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Metasurfaces and Epsilon-Near-Zero Modes in Semiconductors

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Outline

- **What are Epsilon Near Zero modes, what can we do with them?**
  - **Fundamentals**
  - **ENZ modes: coupling to metamaterial resonators**
  - **Berreman modes: Thermal emission**

- **Other examples and uses of Epsilon Near Zero modes**
  - **ENZ modes coupled to Intersubband transitions and Metamaterials**

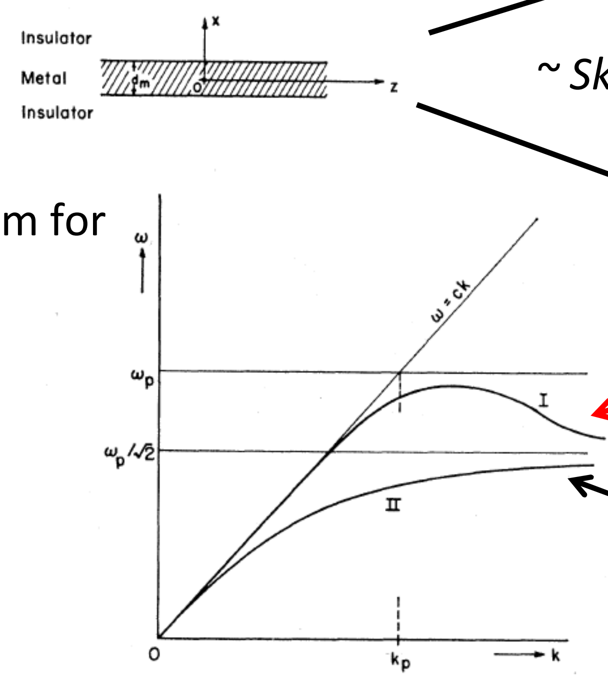
PHYSICAL REVIEW VOLUME 182, NUMBER 2 10 JUNE 1969

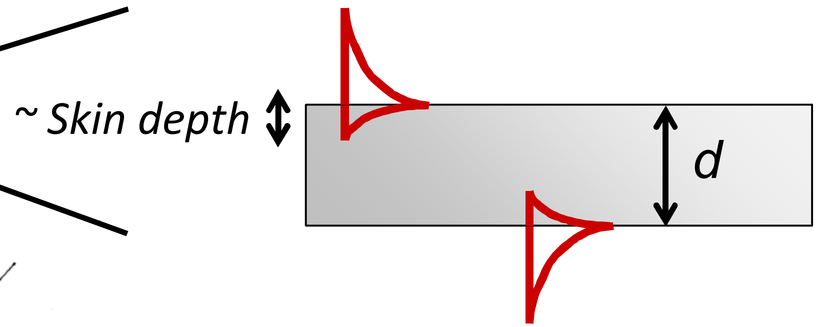
Surface Plasmons in Thin Films

E. N. ECONOMOU*†
The James Franck Institute and Department of Physics, The University of Chicago, Chicago, Illinois 60637
(Received 15 January 1969)

Econoumou, 1969
Burke et al, 1986
etc

"Thin" here: ~20nm for ~400nm plasma wavelength





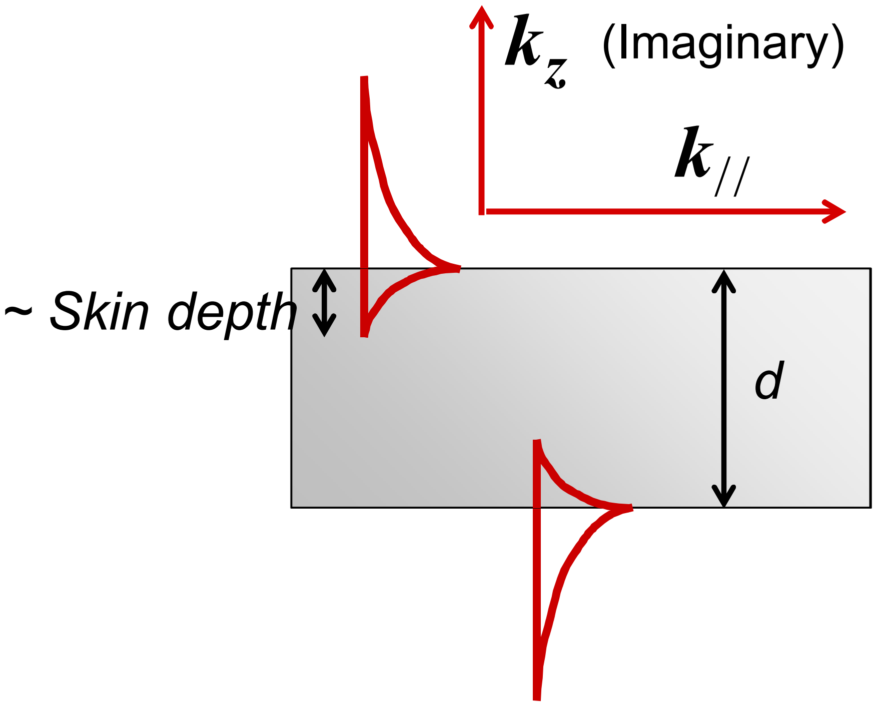
Long range surface plasmon

Short range surface plasmon

FIG. 4. Geometry and the dispersion relations for SPO of a metal film between two semi-infinite insulators ($\epsilon_m = 1 - \omega_p^2/\omega^2$, $\epsilon_i = 1$). The analytical expressions for $k \gg k_p$ or $k \ll k_p$ for the curves shown schematically here are (3.23b) and (3.18).

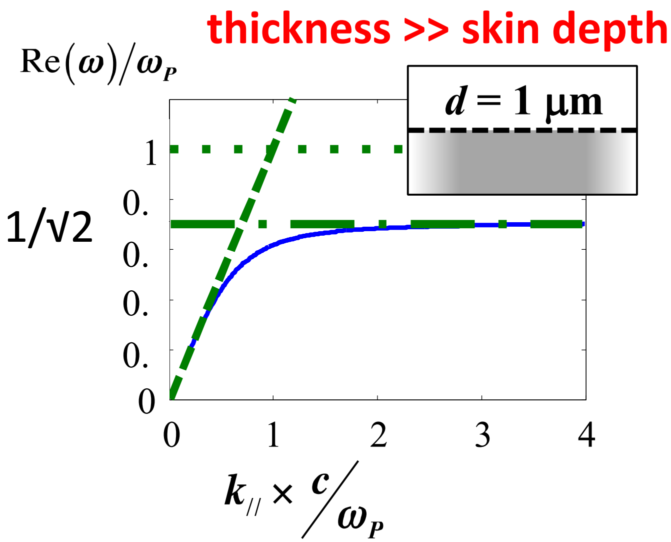
What happens when the layer becomes much thinner?
(<< skin depth)

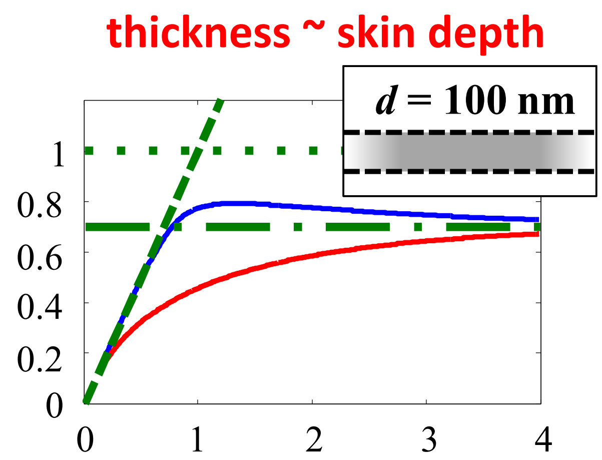
Dispersion relations

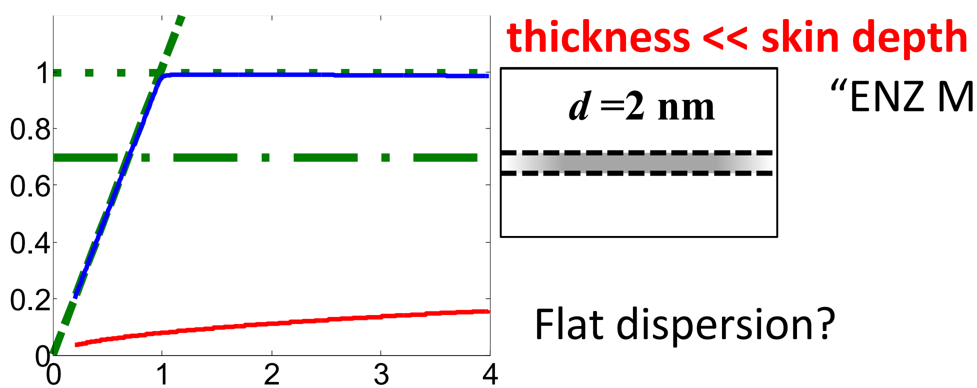


$$1+\frac{\varepsilon_1 k_{z3}}{\varepsilon_3 k_{z1}} = i\tan\left(k_{z2}d\right)\left(\frac{\varepsilon_2 k_{z3}}{\varepsilon_3 k_{z2}}+\frac{\varepsilon_1 k_{z2}}{\varepsilon_2 k_{z1}}\right)$$

Film thickness dependence on surface plasmons and ENZ mode dispersions







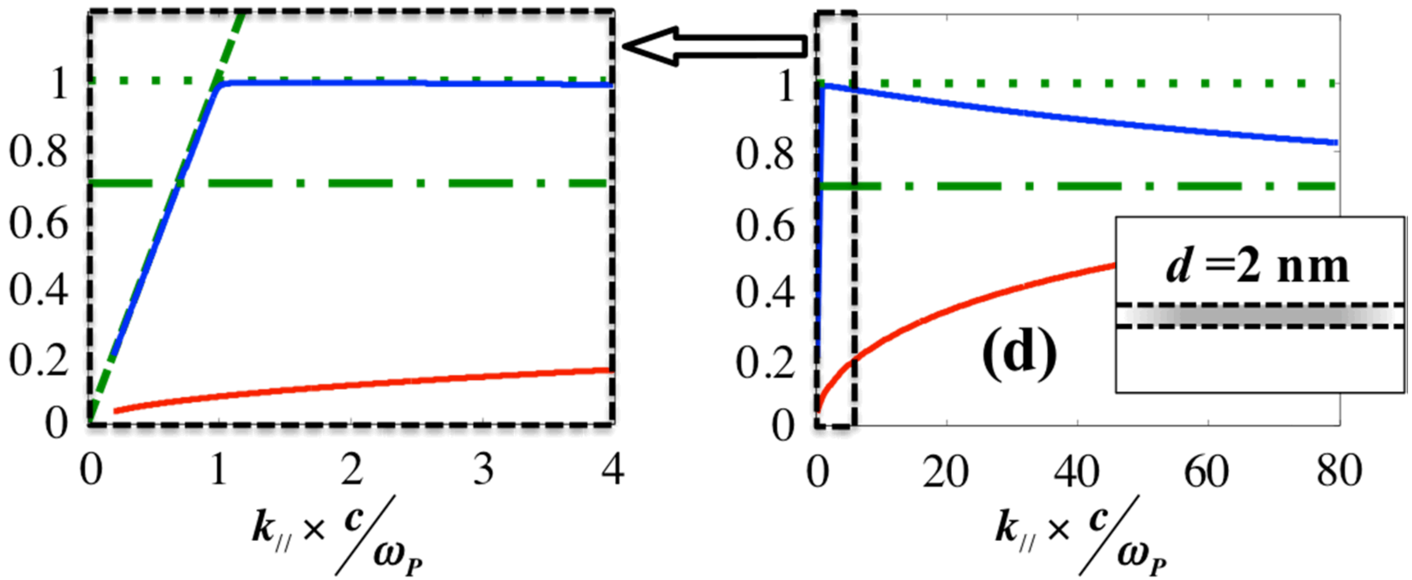
"ENZ Mode"

Flat dispersion?

