# Space Power Workshop 2018

# Ultralight Emissive Mirrors for Thermal Management in Space

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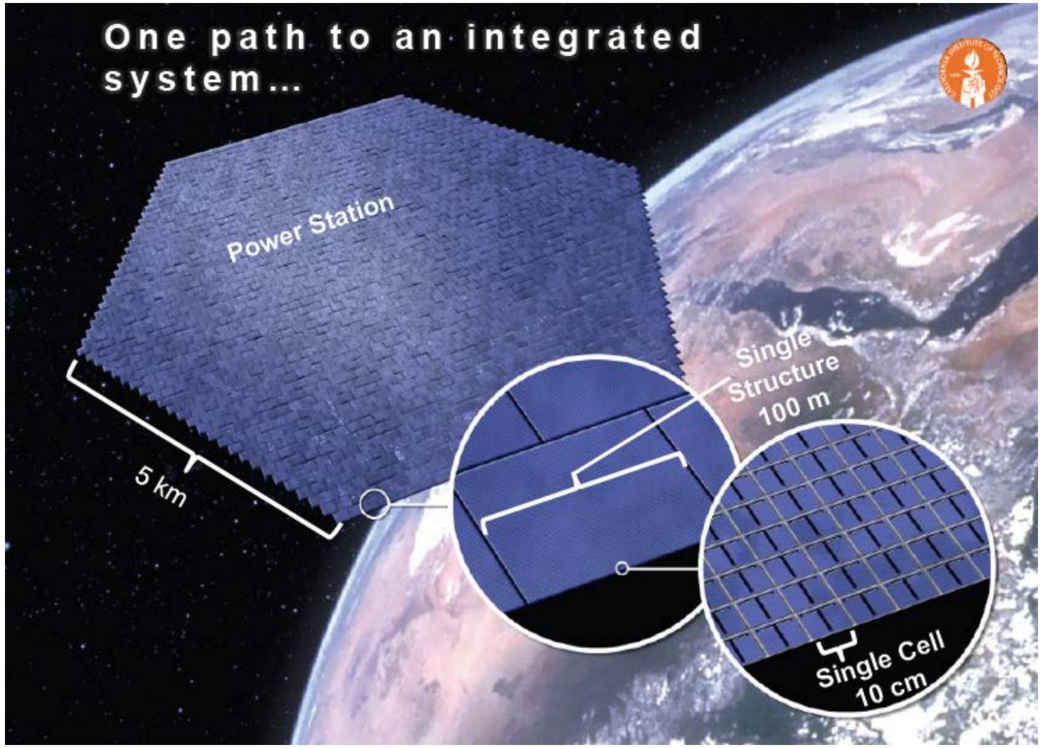
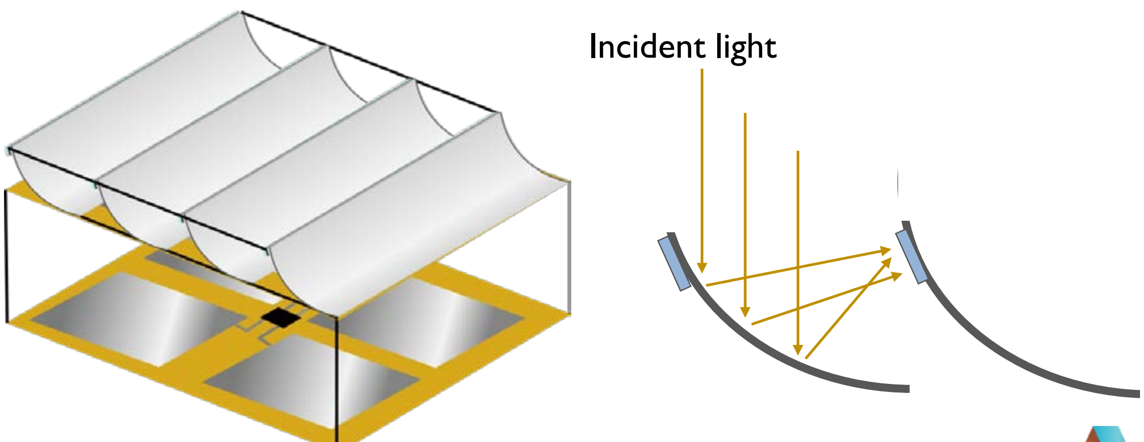
# Motivation: Space Solar Project Initiative




The Parabolic Concentrator

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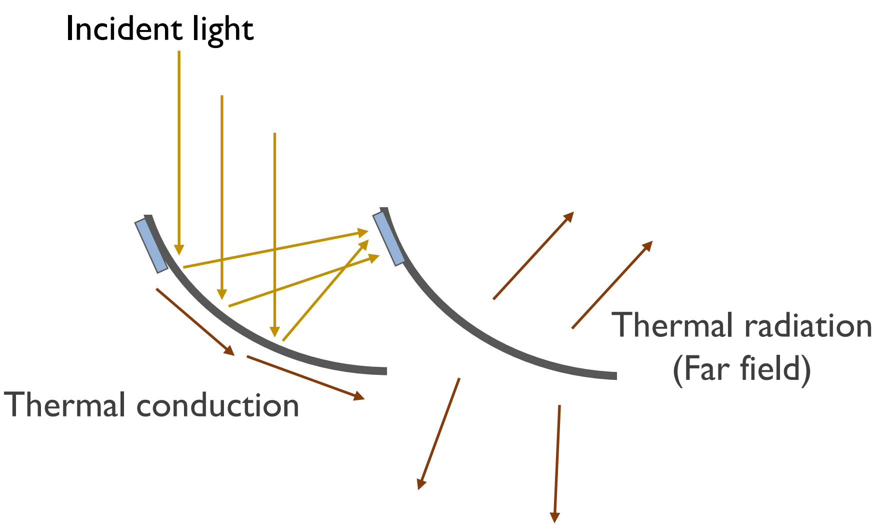
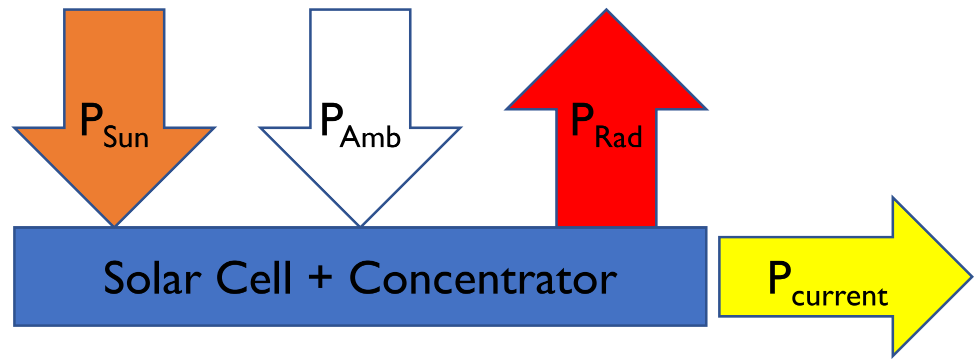
# Radiative Laws: Stefan-Boltzmann Law and Steady State Power Balance



