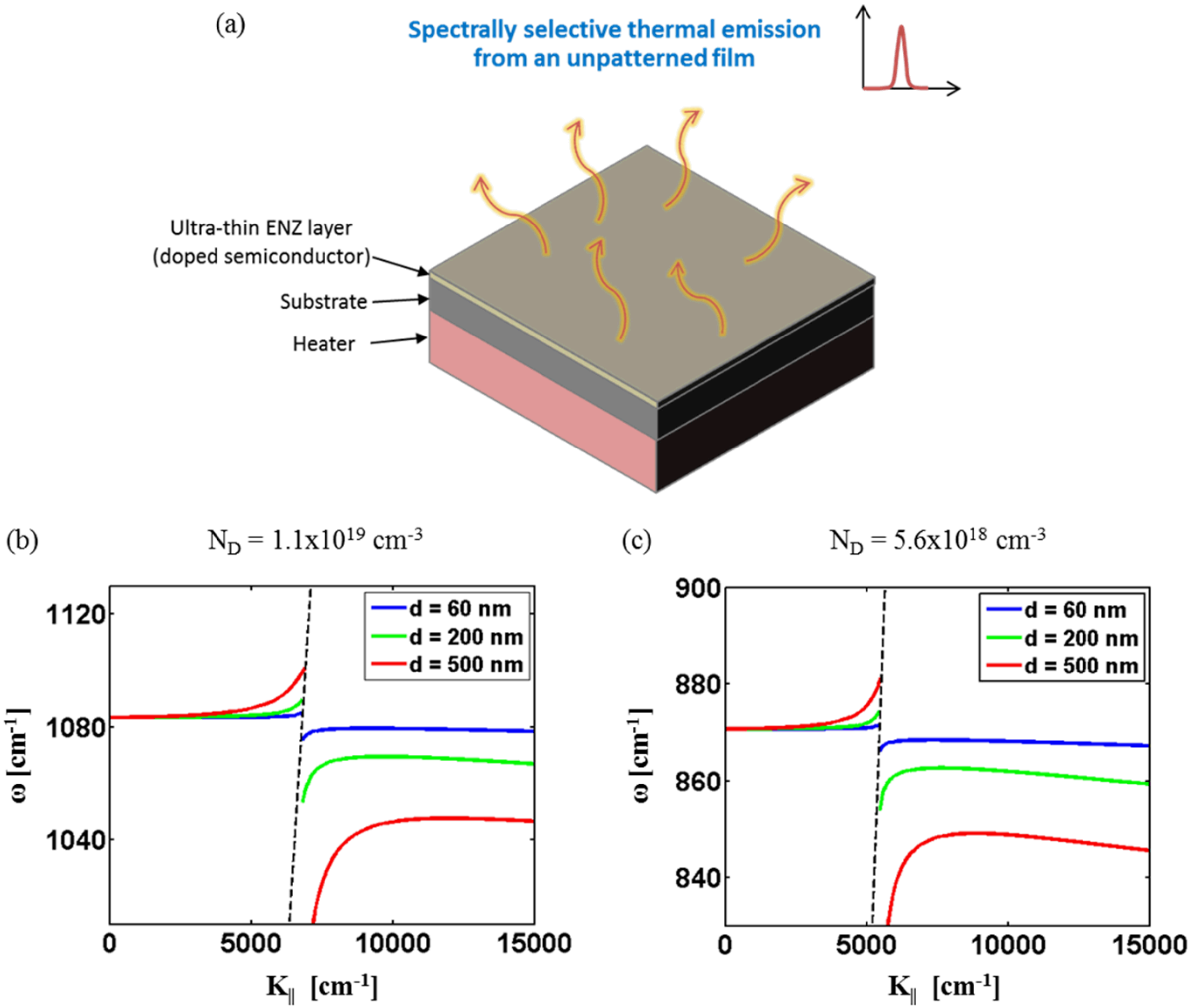
("Berreman" dip)

Berreman, Physical Review 130 (6), 2193 (1963).
McAlister and Stern, Physical Review 132, 1599 (1963).

Thermal Emission: Berreman Modes



Young Chul



Kirchhoff's law of thermal radiation: the absorptivity of an object should be equal to its emissivity ($A = \epsilon$)

