

Tailored absorption/emission from epsilon-near-zero materials

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Why tailored absorption and how?

Absorption/emission are two fundamental processes in light-matter interaction

- Photovoltaic and thermo-photovoltaics
- Infrared sources
- Sensing

How to control absorption/emission?

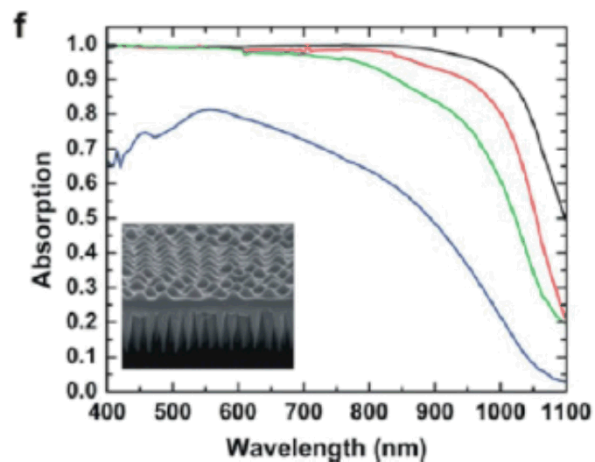
- $\varepsilon'' \neq 0$
- Control photonic density of states
- Control ε and μ
- Control impedance

Examples

- Gradual index change
- Photonic crystal
- Slow light
- Intersubband plasmon
- Metasurfaces
- Salisbury screen revisited

Impedance matching schemes

Graded index (effective medium)

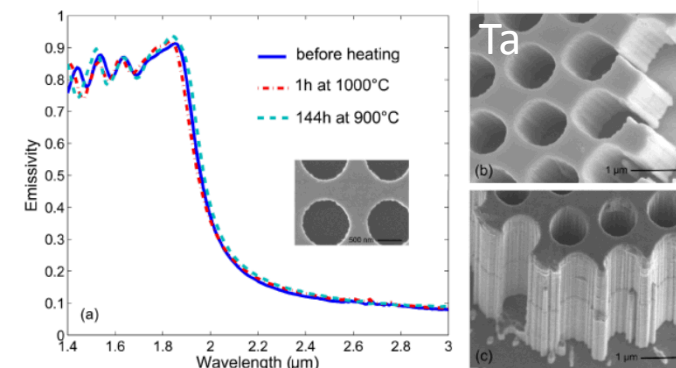


S. Wang, S. Fan and Y. Cui et. al., Nano Letters (2013)

Photonic crystal

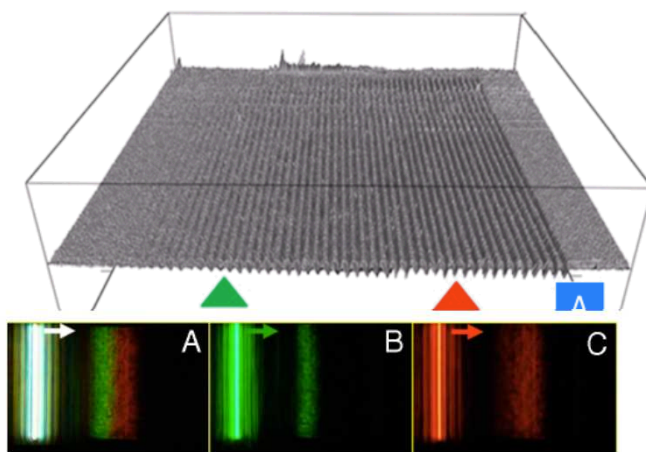


F. O'Sullivan et. al., JAP(2005)



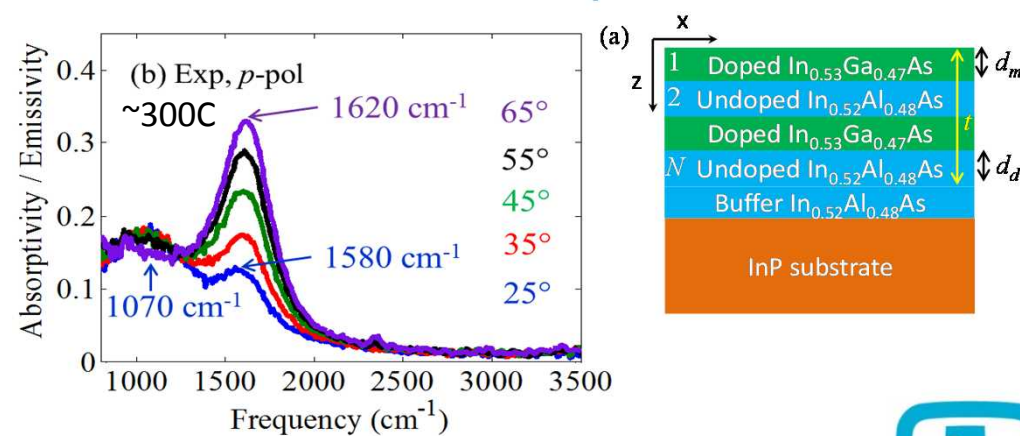
Rinnerbauer, Soljagic, Celanovic et. al., OE (2013)

Slow light



Q. Gan et. al., PNAS (2011)

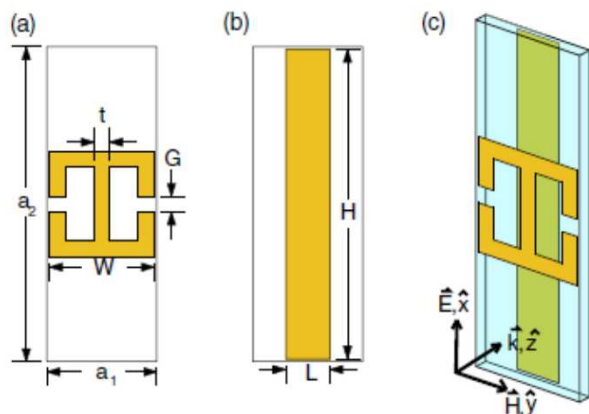
Intersubband plasmon



S. Campione, T. S. Luk et. al., submitted

Impedance matching: anti-reflection using metasurfaces

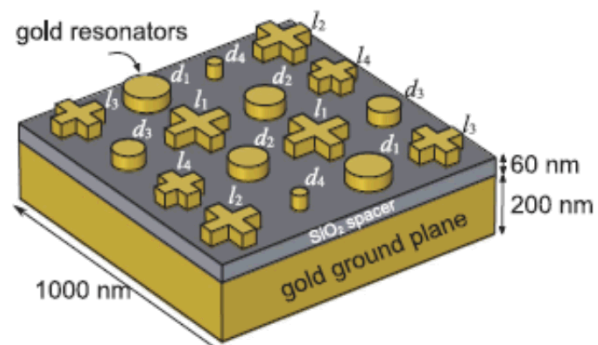
Meta-surface



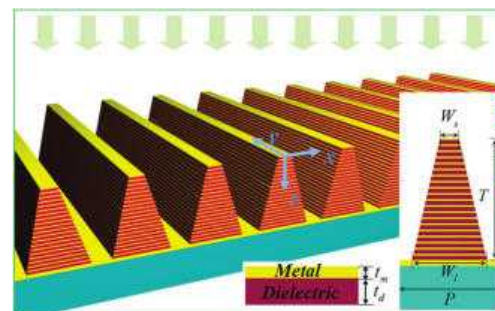
- Use nano-antenna to create matched electric and magnetic dipole to engineer ϵ and μ to achieve free-space impedance
- Electric cancellation of electric and magnetic resonances
- Metal back plane is often used

N. I. Landy, S. Sajuyigbe, J. J. Mock, D. R. Smith, and W. J. Padilla, "Perfect Metamaterial Absorber," PRL (2008)

Many variations of this theme with different antenna designs



A. K. Azad, H.-T. Chen, et. al., Scientific Reports (2016)

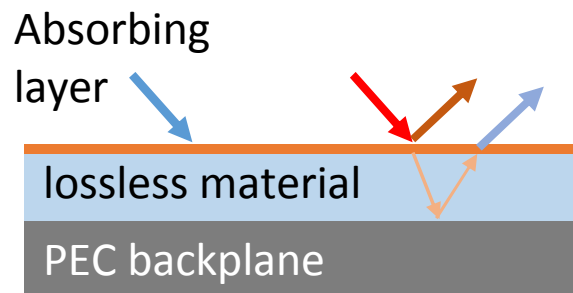


Y. Cui, N. X. Fang, et. al., Nano Letters (2012)

Salisbury screen revisited

Salisbury screen: anti-reflection of planar structures

[US 2599944 \(A\)](#) "Absorbent body for electromagnetic waves". Salisbury W. W. June 10, 1952