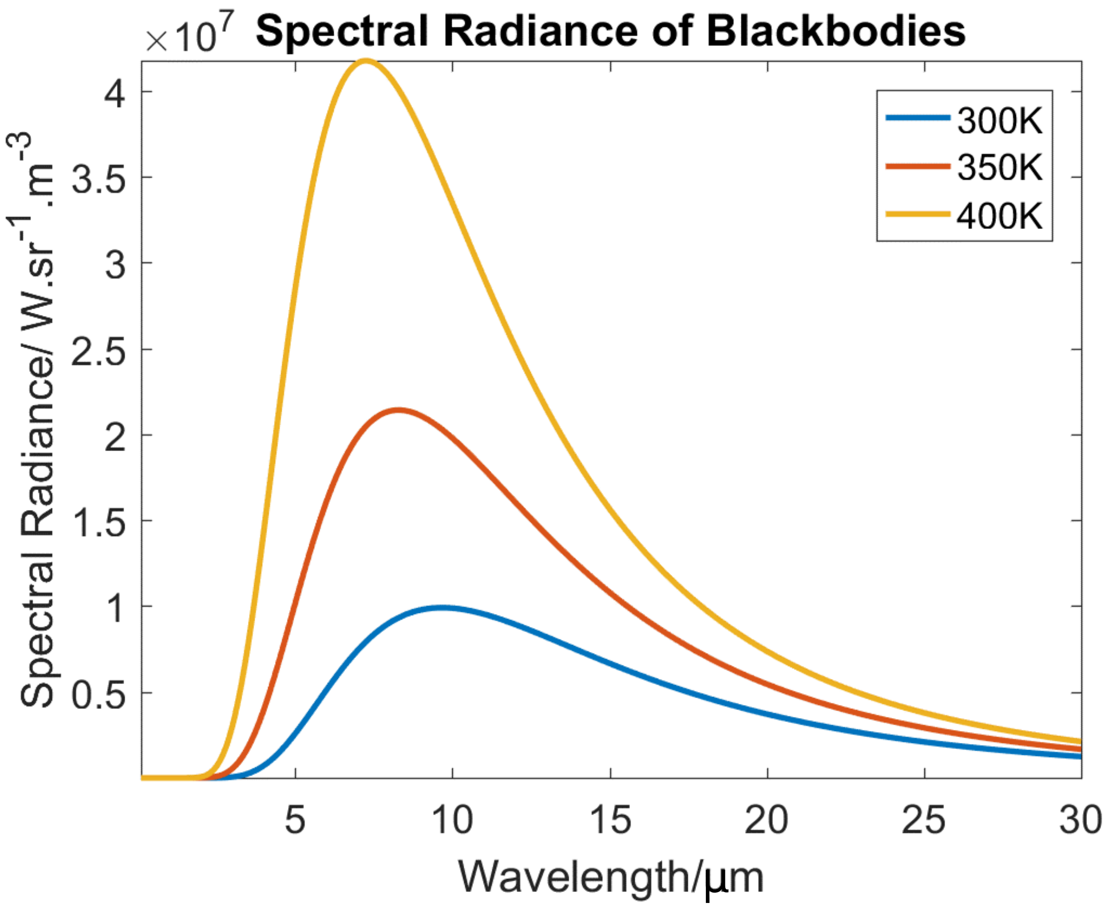

$$P_{net} = P_{Rad}(T_{Rad}) - P_{amb}(T_{amb}) - [P_{Sun} - P_{Current}]$$

$$P_{Rad}(T_{Rad}) = A\int d\Omega \int d\lambda\, I_{BB}(\lambda, T_{Rad})\varepsilon(\lambda, \Omega) = \boxed{A\varepsilon\sigma T_{Rad}{}^{4}}$$

At Steady State, $P_{net}$=0, allowing us to solve for the blackbody temperature $T_{Rad}$ at any given surface emissivity ε

# Radiative Laws: Planck's Law for Blackbodies

$$I_{BB}(\lambda,T) = \frac{2hf^3}{c^2}\cdot\frac{1}{\exp\left(\frac{hf}{k_BT}\right)-1} = \frac{2hc^2}{\lambda^5}\cdot\frac{1}{\exp\left(\frac{hc}{\lambda k_BT}\right)-1}$$




Non-Blackbodies:

$$I_{Real}(\lambda,\Omega,T) = I_{BB}(\lambda,T)\cdot\varepsilon(\lambda,\Omega)$$

Kirchhoff's Law: $\alpha = \varepsilon$

By studying a surface's Absorptivity, we may design highly Emissive structures for IR Cooling

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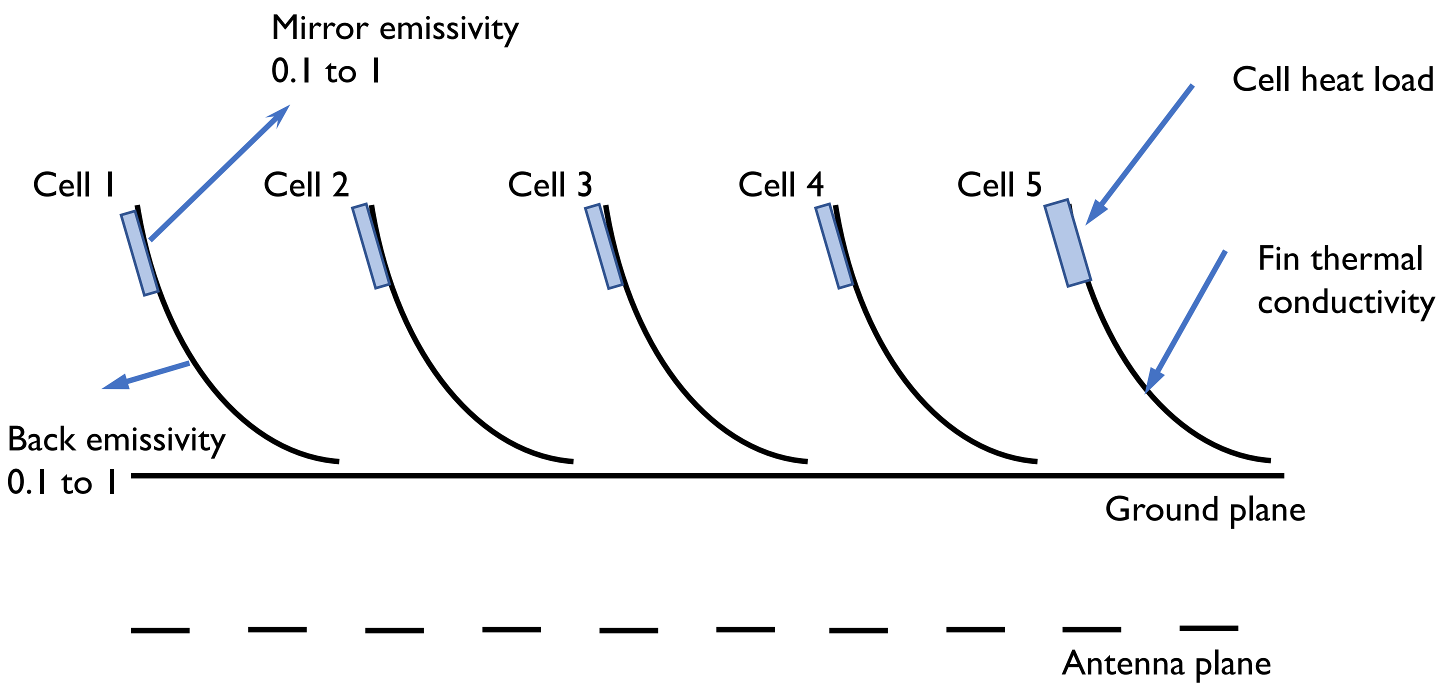
# Photovoltaic array modeling