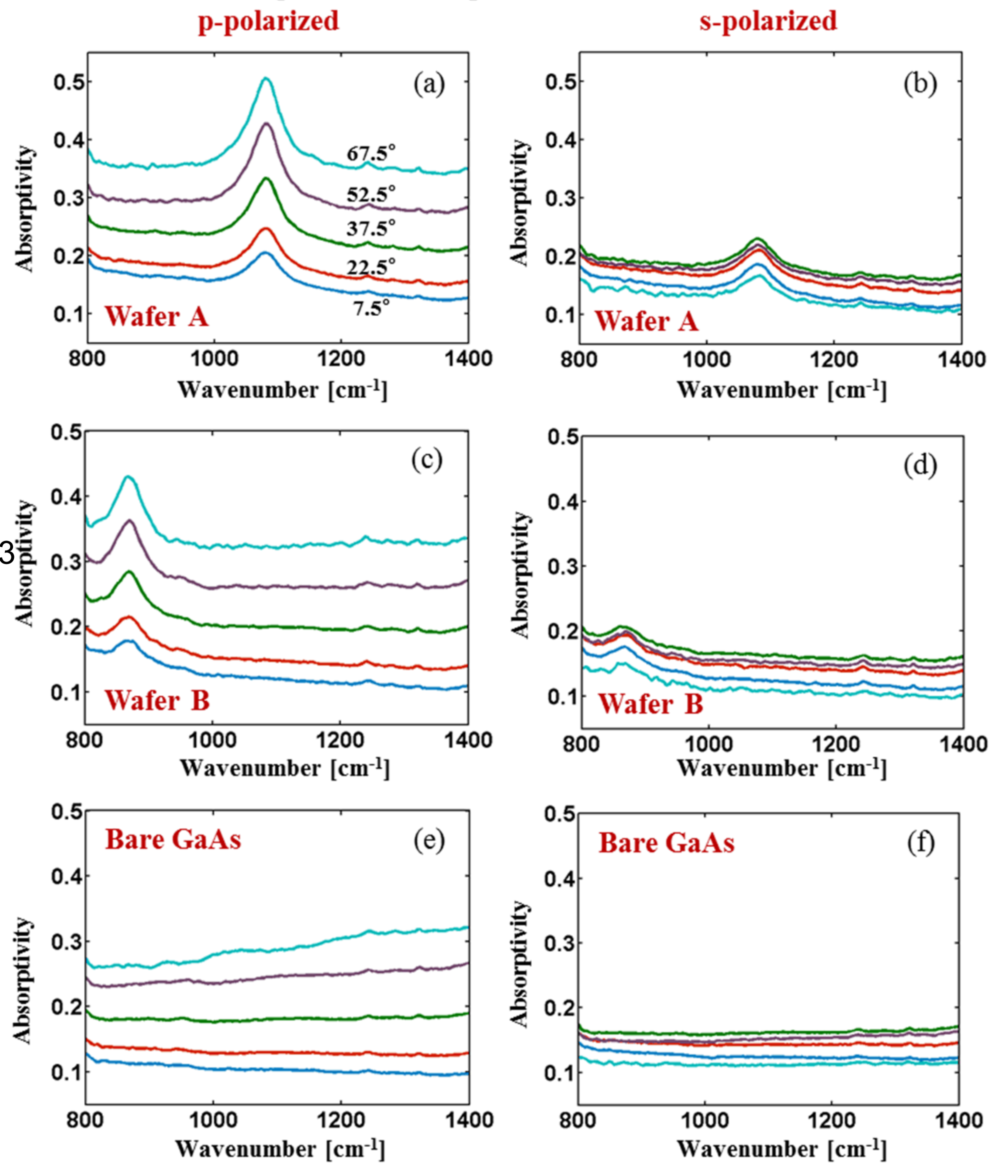
APL, *in press*

Angle-resolved, polarization-dependent absorptivity measurements

$N_D = 1.1 \times 10^{19}\ cm^{-3}$

$N_D = 5.6 \times 10^{18}\ cm^{-3}$

Bare GaAs

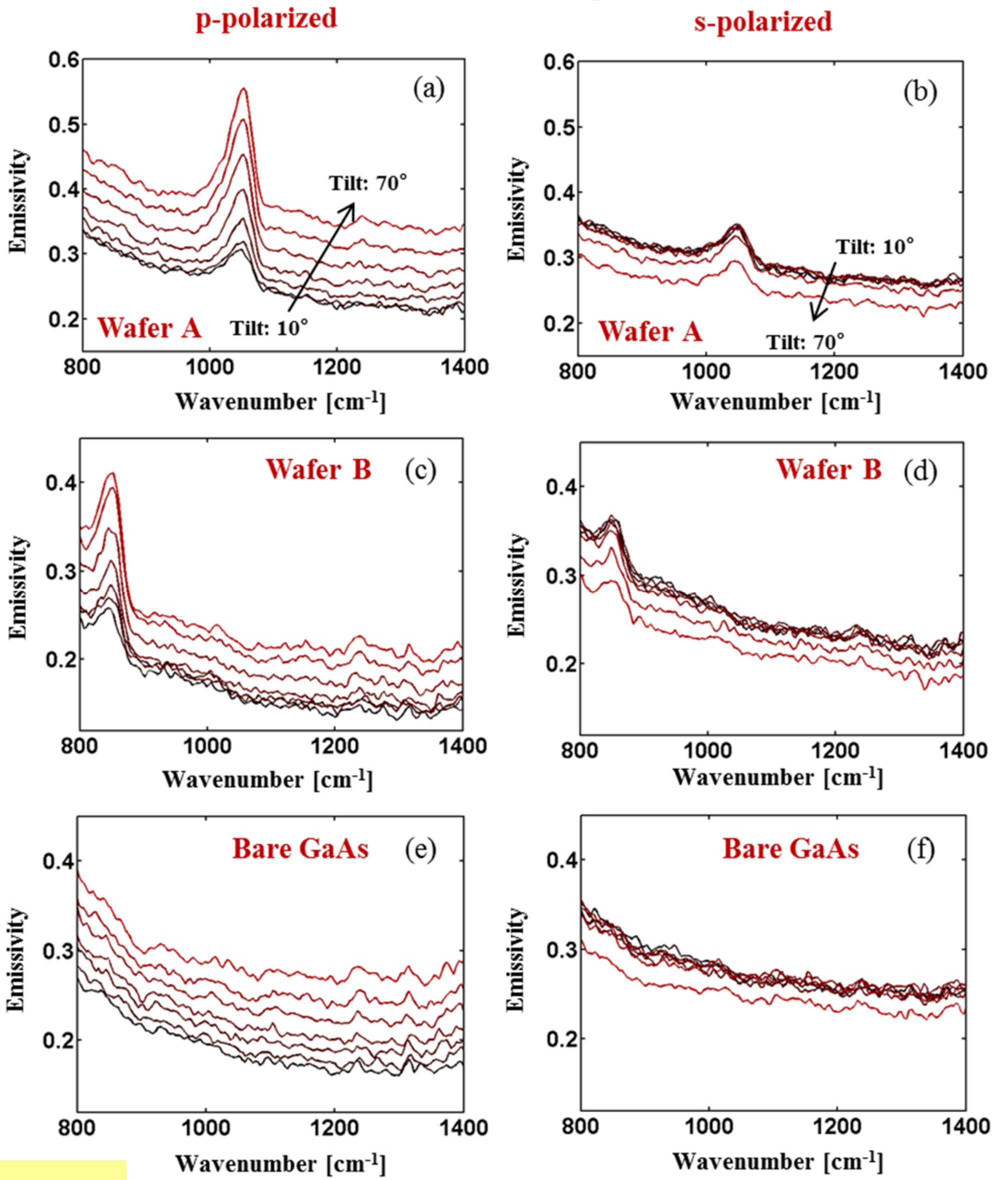


60nm InAs

Hyperhemispherical Directional Reflectometer

$A = 1 - R - T$

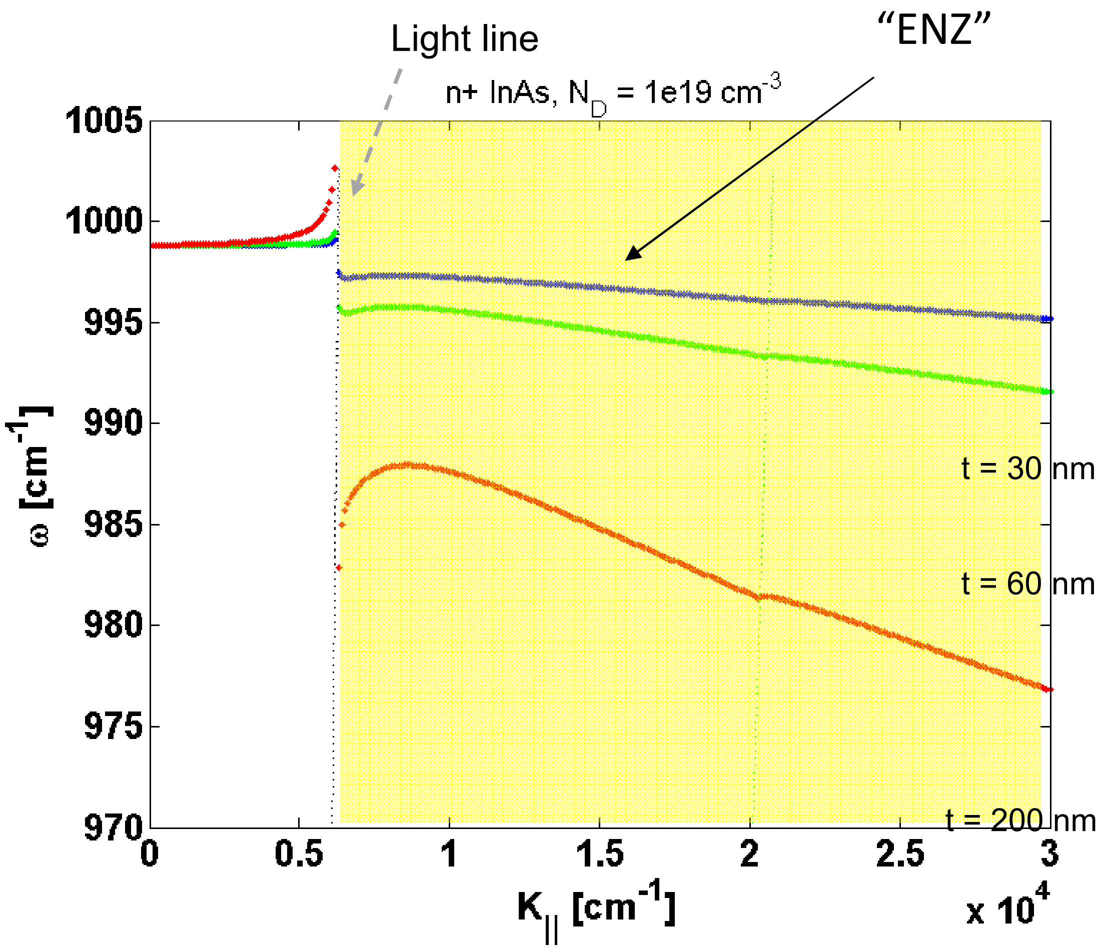
Angle-resolved, polarization-dependent emissivity measurements (140°C)



- **Unpatterned semiconductor thin films generate spectrally selective thermal emission near the ENZ frequencies.**
- **Wavelength determined purely by doping densities**
- **An ENZ film works as a "leaky wave antenna"**

APL, *in press*

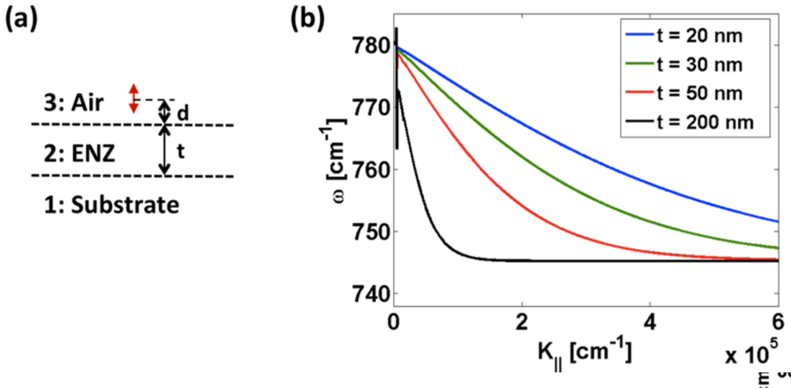
ENZ Modes



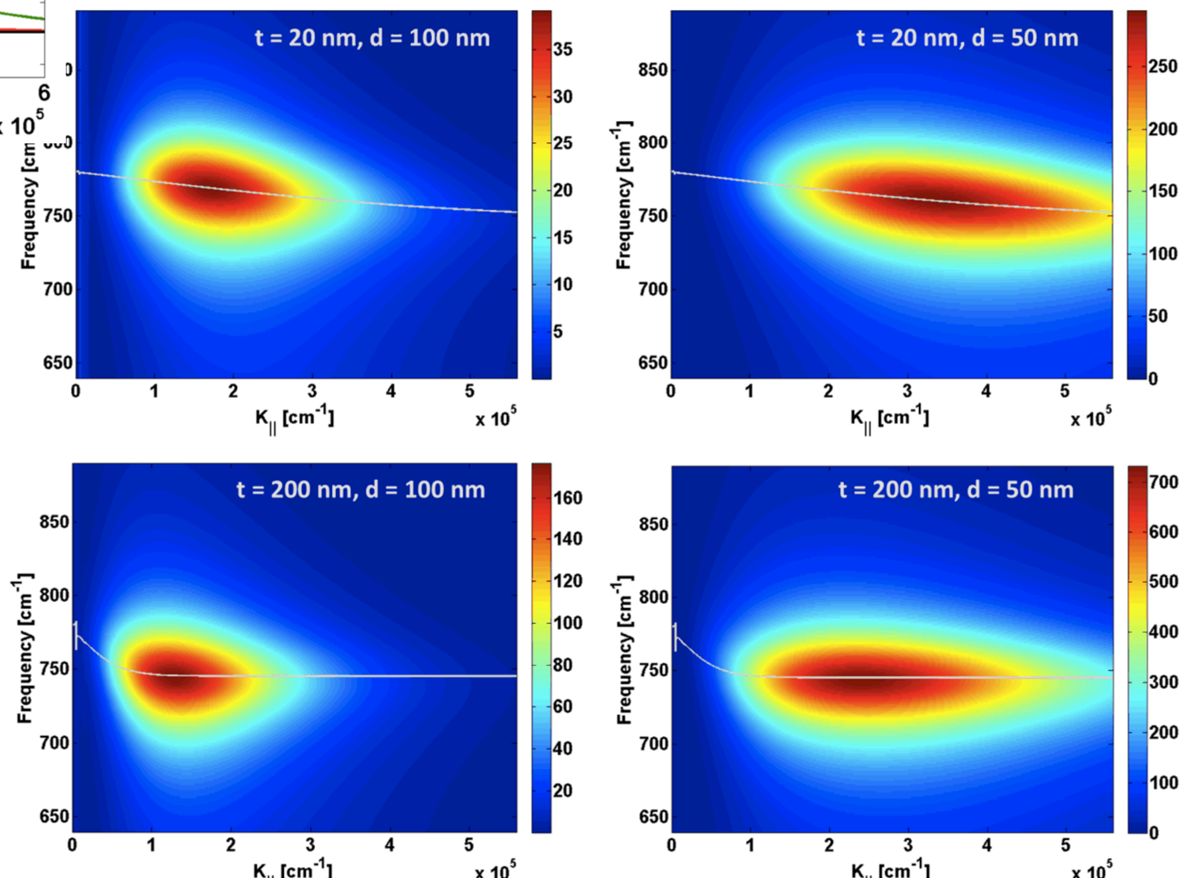
To the right hand side of the light line: cannot couple from free space

