SAND2017-9423C

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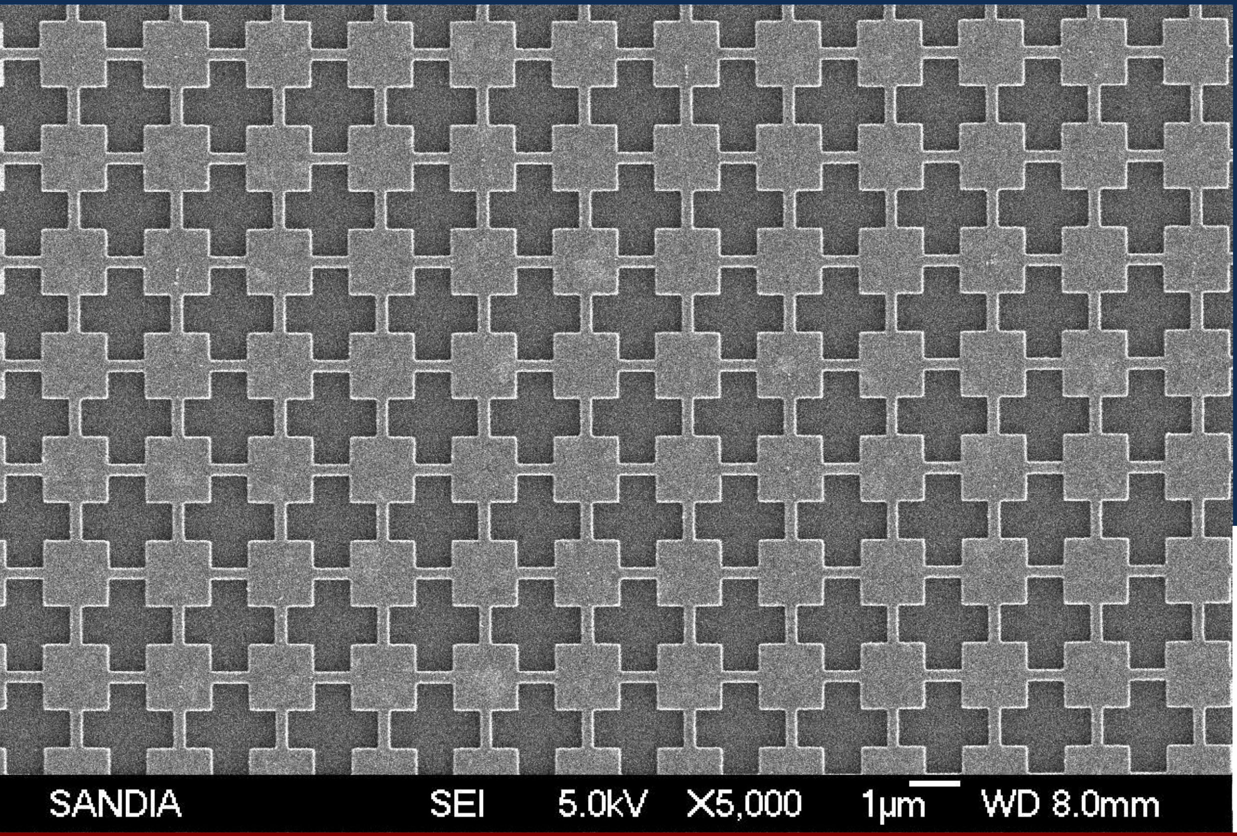
Nanoantenna-enhanced absorption in thin infrared detector layers

ICEAA 17
September 12, 2017



Michael B Sinclair
Larry K Warne
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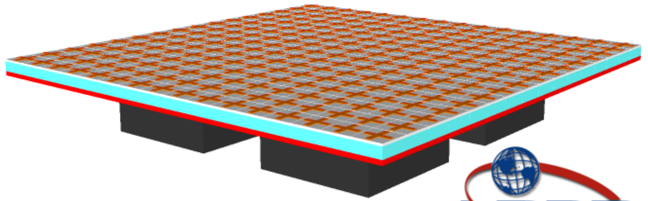

LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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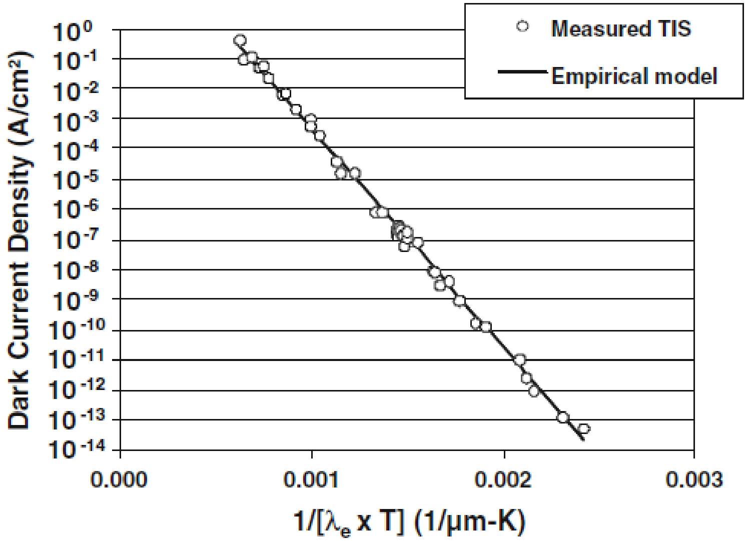
Motivation

- IR Detectors are essential for a wide variety of commercial and defense applications
- Current state-of-the-art is $Hg_xCd_{1-x}Te$ (MCT)
  - mature, highly developed technology
  - dark current reduced to fundamental limits
  - not much room for improvement
- Most applications would benefit from better SNR
  - larger stand-off range
  - detect lower temperature differences
  - faster frame acquisition times

"Rule 7"



Tennant, W., et al., *J. of Electronic Materials*, **37**, 2008.
Tennant, W., *J. of Electronic Materials*, **39**, 2010.

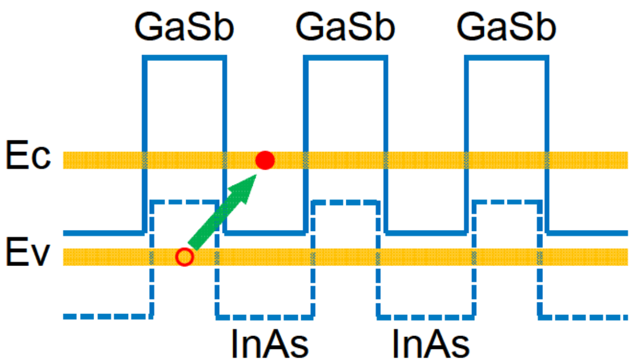
How can we make better IR detectors?

Strategies for better IR detectors

$$J_{diff} = q\frac{n_i}{n_0 \tau_{mc}} W$$

Optimize detector material

Decrease thickness



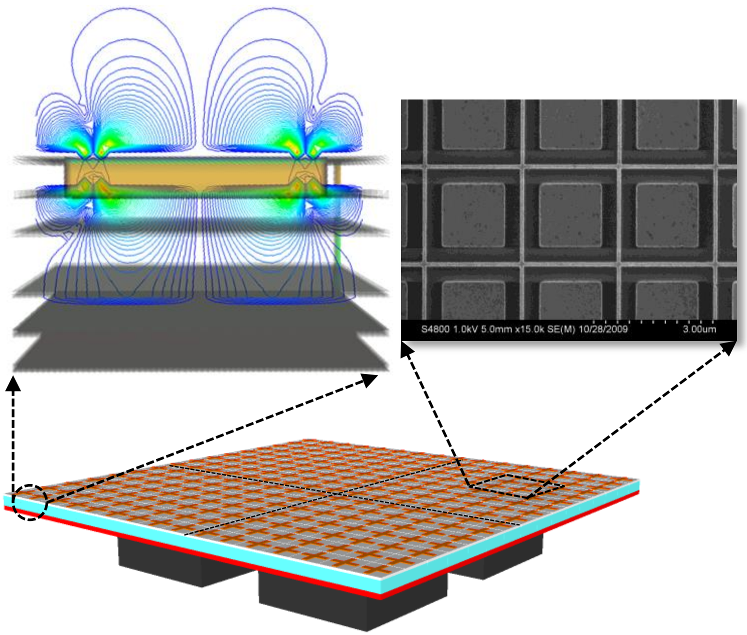
C. Asplund , et al., IR-Nova Rept. irn054479-2

Type II superlattice (T2SL) absorbers have many beneficial material properties

But….

1. T2SLs have weaker absorption than MCT
2. Thinning the detector would lead to incomplete photon absorption

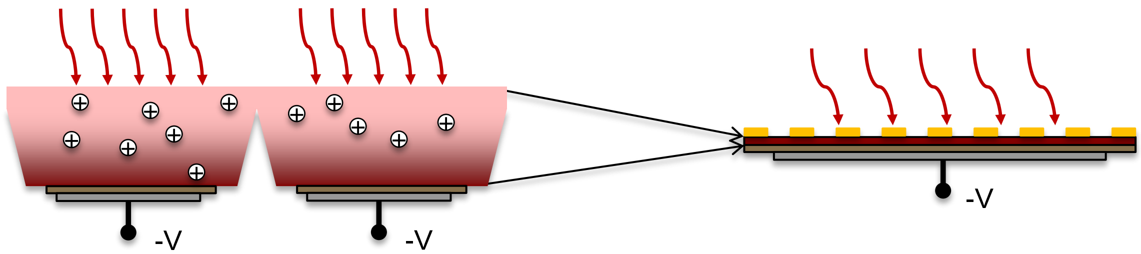
How can we increase the absorption of thin detector layers?



- Use a nanoantenna (metasurface) to couple incoming radiation to the thin detector
    - bound wave absorption
    - traveling wave absorption
- Try to minimize energy absorbed by metal layers.
- Nanoantenna (NA) design can be changed from pixel-to-pixel allowing adjacent pixels to have different spectral or polarization response.