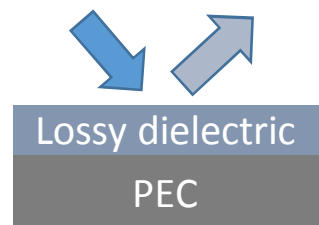


- Requires a metal backplane
- $\lambda/4$ lossless spacer material
- Thin top layer of absorbing material

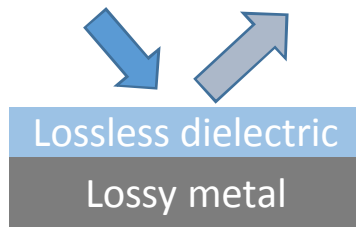
Mid-IR Z. Wang et. al. APL (2015)

Vis J. Guo et. al. Optical Materials Express (2016)

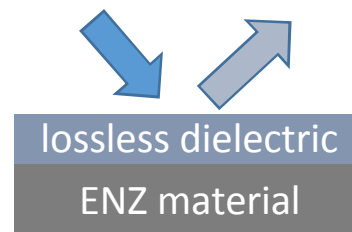
Other Impedance matching variations (2 interfaces)



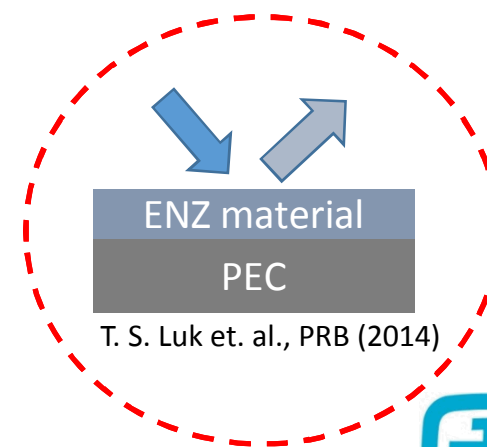
Kats, Nat. Mater. (2013)



Driessen, APL (2009)



S. Campione, T. S. Luk OE (2016)



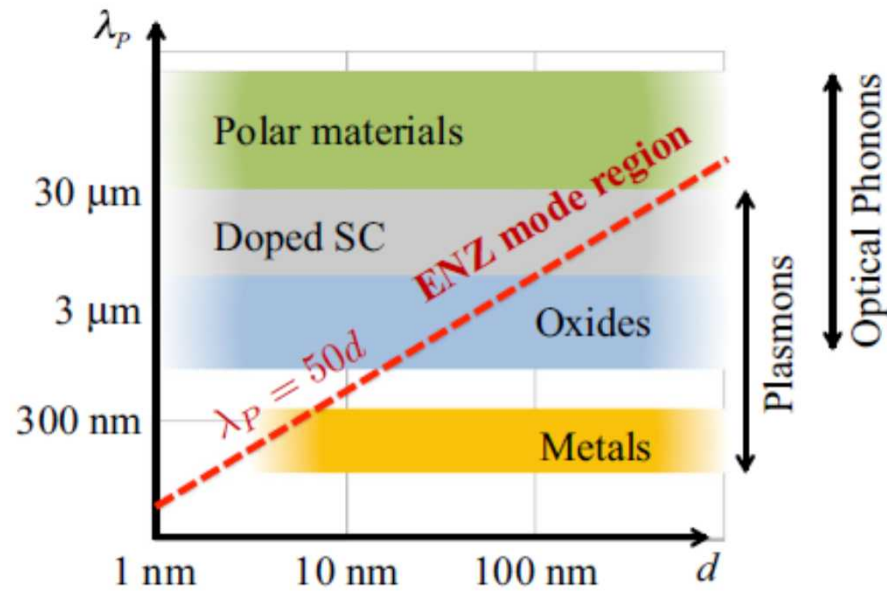
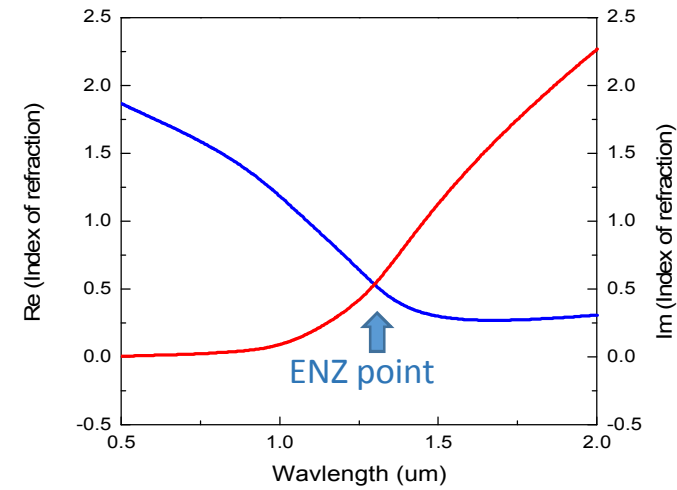
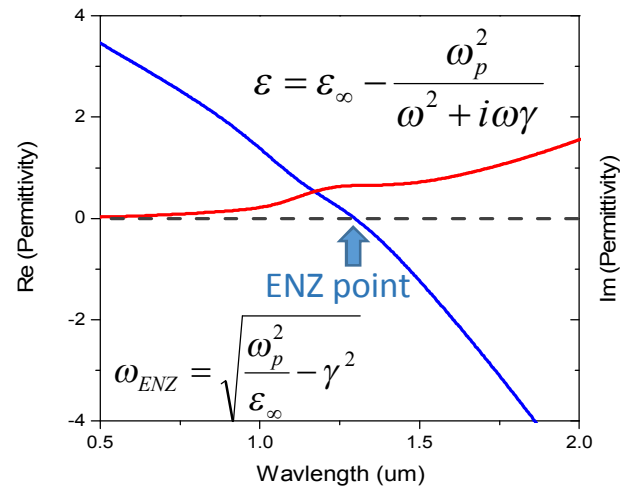
T. S. Luk et. al., PRB (2014)