MM Resonators Provide k-vectors to Excite ENZ Modes

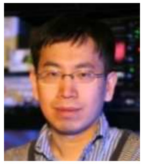
ENZ dispersion



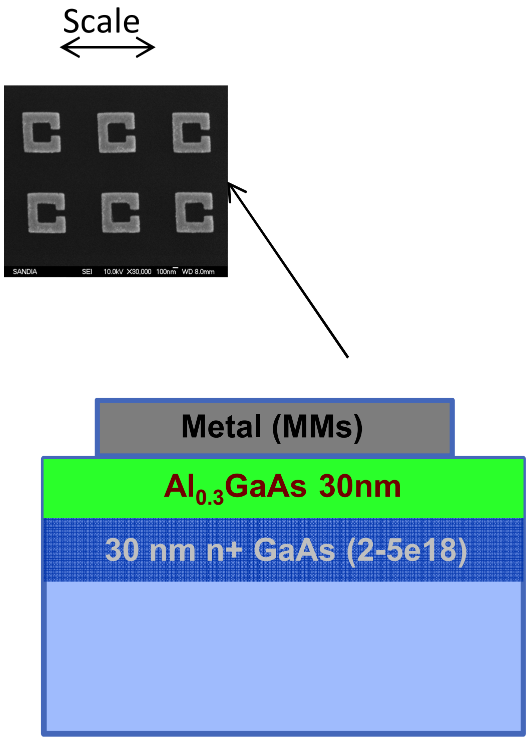
Superimpose dipole emission spectra on the ENZ dispersion



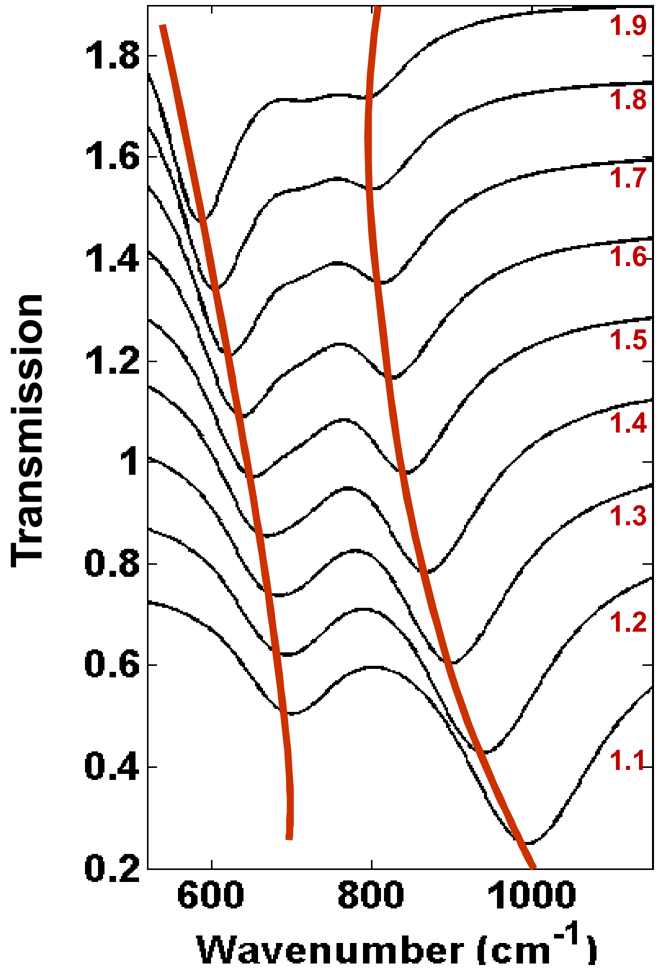
Strong Coupling to ENZ Mode: Theory vs. Experiment



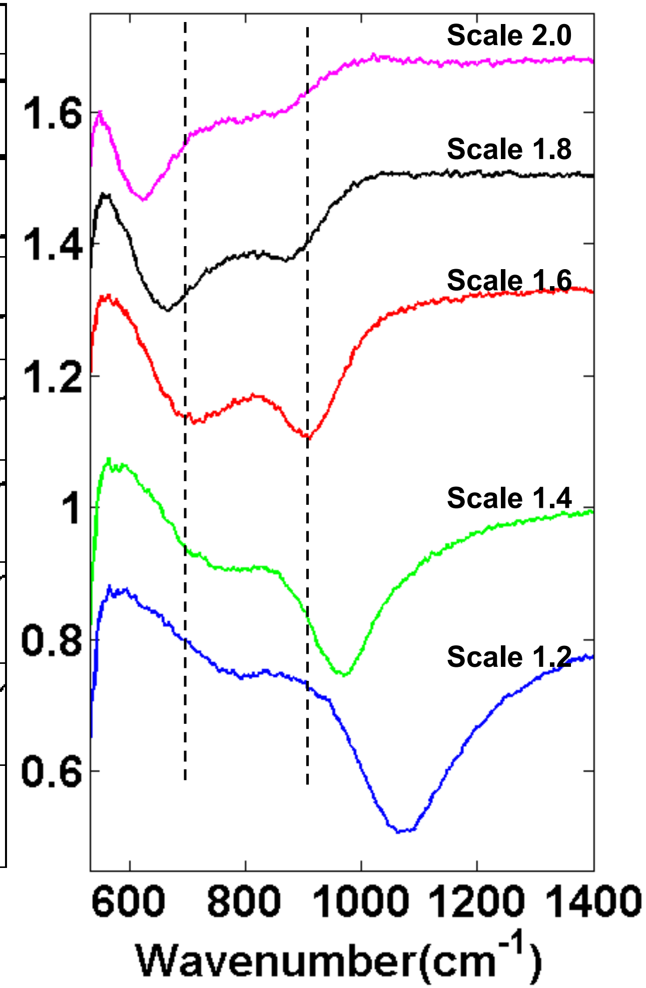
Young Chul



Numerical simulation (FDTD)

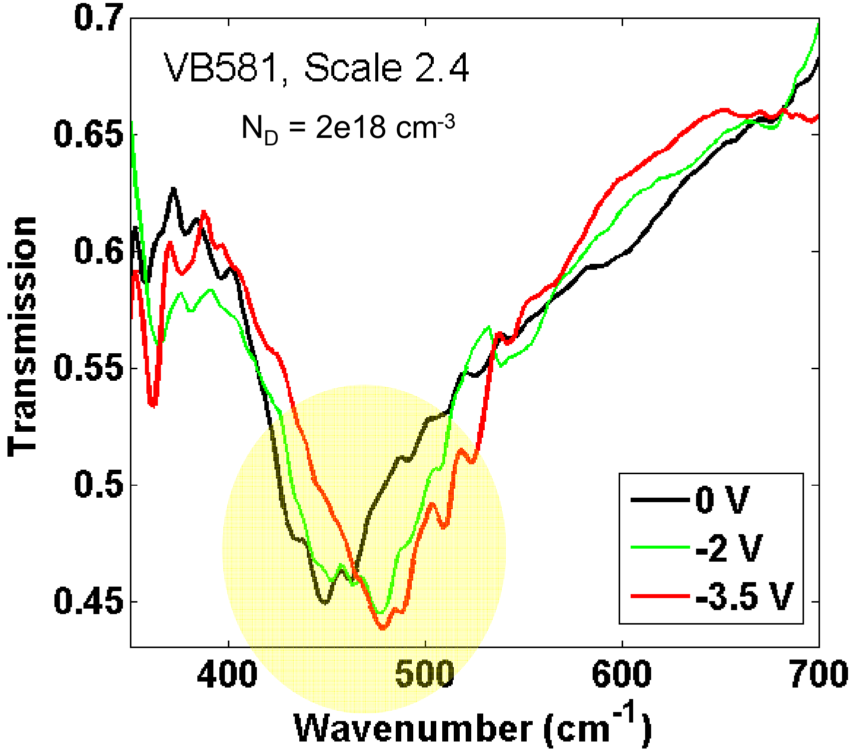


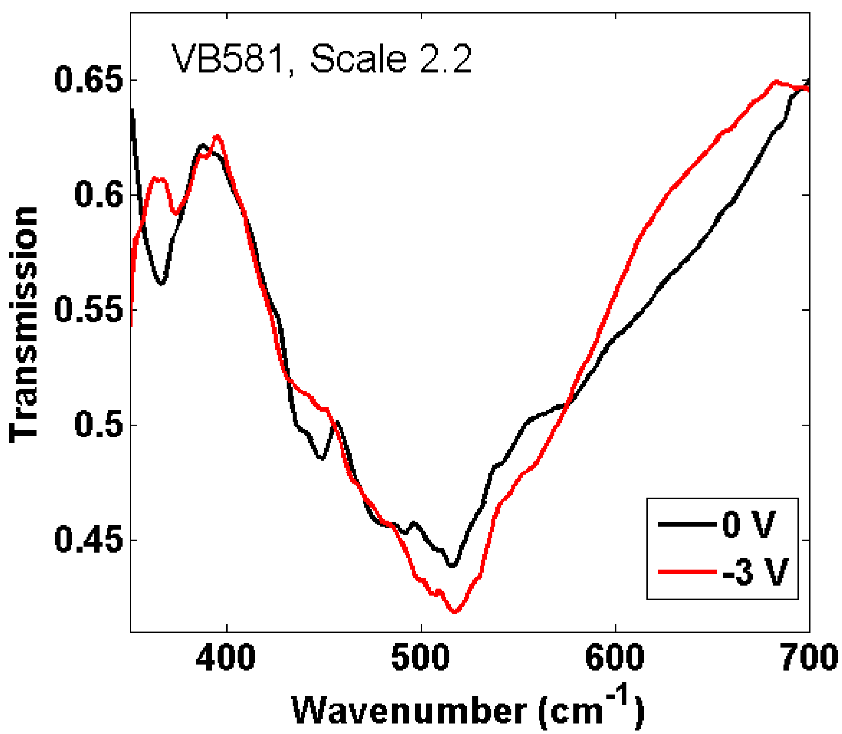
FTIR transmission measurement



Nano Letters **13**, 5391 (2013)

