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Metamaterials-Based High Efficiency Absorbers for High Temperature Solar Applications

(9937-37)

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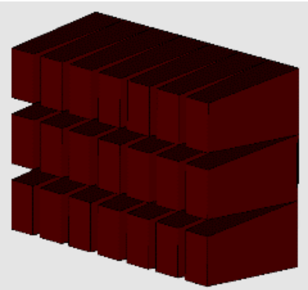
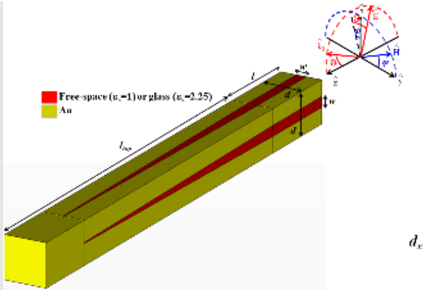
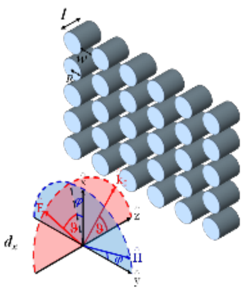


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Outline

- Motivation for This Work – Enhance CSP Receivers
- Background – Metamaterials and CSP
- Simulations on Proposed Designs
- Fabrication Approach
- Optical Testing Approach
- Conclusion & Future Work

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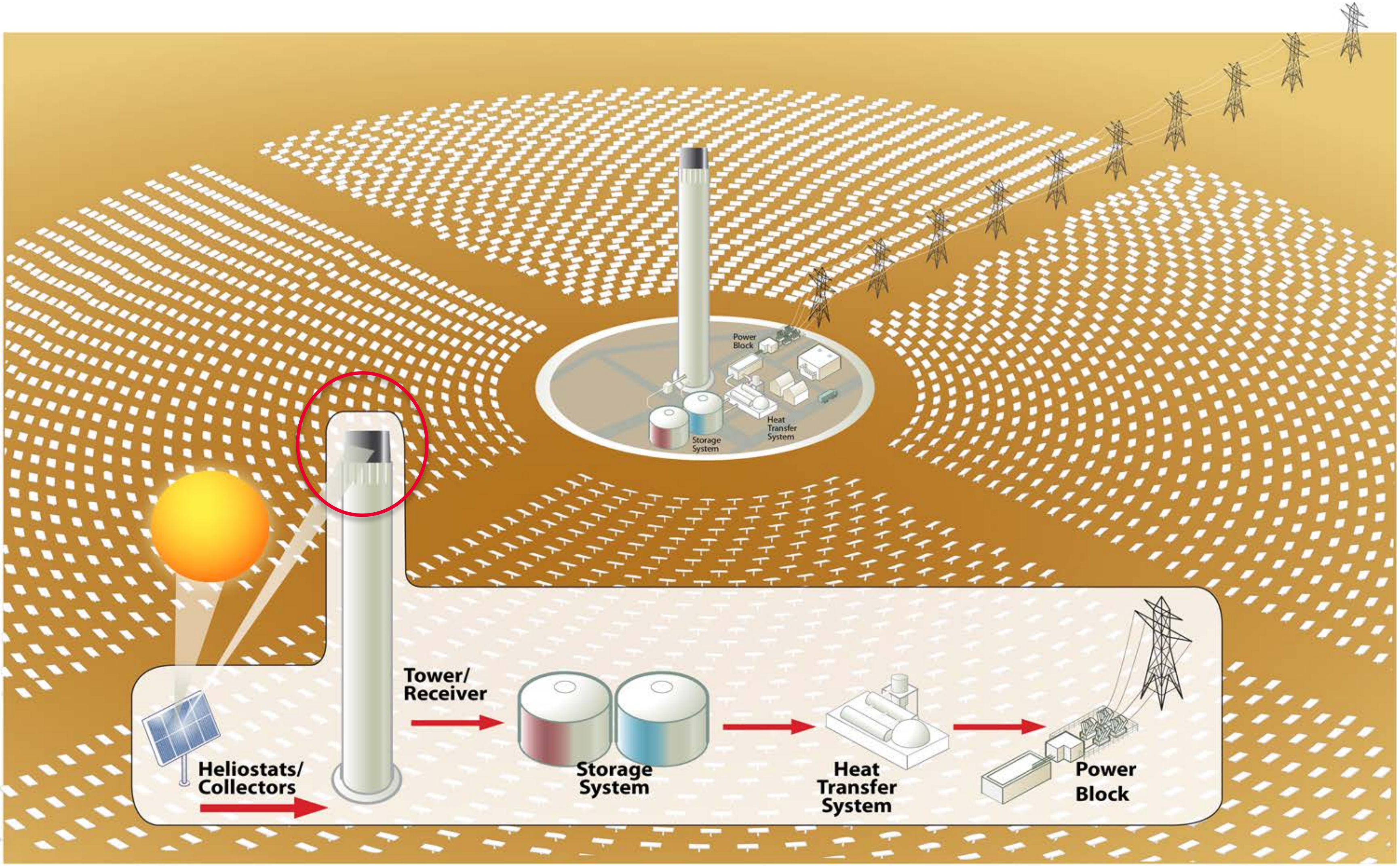
Receivers for Concentrating Solar Power



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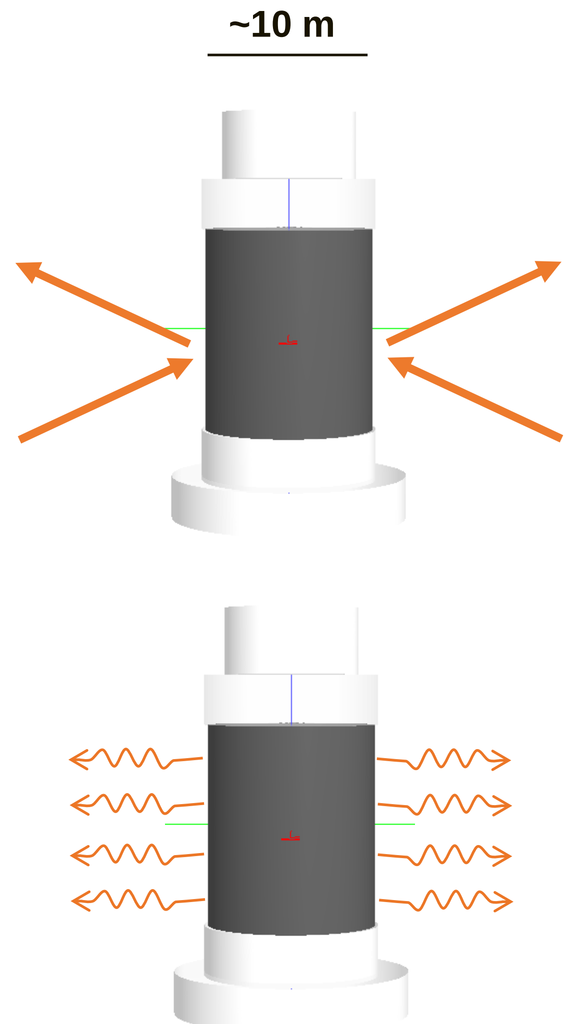
Motivation: High-Temp CSP Receivers

- Goal is to improve receiver thermal efficiency and power block efficiency
  - ≥ 700°C → sCO_2 cycles
  - ≥ 50% power cycle efficiencies
- Thermal efficiency is reduced for CSP receivers at high temperatures
  - Reflection losses
  - Thermal re-radiation in IR dominates > 650°C

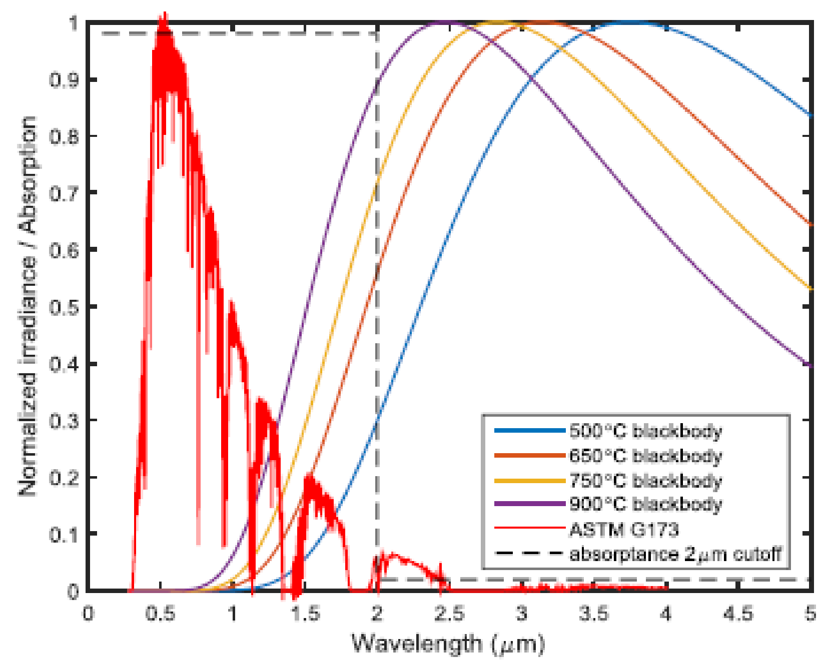


Conventional cylindrical solar receiver

$$\eta_{th} = \alpha - \frac{}{}$$

Motivation: Metamaterials for Enhanced Solar Absorption

- Pyromark has high absorptance (0.95), but also has high emittance (0.80)
- Current selective coatings degrade in extended high-temperature exposure
- Metamaterials can be designed to absorb the visible spectrum at near unity, and suppress re-radiation in IR
  - High temperature materials (e.g., refractory metals)
  - Broadband and wide range of incidence angles



