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Thermal Radiation from Semiconductor Hyperbolic Metamaterials

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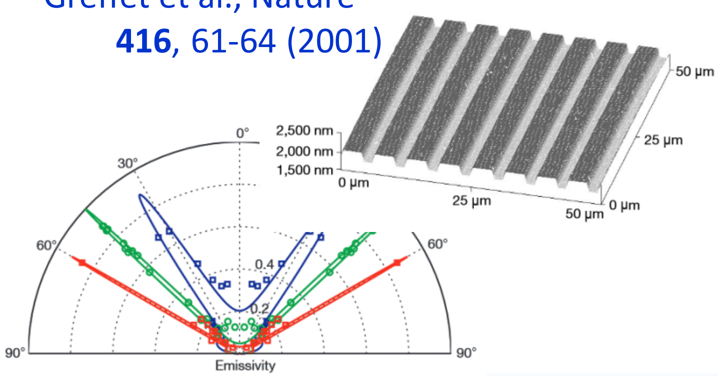
Literature review (non-exhaustive)

- High interest in mid-infrared (MIR) for e.g. spectroscopy, sensing, or thermography
- In MIR, only a few kinds of sources are available, mainly quantum cascade lasers and thermal sources (blackbodies)
- Thermal sources can be inexpensive, however they have poor efficiency because of
  - the wide wavelength range
  - the isotropy of the emission

The development of novel sources that control the emission spectrum and the angular emission pattern is thus of fundamental importance

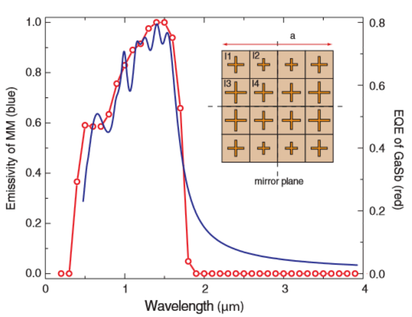
Spatially coherent (i.e. directional)

Greffet et al., Nature **416**, 61-64 (2001)



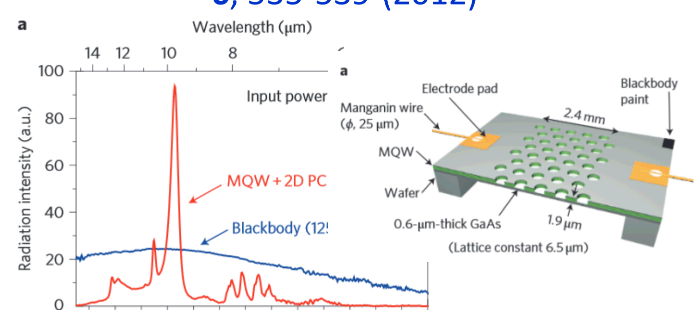
Temporally coherent

Liu et al., Phys. Rev. Lett. **107**, 045901 (2011)



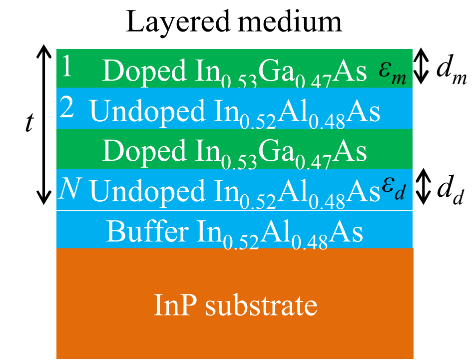
Directional and monochromatic

De Zoysa et al., Nat. Phot. **6**, 535-539 (2012)

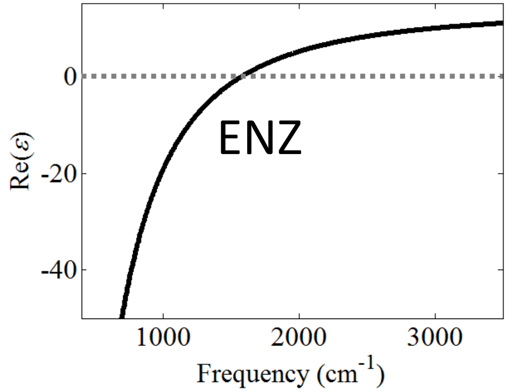


Outline of the talk

- We show that a semiconductor hyperbolic metamaterial (SHM) behaves as a quasi-monochromatic and directional thermal emitter



- And that the different thermal emission properties observed for *s* and *p* polarizations arise because of epsilon-near-zero conditions in the doped layers composing the SHMs

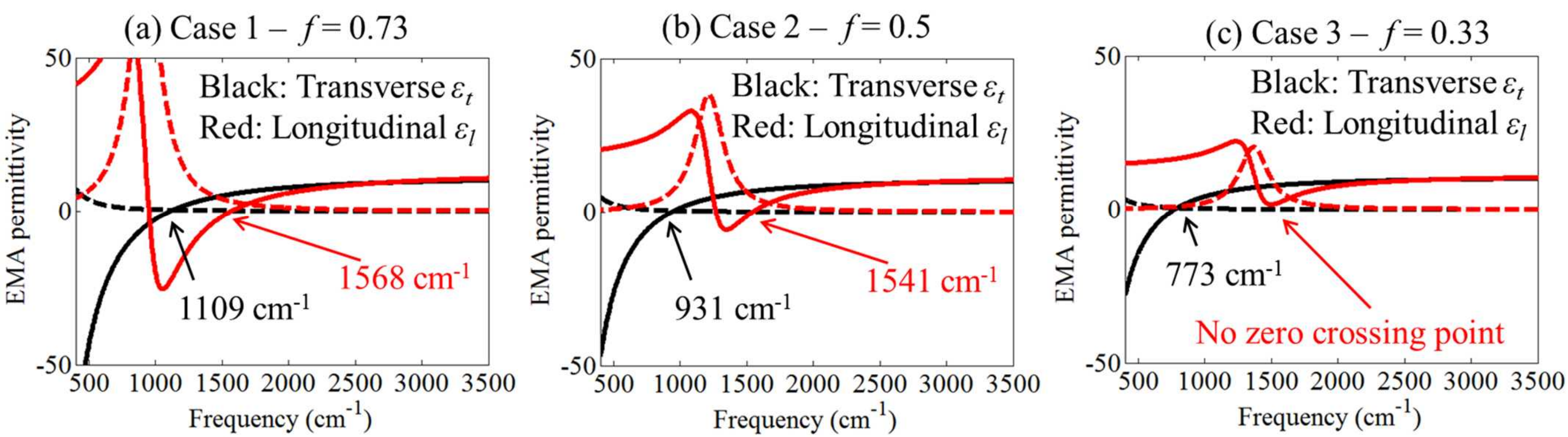


- Furthermore we claim that the zero-crossing of effective permittivities not always captures the entire story

Take-home message

- We argue that looking at the ENZ point of effective parameters may not convey the full story when interested in absorption capabilities

