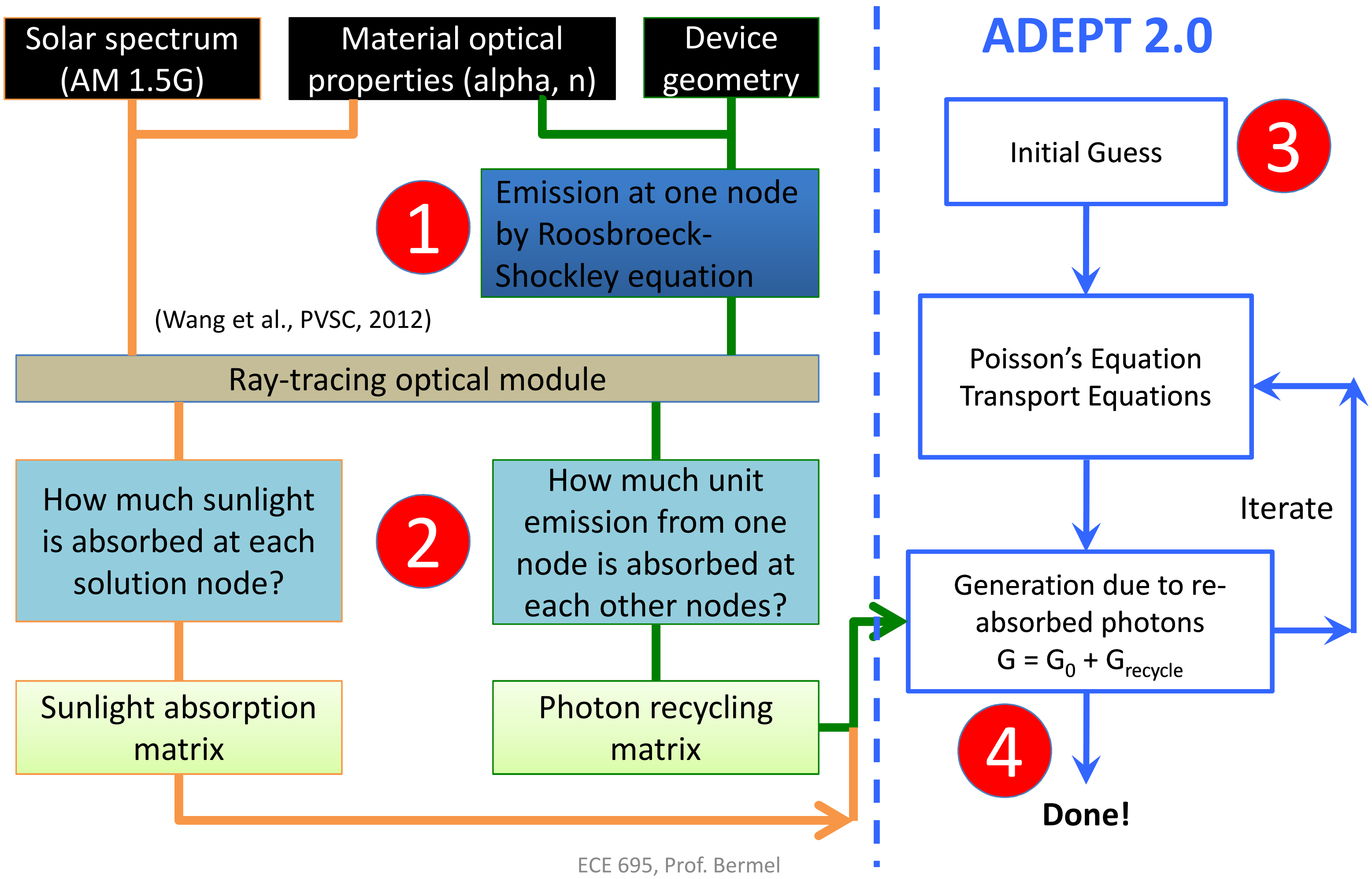
ECE 695
Numerical Simulations
Lecture 33: Finite-Difference Time Domain Band Structures

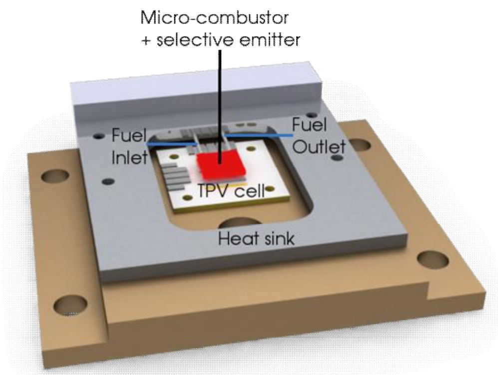
Prof. Peter Bermel

April 7, 2017

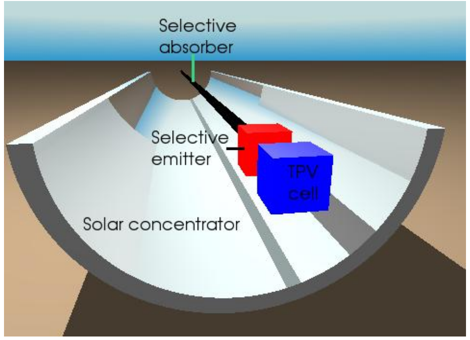
Recap from Wednesday: Photon-recycling in device simulator