Finite element model

COMSOL Multiphysics including

- Surface to surface radiation
- Conductive heat transfer

Model validated using analytic and planar cell (no array) references

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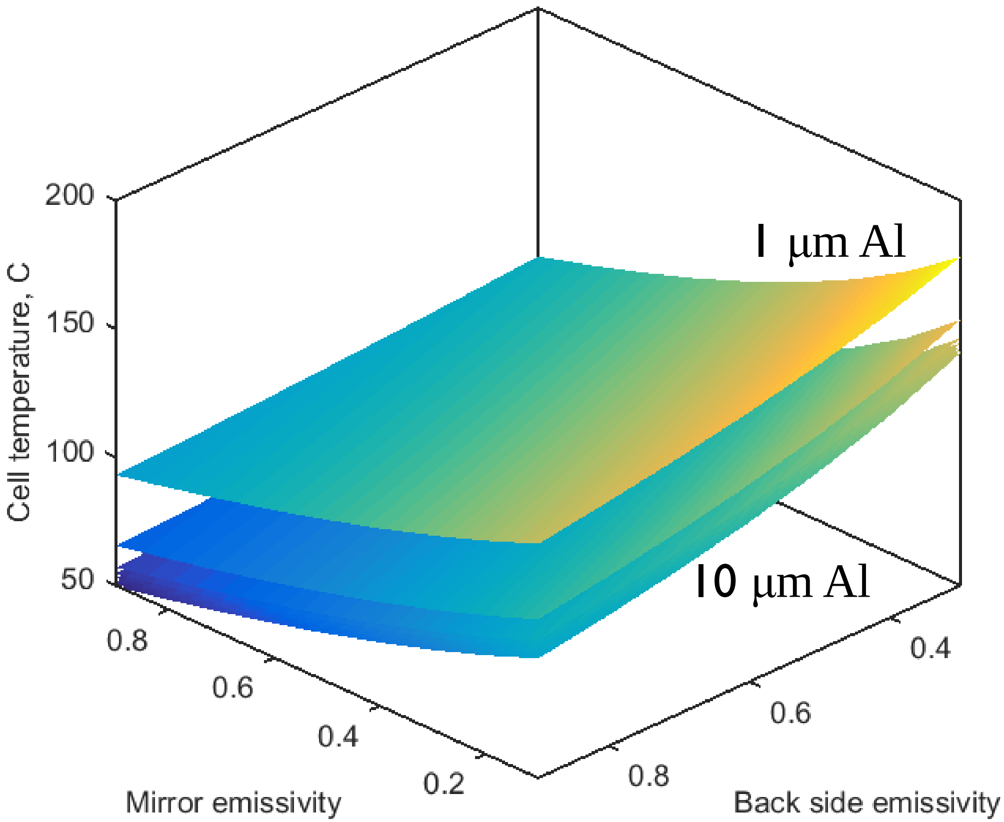
# Controlling cell temperature

10 suns, 650 W/m$^2$ cell heat load (3J IMM at one sun)




Affect temperature with:

Mirror emissivity

Back side emissivity

Aluminum thickness

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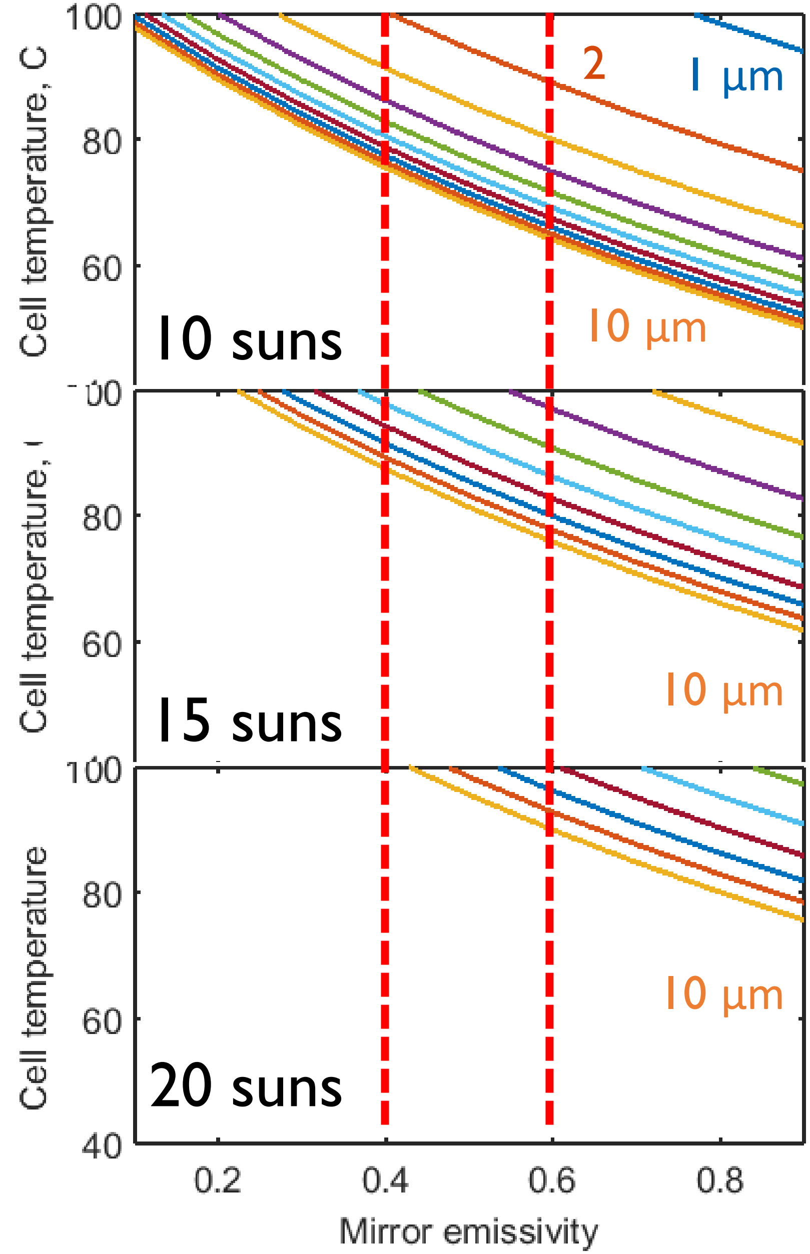
# Thermal Modelling

All assume:

- **650 W/m²** heat load (3J IMM)
- Back side emissivity 0.85

For mirror emissivity of 0.4 to 0.6 :

- Cell temps under 100 C with 3 um Al at 10 suns
- At 15 suns
  - 80 C with 10 µm Al
  - 100 C with 4 µm Al
- At 20 suns
  - 90 C with 10 µm Al
  - 100 C with 7 µm Al