Electrically Tuning the Coupling to the ENZ Mode



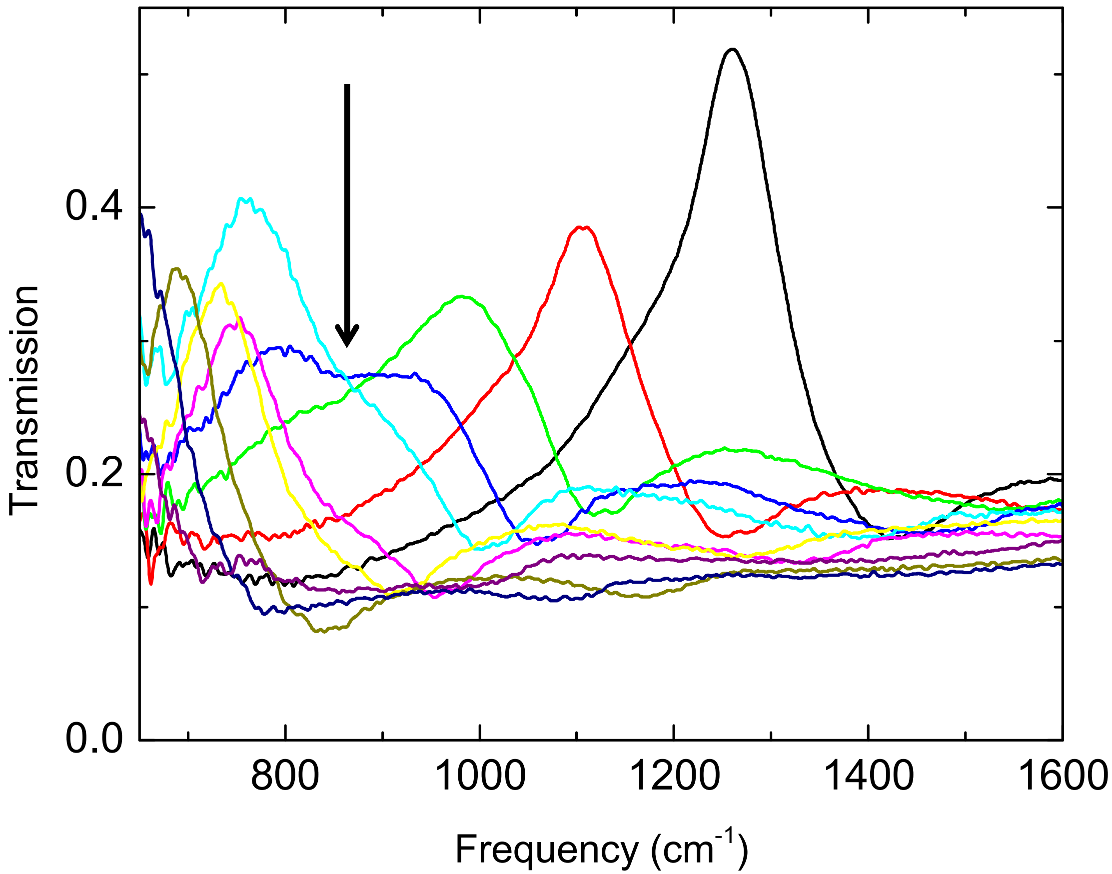


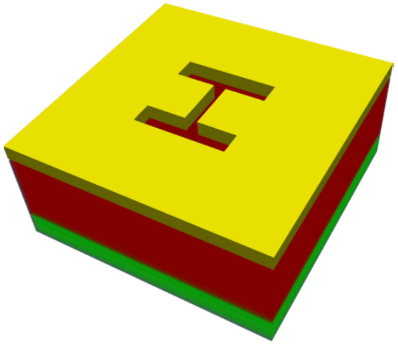
Fundamentally different than tuning just by changing a local permittivity!
Removal of carriers -> removal of ENZ mode

Nano Letters **13**, 5391 (2013)

Inverted Dogbone + ENZ

Tunable Passband Filter





Outline

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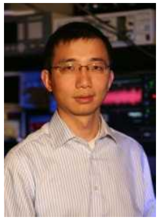
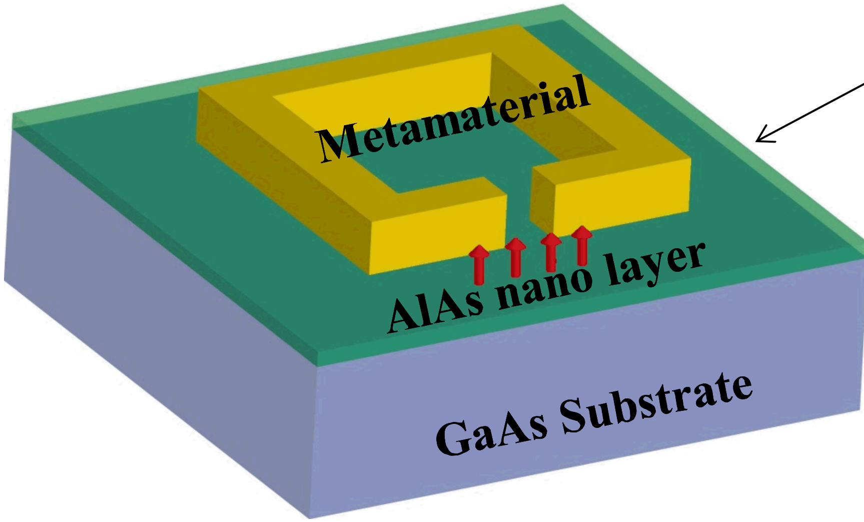
  - **Optical Phonons**
  - **Intersubband transitions**

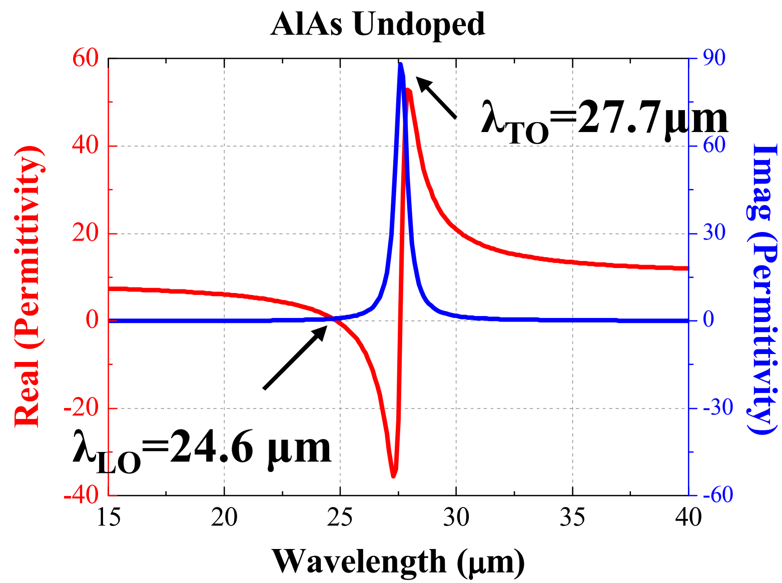
ENZ Layer With an Optical Phonon Resonance



Sheng

Optical Phonon



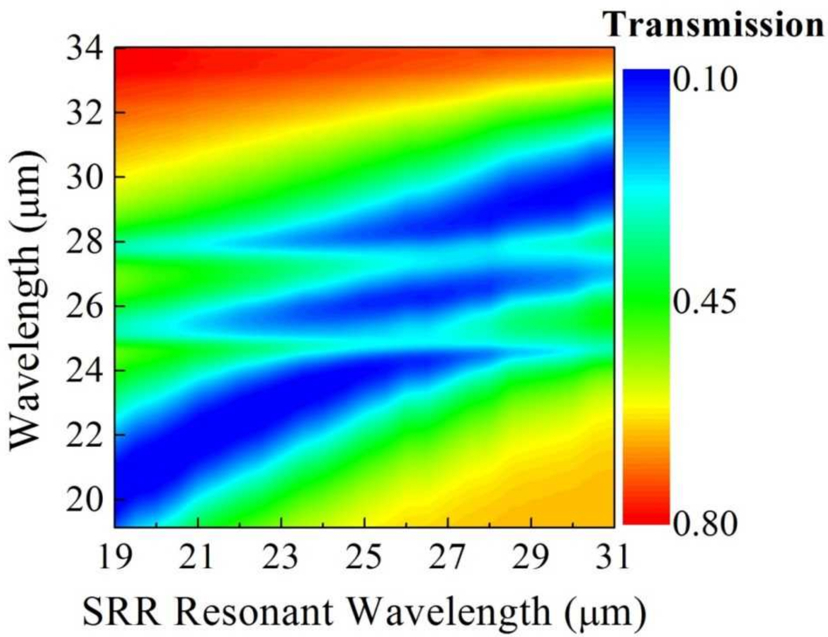


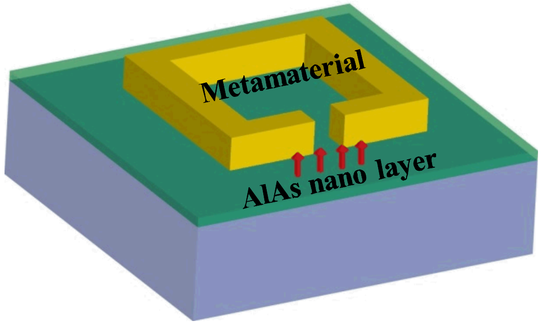
One thin layer contains:

- ε~0 crossing -> ENZ mode
- TO Phonon: "dipole" transition

Strong Coupling: 2 Polariton Branches

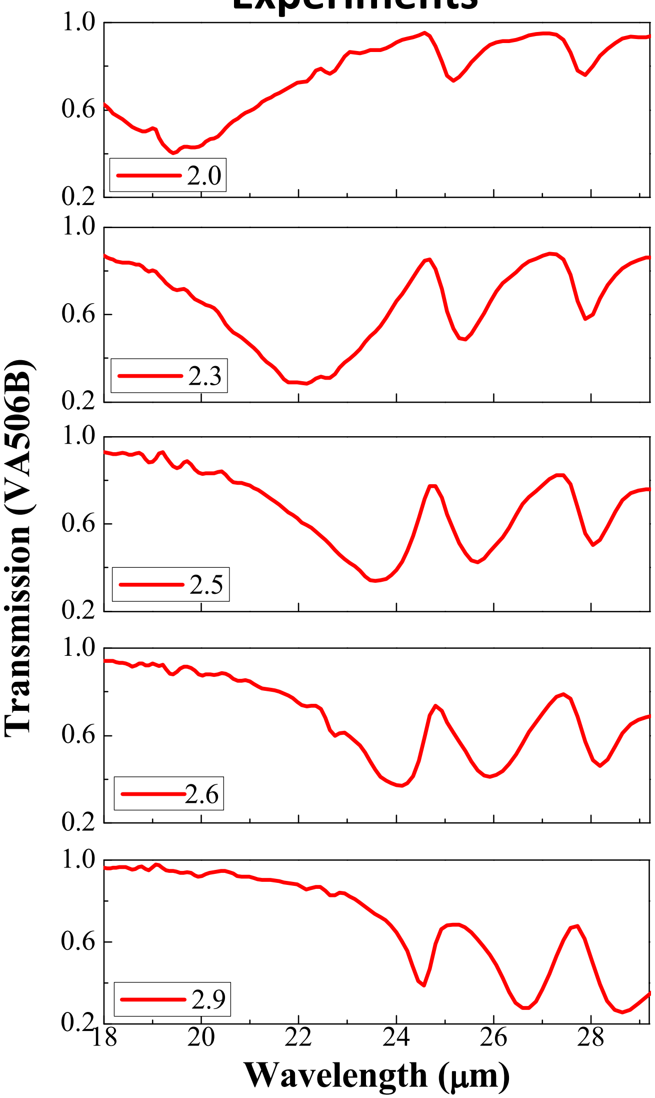
Simulations





Increasing SRR size

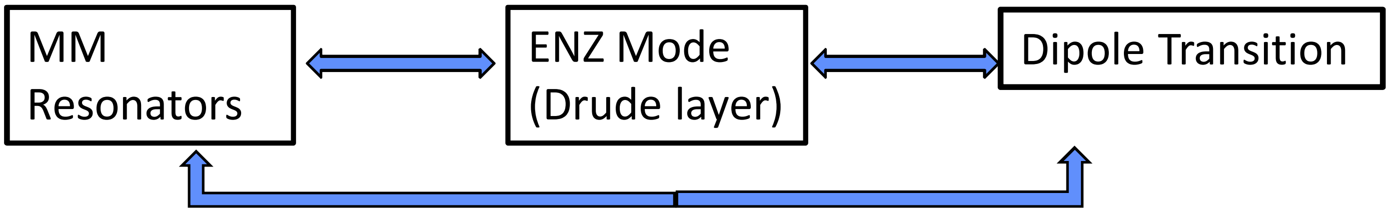
Experiments

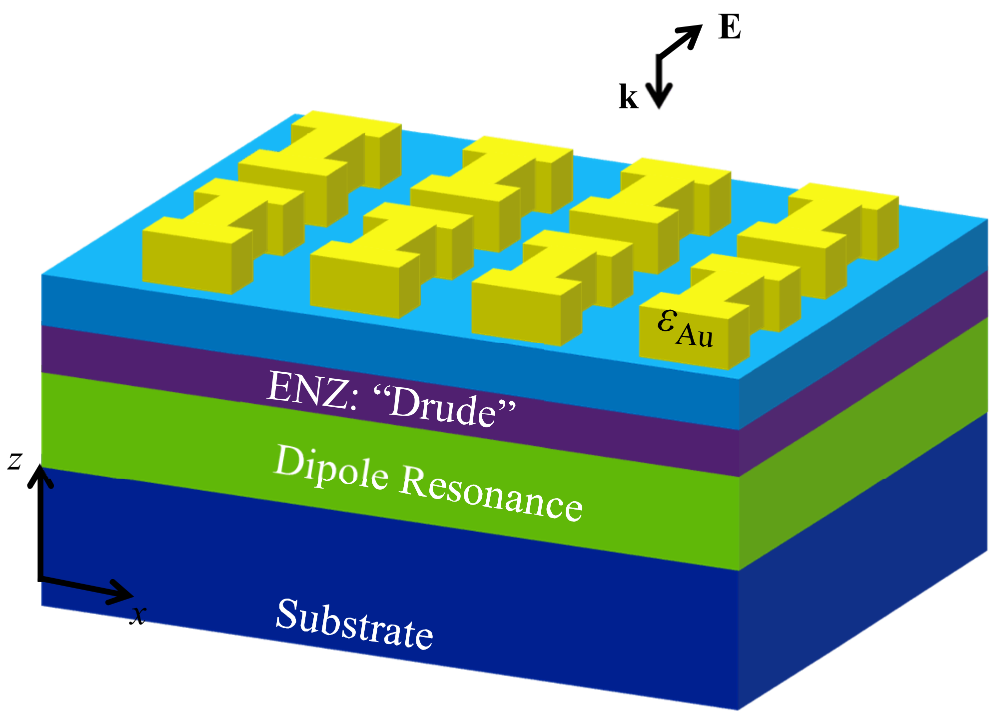


Let’s Separate the ENZ Layer and the Dipole Resonance Layer

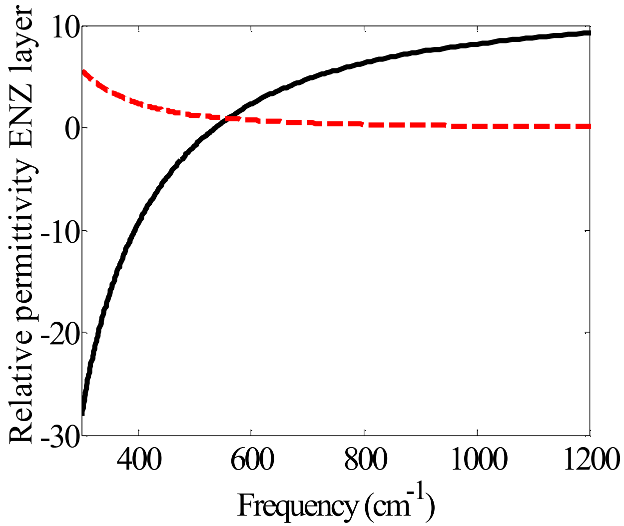
Salvo

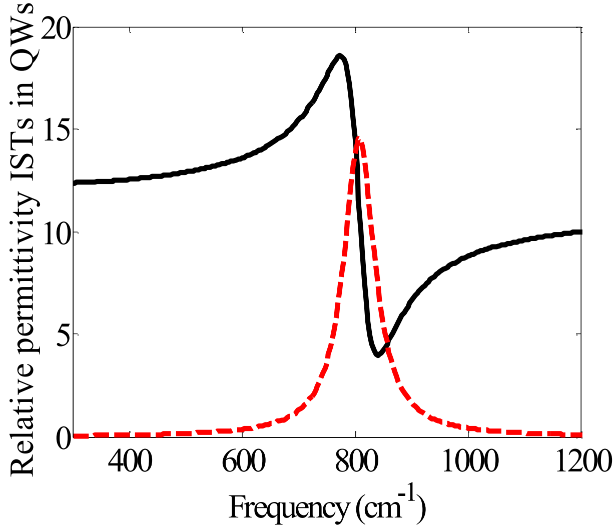
3 Interacting Systems



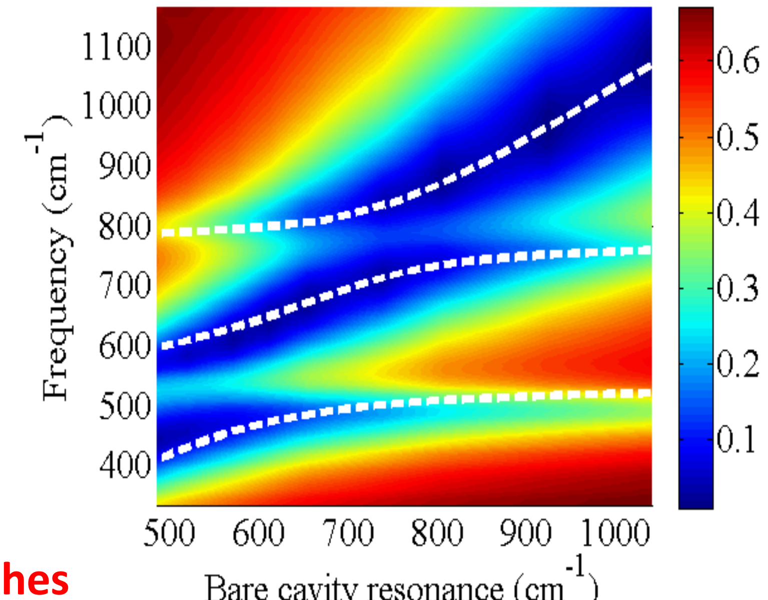


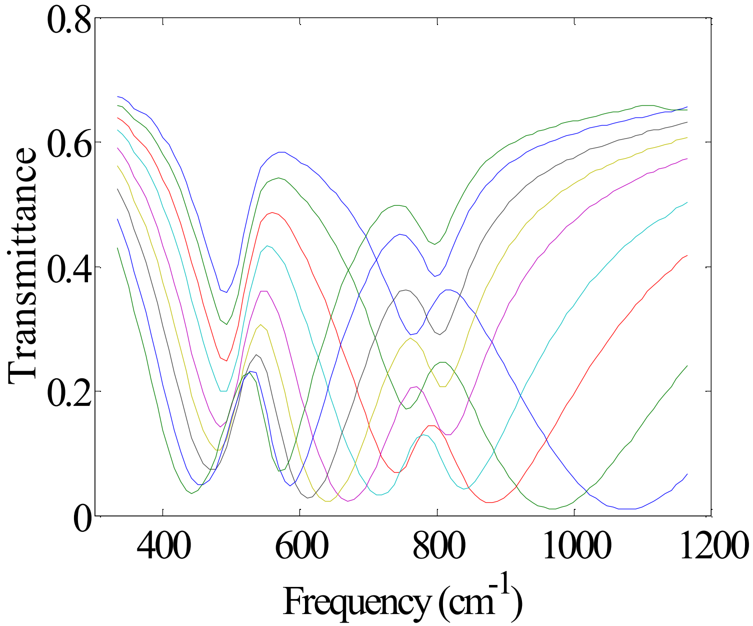
Case 1: Different Frequencies for Dipole Transition and ENZ