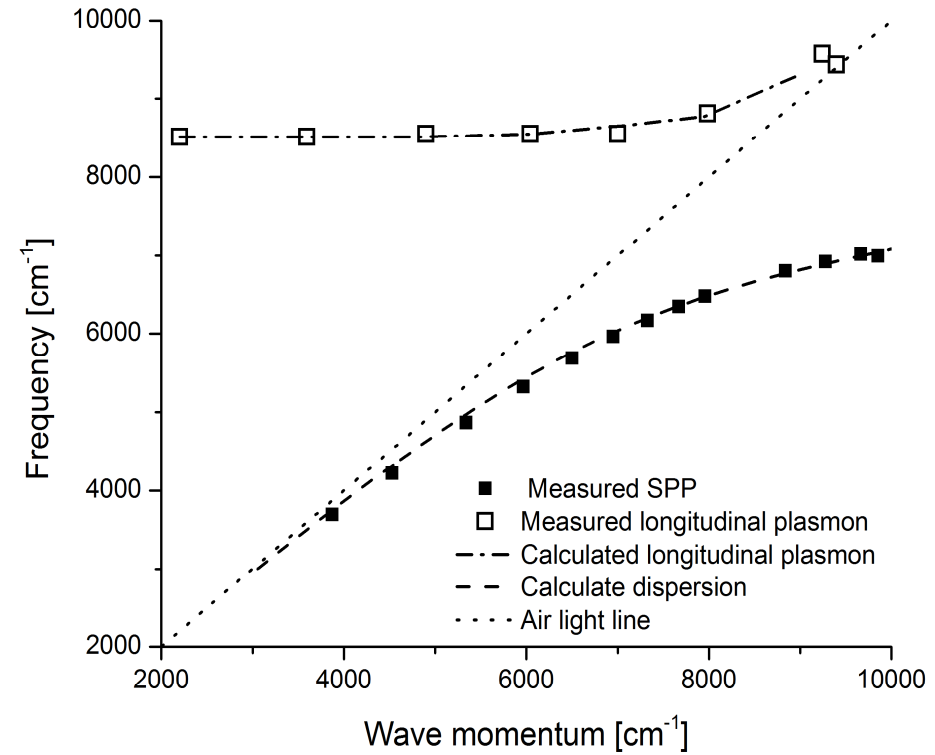
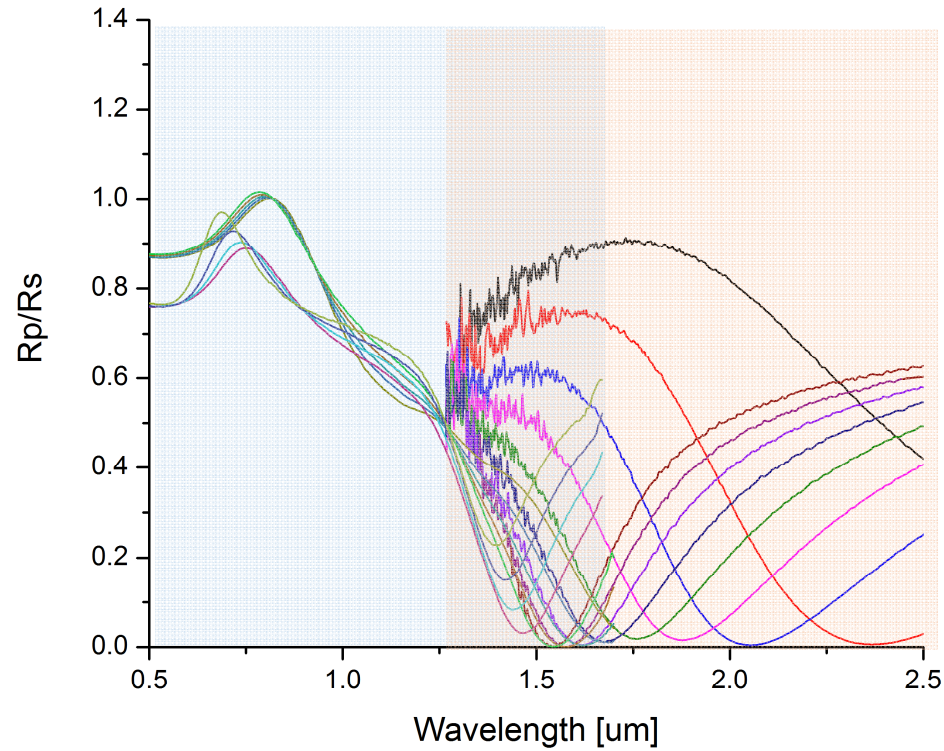
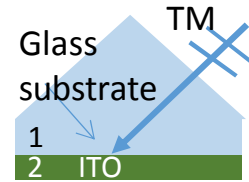
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Epsilon-near-zero is not so exotic

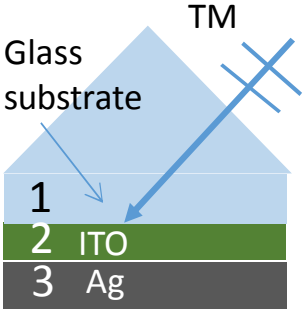
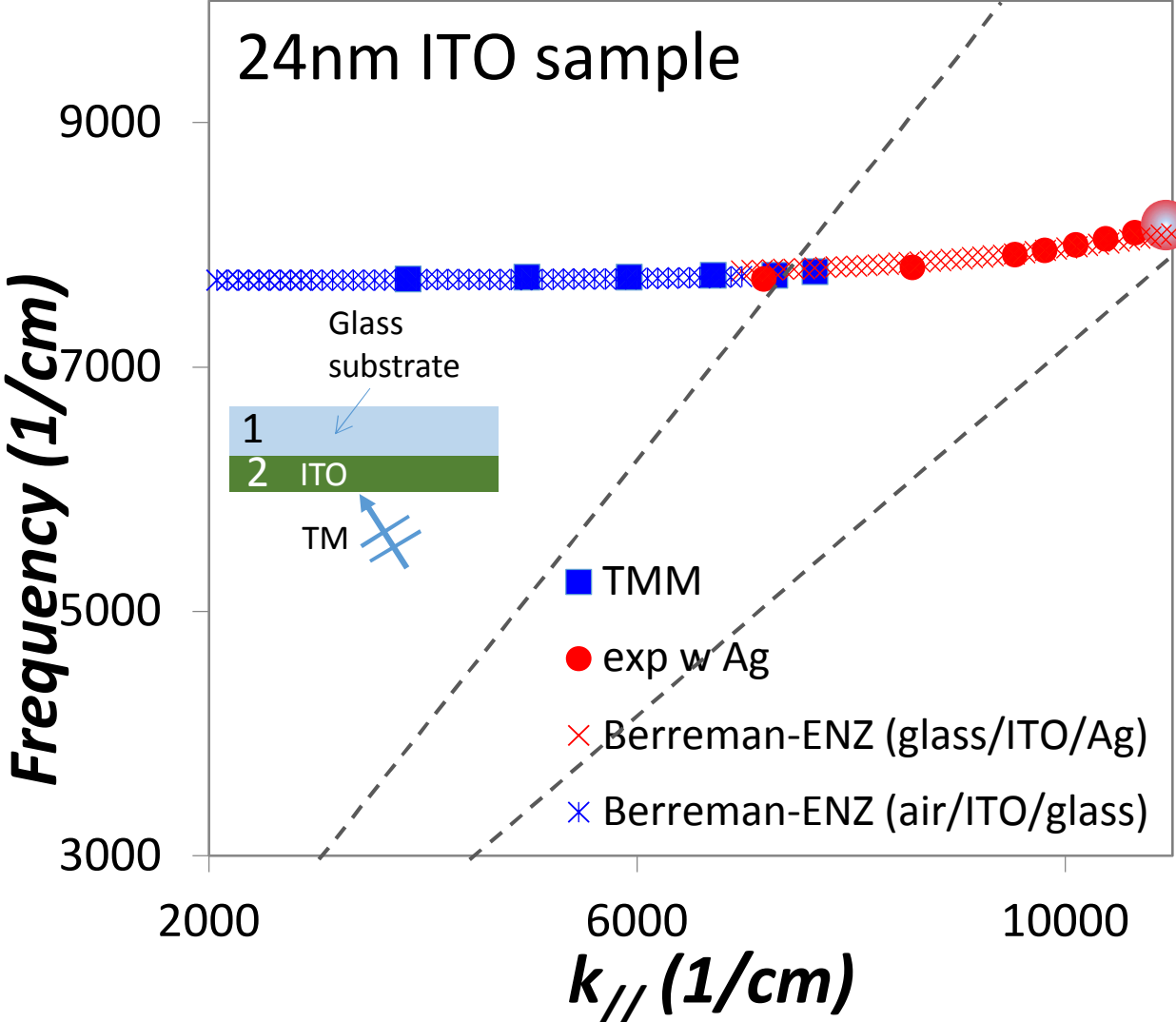
Dielectric function of Drude model