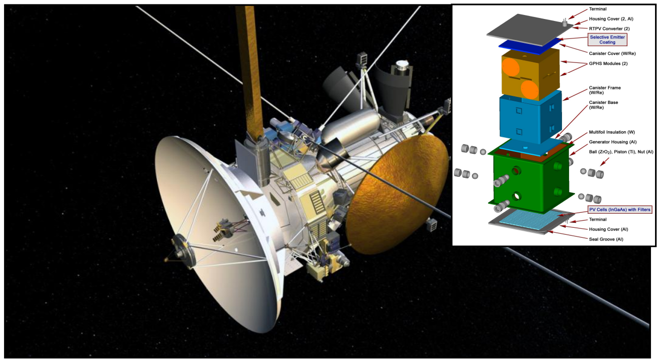
TPV Applications



Mobile TPV portable power generator*



Solar TPV utility scale electricity†



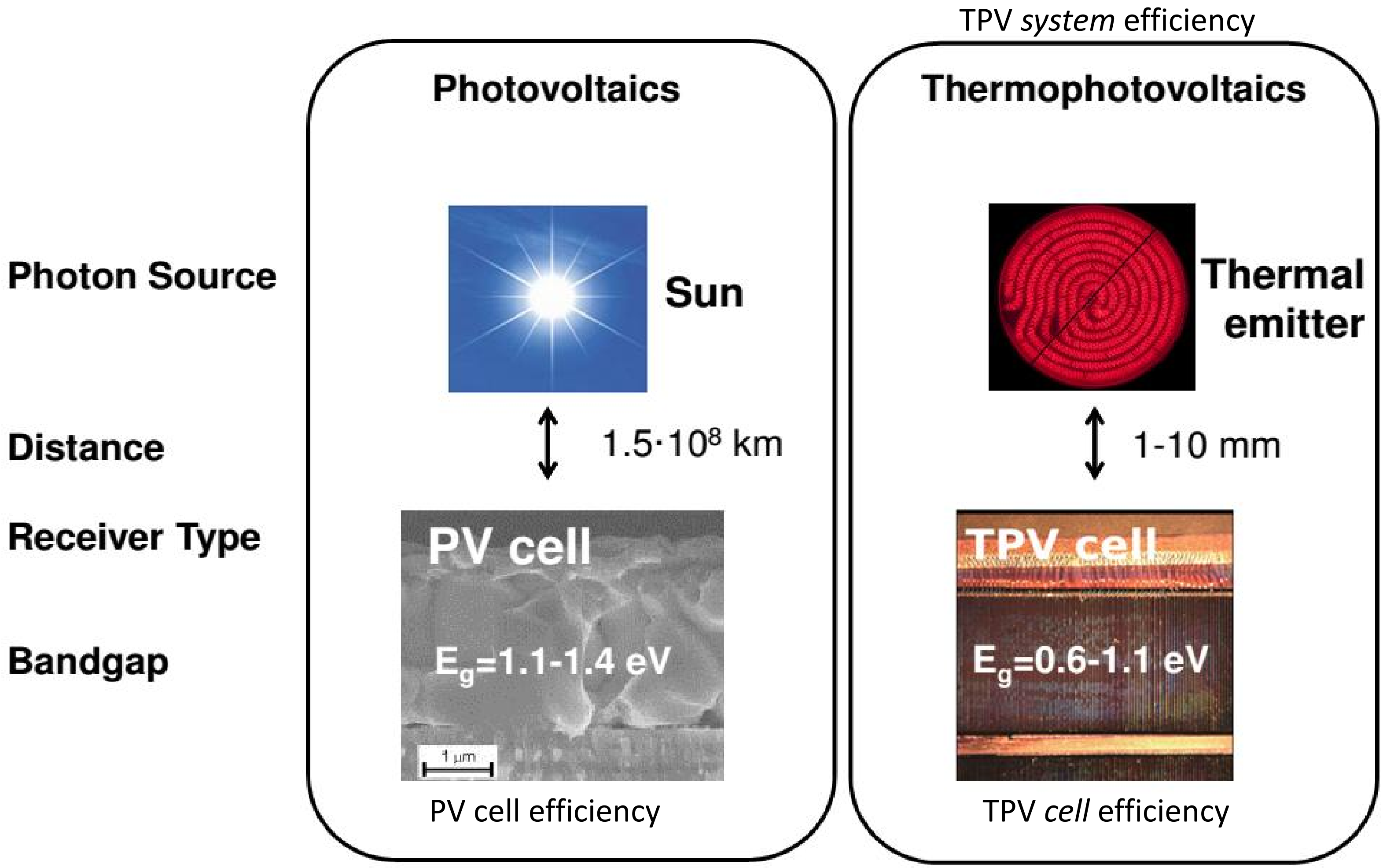
RTPV for long, remote missions‡

*R. Pilawa-Podgurski *et al.*, *APEC* **25**, 961 (2010); W.R. Chan, P. Bermel *et al.*, *Proc. Natl. Acad. Sci.* (2013)

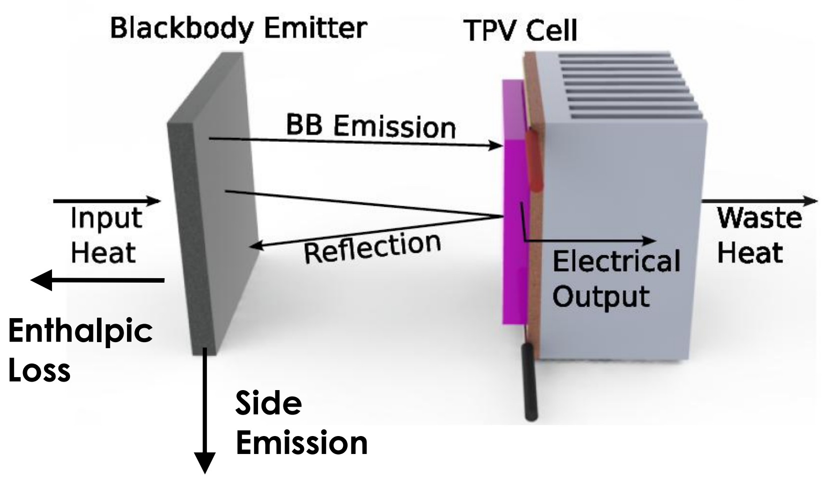
† M. Castro *et al.*, *Solar Energy Mater. Solar Cells* **92**, 1697 (2008); E. Rephaeli & S. Fan, *Opt. Express* **17**, 15145 (2009)

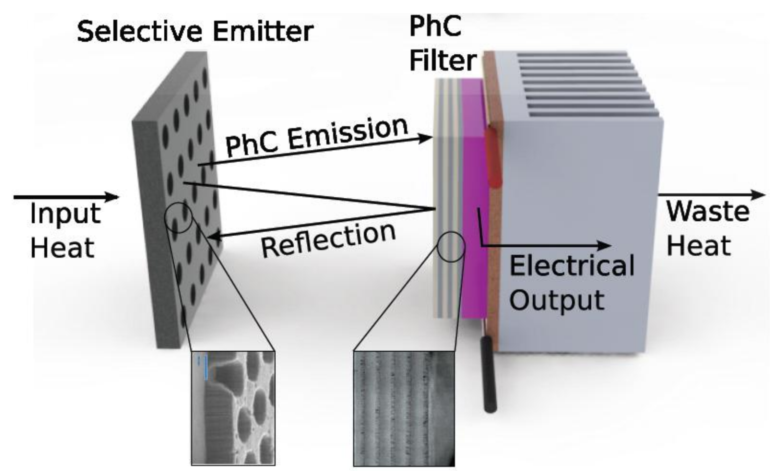
‡ A. Schock *et al.*, *Acta Astronaut.* **37**, 21 (1995); S.-Y. Lin *et al.*, *Appl. Phys. Lett.* **83**, 380 (2003); D. Wilt *et al.*, *AIP Conf. Proc.* **890**, 335 (2007)

What Makes TPV Different from PV?



Photonic Crystals Can Greatly Improve TPV Performance



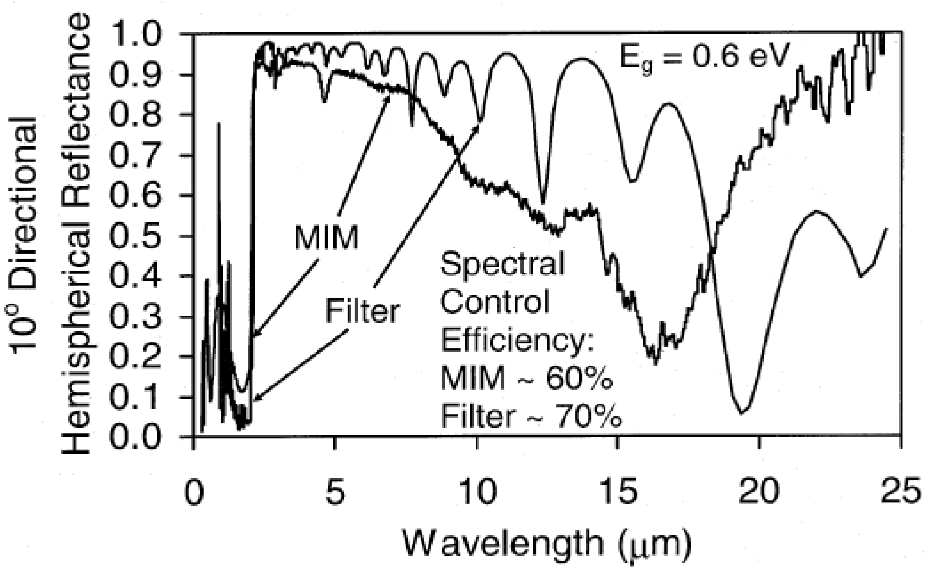


Traditional Approach:
- Photons emitted below TPV bandgap/off to side
- Overall efficiency low