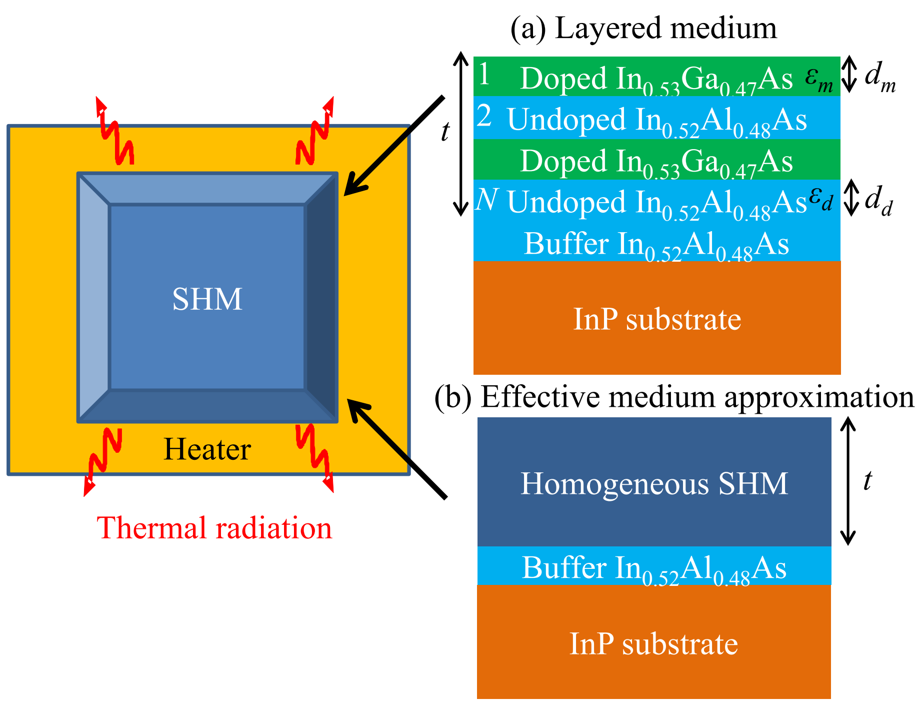
Effective permittivities



- A better figure of merit is $|\mathrm{Im}(1/\varepsilon)|$ as shown in next slides

Proposed thermal emitter

- We aim to show that simple multilayer structures without any periodic corrugation behave as *directive and monochromatic* thermal sources in the infrared
- We take advantage of an absorption resonance in a semiconductor hyperbolic metamaterial (SHM), fabricable at MIR since highly doped semiconductor materials behave like metals



Hoffman et al., Nat. Mater. **6**, 946-950 (2007); J. Appl. Phys. **105**, 122411 (2009)

Shekhar et al., Phys. Rev. B **90**, 045313 (2014)

Campione et al., Opt. Mater. Express **5**, 2385-2394 (2015); J. Opt. Soc. Am. B **32**, 1809-1815 (2015)

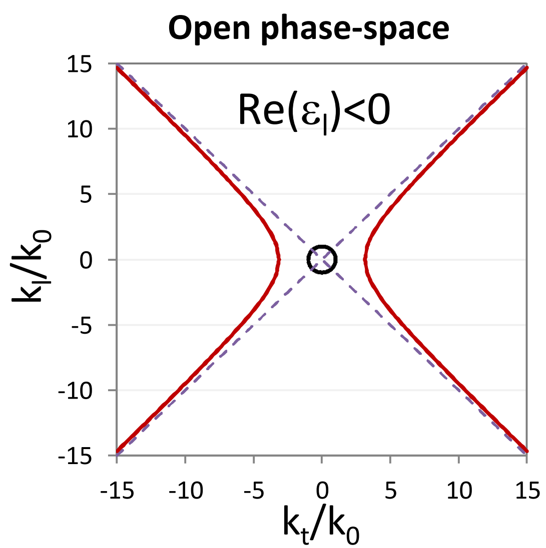
Brief explanation of hyperbolic metamaterials

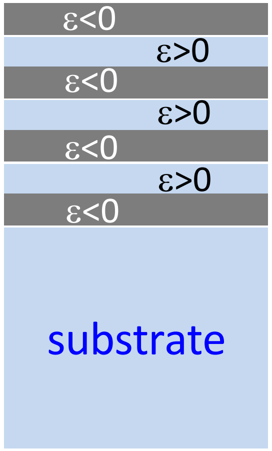
- Such a multilayered structure can be modeled homogeneously as $\boldsymbol{\varepsilon}_{\mathrm{HM}} = \varepsilon_t \hat{\mathbf{t}} + \varepsilon_l \hat{\mathbf{l}}$

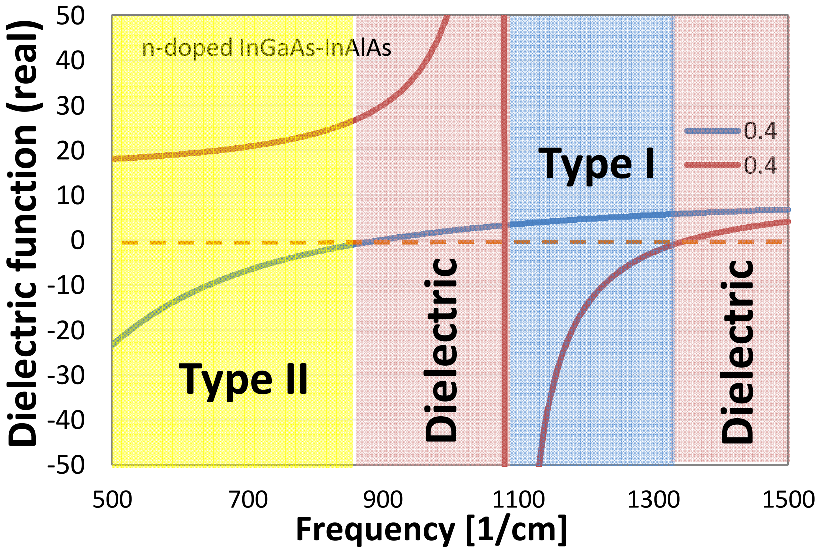
$$\text{Dispersion}: \frac{k_t^2}{\varepsilon_l} + \frac{k_l^2}{\varepsilon_t} = k_0^2$$

Hyperbolic isofrequency surface when $\mathrm{Re}(\varepsilon_t)\mathrm{Re}(\varepsilon_l) < 0$

Local effective medium theory $\varepsilon_t = \dfrac{\varepsilon_m d_m + \varepsilon_d d_d}{d_m + d_d}$ $\varepsilon_l = \left(\dfrac{\varepsilon_m^{-1} d_m + \varepsilon_d^{-1} d_d}{d_m + d_d}\right)^{-1}$

