SAND2014-17062PE

Voltage Tunable Strong Coupling with Planar Metamaterials: From Fundamentals to Optoelectronic Devices

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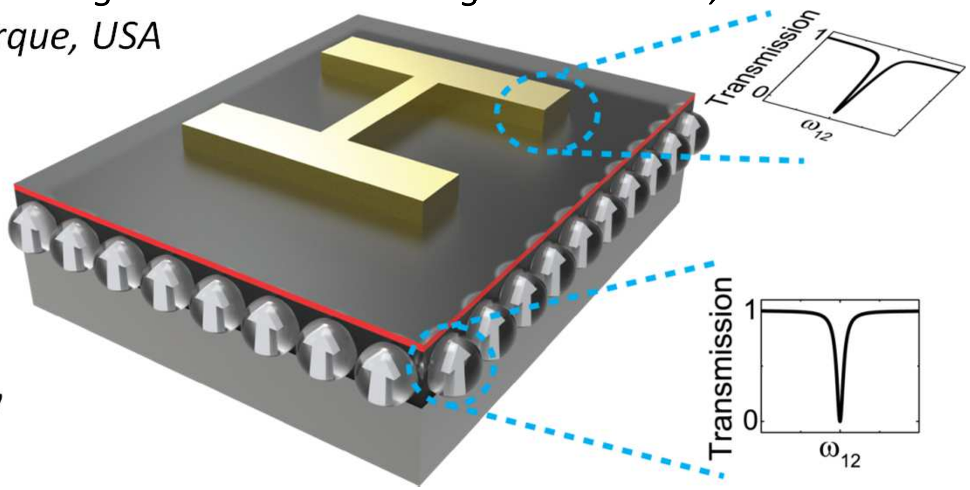

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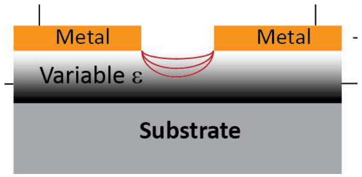
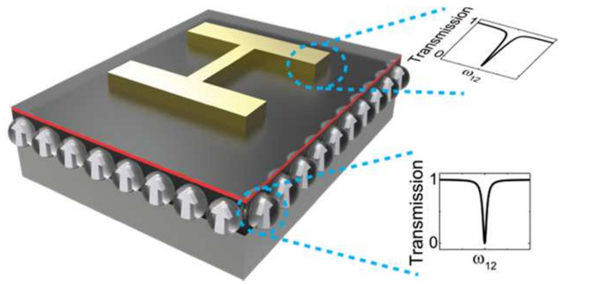
Planar Metamaterials: Strong Coupling & Tuning

MM resonators interact strongly with thin layers underneath

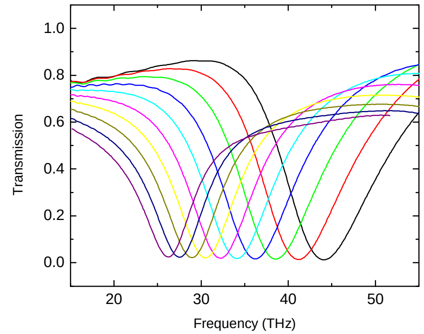


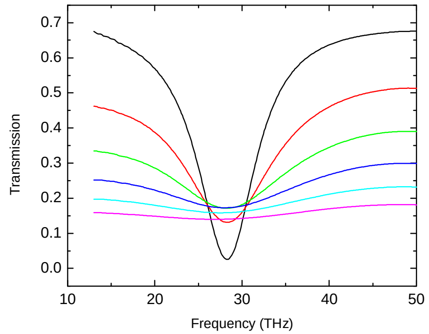


Change ε_1 (n)

Change ε_2 (n)

- Nonresonant

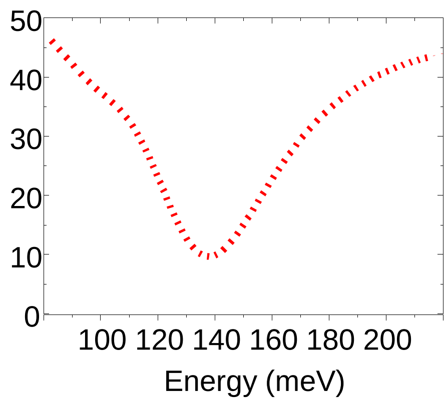


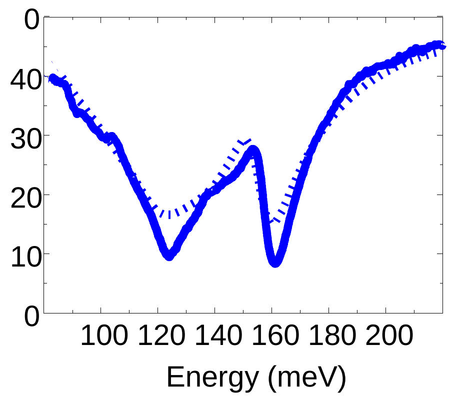


- Resonant

(Create a dipolar resonance, example: phonon)

Nano Letters 11, 2104 (2011)





Outline

- Strong Coupling to Intersubband Transitions
  - Fundamentals
  - Voltage Tuning
  - Wavelength scaling
- Strong Coupling to Epsilon-near-zero modes
  - Fundamentals
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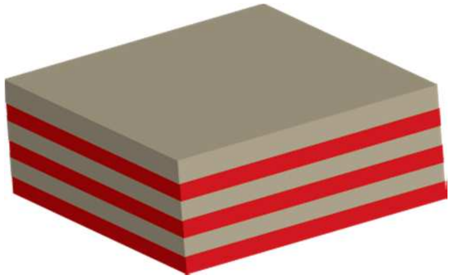
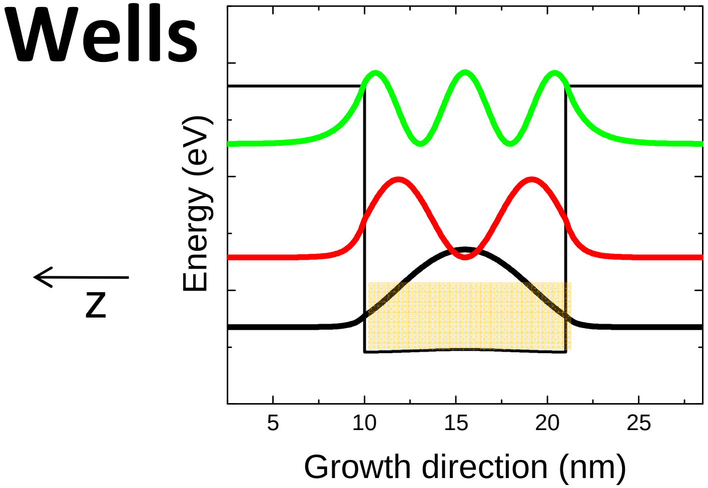
- Combining coupling to ENZ modes and Intersubband Transitions

Strong Coupling to Inter-subband Transitions in Quantum Wells

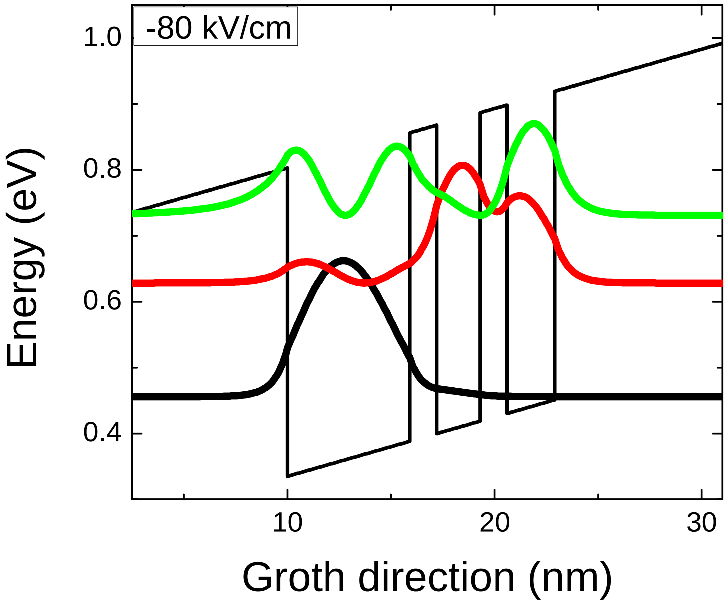
•Scalabe (far IR to near IR), Mature, Versatile

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

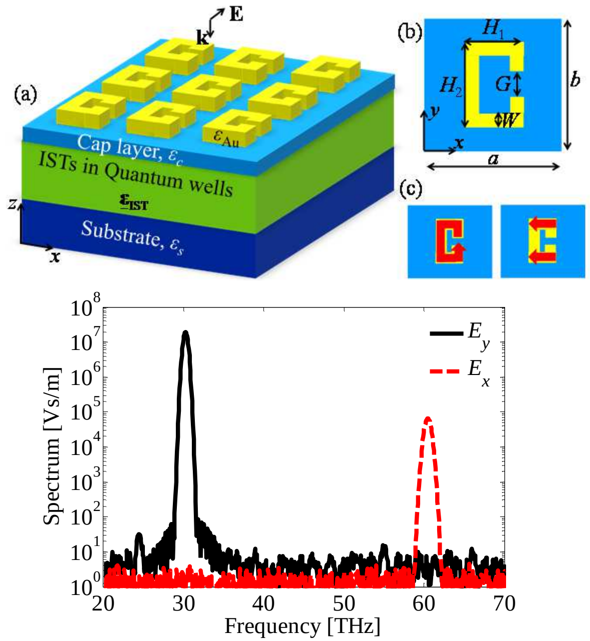




Tunable by changing levels using an electric field



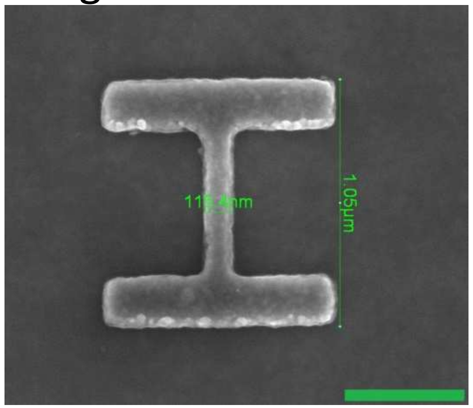
•Also good for nonlinear optics

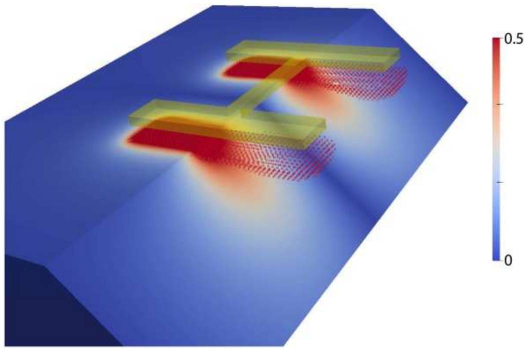


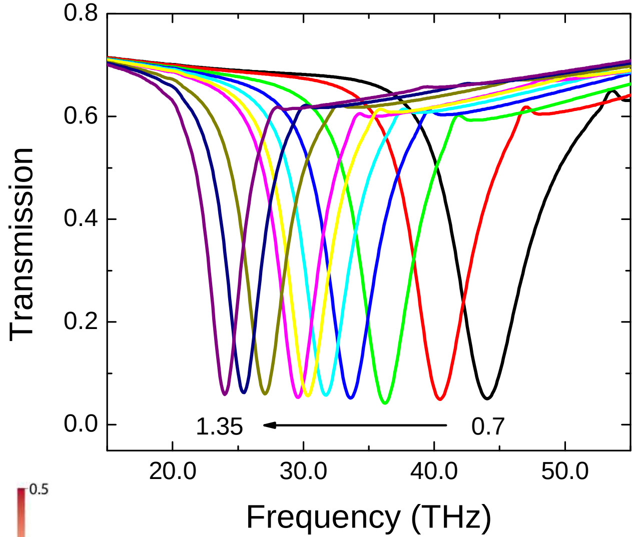
APL **104**, 131104 (2014)

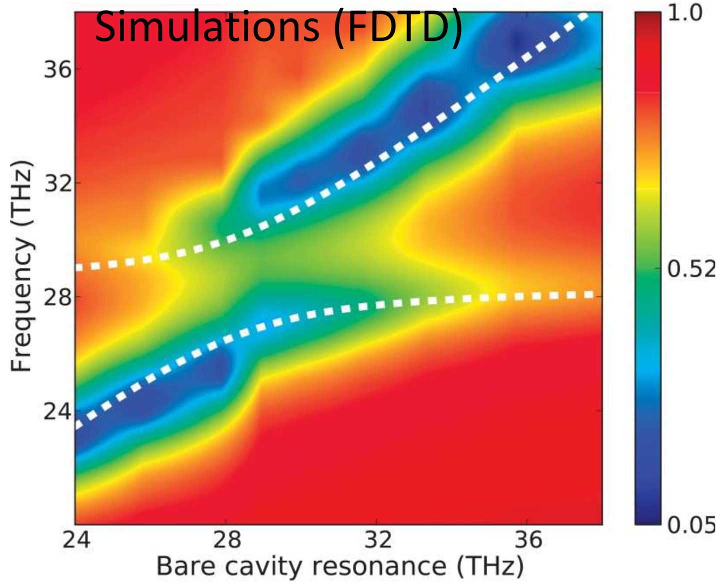
Strong Coupling Theory vs. Experiment

"Dogbone" resonators





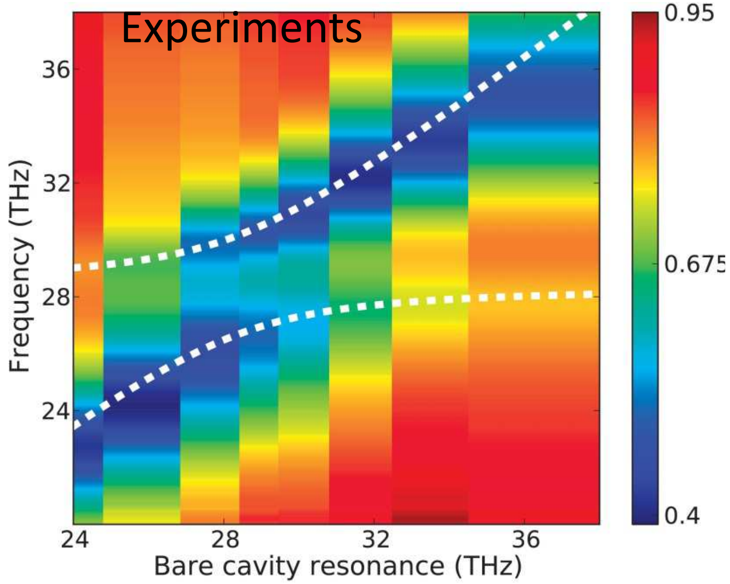




Plasma frequency

$$\Omega_R = \sqrt{f_W}\,\omega_p/2$$

Geometry factor

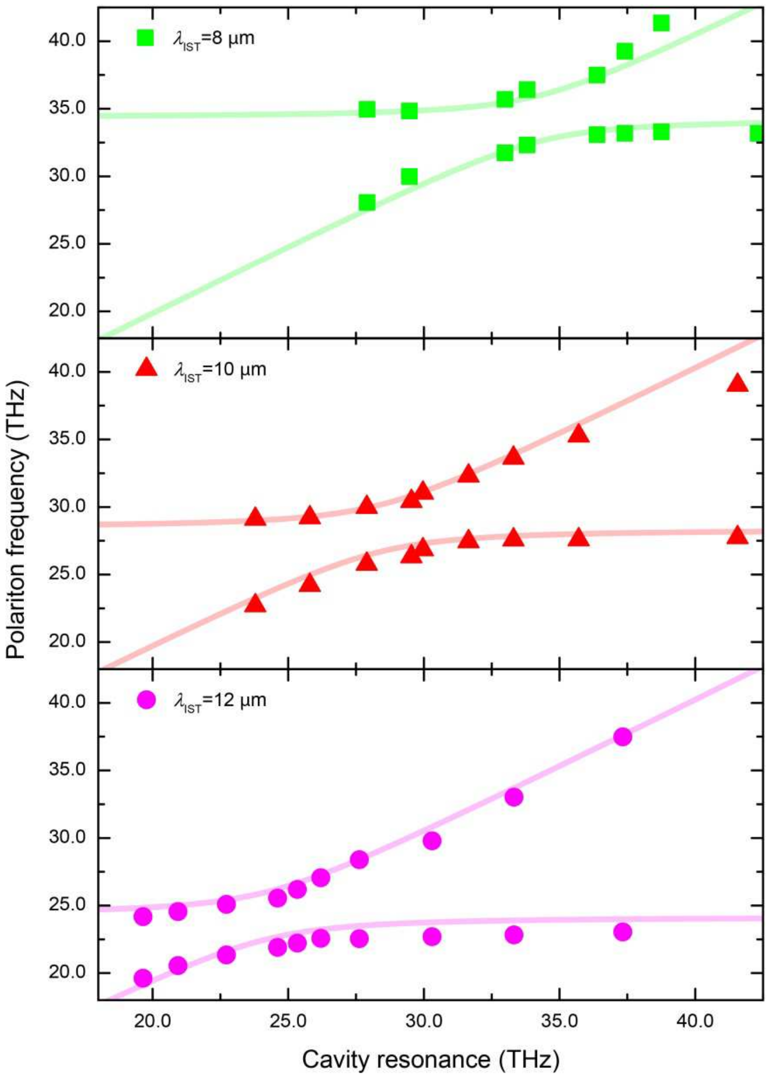


Rabi frequency depends on simple parameters

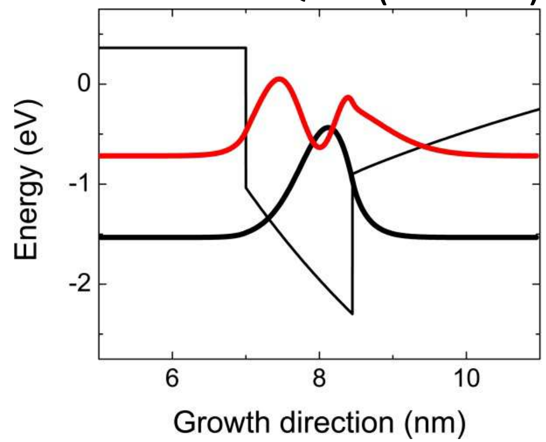
Nature Communications 4, (2013)

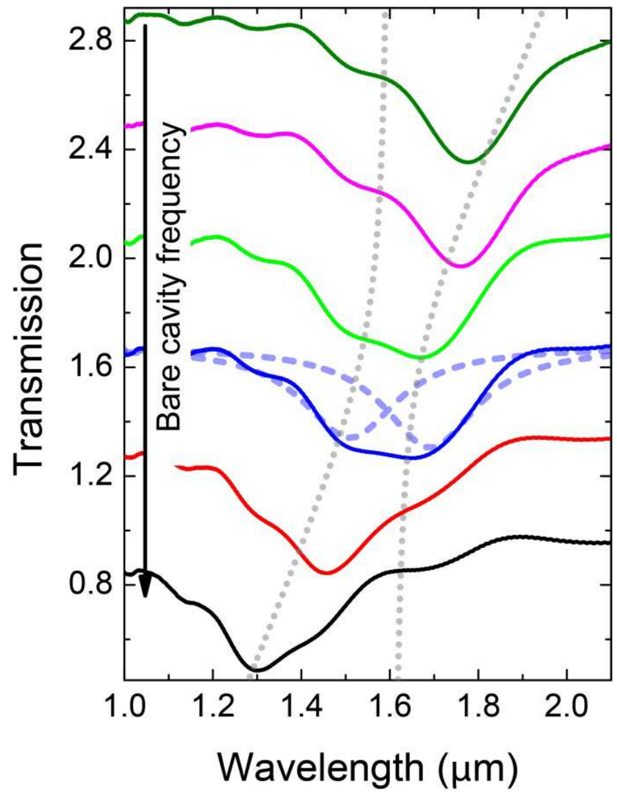
From Mid-IR to Near IR

InGaAs QWs (mid IR)



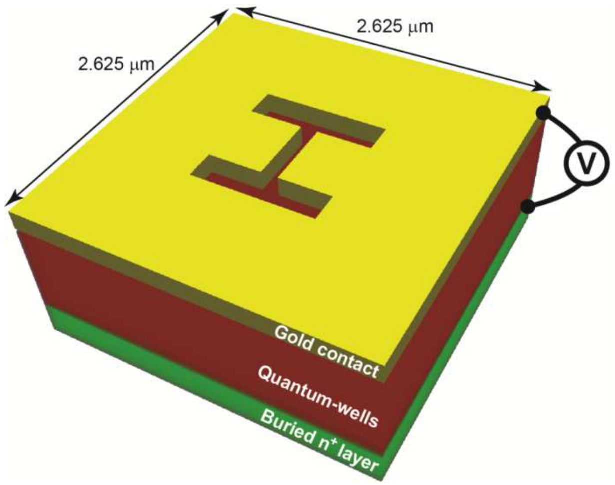
GaN QWs (near IR)