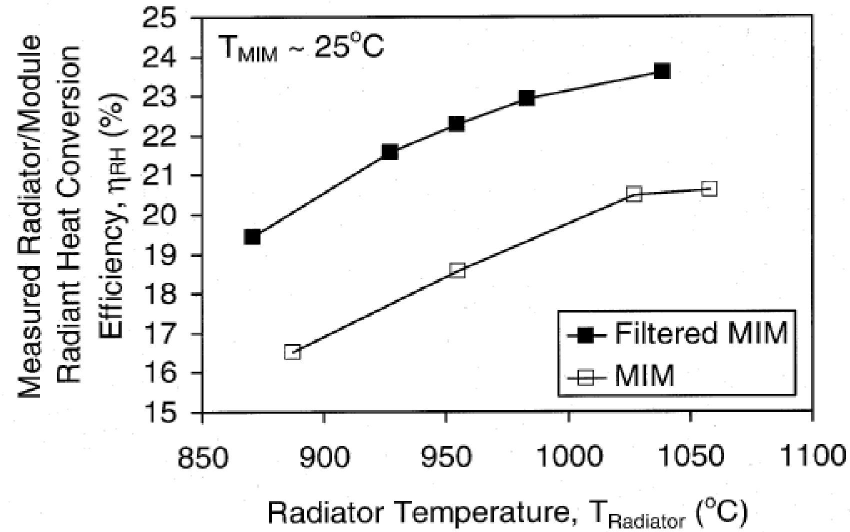
Current Approach:
- Photons emitted above TPV bandgap or reused
- Overall efficiency high

P. Bermel *et al.*, *Opt. Express* **18**, A314 (2010)

23% Demonstrated TPV Electric Generation Efficiency with Spectral Control



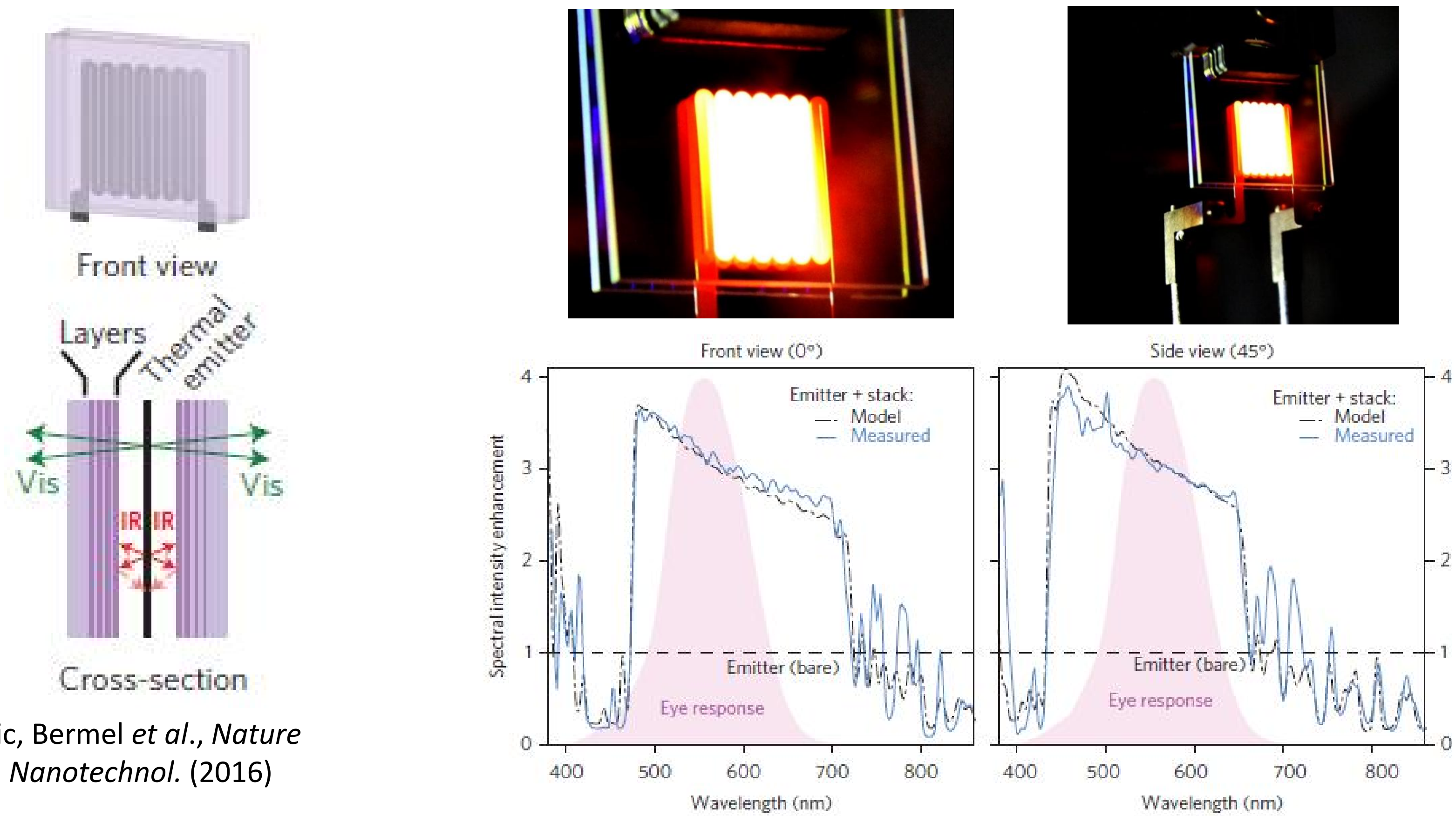
Reflection spectrum for optical filter and receiver