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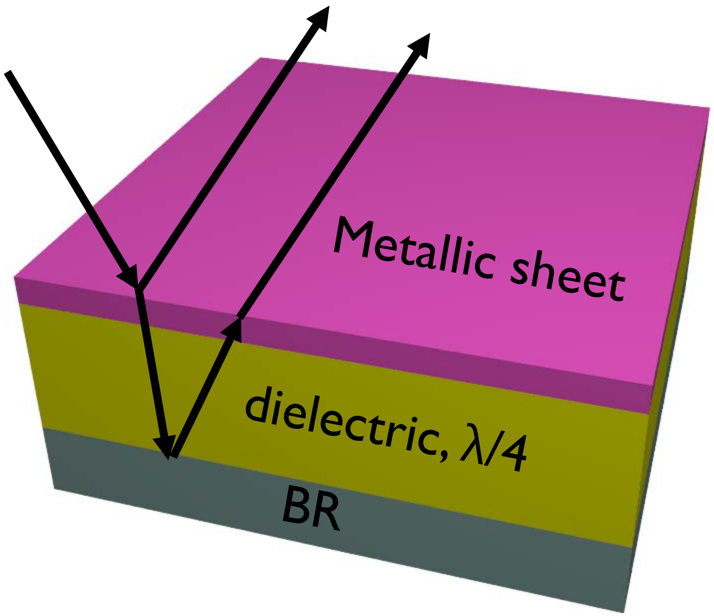
# Salisbury Screen




*Salisbury, US 2599944 (A), 1952*

Flat structure: easily implemented

Potential for low mass per unit area

Recently reported to be broadband in IR

*Hocer et al, Scientific Reports Vol 5, No. 8157, 2015*

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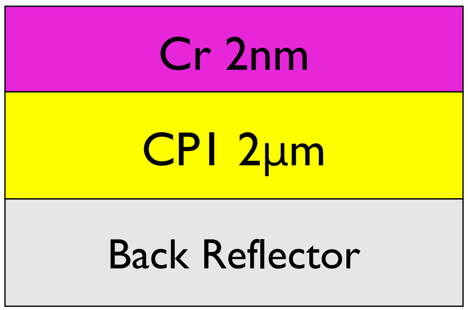
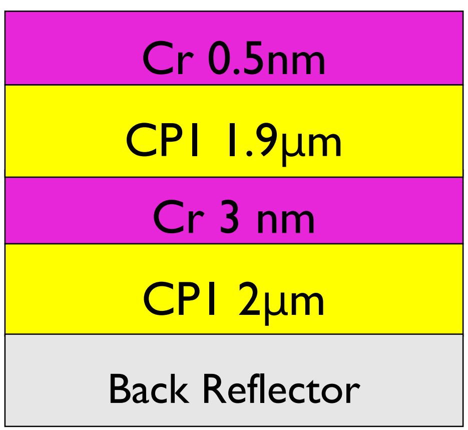
# Backside Emitter Optimization

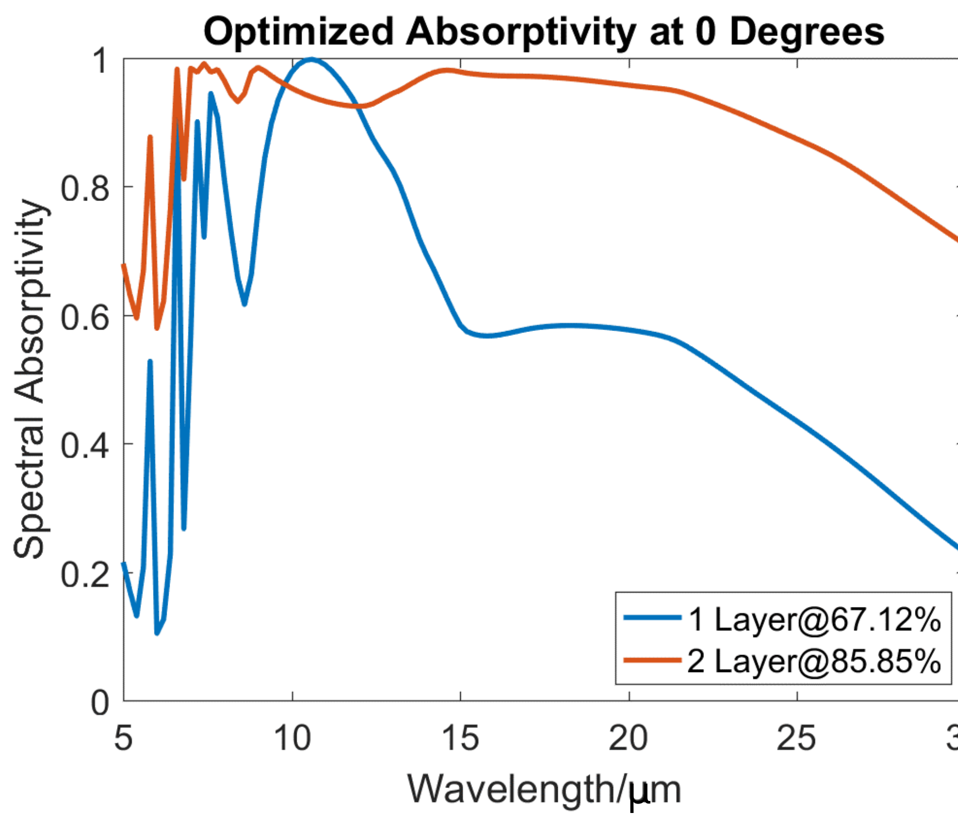
Vary thicknesses of Cr and CP1 to maximize Absorptivity
Additional layer added to increase Absorptivity over the spectrum