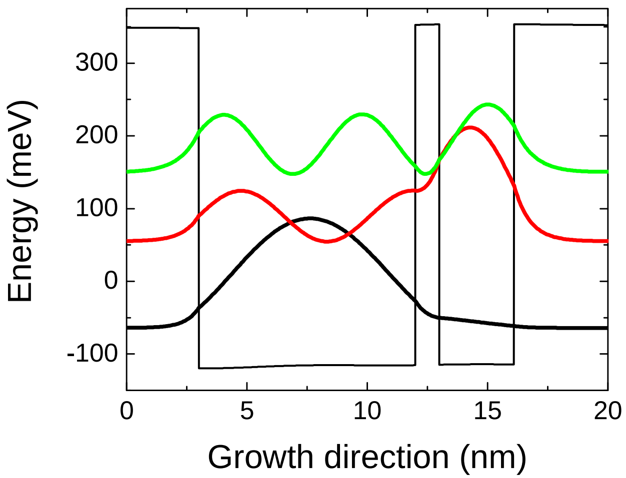


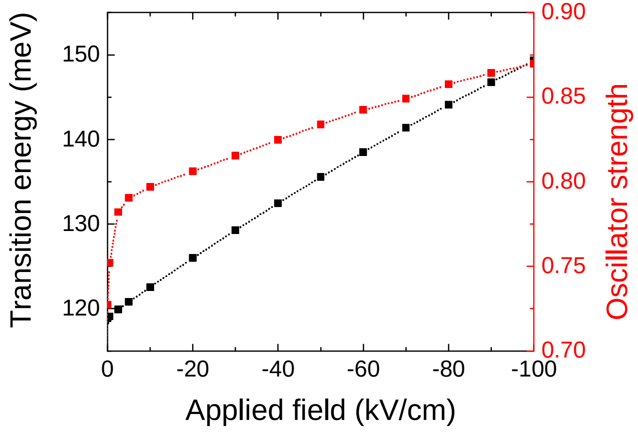


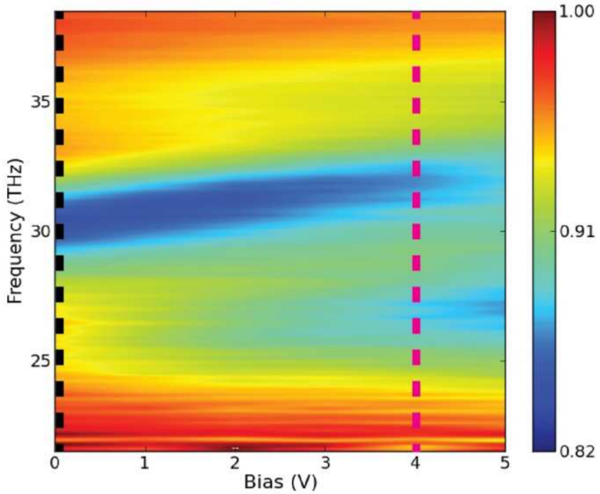
Nature Communications 4, (2013)

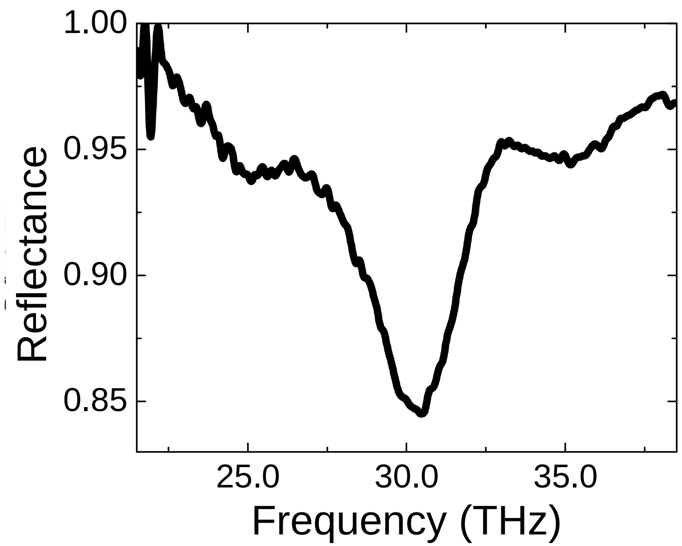
Electrically Tunable Strong Coupling

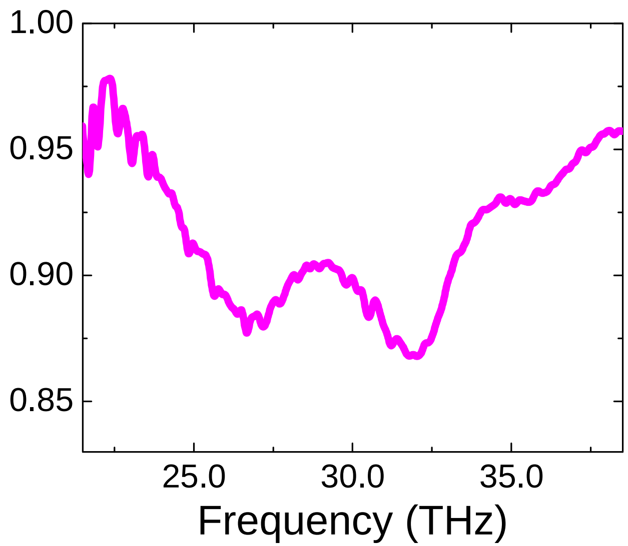












Appl. Phys. Lett. 103, 263116 (2013)

Upper polariton shifted by 2.5 THz (=8% of center frequency or one full intersubband linewidth)

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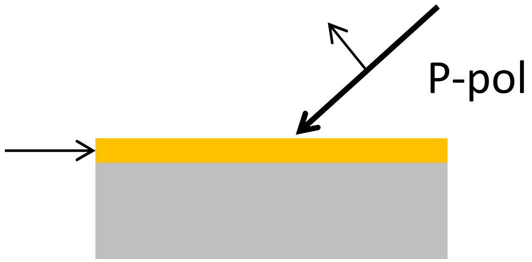
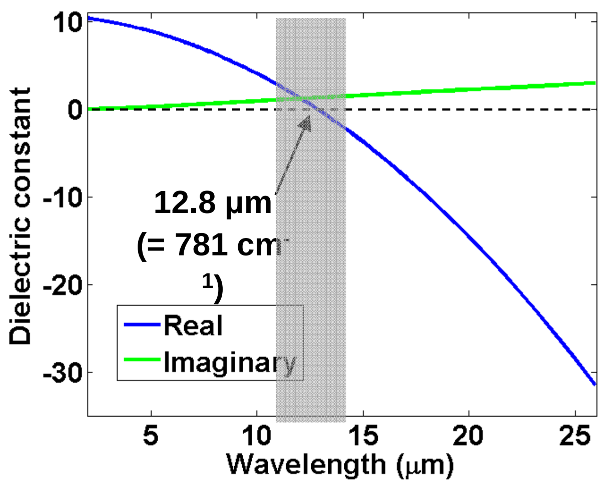
"Epsilon Near Zero" Modes

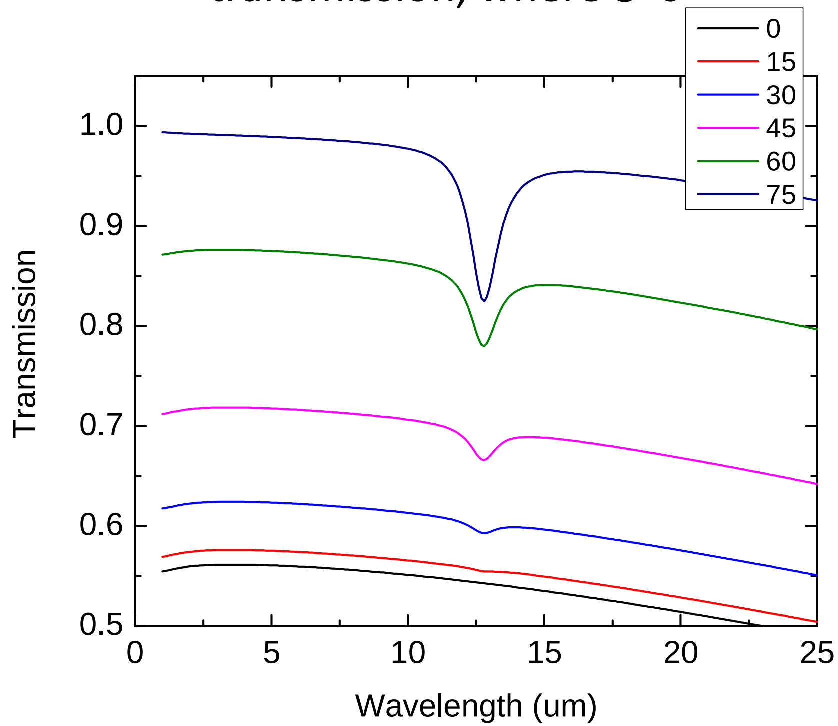
Thin (<<λ) layer where ε crosses 0 (Drude, phonon, etc)



Example: "Drude" layer



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



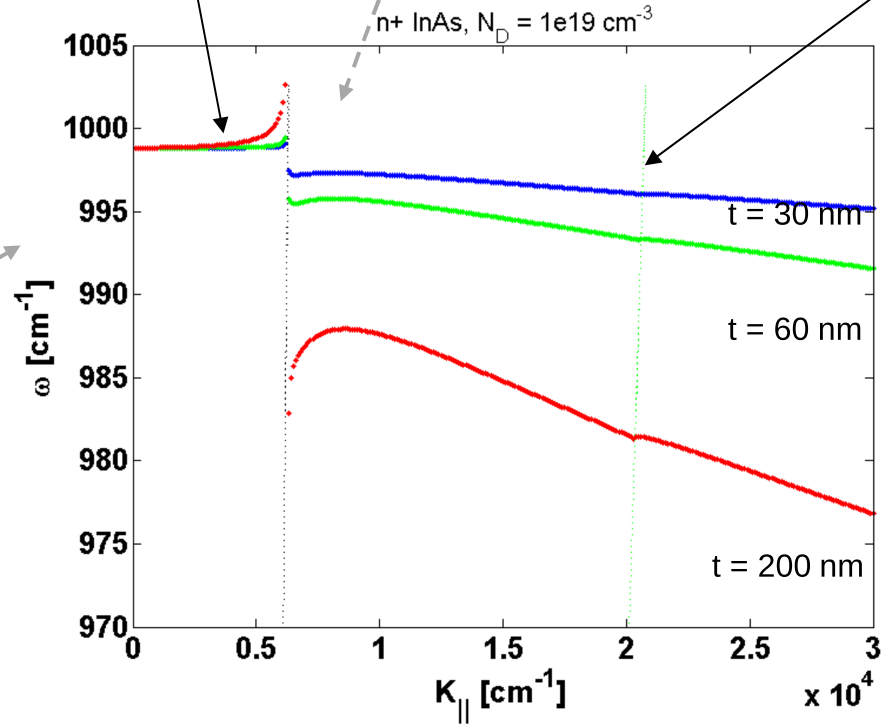
("Berreman" dip)

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

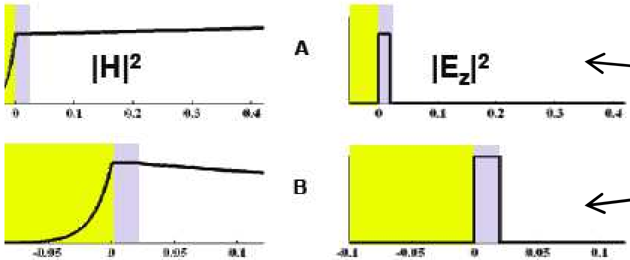
"Epsilon Near Zero" vs Berreman Modes

Dispersion relation of the TM mode in a 3-layer

$$\left(1+\frac{\epsilon_1 k_{z,1}}{\epsilon_3 k_{z,3}}\right) = i\tan(k_{z,2}d)\left(\frac{\epsilon_2 k_{z,3}}{\epsilon_3 k_{z,2}}+\frac{\epsilon_1 k_{z,2}}{\epsilon_2 k_{z,1}}\right)$$



Numerical solution in complex domain
(assuming complex freq, real k)

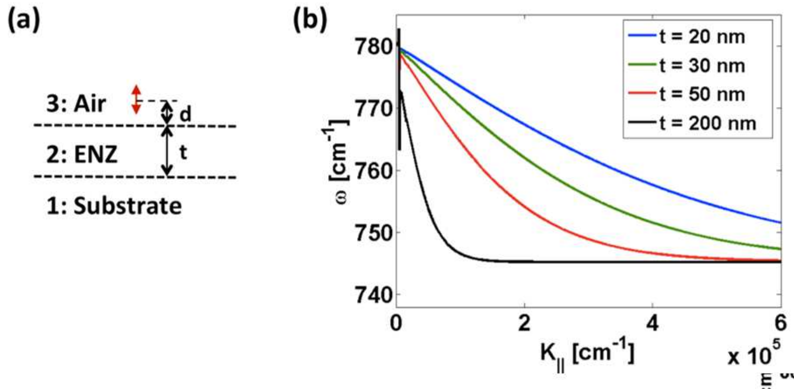


- **Berreman mode (leaky mode),**
- **ENZ mode (bound mode)**
- ENZ mode is a special type of a plasmon polariton

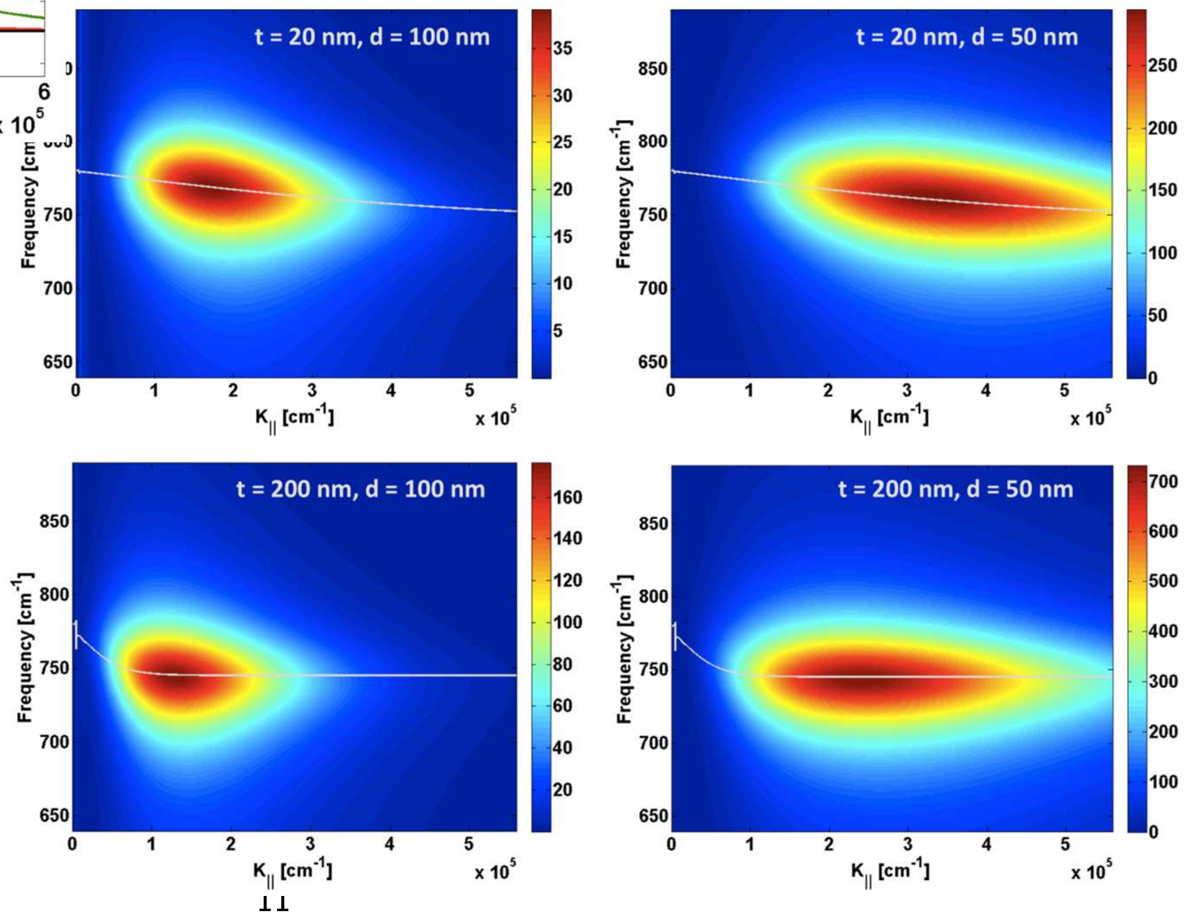
Greffet et al, PRL 109, 237401 (2012)
Opt Exp (2012)

MM Resonators Provide k-vectors to Excite ENZ Modes

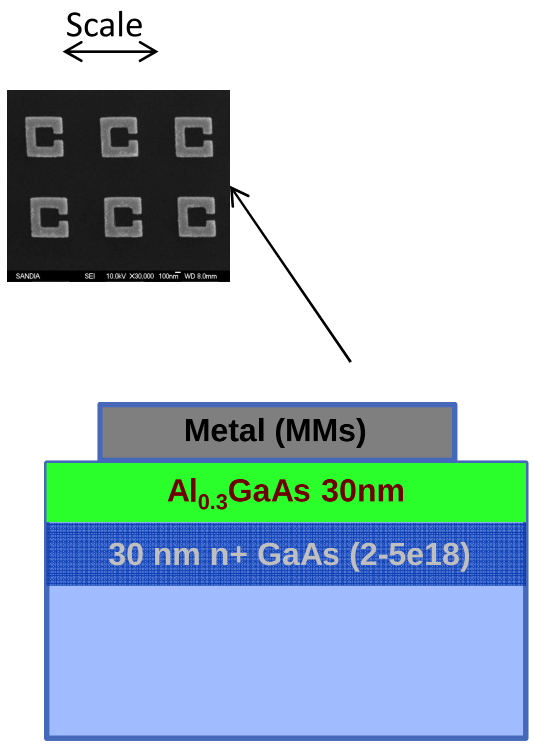
ENZ dispersion



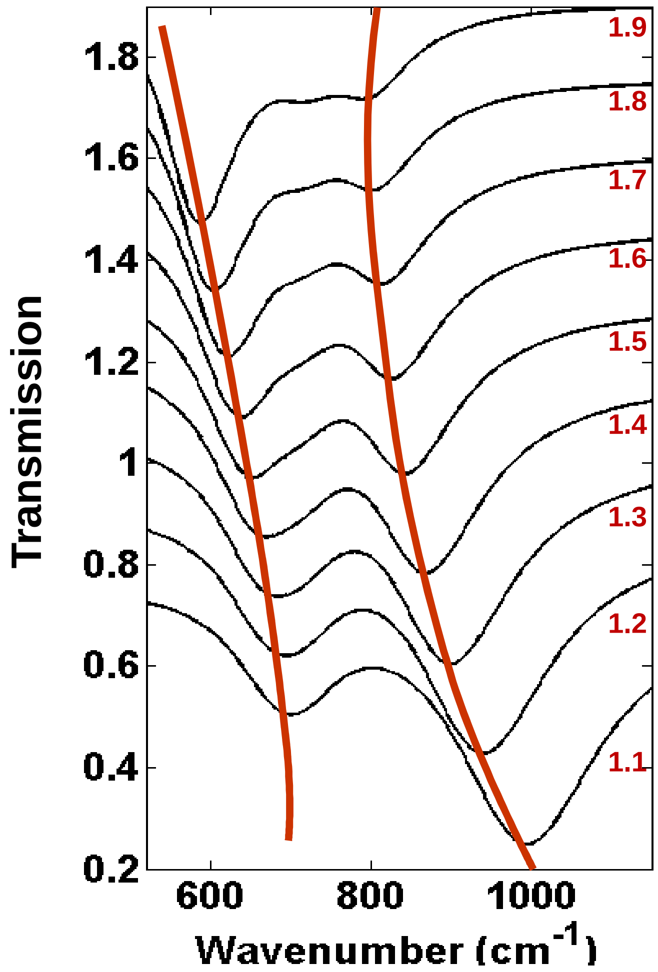
Superimpose dipole emission spectra on the ENZ dispersion



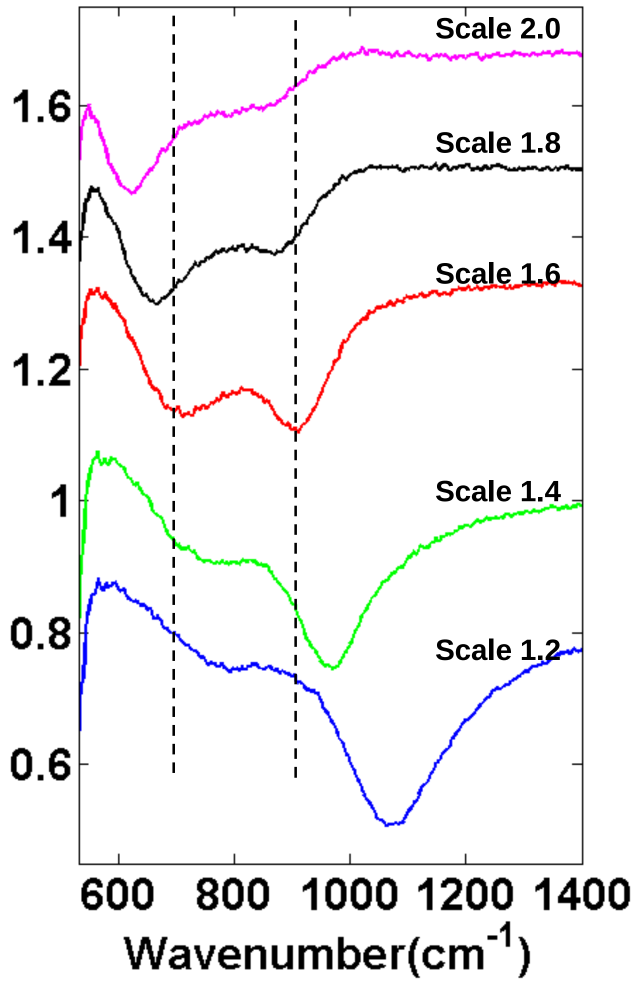
Strong Coupling to ENZ Mode: Theory vs. Experiment



Numerical simulation (FDTD)