Efficiency in converting radiation to electricity

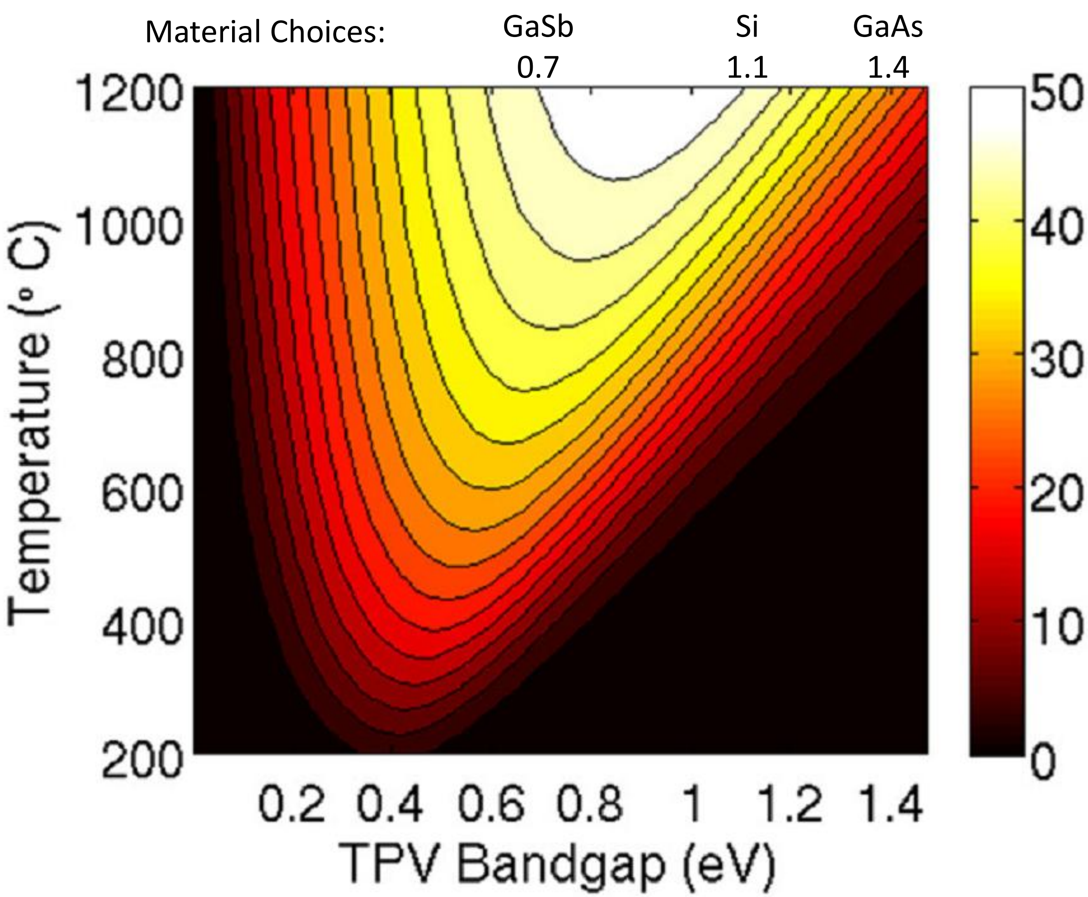
B. Wernsman *et al.*, *IEEE Trans. Electron Dev.* **51**, 512 (2004)

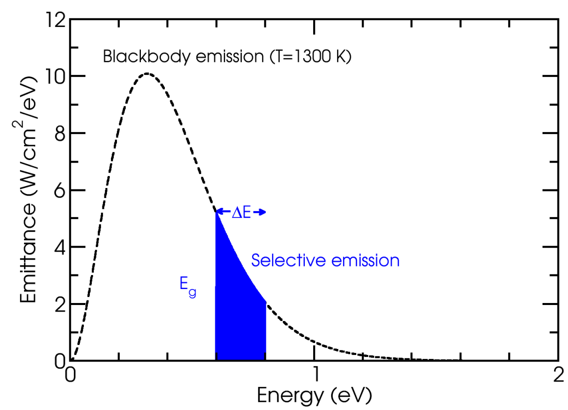
Photon Recycling Can Greatly Reshape High Temperature Thermal Emission



Ilic, Bermel *et al.*, *Nature Nanotechnol.* (2016)