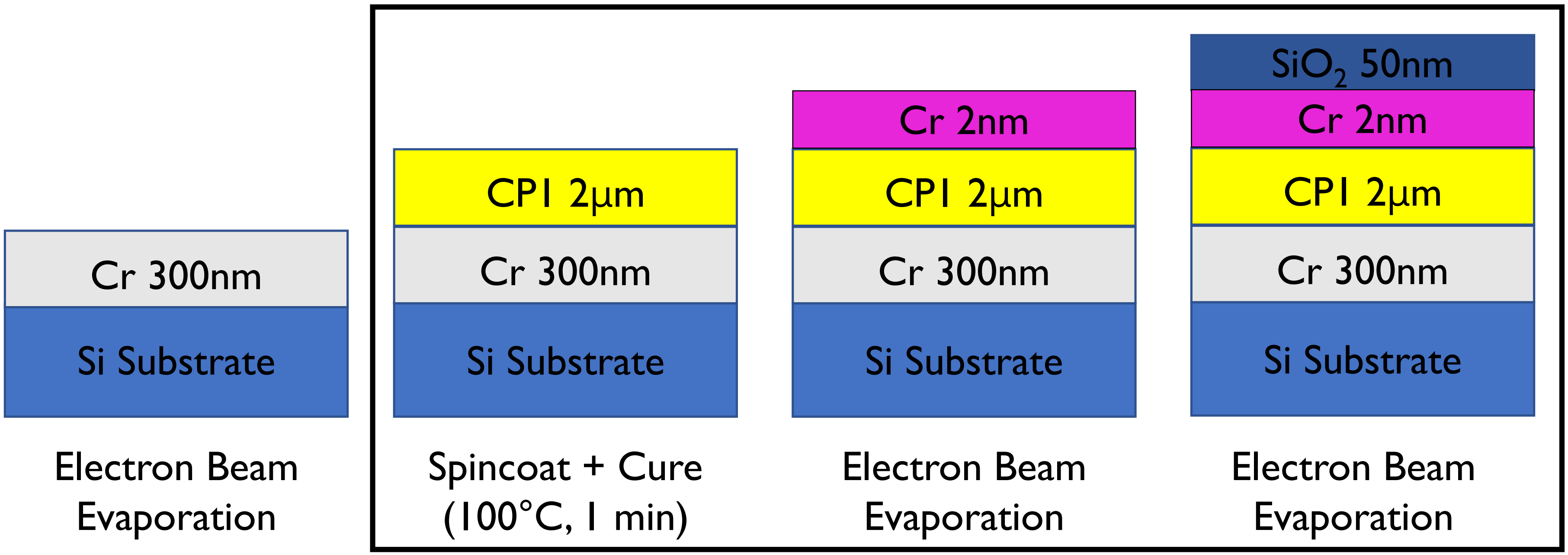

1 Layer Salisbury Screen




2 Layer Salisbury Screen



# Salisbury Screen Fabrication




Repeat Again for 2 Layer Salisbury Screen with appropriate thicknesses

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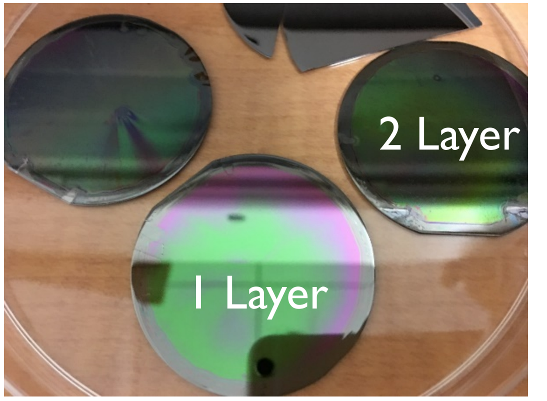
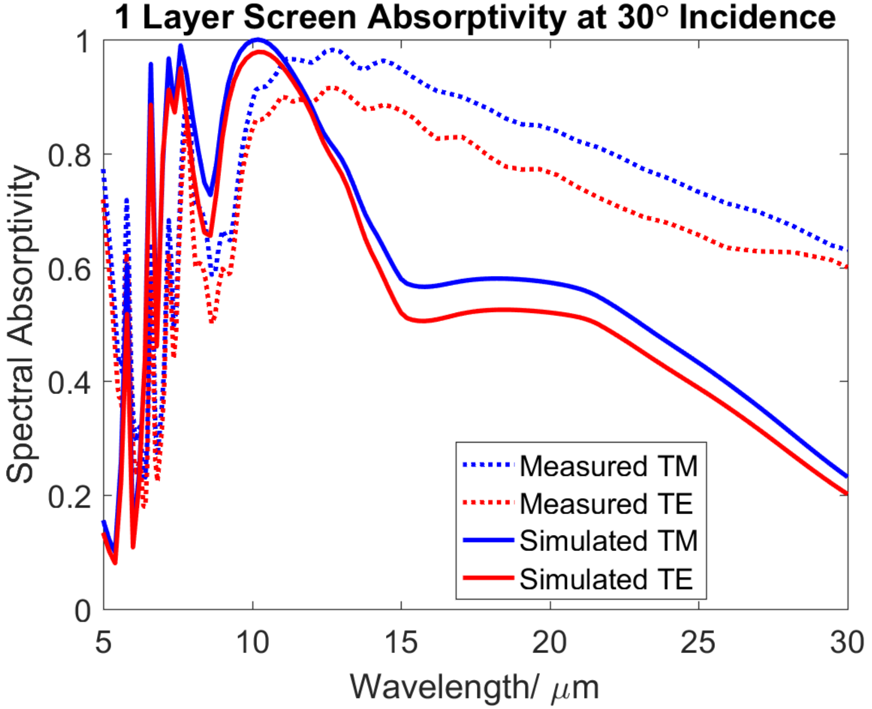
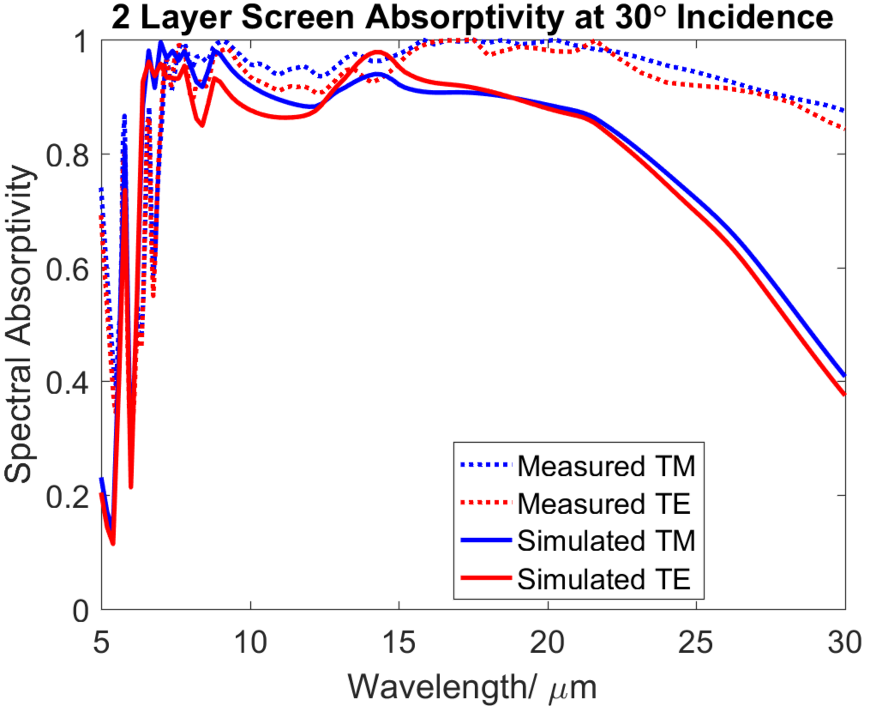
# Backside Emitter Results