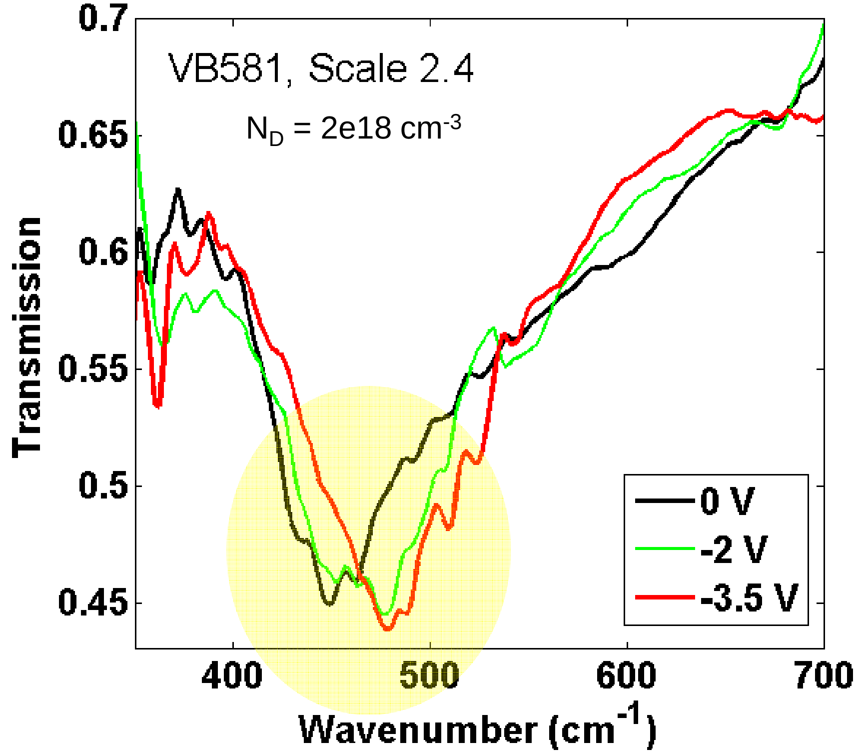


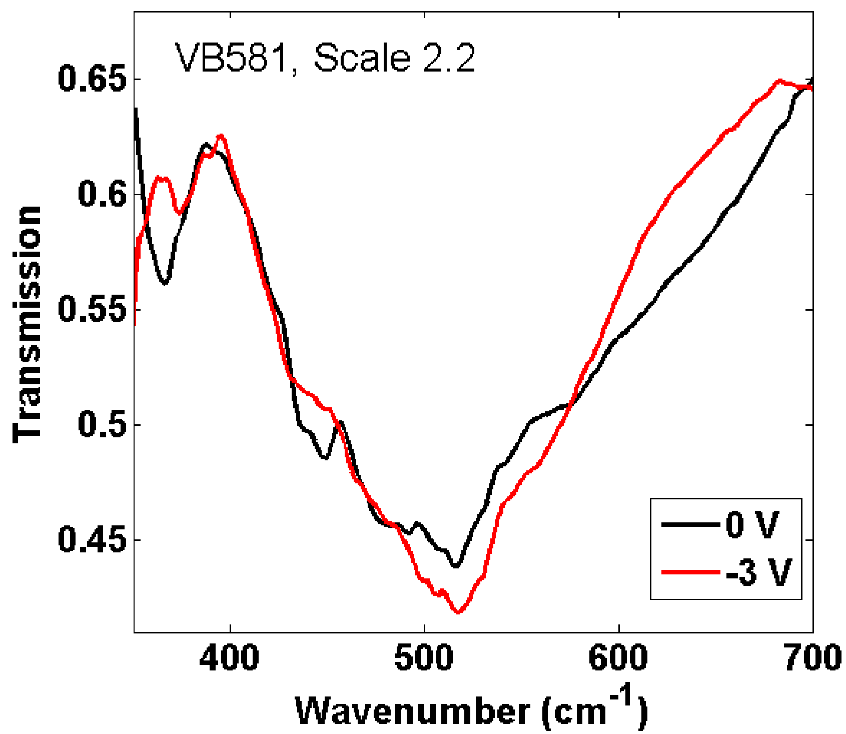
FTIR transmission measurement



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

Electrically Tuning the Coupling to the ENZ Mode

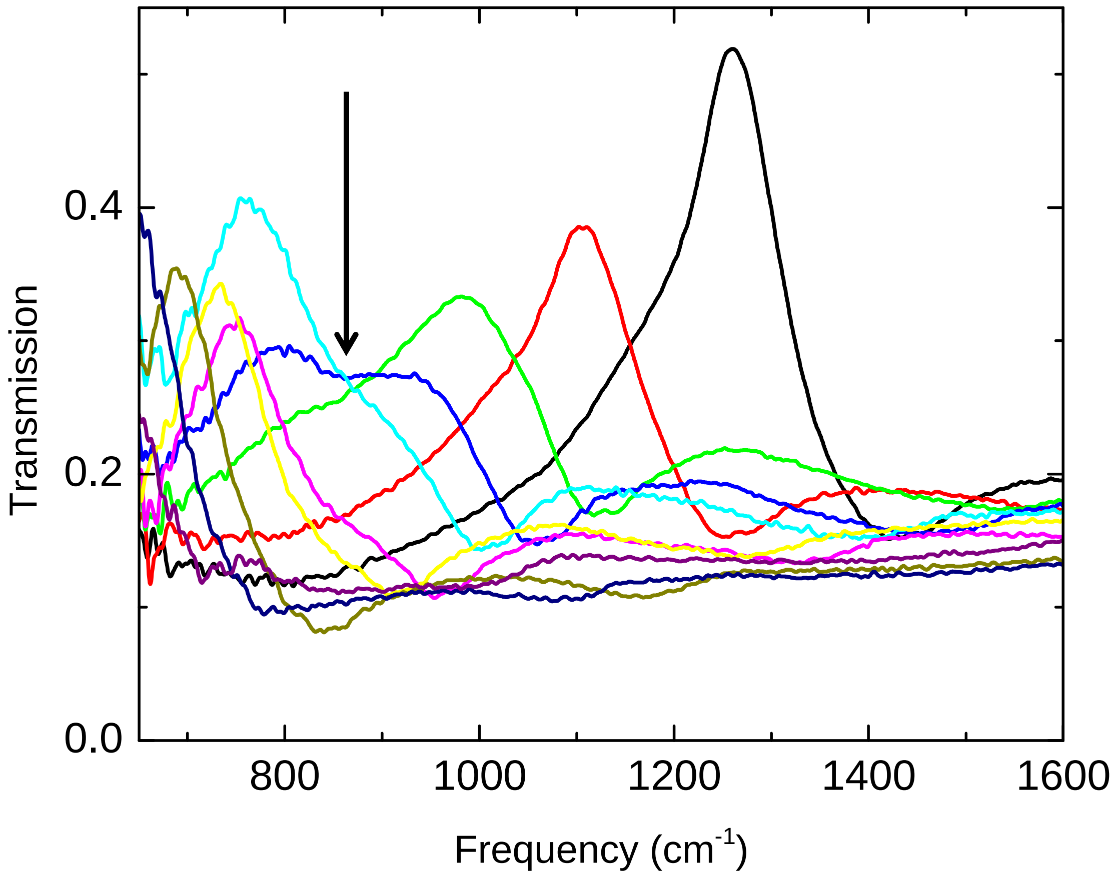


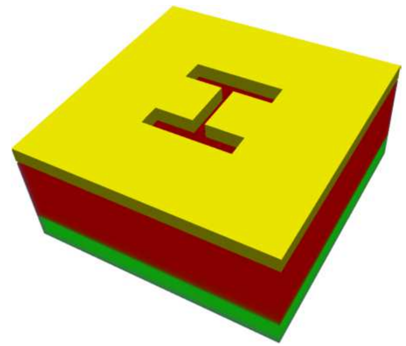


Fundamentally different than tuning just by changing a local permittivity!
Removal of carriers -> removal of ENZ mode

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

Inverted Dogbone + ENZ





Tunable Passband Filter

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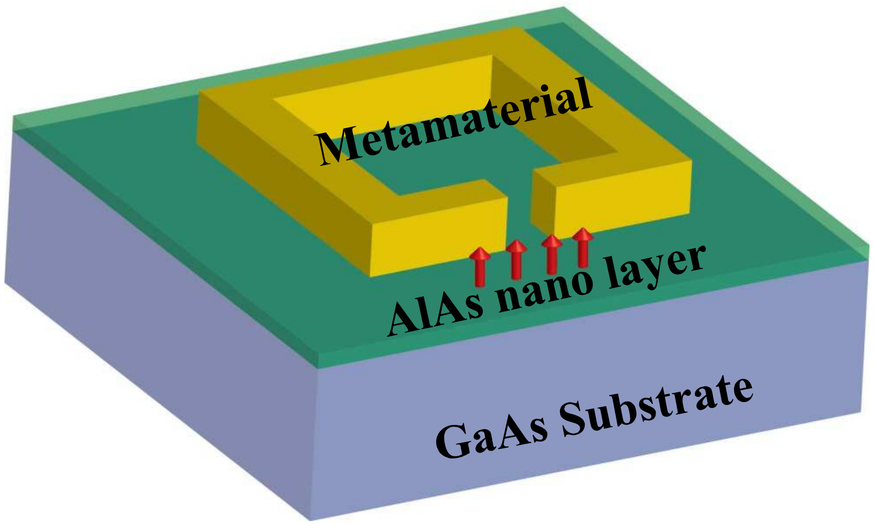
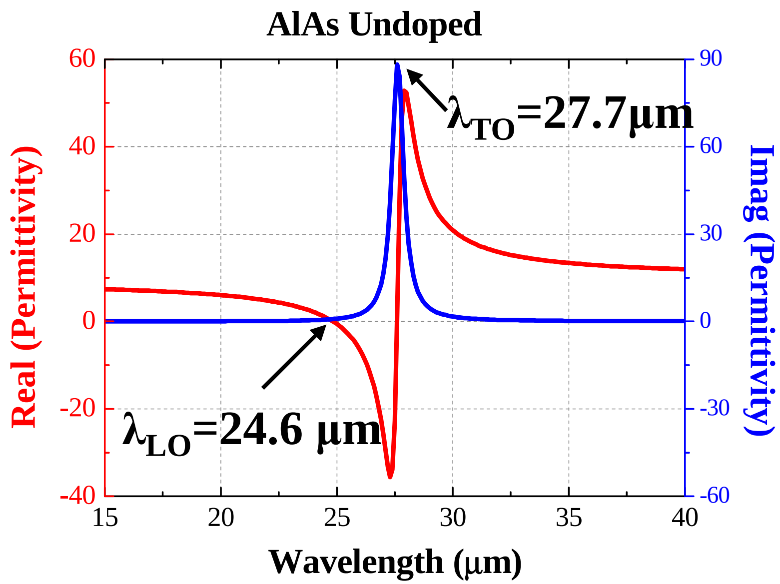
Coupling of Metamaterial Resonators to Dipole Resonances + ENZ modes





Lorentz model

$$\epsilon = \epsilon_\infty \left(1 + \frac{\omega_L^2 - \omega_T^2}{\omega_T^2 - \omega^2 + i\omega\Gamma} - \frac{\omega_p^2}{\omega(\omega - i\gamma)}\right) = (\eta - i\kappa)^2$$

Γ: Phonon damping constant
ω_p: Plasma frequency
γ: Free carrier damping constant

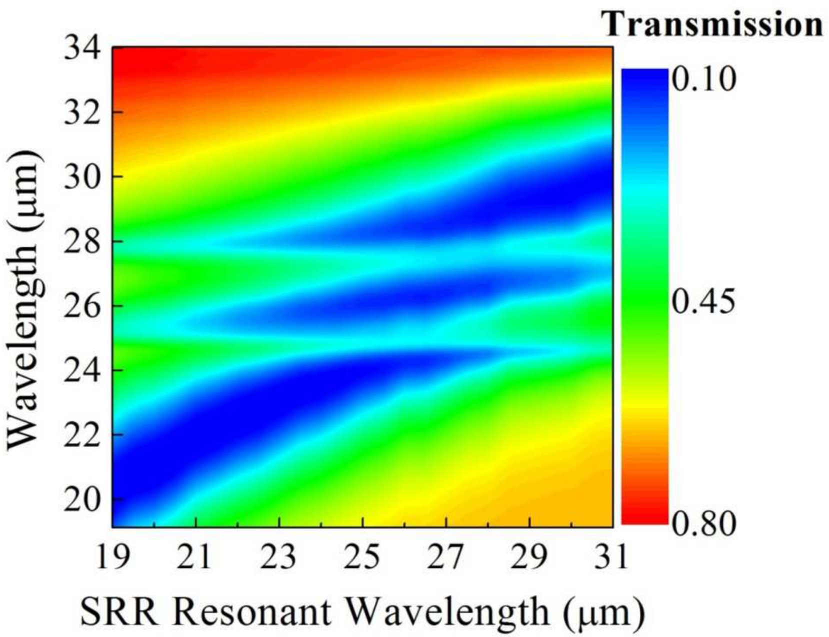
J. Appl. Phys., **48**, 212 (1976).
Solid State Communications, **62**, 645-647, (1987).

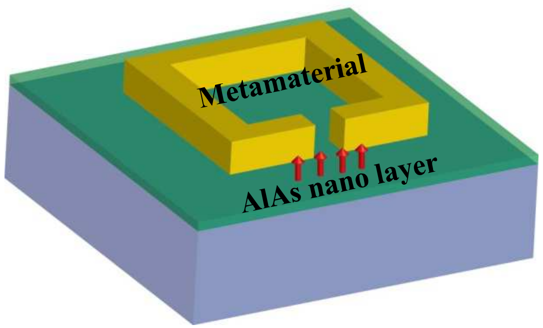
One thin layer contains:

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

Strong Coupling: 2 Polariton Branches

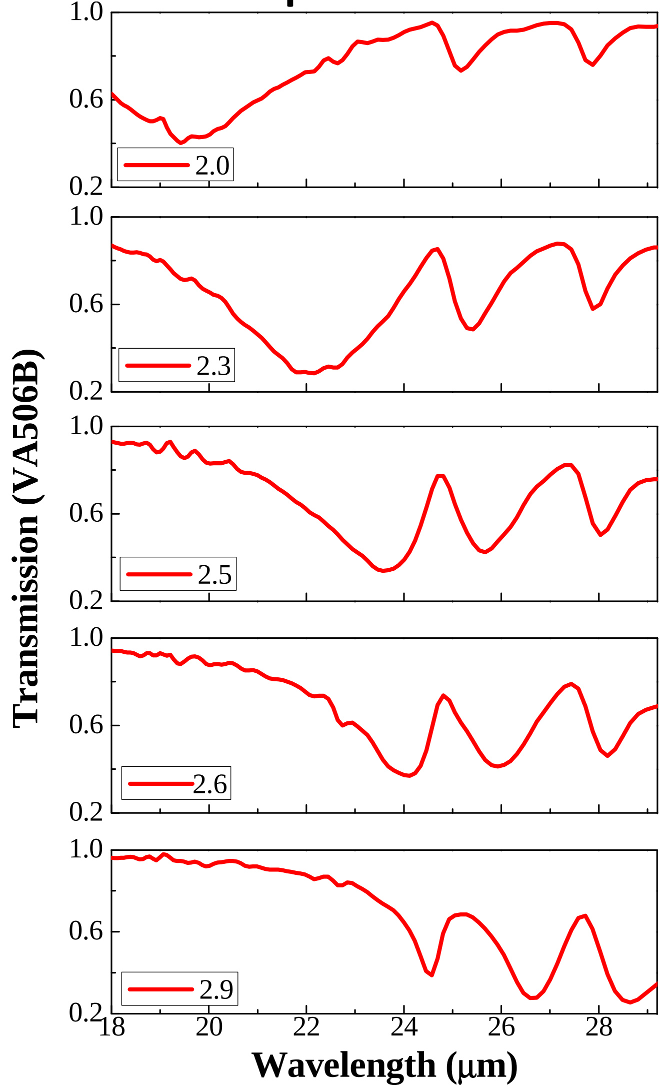
Simulations





Increasing SRR size

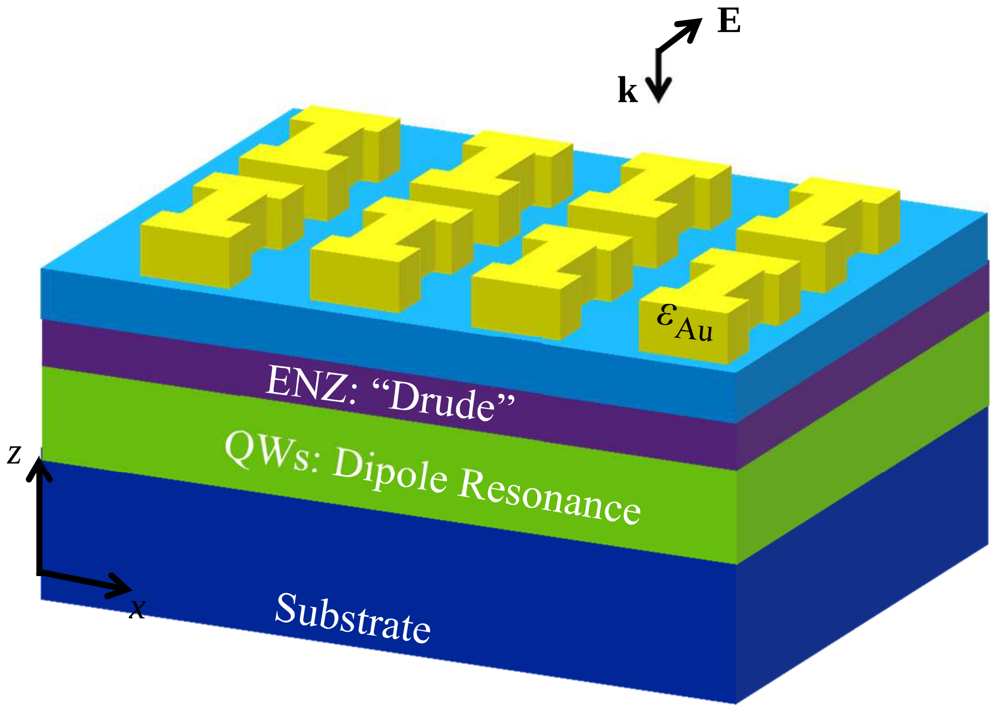
Experiments



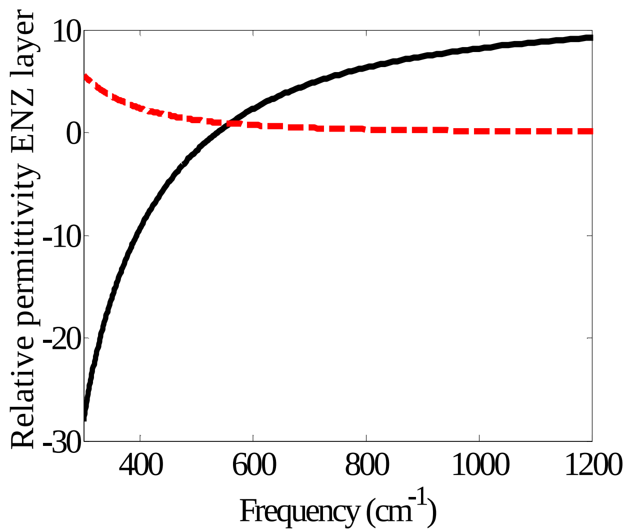
Let's Separate the ENZ Layer and the Dipole Resonance Layer

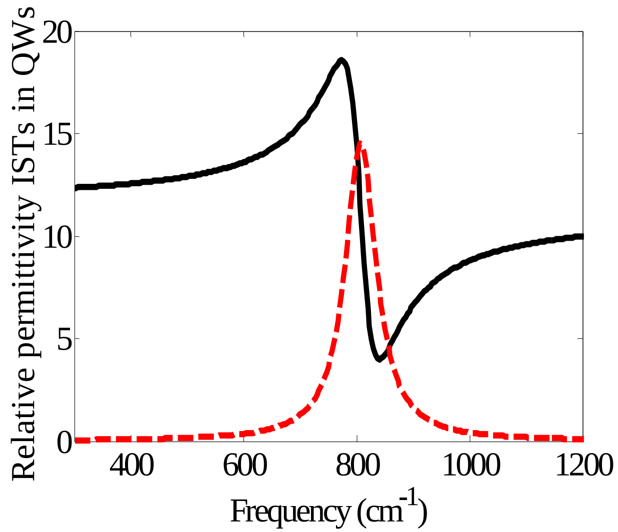
3 Interacting Systems

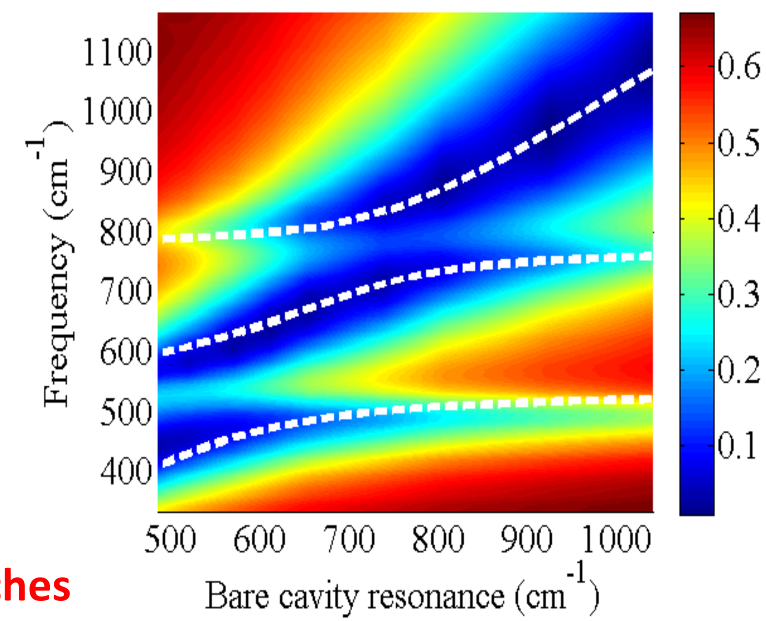
MM Resonators	ENZ Mode (Drude layer)	Dipole Transition (ISTs in QWs)