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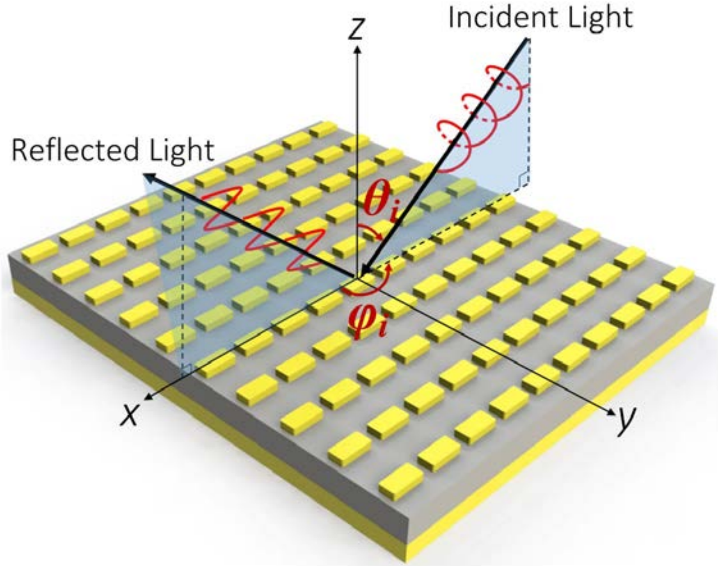
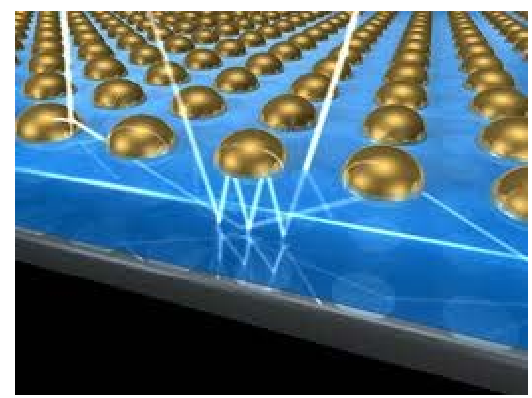
Metamaterials Introduction

- Metamaterials are man-made periodic micro/nano structures to enhance interaction of light with matter
- Instead of manipulating chemical composition materials, the material surface structures are engineered and manipulated



http://phys.org/news/2015-01-two-dimensional-metamaterial-surface.html



Plasmonic solar cells {A. Polman]

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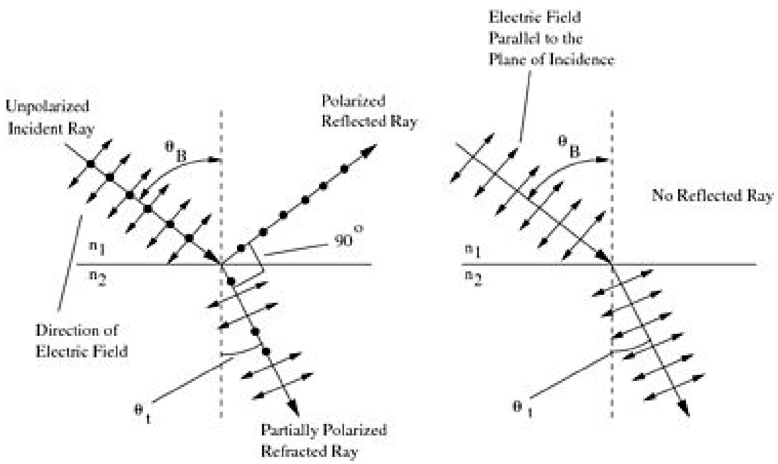
Plasmonic Brewster Angle

Conventional Brewster transmission

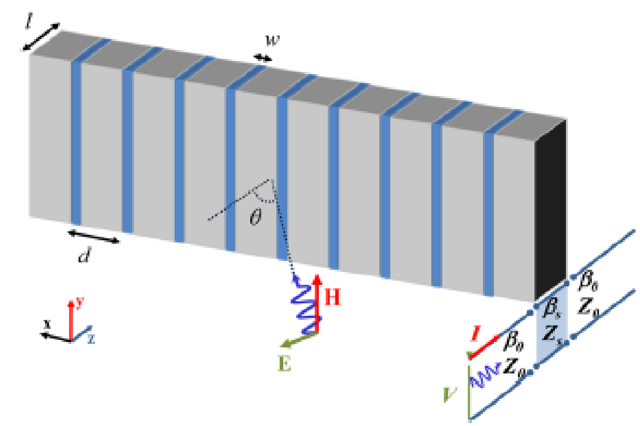


$$Z_s = \frac{E}{H} = \sqrt{\mu \quad \varepsilon_s} \qquad \theta_r$$

$$=$$

$$Z \ = \frac{E}{H} = \sqrt{\mu \quad \varepsilon} \qquad \theta_i$$

Plasmonic Brewster angle



$$Z_s = \frac{\bar{E}}{\bar{H}} = \frac{w}{d}\eta_{TM}$$

$$=$$

$$Z \ = \frac{E}{H} = \sqrt{\mu \quad \varepsilon} \qquad \theta_i$$

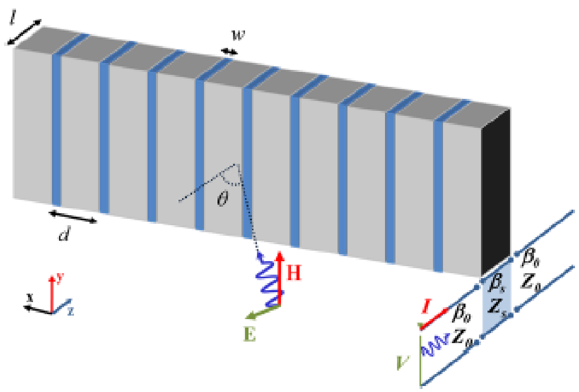
Brewster angle transmission is inherently broadband - can we use the same concept to squeeze energy in small volumes?

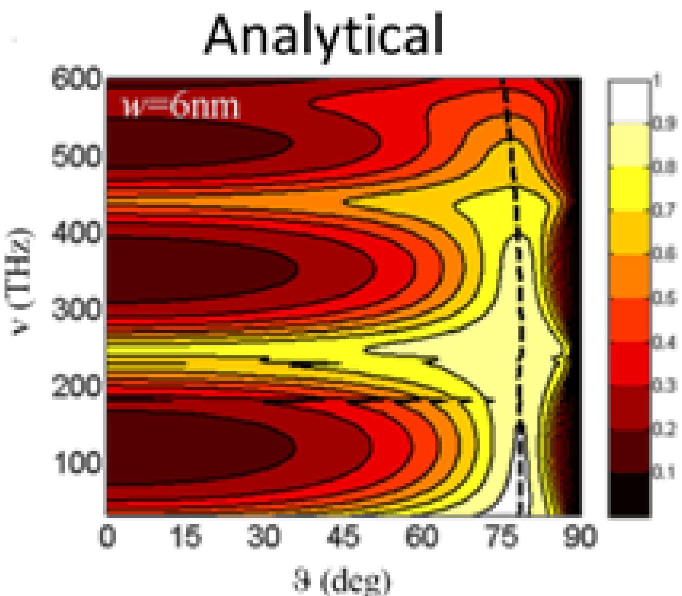
$$\theta_B = \frac{\beta_s w}{k \ d}$$

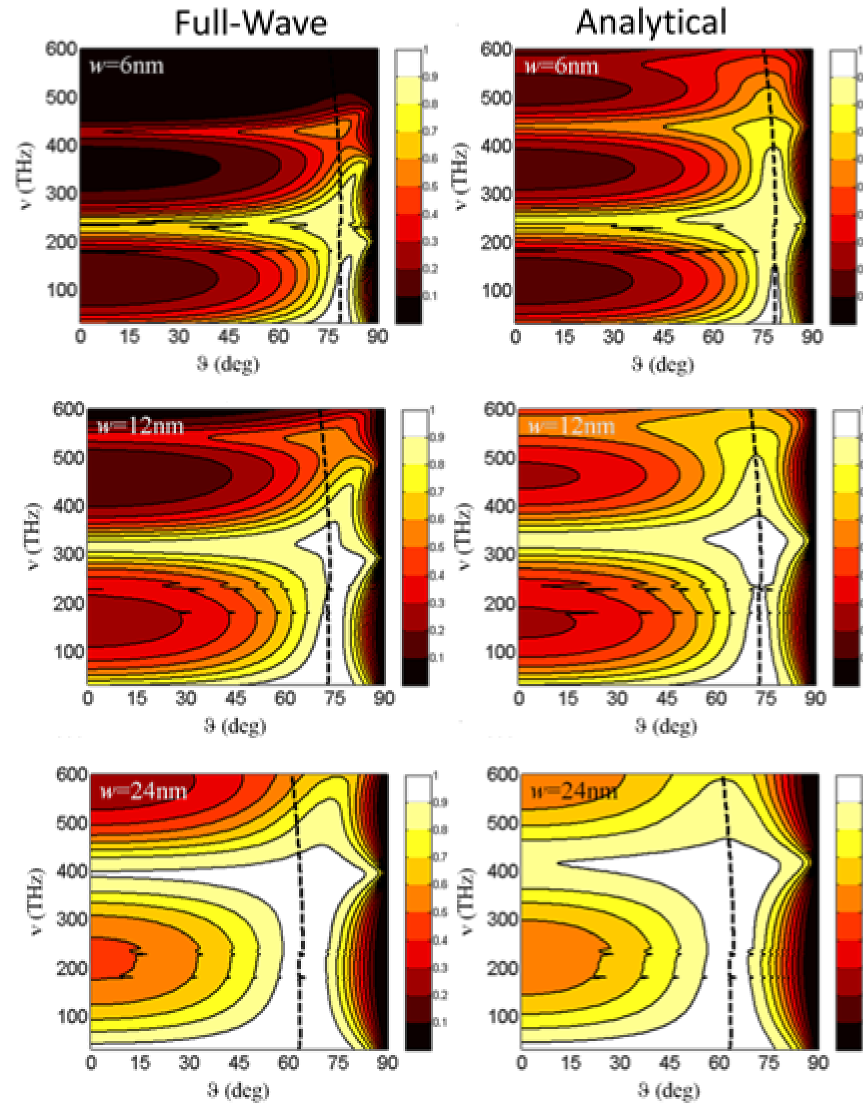
A. Alù, G. D'Aguanno, N. Mattiucci, M. Bloemer, **106**, 123902 (2011)