1. Vassant, Marquier, Greffet et al., Phys. Rev. Lett. **109**, 237401 (2012)
2. Vassant, Marquier, Greffet et al., Opt. Express **20**, 23971 (2012)
3. Campione, Brener, Marquier, Phys. Rev. B Rapid Commun. **91**, 121408 (2015)

ENZ mode dispersion

Flat?...



The ENZ mode dispersion is a part of the the long-range surface plasmon dispersion that reaches the plasma frequency, where the metal dielectric constant vanishes.

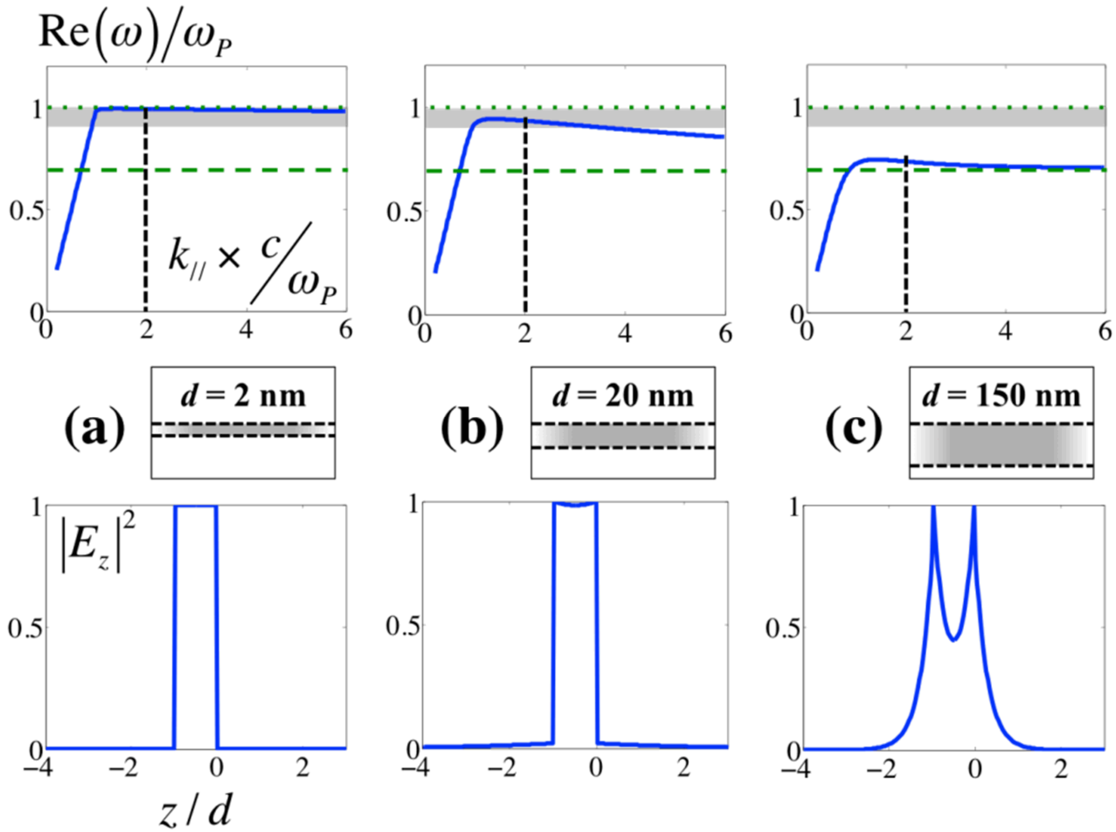
Campione, Brener, Marquier, Phys. Rev. B Rapid Commun. **91**, 121408 (2015)

ENZ Modes: E_z is Constant and Large

$$\varepsilon_1 E_{z1} = \varepsilon_2 E_{z2}$$

$$\frac{\varepsilon_1}{\varepsilon_2} E_{z1} = E_{z2}$$

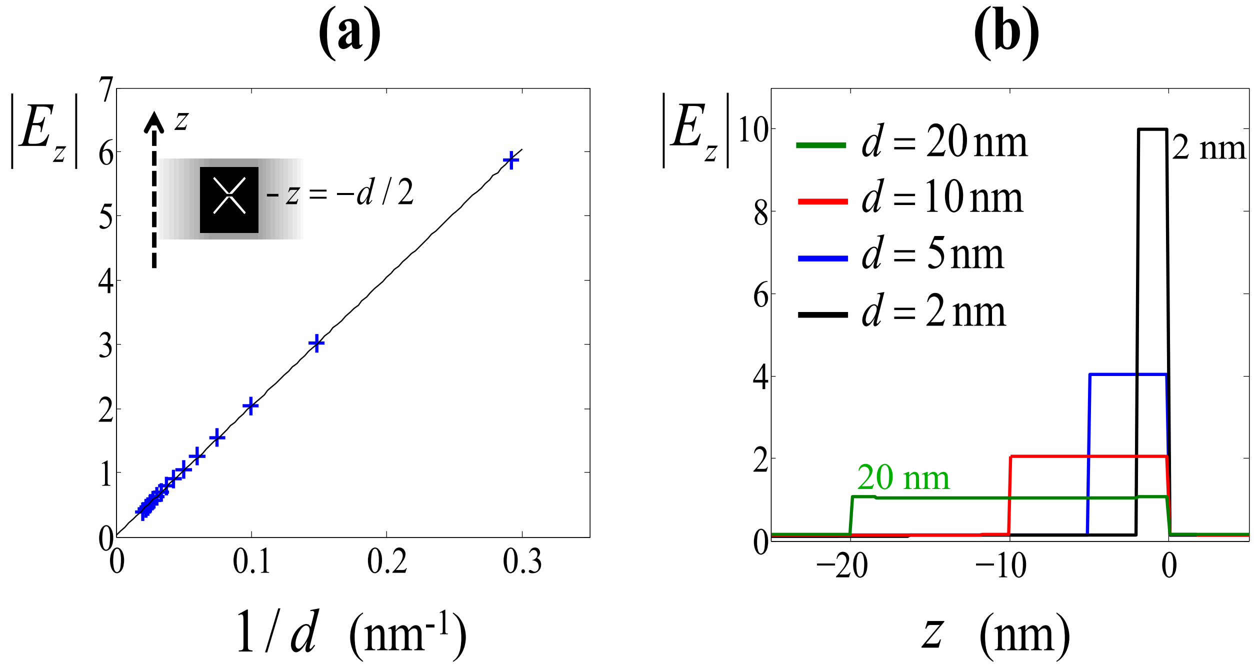
~ 0 (→ ε_2)



Campione et al., Phys. Rev. B **87**, 035120 (2013)

Campione, Brener, Marquier, Phys. Rev. B Rapid Commun. **91**, 121408 (2015)

ENZ Modes: E_z is Constant and Large

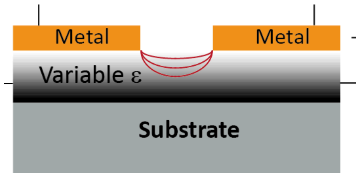


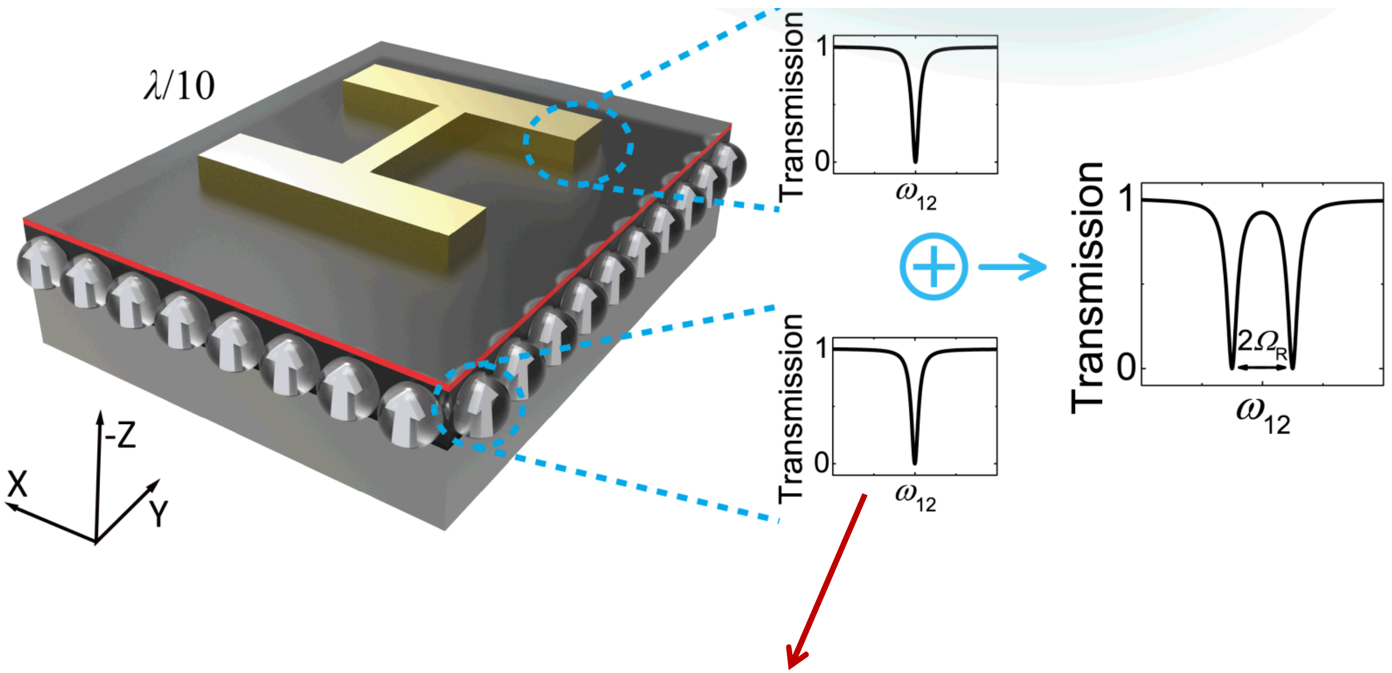
$$E_z \propto \frac{1}{d}$$

Campione, Brener, Marquier, Phys. Rev. B Rapid Commun. **91**, 121408 (2015)