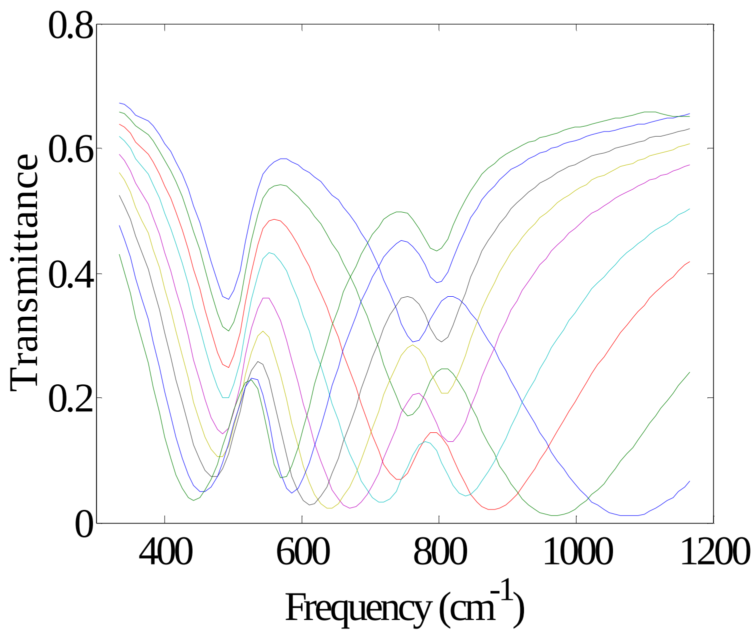


Case 1: Different Frequencies for Dipole Transition and ENZ



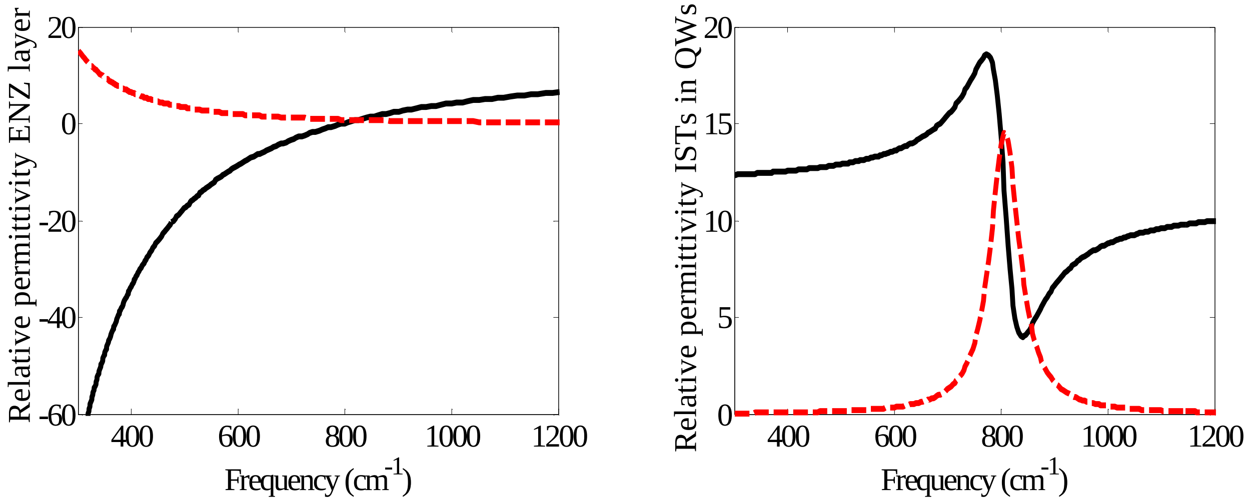


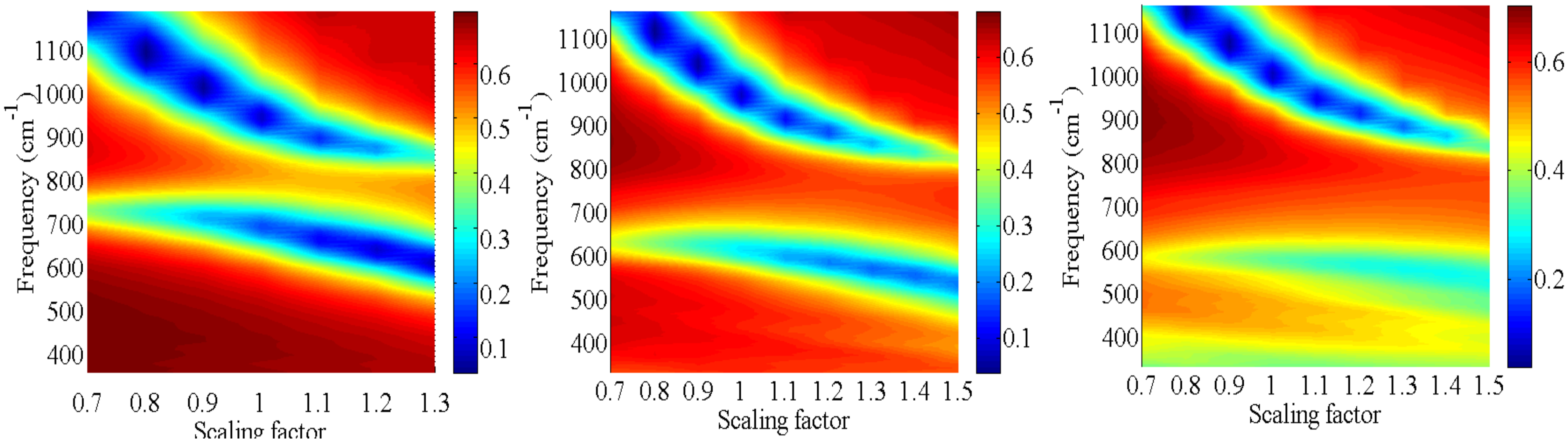




2 Different Polariton Branches

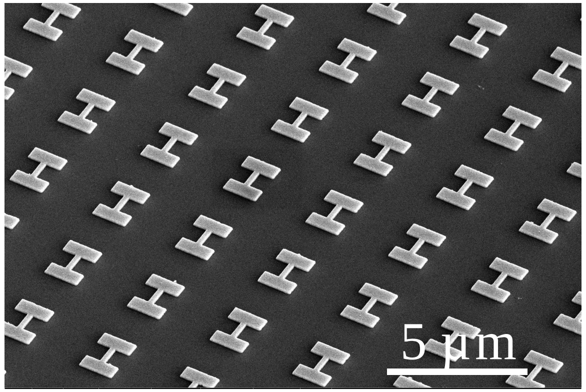
Case 2: Same Frequencies for Dipole Transition and ENZ

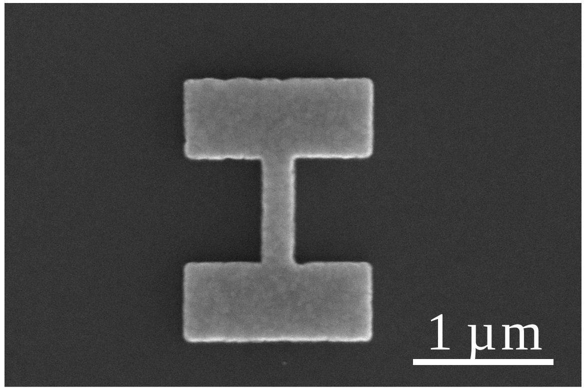


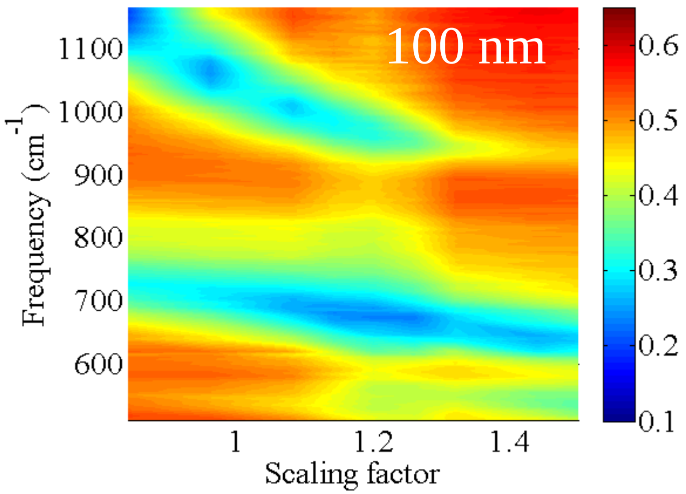


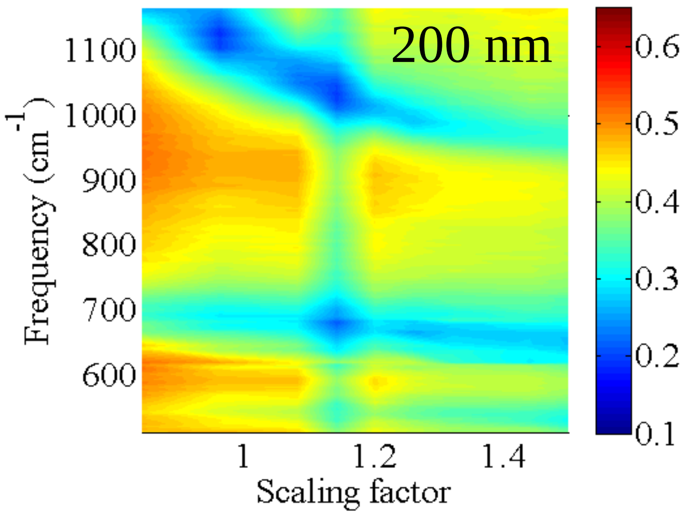
Only 1 Polariton, larger Rabi Splitting!

Experimental verification for 100 nm and 200 nm ENZ + QWs

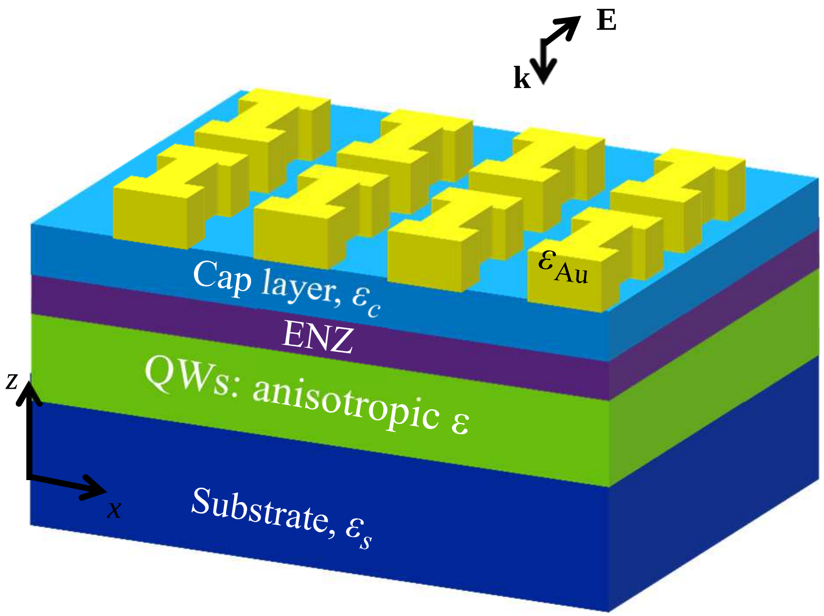




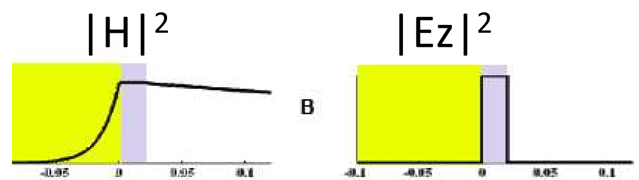




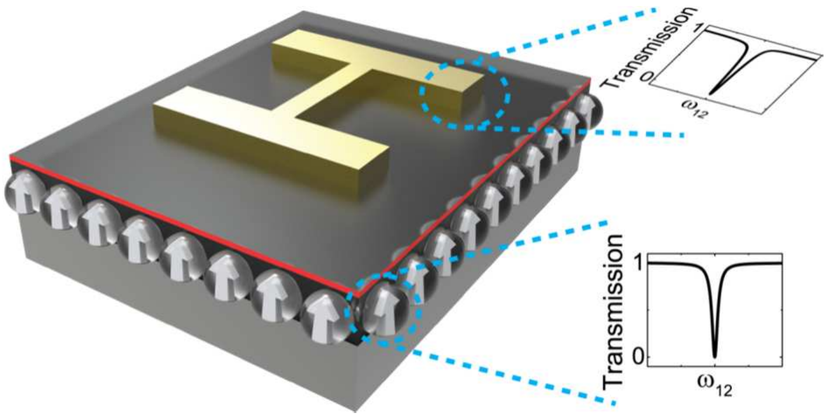
Combining ENZ Modes and Intersubband Transitions for Stronger Coupling



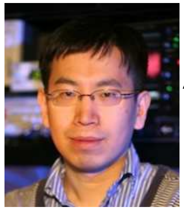
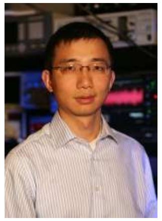
- Field decays exponentially with distance from MM resonators
- An ENZ thin layer acts as a "transducer" of Ez field



Summary & Acknowledgments



Strong coupling to
Intersubband Transitions

Postdocs: Young Chul Jun (n+),  Alex Benz (QWs),  Sheng Liu (TDS), 

Salvo Campione, 

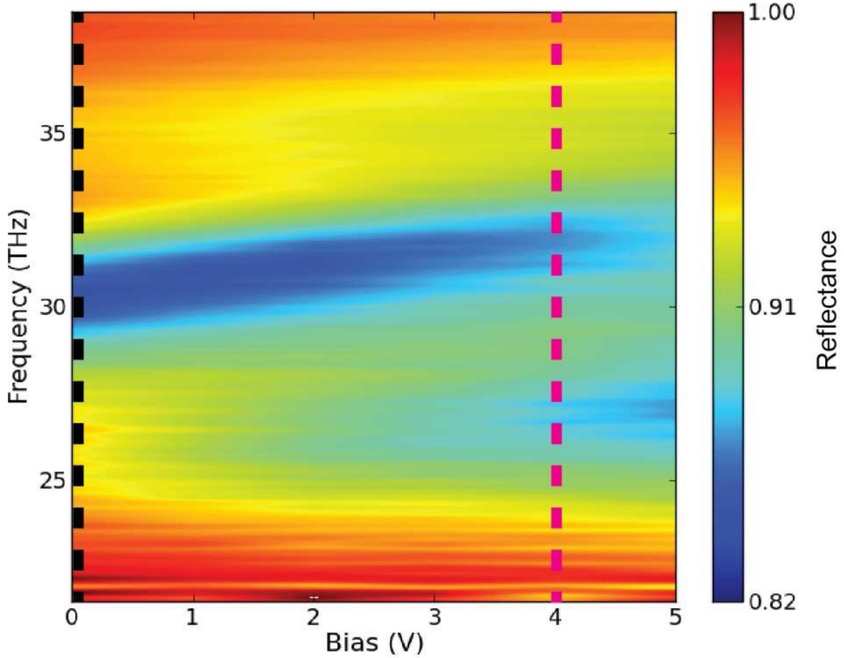
CINT + Sandia: John Reno, Mike Sinclair, Ines Montano, John Klem (InGaAs), Andy Allerman (GaN)

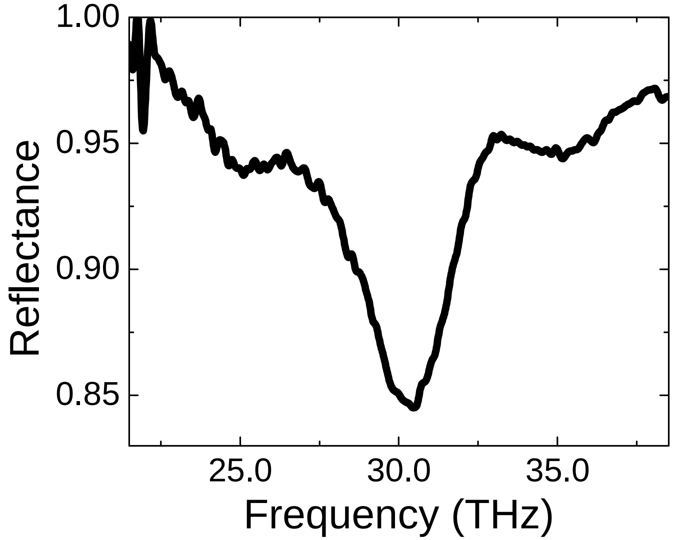
UC Irvine: Filippo Capolino

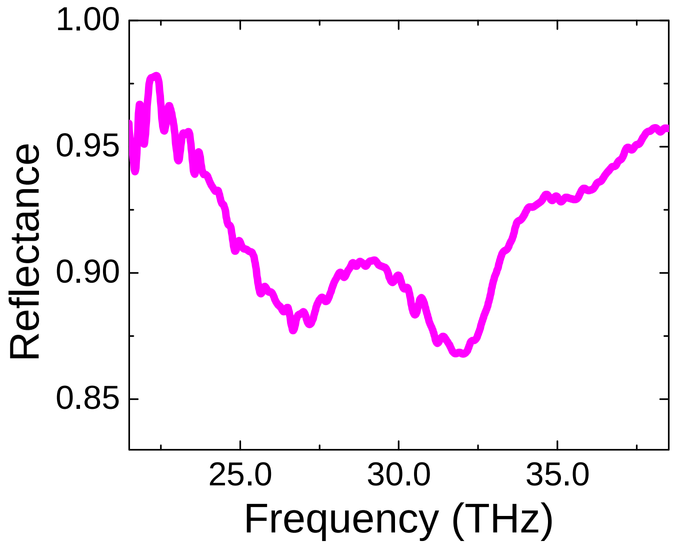
France: J.J. Greffet, F. Marquier (ENZ)

SPARES

Electrically Tunable Strong Coupling



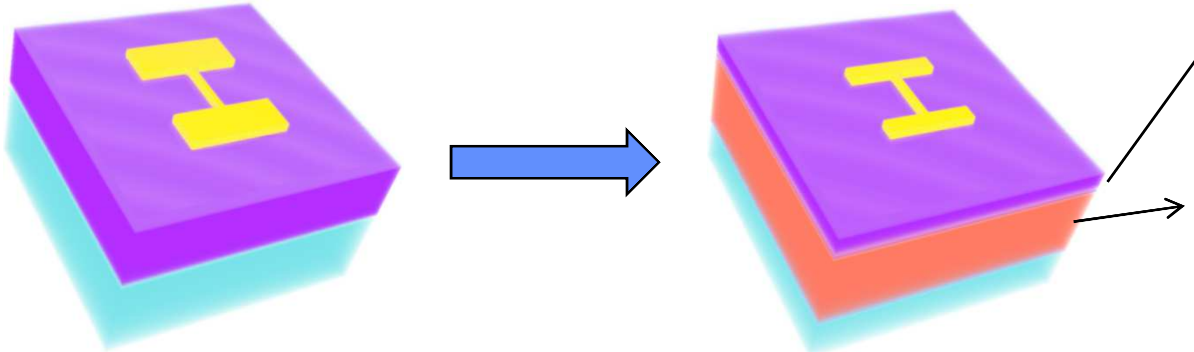


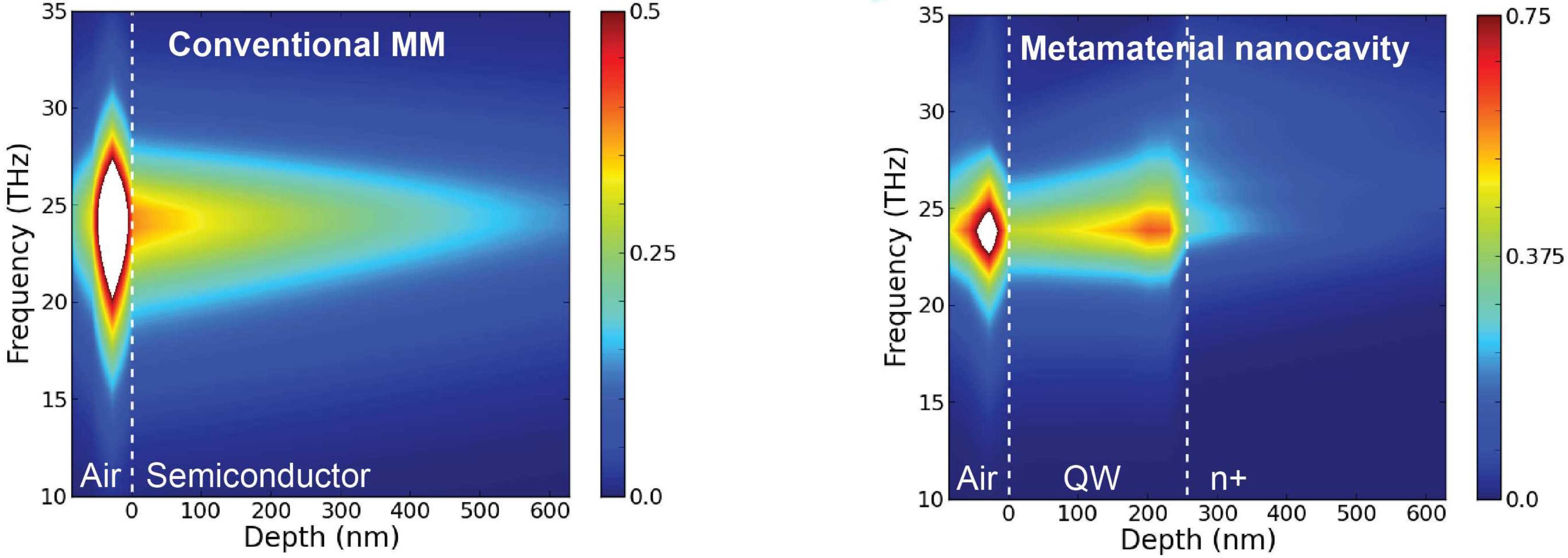


- **Metamaterial spectral response tuned by voltage**
- **Upper polariton shifted by 2.5 THz (=8% of center frequency or one full intersubband linewidth)**