Average Measured: 77.61%
Simulated: 67.12%
Areal Density: 3.3 $gm^{-2}$




Average Measured: 92.69%
Simulated: 85.85%
Areal Density: 6.0 $gm^{-2}$

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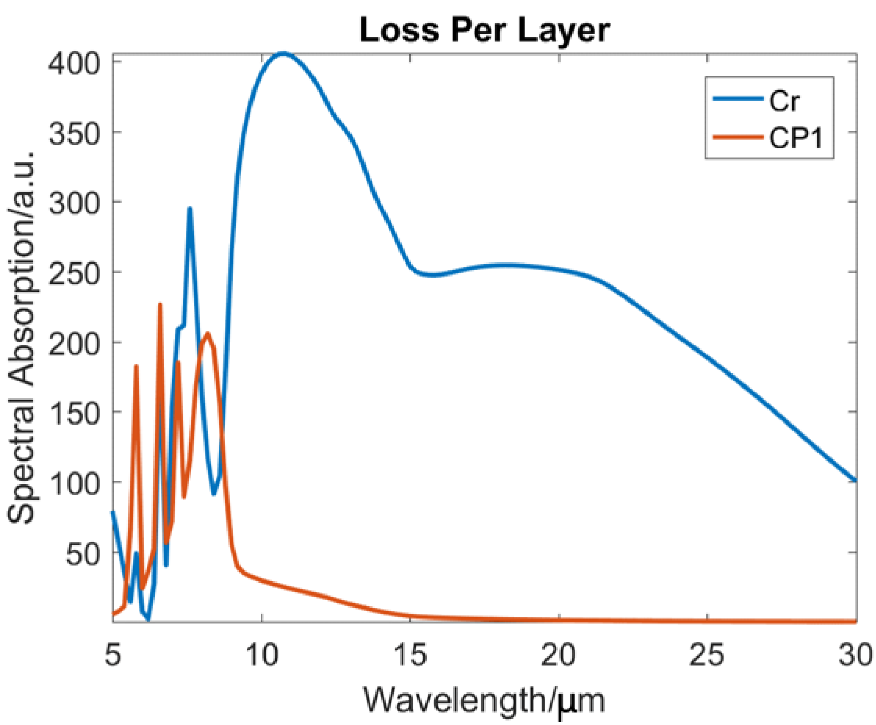
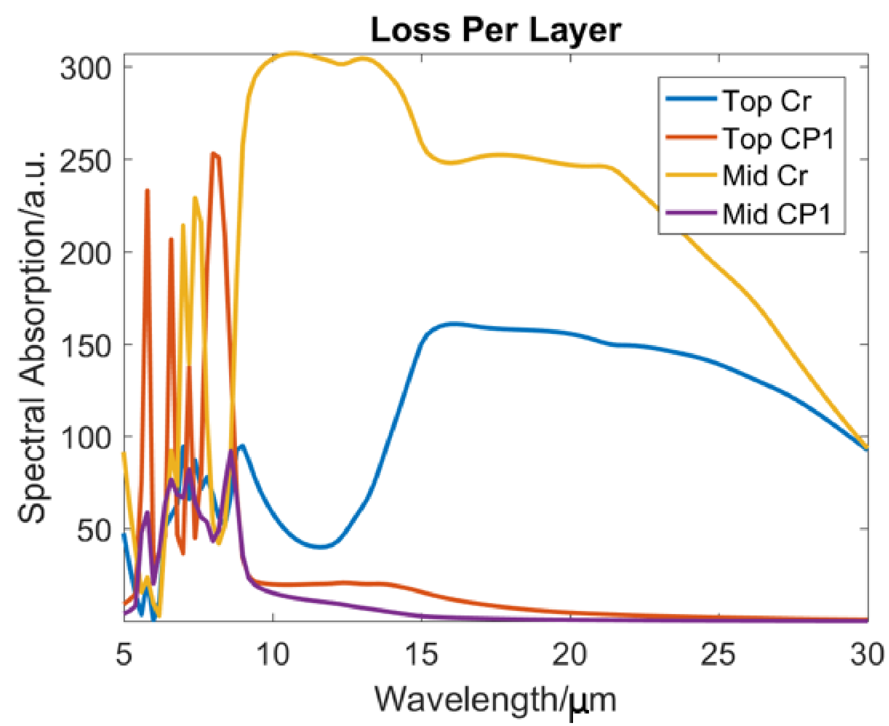
# Salisbury Screen Simulated Layer-by-Layer Analysis

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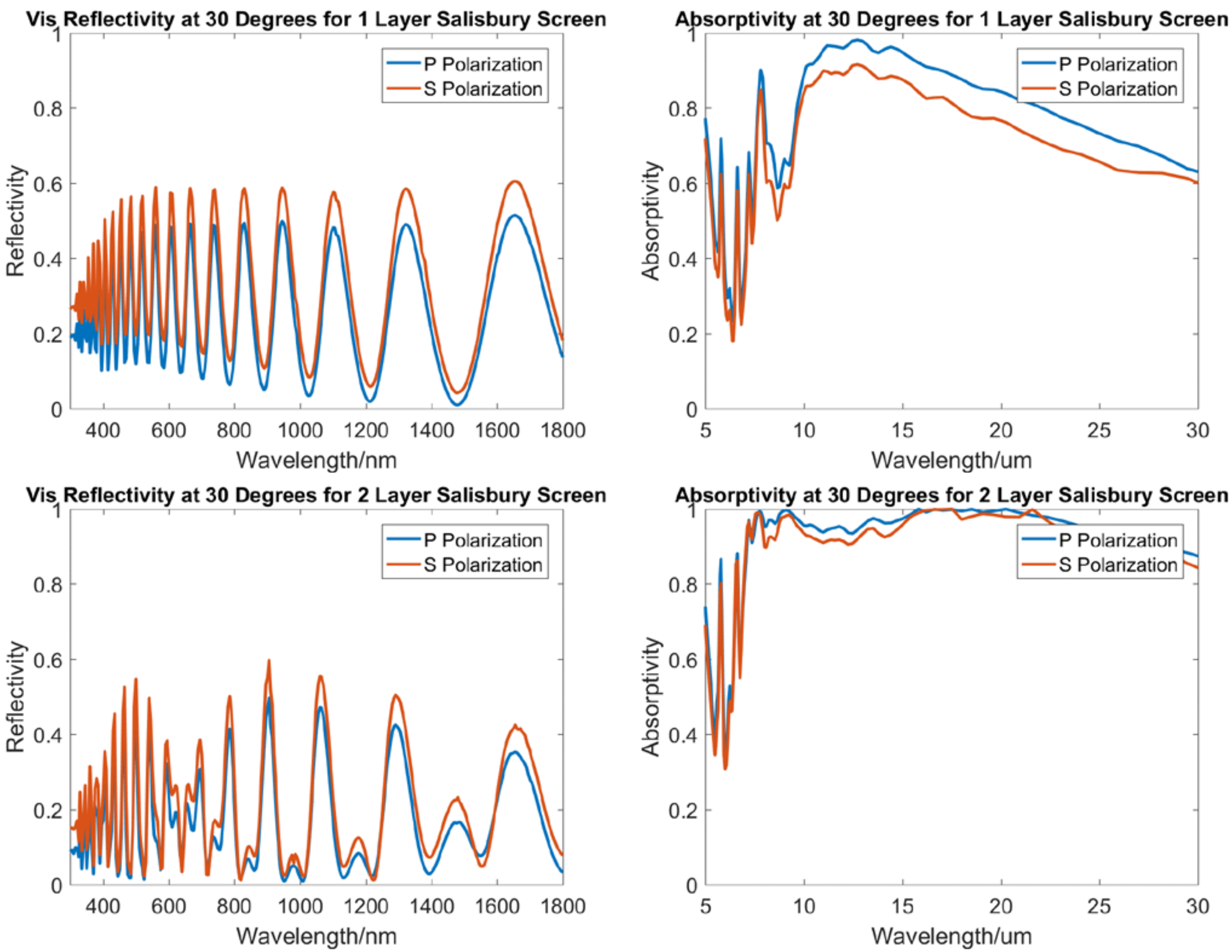
# Need for a Frontside Emitter