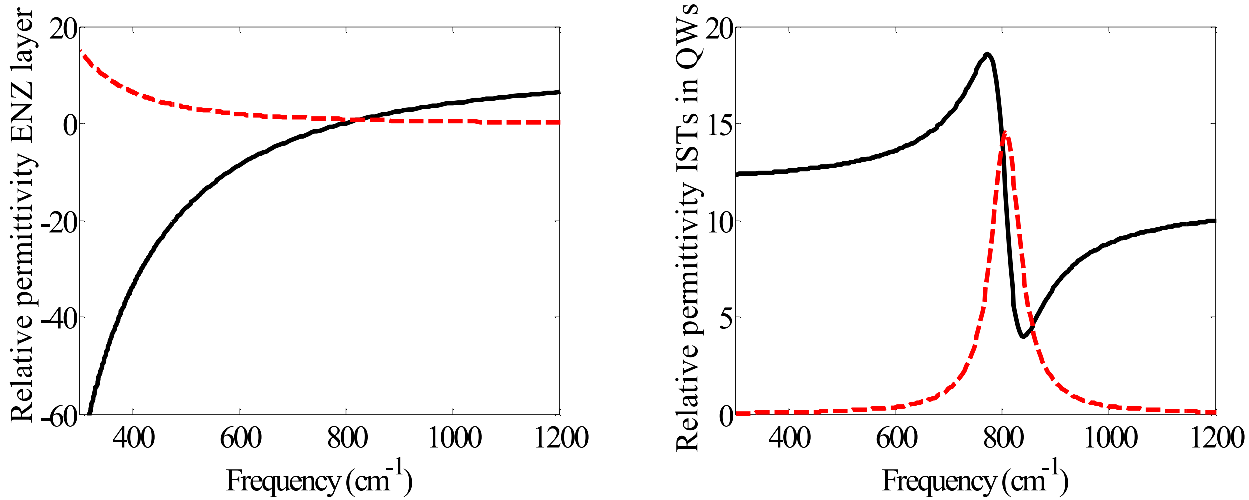
(simulations)



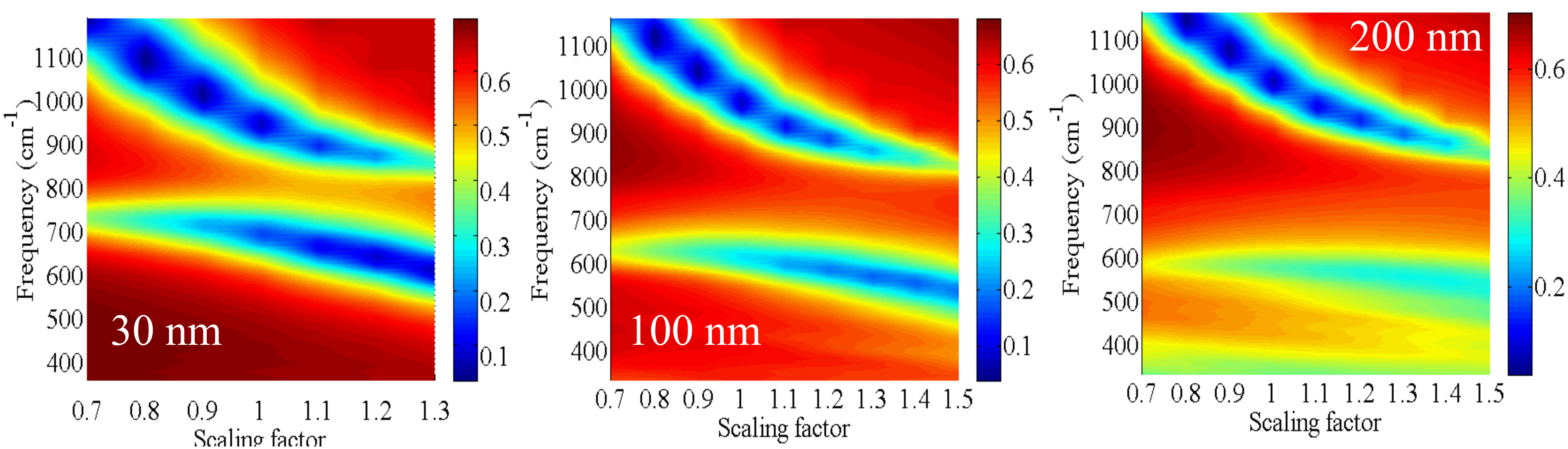


2 Different Polariton Branches

Case 2: Same Frequencies for Dipole Transition and ENZ

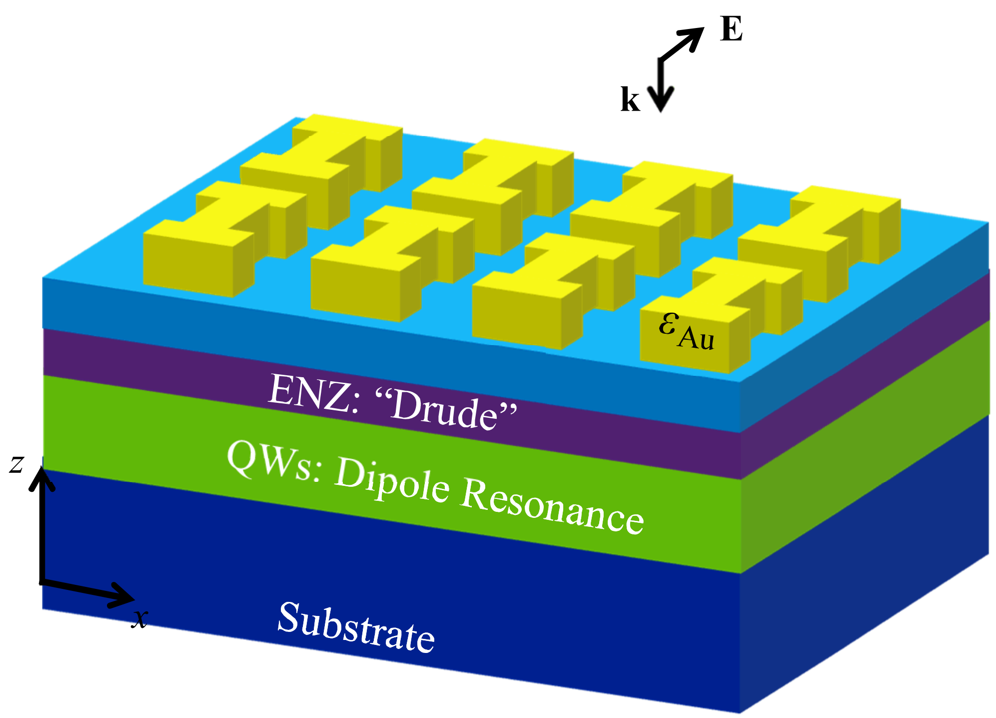


(simulations)



Only 1 Polariton, larger Rabi Splitting!

Experimental Verification:
MMs+ENZ+Dipole Transition



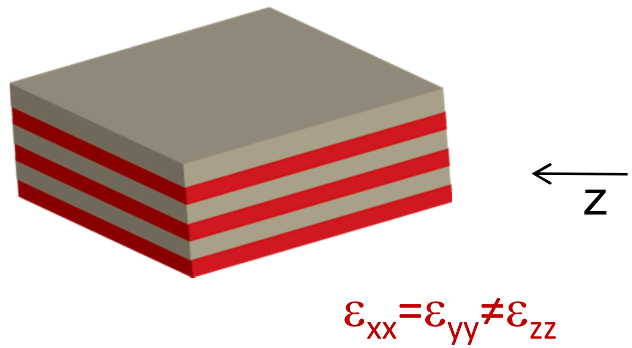
Inter-subband Transitions in Quantum Wells:

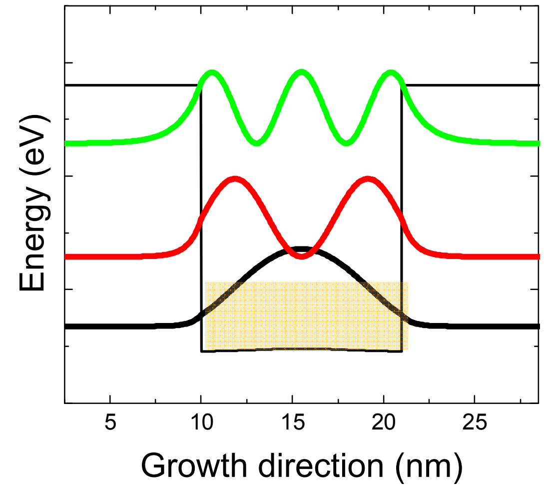
Anisotropic Dipole

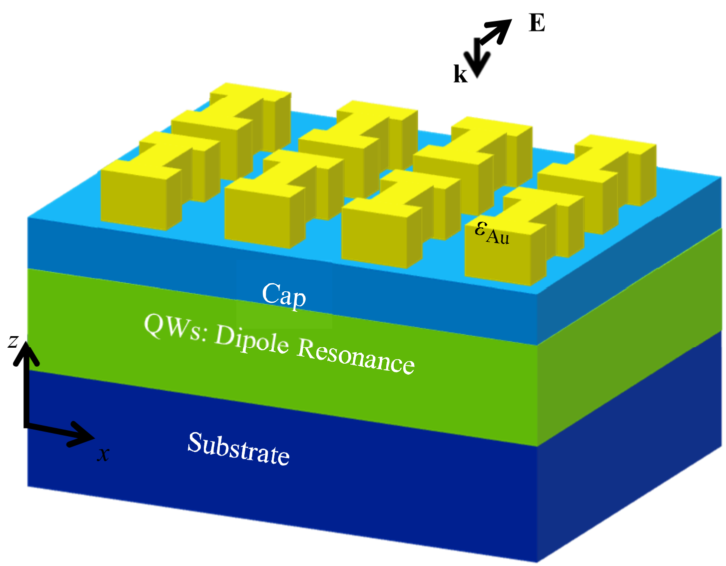
Alex

•Scalabe (far IR to near IR), Mature, Versatile

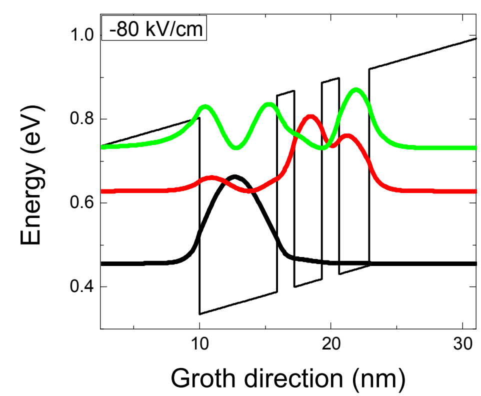
Opt. Express 20, 6584 (2012), APL 98, 203103 (2011)