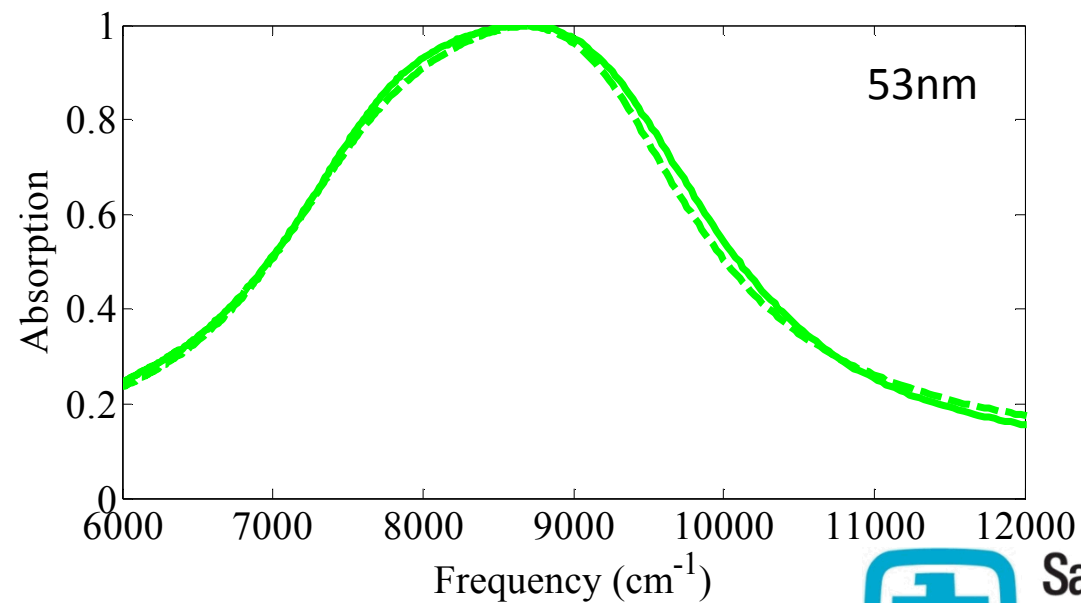
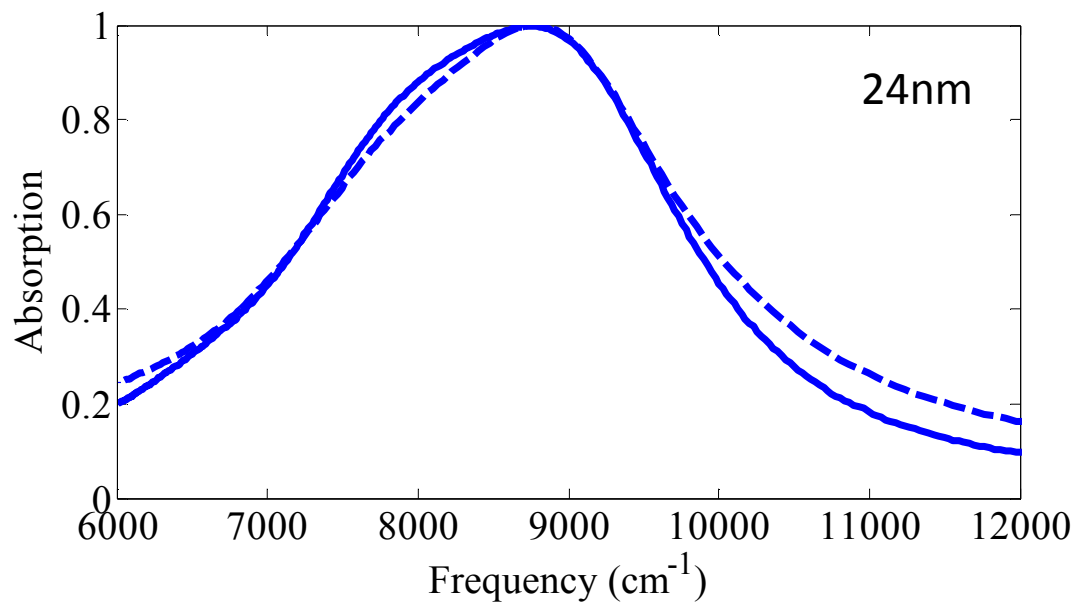
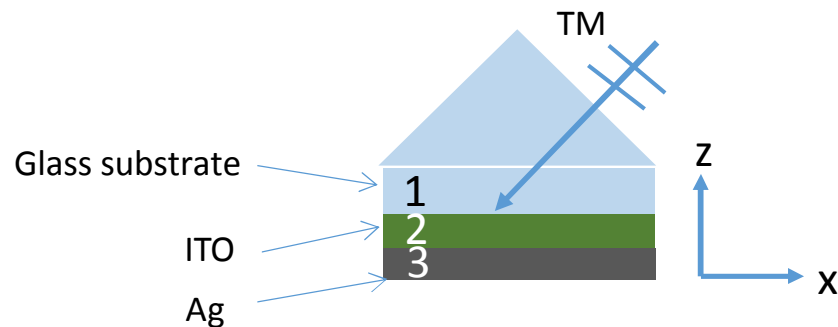
SPP of thin(137nm) ITO film



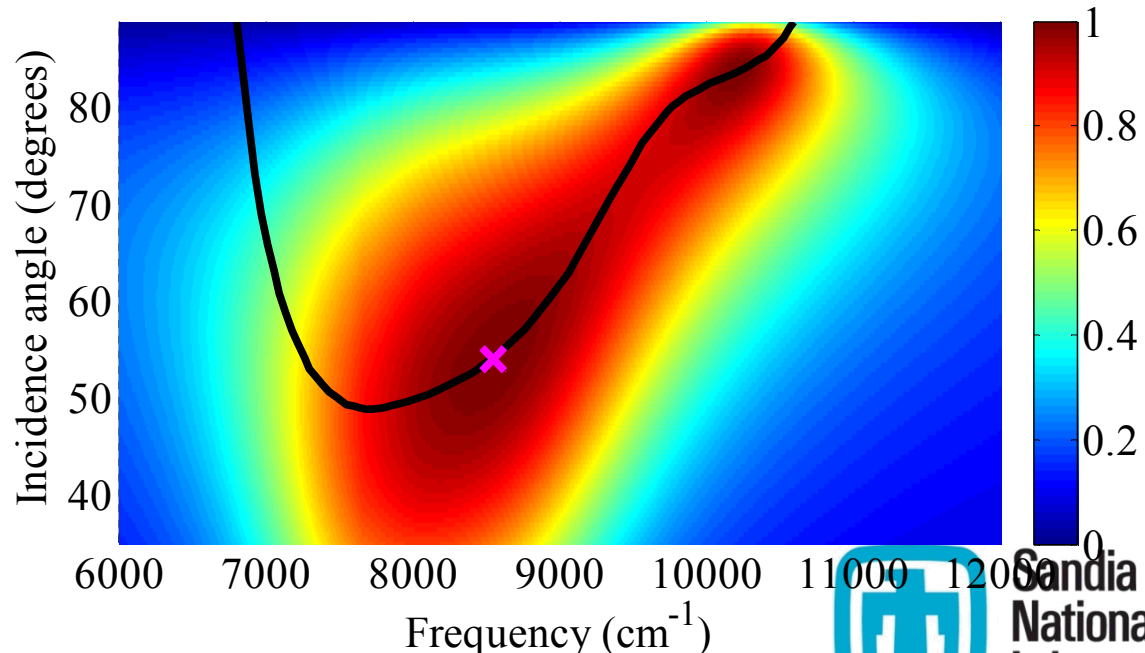
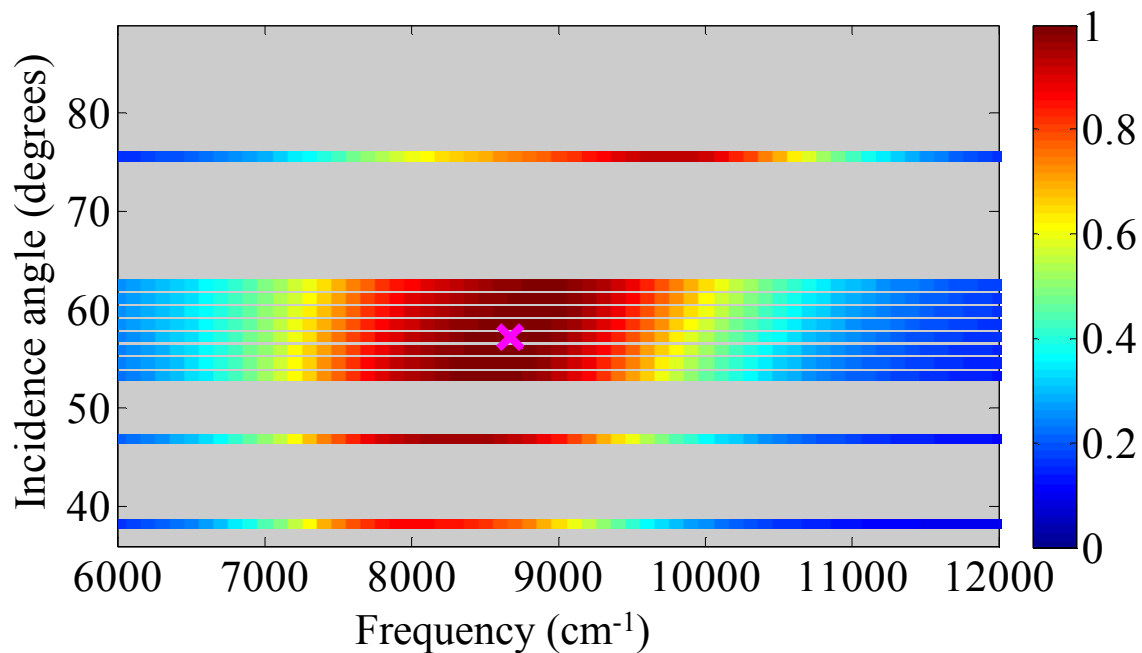
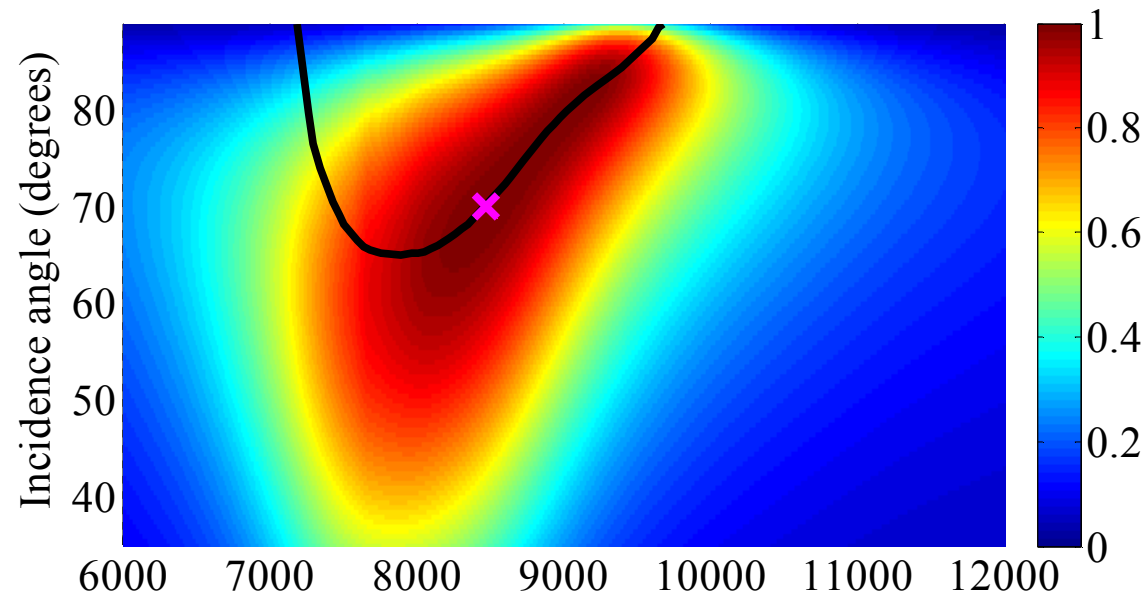
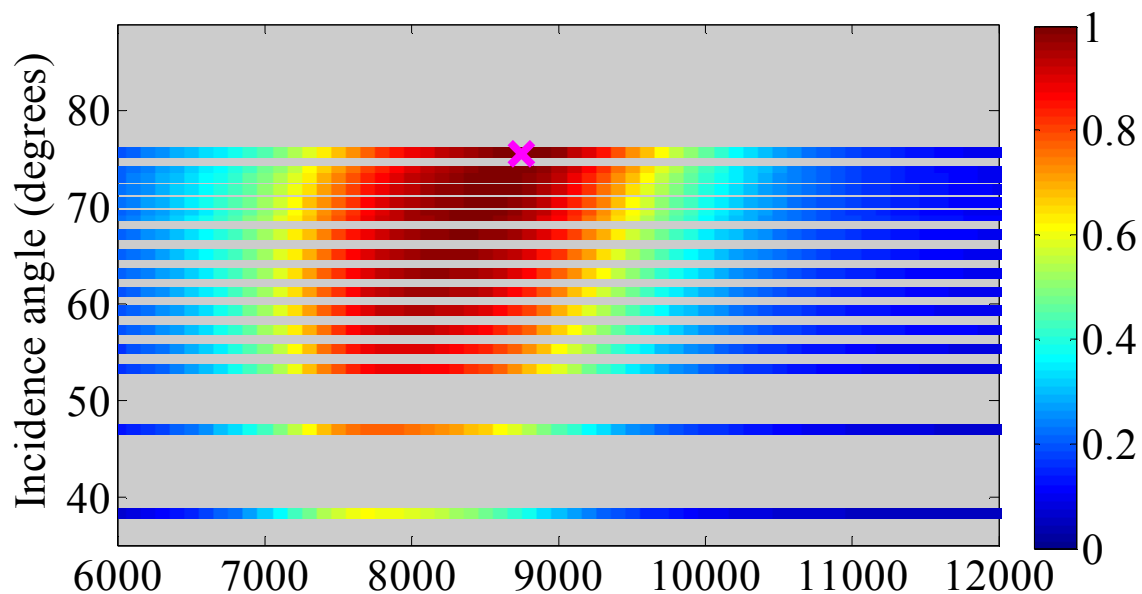
SPP of ultrathin (24nm) ITO film