Standard Reticulated Detector

Nanoantenna-Enabled Detector



Dark Current $J_{Diff} = \dfrac{e \cdot n_i^2 \cdot t_{abs}}{N_D \cdot \tau_p}$

Example: Nanoantenna enhanced T2SL

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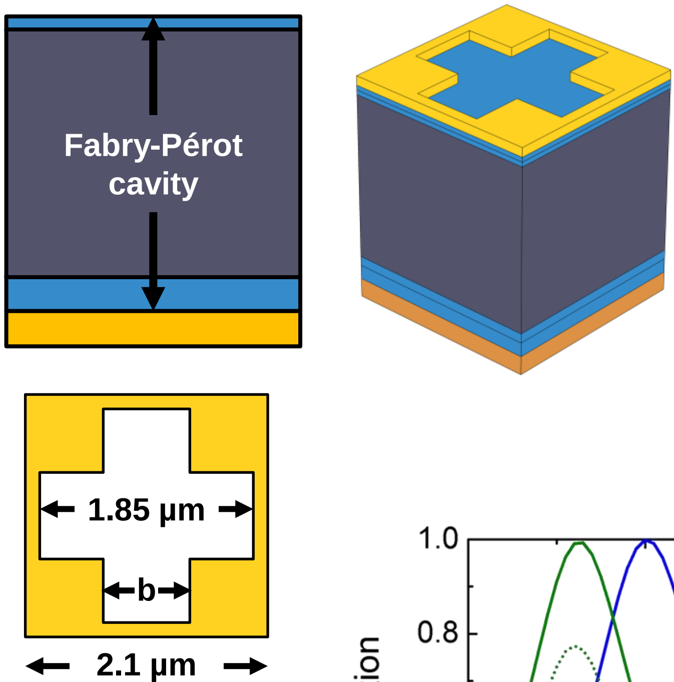
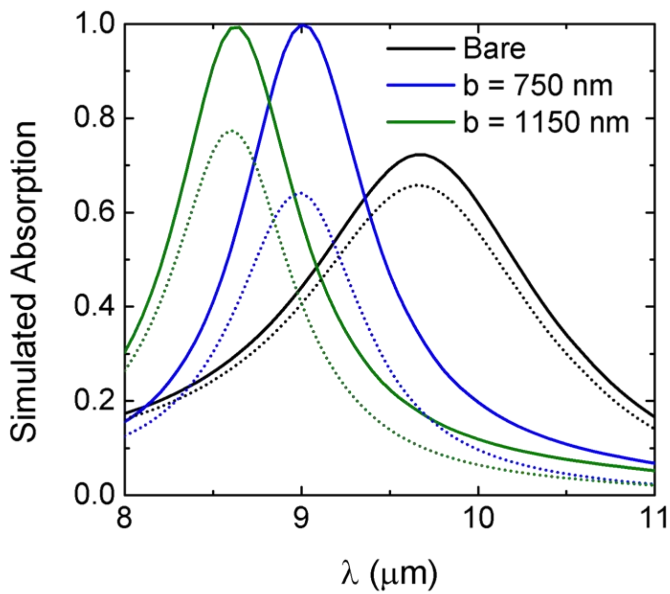
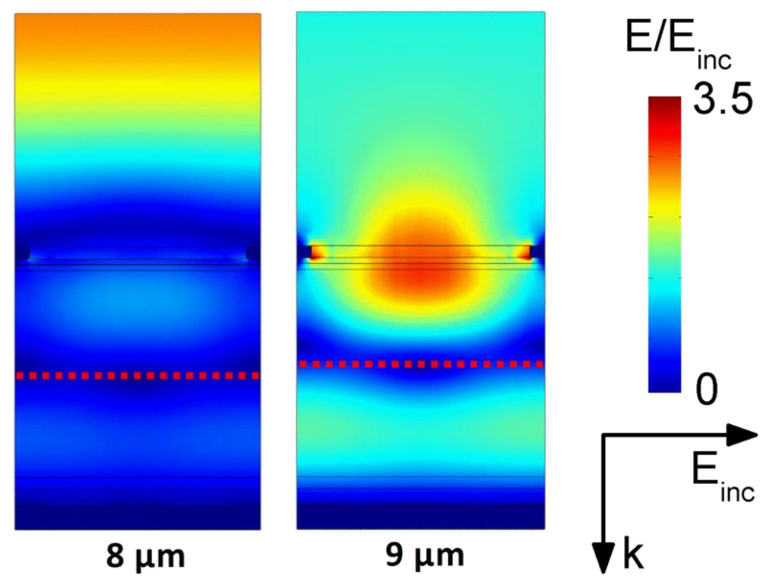
- 1.77 μm thick absorber
- ~5% single pass absorption
- Can achieve nearly 100% absorption (~70% in T2SL)
- Absorption band shifts with NA design
- Full-wave EM modeling is computationally intensive.
- “Trial and error” design







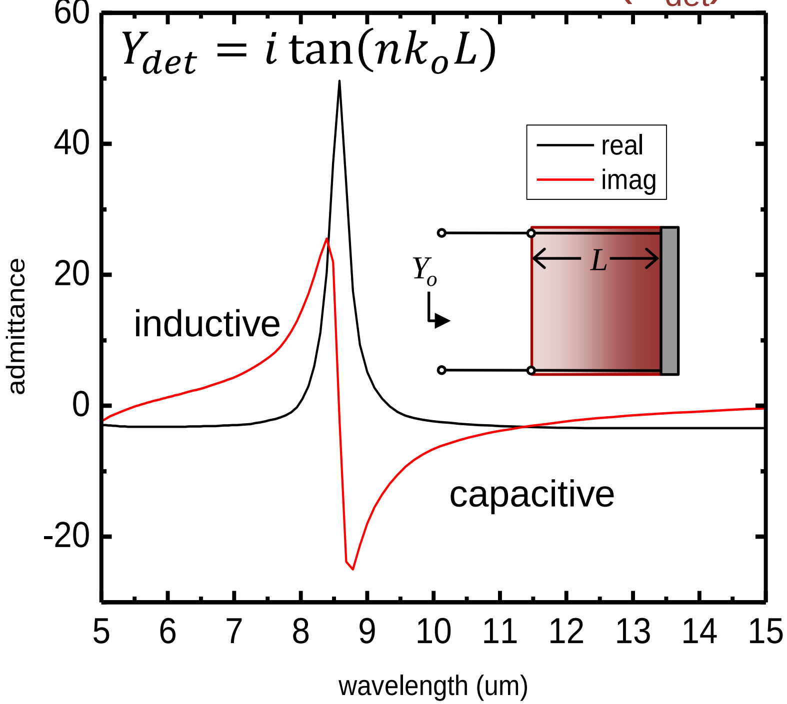
M. D. Goldflam, *et al.*, *Appl. Phys. Lett.*, vol. 109, 251103, Dec. 2016.

Systematic Approach to NA Design: The Admittance Method

impedance Z
admittance Y=1/Z

1. Treat T2SL/NA system as transmission line
2. Compute NA admittance using FDTD simulation (hybrid version)
3. Add NA admittance in parallel to T2SL admittance
4. Make total admittance match admittance of free space

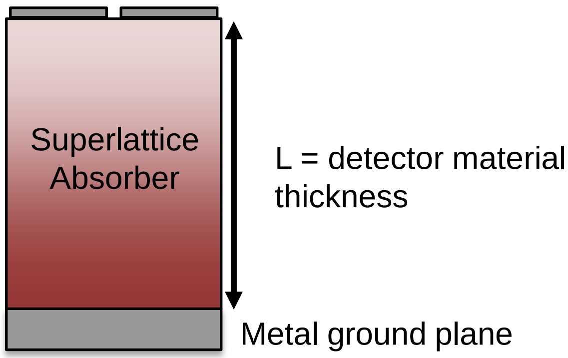
Admittance of detector (Y_{det})

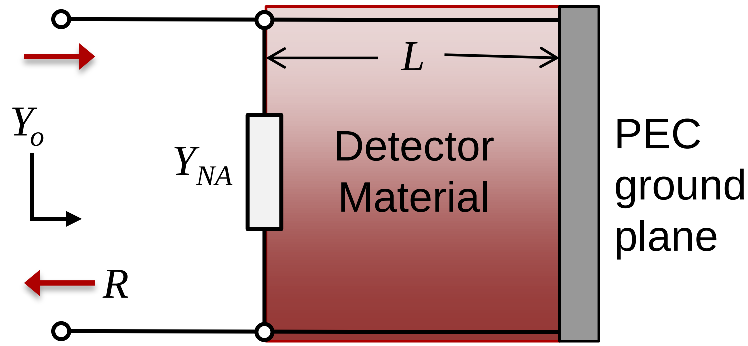


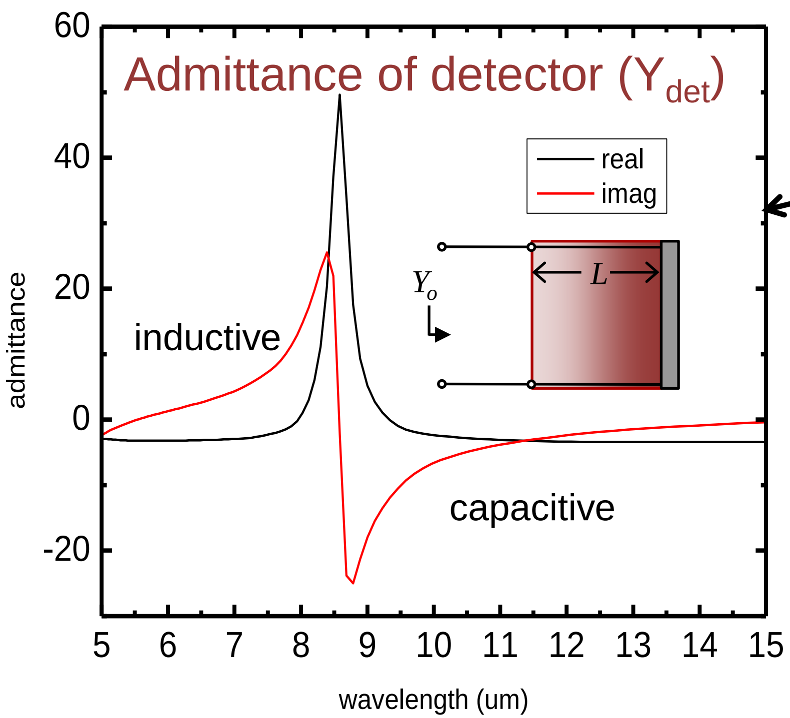
PEC Model

- Detector is backed by PEC ground plane.
- Uses the complex permittivity of the dispersive T2SL absorber
- Vanishingly thin PEC nanoantenna