Appl. Phys. Lett. 103, 263116 (2013)

How to Increase the Rabi Frequency: Metamaterial Nanocavity + Ground-plane

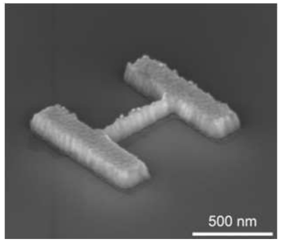


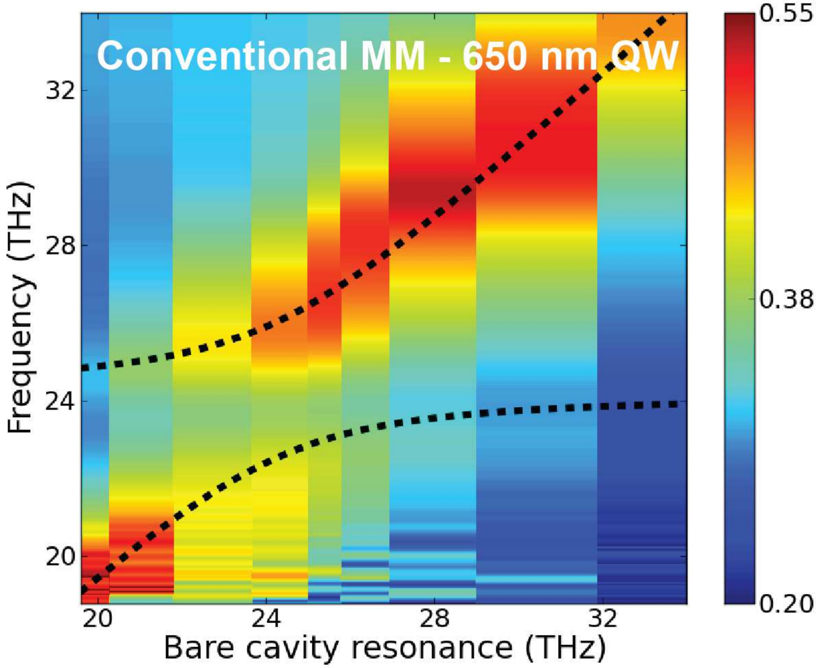


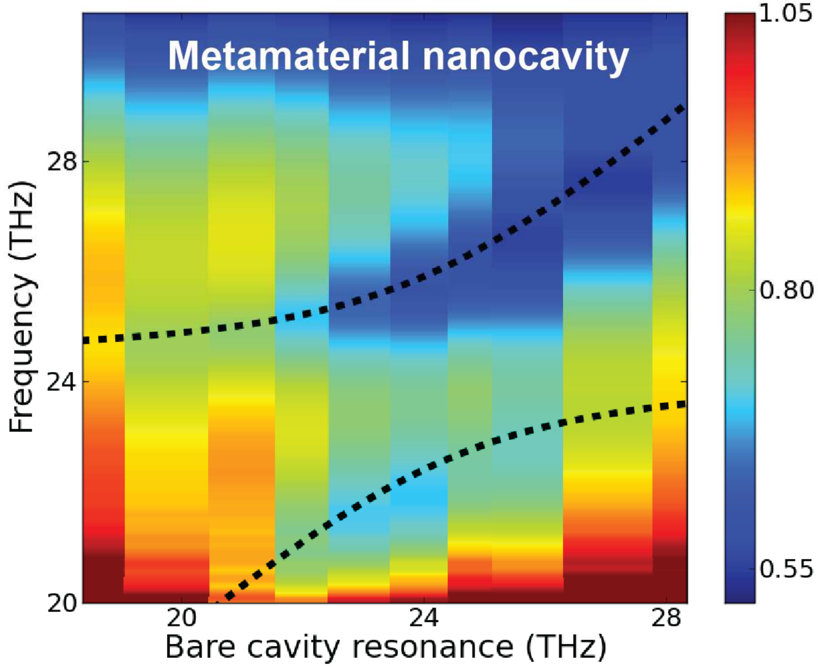
- **Ground plane limits field penetration into the semiconductor**
- **Mode volume reduced from: 2.49×10^{-3} $(\lambda/n)^3$ to 1.34×10^{-3} $(\lambda/n)^3$**

Optics Express **21**, 32572 (2013)

Reduced Mode Volume: Experiments



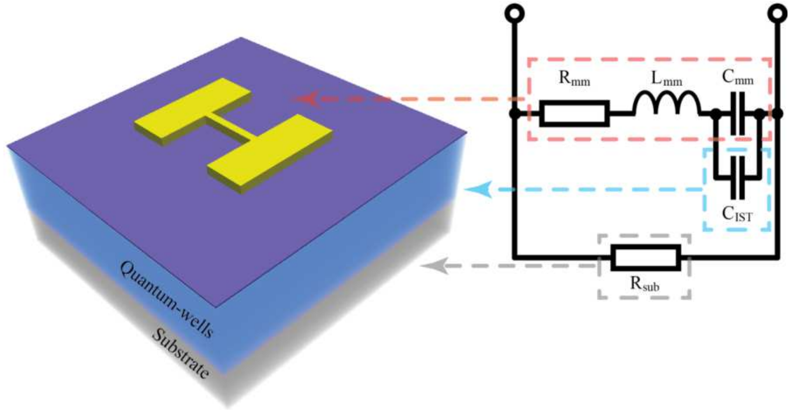


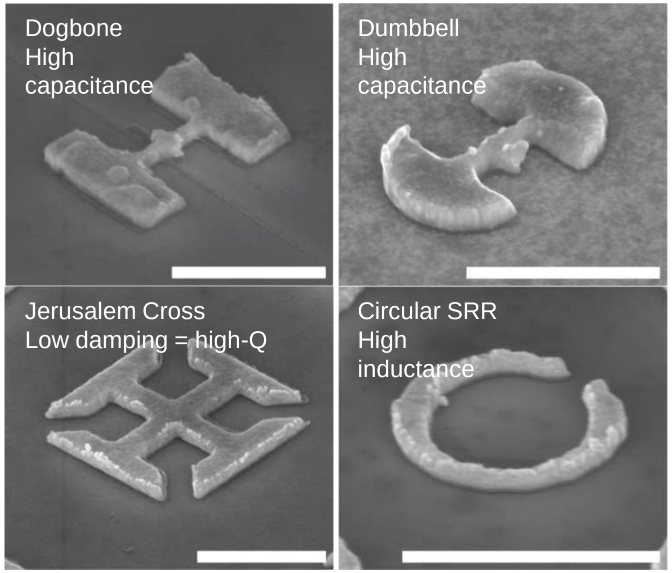


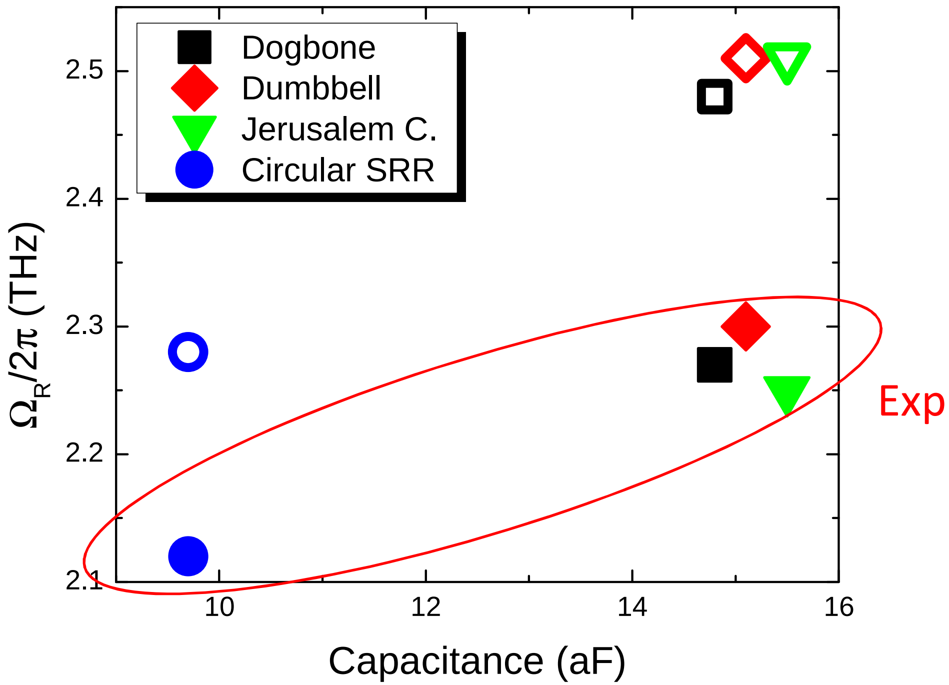
- **Rabi frequency remains almost identical despite reduced QW-stack thickness (factor 3.3) or reduced mode volume (factor 1.9)**
- **Conventional sample: 2.1 THz vs. Nanocavity: 2.5 THz**

Optics Express **21**, 32572 (2013)

Rabi Frequency vs. Geometry







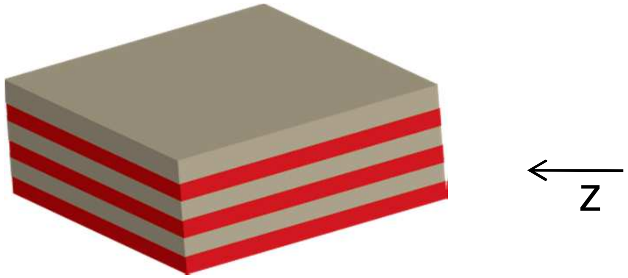
Physical Review **B89,** 165133 (2014)

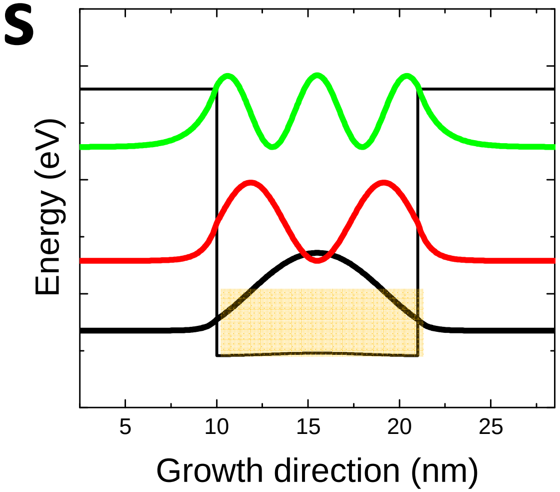
- **<u>Larger capacitance leads to larger Rabi splitting</u>**

Strong Coupling to Inter-subband Transitions in Quantum Wells

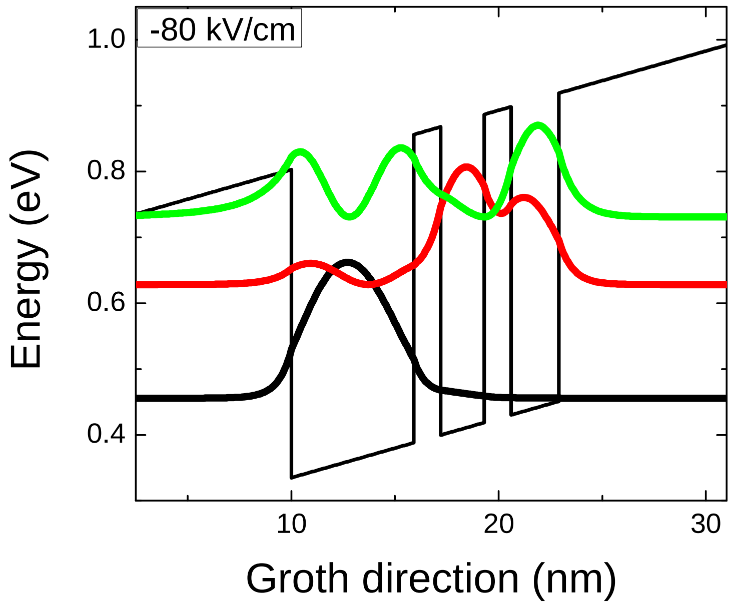
•<u>Scalabe</u> (far IR to near IR), <u>Mature, Versatile</u>

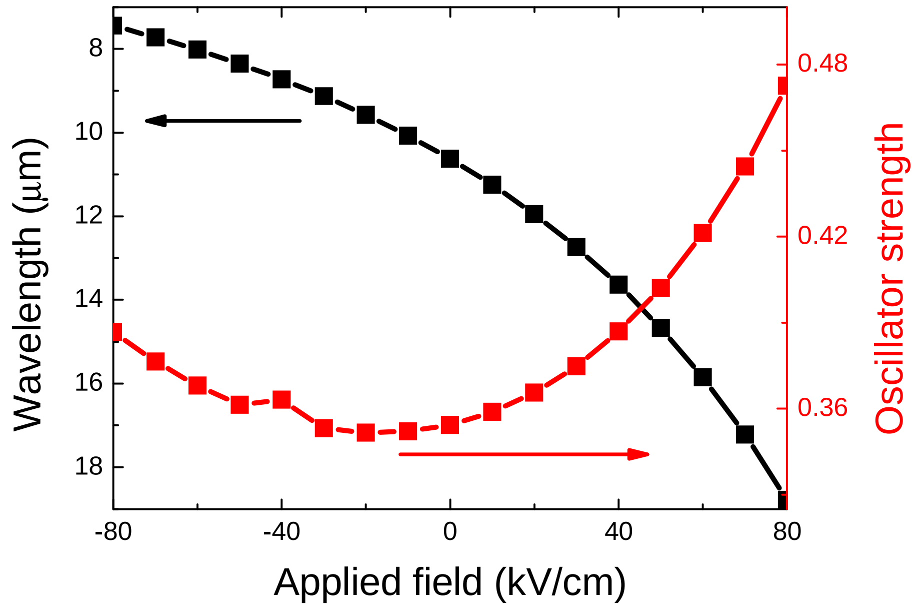
Opt. Express 20, 6584 (2012), APL 98, 203103 (2011)



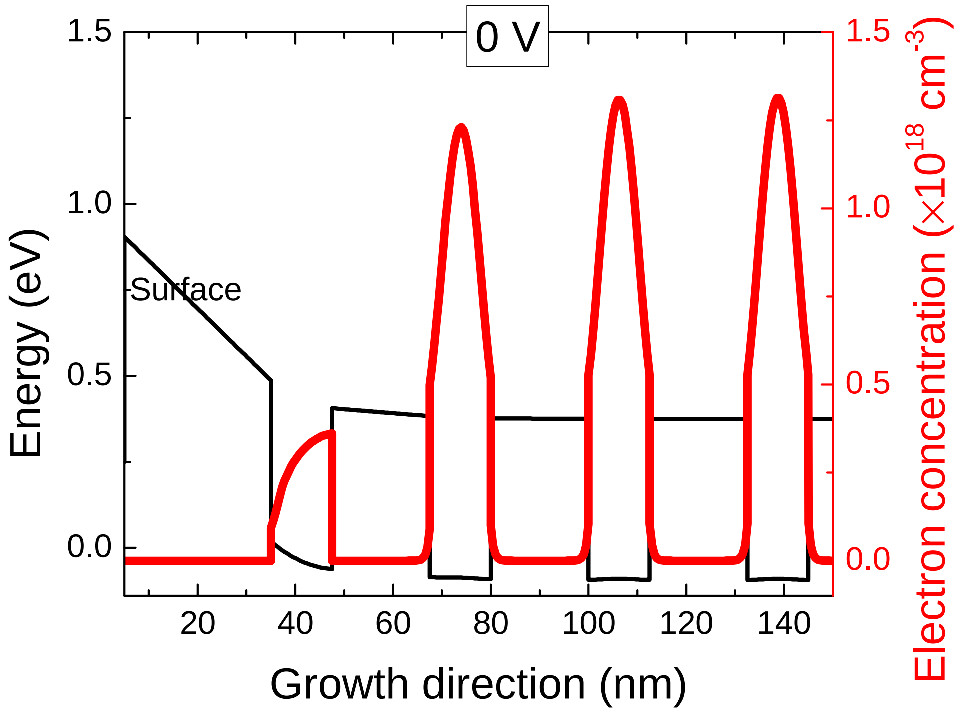


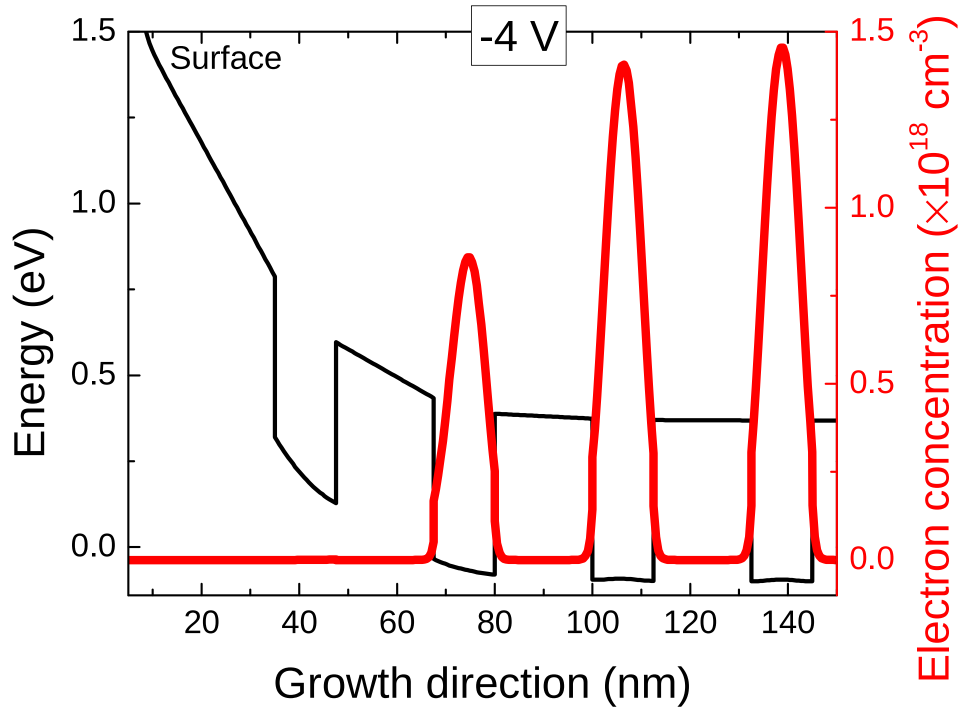
Change levels using an electric field





Reverse Biasing Highly Doped QWs: Problem!