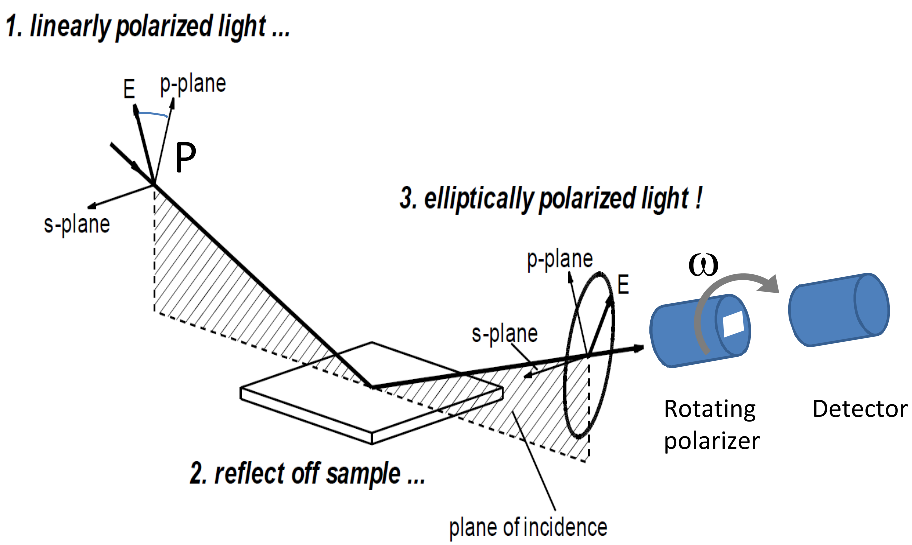






Ellipsometry characterization of SHM sample

Ref: J. A. Woollam WVASE manual



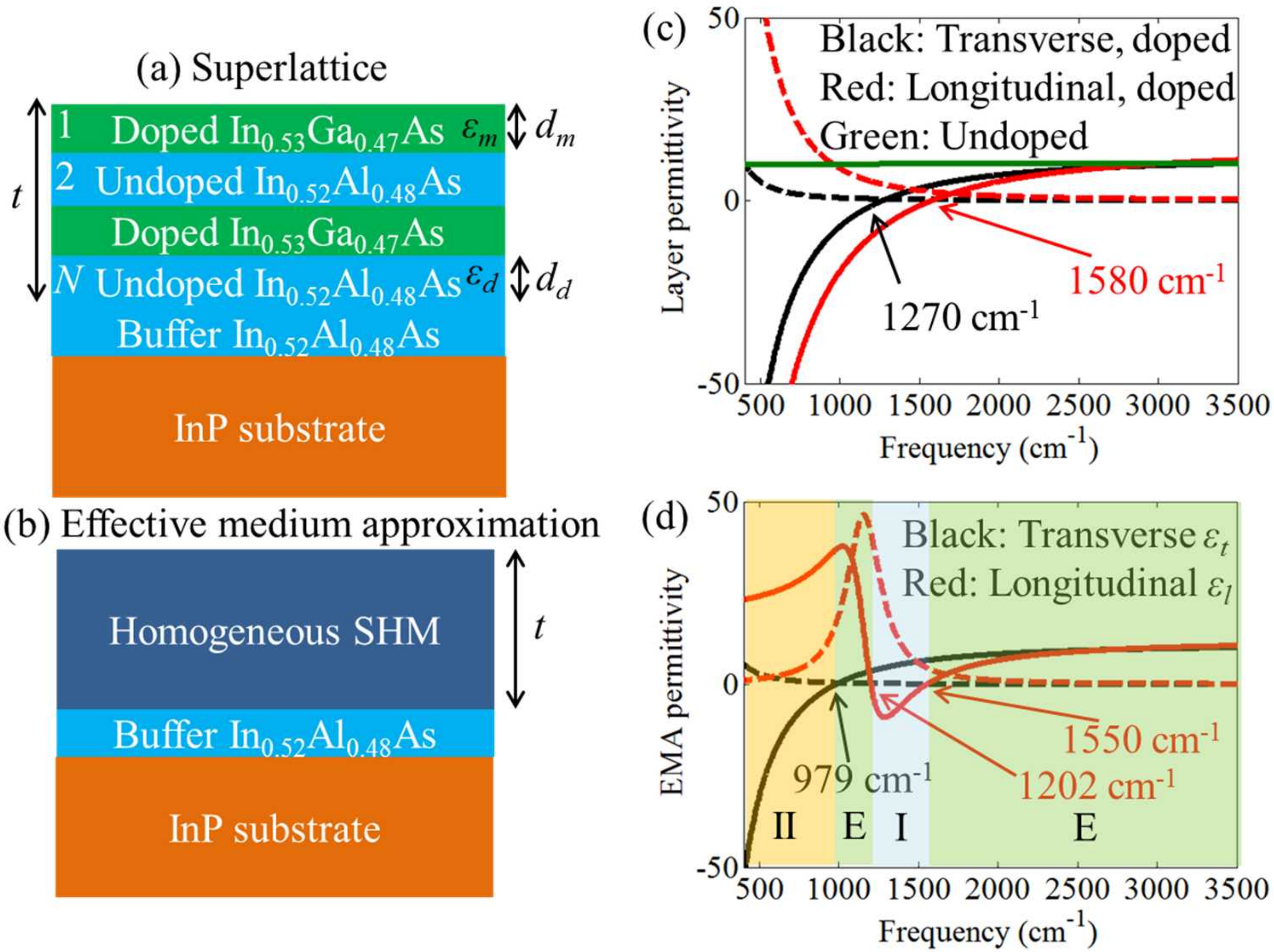
J. A. Woollam IR-VASE
(Variable Angle Spectroscopic Ellipsometer)

- The ellipsometric measurement provides the quantity

$$\rho = \tan(\psi)\exp(i\Delta) = \frac{R_p}{R_s}$$

- Which is used to extract the optical parameters of the layers composing the SHM

Extracted optical parameters from ellipsometry (empirical model)