Ideal Admittance of Detector Layer







$$Y_{tot} = Y_{NA} + Y_{det}$$

$$Y_{det} = i\tan(nk_oL)$$

$$\text{if} \quad Y_{NA} = -i\tan(nk_oL) + \frac{1}{\eta_o}$$

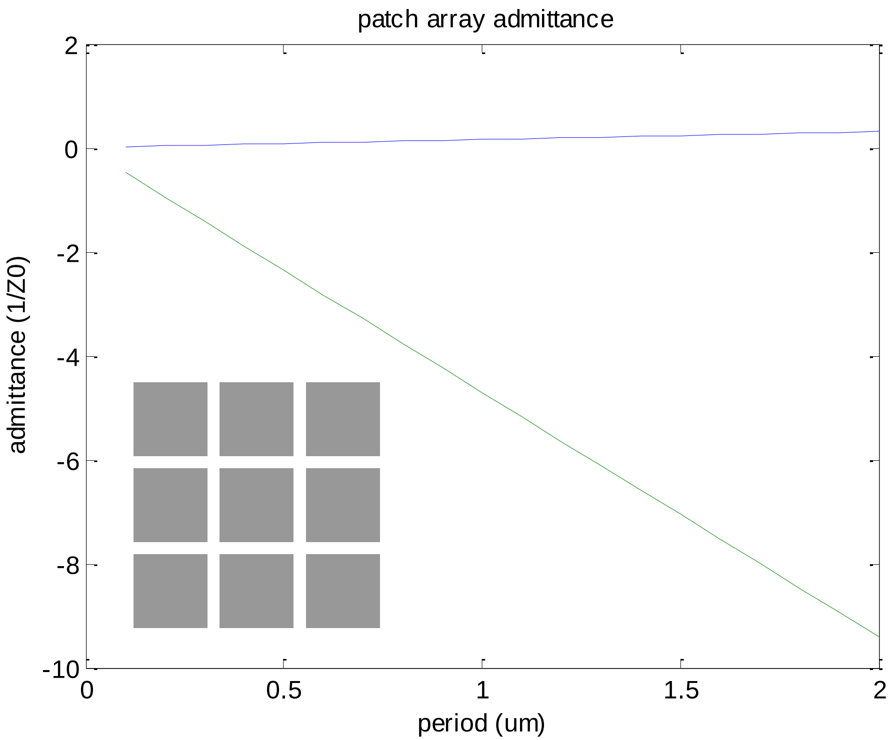
$$\text{then} \quad Y_{tot} = \frac{1}{\eta_o}$$

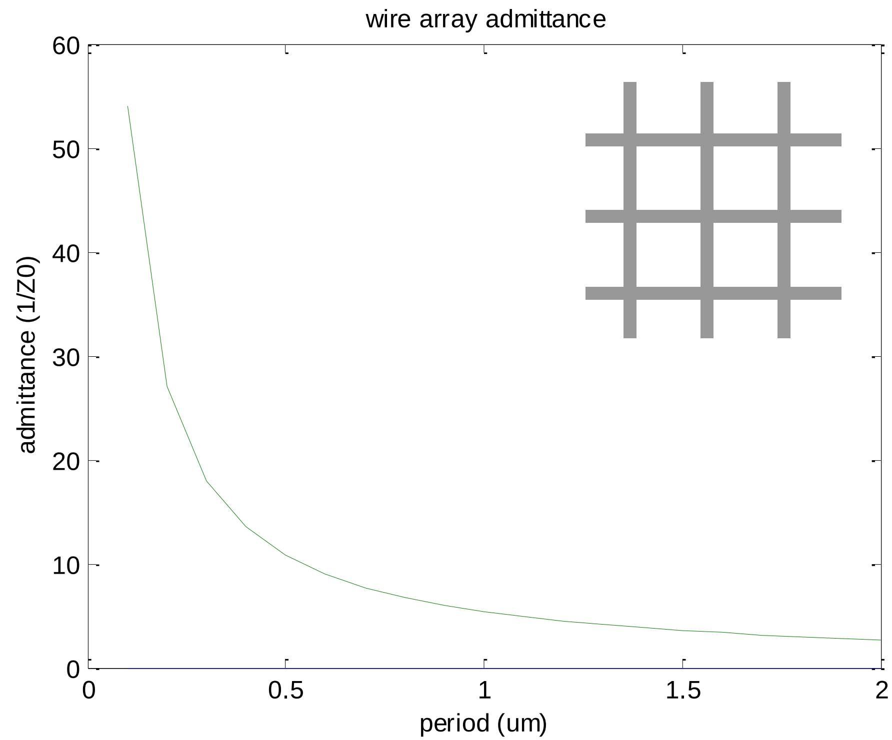
- Matched to free space: 100 % absorption

S. Tretyakov, IEEE Electromagnetic Compatibility, 5, 61, 2016
Y. Radi, et al., PRA, 3, 037001, 2015
F. Costa, IEEE Electromagnetic Compatibility, 5, 67, 2016

Analytic Nanoantenna Admittances

λ=10 μm
substrate=T2SL





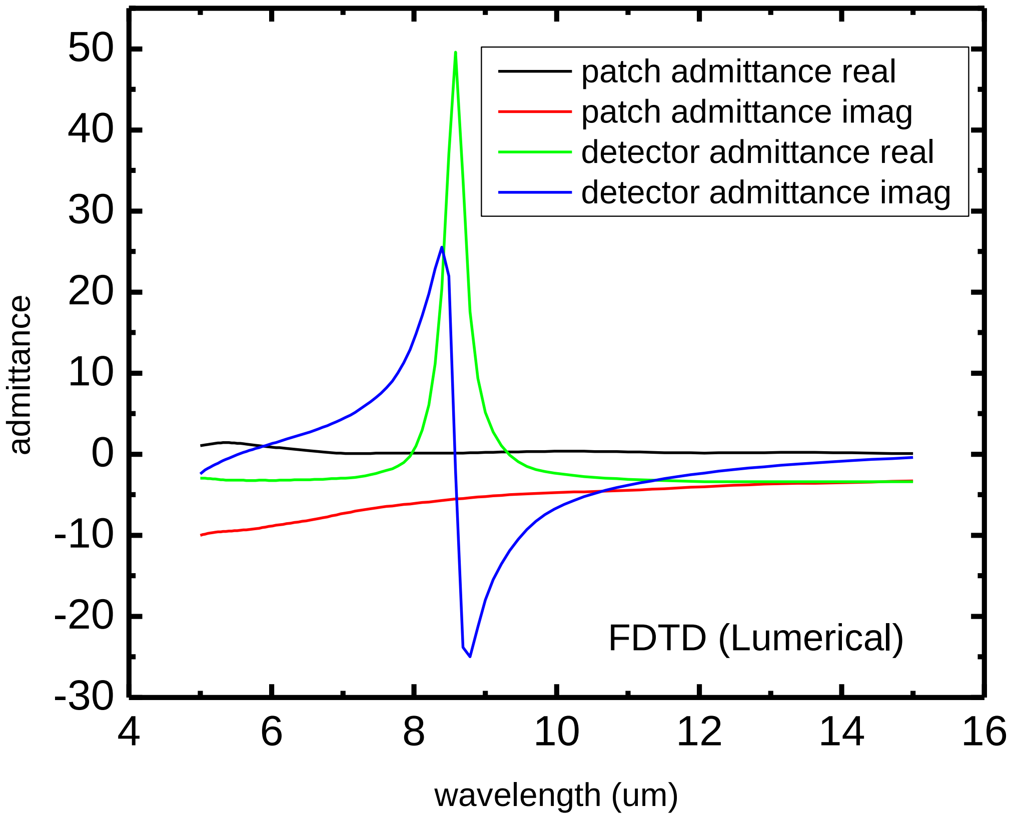
- PEC model: ultrathin PEC patches & wires
- Patch array is capacitive, wire grid is inductive.
- We can use these to cancel the imaginary component of the detector layer.

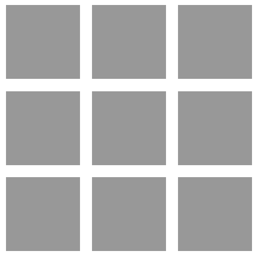
S. Tretyakov, “Analytical Modeling in Applied Electromagnetics”, London, UK: Artech House (2003).

Example: Patch Array

Admittance of detector and patch array

- 1 µm period
- 90% duty cycle

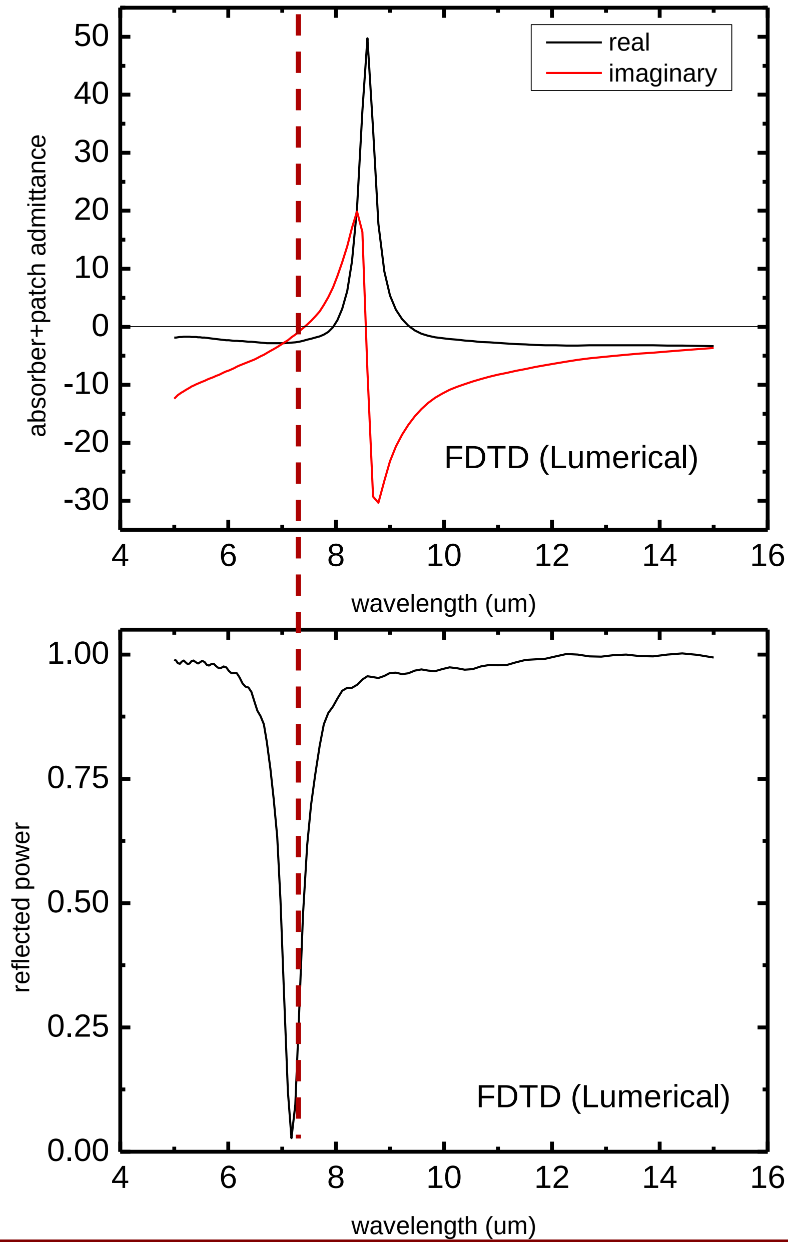


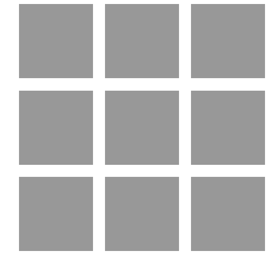


Example: Patch Array

sum of admittances

reflected power





Close agreement between zero crossing of total admittance and reflection minimum.