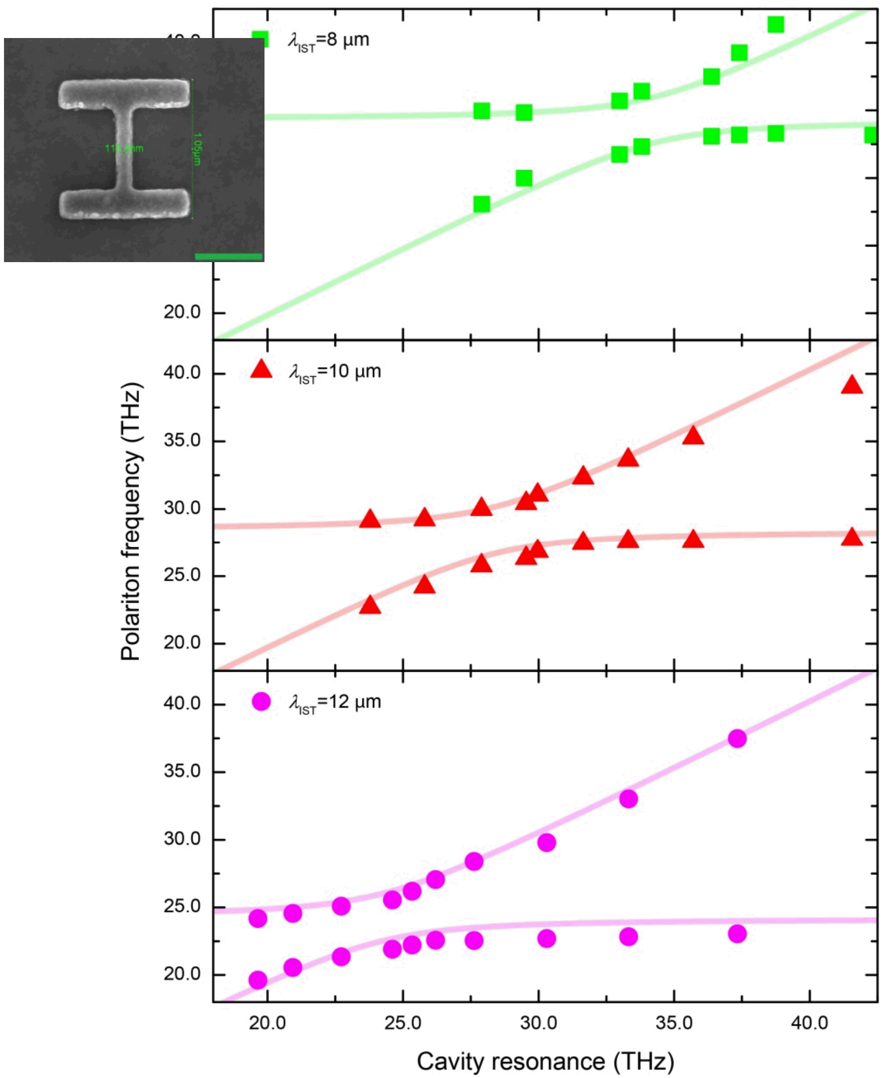


Tunable by changing levels using an electric field (voltage bias)

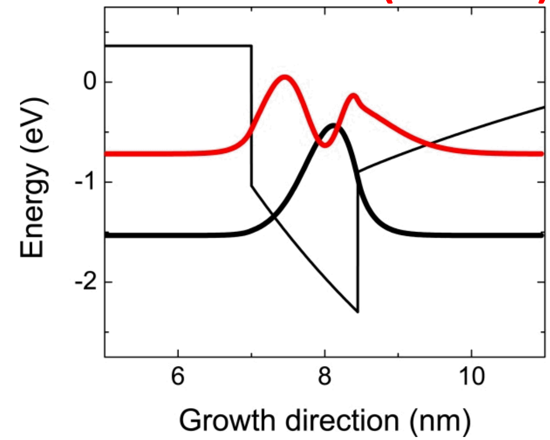


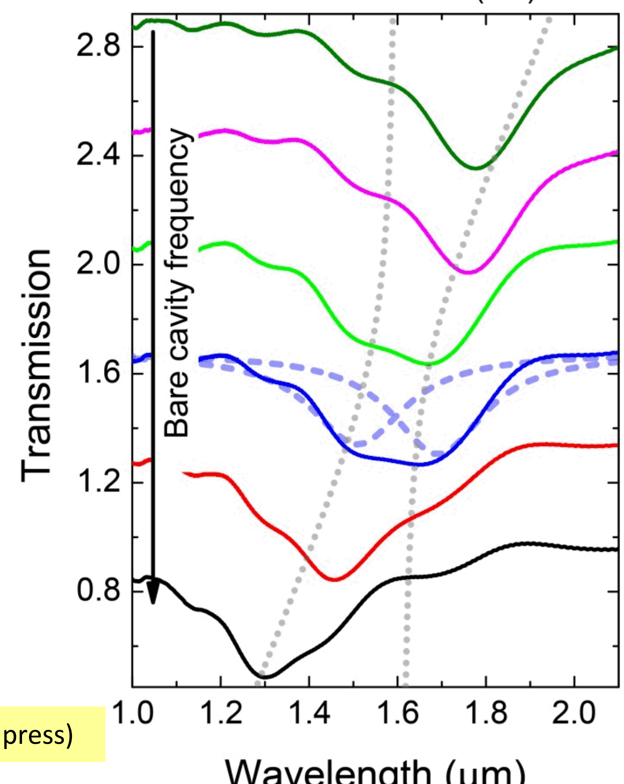
From Mid-IR to Near IR

InGaAs QWs **(mid IR)**



GaN QWs **(near IR)**





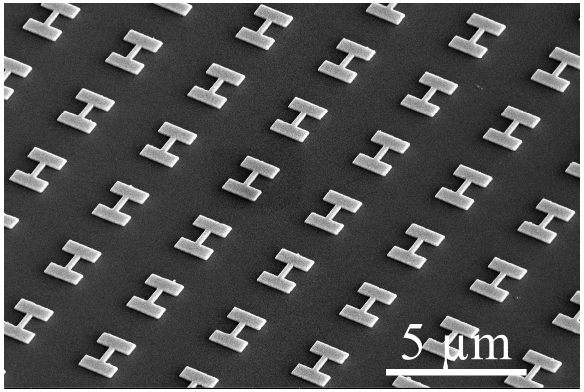
ACS Photonics (in press)

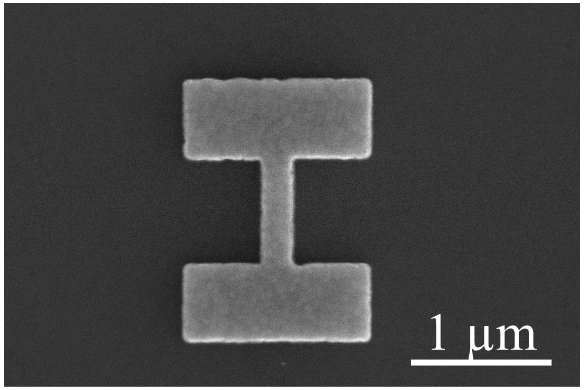
Nature Communications 4, (2013)

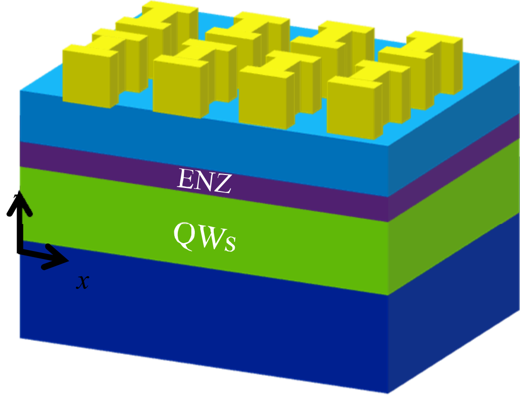
Experimental Verification of Combined Strong Coupling:

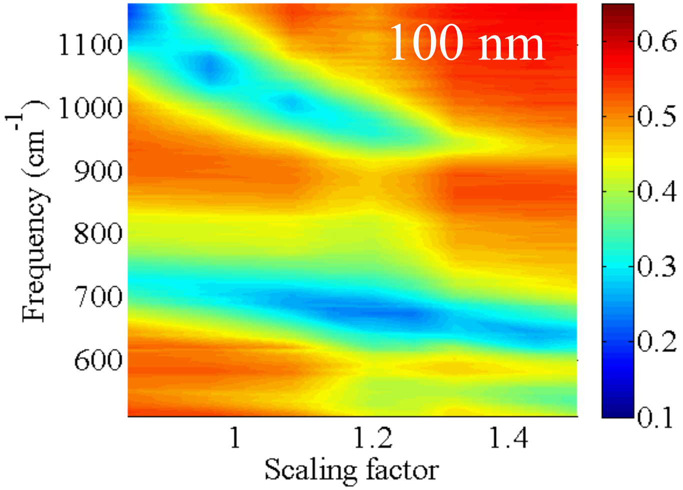
(ENZ layer + dipole transition in QWs)