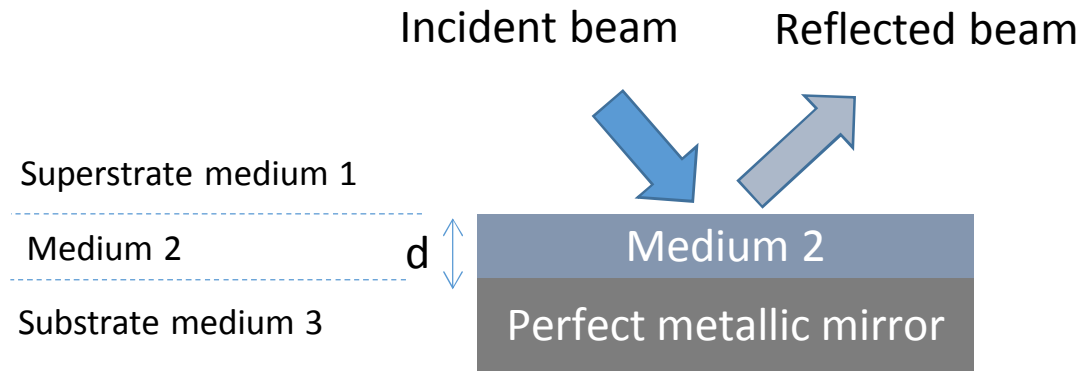
Perfect absorption from a $\lambda/50$ thick ITO film



Angular dependence of perfect absorption



Perfect absorption is an impedance matching phenomenon



Airy Formula

$$\Gamma = \frac{r_{12} + r_{23}e^{2i\phi}}{1 + r_{12}r_{23}e^{2i\phi}} \quad \phi = k_{2\perp}d$$

If you have a mirror back plane,

$$A=1-\Gamma-T=1 \quad \text{when } \Gamma=0$$

For perfect mirror

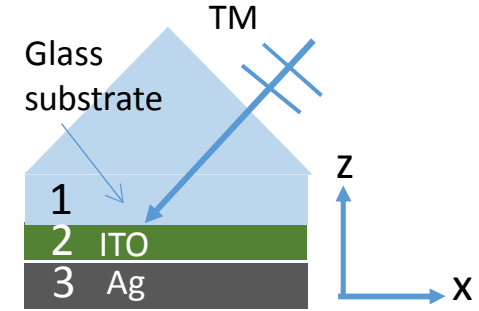
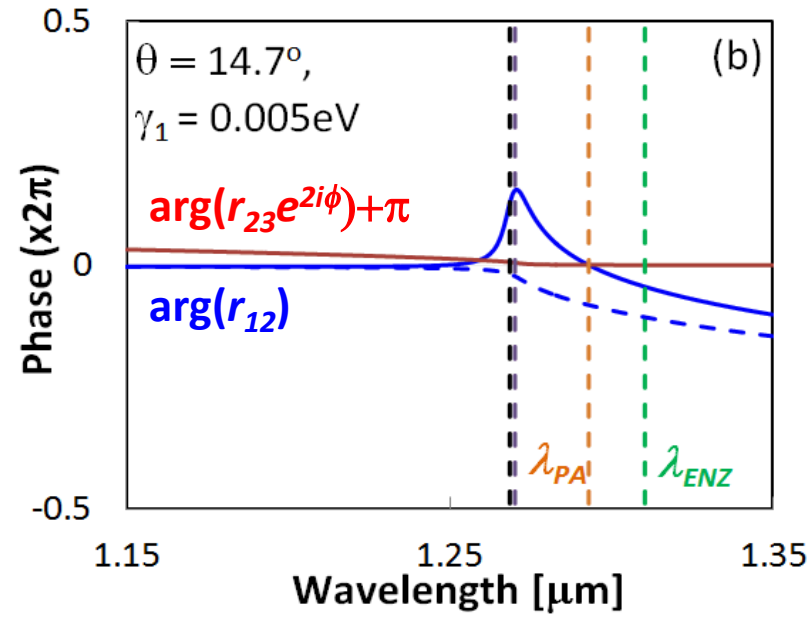
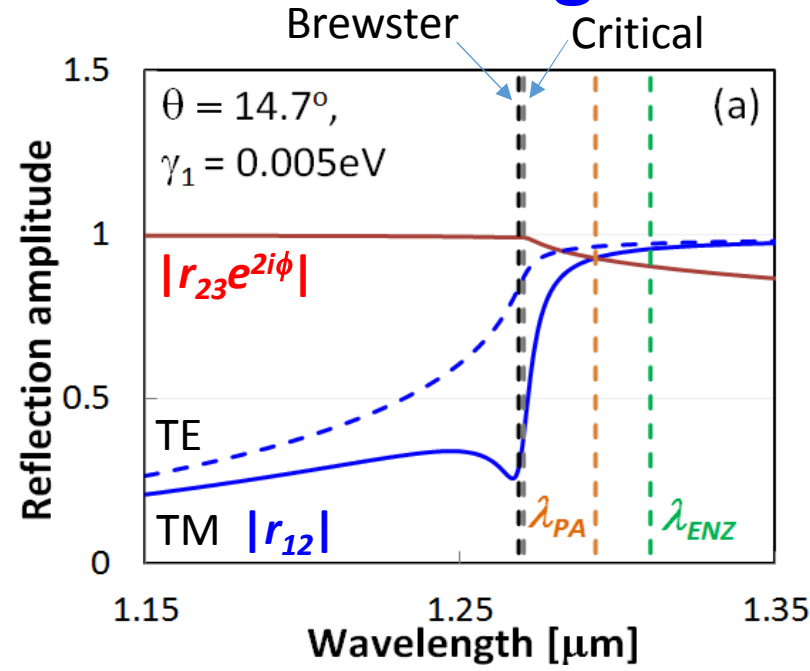
$$r_{23} = -1$$