What Can We Do With ENZ Modes: Coupling to Planar Metamaterials

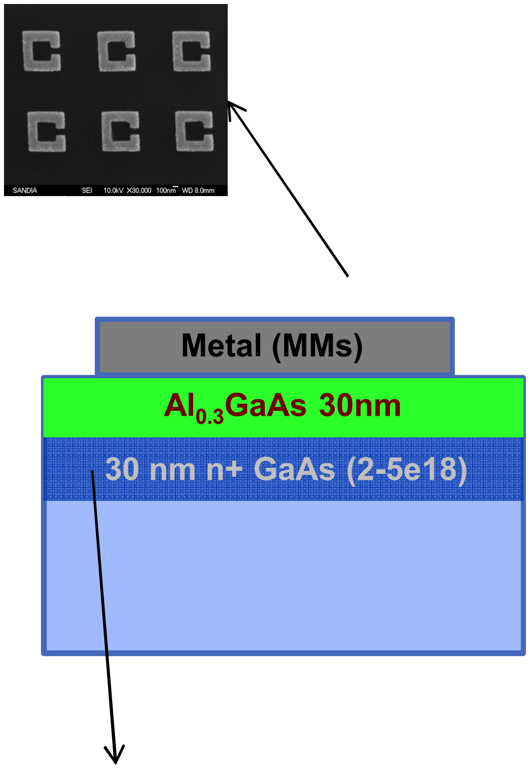
MM resonators create strong optical fields that lead to strong coupling





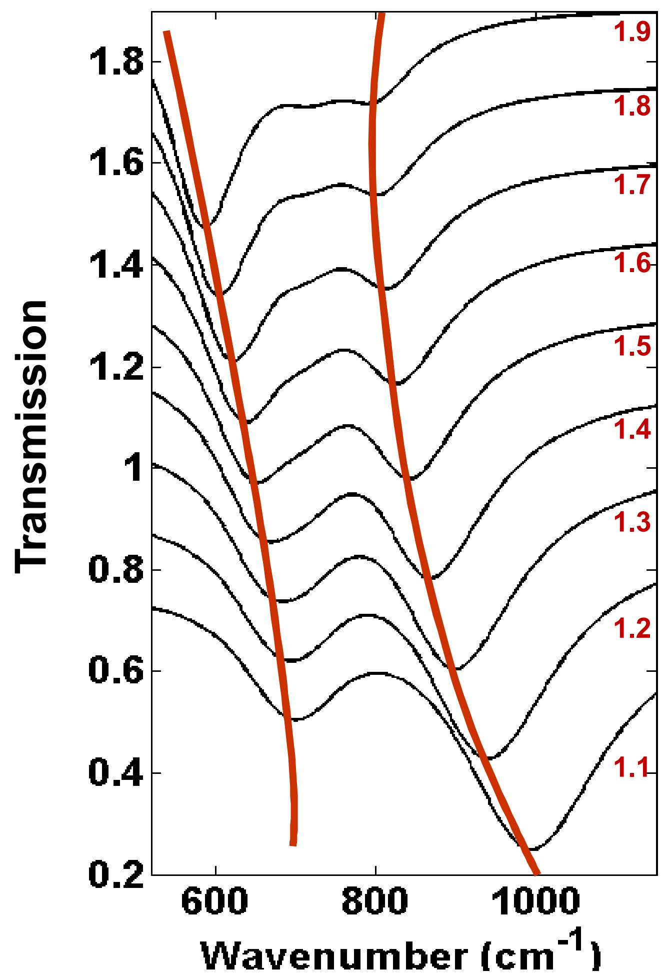
Optical Phonons: Nano Letters 11, 2104 (2011); Journal of Physical Chemistry C 114, 7299 (2010)
Intersubband Transitions: Nature Communications 4, 2882 (2013) ; Advanced Optical Materials 2, 1057 (2014)
Epsilon Near Zero modes: Nano Letters **13**, 5391 (2013); New J. Phys. 16, 043029 (2014)

Strong Coupling to ENZ Modes

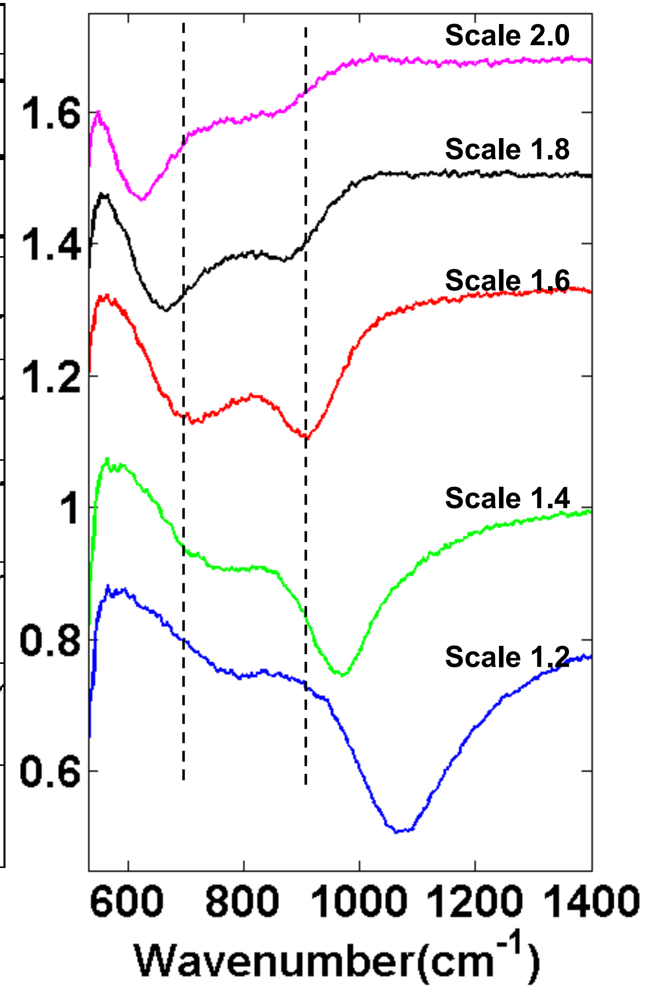


Drude Layer
ω_P~800cm^{-1}

Numerical simulation (FDTD)

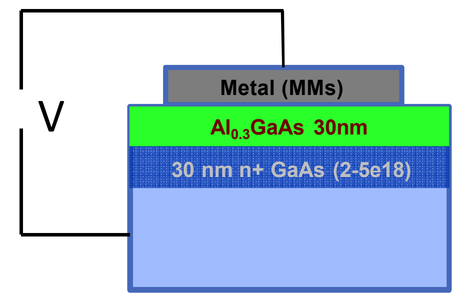


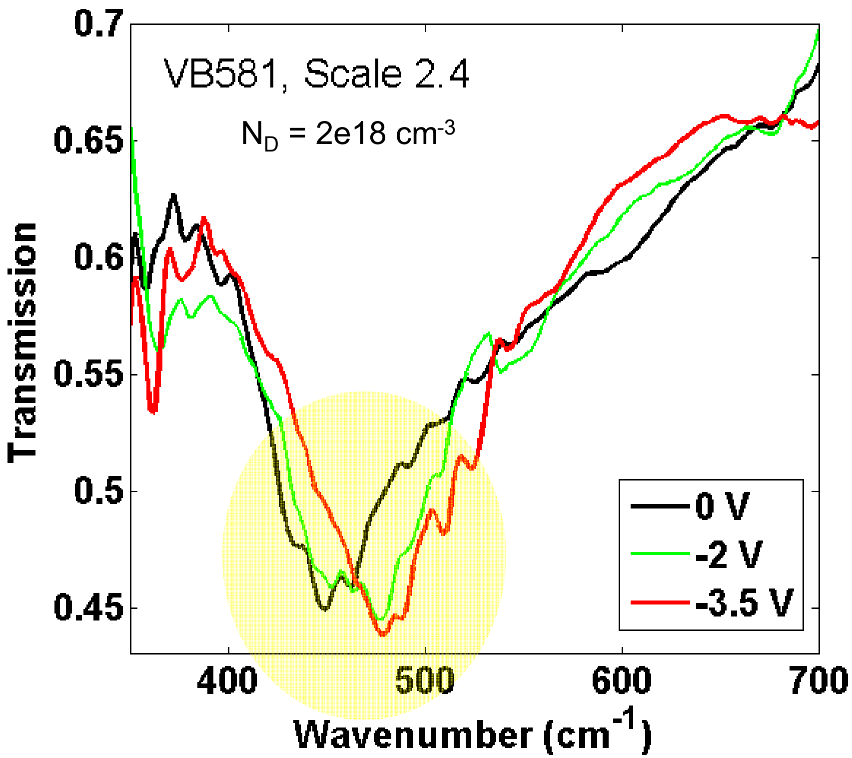
FTIR transmission measurement

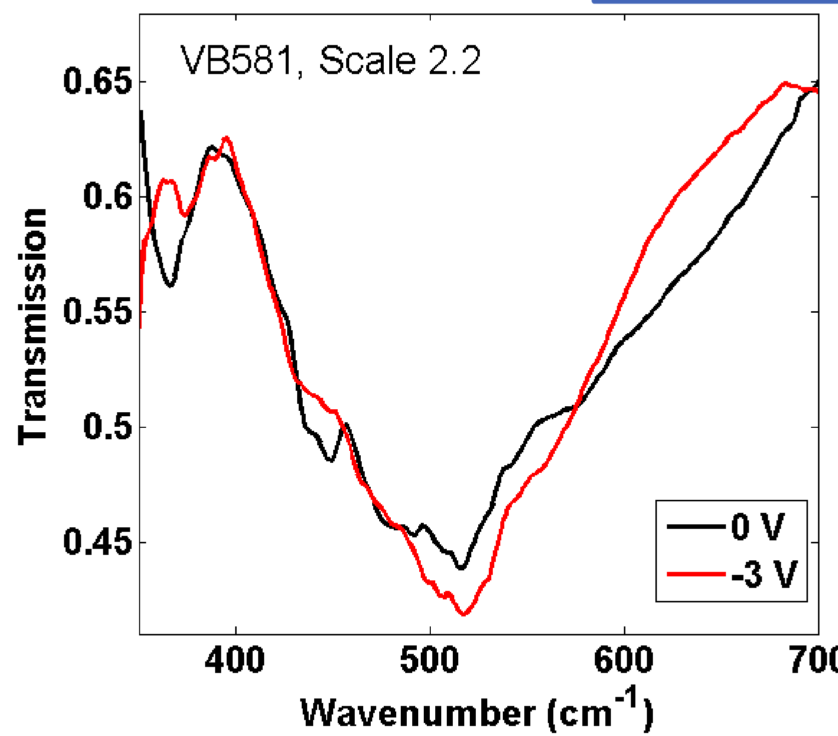


Nano Letters **13**, 5391 (2013)