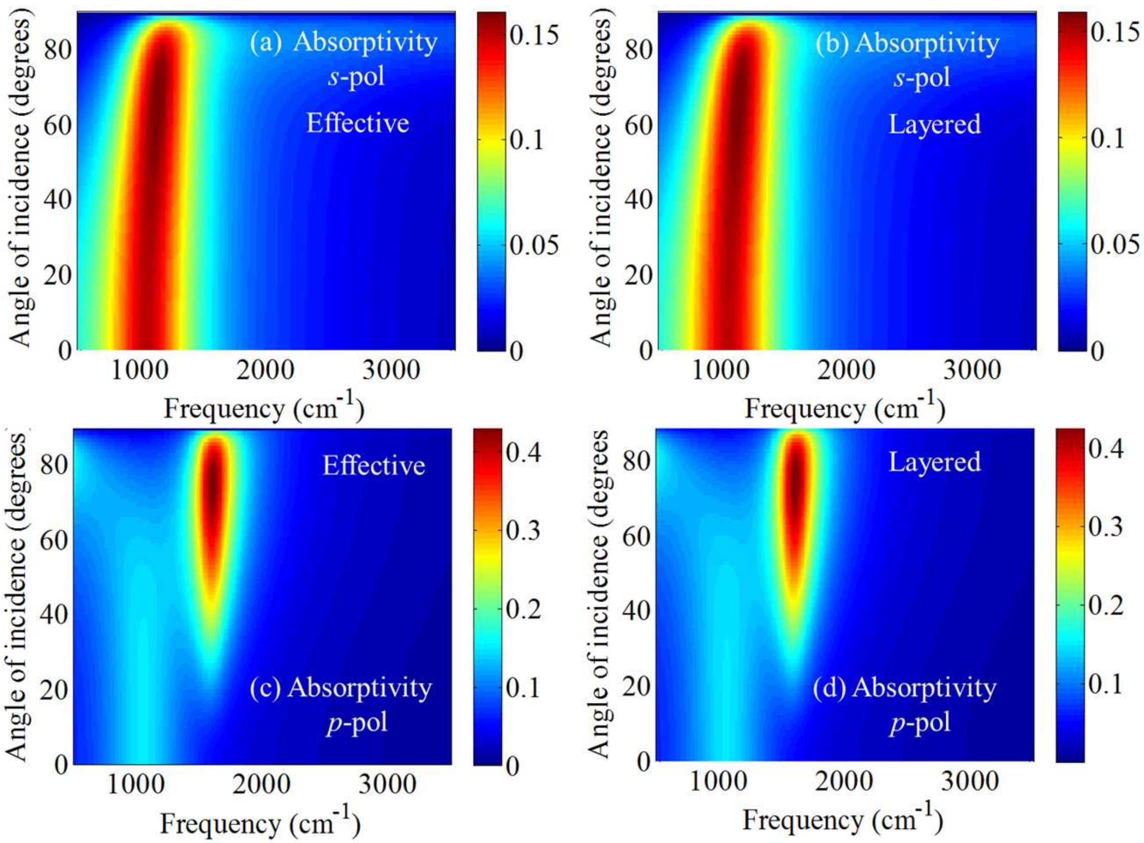
The doped layers are modeled as anisotropic Drude layers

Askenazi et al., New J. Phys. **16**, 043029 (2014)

Use of anisotropic effective medium approximation

Agranovich, Solid State Communications **78**, 747-750 (1991)

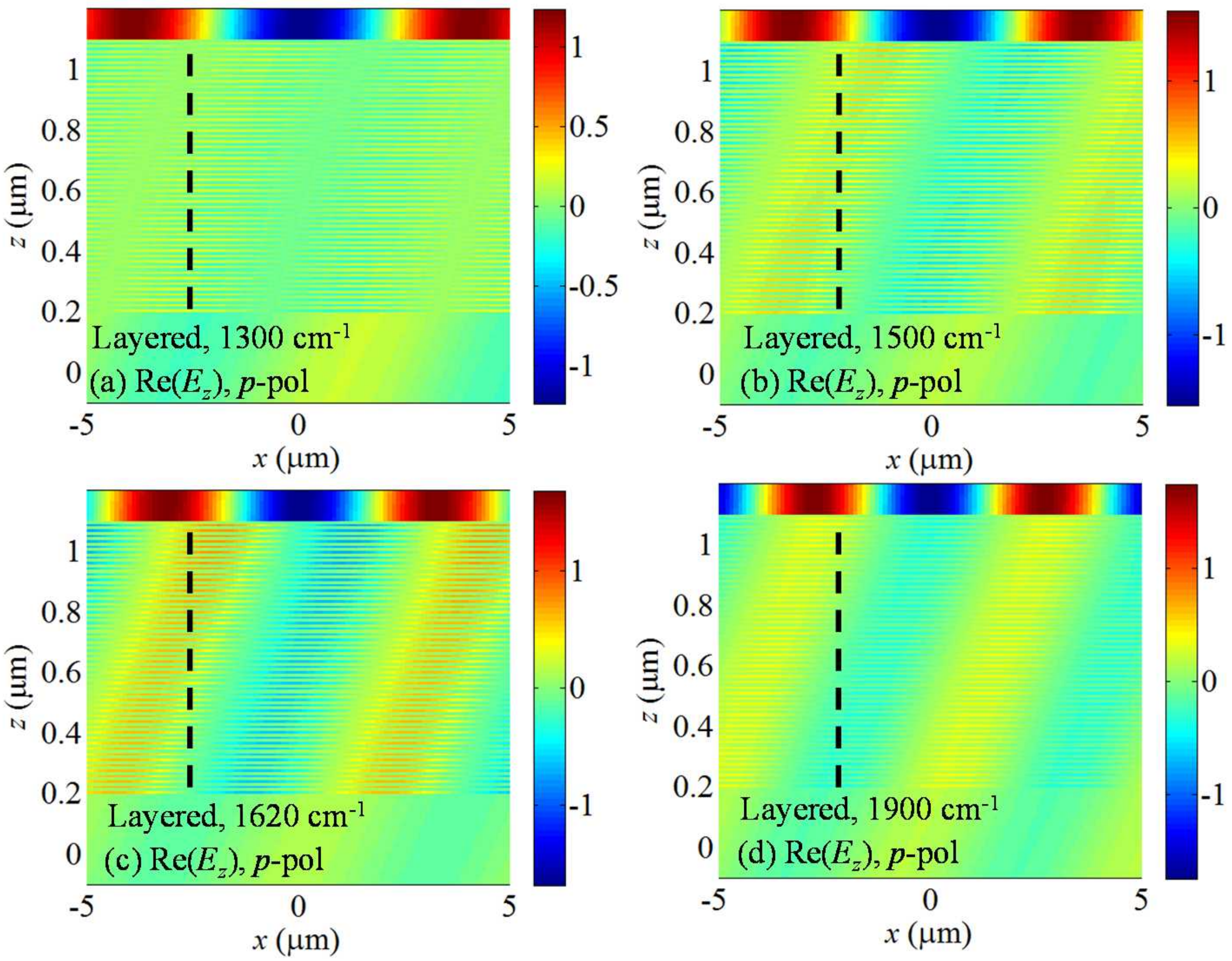
Absorptivity: Effective medium versus layered implementation



- The layered and effective medium implementations agree very well
- For *s*-pol incidence, a main feature around ~1060 cm^{-1} is observed
- For *p*-pol incidence, two features are present: one around ~1060 cm^{-1} is barely seen, compared to the other around ~1600 cm^{-1}.