Broadband Impedance Matching

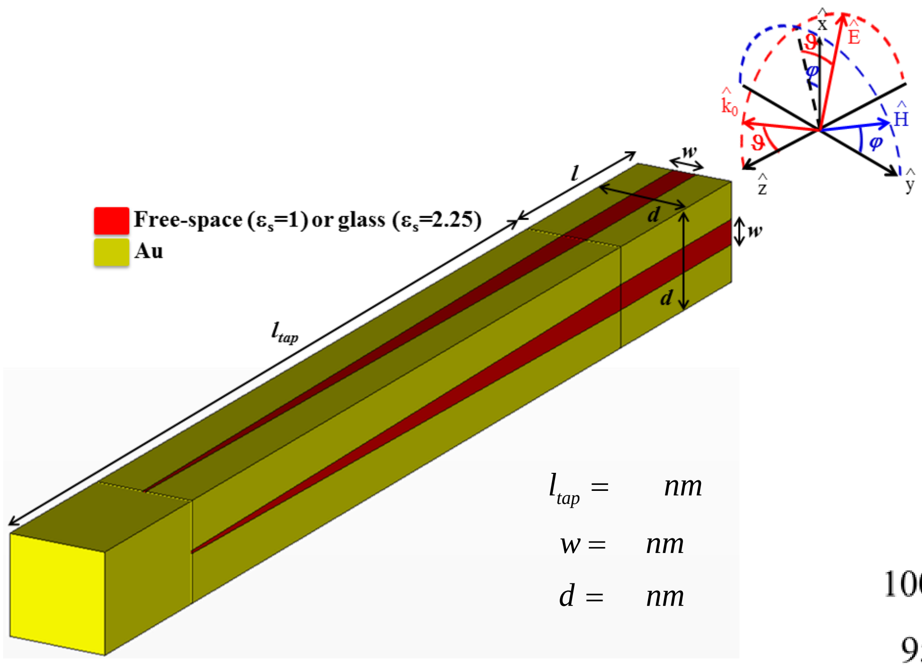
- Thickness , period

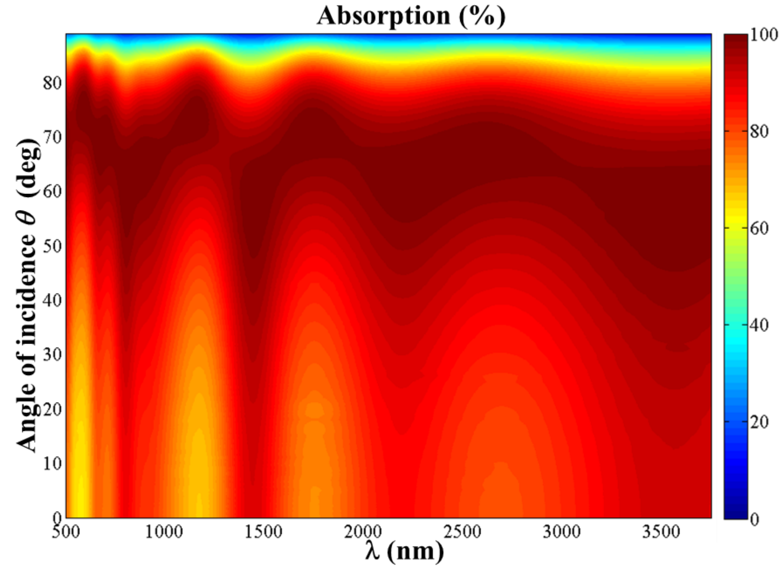


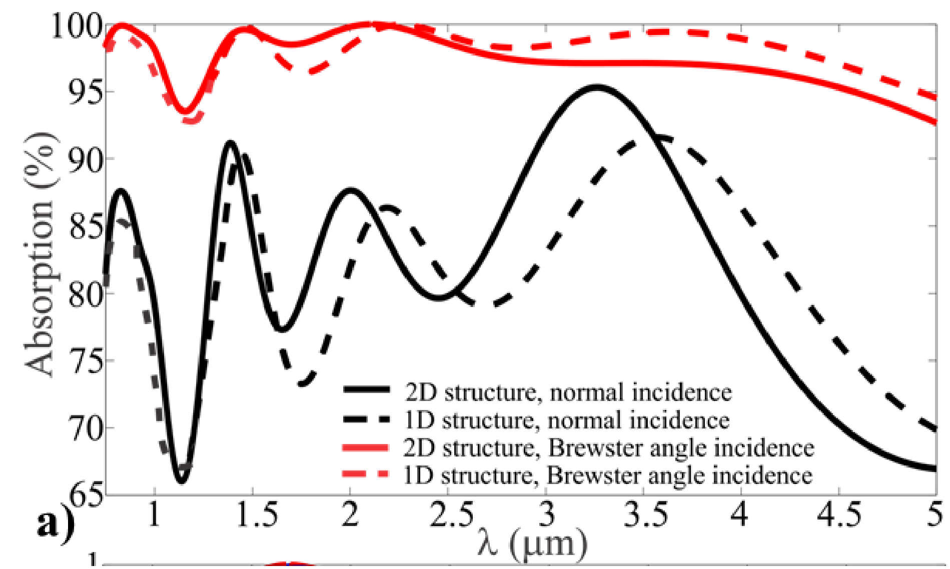




Broadband Absorbers







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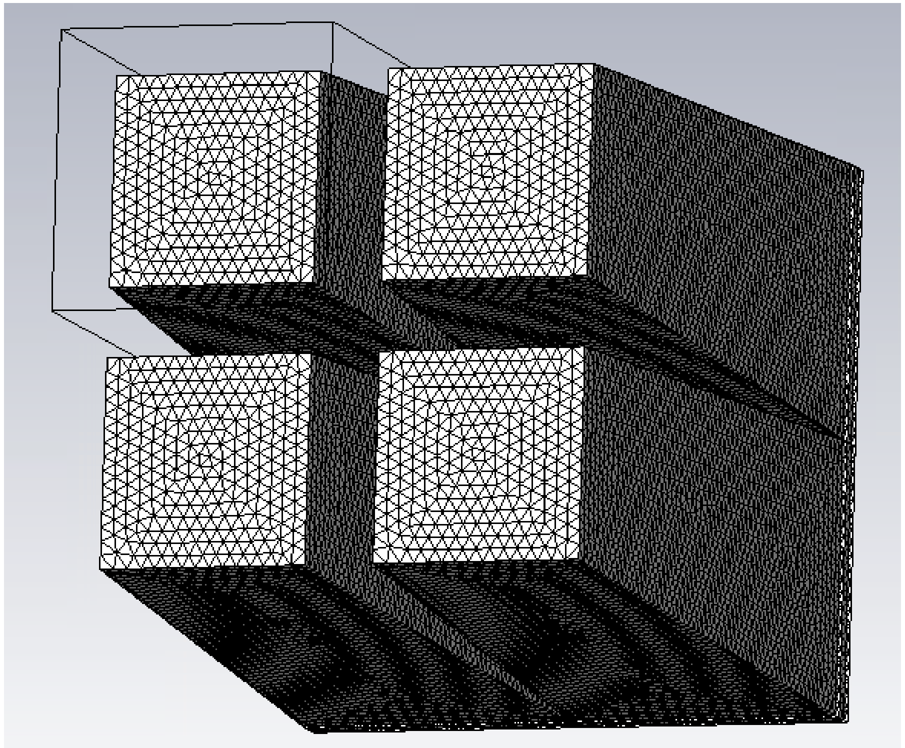
Simulation Background



Varying: materials (Tungsten, refractory materials, Si)
Width, period, thickness, taper/no taper