TPV Efficiencies May Approach 52%* at Reasonable Temperatures†



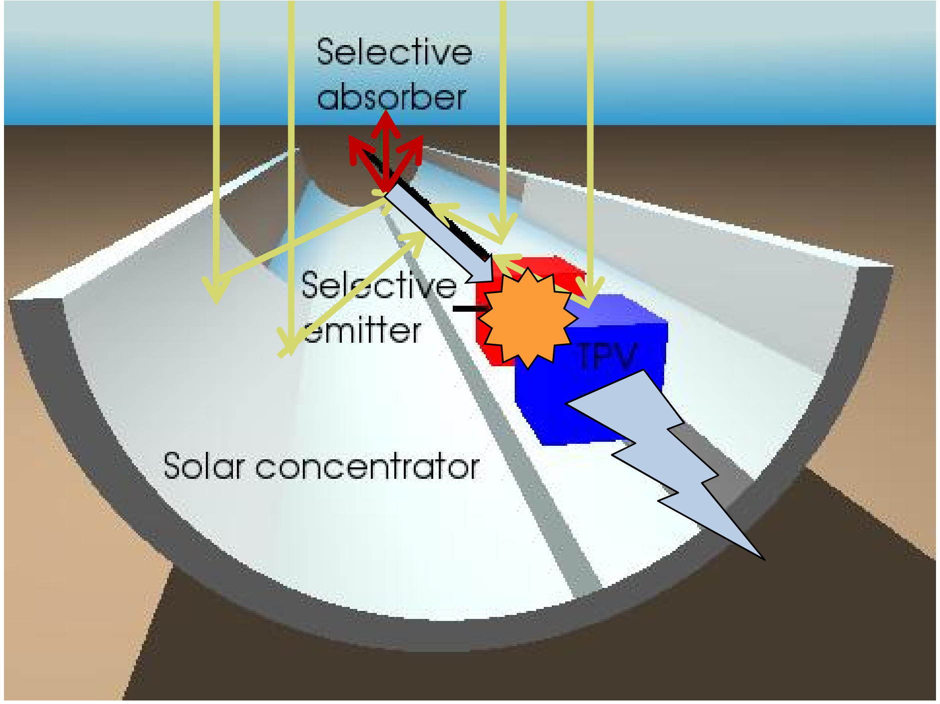


*Using highly selective emitters shown above, with MOVPE-grown GaSb TPV cells

† World record $\eta = 23\%$ at 1050 °C

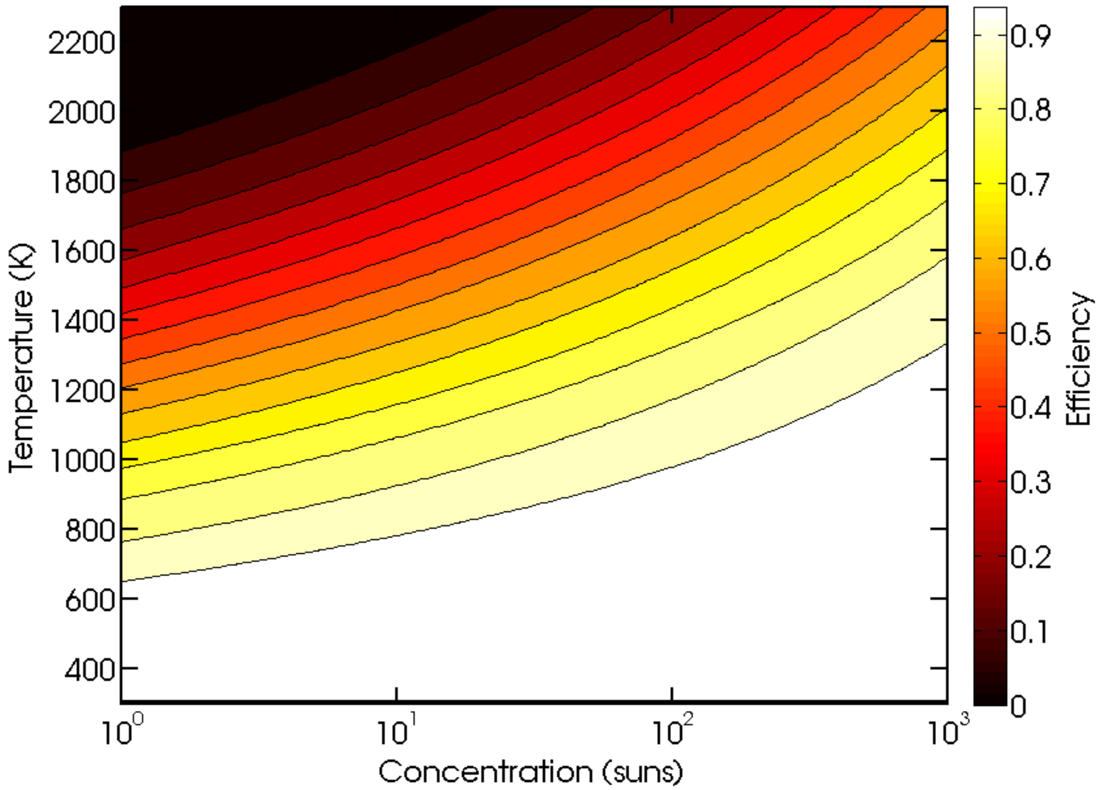
B. Wernsman *et al*., *IEEE Trans. Electron Dev.* **51**, 512 (2004)

Solar Thermophotovoltaics: System Design



M. Castro *et al.*, *Solar Energy Mater. Solar Cells* **92**, 1697 (2008)
P. Bermel *et al.*, *Opt. Express* **18**, A314 (2010).
D. Chester *et al.*, *Opt. Express* **19**, A245 (2011).
Z. Zhou, P. Bermel *et al.*, *J. Nanophotonics* (2016).

Selective Absorber: Maximum Thermal Transfer Efficiency



P. Bermel *et al.*, *Ann. Rev. Heat Transfer* (2012).

Thermal Transfer Efficiency

$$\eta_t = B\overline{\alpha} - \frac{\overline{\epsilon}\sigma T^4}{CI}$$

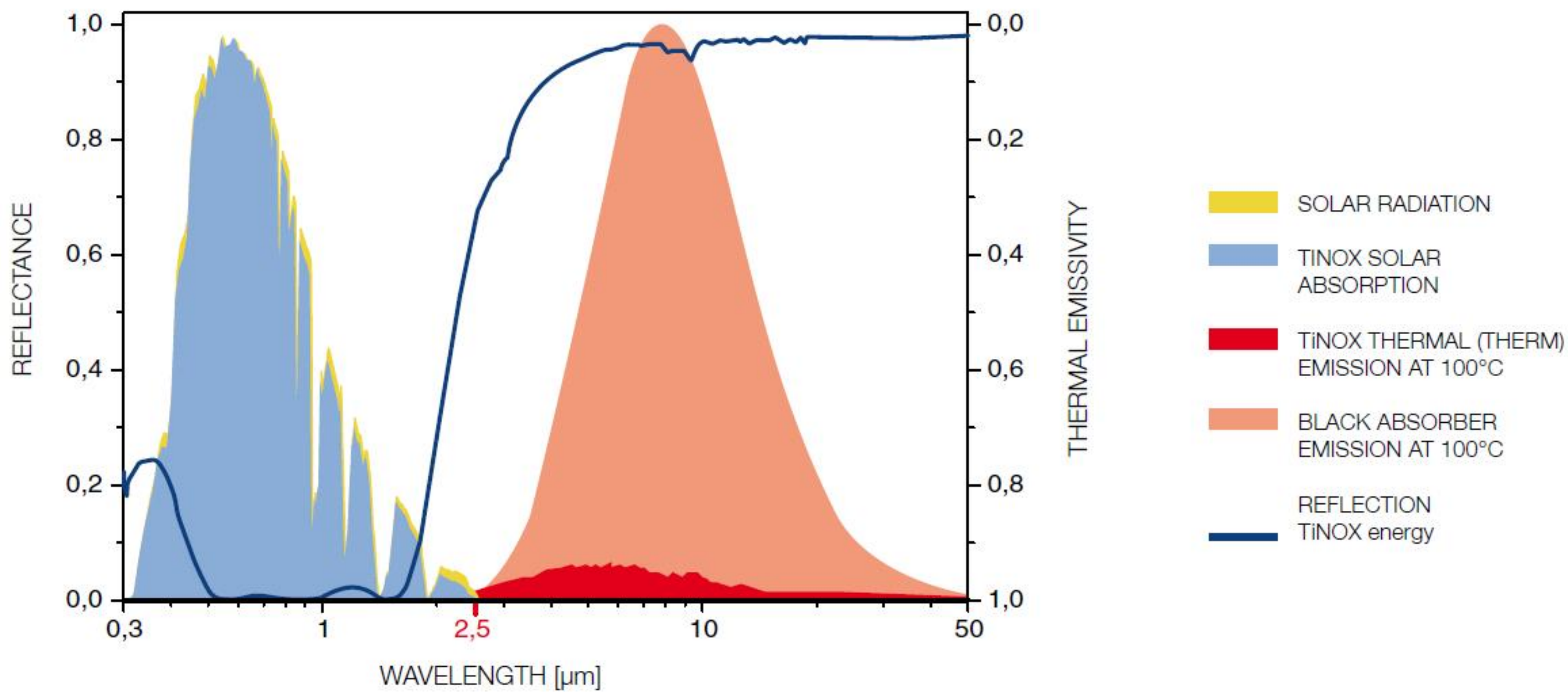
Spectrally-averaged absorptivity

$$\overline{\alpha} = \frac{1}{I}\int_0^\infty d\lambda \int_0^{\theta_c} d\theta \left[\epsilon(\lambda,\theta)\sin 2\theta \frac{dI}{d\lambda}\right]$$

Spectrally-averaged emissivity

$$\overline{\epsilon} = \frac{1}{\sigma T^4}\int_0^\infty d\lambda \int_0^{\pi/2} d\theta \left\{\frac{2hc^2\epsilon(\lambda,\theta)\sin 2\theta}{\lambda^5\left[e^{hc/\lambda kT}-1\right]}\right\}$$

Best Commercial Selective Solar Absorbers: T=400 K (1 sun)