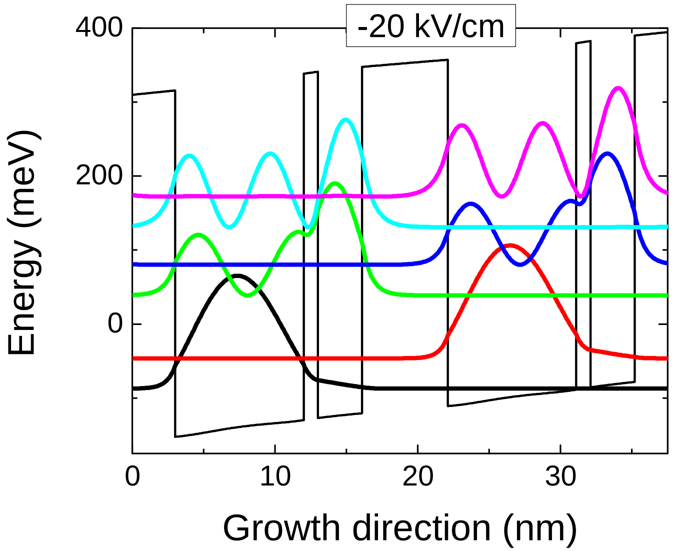


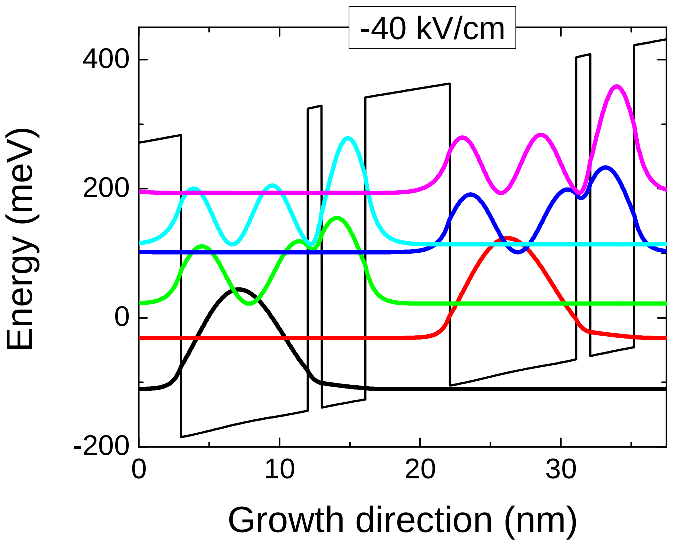


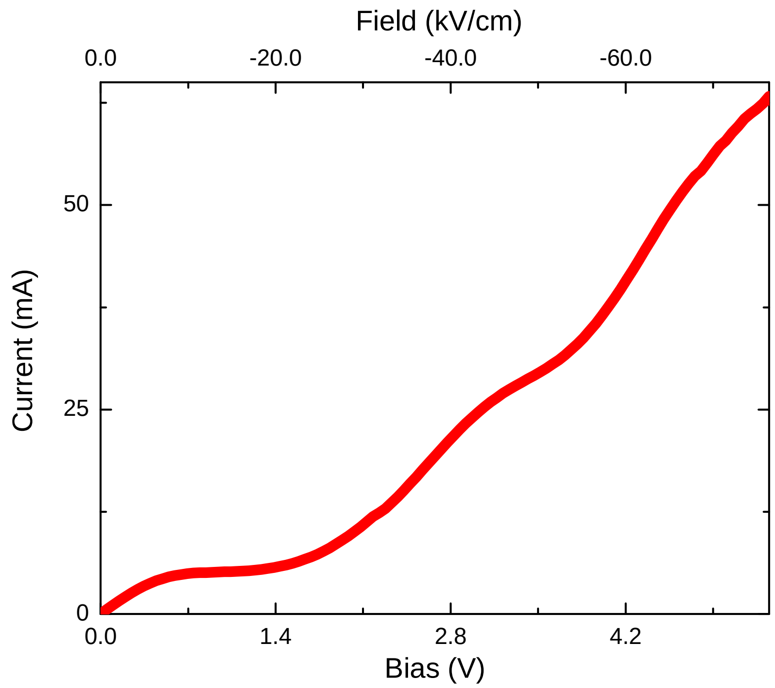
- **Applying reverse bias across QW-stack depletes well by well => no continuous tuning**
- **High doping concentration limits effect to first few wells only**

Stabilizing Internal Electric Field

Allow a small forward bias current



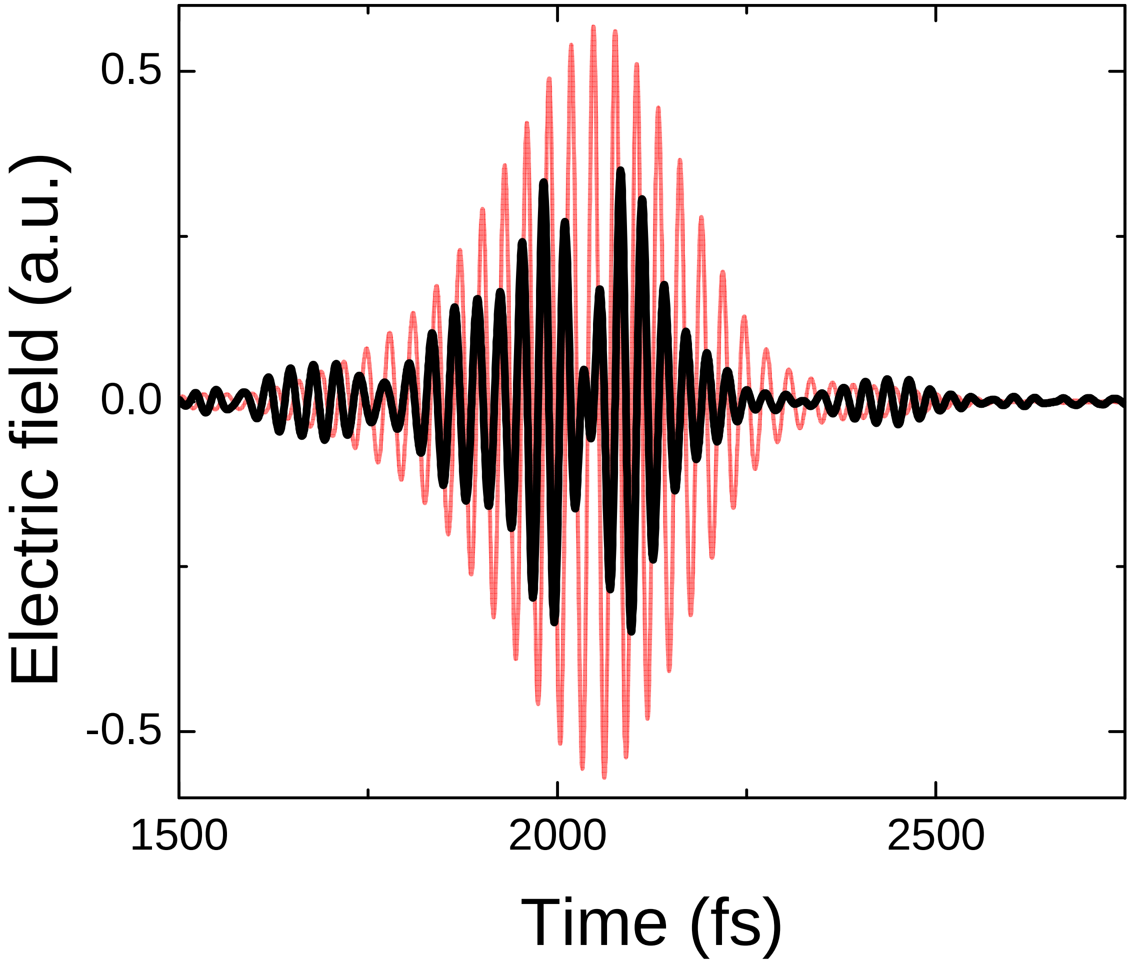




- **Current flow through QW-stack stabilizes internal electric field**
- **Alignment and miss-alignment of subbands show up in IV curve**

Experimental Rabi Oscillations

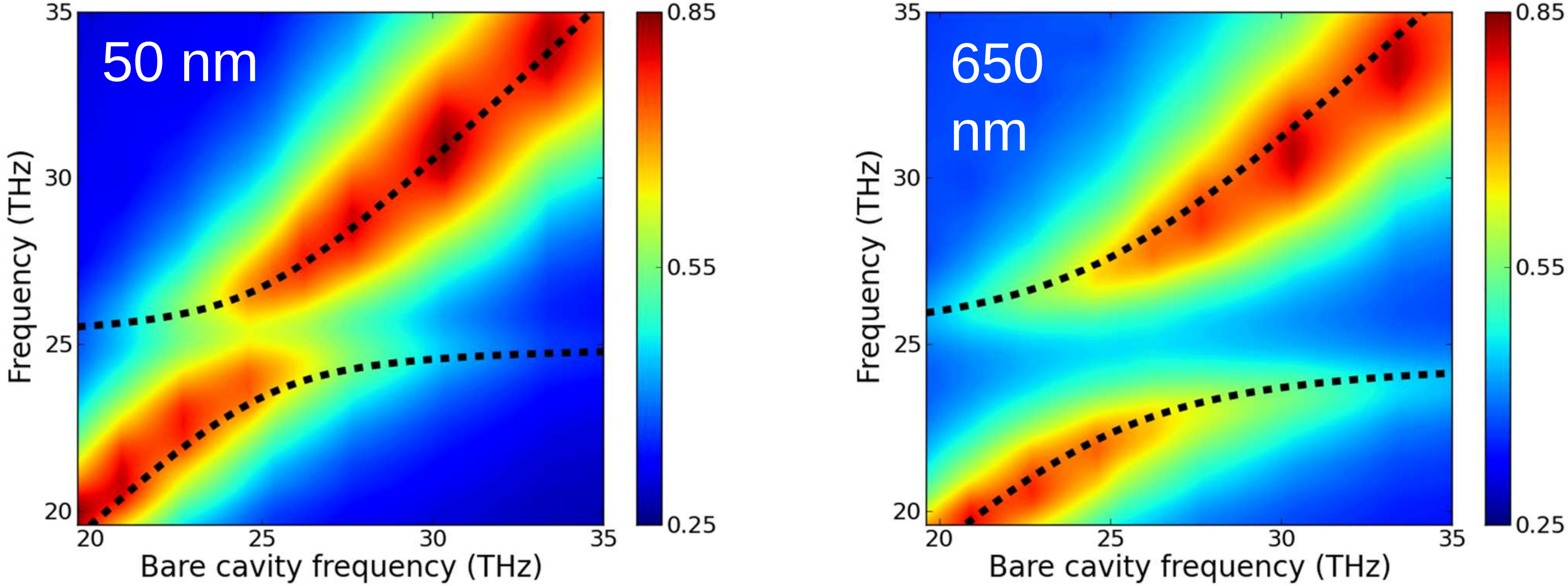
(using a mid-IR Time-domain fsec system)



- **Energy exchange probed in time**
  - **33 fs oscillation**
  - **480 fs beating**
- **System strongly coupled**
- **Splitting of 4.2 THz measured**
  - **15 % of ω_{12}**

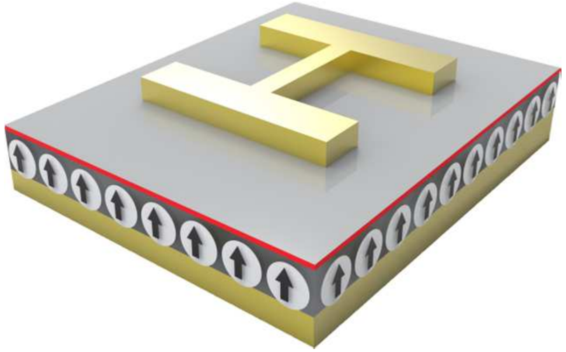
How to Increase the Rabi Frequency

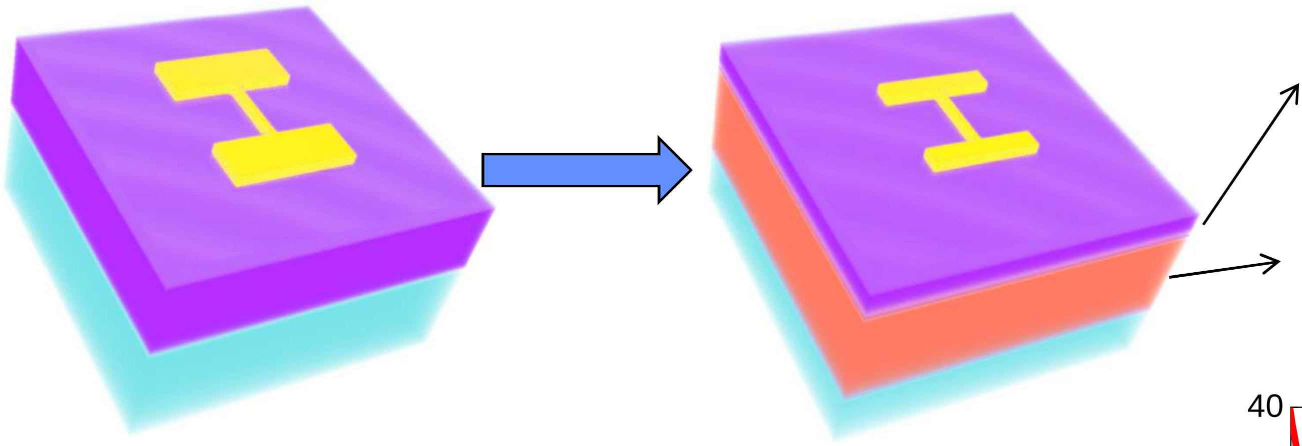
Effect of QW-stack thickness

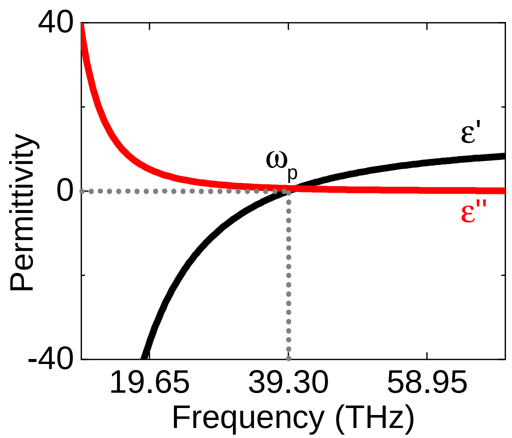


- Thickness of the QW-stack influences the Rabi frequency
- Increased from 1.65 to 2.64 THz

How to Increase the Rabi Frequency: Metamaterial Nanocavity + Ground-plane

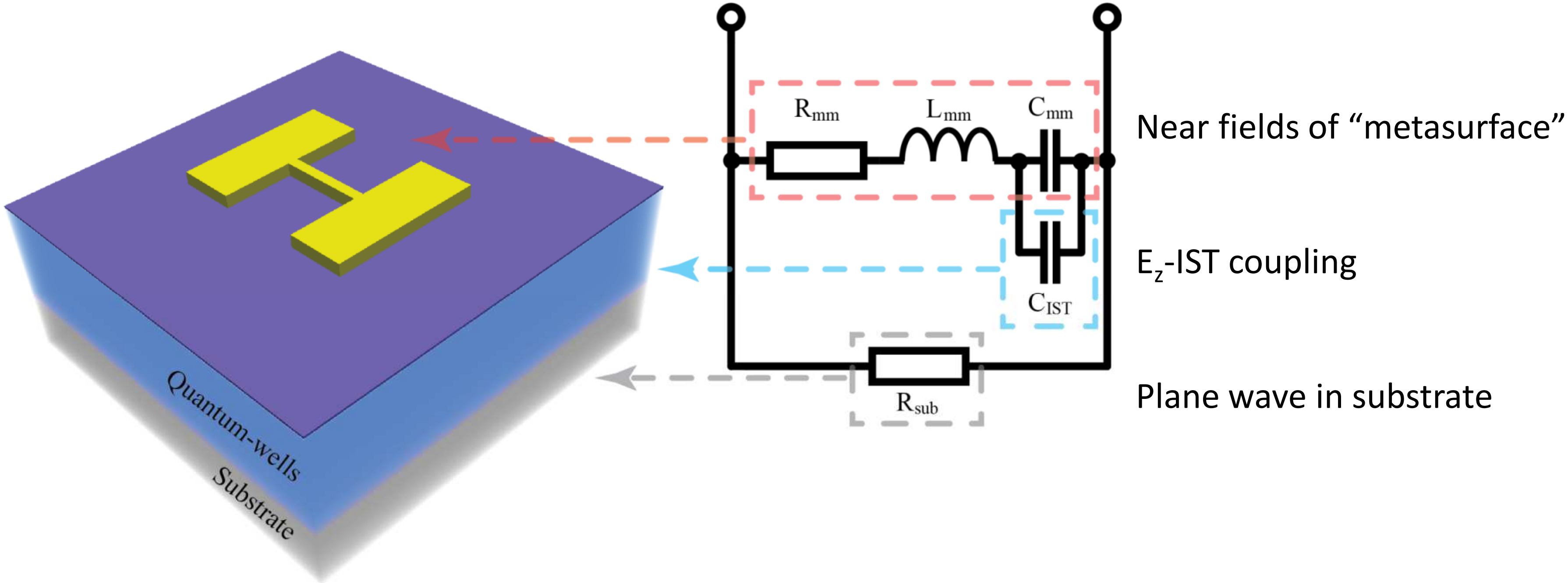






Opt. Express 21, 32572 (2013)

Circuit Model for Strong Coupling

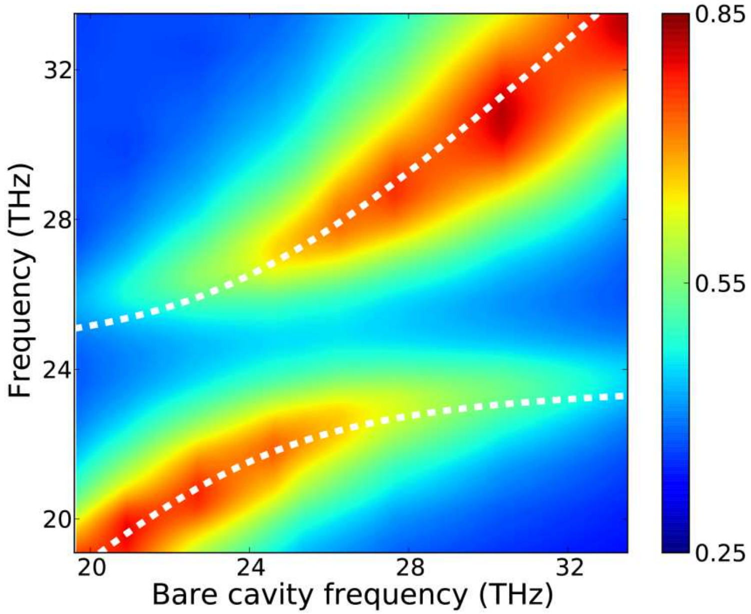


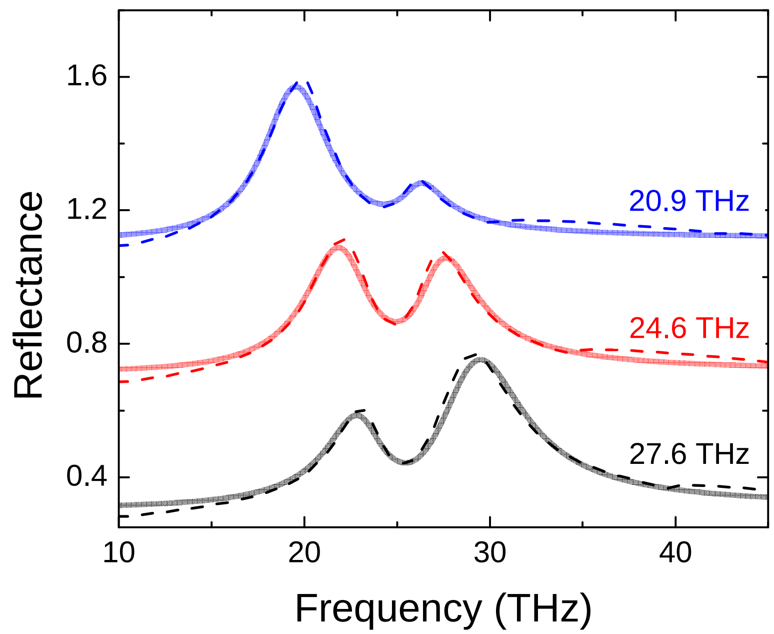
- **Metamaterial modelled as simple RLC harmonic oscillator**
- **Strong coupling represented by dispersive capacitor**
- **No free fitting parameters for dispersive capacitor**

$$\varepsilon_{IST}(\omega) = \varepsilon_{back} + \frac{\Delta N_{12} e^2}{\epsilon_0 m^*} \frac{f_{12}}{\omega_{12}^2 - \omega^2 + 2i\omega\delta}$$

$$C_{IST}(\omega) = \frac{\sqrt{\varepsilon_{back}\varepsilon_{IST}(\omega)} - \varepsilon_{back}}{\varepsilon_{back} + 1} C_{mm}$$