Electrically Tuning the Coupling to the ENZ Mode







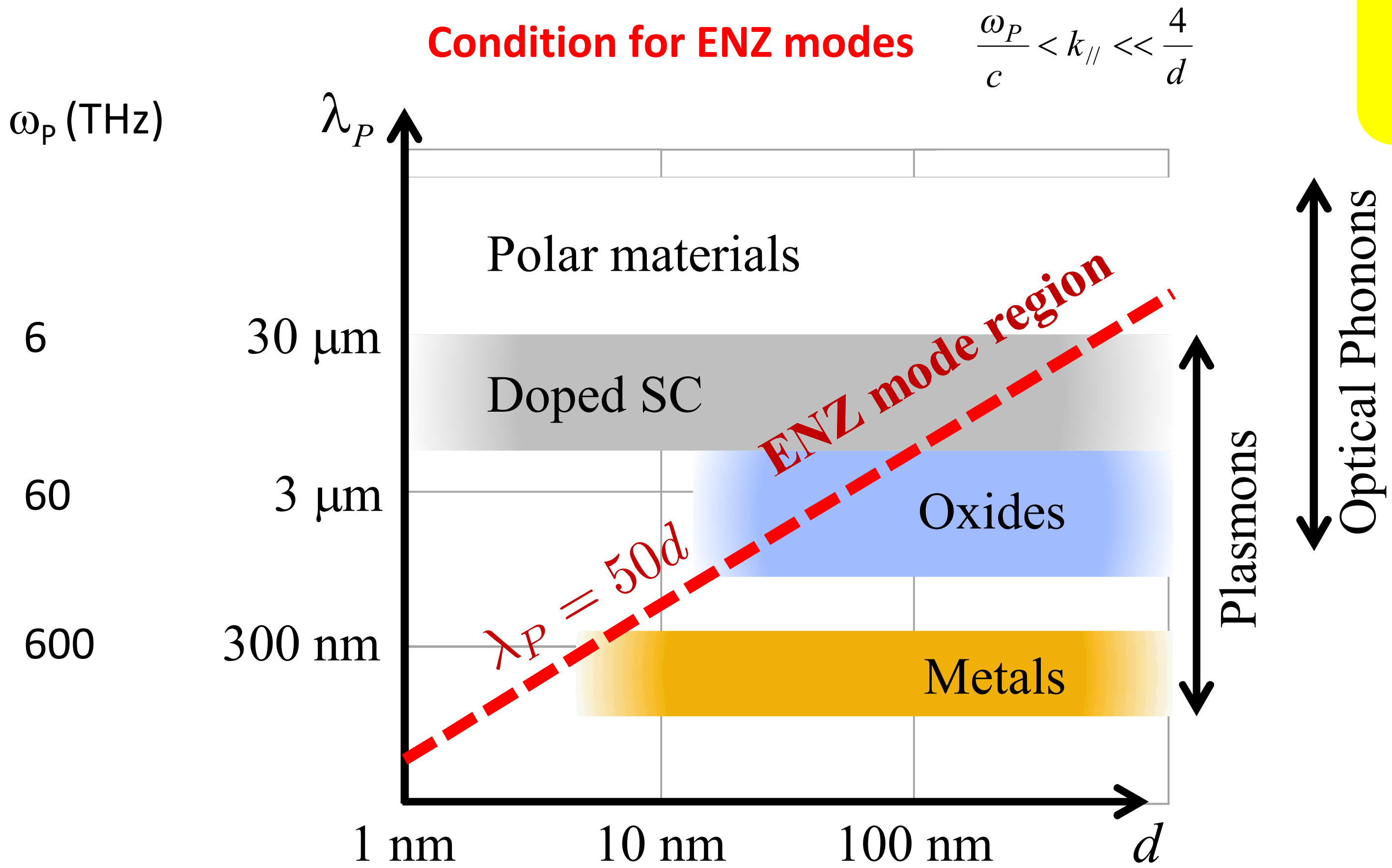
Fundamentally different than tuning just by changing a local permittivity!

Removal of carriers -> removal of ENZ mode

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

Where Can We Find ENZ Modes?

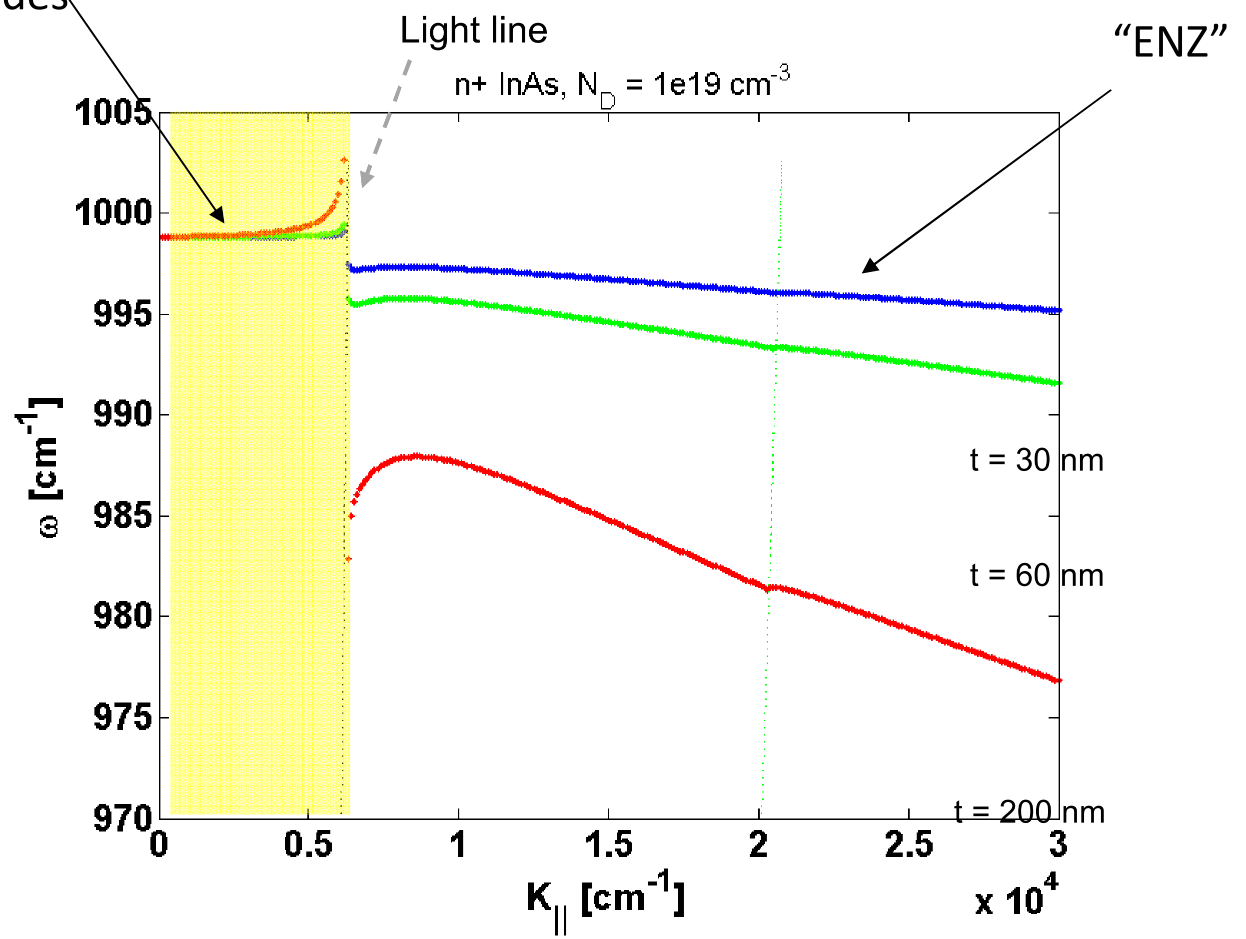
Rule of Thumb: $d <\approx \frac{\lambda_P}{50}$



Campione, Brener, Marquier, Phys. Rev. B Rapid Commun. **91**, 121408 (2015)