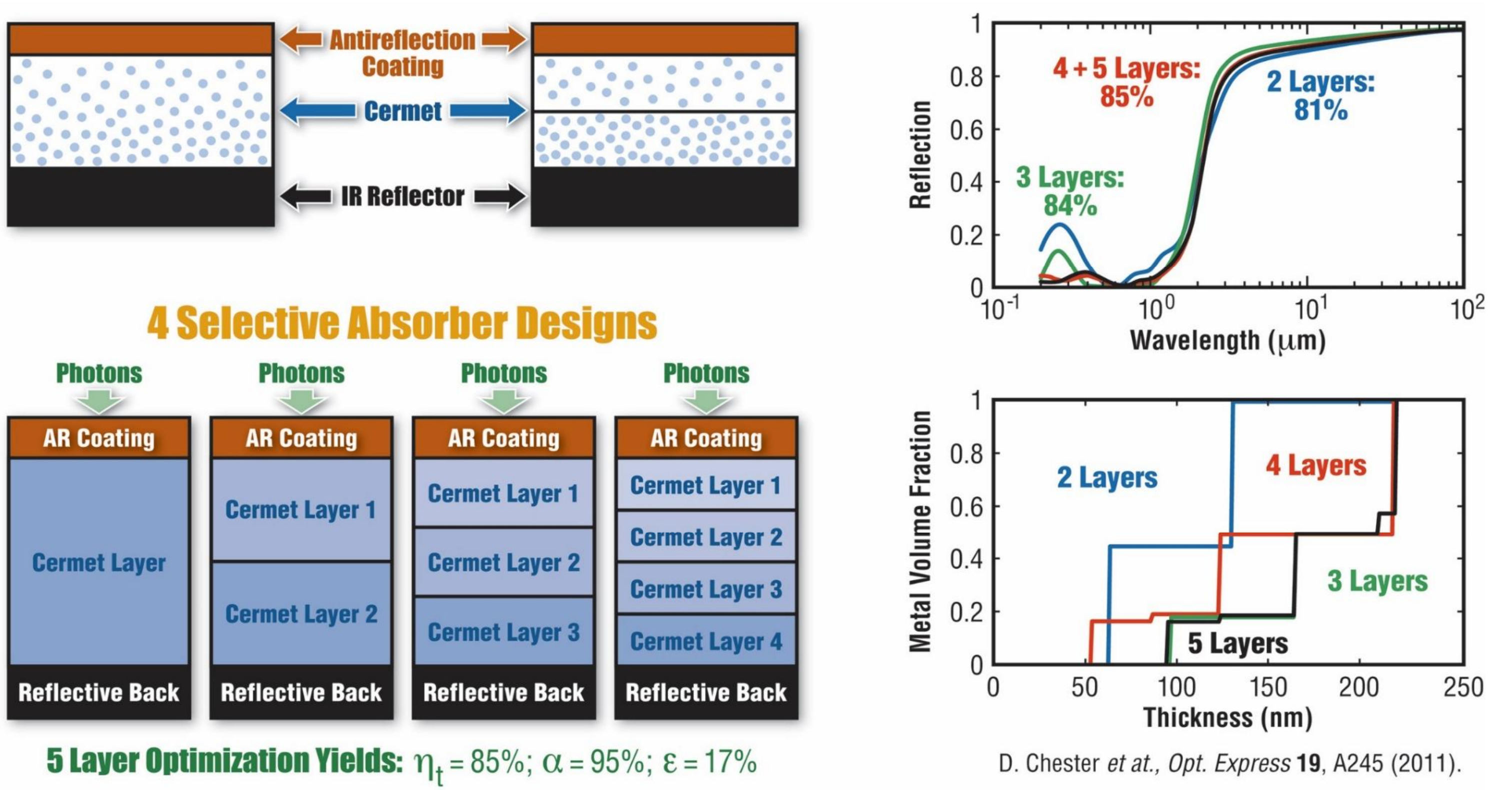


Almeco-TiNOX Solar

$\eta_t = 90\%;\ \alpha = 95\%;\ \varepsilon = 5\%$

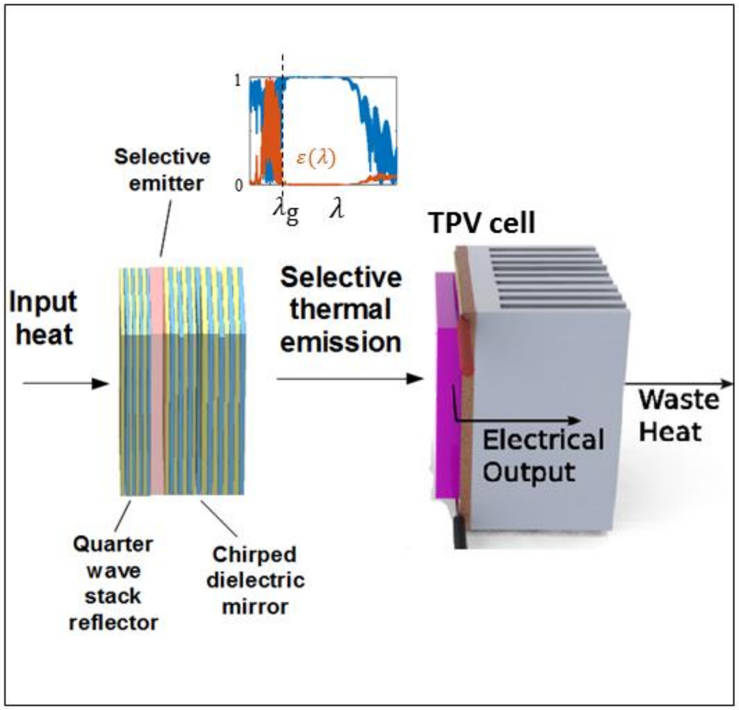
http://www.almecogroup.com/en/pagina/16-solar

Selective Solar Absorbers at T=1000 K (100 suns)