Hybrid Admittance Model Summary

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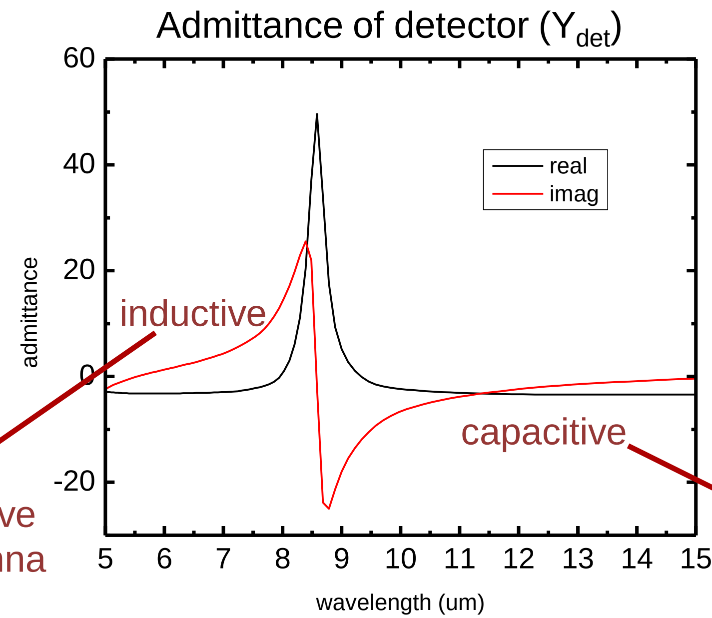
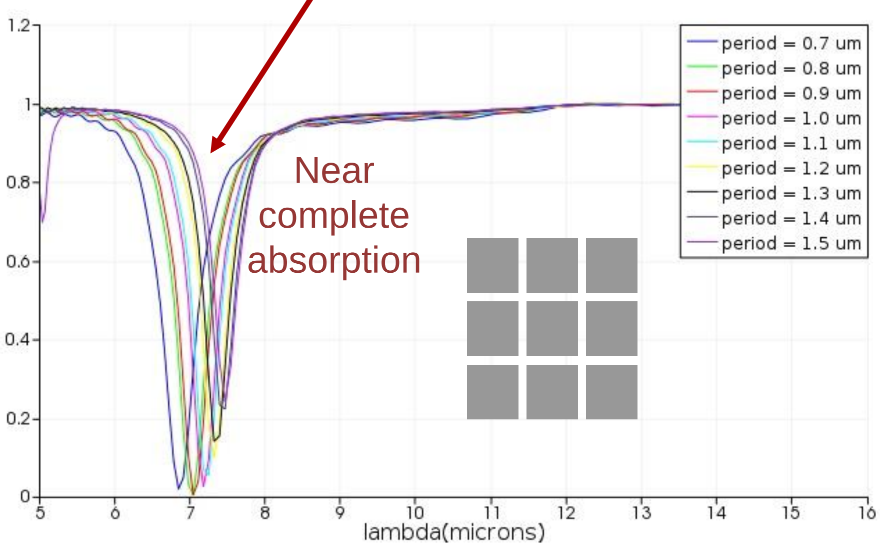
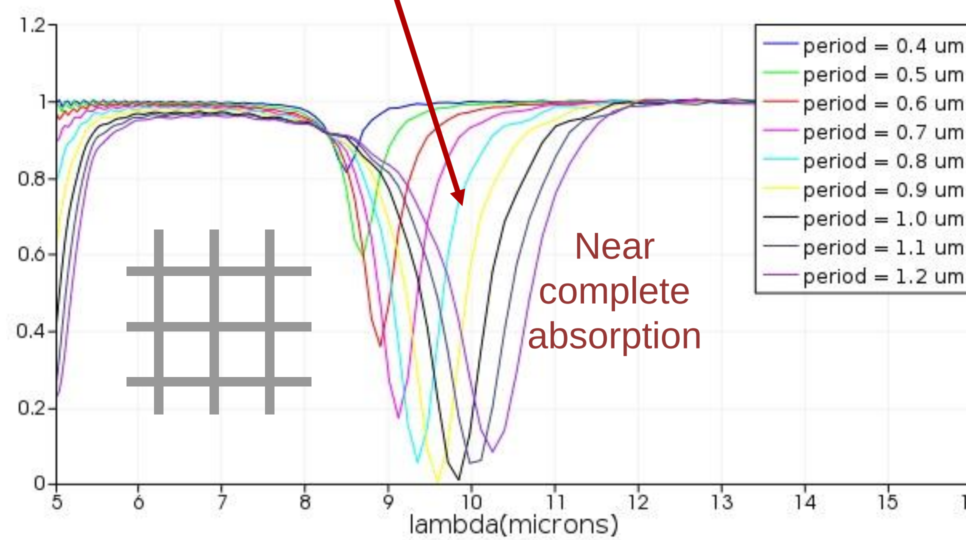


We can use NA arrays on either the inductive or capacitive side of the bare detector to make a near perfectly absorbing detector.

+ capacitive nanoantenna



+ inductive nanoantenna



Fully-analytic admittance method

Want to optimize these structures using an accurate analytic model

Requires development of advanced circuit model for NA array

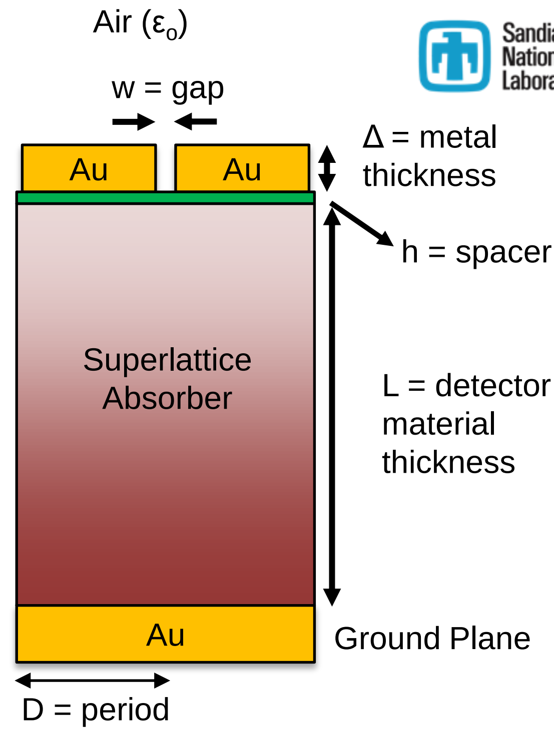
- very complicated expressions (but still analytic & fast to compute).

Benefits:

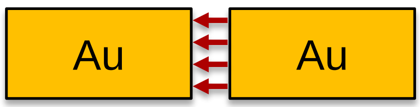
- provides design intuition - can guide numerical studies.
- can rapidly & accurately survey multidimensional parameter space.
  - array period & duty cycle
  - metal thicknesses
  - metal types

Advanced Circuit Model

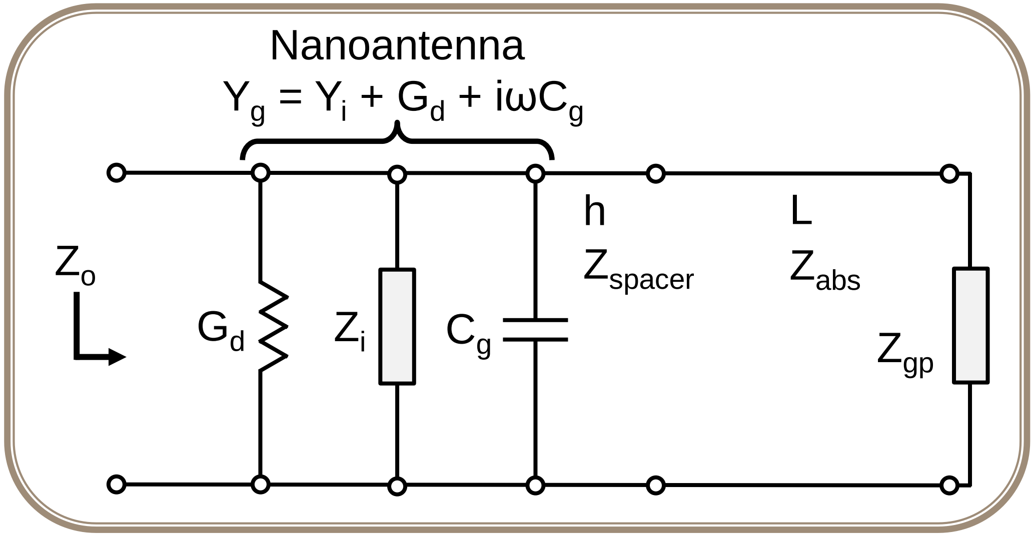
- ➢ Fast and accurate circuit model to let us design and optimize quickly
- ➢ Based on the thin PEC analytic model*
- ➢ Increased complexity to accurately model "real world" devices, accounts for:



- Finite metal conductivity in nanoantenna and ground plane.
- Finite metal patch thickness including field between metal elements



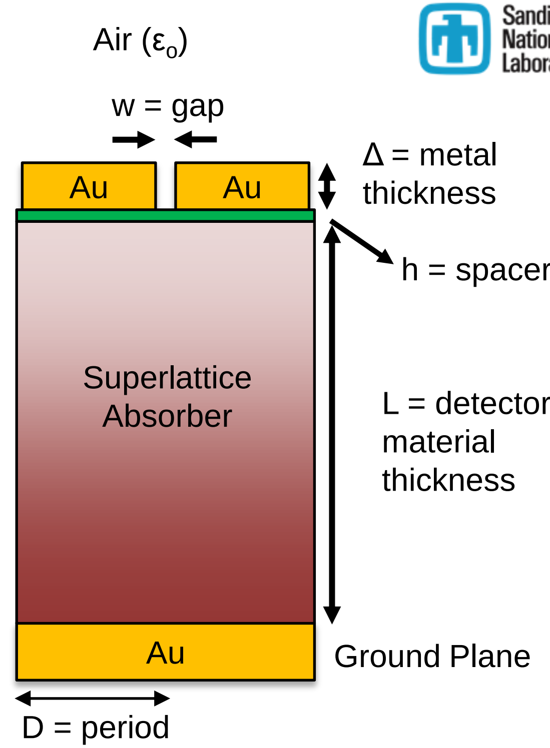
- Unequal permittivities above and below patch layer.
- account for effects of dielectric spacer layer (G_d term)