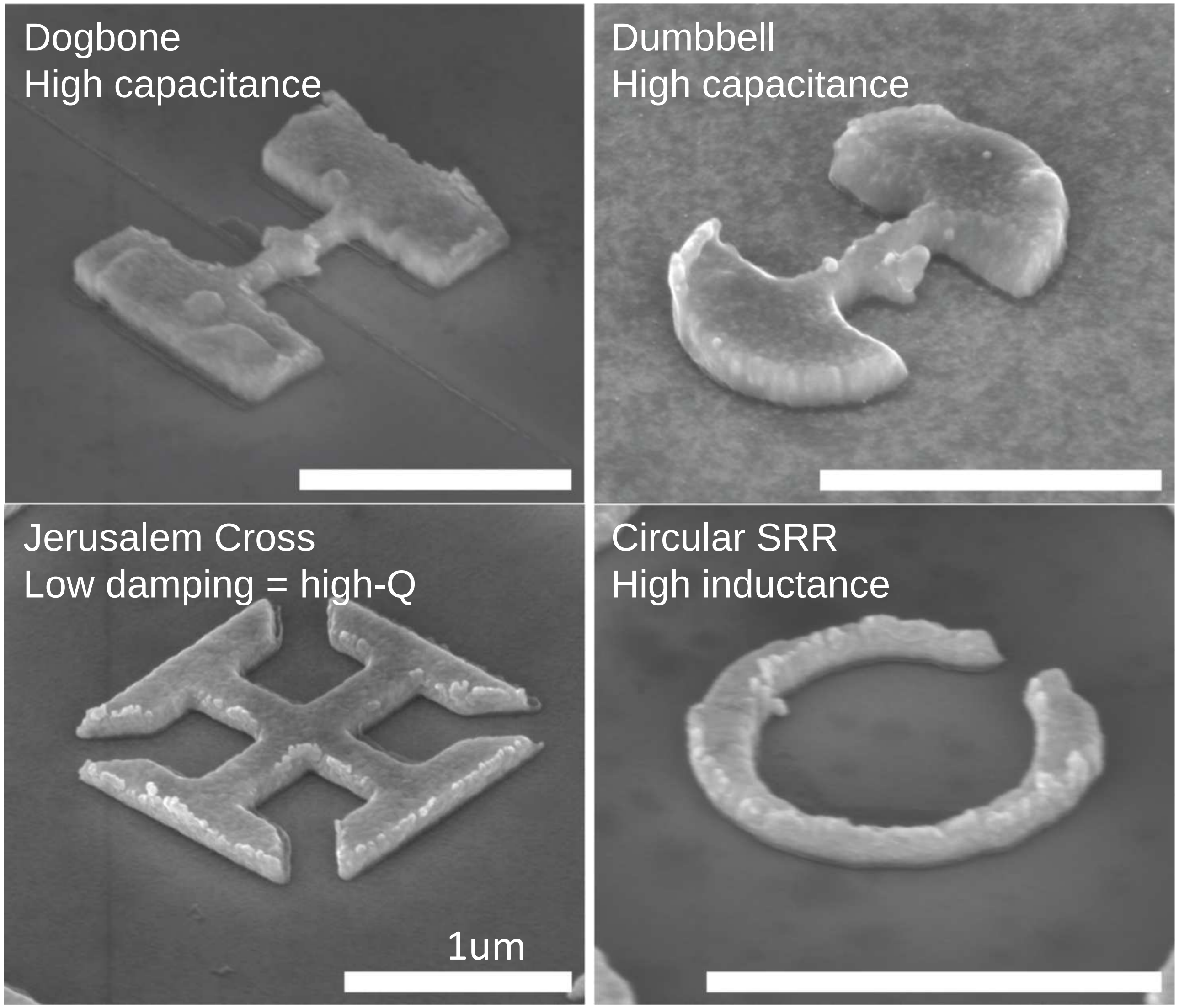
Accuracy of circuit model





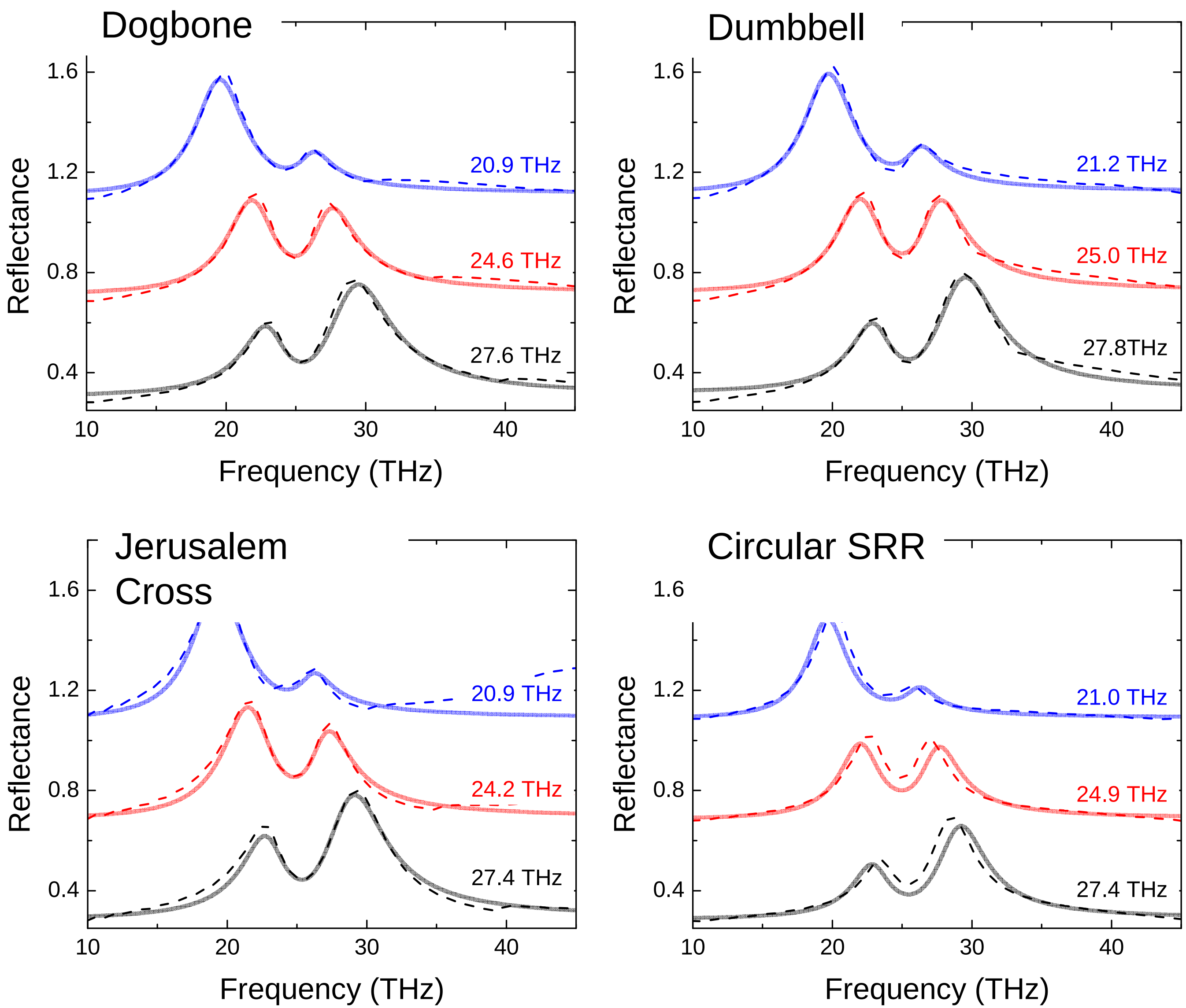
- FDTD simulations show clear anti-crossing as a function bare cavity frequency
- Circuit model can recover full lineshape of reflectance (or transmittance) spectra

Resonator Geometries Analyzed



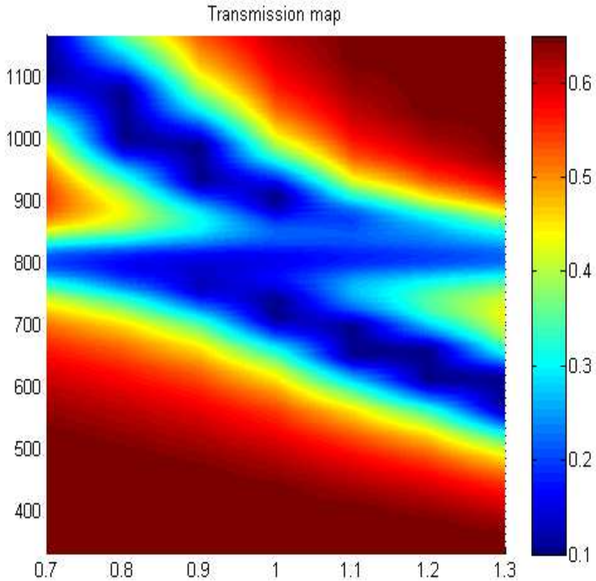
- **All metamaterial have identical bare cavity resonances but different RLC values**
- **Metamaterial defined by electron-beam lithography**
- **Same QW-stack used for all samples**
- **Study only geometry effect**

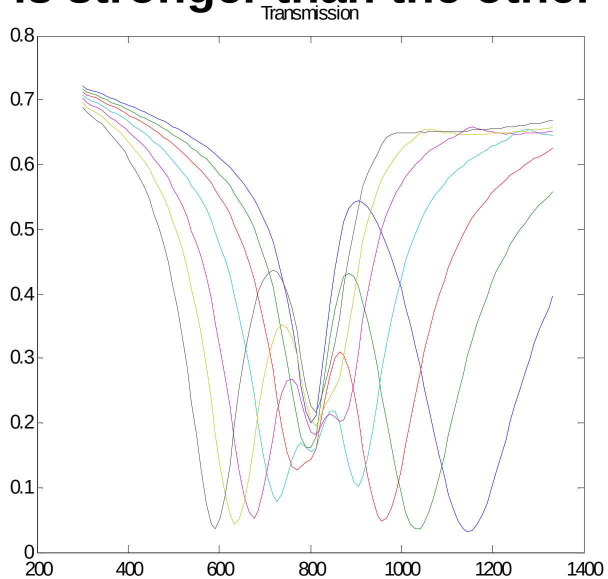
Circuit model accuracy

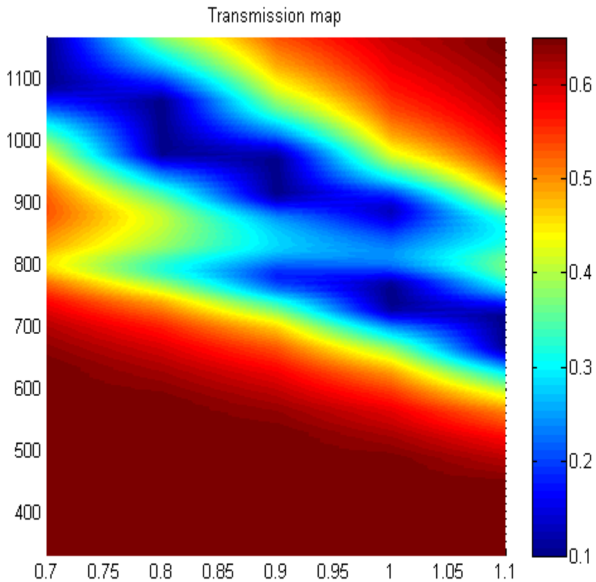


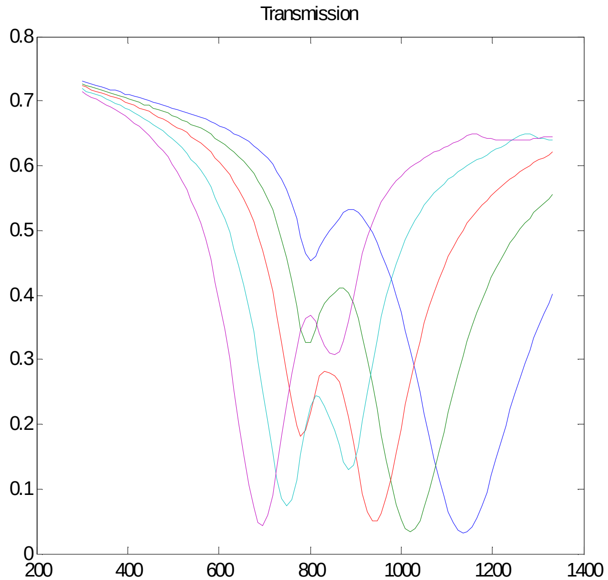
- **RLC model describes strong coupling accurately despite the exact geometry**
- **Only cold cavity requires fitting**

Top: Two isotropic Lorentzians; one is stronger than the other





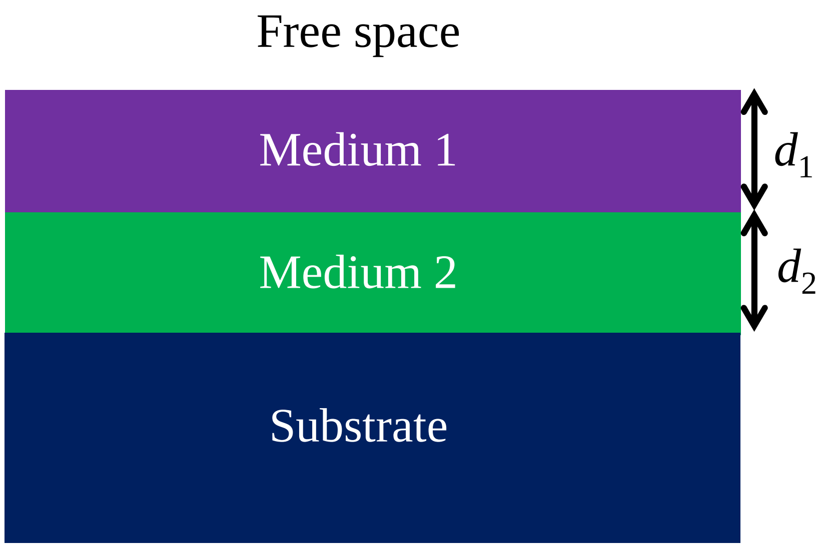


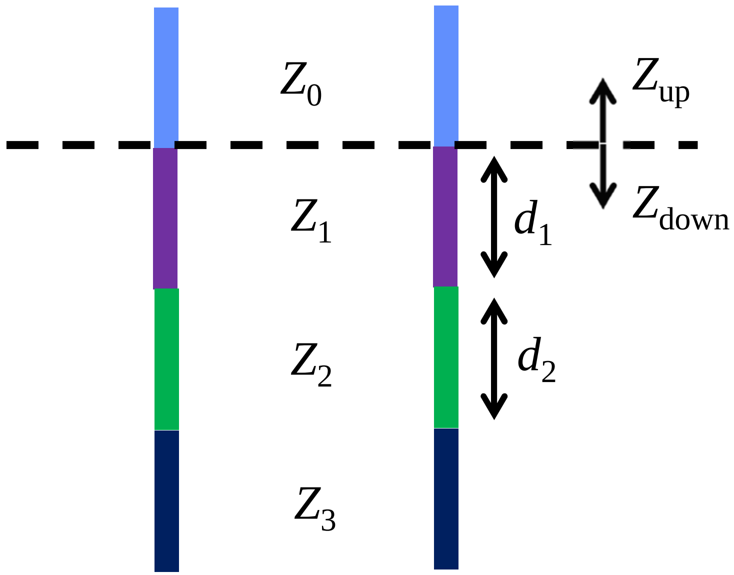


Bottom: Two anisotropic Lorentzians; one is stronger than the other

Modal analysis

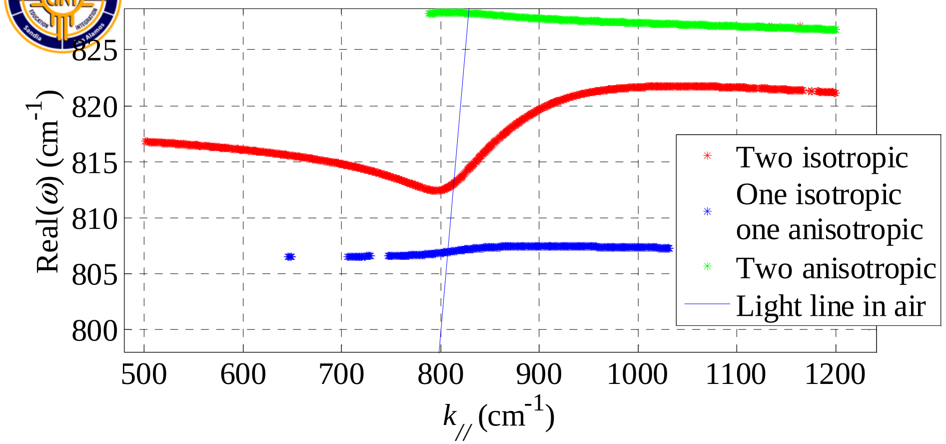
The layered medium can be modeled as a set of cascaded transmission lines



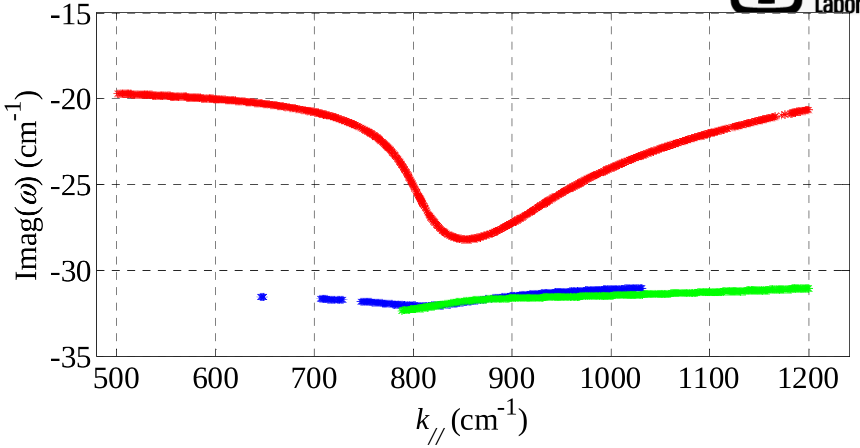


Select a reference plane, then compute the impedances looking up and looking down accounting for the dispersion in each medium

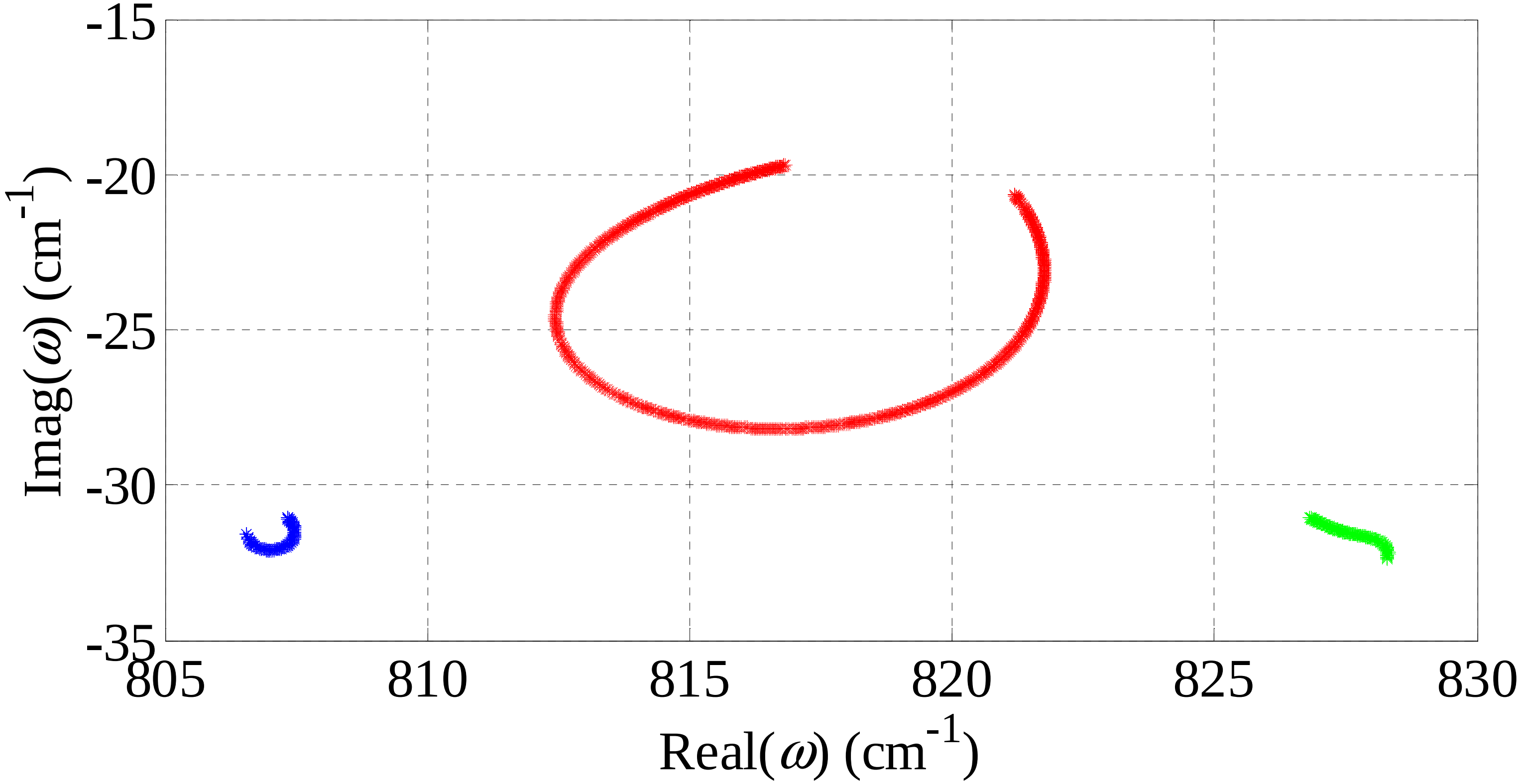
Compute the (complex) modes as the zeroes of $Z_{up} + Z_{down} = 0$



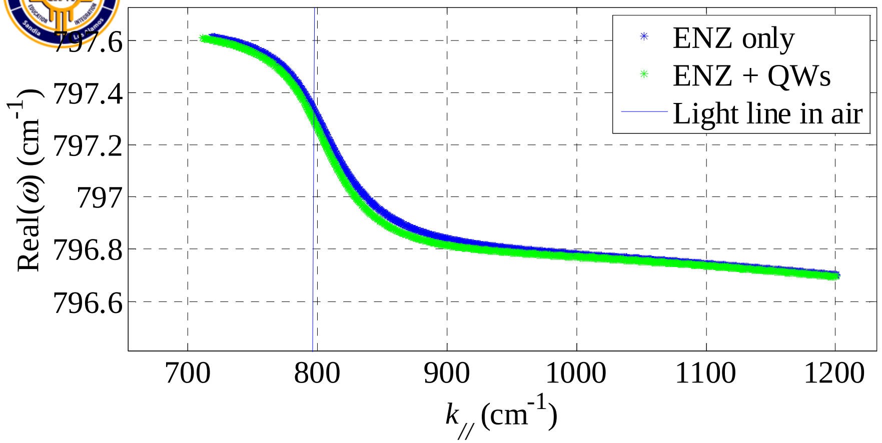
825
820
815
810
805
800
500 600 700 800 900 1000 1100 1200
Real(ω) (cm-1)
k// (cm-1)
Two isotropic
One isotropic
one anisotropic
Two anisotropic
Light line in air