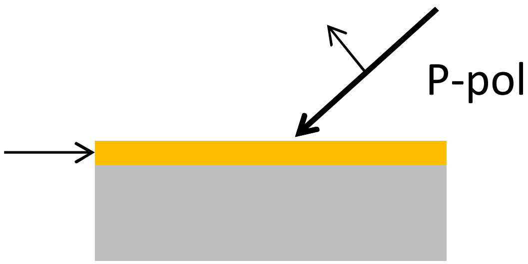
Related to ENZ: Berreman Modes

“Berreman Modes” → **Leaky modes: can couple from free space**

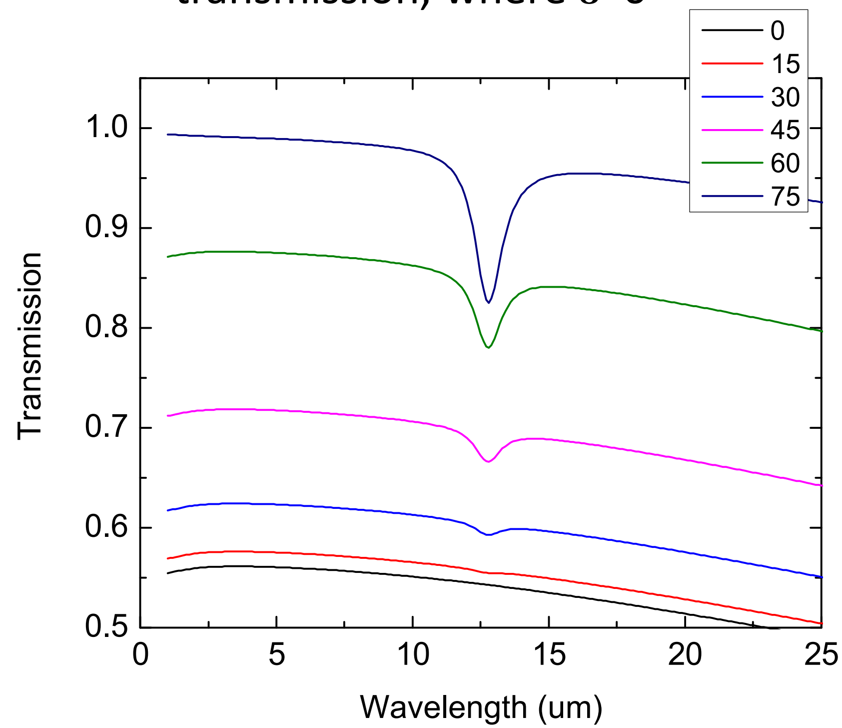


Coupling to Berreman Modes From Free Space

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

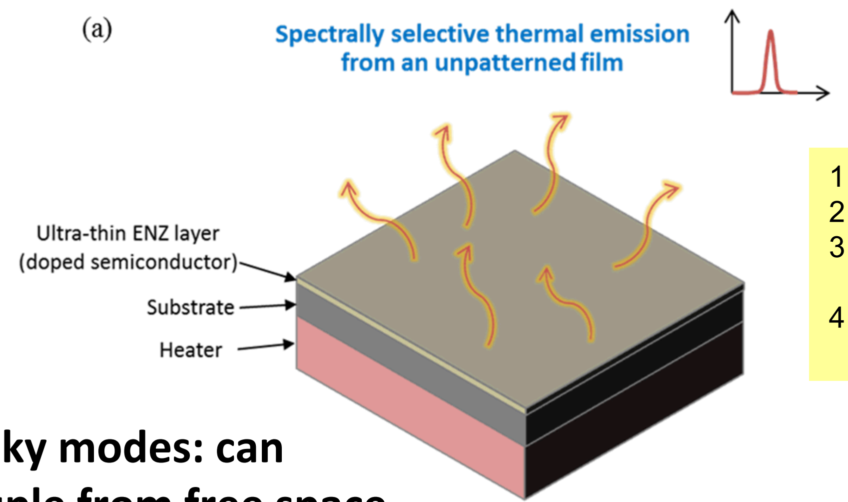


("Berreman" dip)

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

Berreman Modes for Thermal Emission

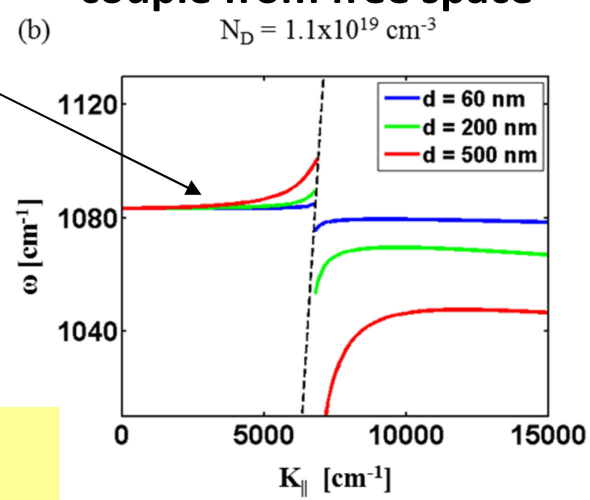
Kirchhoff's law of thermal radiation: the absorptivity of an object should be equal to its emissivity ($A = \epsilon$)

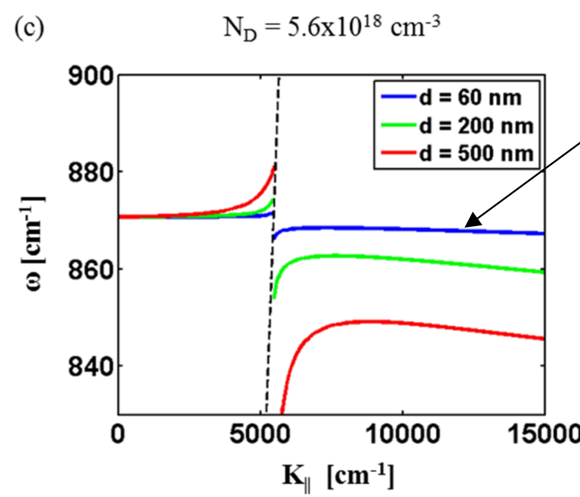


1. Ferrel, Phys. Rev. **111**, 1214 (1958)
2. Berreman, Phys. Rev. **130**, 2193 (1963)
3. Vassant, Marquier, Greffet et al., Opt. Express **20**, 23971 (2012)
4. Ward, Jacob et al., ACS Photonics **2**, 2 (2014)

"Berreman Modes" → **Leaky modes: can couple from free space**

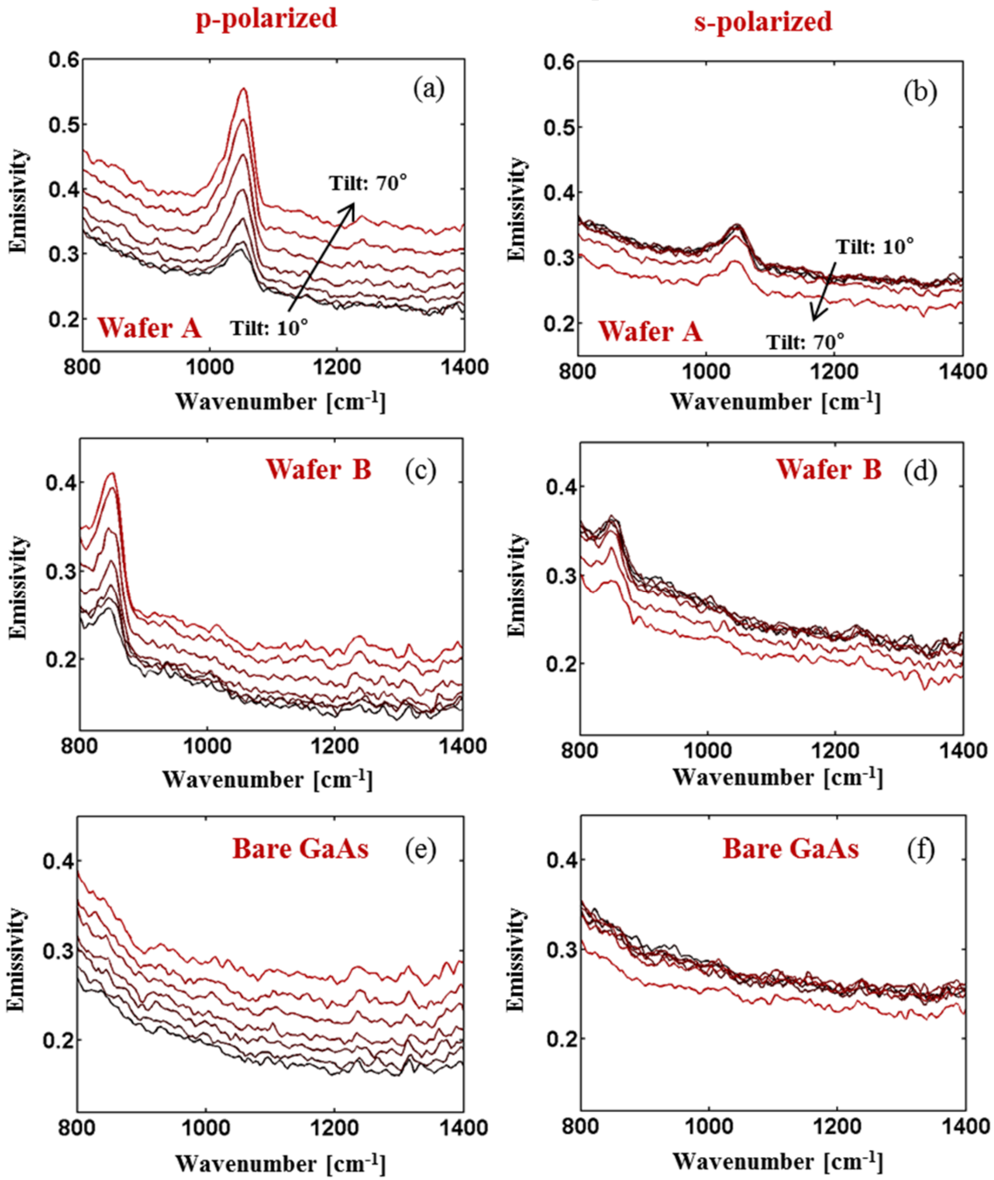
"ENZ"





Appl. Phys. Lett. **105**, 131109 (2014)

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"**

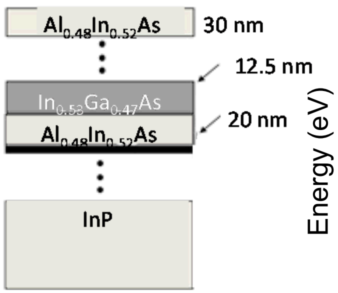
Appl. Phys. Lett. **105**, 131109 (2014)
See also recent work by Z. Jacob

Outline

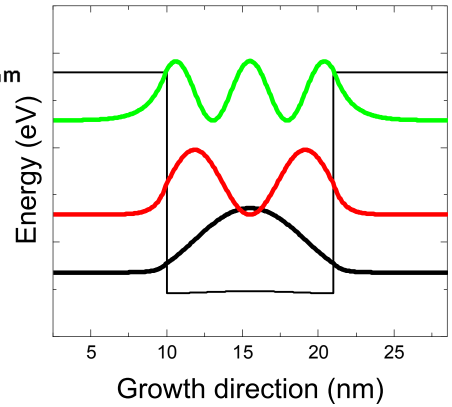
- What are Epsilon Near Zero modes, what can we do with them?
  - Fundamentals
  - ENZ modes: coupling to metamaterial resonators
  - Berreman modes: Thermal emission

- **Other examples and uses of Epsilon Near Zero modes**
  - **ENZ modes coupled to Intersubband transitions and Metamaterials**

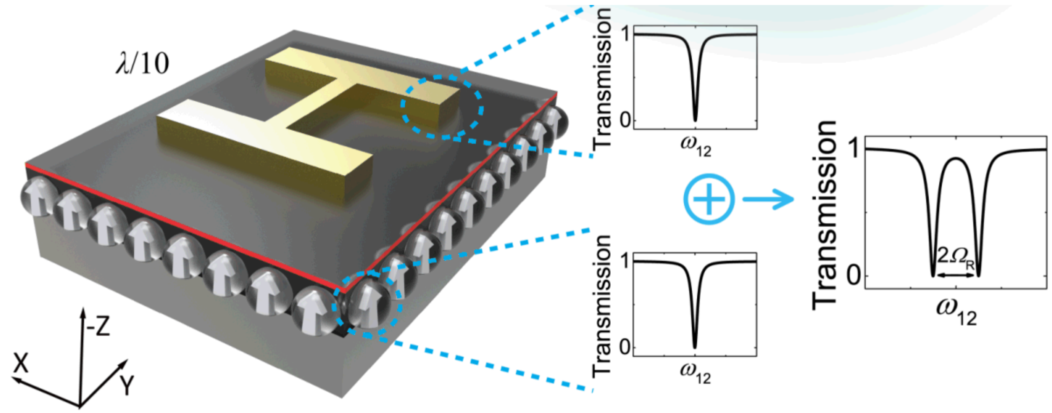
Strong Coupling of Metamaterials to Inter-subband Transitions in Quantum Wells