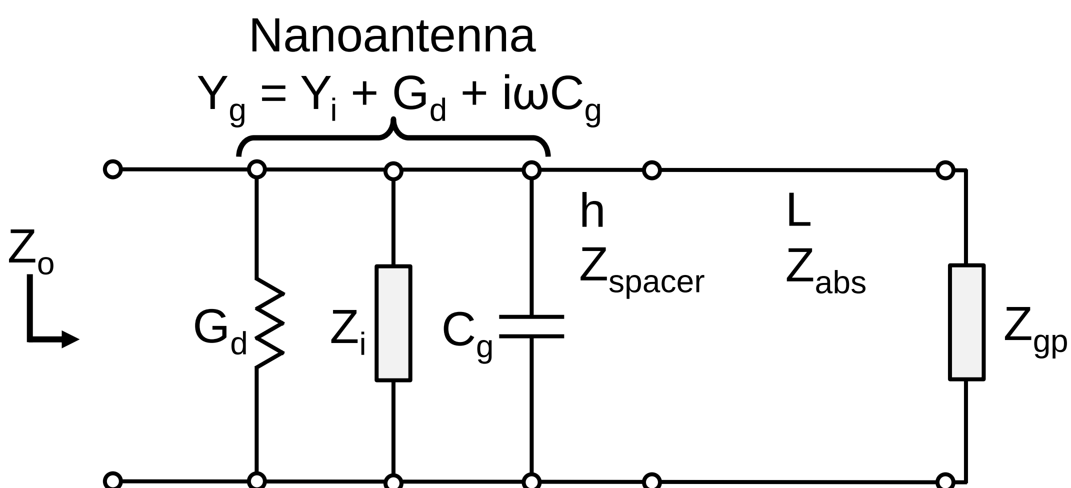


* S. Tretyakov, "Analytical Modeling in Applied Electromagnetics", London, UK: Artech House (2003).

Advanced Circuit Model

- Non-trivial to accurately account for the non-idealities described on previous slide.
- Paper in preparation to describe in detail.





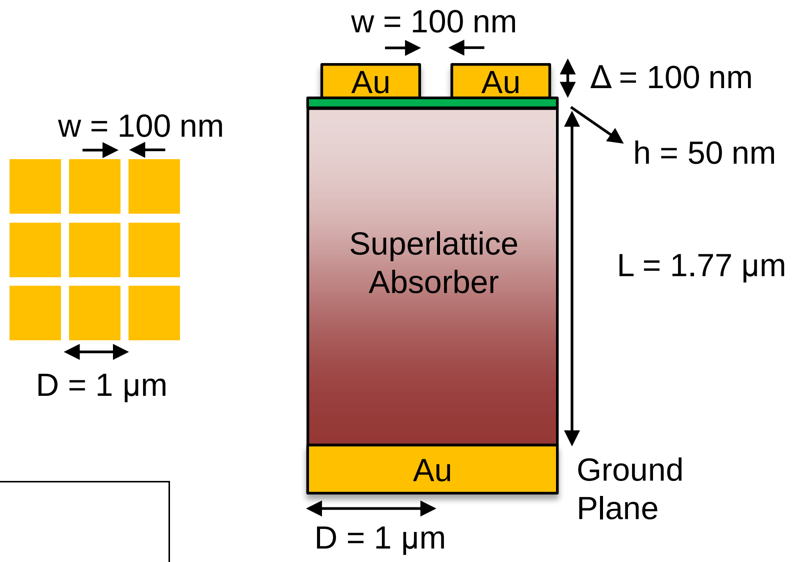
$$Y_g = Y_i + G_d - i\omega C_g \ , \ G_d - i\omega C_g = -i\omega(\varepsilon_0+\varepsilon)\frac{1}{\pi}D\ln\left(\frac{D}{2\pi a_e}\right) \sim -i\omega(\varepsilon_0+\varepsilon)\frac{1}{\pi}D\ln\left(\frac{2D}{\pi w}\right), \Delta/w<<1$$

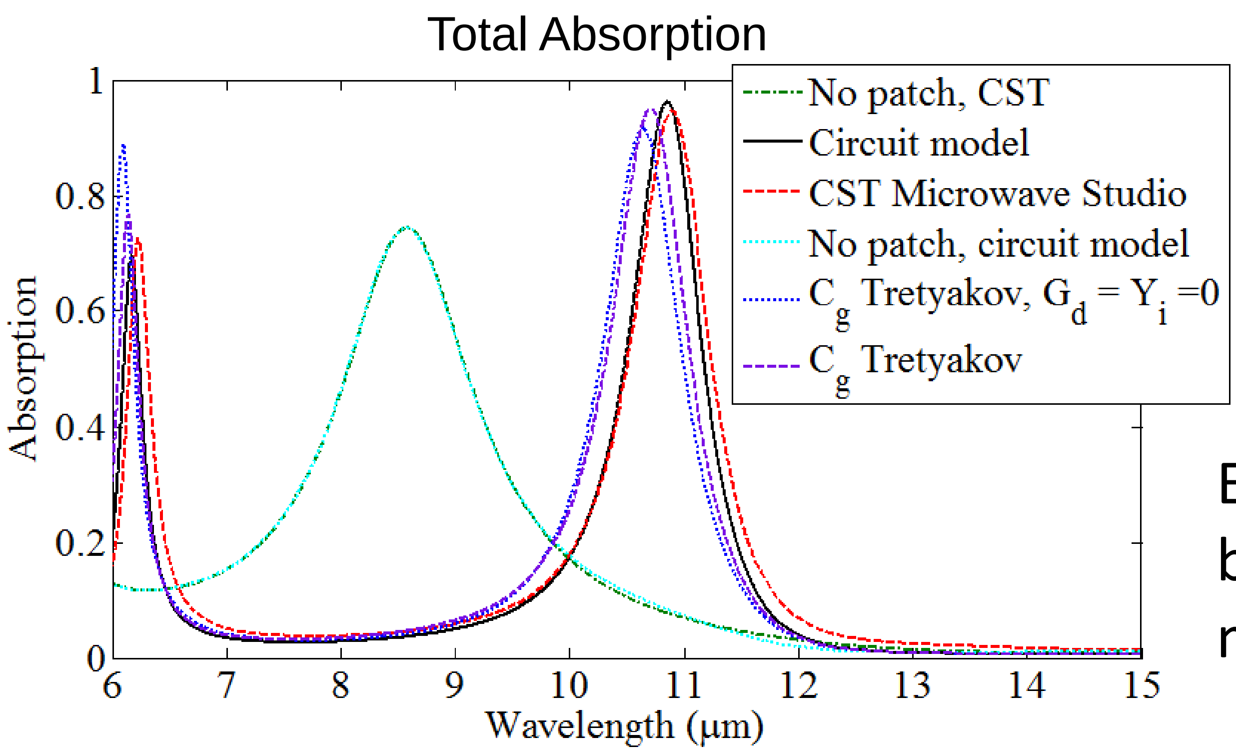
$$(\varepsilon+\varepsilon_0)\ln(a_e) = (\varepsilon+\varepsilon_0)\ln(a_e^0) - \varepsilon_0\pi\Delta/w$$

$$[(\varepsilon/\varepsilon_0+1)/2]\ln(a_e^0/a^0)/\ln(a_e^{0\varepsilon}/a^0) \approx 1+0.67\frac{\varepsilon/\varepsilon_0-1}{\varepsilon/\varepsilon_0+1.5}\frac{\Delta/w}{\Delta/w+0.035}$$