Condition for perfect absorption

$$r_{12} = e^{2i\phi}$$

Impedance matching: intricate amplitude and phase control

LOW LOSS



Brewster angle
 $\text{Re}(\sqrt{\epsilon_{ITO}}) = \tan(\theta)$

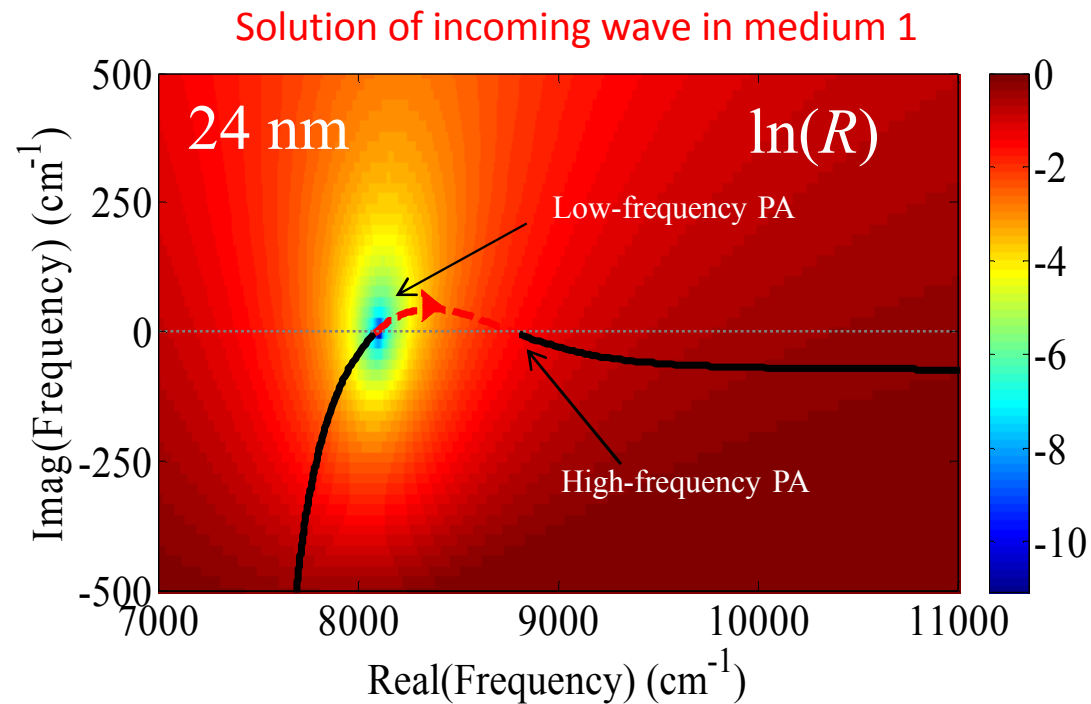
Critical angle
 $\text{Re}(\sqrt{\epsilon_{ITO}}) = \sin(\theta)$

Finding the mode in complex frequency approach

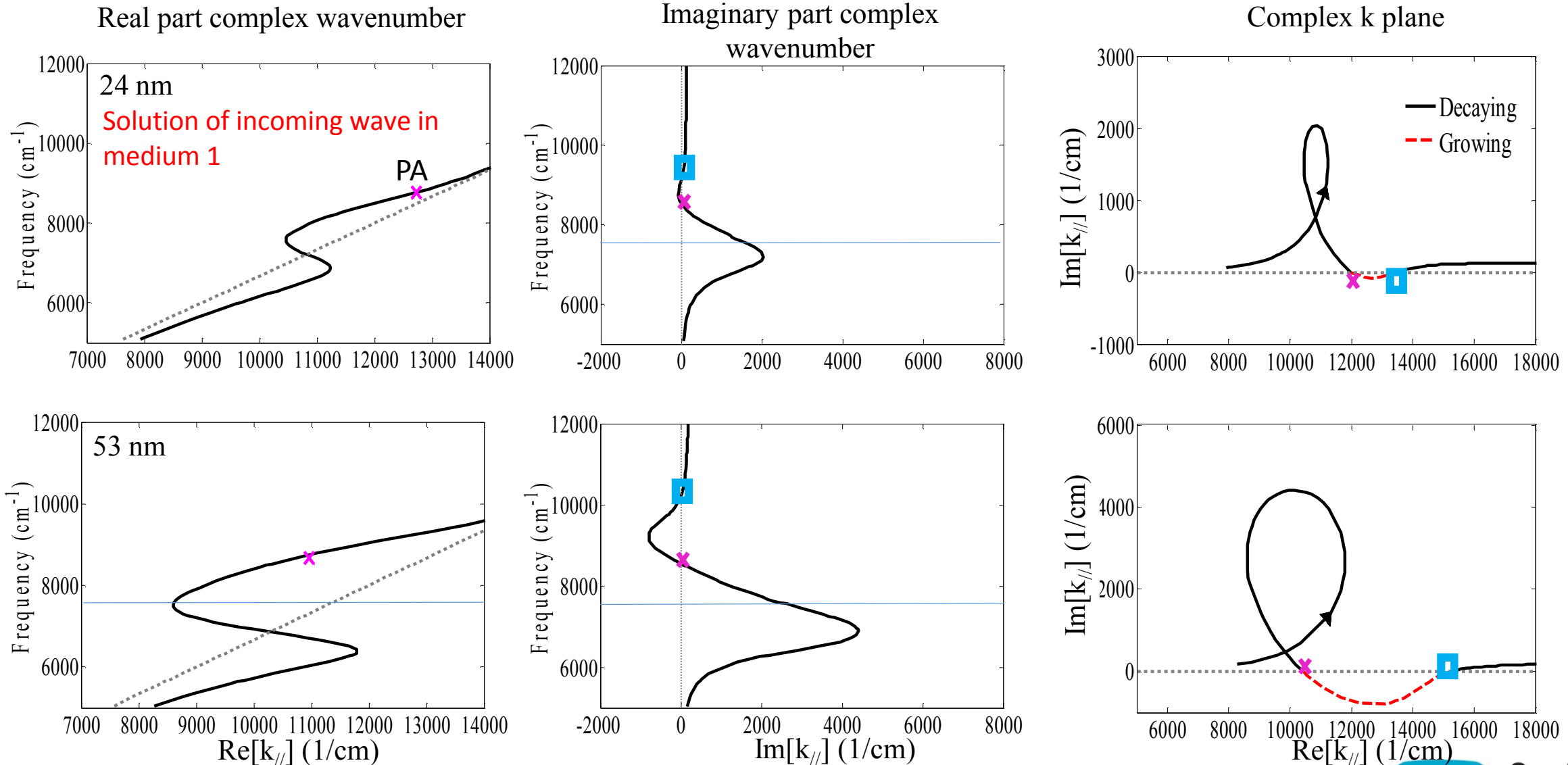
$$1 + r_{12}r_{23}e^{2i\phi} = 0 \quad k_x \text{ is real} \quad \omega = \omega_{real} + i\omega_{imag}$$

