SAND2012-7597C

Semiconductor Approaches for Tunable Metamaterials in the Infrared

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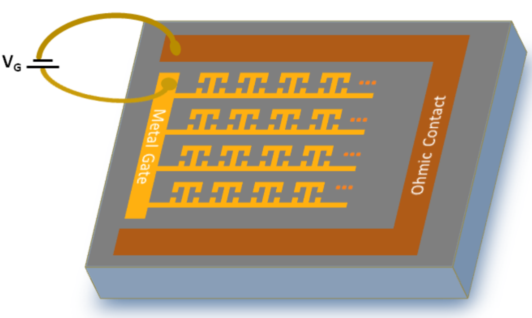
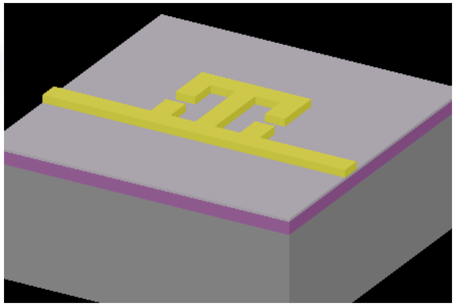
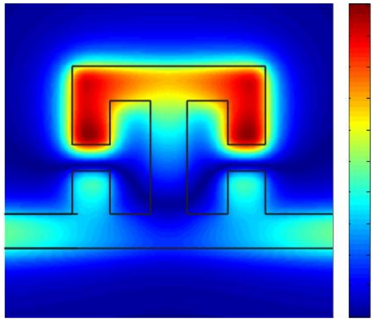
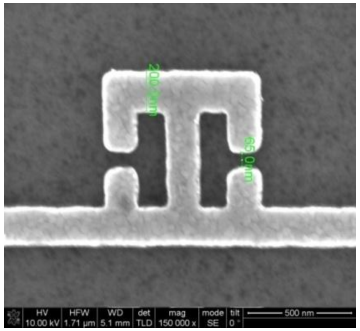
Albuquerque, New Mexico









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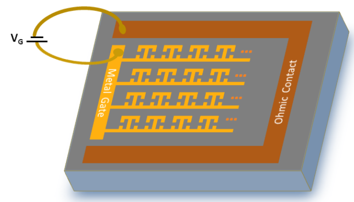
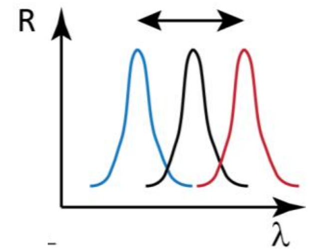
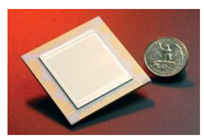
Why Infrared Tunable Metamaterials?

We would like to have semiconductor based, planar, electrically tunable IR filters that can be integrated with array detectors.



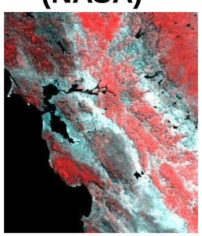


Examples: hyperspectral imaging



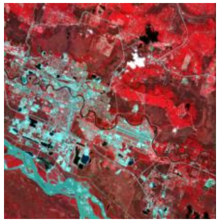
(JPL)

(NASA)



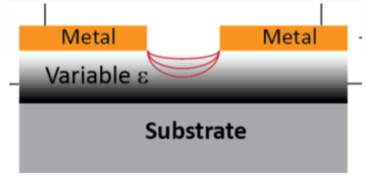
(Cedip)

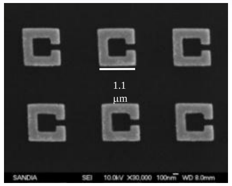
Mechanical filters!



Tunable interactions with planar metamaterials are needed

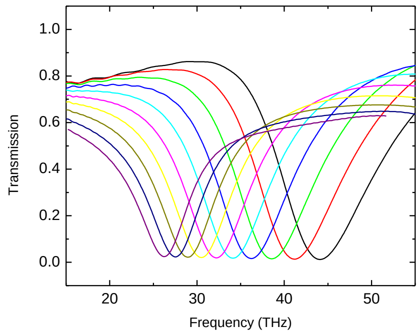
Example, SRRs interact strongly with thin layers underneath



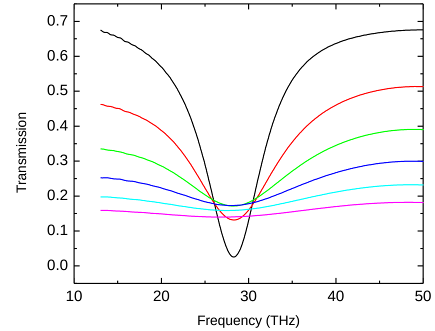


- **Nonresonant**

Change ε_1 (n)

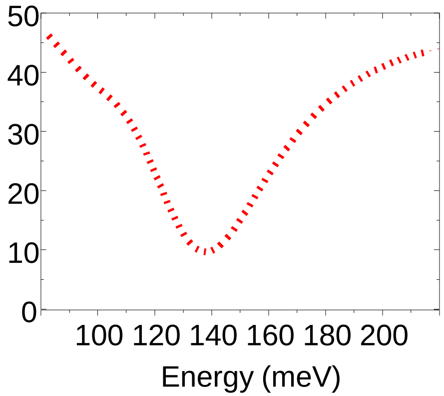


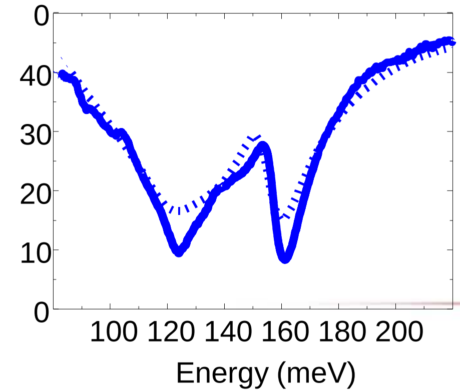
Change ε_2 (n)



- **Resonant**

(Create a dipolar resonance, example: phonon)





Nano Letters 11, 2104 (2011)

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Metamaterials Science & Technology

Outline

- Tuning through interaction with *Semiconductor Free Carriers*.

- Tuning through interaction with *Intersubband Transitions in Semiconductor Heterostructures*

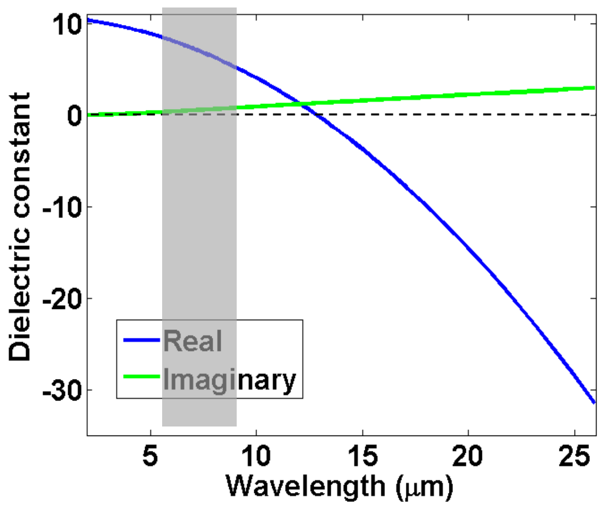
Interactions between metamaterials and electrons in doped semiconductors

Drude Model: $$\varepsilon \approx \varepsilon_\infty\left(1-\frac{\omega_p^2}{\omega^2+i\omega\Gamma}\right)=\varepsilon_\infty\left(1-\frac{\omega_p^2}{\omega^2+\Gamma^2}+i\frac{\omega_p^2\Gamma}{\omega(\omega^2+\Gamma^2)}\right)$$

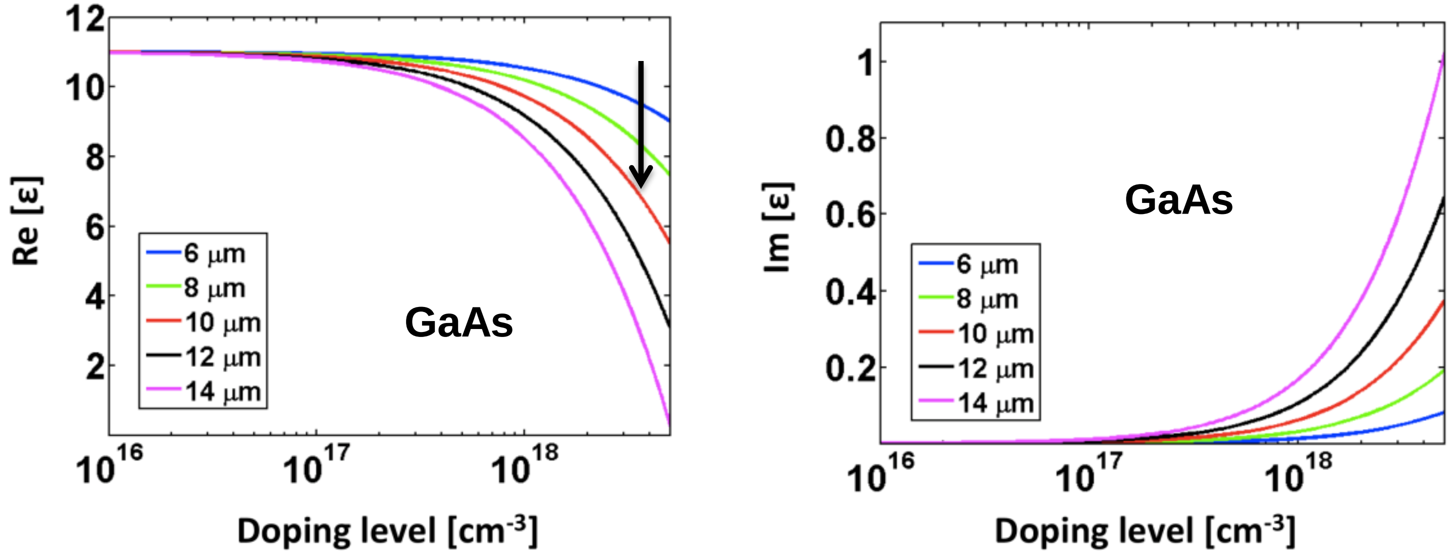
$$\Gamma = 1/\tau = \frac{q}{\mu m^*}$$

$$\omega_p^2 = \frac{Nq^2}{\varepsilon_0\varepsilon_\infty m^*}$$

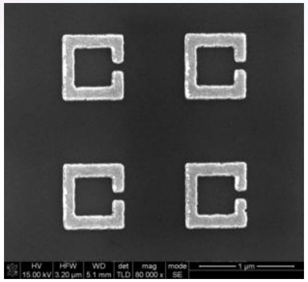
ex: n+ GaAs, $5\times10^{18}cm^{-3}$



(a)