Comparison of Circuit Model to Electromagnetic Codes

Comparison of circuit model with PEC model and CST Microwave Studio

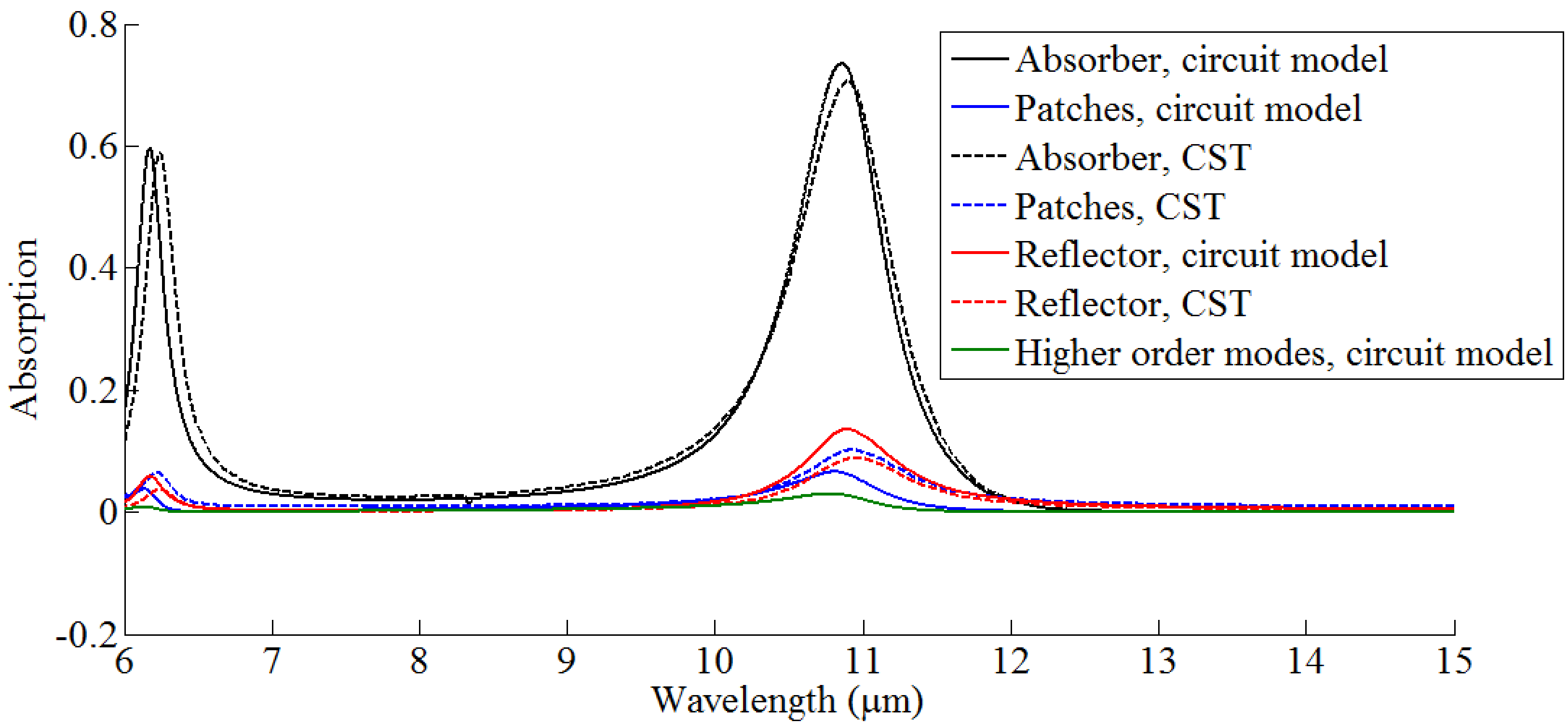




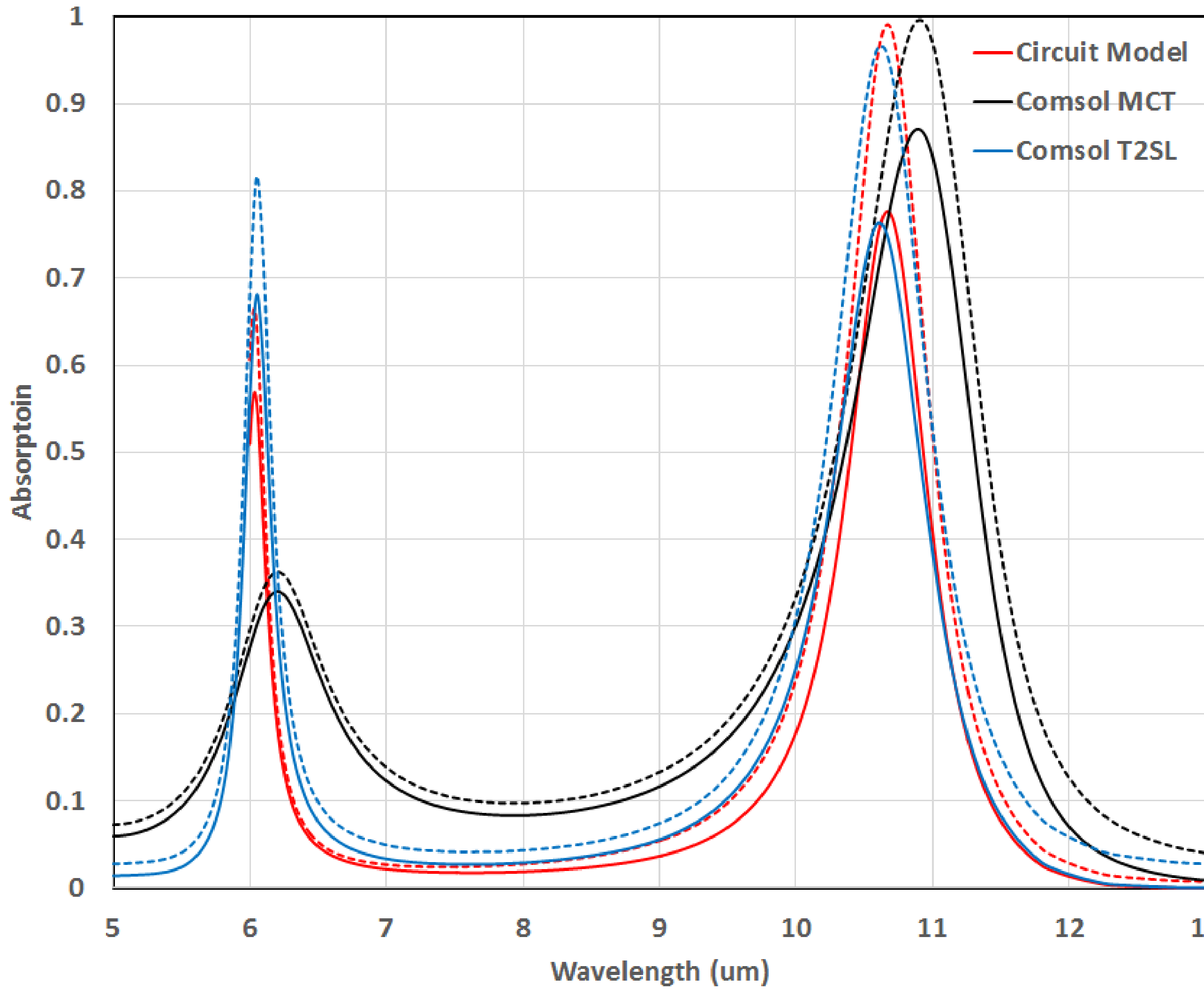
Excellent agreement between the circuit model and CST.

Comparison of Absorption in T2SL Layer

- Want to maximize absorption in the T2SL layer L = 1.77 μm

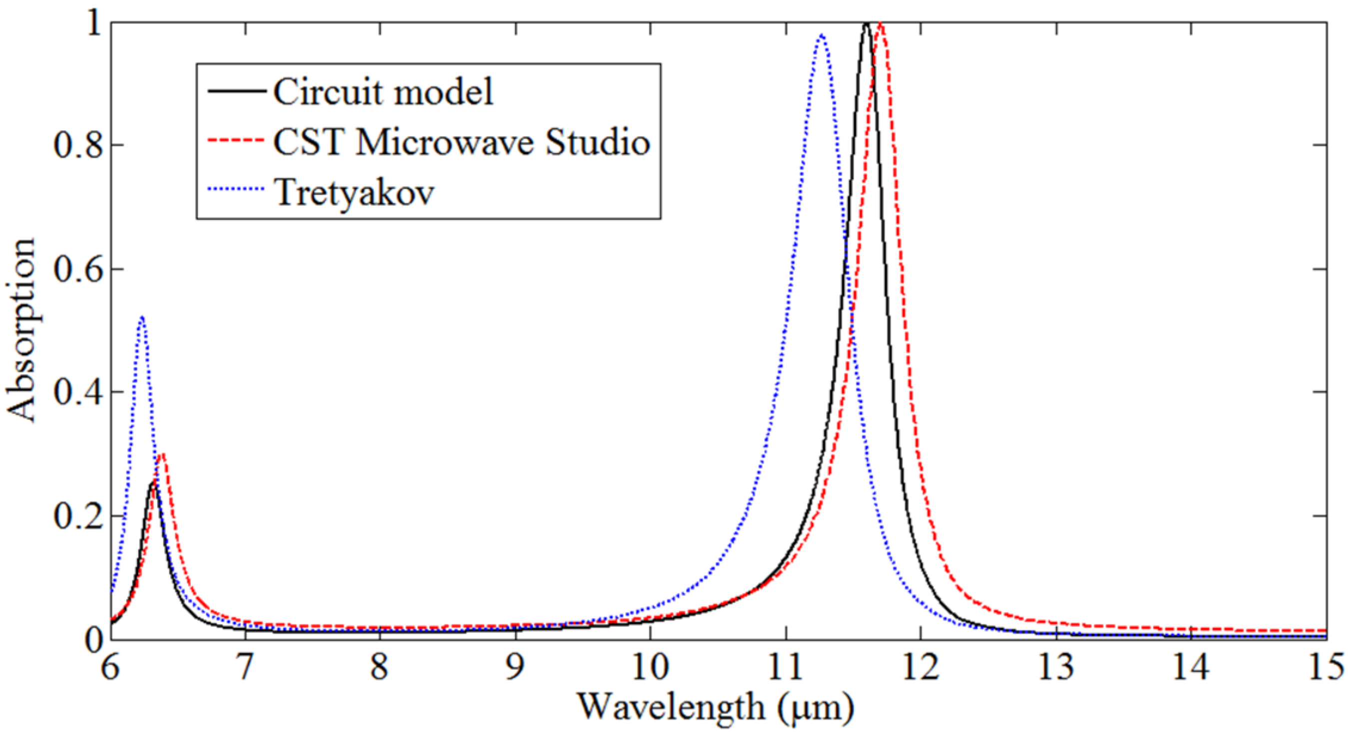


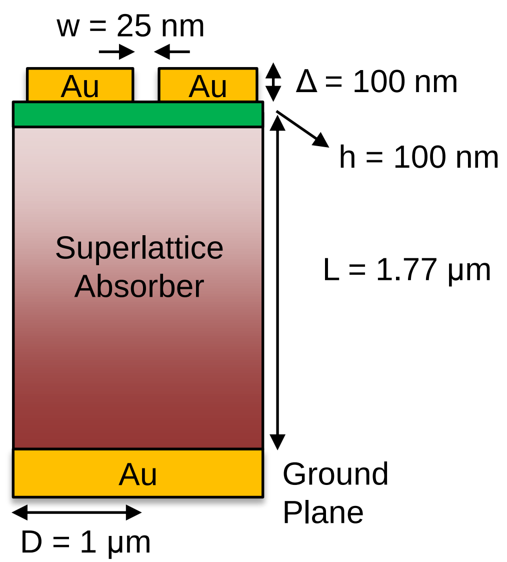
Use Circuit Model to Optimize T2SL Absorption



L = 1.77 μm

Circuit model test: smaller gap and more dielectric



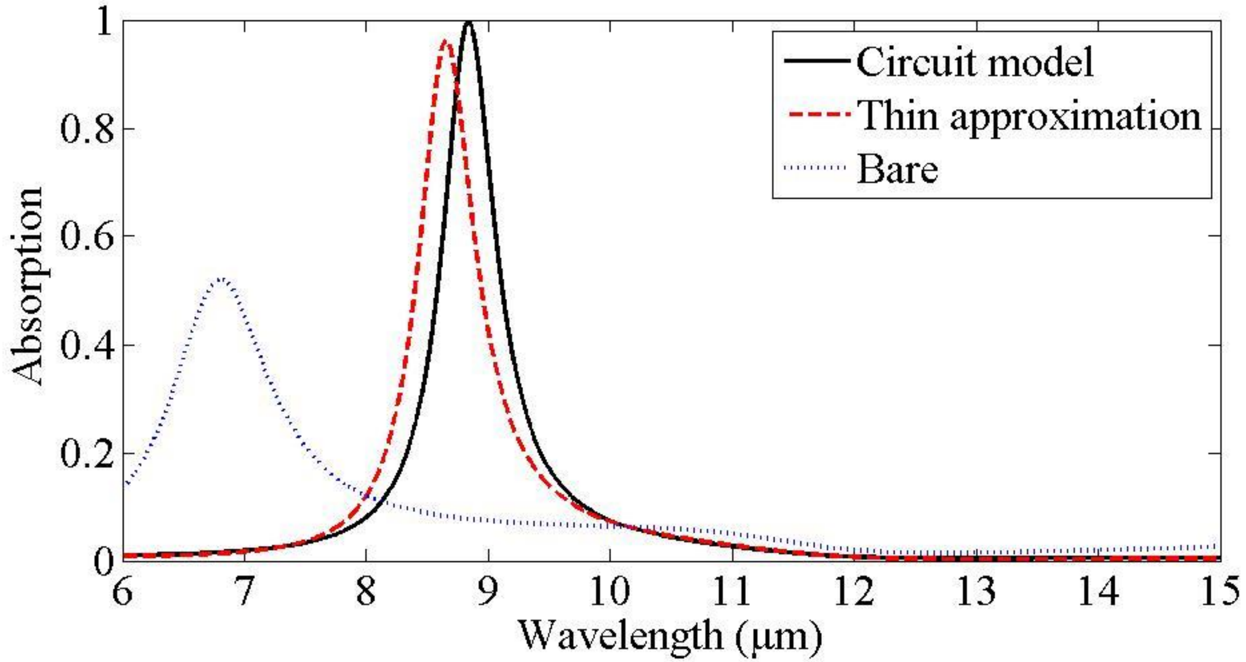


Much better accuracy that PEC model.