- Feature at ~1060 cm^{-1}: originates from a slab impedance matching condition
- Feature at ~1600 cm^{-1} is due to an epsilon-near-zero condition in the doped quantum wells

Epsilon-near-zero effect: Field profiles for different frequencies under p-pol



- It is clear that the fields are enhanced around the ENZ frequency
- These enhanced fields justify an enhanced absorption at ~1600 cm^{-1}

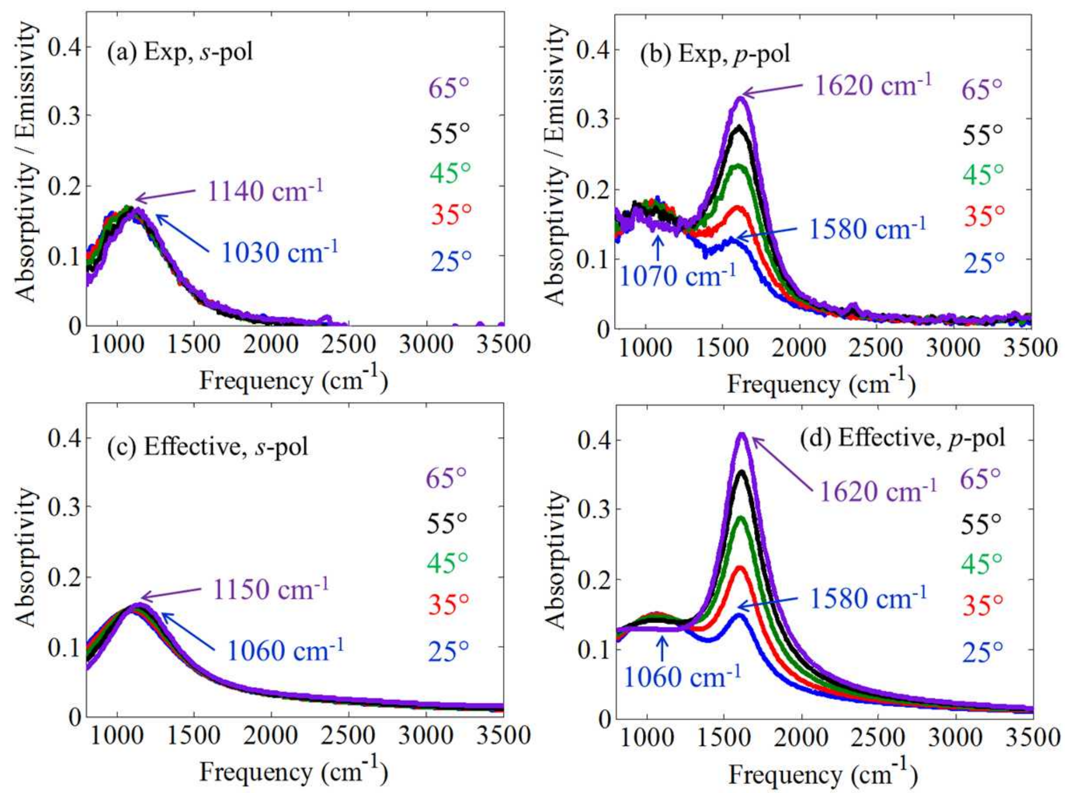
Absorptivity measurements

- Thermal radiation intensity emitted from a body is $E^{(e)}(\lambda,T,\theta)=\varepsilon_\lambda(\theta)E_b(\lambda,T)$
- The emissivity acts as a filter of the blackbody spectral radiance to shape the emitted radiation from the thermal source.
- Kirchhoff's law: $\alpha_\lambda(\theta)=\varepsilon_\lambda(\theta)$

  Greffet et al., J. Opt. Soc. Am. A **15**, 2735-2744 (1998)

- Using the IR-VASE, we measure reflection and transmission for both s- and p-polarized light, and retrieve absorptivity as 1-R-T

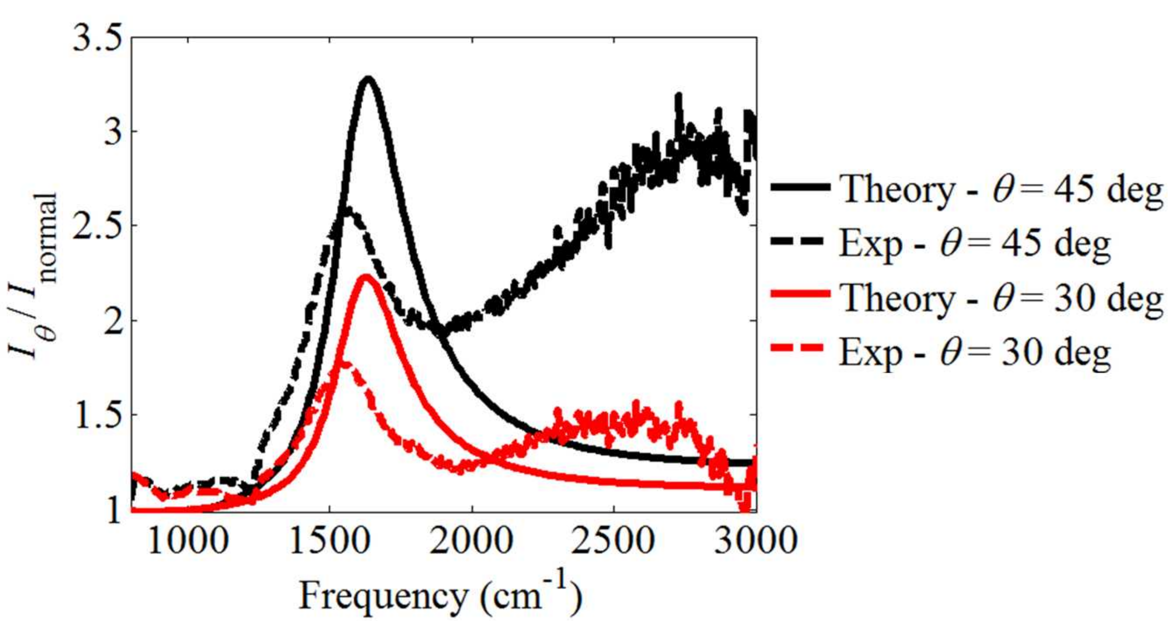
- We observe very good agreement between theory and experiments



Campione et al., under review (2016)

Thermal emission measurements

- We then use a custom-built thermal emission measurement setup to characterize the thermal emitter
- We perform two sets of unpolarized measurements at 300 degrees centigrade (the insertion of a polarizer would introduce too much loss in our setup)
  - with sample, at normal incidence, 30 and 45 degrees
  - without the sample, at normal incidence, 30 and 45 degrees



- The experimental emission is observed at ~1580 cm^{-1} close to the ENZ frequency of the doped quantum wells (some background noise is present for high frequencies)