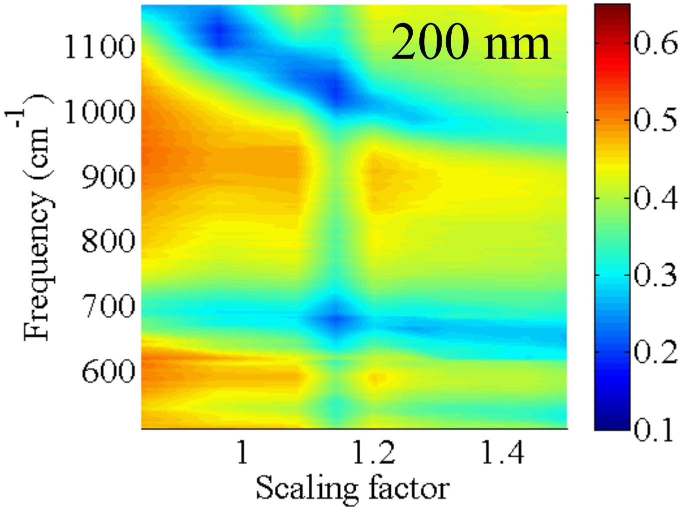
Salvo





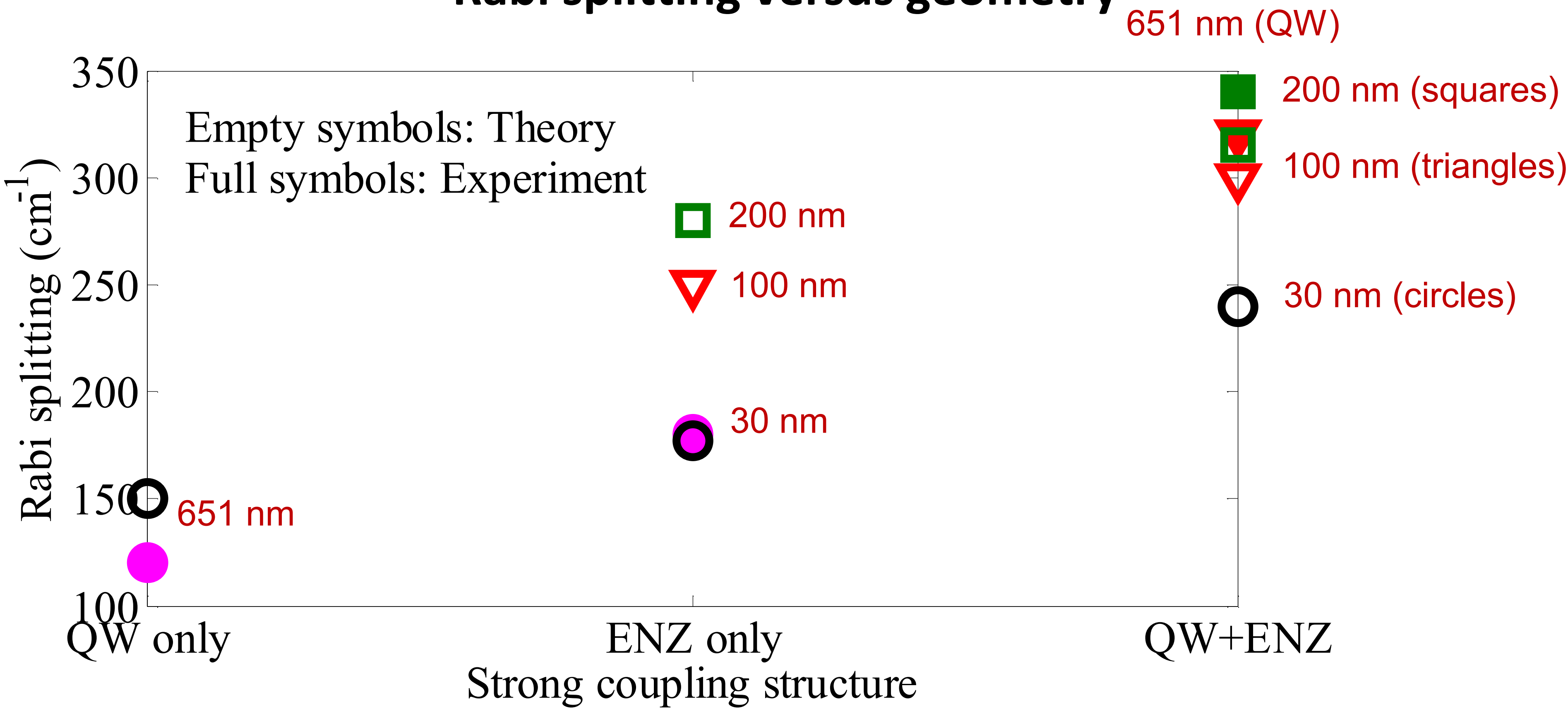






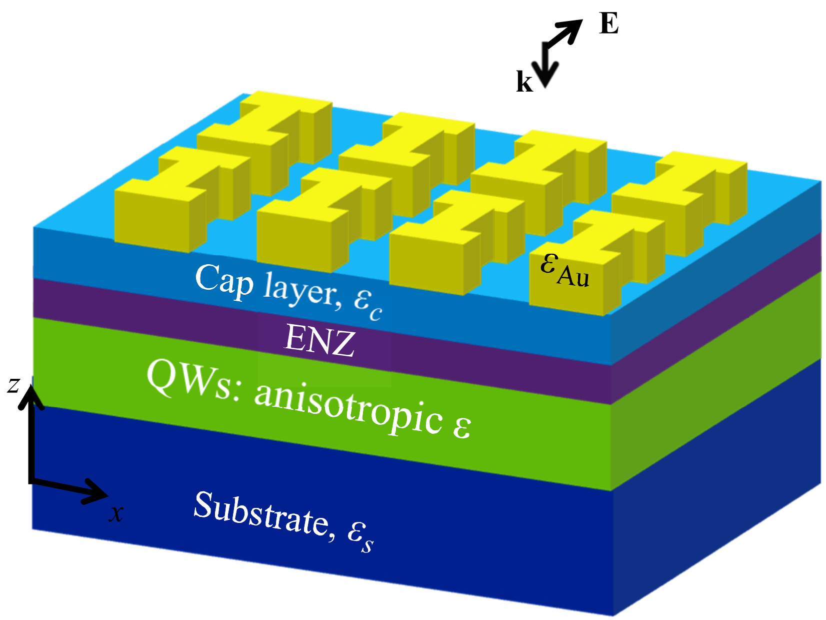
ENZ layer + dipole transition in QWs

Rabi splitting versus geometry

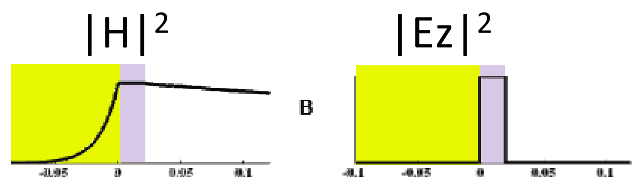


The structures comprising QW+ENZ exhibit the largest Rabi splittings for a given ENZ thickness

Combining ENZ Modes and Intersubband Transitions for Stronger Coupling

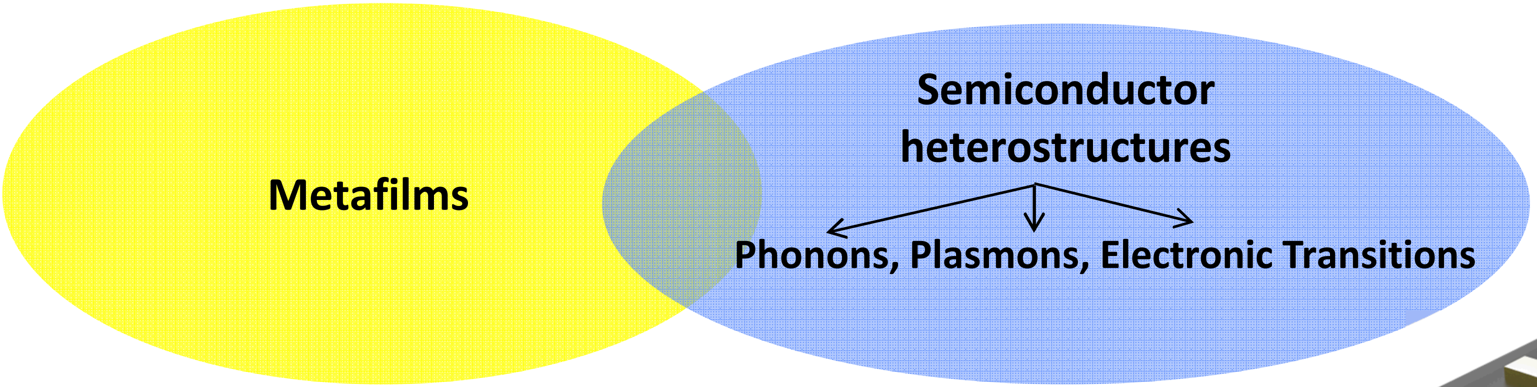


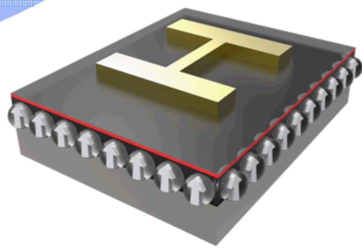
- Field decays exponentially with distance from MM resonators
- An ENZ thin layer acts as a "transducer" and potential "amplifier" of Ez field



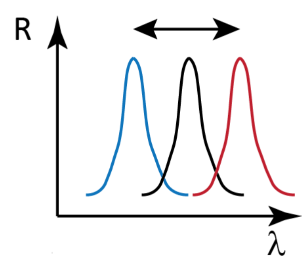
The addition of an ENZ layer <u>enhances</u> the coupling -> larger Rabi splitting

Summary





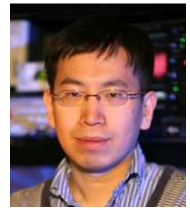
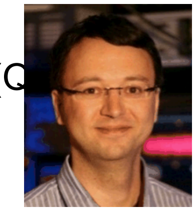
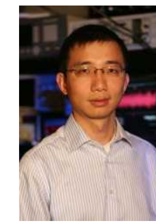
- **Metamaterial resonators + semiconductors offer a nice platform for tunable spectral behavior and variable coupling**



- **Applications: *low-voltage* tunable "filters" (or modulators) in the IR**

- **Fundamentals:**
  - **Very high ratio of Rabi splitting to carrier frequency (beyond the strong coupling model)**
  - **Combining different excitations (phonons, plasmons, ISTs) in unexpected ways**
  - **Next: Purcell, emission, nonlinearities….**

Acknowledgments

Postdocs: Young Chul Jun (n+, ENZ),  Alex Benz (Q  Sheng Liu (Phonons), 

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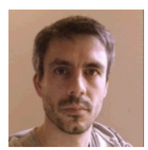
France: J.J. Greffet, F. Marquier  (ENZ)