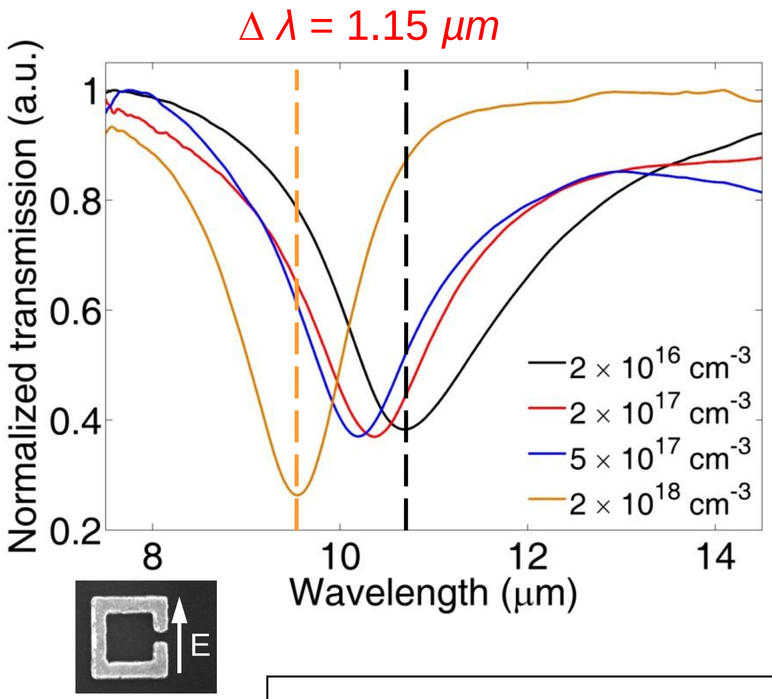


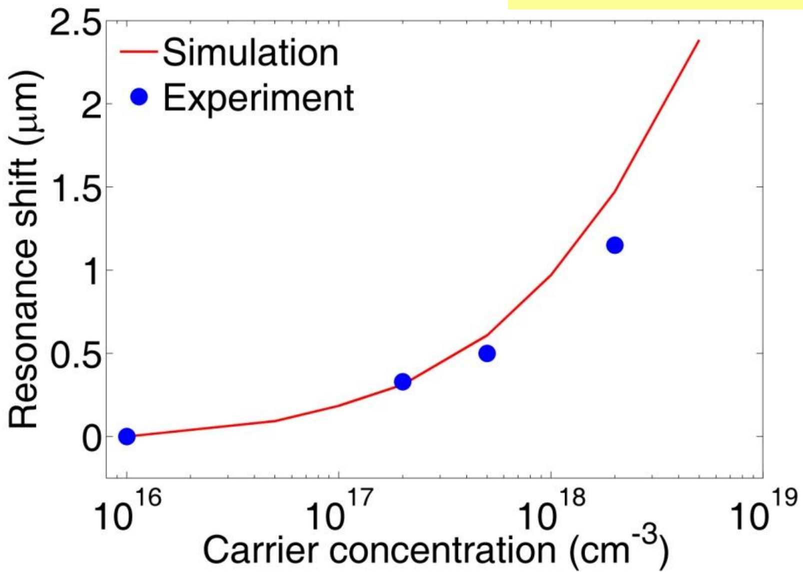
Demonstration of "static" tuning: SRRs on n+ InSb



- Thin n-type doped layer grown on semi-insulating InSb wafer.
- SRRs are made by EBL+liftoff, Au/Ti

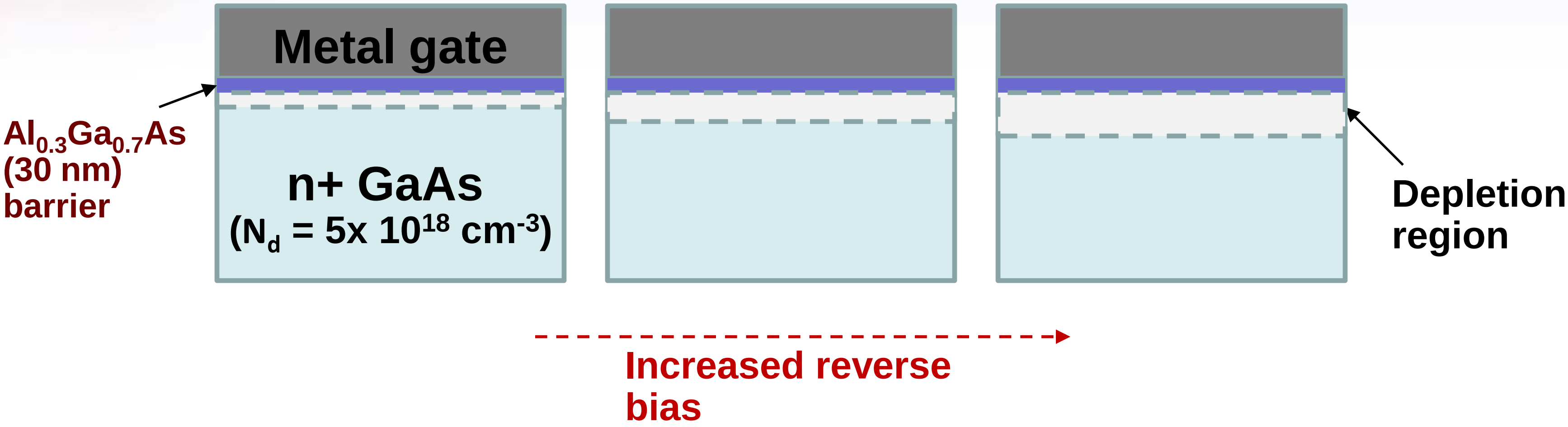
Appl. Phys. Lett. 96, 10 (2010)





Resonance shift of 1.15 µm with <u>no appreciable damping.</u>

Tuning metamaterials by depletion of carriers



Change in ε increases with N_d

$$\Delta\varepsilon \approx \frac{1}{\omega^2}\frac{N_d q^2}{\varepsilon_0 m^*} \propto N_d$$

Depletion width decreases with N_d

$$W_{depletion} = \left[\frac{2\varepsilon_{GaAs}\varepsilon_0}{qN_d}(-\phi_s)\right]^{1/2}$$

Overall resonator capacitance change ~ $\sqrt{N_d}$

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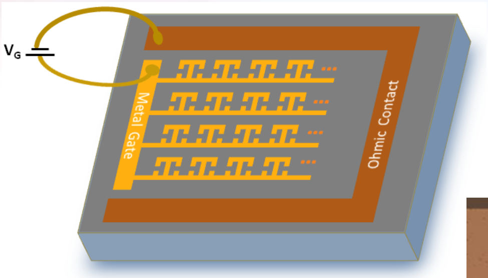
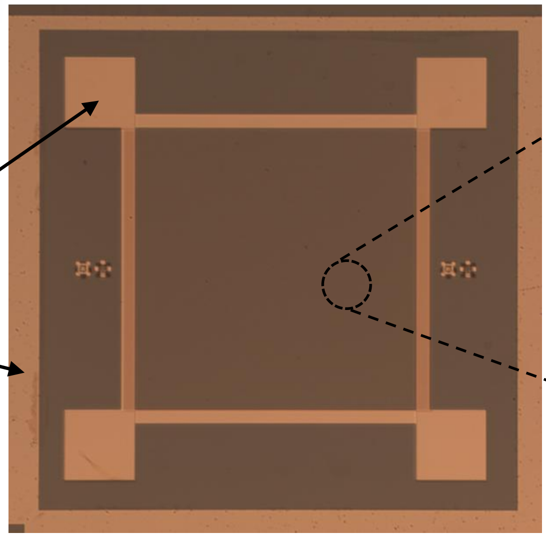
Mid IR (~10μm) tunable metamaterial

(Young Chul Jun)