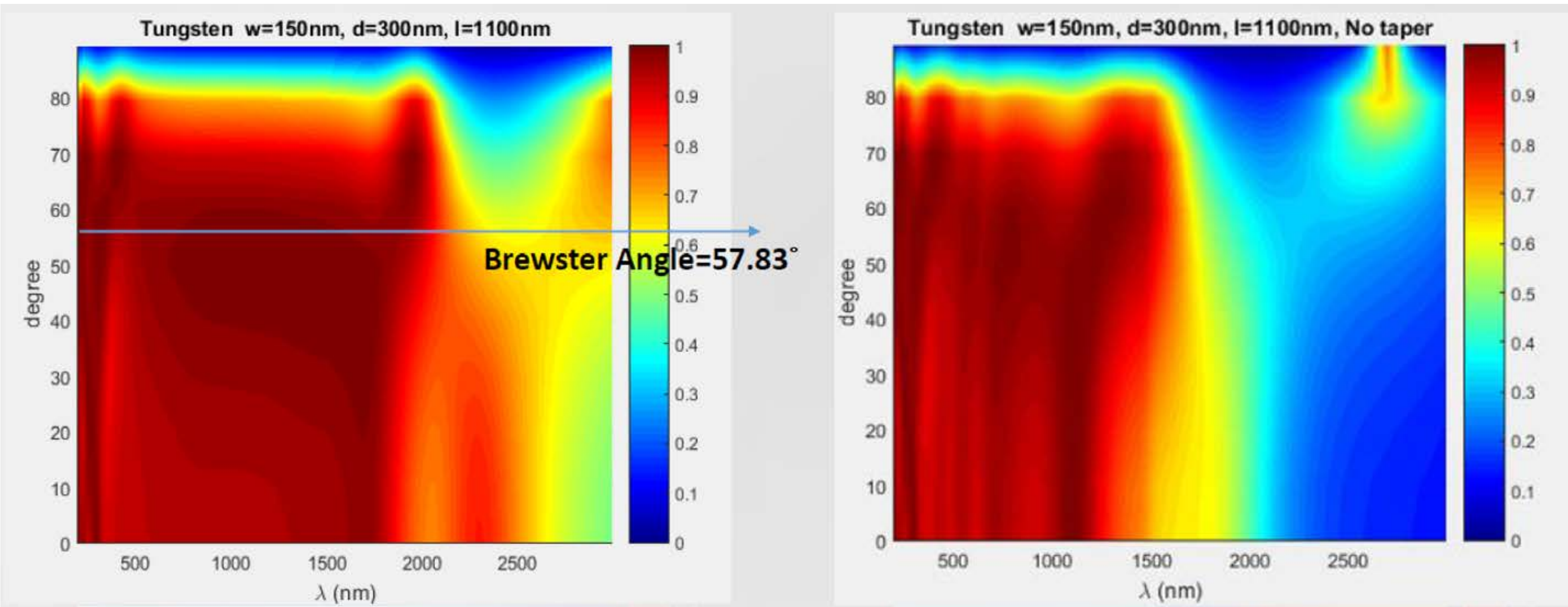
Bandwidth bounds:

- Upper cut-off: period
- Lower cut-off: thickness

The width controls the Brewster angle and angular beam width

Taper is chosen carefully to cut off at 2 μm, or taper depth of 1.1 μm

Simulation Results – Tungsten



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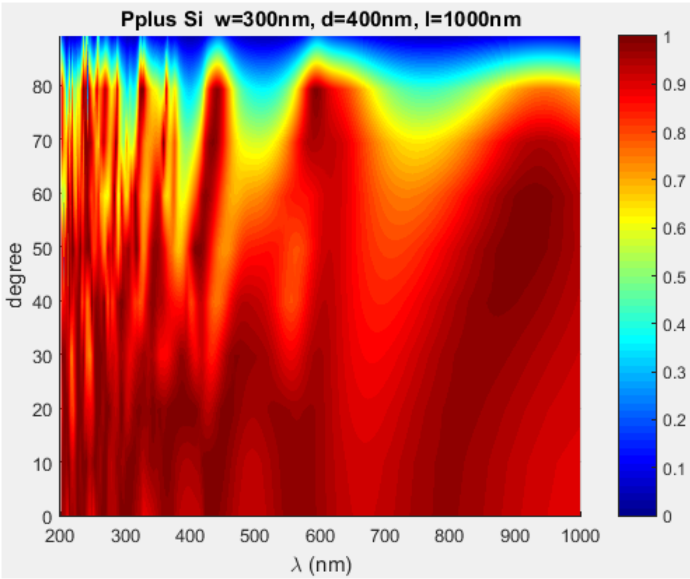
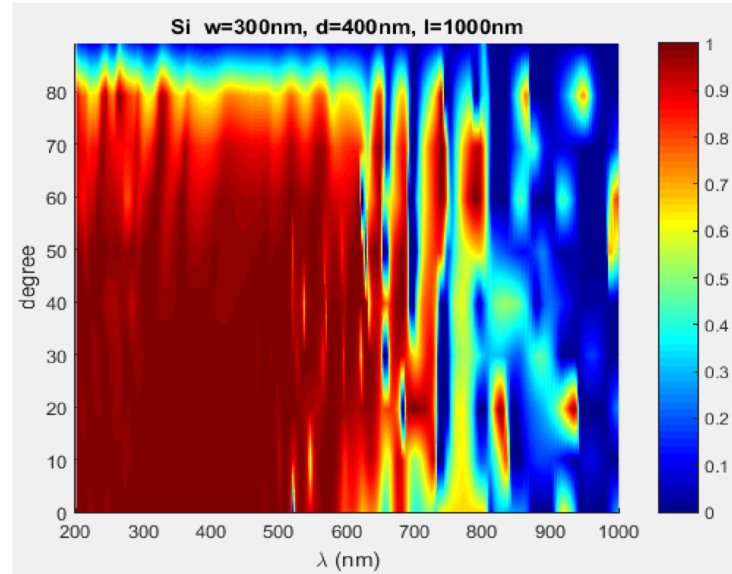
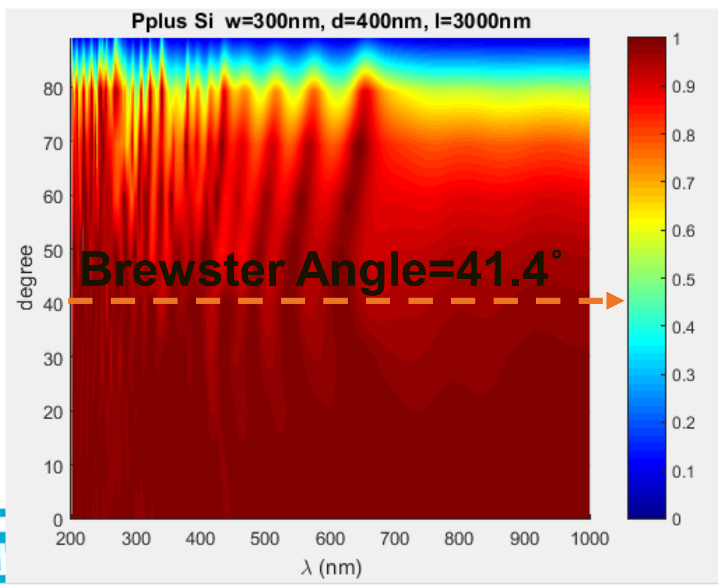
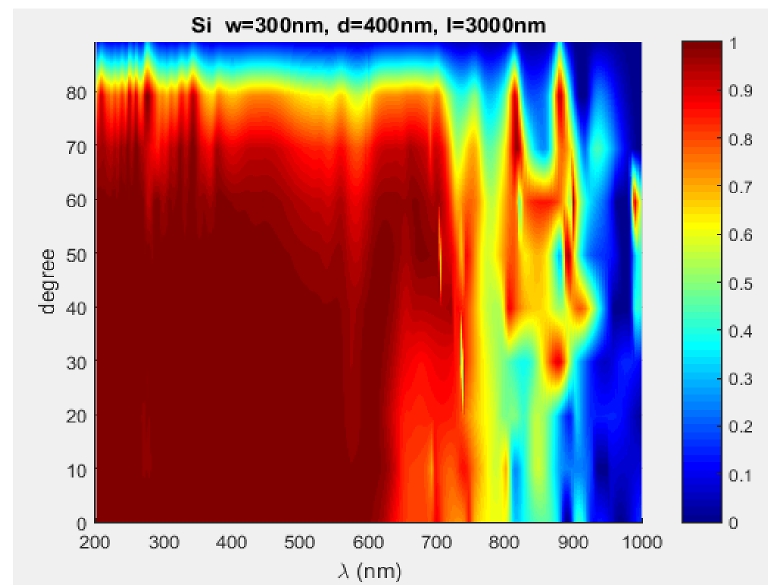
Simulation Results – Si









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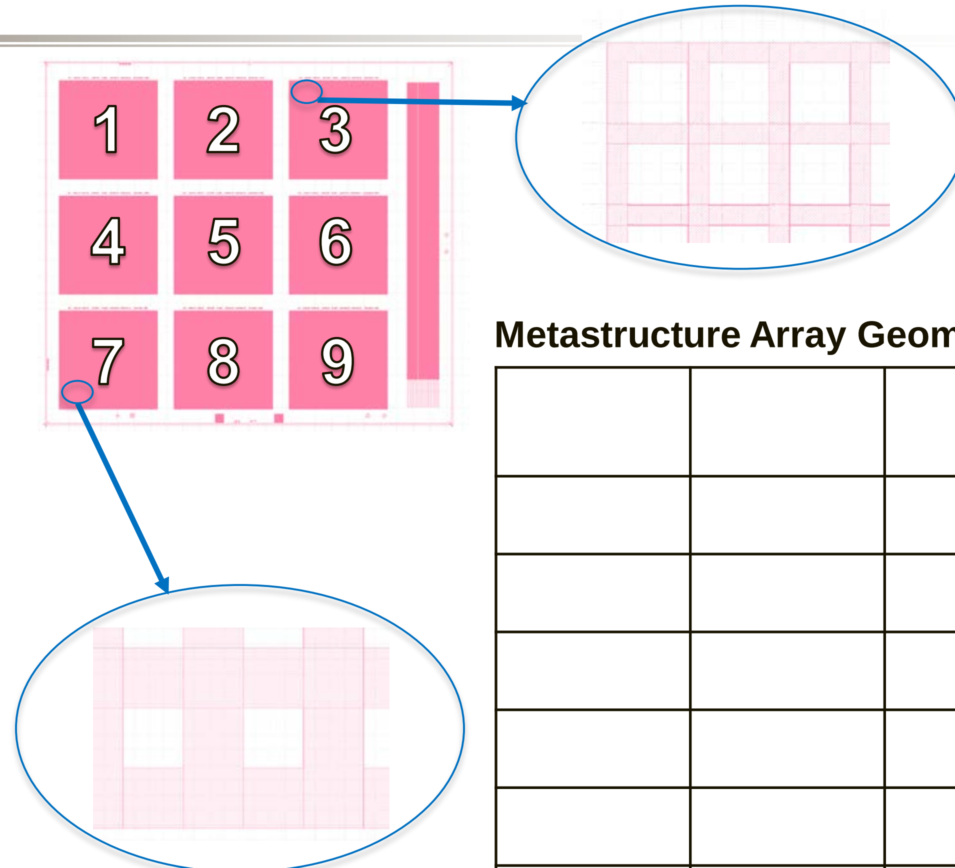
Fabrication Preparation – Mask Development