- A good qualitative agreement is observed between experiments and simulations

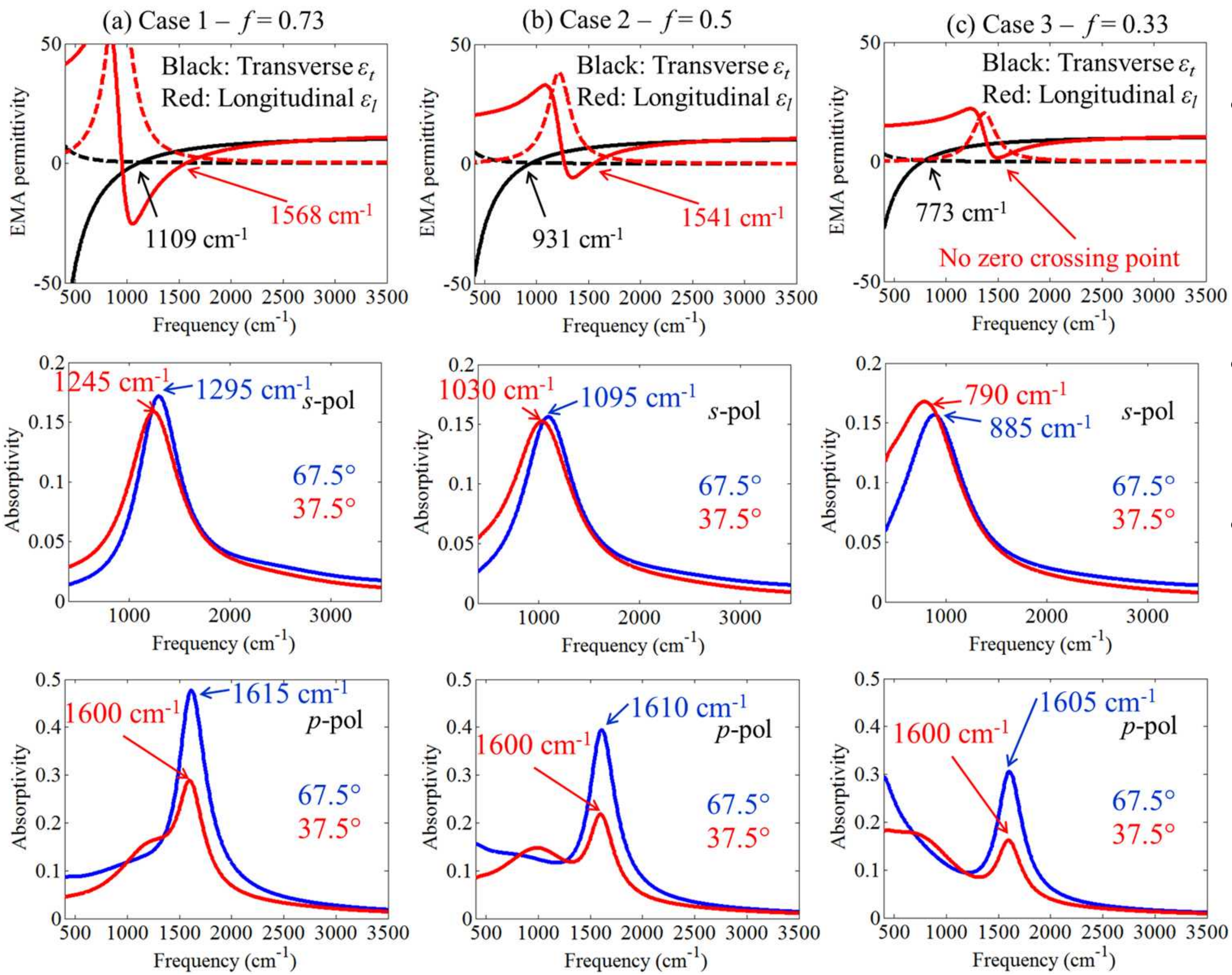
Campione et al., under review (2016)

Numerical experiment – Dilution of effective medium parameters

- We claim the absorption at ~1600 cm^{-1} is due to the ENZ frequency of the doped layer and not to the ENZ effect of the homogeneous permittivity
- We analyze the following three cases (overall thickness kept)

Case	Doped layer thickness [nm]	Undoped layer thickness [nm]	Number of pairs
1	11	4	60
2	9	9	50
3	5	10	60

Numerical experiment – Dilution of effective medium parameters



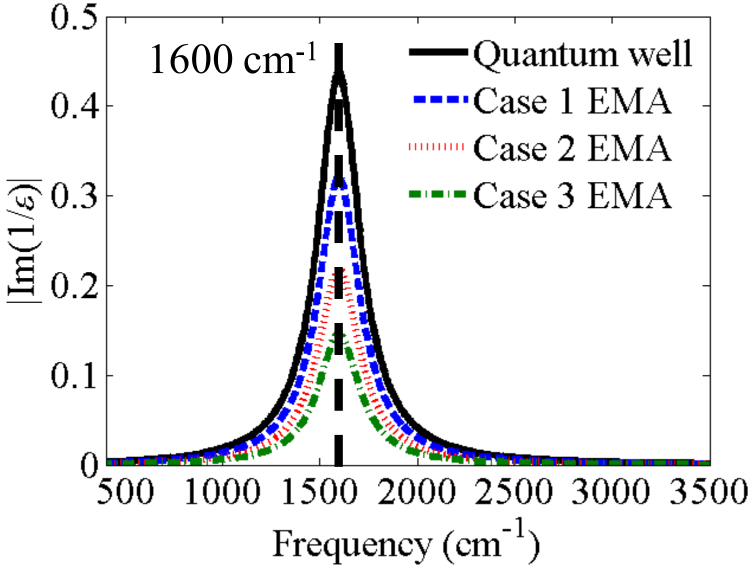
- Case 3 does not support an ENZ transition in the longitudinal component
- However, an absorption feature around ~1600 cm^{-1}
- This supports the interpretation that the origin of the absorption is due to an ENZ condition of the longitudinal component of the doped quantum wells, still kept at ~1600 cm^{-1} in these simulations

Numerical experiment – Dilution of effective medium parameters

- The result in the previous slide confirms that the knowledge of the optical characteristics of the layers composing the SHM stack is necessary for a good understanding of the observed optical properties

- It is clear however that although the effective parameters change dramatically, all models predict the absorption resonance at ~1600 cm^{-1}

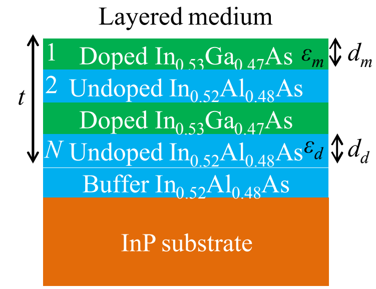
- Absorption is proportional to the imaginary part of the permittivity and the magnitude squared of the field. A parameter that embeds these two quantities is $|\mathrm{Im}(1/\varepsilon)|$



$|\mathrm{Im}(1/\varepsilon)|$ always shows an absorption peak around ~1600 cm^{-1}

Conclusion

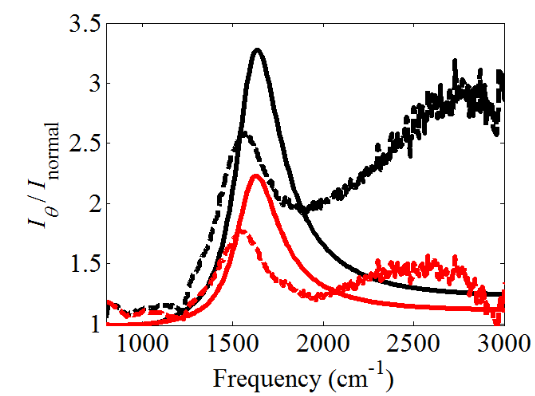
- Simple multilayered semiconductor heterostructures behaving as semiconductor hyperbolic metamaterials