InGaAs homogeneously doped

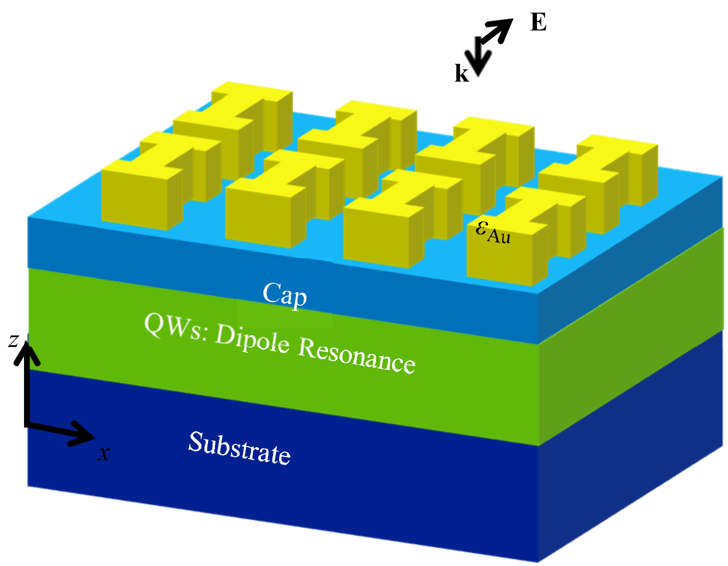


Optically active transition: between ground state (black) and first excited state (red)



- Stack of different semiconductors
- Quantized energy level designed
- Narrow absorption

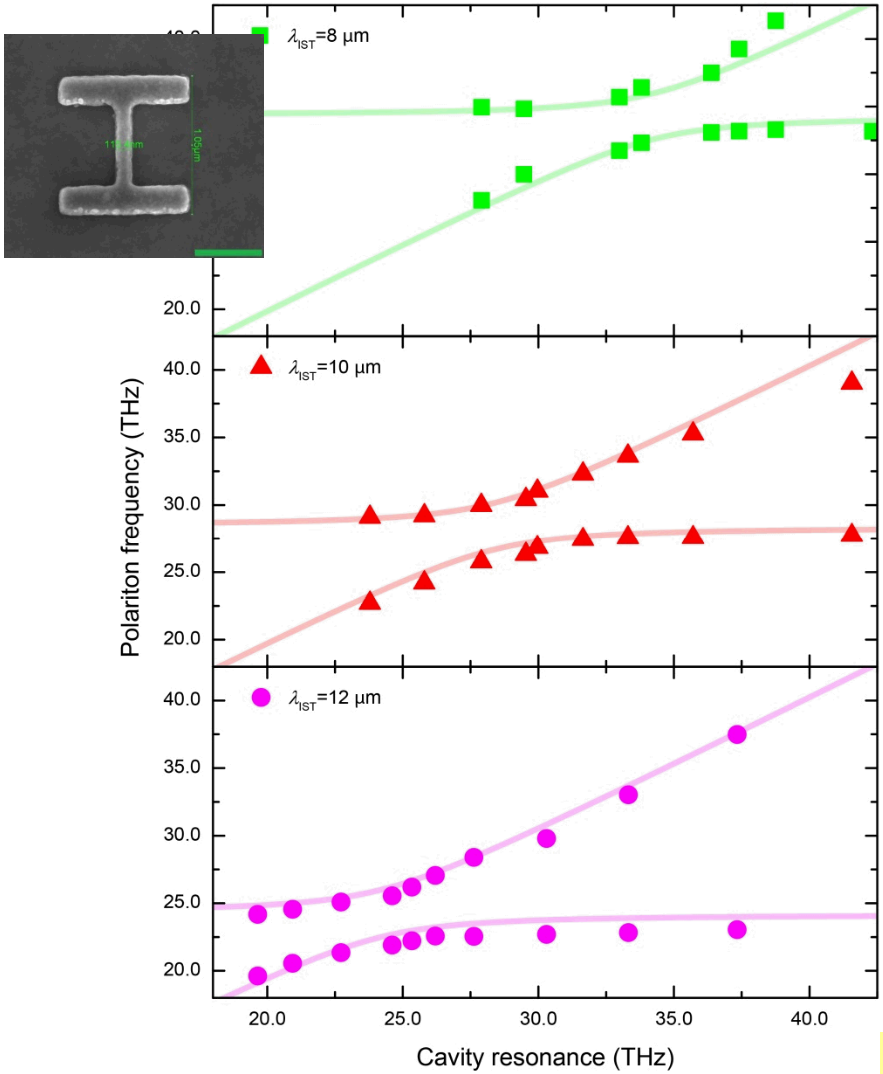
$\varepsilon_{xx}=\varepsilon_{yy}\neq\varepsilon_{zz}$



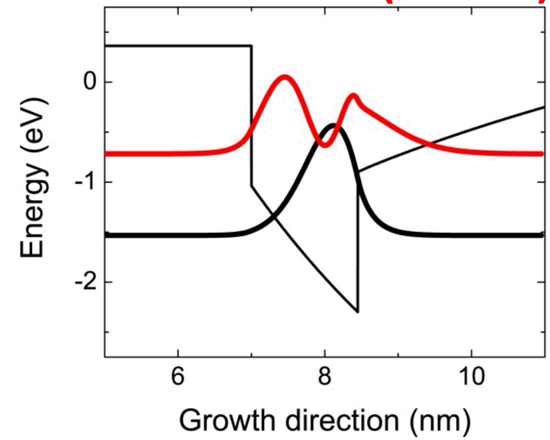
Opt. Express 20, 6584 (2012)
Appl. Phys. Lett. 98, 203103 (2011)
Nat. Commun. 4, 2882 (2013)
Appl. Phys. Lett. 104, 131104 (2014)
Phys. Rev. B 89, 165133 (2014)
Nano Lett. 15, 1959 (2015)
Nat. Commun. 6, 7667 (2015)

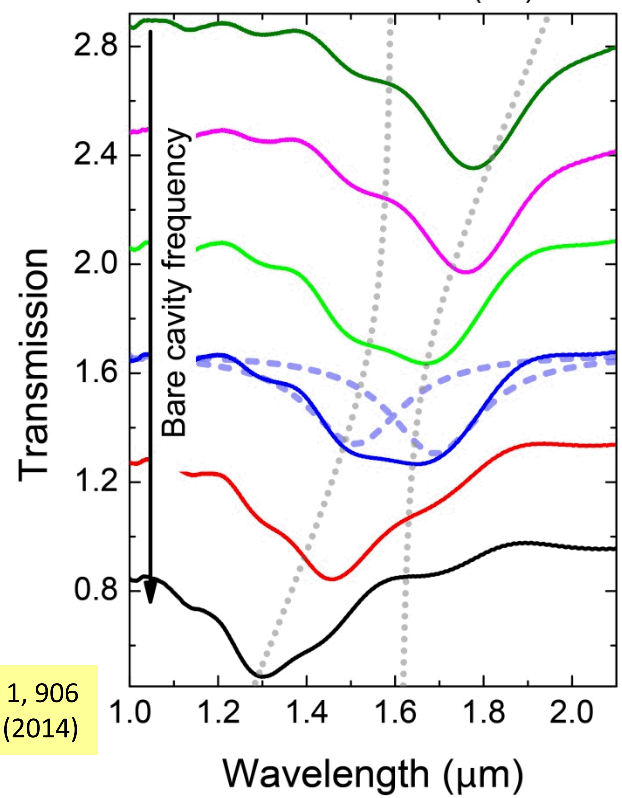
Strong Coupling: From Mid-IR to Near IR

InGaAs QWs **(mid IR)**



GaN QWs **(near IR)**

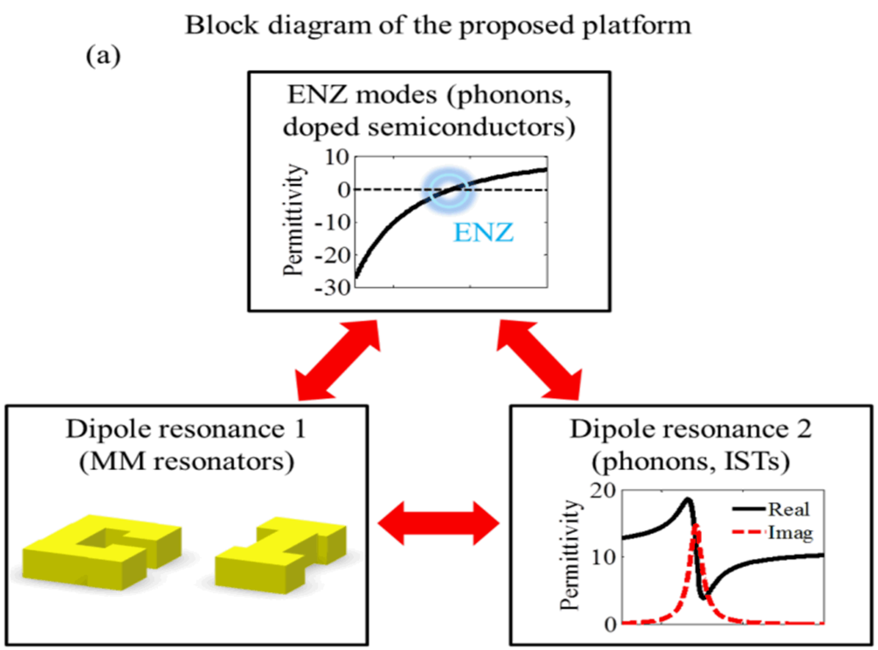


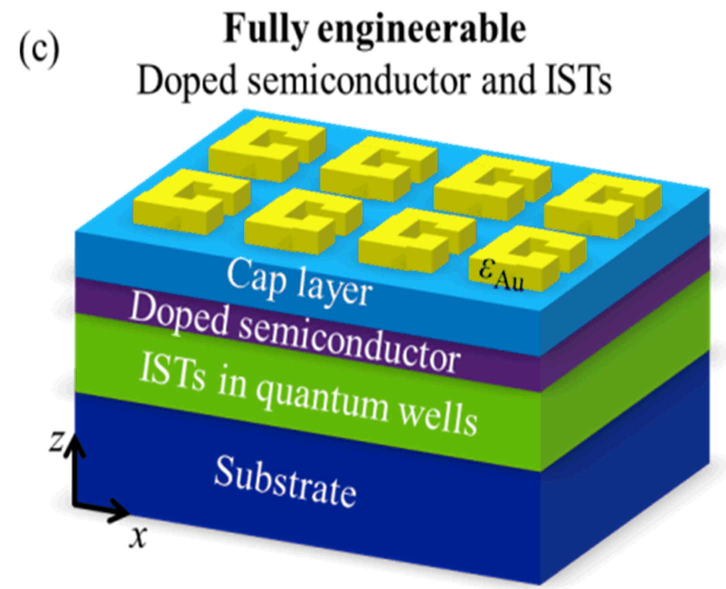


ACS Photonics 1, 906 (2014)