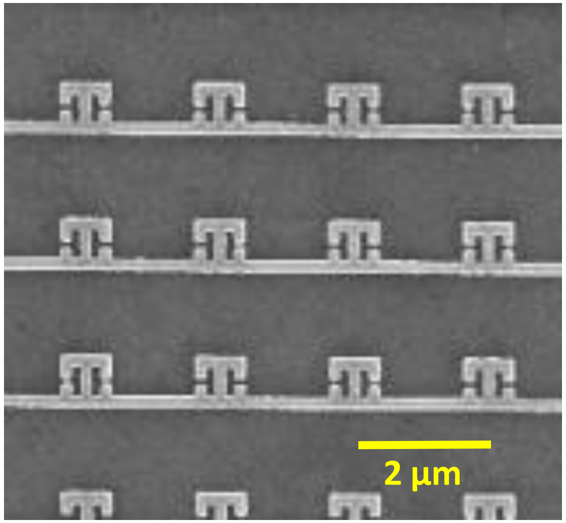
Metamaterials Science & Technology

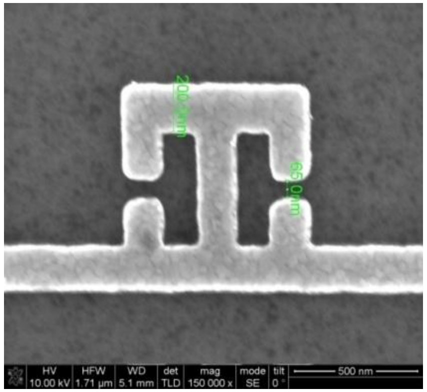


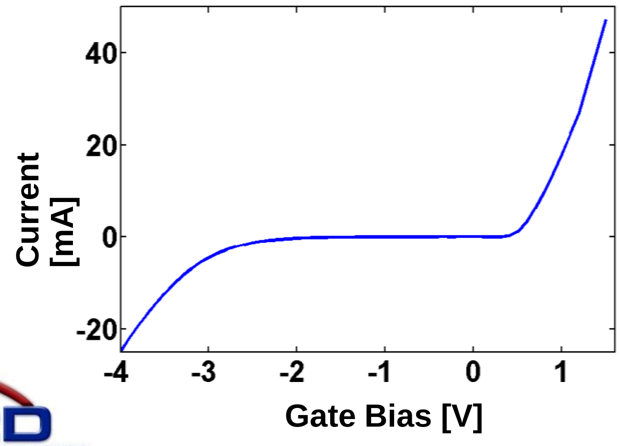


Metal gate (Ti/Au)

Ohmic contact (Ge/Au/Ni/Au)







Gold SRR array patterned by e-beam lithography (connected to metal gate)

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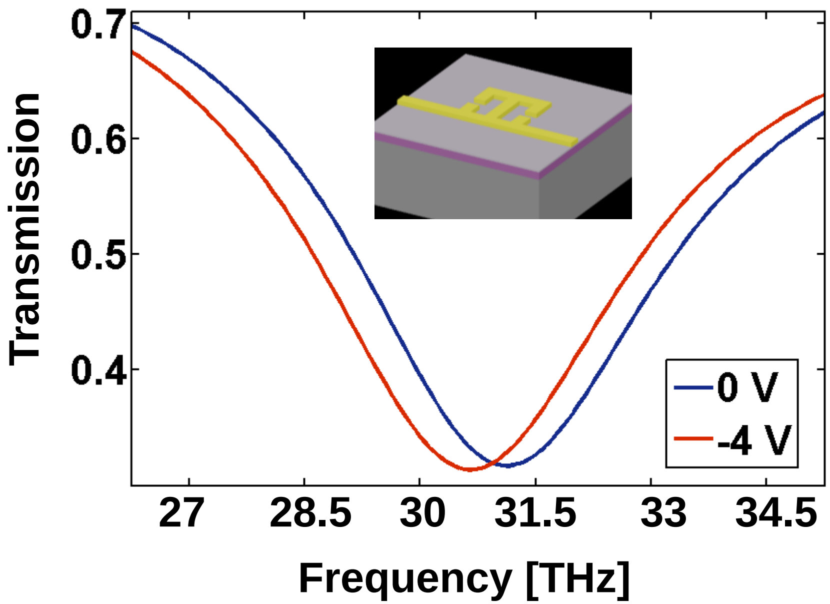
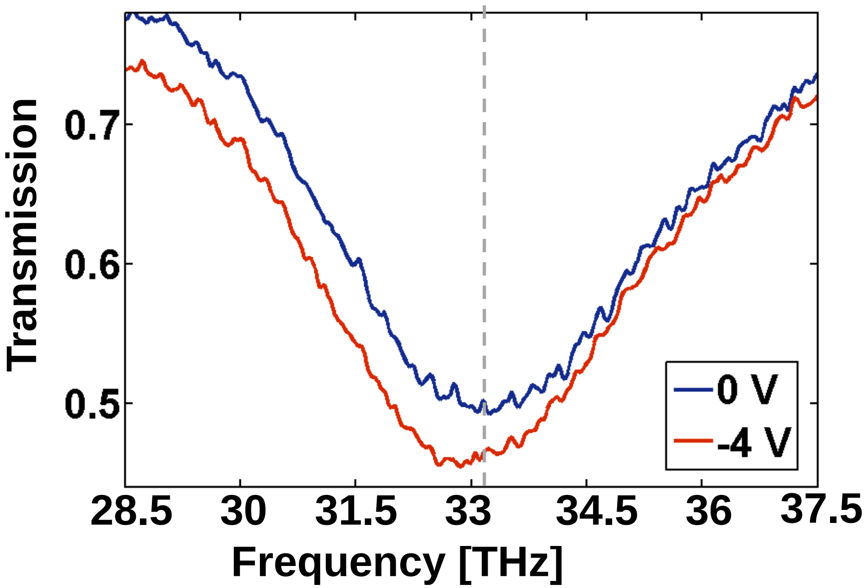
Experimental Results

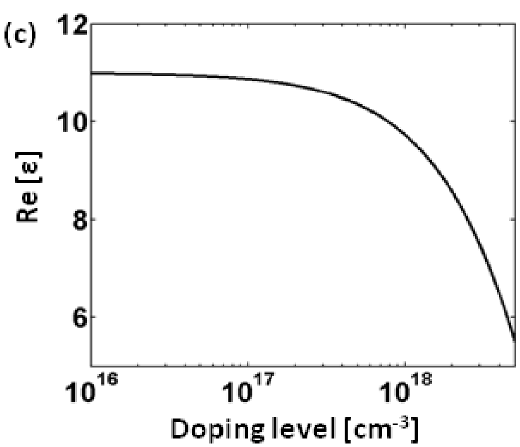
Optics Express 20, 1903 (2012)

Theory



Experiment

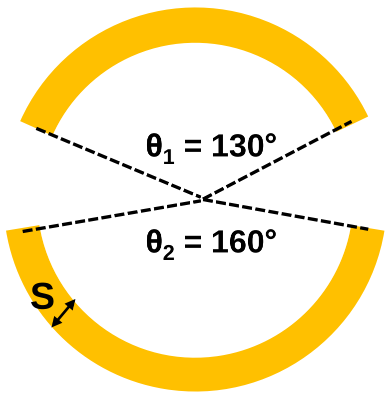




Depleting carriers increases ε → Capacitance increases → Resonant frequency decreases

Better tunability: coupled resonators

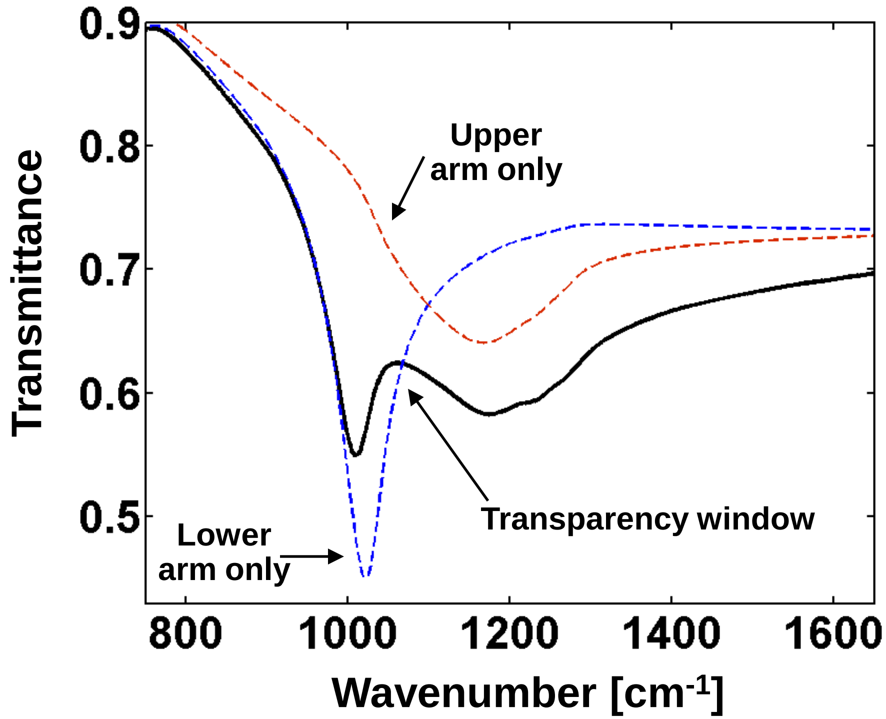
Classical analog of EIT
(N. Zheludev group)



(Radius = 770 nm, S = 150 nm)

Incident light polarized

Numerical simulation



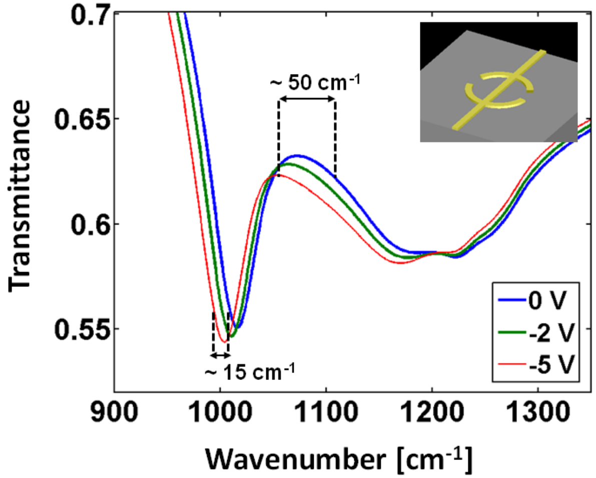
- Scaled-down structure which is resonant at mid-IR
- Transparency window: destructive interference between two resonances
- Interference can be more sensitive to refractive index change

Tunable coupled resonators

- We can electrically address each resonator arm separately
- Different biasing schemes produce different spectral changes