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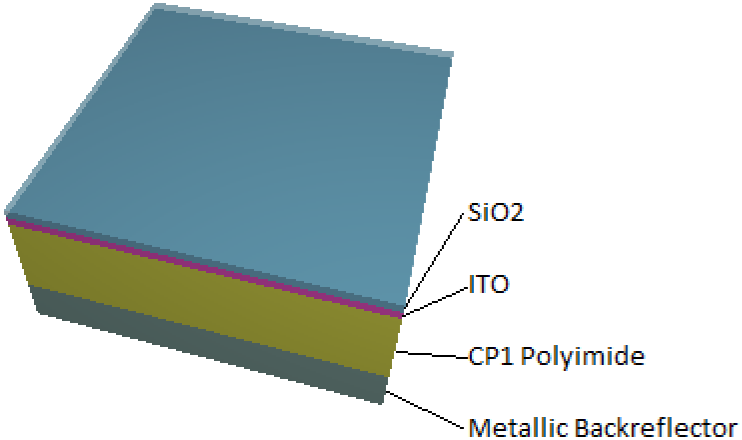
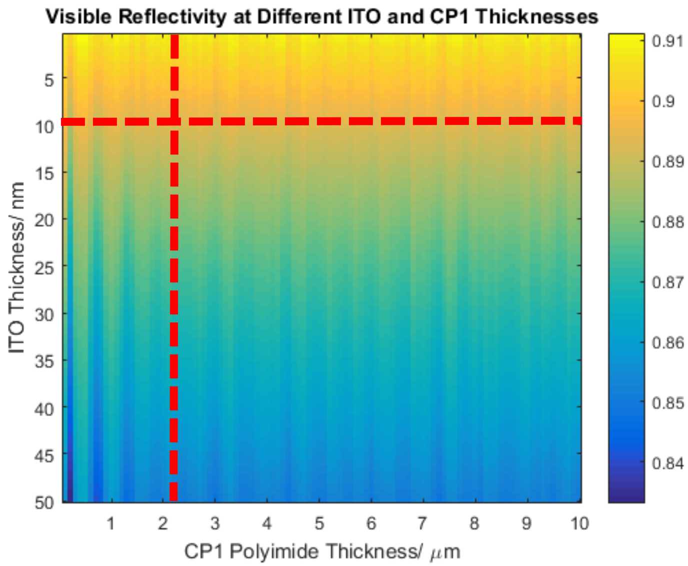
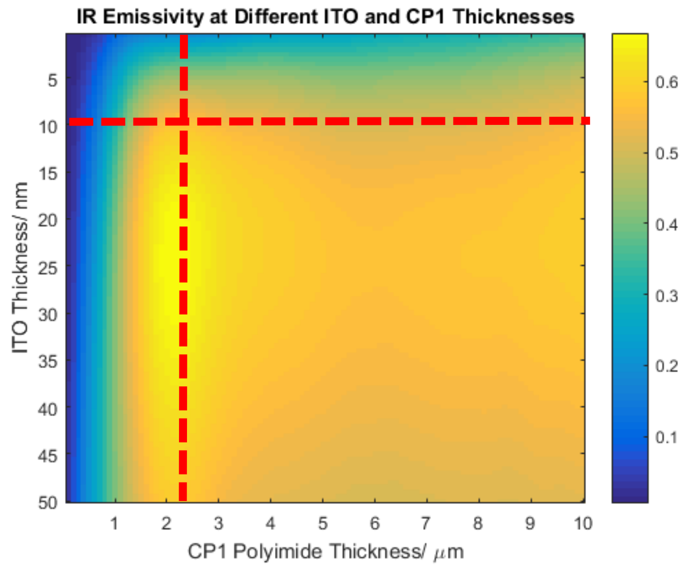
# ITO Emissive Mirror Optimization

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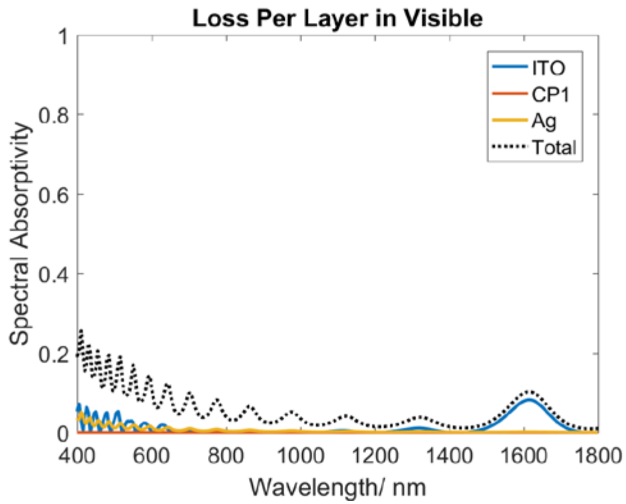
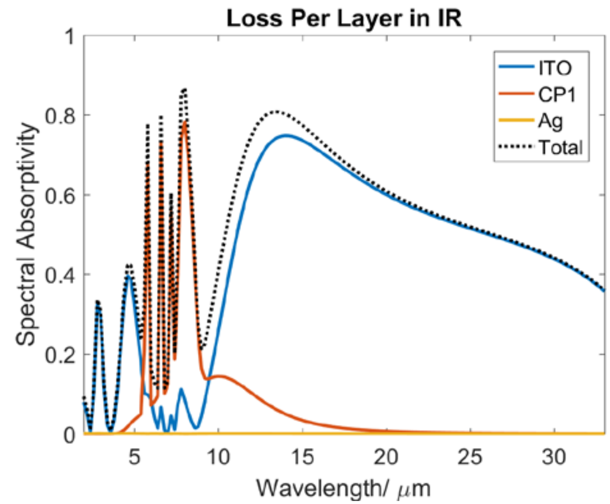
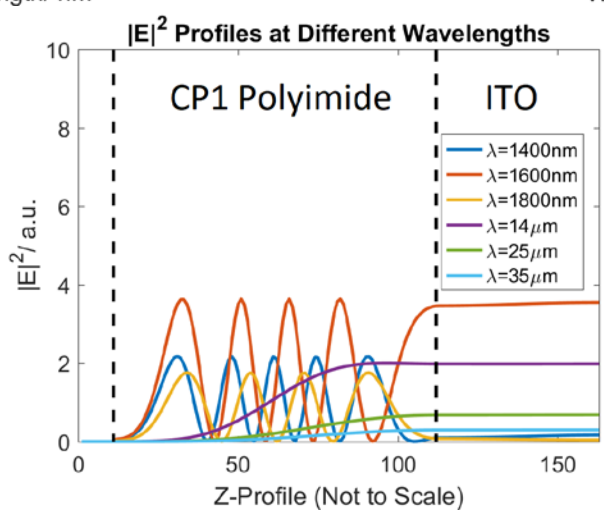
# ITO Emissive Mirror Simulations