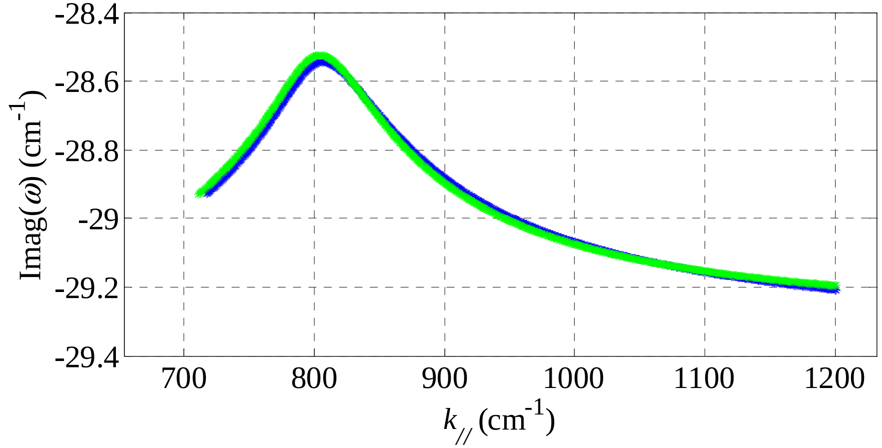


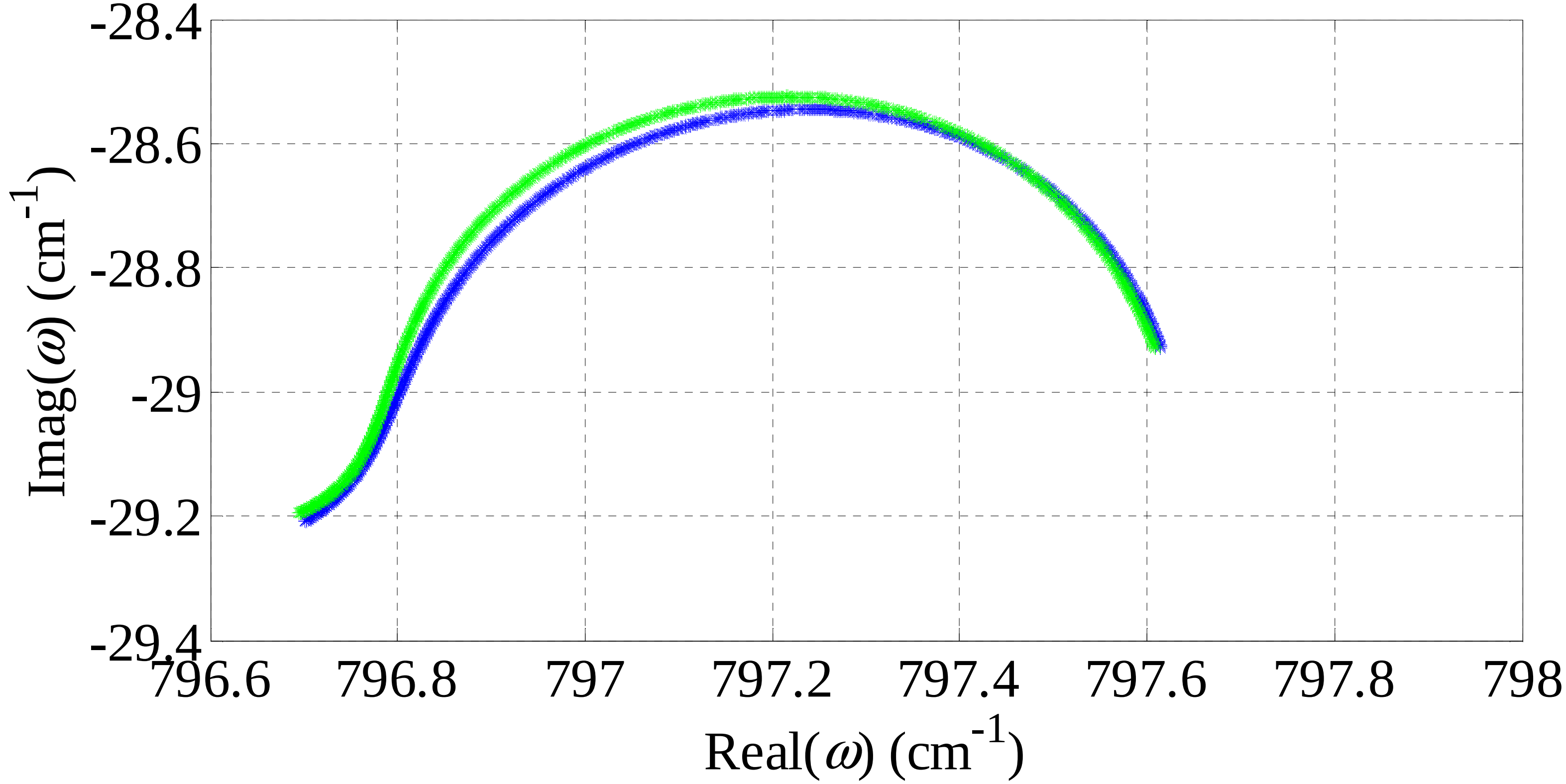
-15
-20
-25
-30
-35
500 600 700 800 900 1000 1100 1200
Imag(ω) (cm-1)
k// (cm-1)



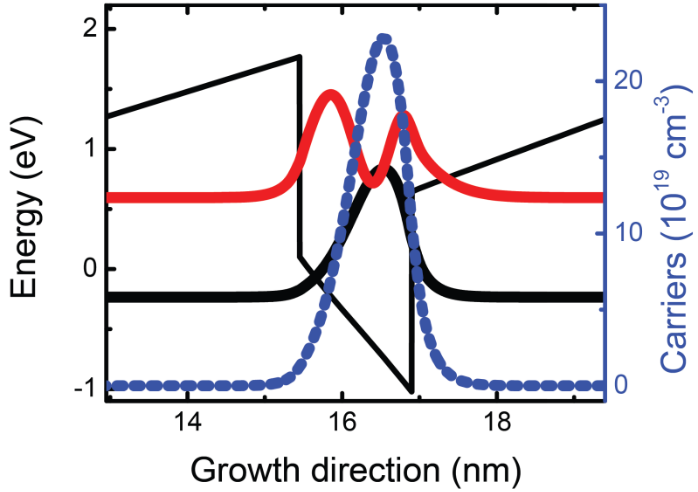
-15
-20
-25
-30
-35
805 810 815 820 825 830
Imag(ω) (cm-1)
Real(ω) (cm-1)

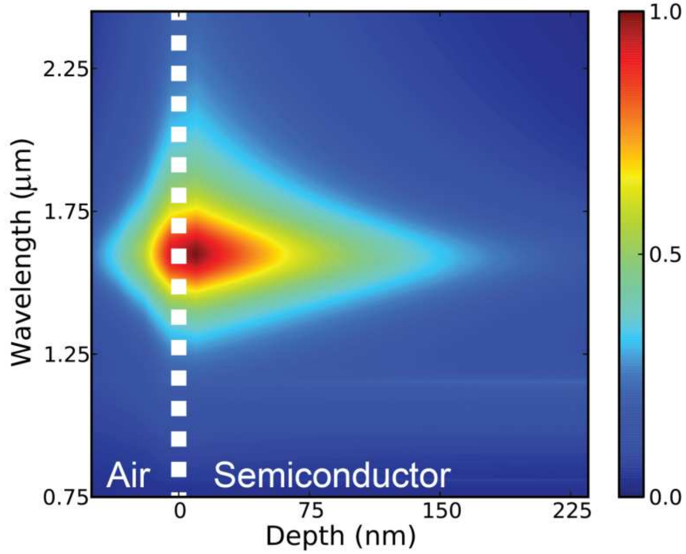

797.6
797.4
797.2
797
796.8
796.6
Real(ω) (cm-1)
700
800
900
1000
1100
1200
k// (cm-1)
ENZ only
ENZ + QWs
Light line in air

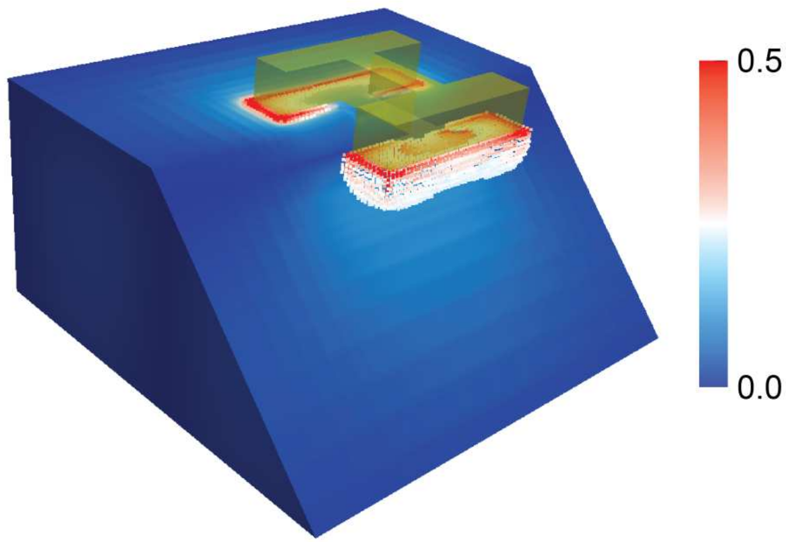

-28.4
-28.6
-28.8
-29
-29.2
-29.4
Imag(ω) (cm-1)
700
800
900
1000
1100
1200
k// (cm-1)


-28.4
-28.6
-28.8
-29
-29.2
-29.4
Imag(ω) (cm-1)
796.6
796.8
797
797.2
797.4
797.6
797.8
798
Real(ω) (cm-1)

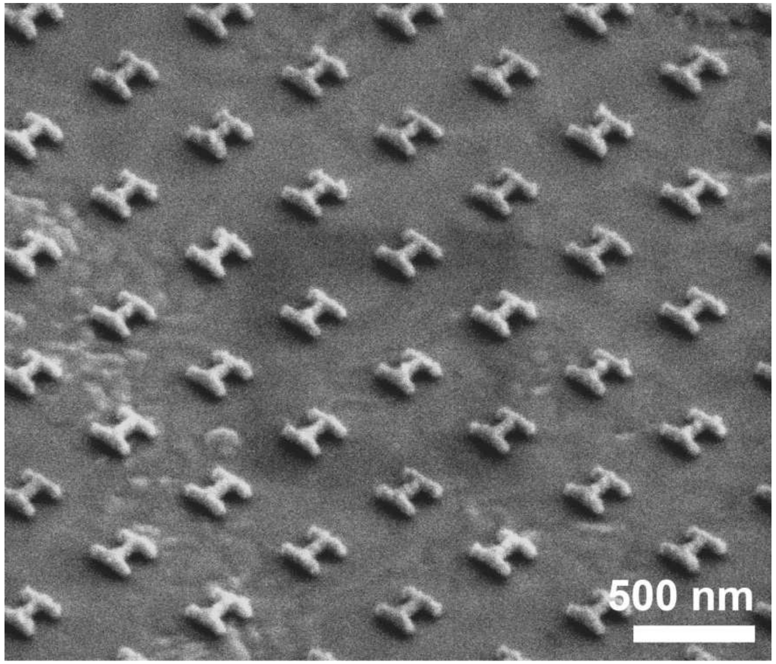
Strong Coupling, Near IR

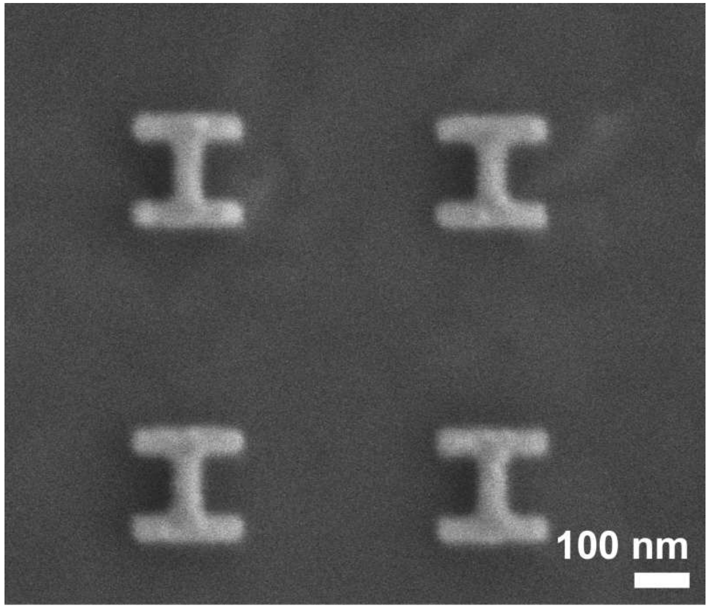




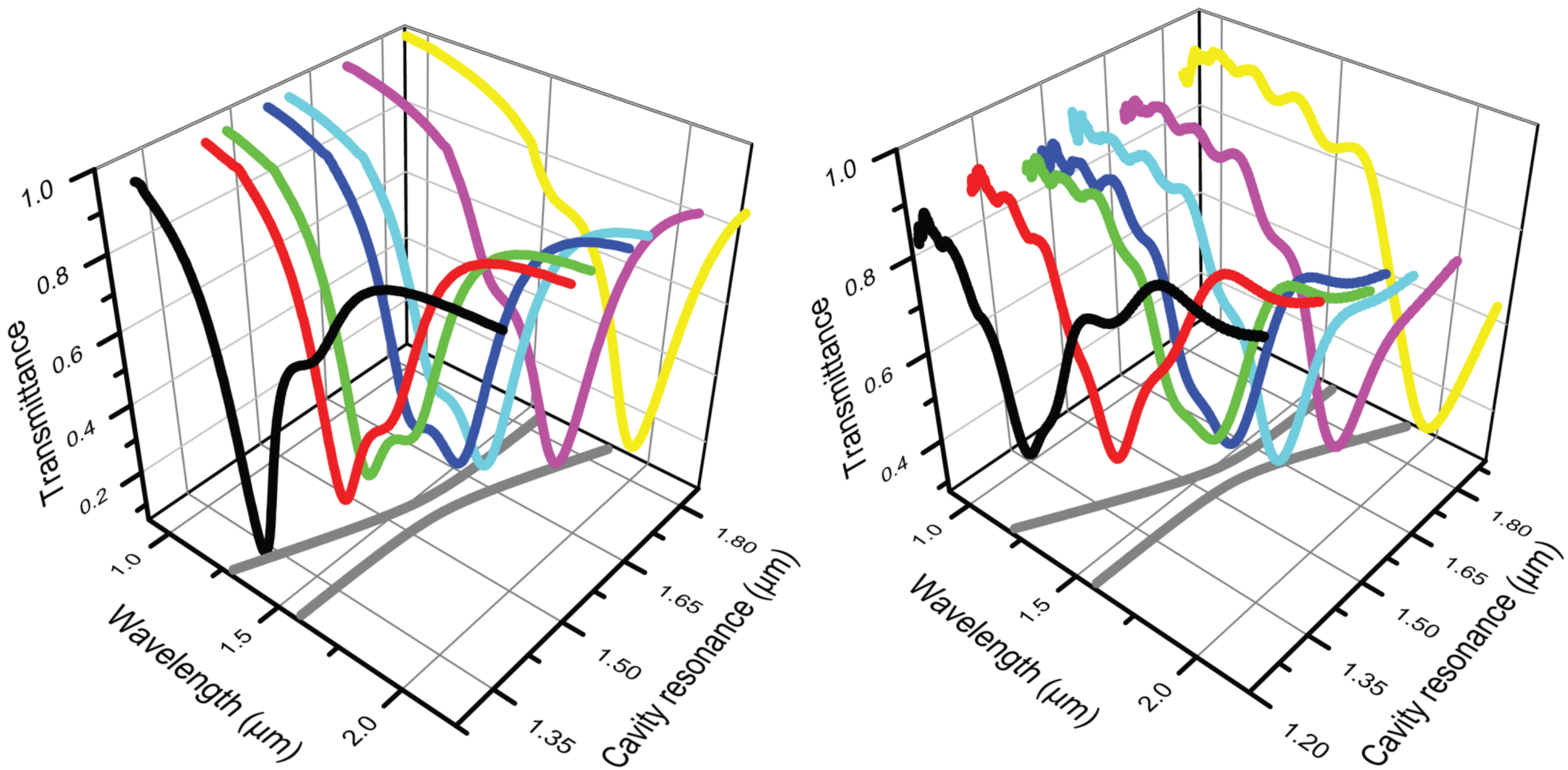


Dogbone Resonators, Near IR

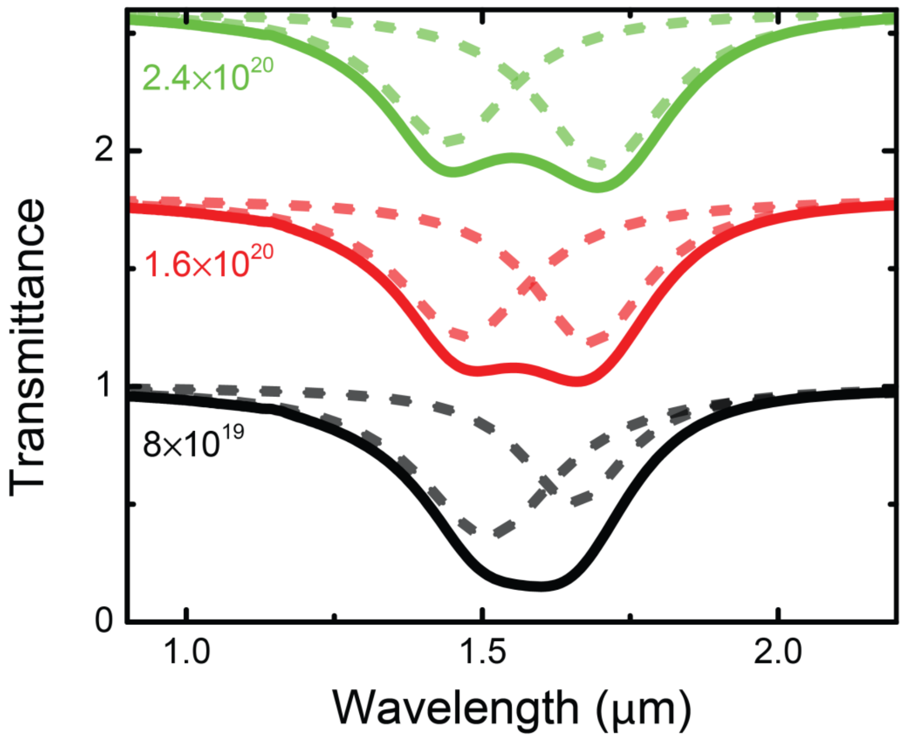


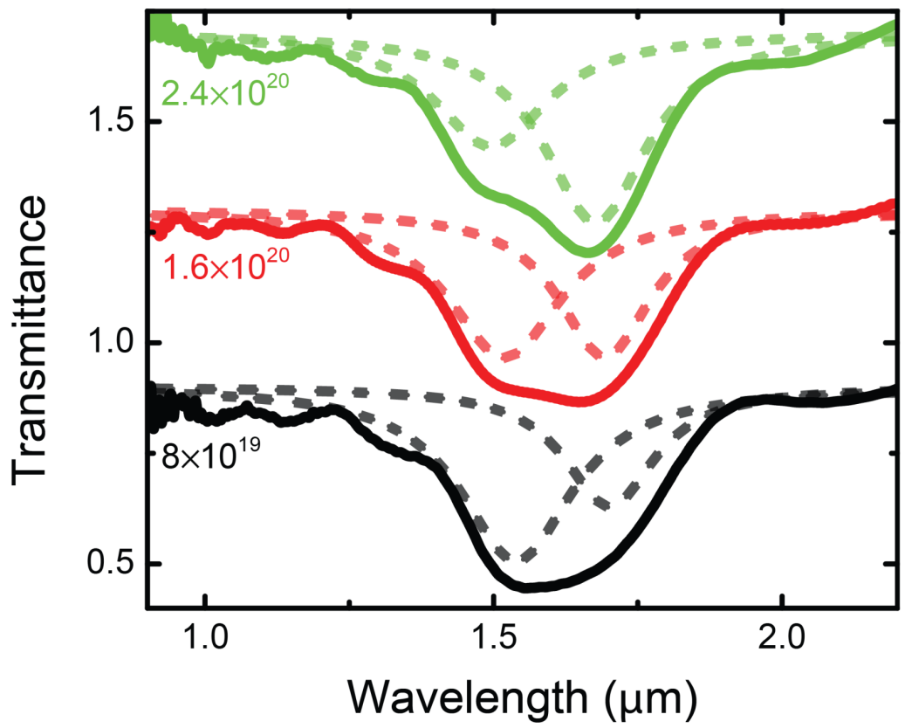


Strong Coupling, Near IR

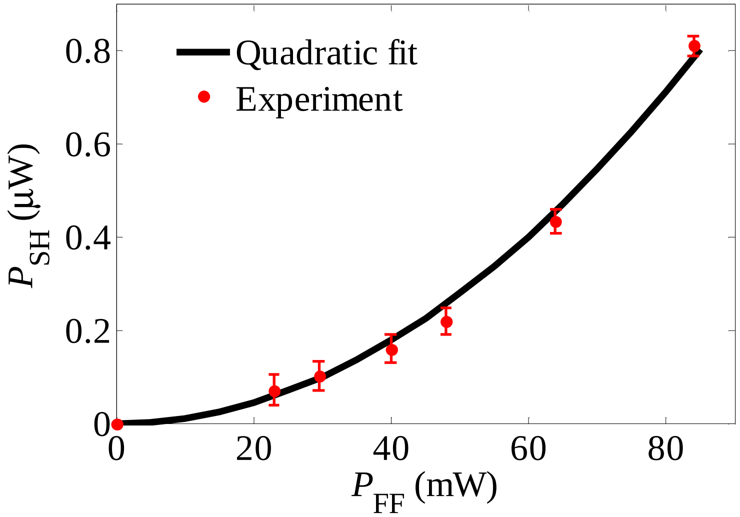


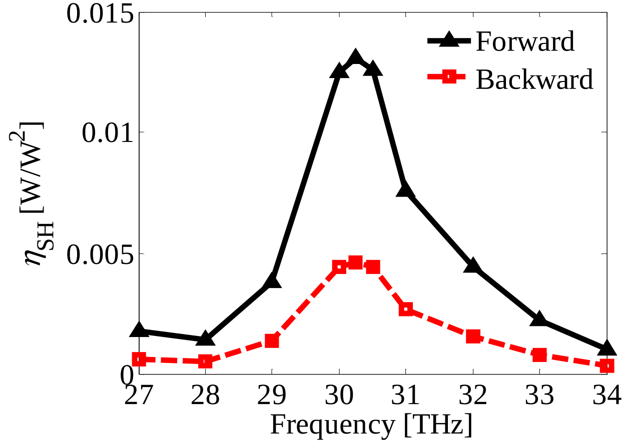
Strong Coupling, Near IR

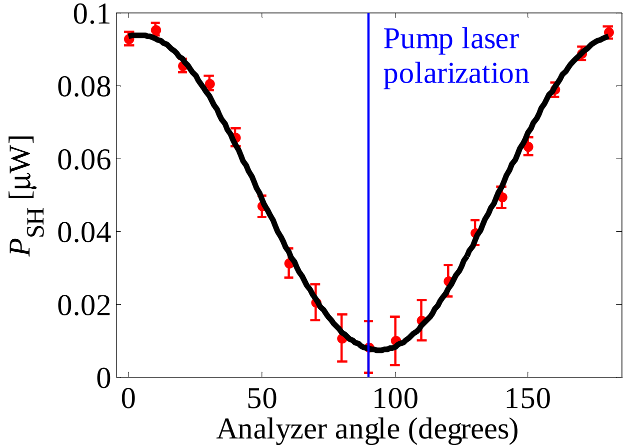




SHG







Appl. Phys. Lett. **104**, 131104 (2014)