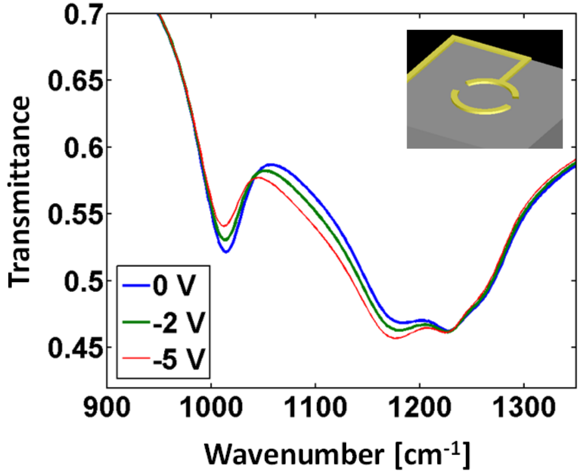
Numerical simulations

Both arms connected to electrical bus line



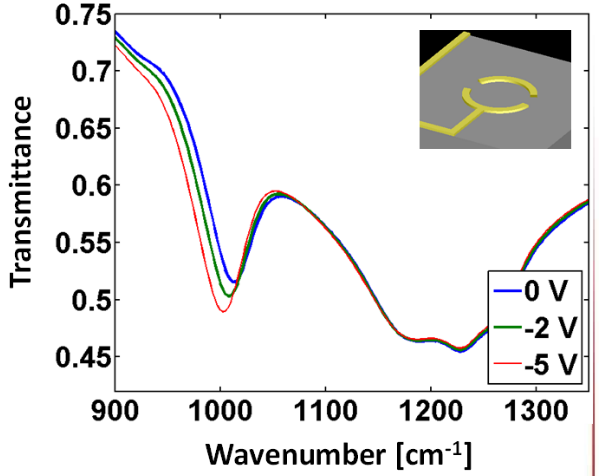
All resonances shift with bias

Only upper arm connected to electrical bus line



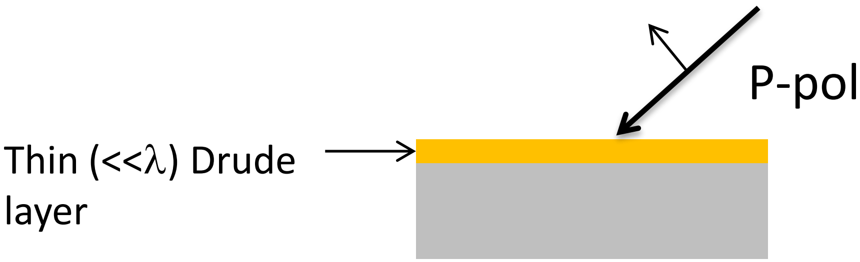
Transmission of 1000 cm^{-1} dip increases with bias

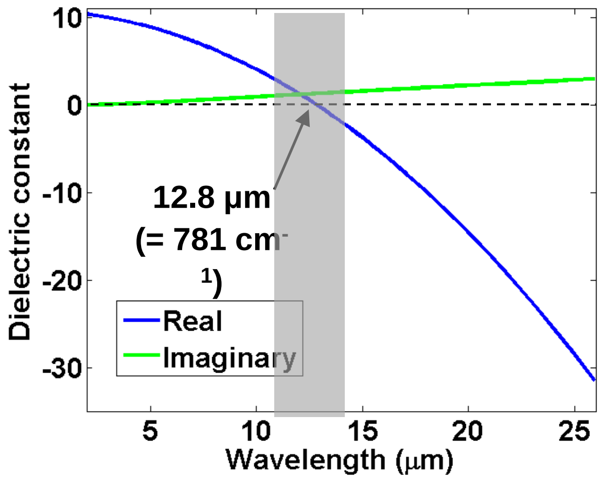
Only lower arm is connected to the electrical bus line

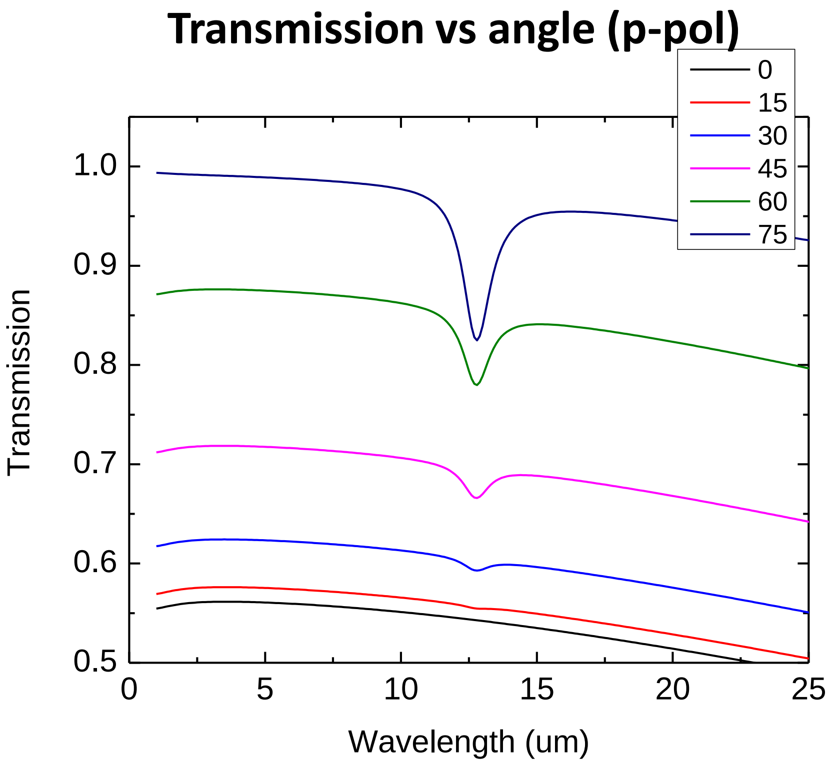


Transmission of 1000 cm^{-1} dip decreases with bias

Interaction with a thin Drude layer near ε~0 (Berreman effect)





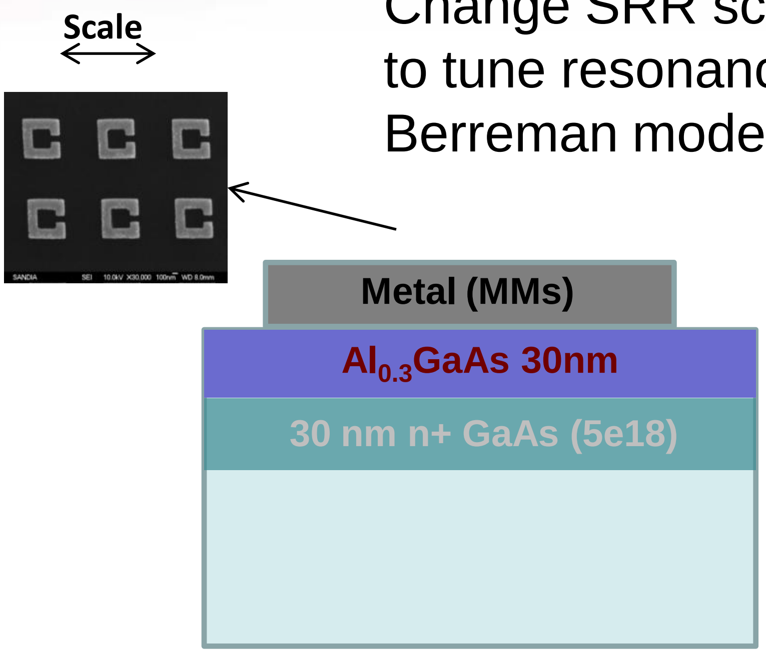


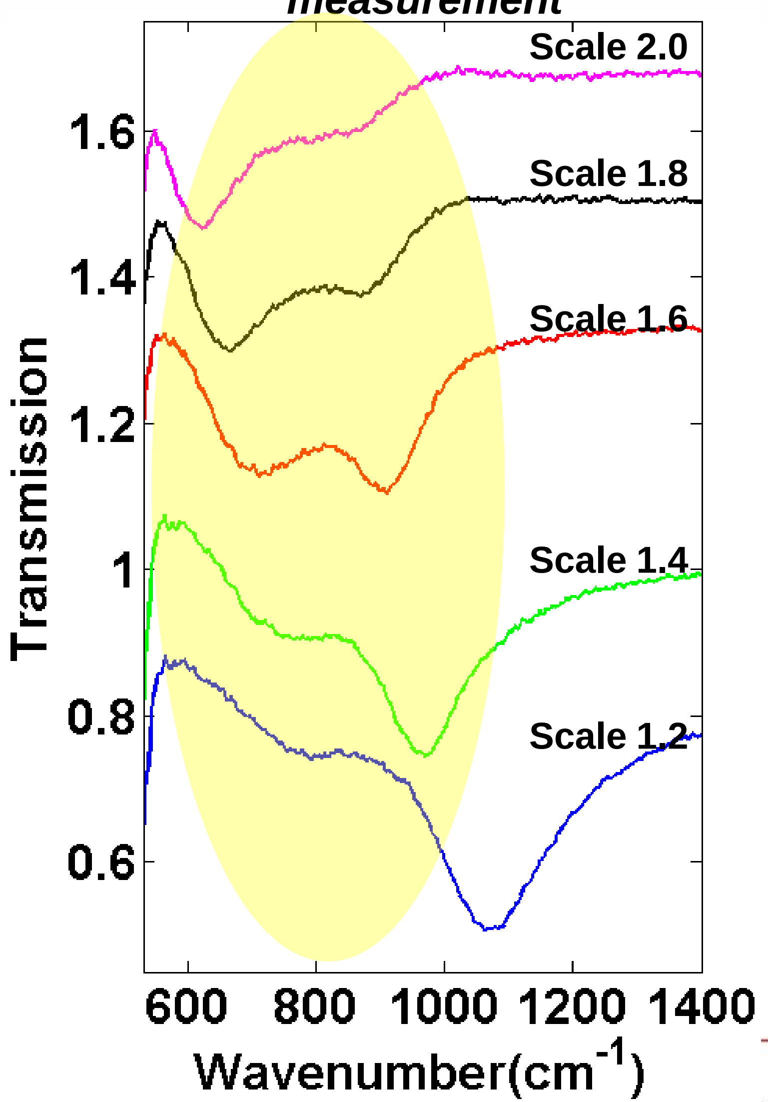
- A sharp dip is observed in transmission, where ε~0
- Berreman effect, can be observed with plasmons or phonons

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

What happens when metamaterials resonate with ε~0 Layer?