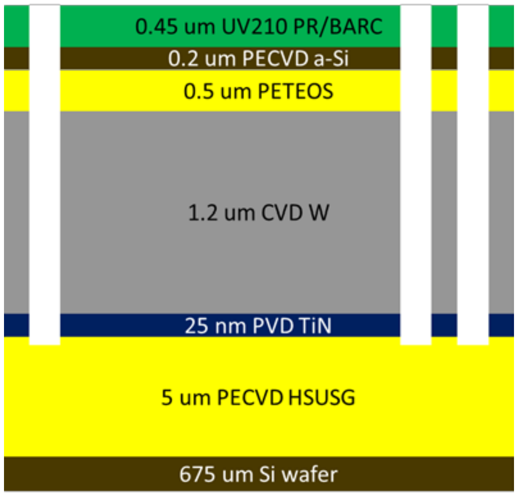
- 5 µm PECVD HSUSG
- 1.2 µm CVD tungsten on 25 nm PVD TiN
- CMP touch polish, 75 nm
- 200 nm a-Si/500 nm PETEOS hard mask
- ASML 248 nm scanner
- SF_6/C_4F_8 and SF_6/O_2 dry etch options in AMAT “DT” DPS Centura deep-Si etcher
- Future e-beam litho options

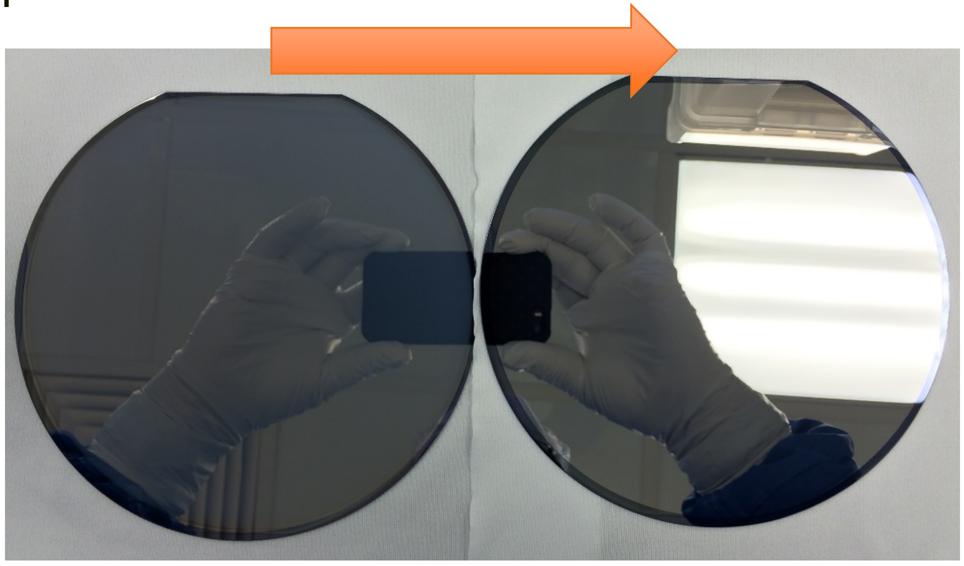


Metastructure Array Geometries

Fabrication Approach

- Good stress compensation from compressive HSUSG underlayer
  - Net radius of curvature >70 meters
- Short W-CMP polish seems effective at improving surface roughness
- Remaining issues:
  - Optical lithography performance on fine-pitch 2D gratings
  - Hard mask etch optimization
  - High-aspect ratio W etch development.





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Optical Testing Approach

- Optical spectroscopy testing
  - Absorption and reflection measurements
- On-sun FTIR
  - Heat the samples to ≥ 700°C and measure emission

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Conclusions

- At high temperatures (>700°C) CSP receivers suffer large thermal losses, which reduce thermal efficiency
- To improve solar absorption and reduce thermal losses, we propose using structured receiver surfaces using metamaterials
- Simulation of metamaterial geometries showed near unity absorption in majority of solar spectrum while suppressing re-radiation in the IR

Future Work

- Fabrication
  - Optimize tungsten dry etch
  - Explore e-beam litho options
  - Alternate material stacks
    - Thicker tungsten
    - Thermal/chemical stability at temperature
    - Protective coatings
- Perform optical testing on fabricated samples
  - Optical spectroscopy
  - On-sun FTIR

Questions?

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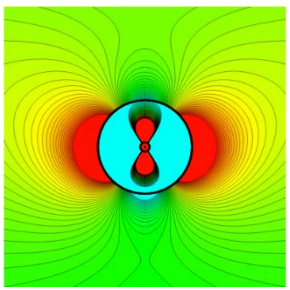
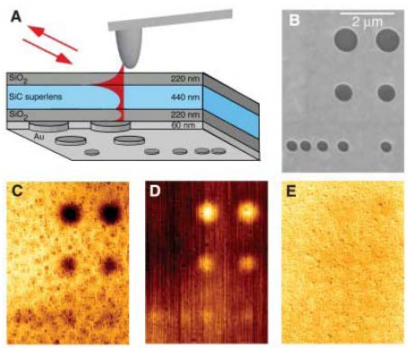
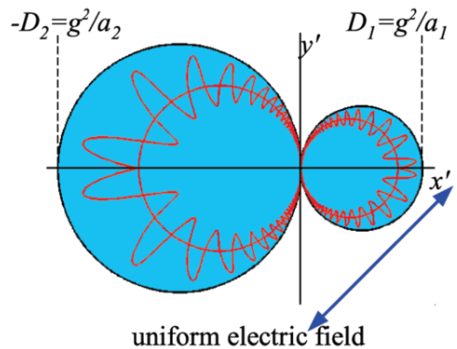
Extra Slides

Metamaterials and Plasmonics Examples

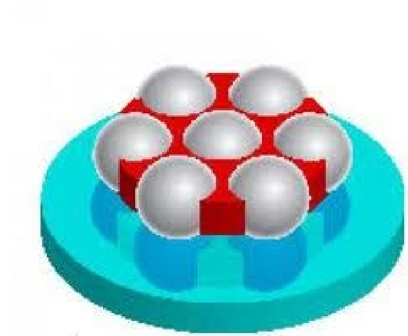


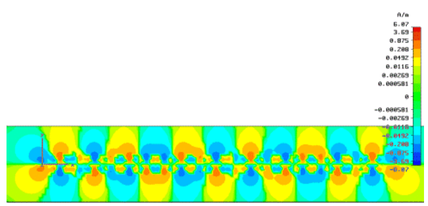


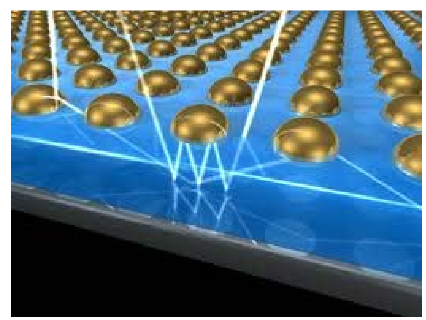
Sub-diffraction imaging [T. Taubner et al., Science 2006]

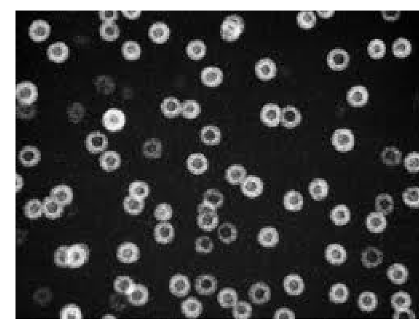


Focusing [D.Y. Lei, et al., N. J. Phys. 2010]


Sensing [J.A. Fan, et al. Science 2010]