**Calculated:**
Visible Reflectivity:
92.12%

IR Absorptivity:
57.73%

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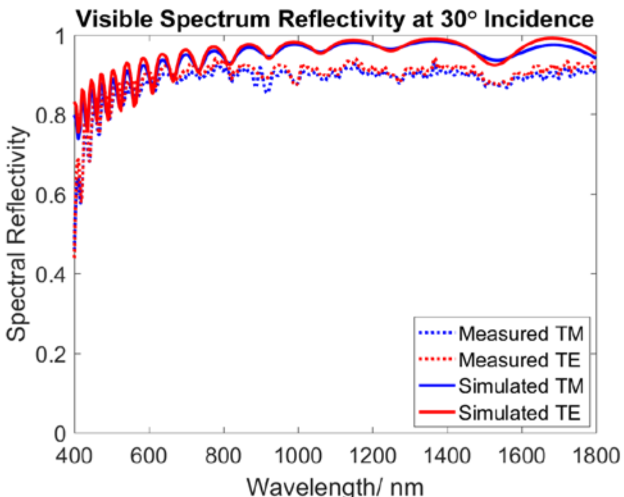
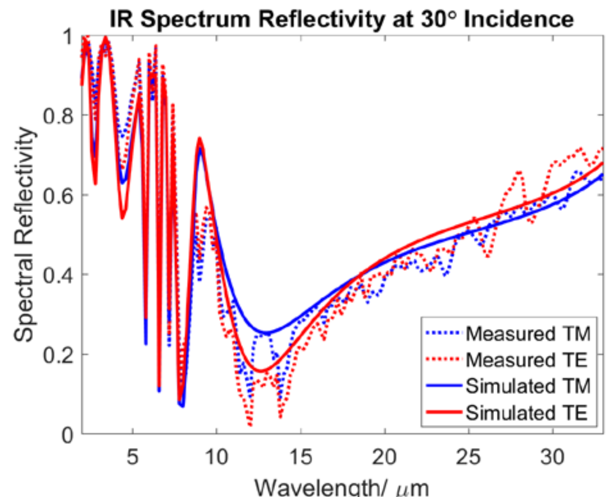
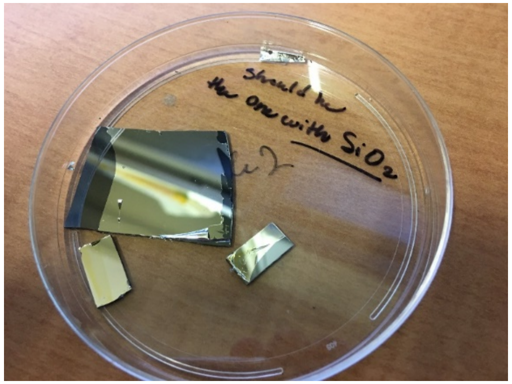
# ITO Emissive Mirrors Results




AREAL DENSITY:
4.07 $gm^{-2}$

**Calculated:**
Visible Reflectivity: 92.12%

IR Absorptivity: 57.73%

**Measured:**
Visible Reflectivity: 87.15%

IR Absorptivity: 62.06%

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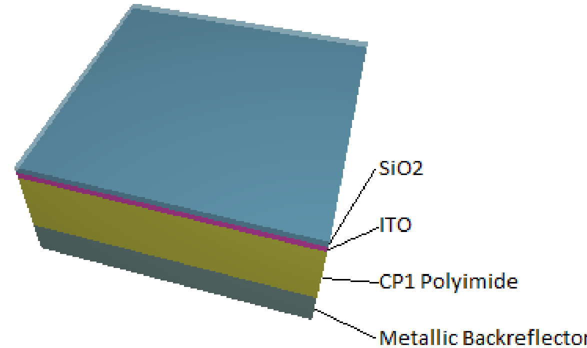
# State of the Art

| |
|---|
| Cr 2nm |
| CP1 2μm |
| Back Reflector |

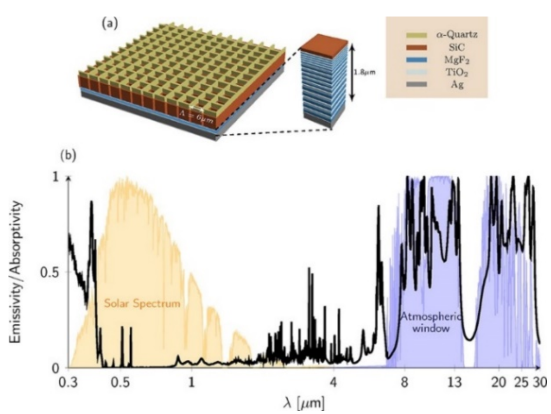
Measured Emissivity: 77.61%
Areal Density: 3.3 gm$^{-2}$

| |
|---|
| Cr 0.5nm |
| CP1 1.9μm |
| Cr 3 nm |
| CP1 2μm |
| Back Reflector |

Measured Emissivity: 92.69%
Areal Density: 6.0 gm$^{-2}$

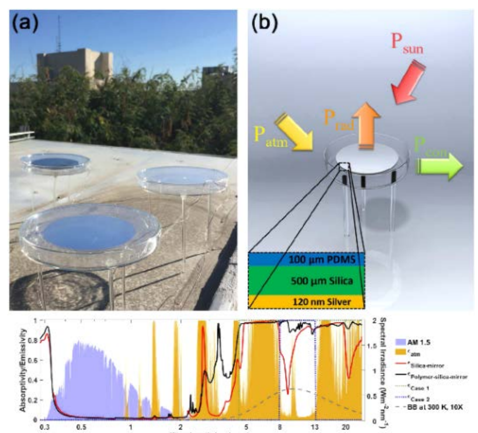



Visible Reflectivity: 87.15%
IR Absorptivity: 62.06%
Areal Density: 4.07 gm$^{-2}$



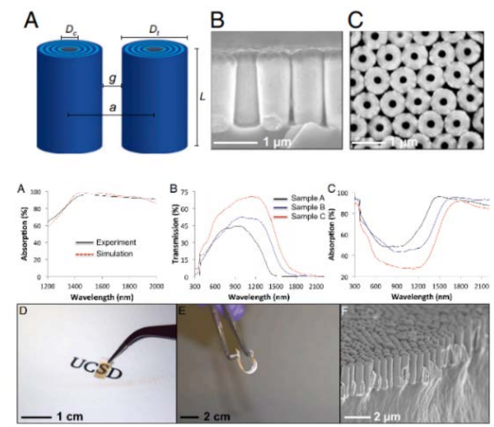

Rephaeli et al, Nano Lett. 13, 1457 (2013)

**Lithographically Complicated**




Kou et al, ACS Nanophot. 4, 626 (2017)

**High Areal Density: 1422.8 gm$^{-2}$**




Riley et al, PMAS 114, No. 6, 1624 (2017)

**Poor Visible Response**

# Thanks for Listening!

ACKNOWLEDGEMENTS:

Will Wheatney, Dagney Fleischmann and theAtwater Team

George Rossman, California Institute of Technology

Mark Kruer & the Northrop Grumman Team

Tom Tiwald, J. A. Woollam Ellipsometry

Lynn Rodman, Nexolve

Ryan France, NREL

SINGAPORE Agency for Science, Technology and Research

NORTHROP GRUMMAN

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