Change SRR scaling factor to tune resonance through Berreman mode

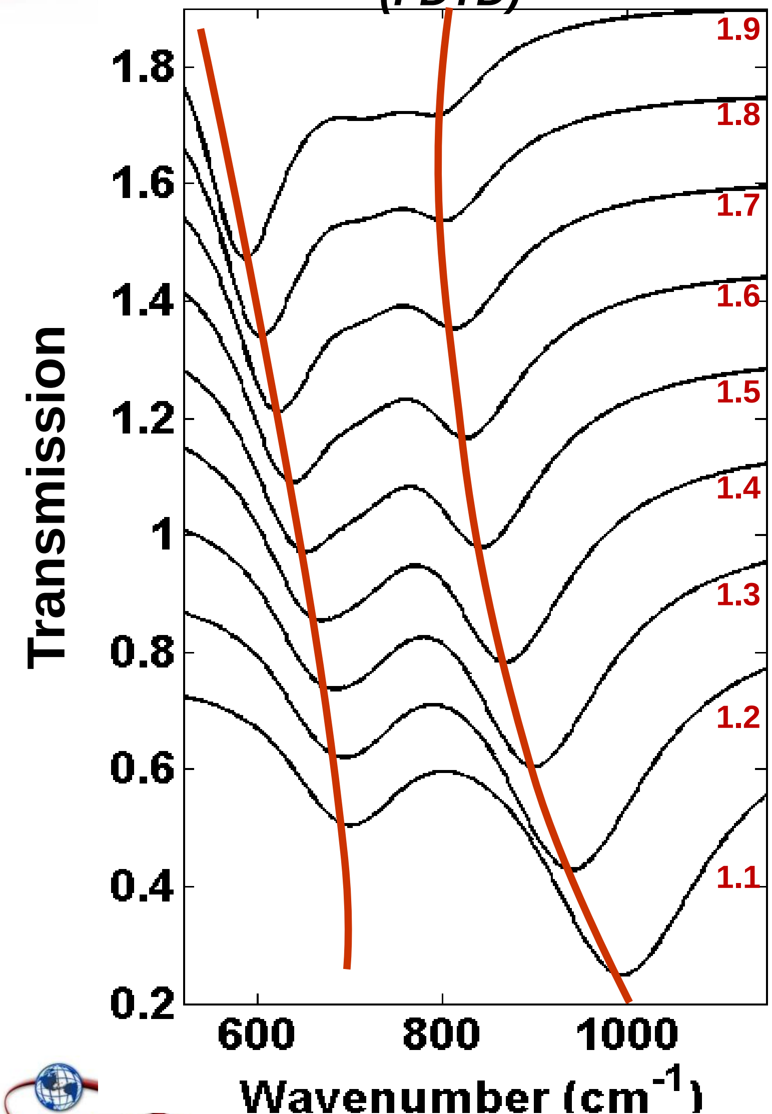




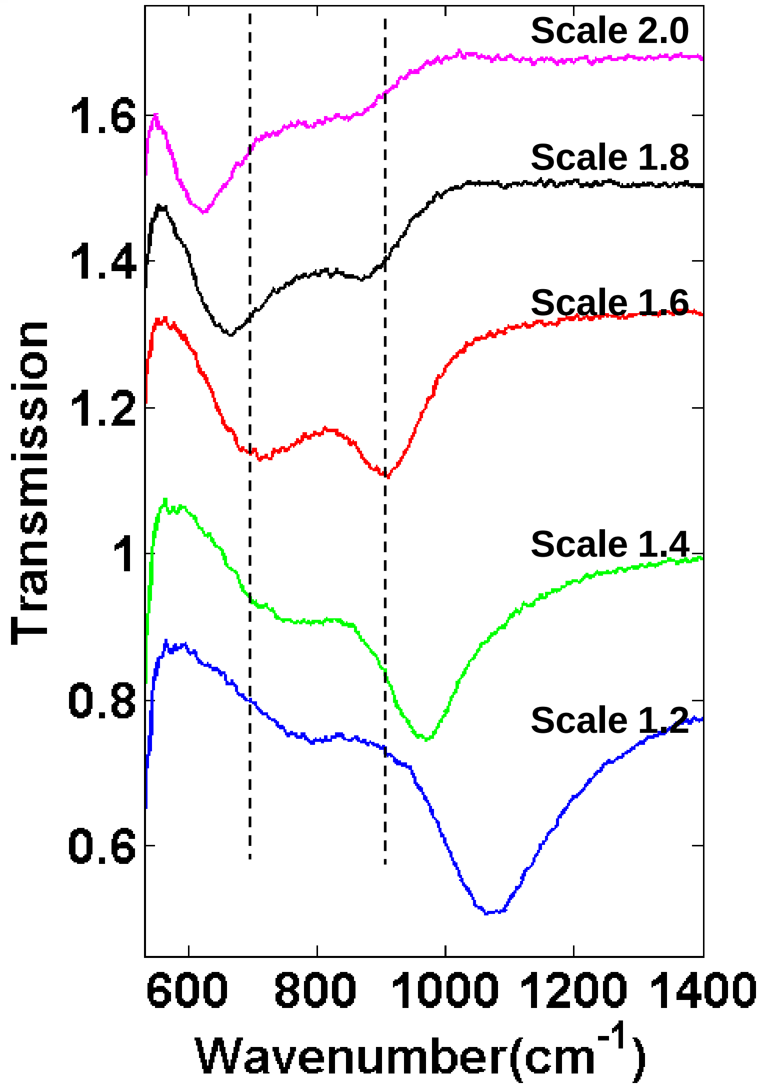
- **Strong coupling between the metamaterial resonance and plasmon resonance in the n+ epilayer**

Strong coupling to ε~0 layer: theory vs. experiment

Numerical simulation (FDTD)



FTIR transmission measurement



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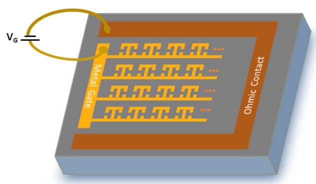
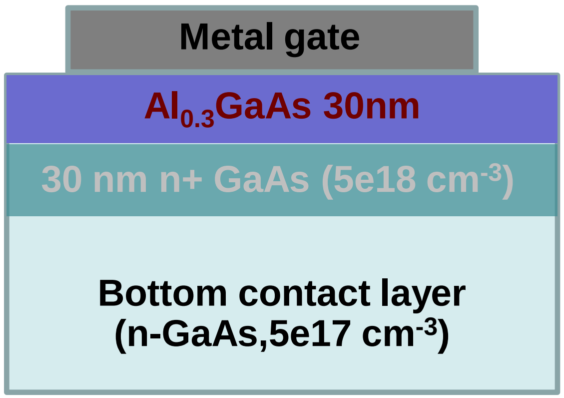
Metamaterials Science & Technology

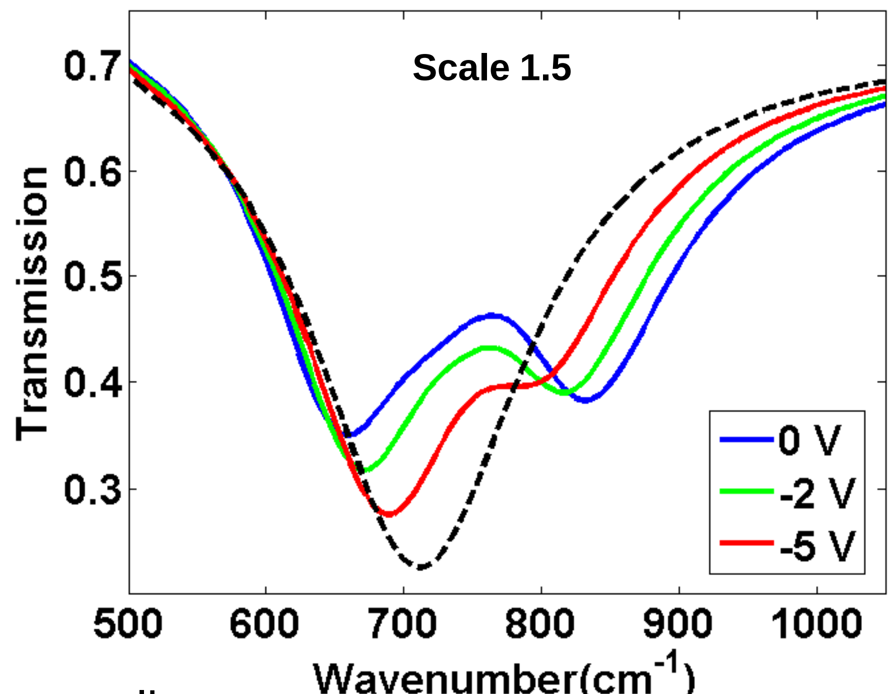
Metamaterial – plasmon strong coupling: electrical tuning