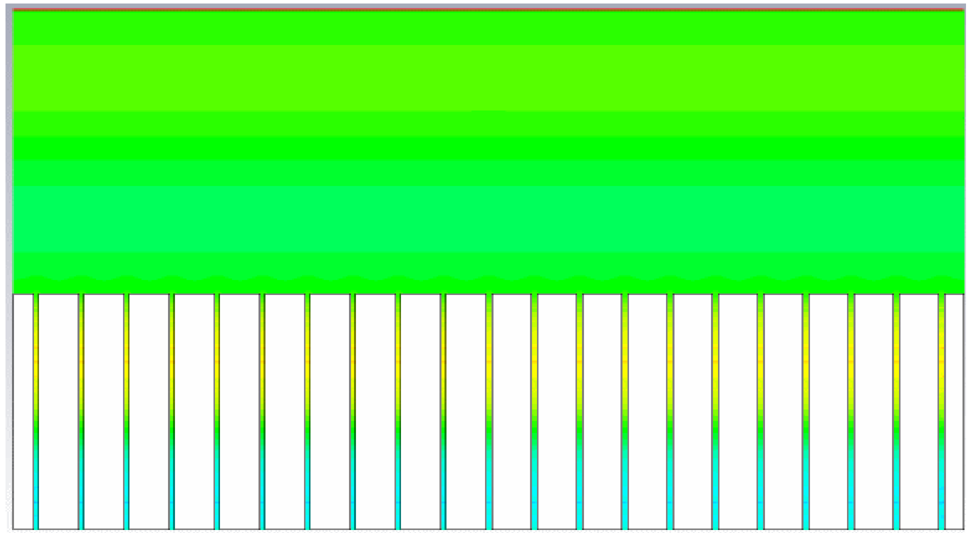

Sub-diffraction guiding [A. Alu, N. Engheta, Opt. Expr. 2008]


Plasmonic solar cells {A. Polman]

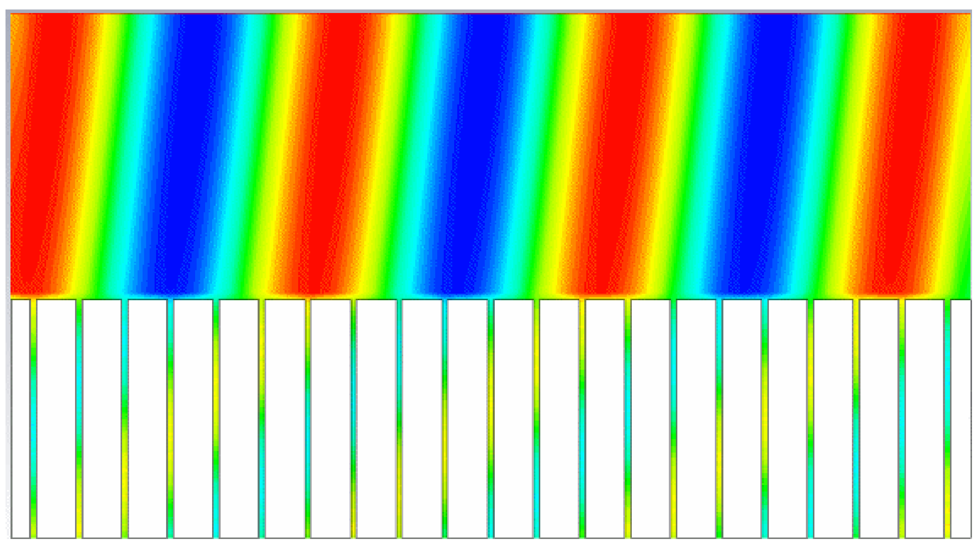

Core-shell for biomedical treatments [N. Halas]