Campione et al., Opt. Mater. Express **5**, 2385-2394 (2015)
Campione et al., J. Opt. Soc. Am. B **32**, 1809-1815 (2015)

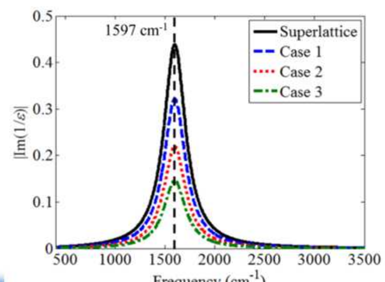
- Behave as quasi-monochromatic and directional thermal emitters in the mid-infrared region of the spectrum

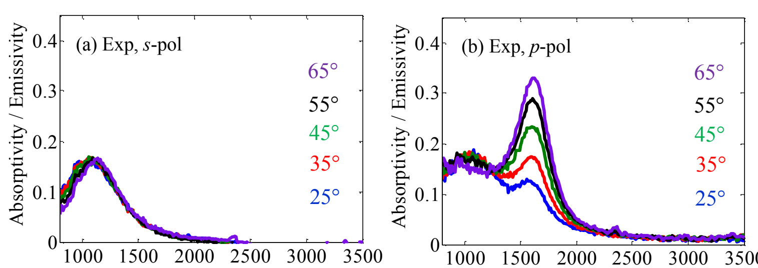
Campione et al., under review (2016)



- And exhibit different properties for s- and p- polarization

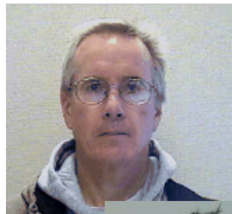
- $|\mathrm{Im}(1/\varepsilon)|$ always shows an absorption peak around ~1600 cm^{-1}