Depletion moves the ε~0 frequency → moves plasmon mode





Numerical simulation



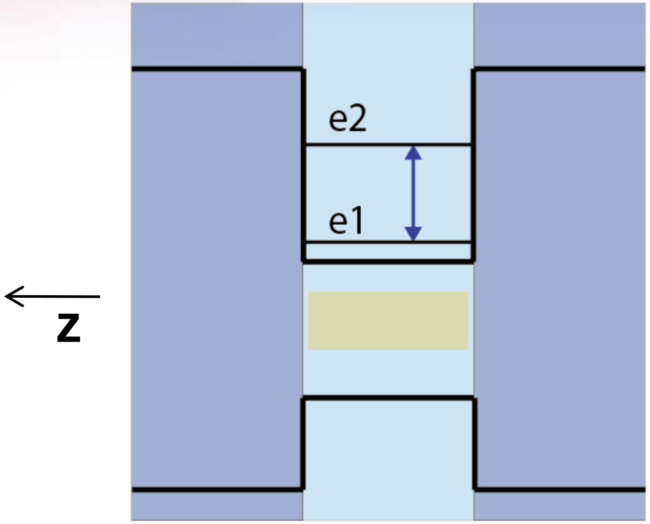
- V_G = 0 V : double peak, coupling
- V_G = -5 V : coupling almost destroyed
- Dotted black line: Complete depletion of 30 nm n+ GaAs layer

Optical coupling is bias controlled

Outline

- Tuning through interaction with *Semiconductor Electron Sheets*.
- Tuning through interaction with *Intersubband Transitions in Semiconductor Heterostructures*

Coupling to tunable optical transitions: inter-subband transitions in quantum wells



- Scalable from far IR to near IR
- Huge parameter space: Coupled QW systems, parabolic wells, superlattices, etc.
- Mature technology (MBE Growth)
- Material versatility (GaAs, GaN, InGaAs)

For example, GaAs/AlGaAs

$$\varepsilon_{GaAs}^{QW}(\omega) = \begin{pmatrix} \varepsilon_{GaAs}^{b}(\omega) & 0 & 0 \\ 0 & \varepsilon_{GaAs}^{b}(\omega) & 0 \\ 0 & 0 & \varepsilon_{GaAs}^{b}(\omega) \end{pmatrix} + \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \chi_0(\omega) \end{pmatrix}$$

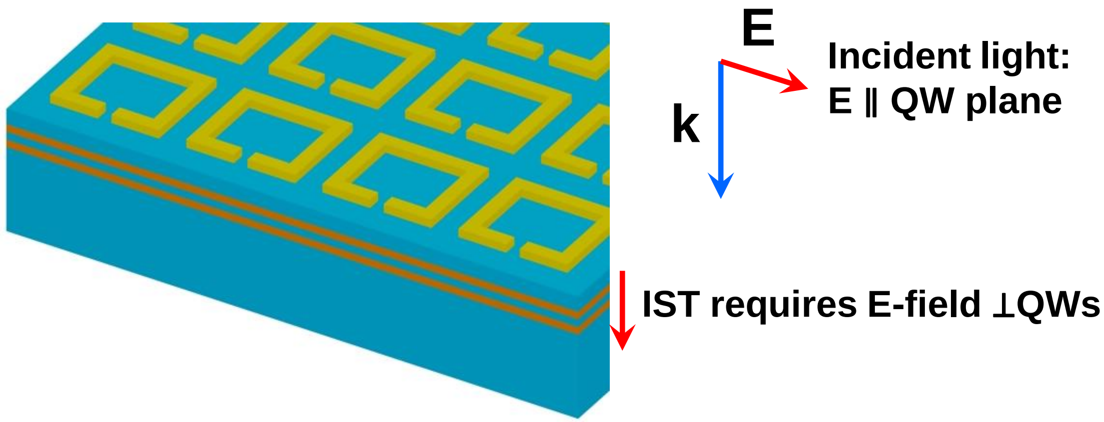
$$\chi_0(\omega) = -\frac{Ne^2}{\varepsilon_0 \hbar} \frac{|z_{21}|^2}{(\omega - \omega_{21} + i\gamma_{21}/2)}$$

Opt. Express 20, 6584 (2012)

Polarization selection rules for coupling to Inter-subband transitions

$$\varepsilon_{\mathrm{GaAs}}^{\mathrm{QW}}(\omega)=\begin{pmatrix}\varepsilon_{\mathrm{GaAs}}^{b}(\omega) & 0 & 0\\ 0 & \varepsilon_{\mathrm{GaAs}}^{b}(\omega) & 0\\ 0 & 0 & \varepsilon_{\mathrm{GaAs}}^{b}(\omega)\end{pmatrix}+\begin{pmatrix}0 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & \chi_0(\omega)\end{pmatrix}$$

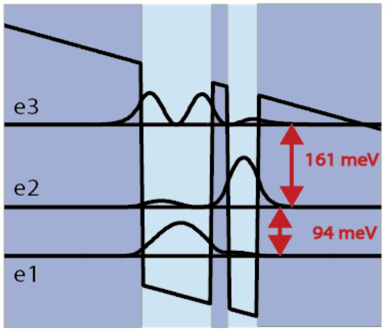
growth direction

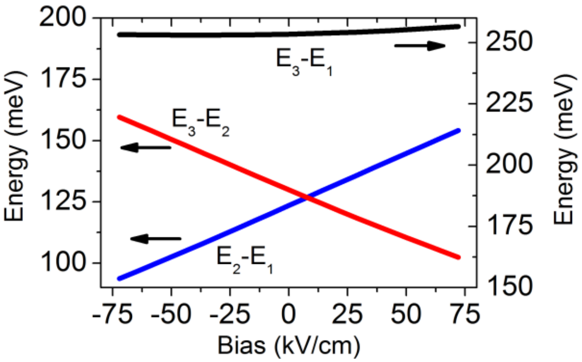


Coupling to ISTs requires longitudinal electric field components:

- ➢ need to optimize metamaterial resonator near-fields (strength & overlap)

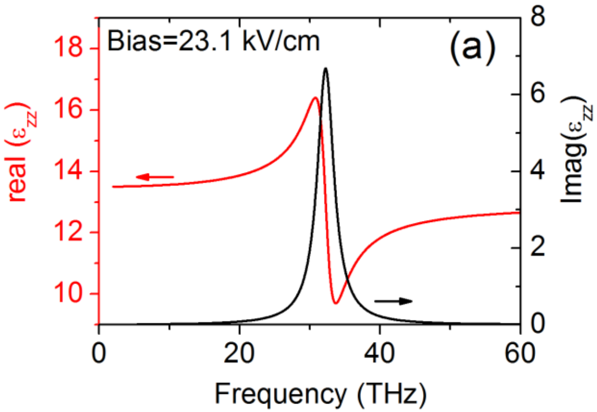
How to achieve electrical modulation by coupling to intersubband transitions

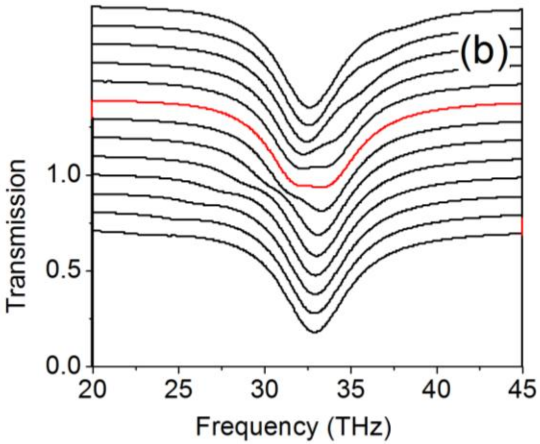


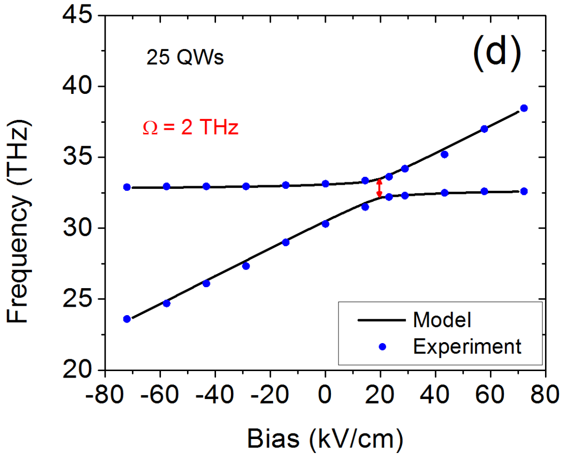


At any given bias, ε_{zz} looks like a Lorentzian

We then change the bias voltage to tune the IST. Anticrossing behavior with bias (modeling)