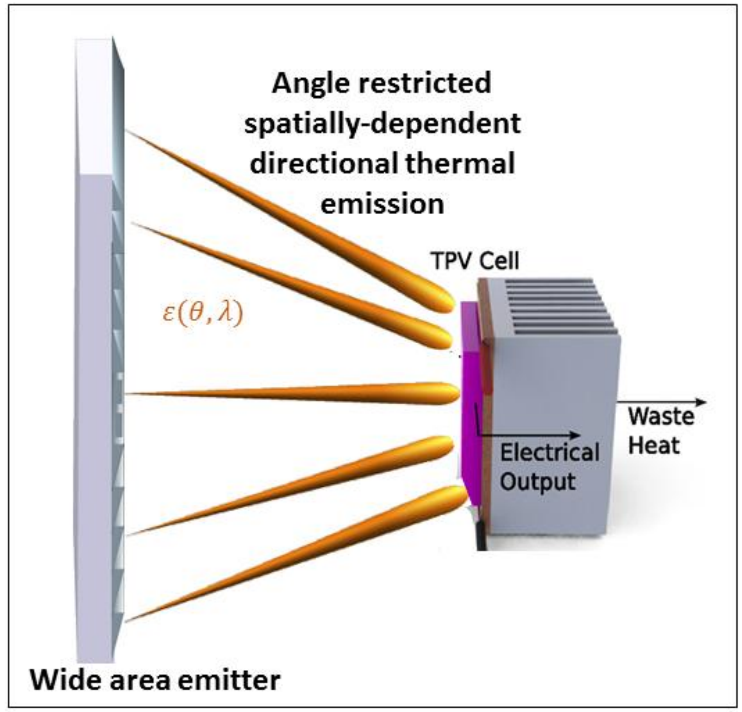


P. Bermel *et al.*, Energy Environ. Sci. (2016)

Angular Control over Thermal Emission

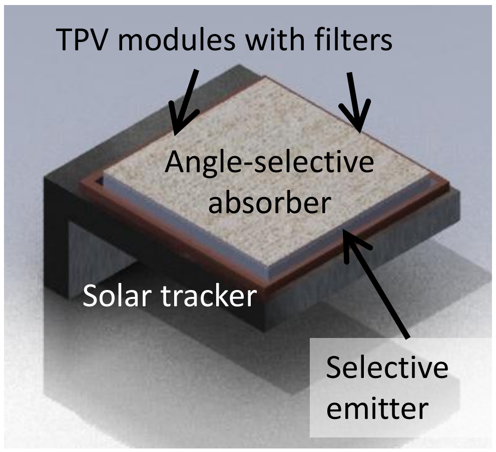


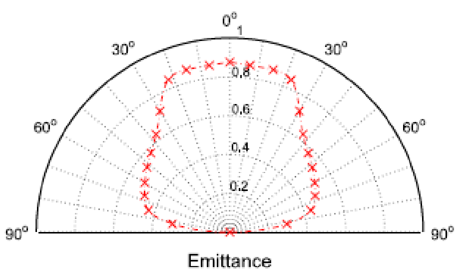
Wavelength-selective thermal emitters

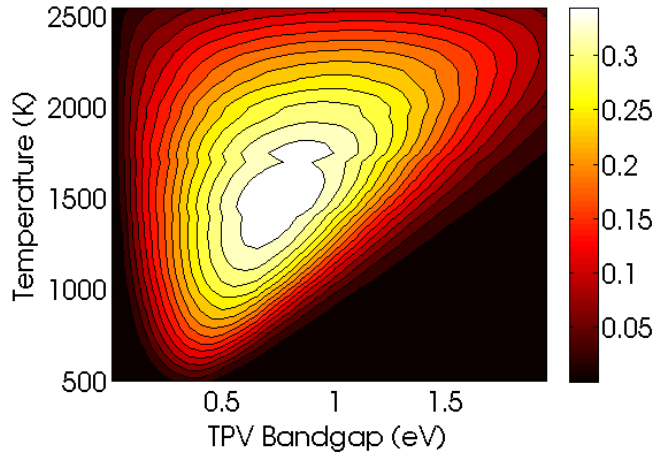


Can extend to angle, wavelength, and polarization-selective thermal emitters

Angular Selectivity Enables High Performance in Flat Plate (Unconcentrated) STPV





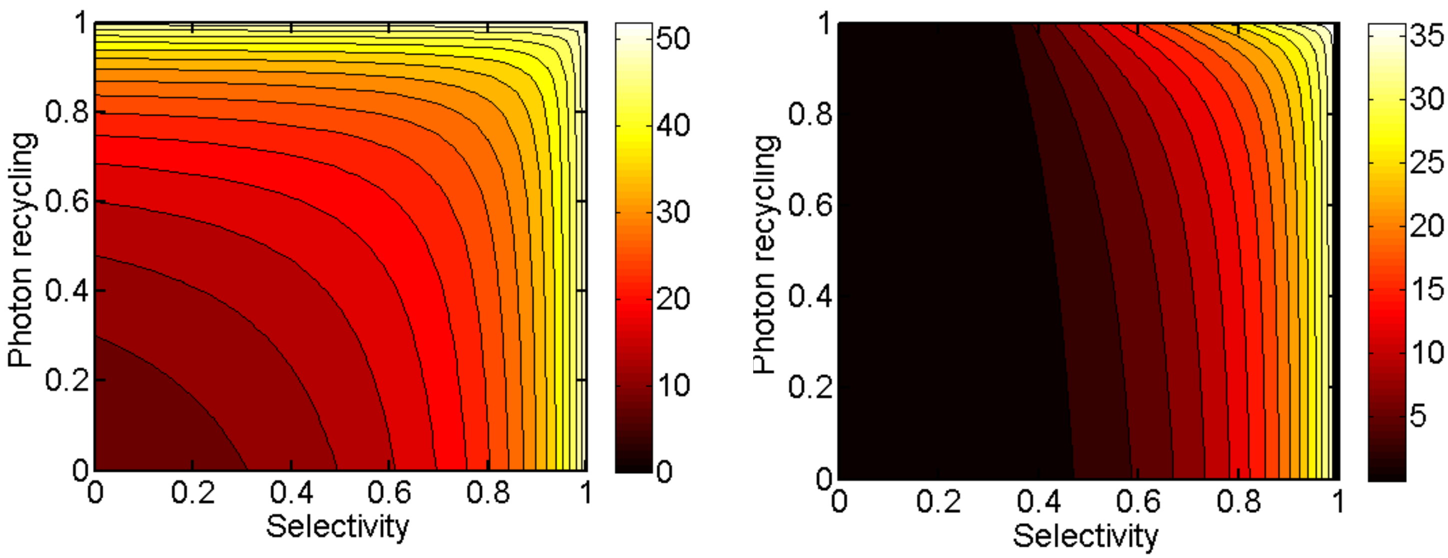


Solar concentration	θ_{max}	η_{max}
1	90°	10%
1000	**90°**	**43%**
1	**4°**	**37%**

P. Bermel *et al*., *Nanoscale Res. Lett.* **6**, 549 (2011)

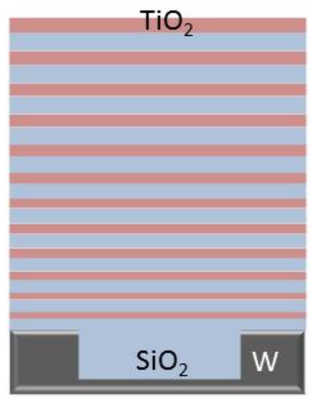
Benefits of Selective Emission + Photon Recycling for TPV

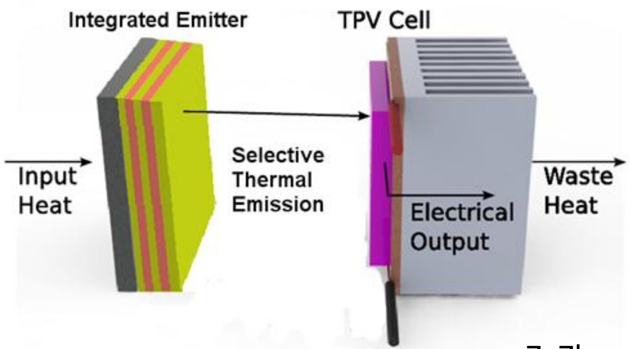
TPV Heat → Electricity | STPV Sunlight → Electricity



- Selective emission improves the fraction of power emitted above bandgap
- Photon recycling send below-bandgap photons back to the emitter for reabsorption
- Not mutually exclusive: **in most scenarios, having both would be preferable**
- Assumptions: 200 suns, 1573 K, E_g=0.75 eV, T_d=300 K

Integrated Filters for TPV





Z. Zhou *et al*., *Phys. Rev. Appl.*, 2015 (in preparation).

Integrate filter directly into selective emitter structure!