Nature Communications 4, 2882 (2013)

ENZ and QW for tailored platform





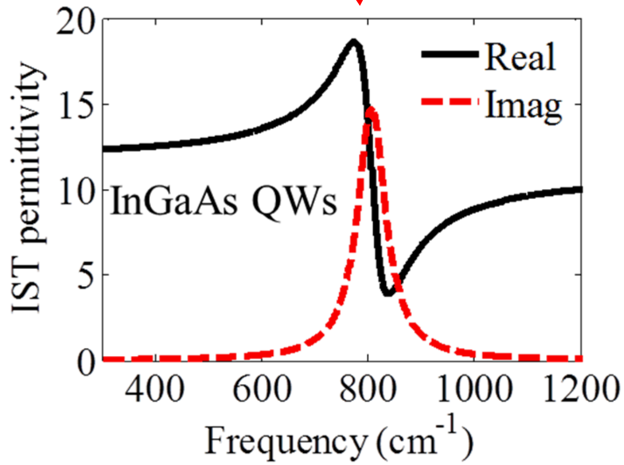
- This is a system where ENZ modes interact with two, distinct, dipole resonant systems

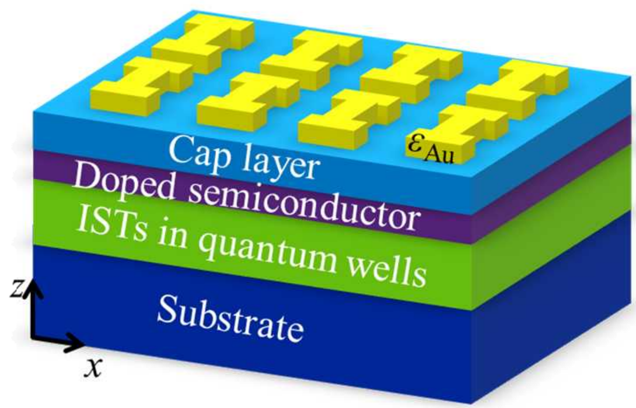
- One of the resonant systems will always be MM resonators
- The other will be quantum well ISTs
    - also semiconductor phonons may be possible, limited capabilities