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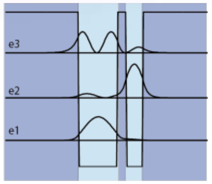
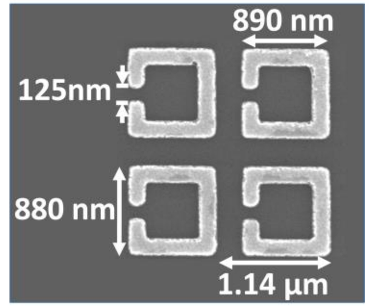
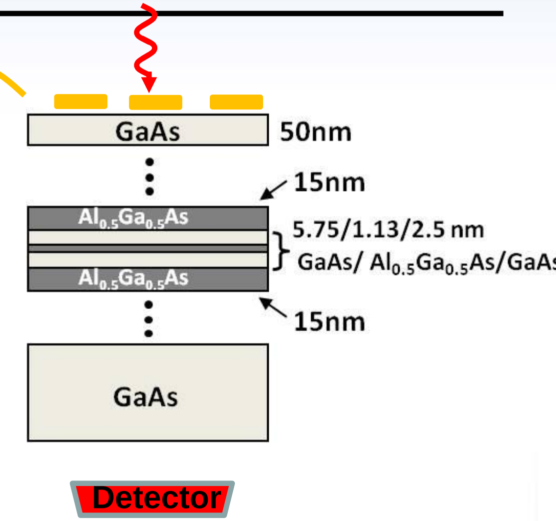
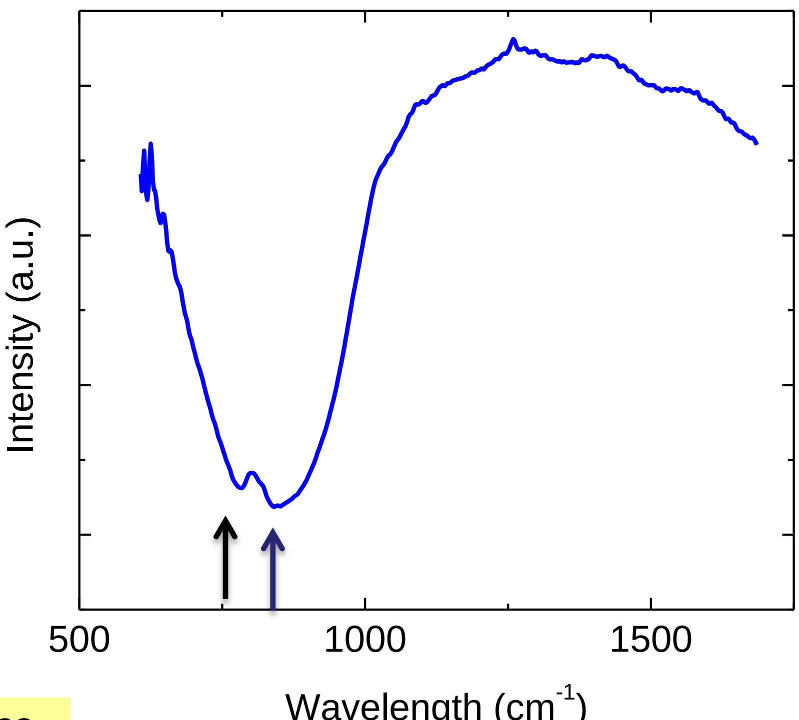
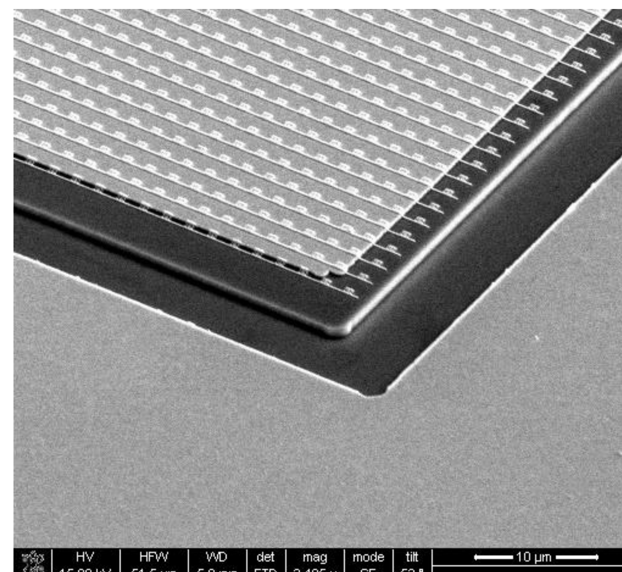
Experiments: Coupling to intersubband transitions







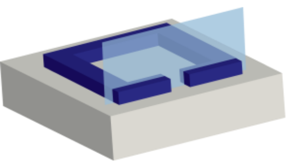


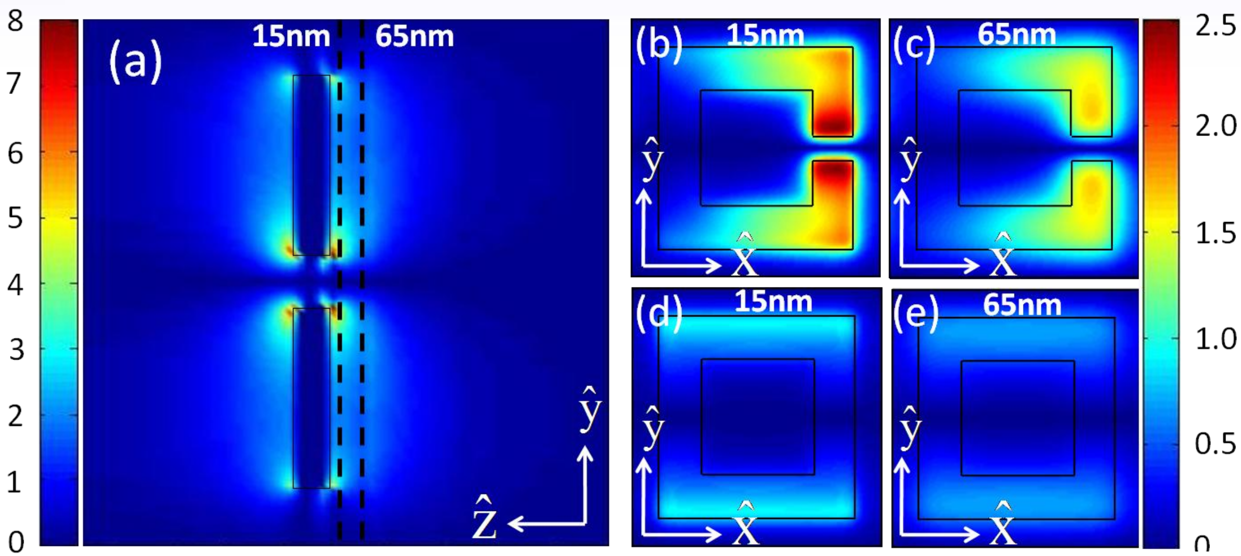


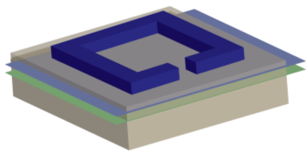
Appl. Phys. Lett. 98, 203103 (2011)

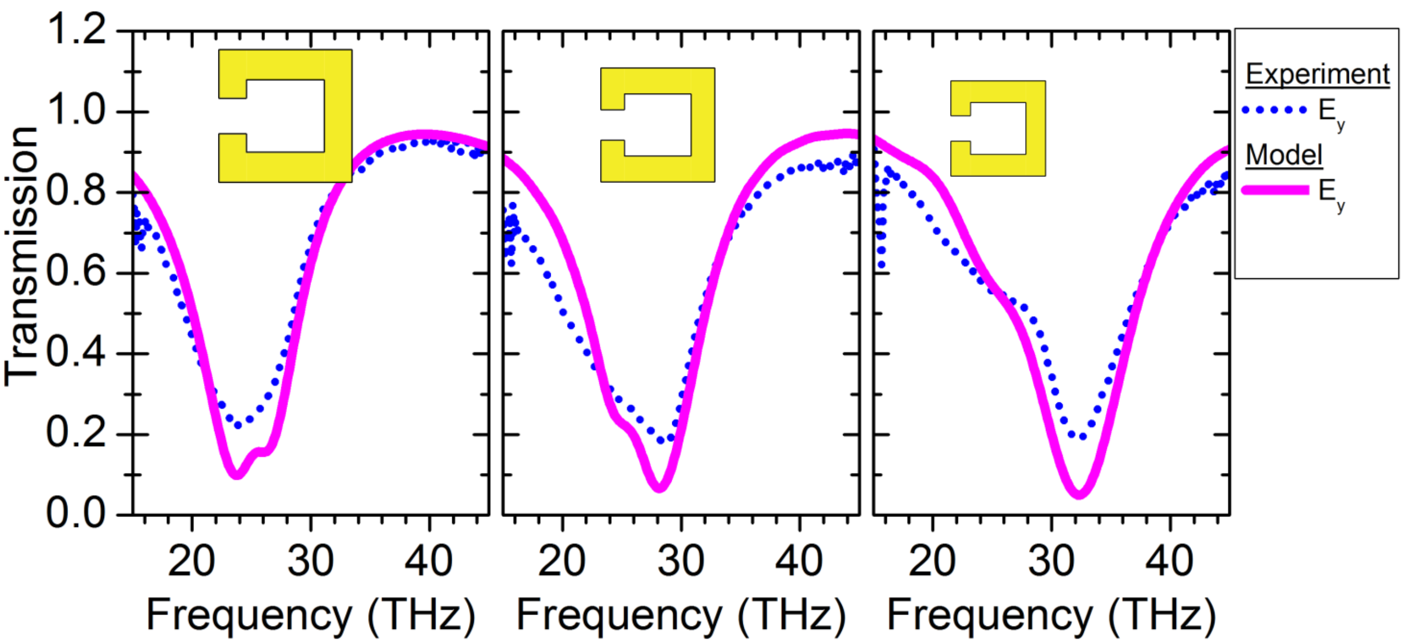
SRR near-field contains correct polarization

$|E_z|/|E_{incl}|$









Appl. Phys. Lett. 98, 203103 (2011)