Broadband Impedance Matching

$\theta_i = \ ^\circ$

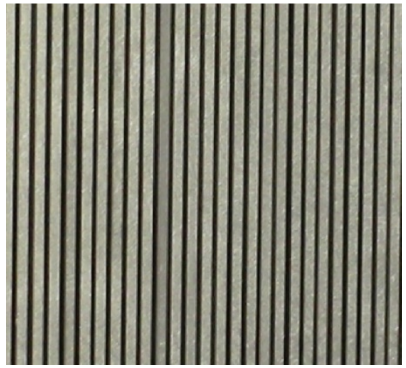


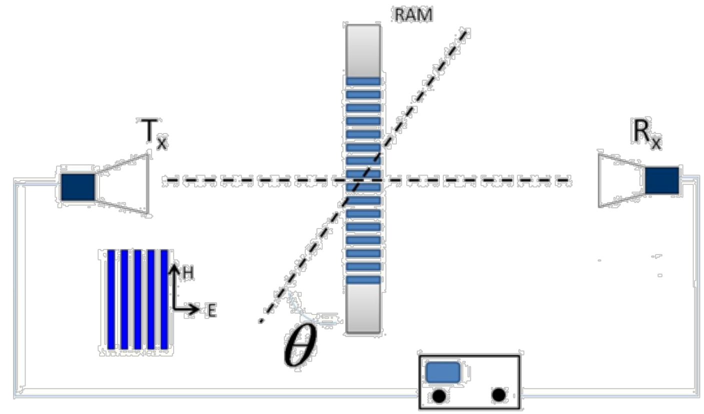
$\theta_i = \theta_B = \ ^\circ$

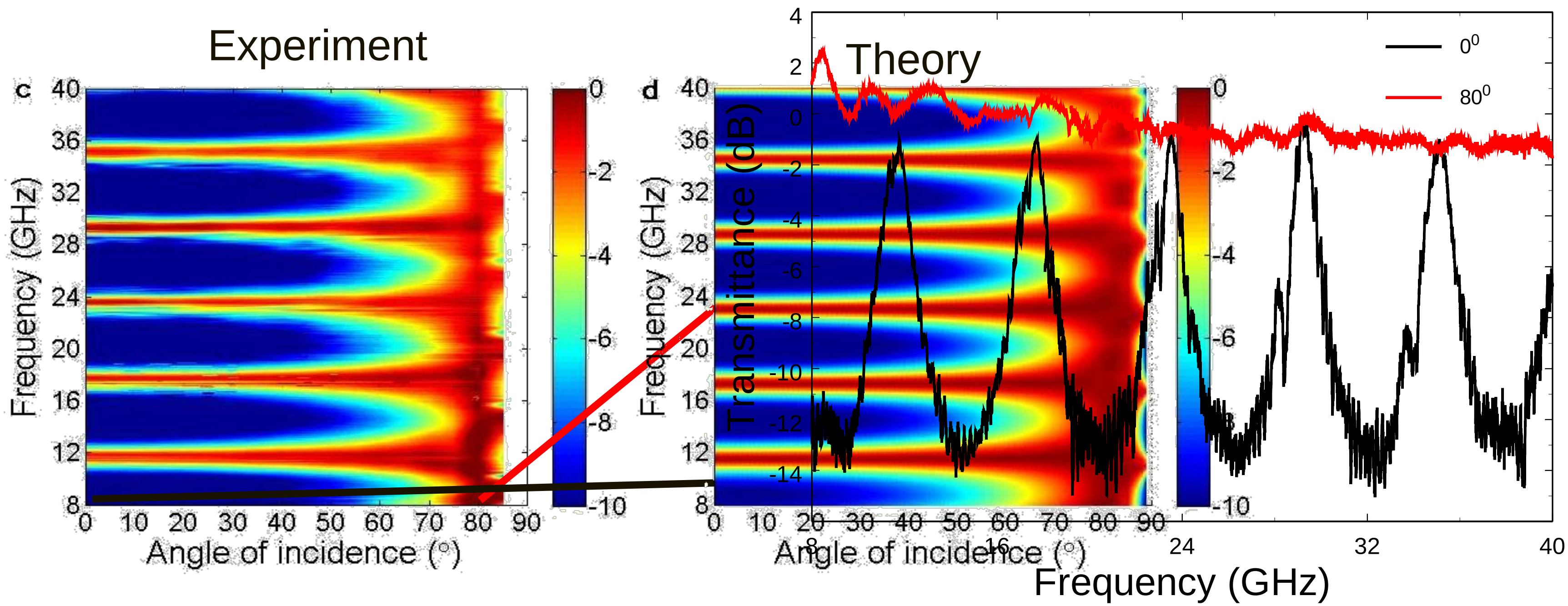


Experimental Verification at RF

- = 400 µm
- = 3.6 mm
- / = 11%
- = 2.54 cm

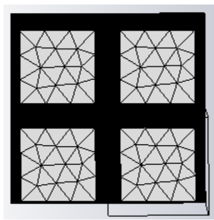






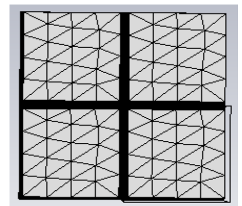
1.Brewster Angle Check

Fix, $w = \quad nm \rightarrow \beta_s \qquad + j \;\; k$



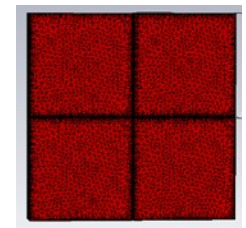
d=24nm

$\theta_b =$



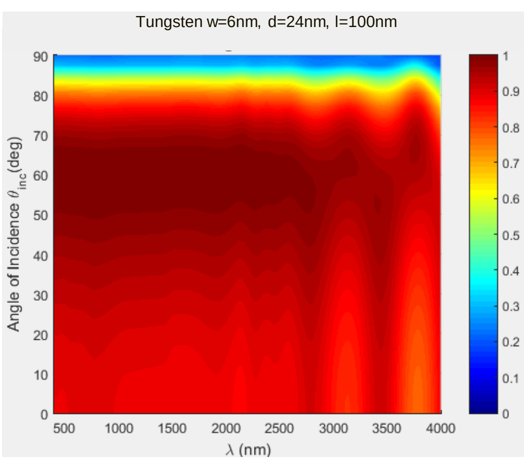
d=72nm

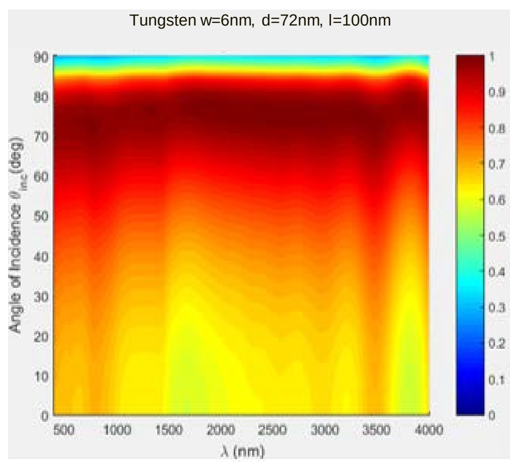
$\theta_b =$

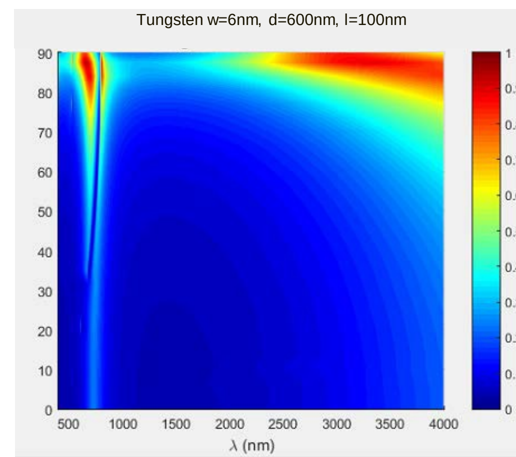


d=600nm

$\theta_b =$



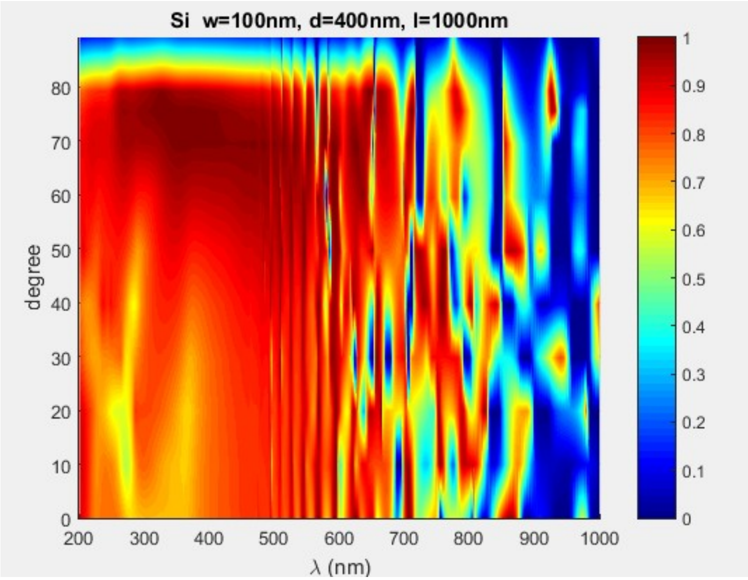


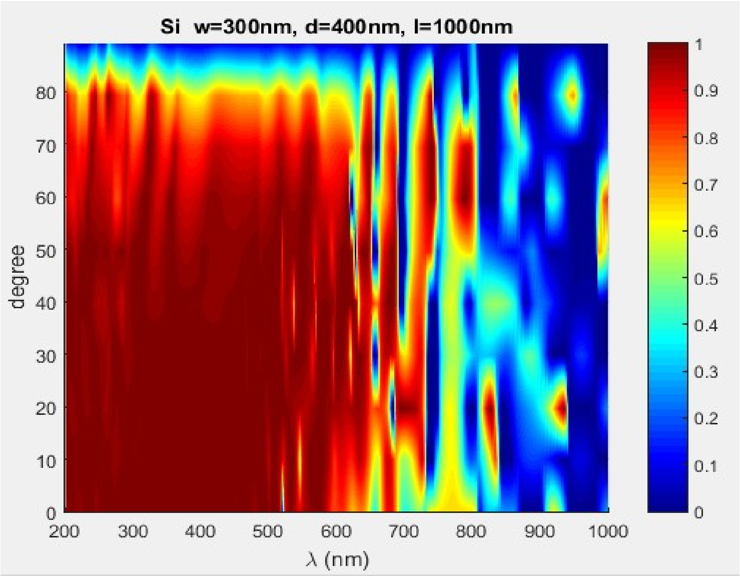


[Absorption]

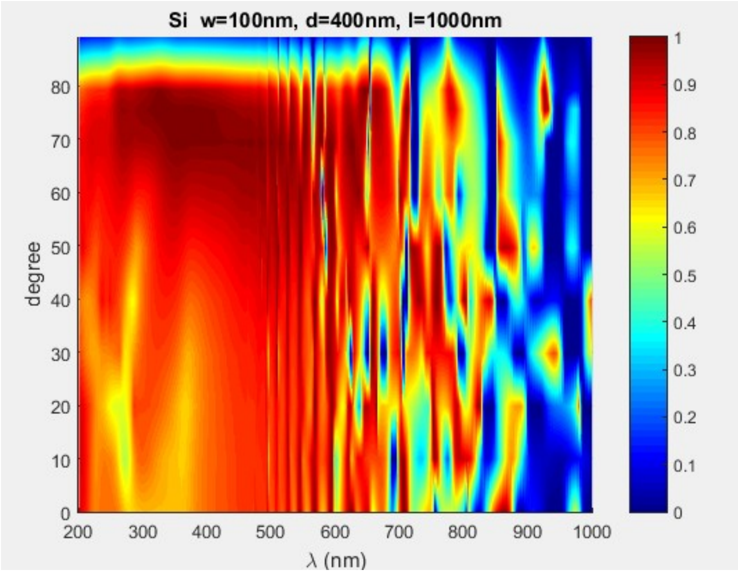
Brewster Angle goes up

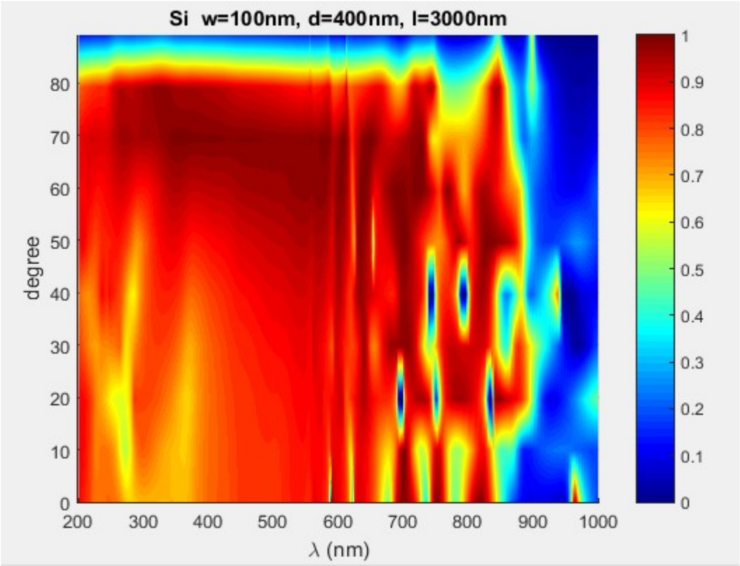
1.Brewster Angle Check





1.Brewster Angle Check





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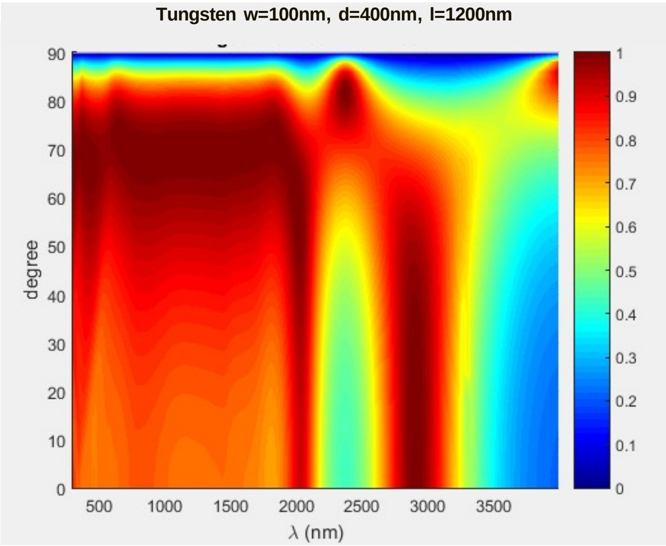