If the mirror is perfect $r_{23} = -1$

Pole condition is $r_{12} = e^{-2i\phi}$

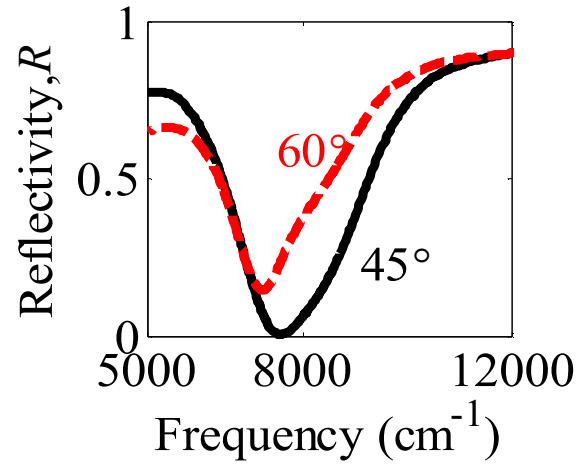


Finding the mode in complex wavevector approach

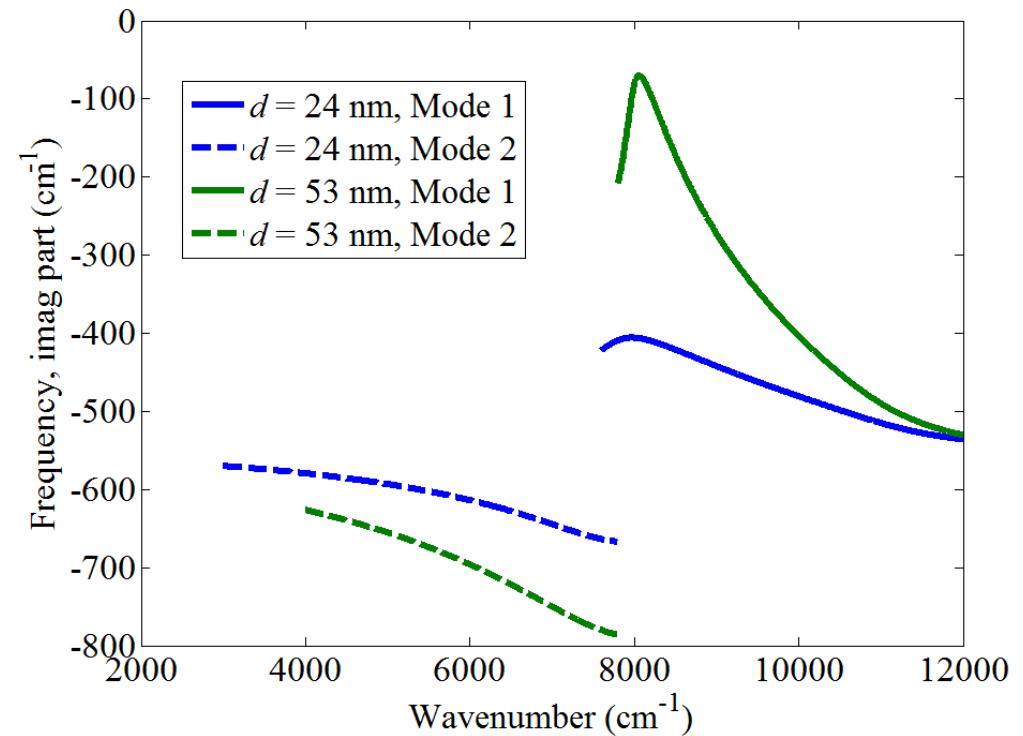
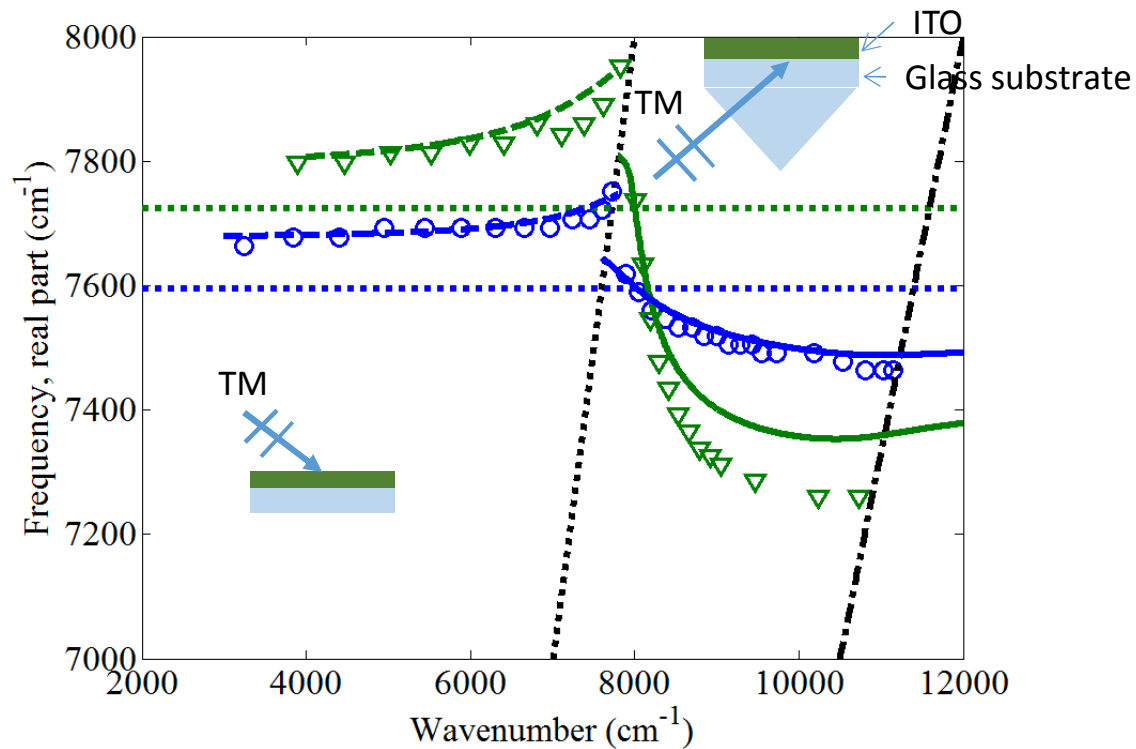


Perfect absorption occurs at the transition point when damping outgoing wave becomes growth wave, ie. Lossless plane wave

ENZ Perfect absorption without metal backplane



S. Campione et. al., "Experimental verification of epsilon-near-zero plasmon polariton modes in degenerately doped semiconductor nanolayers," Optics Express 24, 18782 (2016)