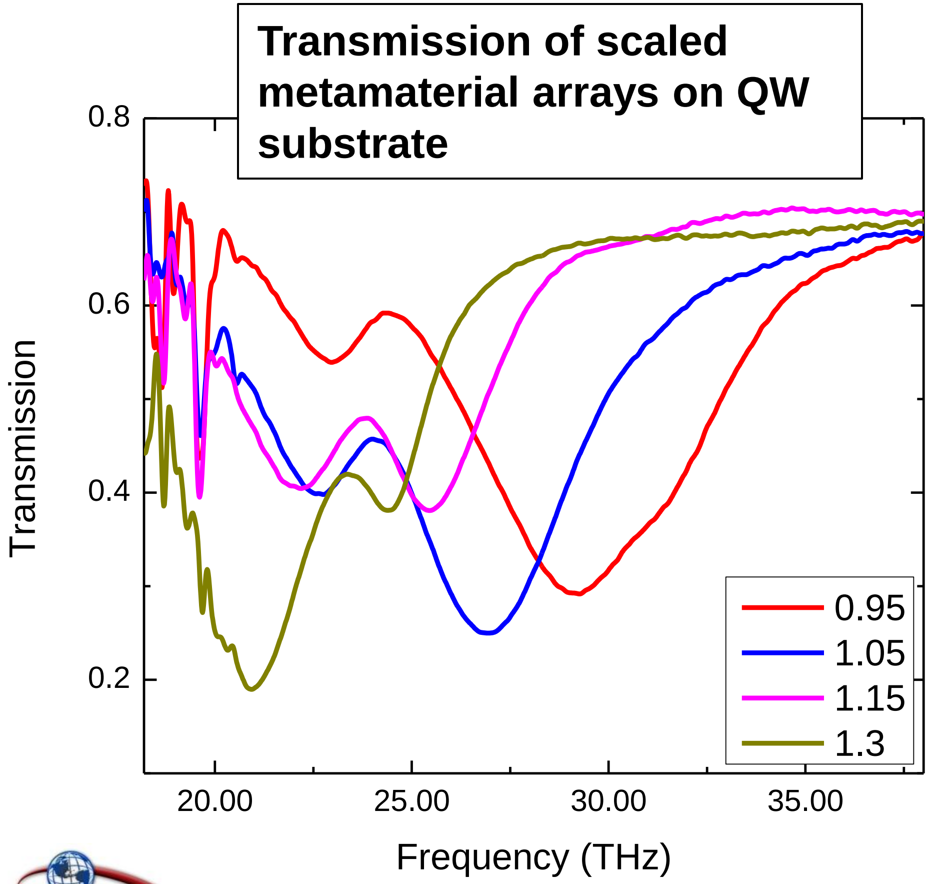
LDRD
LABORATORY DIRECTED RESEARCH & DEVELOPMENT

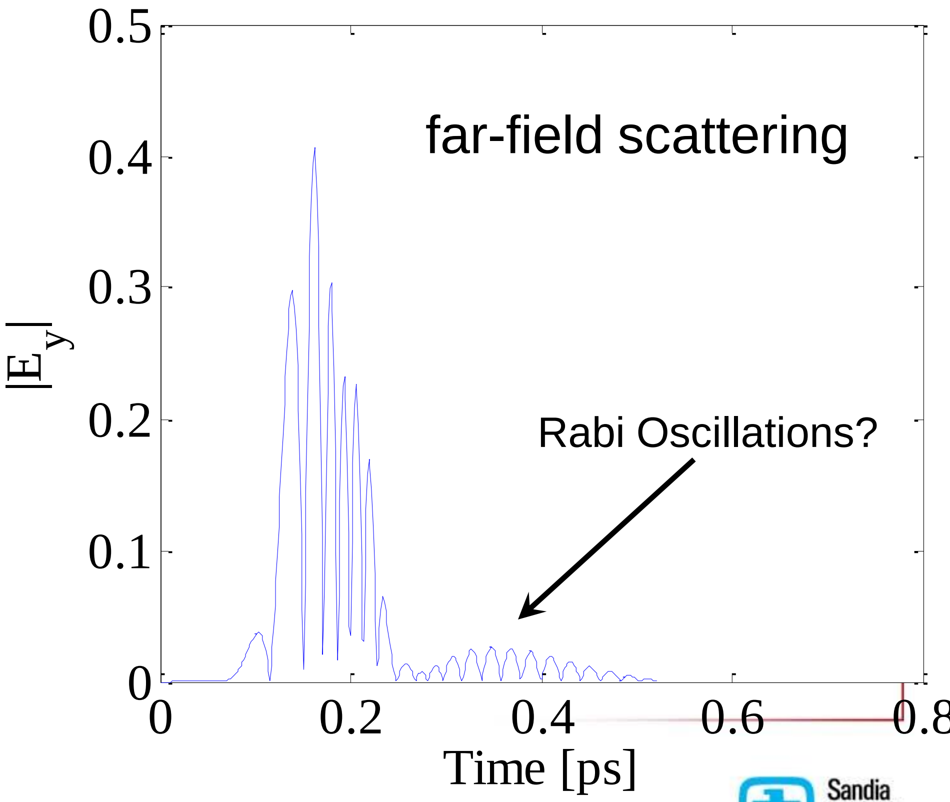
New Result: Strong Coupling to ISTs

(Alex Benz)

Through optimization, we've achieved strong coupling to ISTs

- works for a wide array of resonator types (dipoles, SRRs, etc)
- models show significant E_z
- splitting/center w ~ 15%



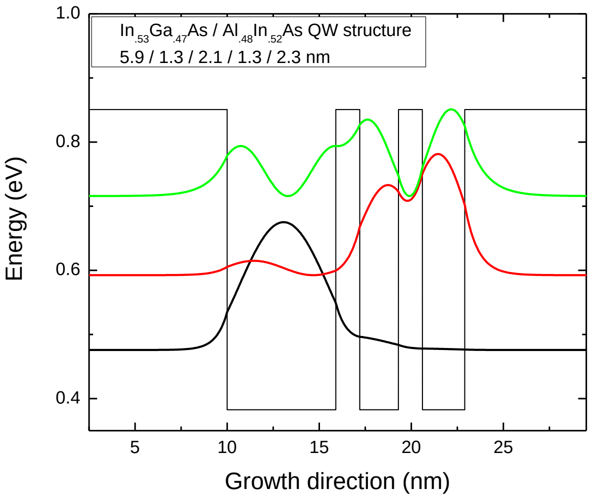


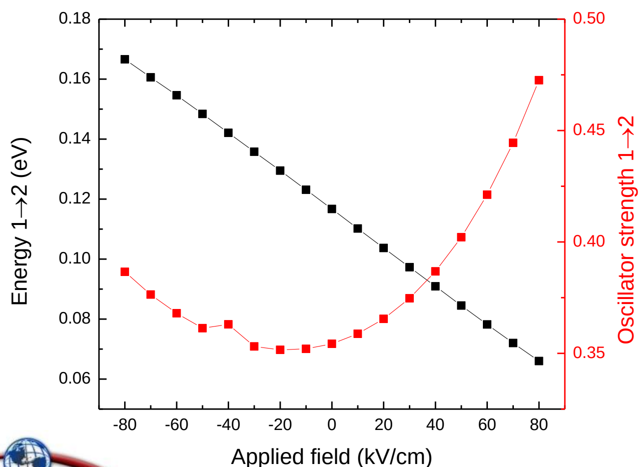
LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

Sandia National Laboratories

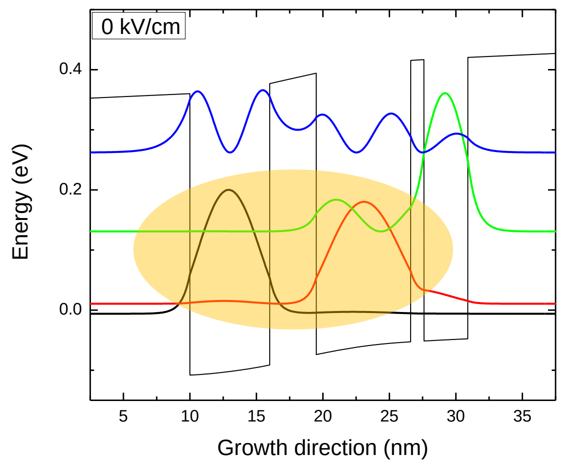
Strategies for achieving tunable coupling to intersubband transitions

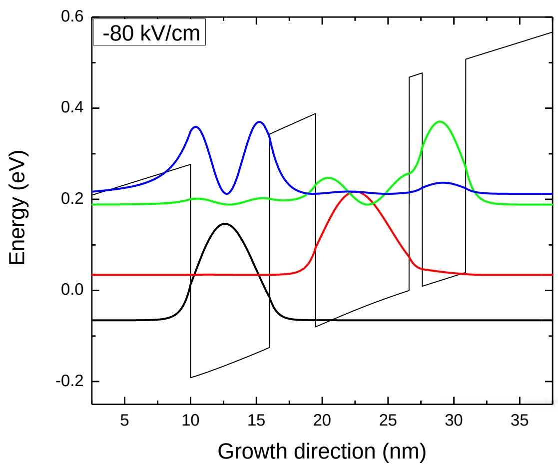
Conventional Approach: Stark tuning changes level splitting





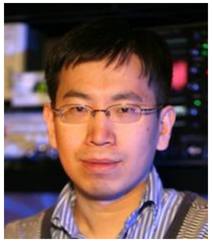
Different Approach: Bias-induced depletion of lower level → turn off transition





nextnano simulations

Acknowledgments

Postdocs: Young Chul Jun,  Alex Benz, 

Alon Gabbay*, Xiaoyu Miao*, Brandon Passmore*

CINT + Sandia: Igal Brener, John Reno, Eric Shaner, Mike Wanke, Joel Wendt, Dave Peters, Ines Montano

UCF : G. Boreman, D. Shelton* (MM-phonon)

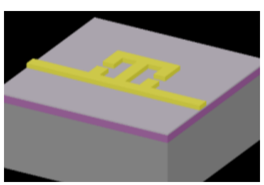
U. of Mass. Lowell: S. Vangala, W. Goodhue (InSb)

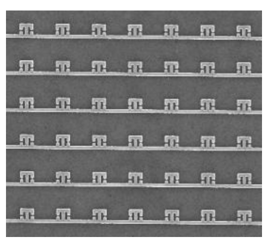
Summary

Metamaterials Science & Technology

- Active tuning of metamaterials can be achieved using voltage-controlled optical transitions in semiconductors in the mid-infrared.
- We have demonstrated strong coupling to underlying semiconductor structures.
- Full device operability requires:
  - optimized electromagnetic coupling
  - low leakage & good current — voltage behavior

Electron Sheets





Semiconductor Heterostructures