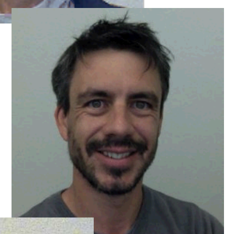


Acknowledgments

- **Michael B. Sinclair**



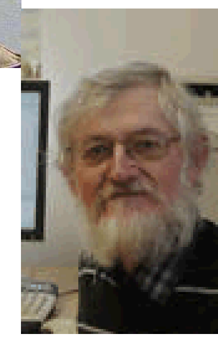
- **Francois Marquier**



- **John F. Klem**

- **Ting S. Luk**

- **Jean-Paul Hugonin**

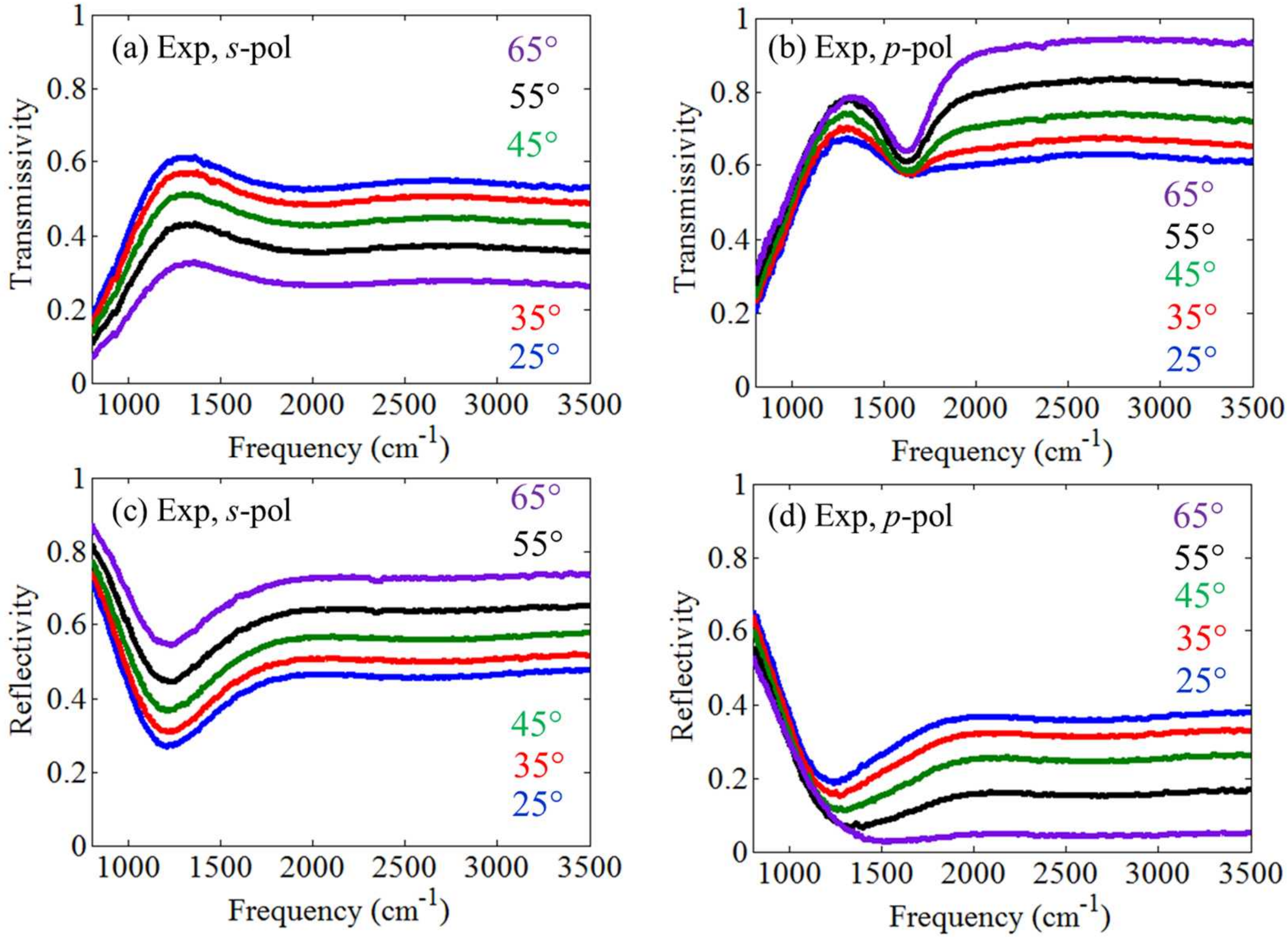


- **A. Robert Ellis**

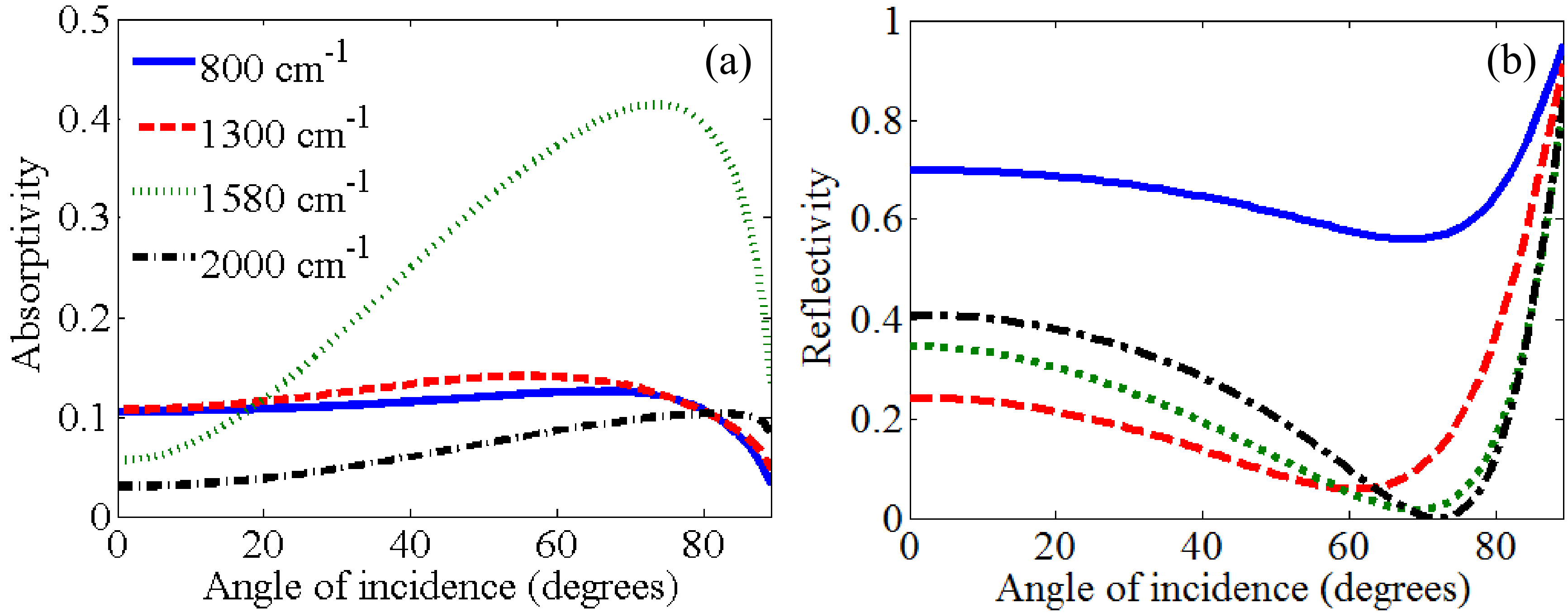
Back up slides

- Back up slides

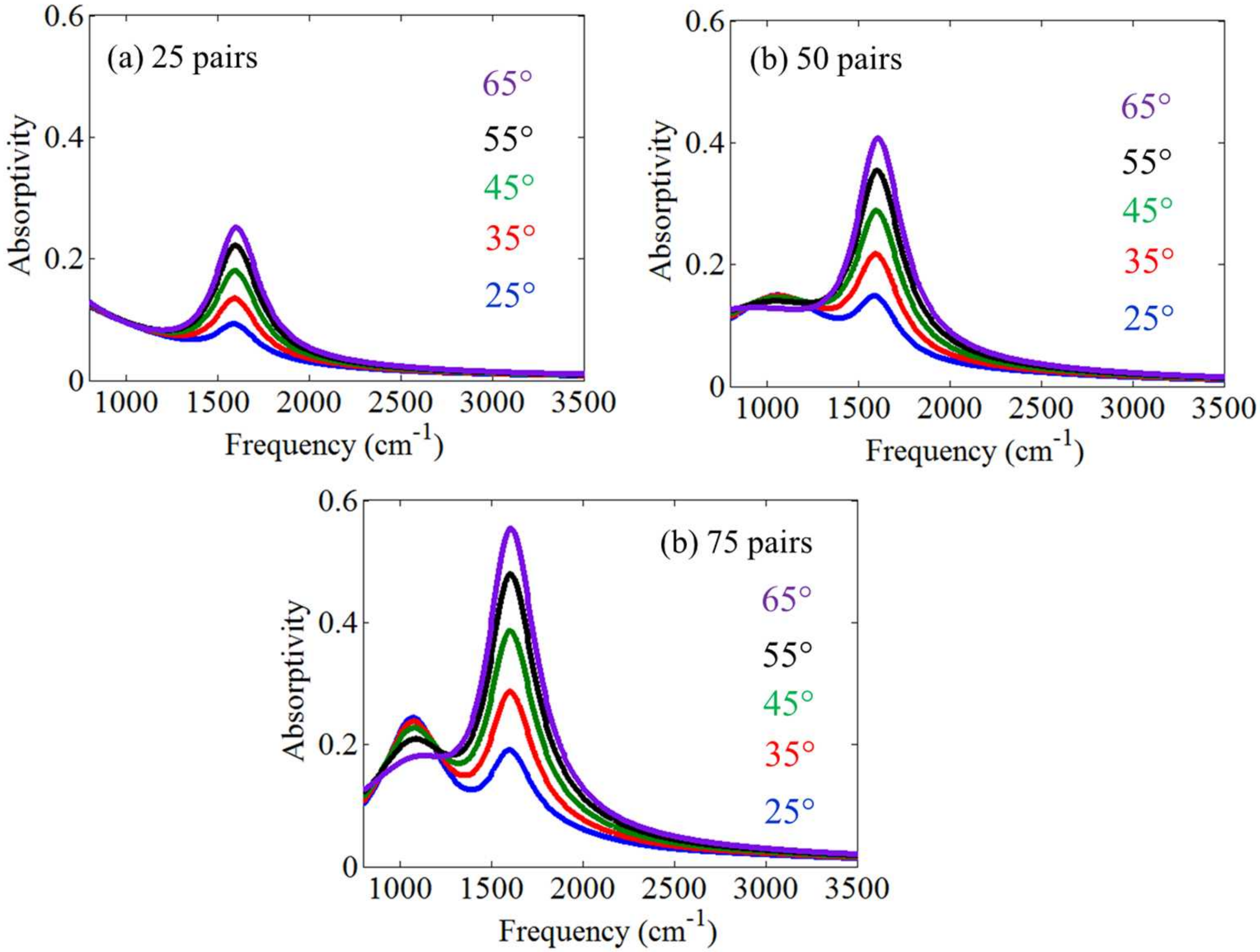
Reflection and Transmission Exp



Absorption and Reflectivity vs angle various frequencies



Absorption vs number of pairs in superlattice



|Ez| in a QW in the middle of the stack vs frequency in cm-1.