Moving to even thinner T2SL layers

Thickness = 0.9 μm

Use circuit model to optimize absorption



Still able to achieve nearly 100% absorption
Single pass absorption of 0.9 um T2SL < 10 % !!

Summary

- Nanoantennas offer a promising route to improve IR detector performance --- beat the “Rule 7”
- Nanoantenna enhanced detectors offer other advantages:
  - can tune the spectral band of maximum absorption on a per-pixel basis
  - can tune polarization dependence
- Hybrid admittance model developed to allow systematic design of nanoantenna arrays
  - Admittance model can also be viewed from the perspective of a Fabry-Perot cavity
- Advanced circuit model developed for “real world” devices
  - fast, accurate
  - provided design intuition
  - allows rapid optimization over key design parameters

Back up slides

Patch Surface Impedance Elements

- Capacitance

$$Y_g = Y_i + G_d - i\omega C_g \;,\; G_d - i\omega C_g = -i\omega(\varepsilon_0+\varepsilon)\frac{1}{\pi} D \ln\left(\frac{D}{2\pi a_e}\right) \sim -i\omega(\varepsilon_0+\varepsilon)\frac{1}{\pi} D \ln\left(\frac{2D}{\pi w}\right), \Delta/w << 1$$

$\varepsilon \to \varepsilon' + i\varepsilon''$ analytic continuation includes dielectric loss (without spacer layer)

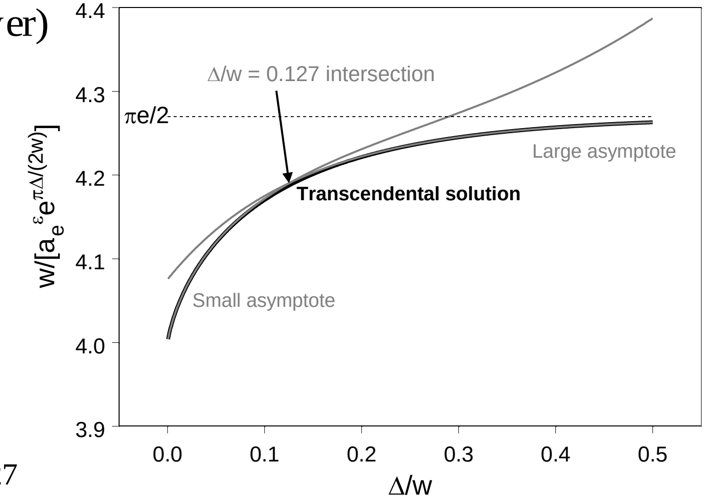
$$a^0 = w/4 \qquad (\varepsilon+\varepsilon_0)\ln(a_e) = (\varepsilon+\varepsilon_0)\ln(a_e^0) - \varepsilon_0 \pi\Delta/w$$

- Equivalent radius for equal permittivities

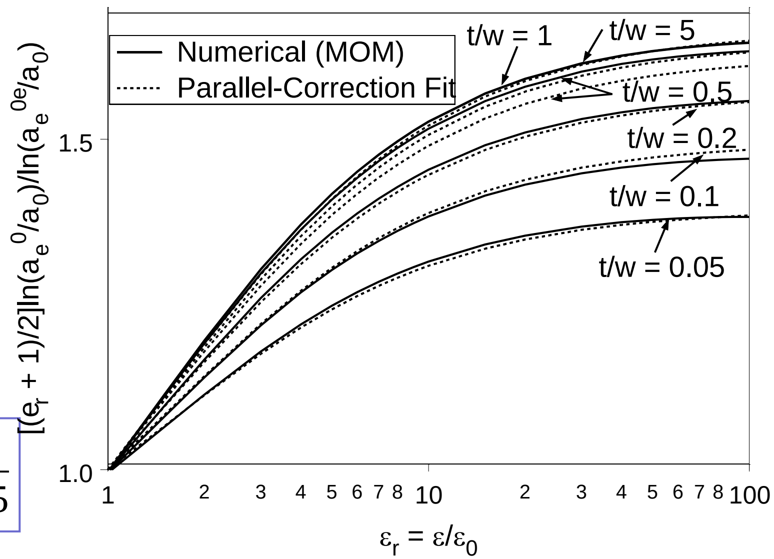
$$a_e^{\varepsilon} = a_e^{0\varepsilon} e^{-\pi\Delta/(2w)} \leftrightarrow 2\ln(a_e^{\varepsilon}) = 2\ln(a_e^{0\varepsilon}) - \pi\Delta/w$$

$$a_e^{0\varepsilon} \approx \frac{w}{4}\left[1 + \{2\ln(\zeta/2) - 1\}\zeta^2 - \{2\ln(\zeta/2) - 1/4\}\zeta^4 + O(\zeta^6)\right] \;,\; \zeta = \sqrt{\Delta/(\pi w)} \;,\; \Delta/w \le 0.127$$

$$a_e^{0\varepsilon} \approx \frac{w}{\pi e/2}\left[1 + \xi^2/8 + \xi^4 33/256 + O(\xi^6)\right] \;,\; \xi = 4/e^{2+\pi\Delta/w}, \Delta/w \ge 0.127$$



- Equivalent radius for unequal permittivities (integral equation solution)



$$\left[(\varepsilon/\varepsilon_0 + 1)/2\right]\ln(a_e^0/a^0)/\ln(a_e^{0\varepsilon}/a^0) \approx 1 + 0.67\frac{\varepsilon/\varepsilon_0 - 1}{\varepsilon/\varepsilon_0 + 1.5}\frac{\Delta/w}{\Delta/w + 0.035}$$

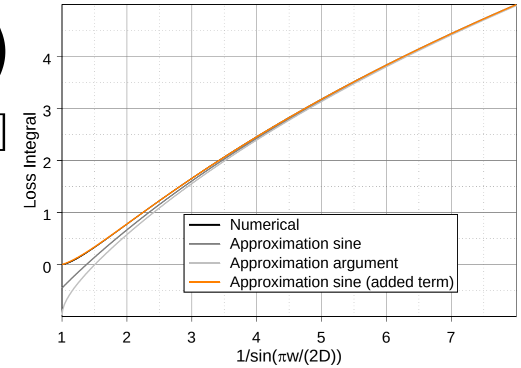
Patch Surface Impedance Elements (Cont.)

- Metallic losses small (K_x current from continuity)

$$P = Y_i|2V|^2 = \int_S Z_s |K_x|^2 dS = 2D\int_{w/2}^{D/2} Z_s |K_x|^2 dx \qquad K_x(x) = i\omega\int_{w/2}^{x}\sigma_s dx = i\omega q(x) = i\omega\left[A_{ez}(x,0) - A_{ez}(w/2,0)\right]$$

$$Y_i \sim Z_s\omega^2\left(\varepsilon_0{}^2 + \varepsilon'^2\right)(D/\pi)^2\left[\begin{array}{l}\pi^2/12 + \ln^2(\sin(\pi w/(2D))) - \frac{4}{\pi}\sin(\pi w/(2D)) \\ -\left(\pi^2/12 - 4/\pi\right)\sin^2(\pi w/(2D))\end{array}\right]$$

$$\phi = \pm V \text{ on patches}$$

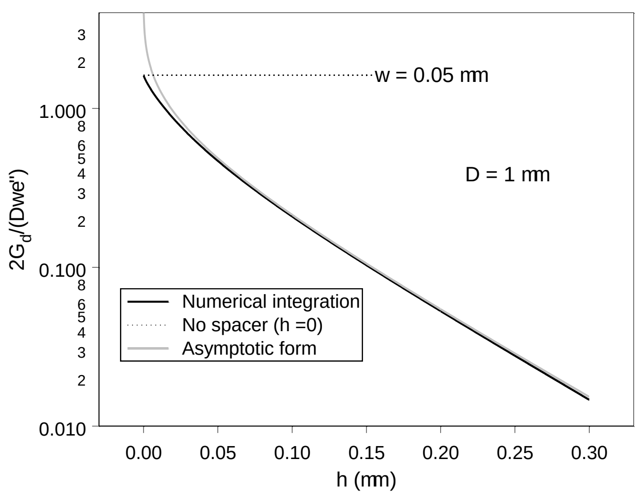


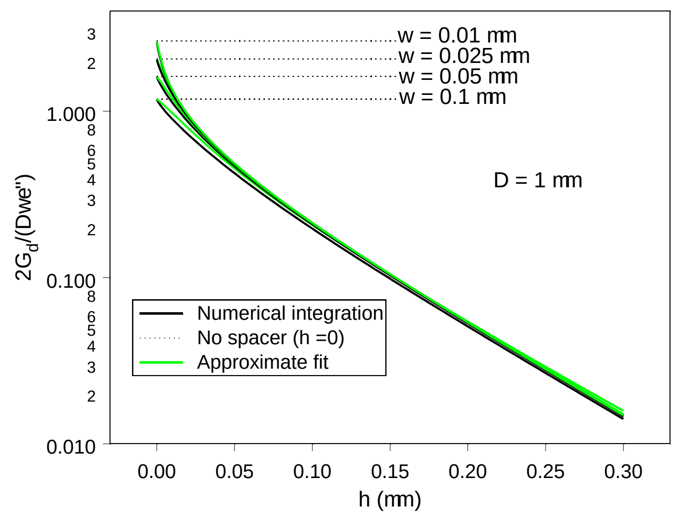
- Detector absorption due to higher-order modes with spacer layer h

$$P_d = \int_{V_h^{y_0}} \sigma E^2 dV = D\oint_{S_h^{y_0}} \omega\varepsilon''\phi\frac{\partial\phi}{\partial n}dS \qquad \varepsilon = \varepsilon' + i\varepsilon''$$

$$\Delta P_d = \lim_{y_0\to\infty}\left[P_d - P_d^U\right] = G_d|2V|^2$$

$$2G_d/(D\omega\varepsilon'') \sim 4h/D - \frac{2}{\pi}\ln\left\{\cosh(\pi h/D) + \sqrt{\cosh^2(\pi h/D) - \sin^2(\pi w/(2D))}\right\} - \frac{2}{\pi}\ln\left\{\sinh(\pi h/D) + \sqrt{\sinh^2(\pi h/D) + \sin^2(\pi w/(2D))/4}\right\}$$