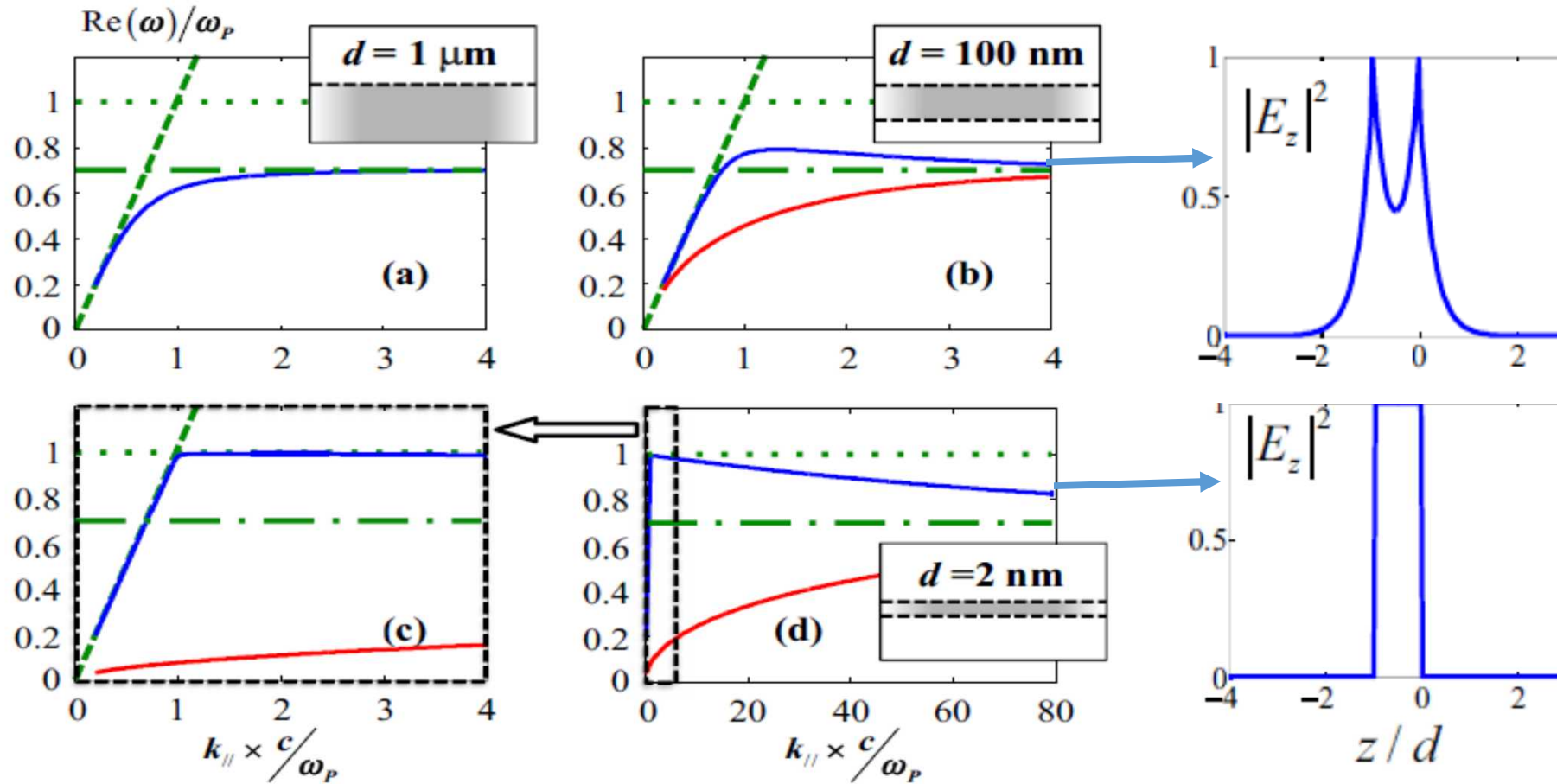
Conclusion

- Enhanced absorption is different from perfect absorption.
- Perfect absorption is an impedance matched phenomena for zero transmission system.
- Deeply subwavelength unpattern planar structure can exhibit perfect absorption phenomena also.
- This structure allows more in-depth understanding of the mode structure associated with perfect absorption.

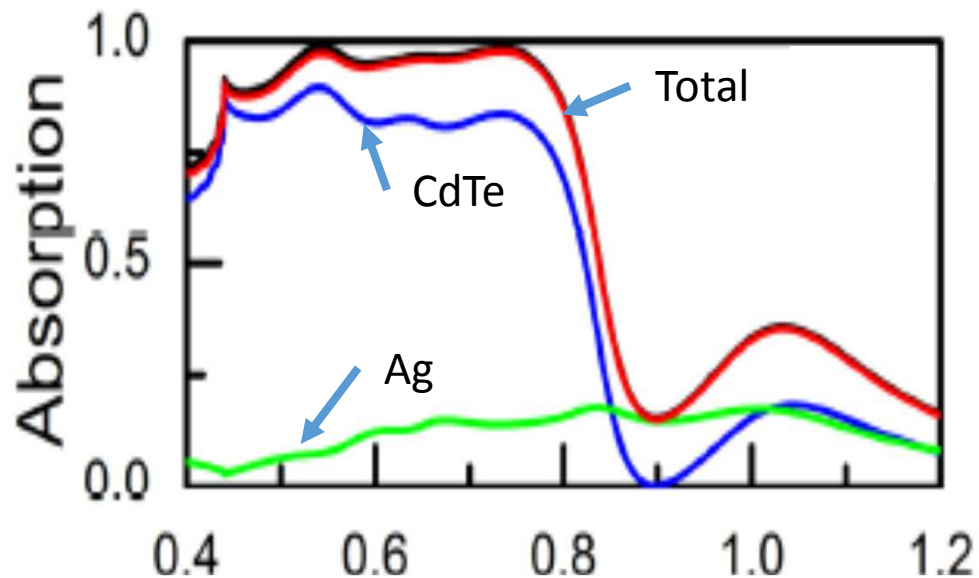
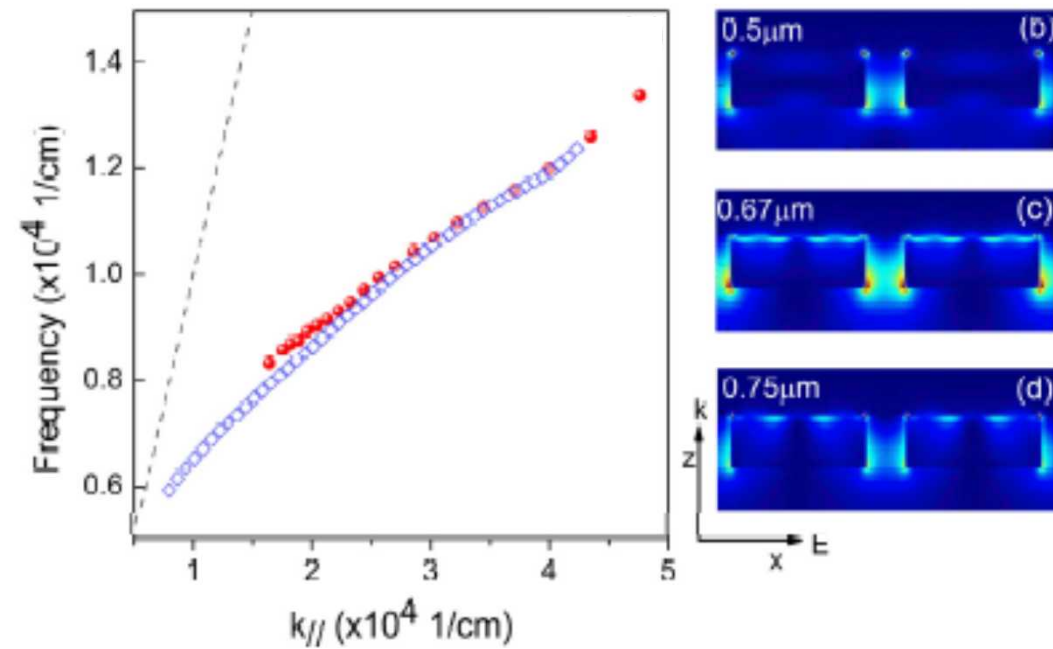
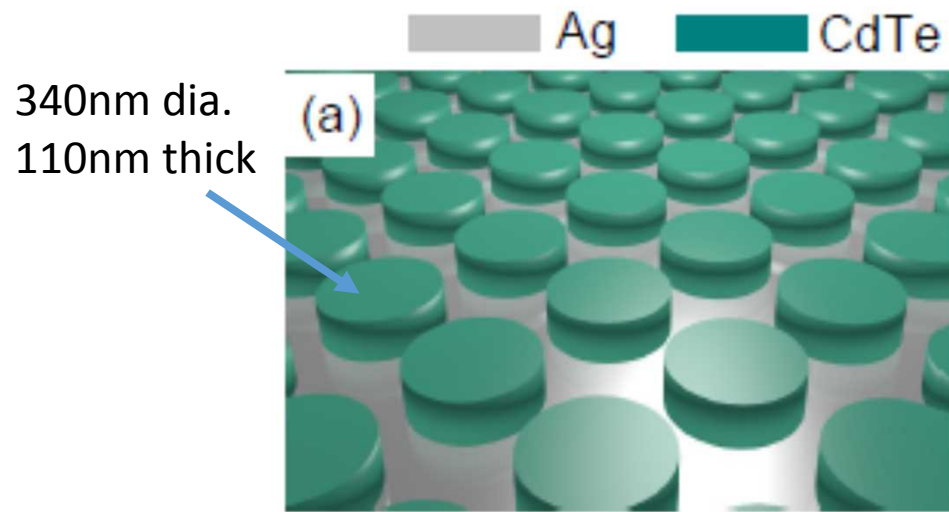
ENZ mode: a cousin of SPP mode

Evolution of SPP to ENZ dispersion

Mode field



Meta-surface for enhanced absorption



- Ultrathin PV cell enables efficiency carrier extraction
- Patterned CdTe structure enables coupling to standing SPP modes
- Lion's share of the absorption occurs in CdTe
- Short circuit current calculated from this structure is 29mA/cm²