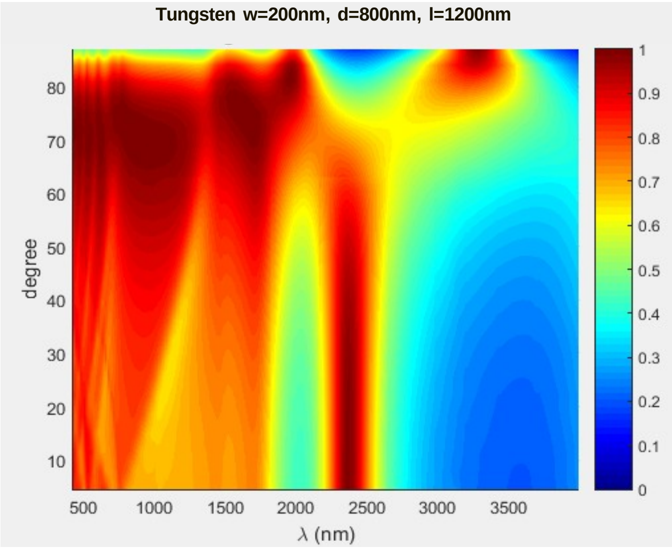

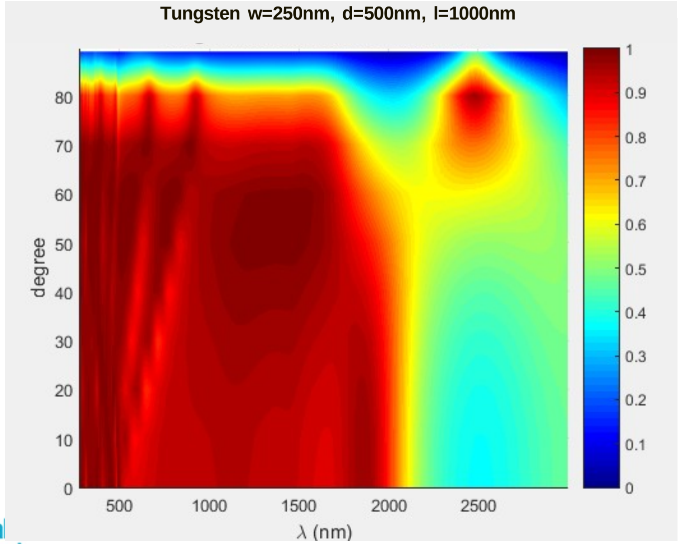

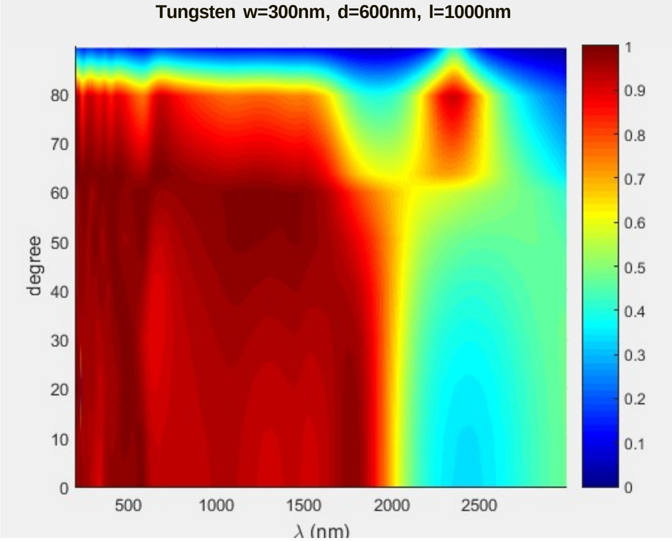

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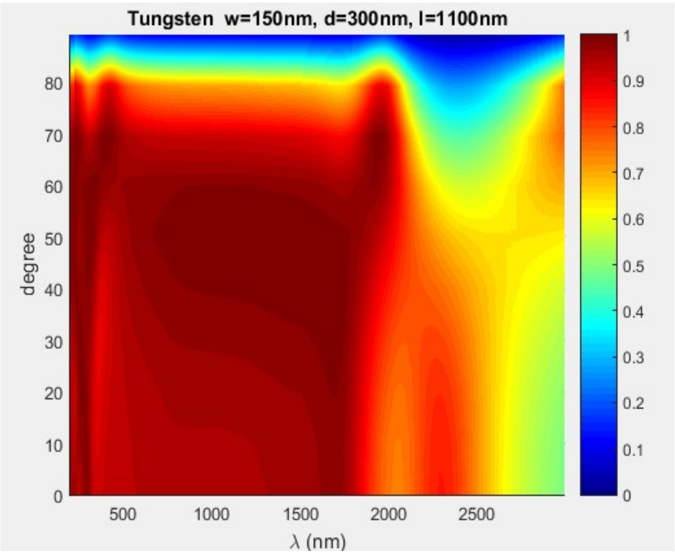
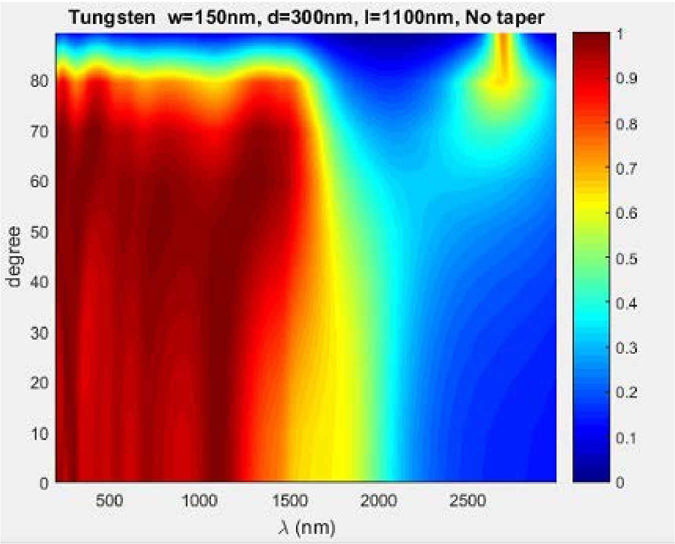
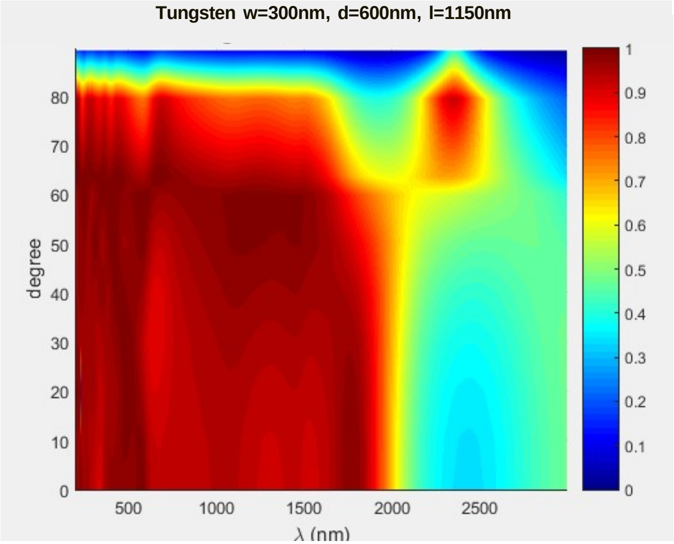
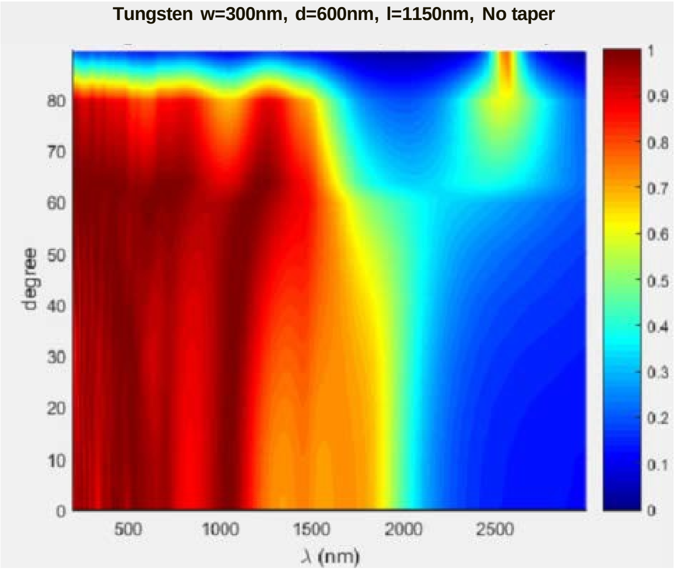
2. Taper & No taper









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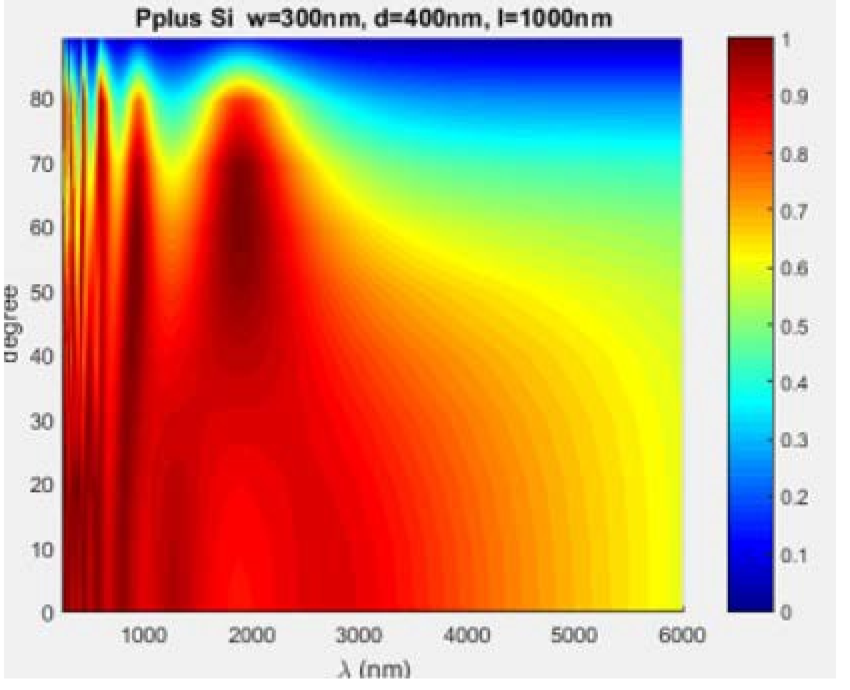
3. Highly Doped Silicon Compliment



Planned Fabrication Stack