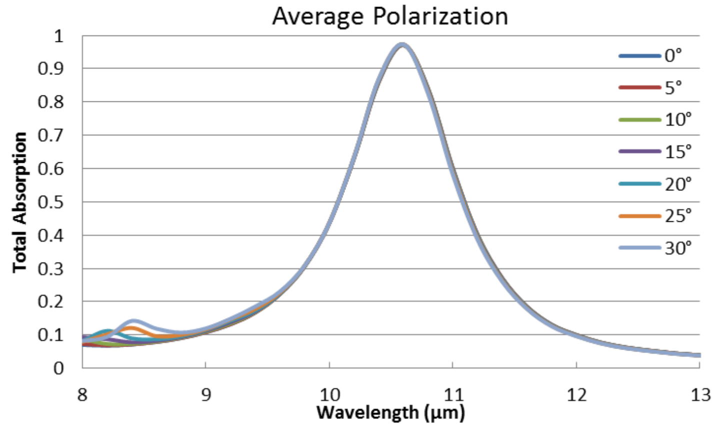


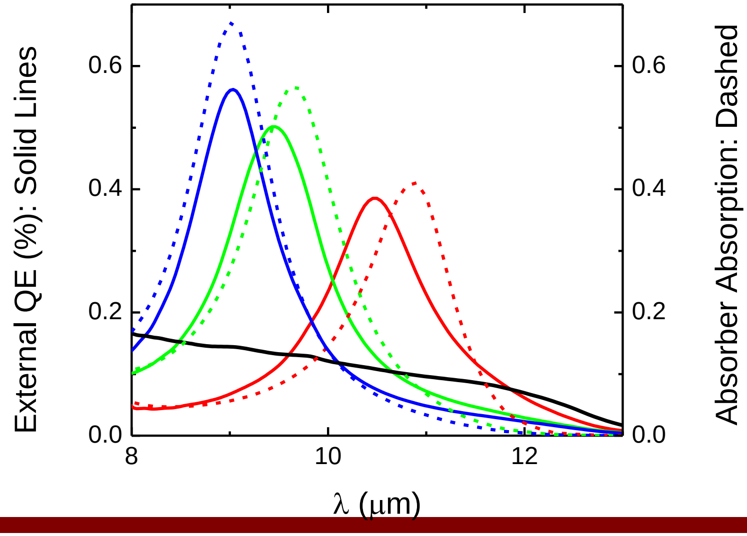
Patch metal losses are typically small compared to higher-order mode absorption unless spacer layer is thick

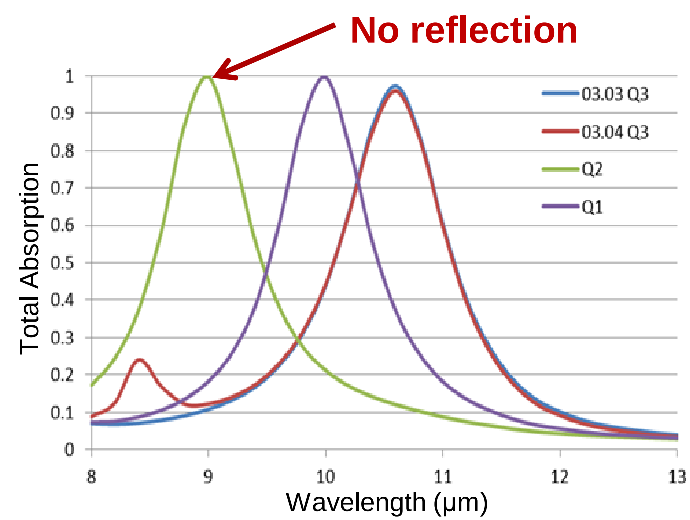
Nanoantenna Optical Properties

- The nanoantenna couples the incoming light to a confined mode with no reflection at the design wavelength.
  - Achieved with a single patterned metal layer.
  - No AR dielectric stack required
- The AR effect does not change with angle as it would with a dielectric AR coat.
- Polarization independence over angular range of interest.
- Increase in EQE over bare material.

Angular Insensitivity





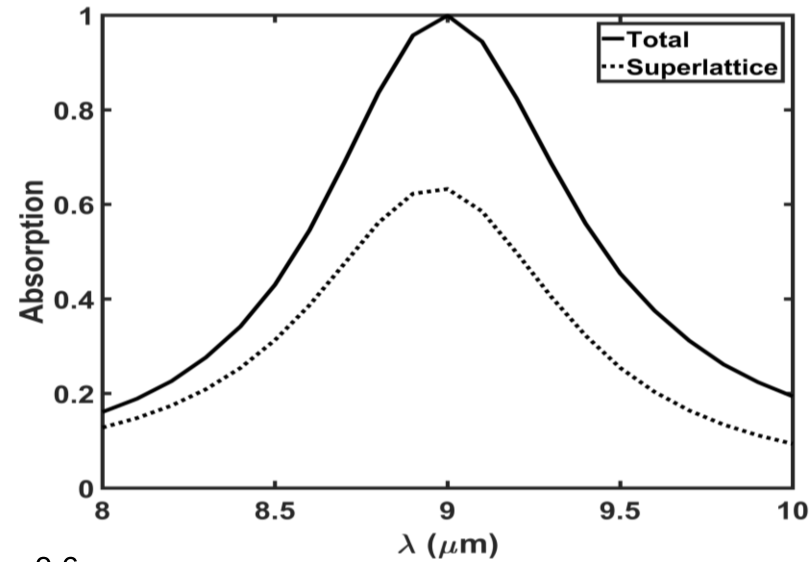


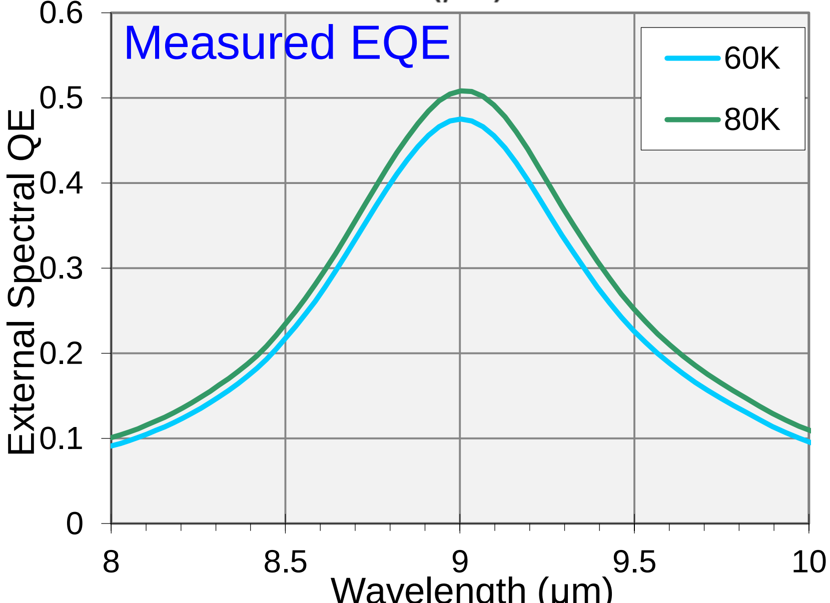
Comparison to Experimental Results

- Demonstrated NA-thinned superlattice photodetector for the first time
  - 2 to 3x higher QE than conventional SL photodetectors
  - Similar dark current to conventional SL photodetector of same thickness
- Good agreement between measured EQE and simulated absorption in detector layer.
  - How to further increase QE
    - Increase absorber α
    - Reduce optical losses

Optical losses may be reduced by optimizing the device parameters.

Simulation of absorption in active layer

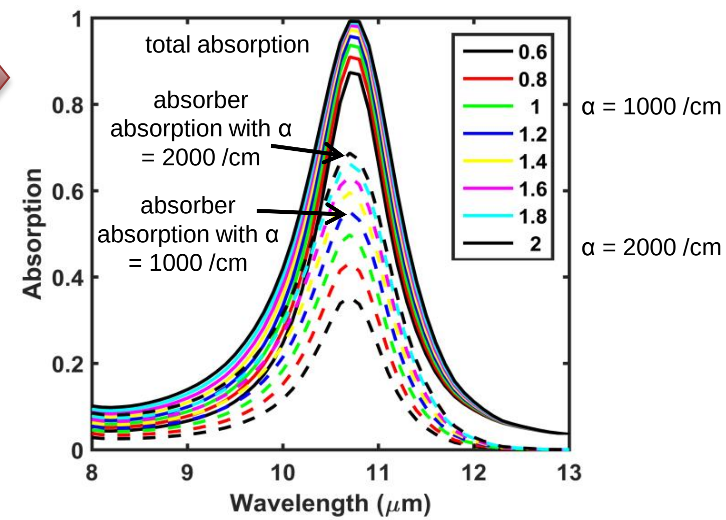


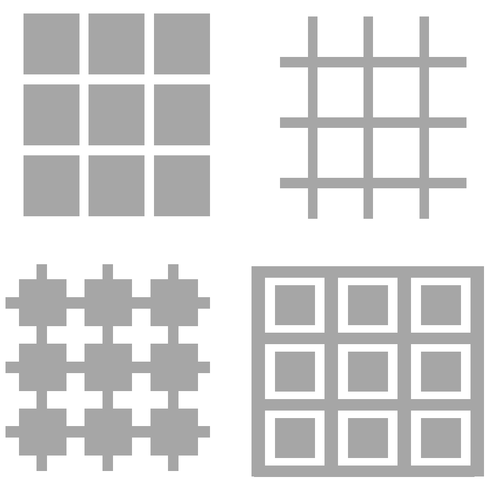


M. D. Goldflam, *et al.*, *Appl. Phys. Lett.*, vol. 109, 251103, Dec. 2016.

Working to Higher EQE

- Increase in absorption in the detector increases EQE
- Use modeling tools to maximize absorption in the absorber
  - Can use patch or mesh designs or a hybrid.
  - Designs may be capacitive or inductive.





We would like to optimize these structures using an accurate admittance model for nanoantenna elements.

- very complicated expressions (but still analytic & fast to compute).
- provides design intuition - can guide numerical studies.
- can rapidly & accurately survey multidimensional parameter space.