Addition of ENZ layer to QWs

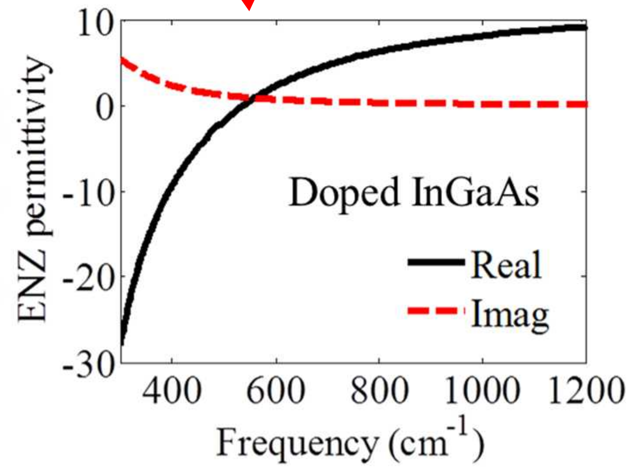
$\omega_p \neq$IST transition frequency

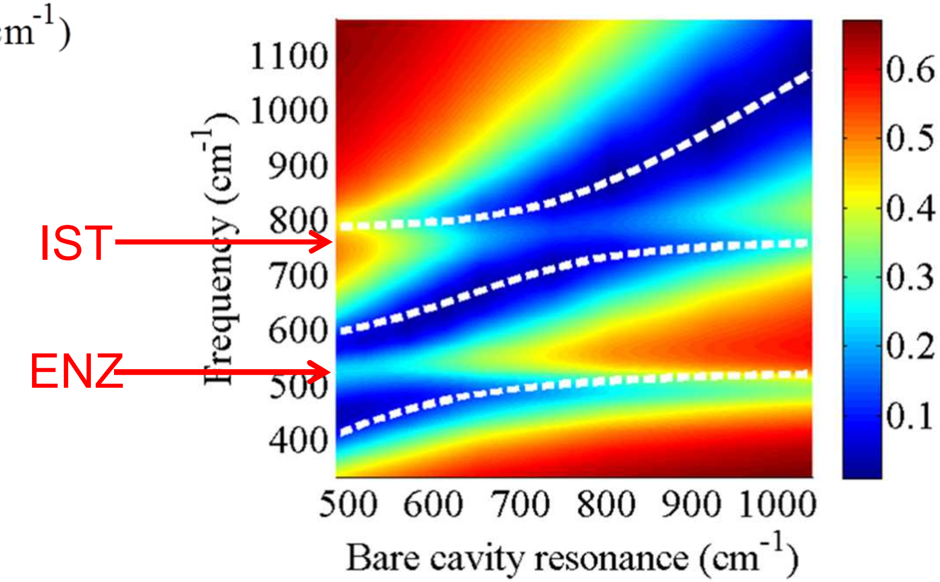
IST ~ 800 cm^{-1}





ENZ ~ 550 cm^{-1}





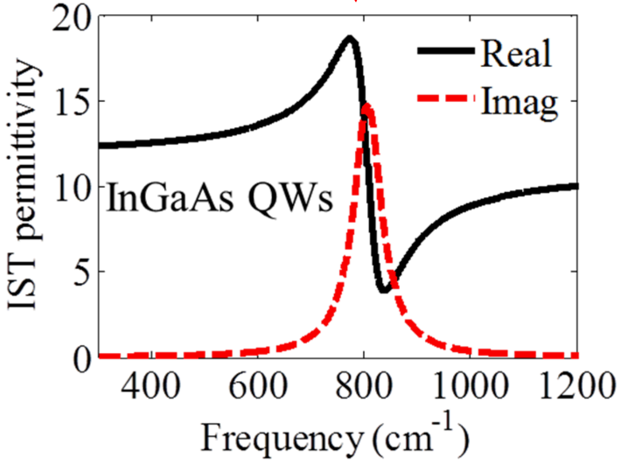
3 Polariton Branches
2 Splittings

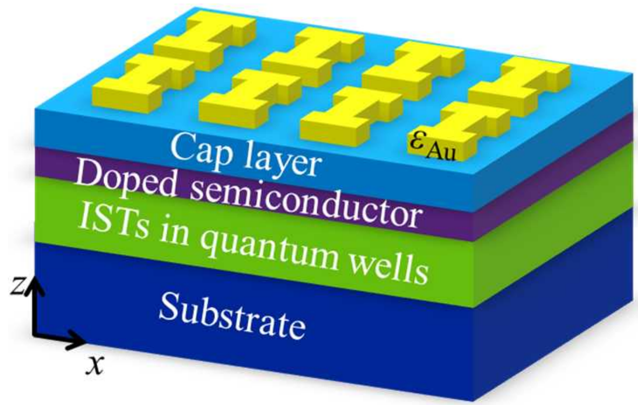
Campione et al. under review

Addition of ENZ layer to QWs

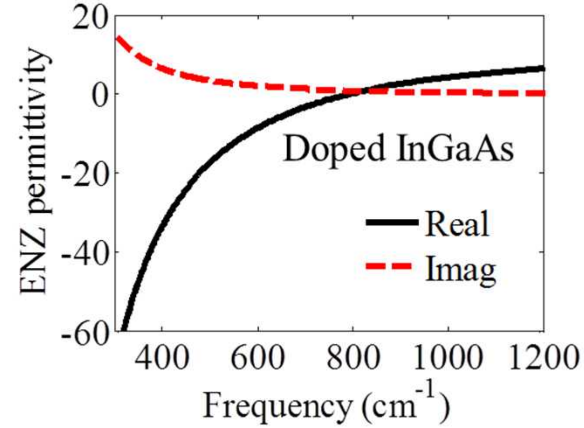
ω_P=IST transition frequency

IST ~ 800 cm^{-1}

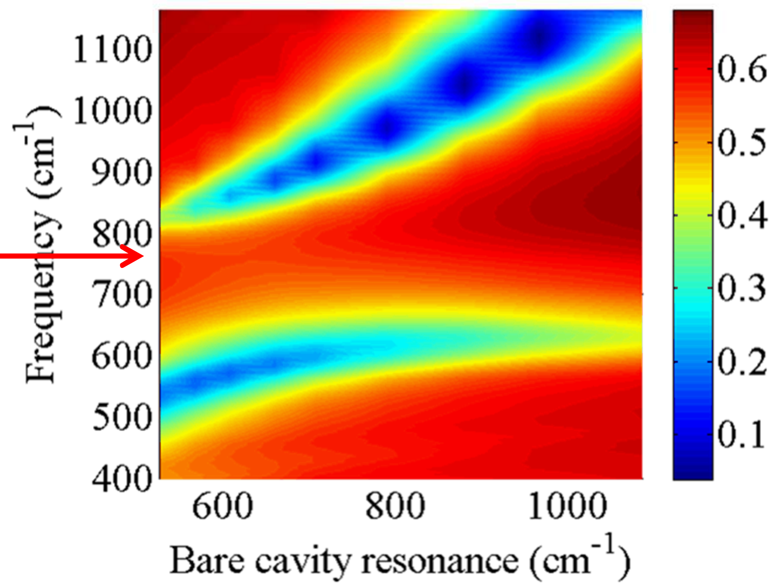




ENZ ~ 800 cm^{-1}



IST+ENZ

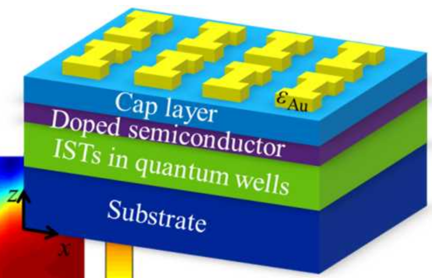


2 Polariton Branches
1 Splitting
Bigger Rabi Splitting

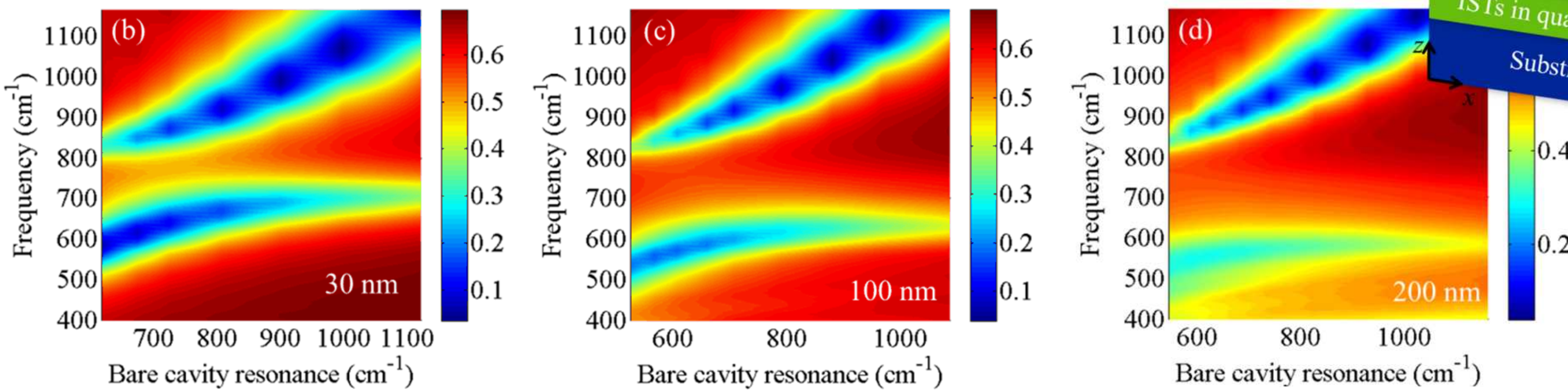
Campione et al. under review

Rabi splitting increases with ENZ thickness

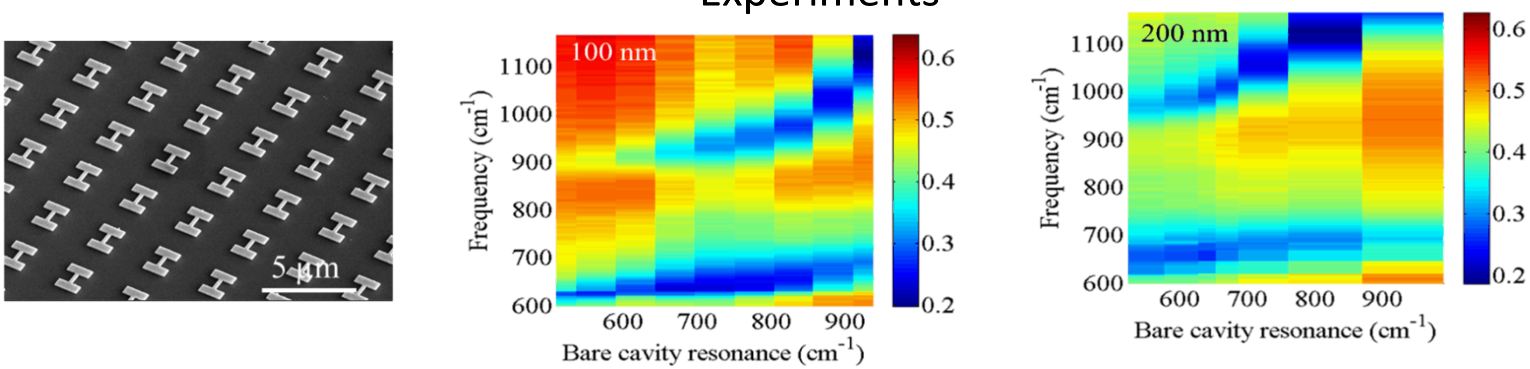
ω_p=IST transition frequency



Simulations



Experiments



(e) Rabi splitting in cm^{-1} versus strong coupling configuration

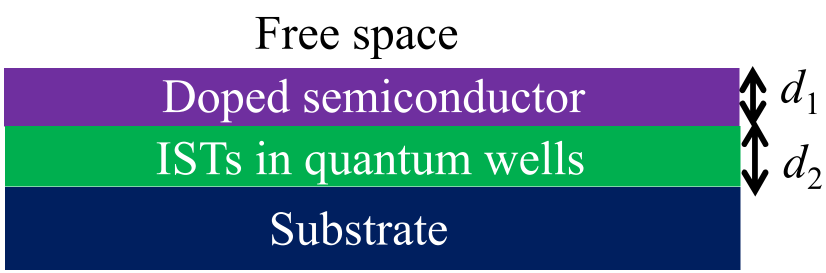
	IST only	ENZ only 30 nm	ENZ only 100 nm	ENZ only 200 nm	ENZ 30 nm and 651 nm IST	ENZ 100 nm and 651 nm IST	ENZ 200 nm and 651 nm IST
Theory	150	177	250	280	240	300	315
Exp	120	180	NA	NA	NA	320	340

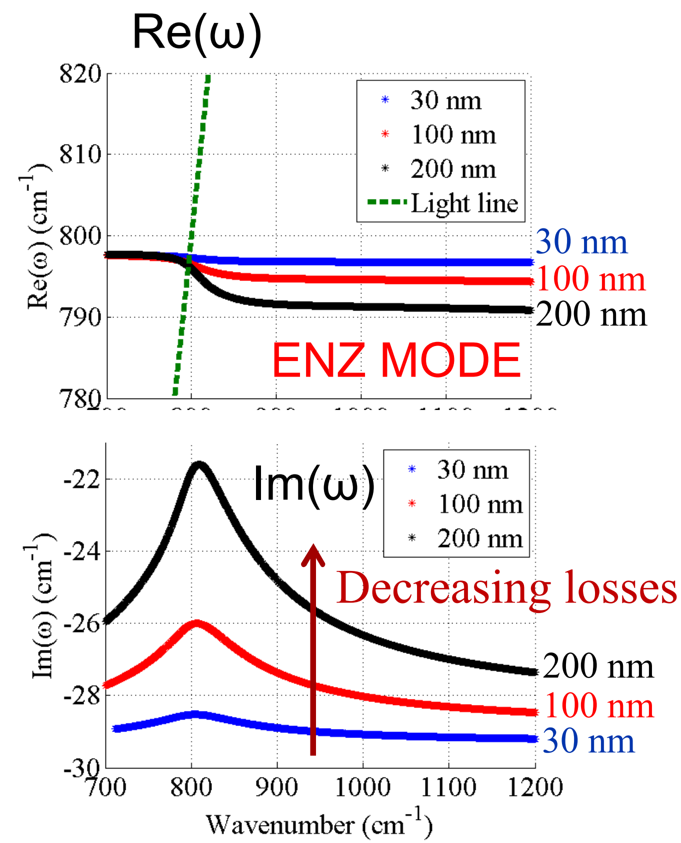
Campione et al. under review

Why does the Rabi splitting increase with ENZ thickness?

ω_p=IST transition frequency

Compute the (complex) eigenmodes of the layered medium **without MM**

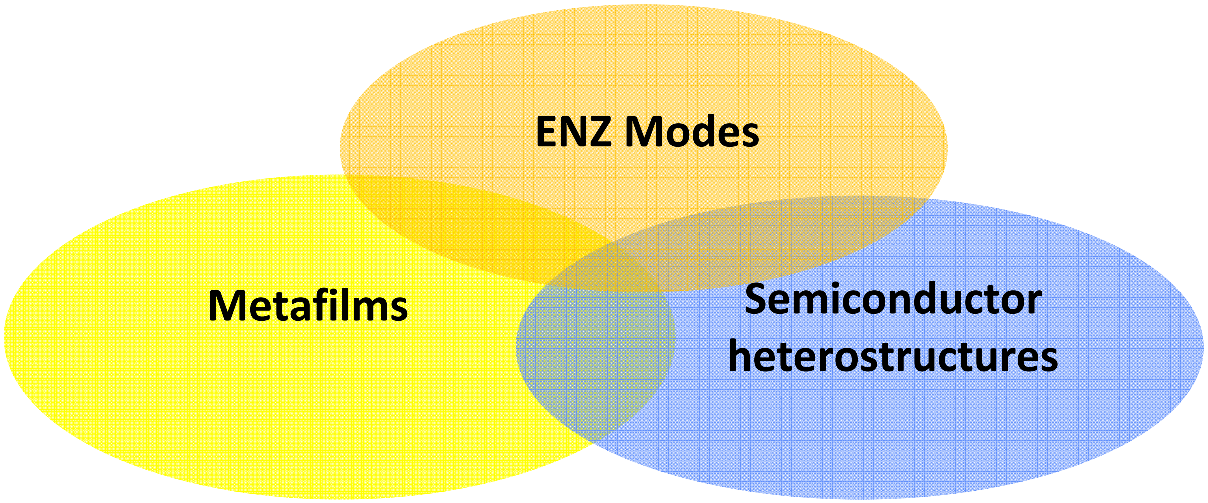


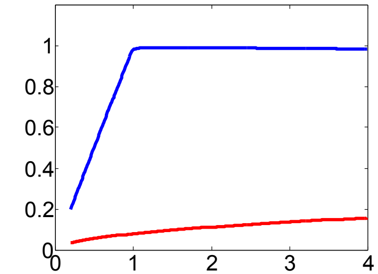


- The semiconductor stack effectively behaves as a "thicker" ENZ structure, leading to an enhanced Rabi splitting
- A lower |Im(ω)| allows better coupling and thus larger Rabi splitting
- The MM then **allows** to couple to this ENZ mode by generating the required wave spectrum

Campione et al. under review

Summary



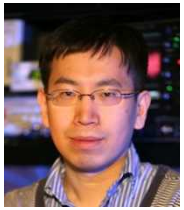
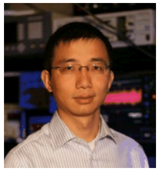


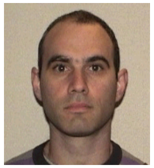
- **Metamaterial resonators + semiconductor heterostructures + ENZ modes : platform for tunable spectral behavior and variable coupling**

- **Addition of ENZ layer to metafilms enhances coupling to other dipole resonances (useful for spectral tuning, enhanced nonlinearities, etc)**

- **Berreman modes (close-relative of ENZ modes) can be used for spectrally selective thermal emission**

Acknowledgments

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

Omri Wolf (SHG) 

CINT + Sandia: Igal Brener, John Reno, Michael B. Sinclair, Ines Montano, John Klem (InGaAs), Andy Allerman (GaN)

UC Irvine: Filippo Capolino

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

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