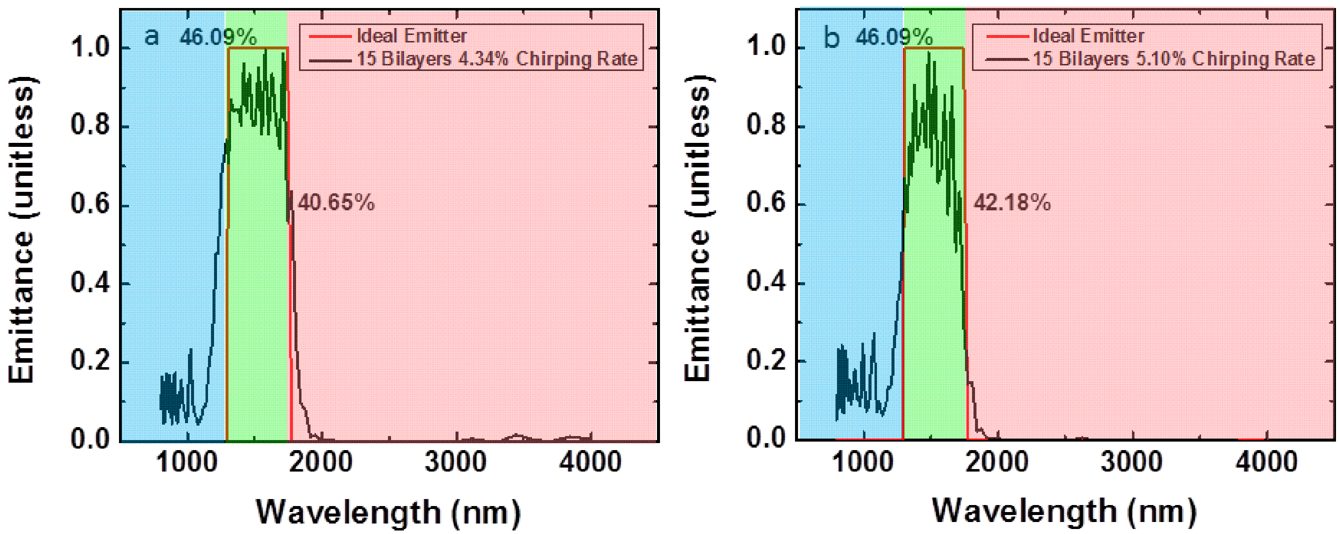
Advantages:

- Unprecedented control of thermal emission
- Lower sensitivity to view factor / allows waveguides
- Nanostructure stability at high temperature

Disadvantages:

- Potential damage from thermal expansion
- More complex fabrication

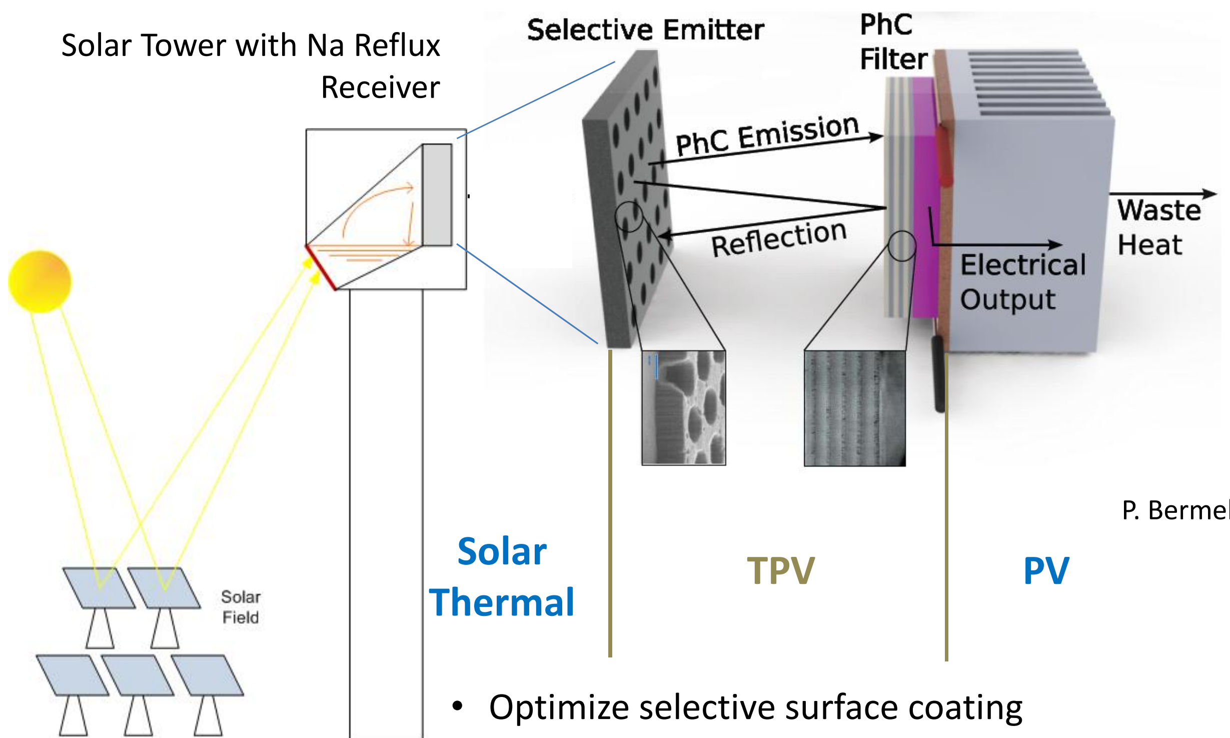
Increasing Useful Emission with Integrated Filters



Integrated Filter Structure	Conversion Efficiency	Total Efficiency Gap	Parasitic Emission	Insufficient Emission	Short-wavelength Emission
15-Bilayer 4.34% Chirped	40.56%	5.44%	3.77%	0.77%	0.90%
15-Bilayer 5.10% Chirped	42.18%	3.91%	1.48%	1.69%	0.74%

Z. Zhou *et al.*, *Phys. Rev. Appl.*, 2015 (submitted).

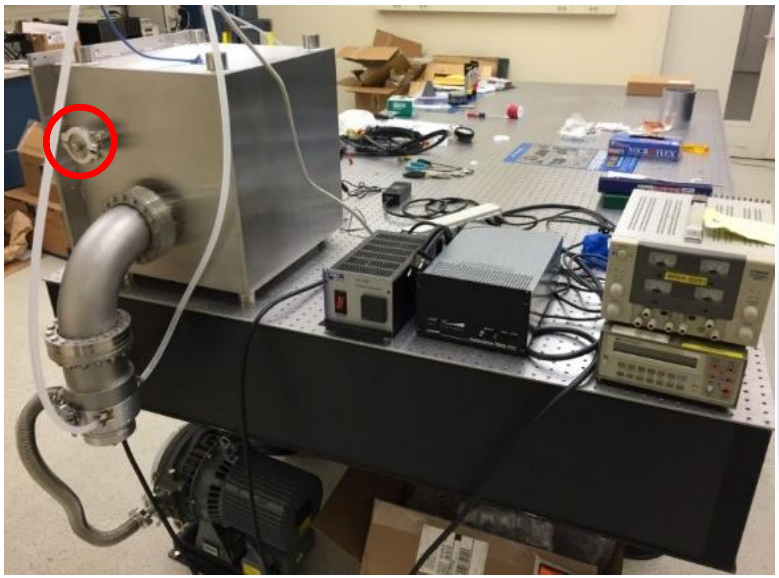
Dispatchable Solar TPV

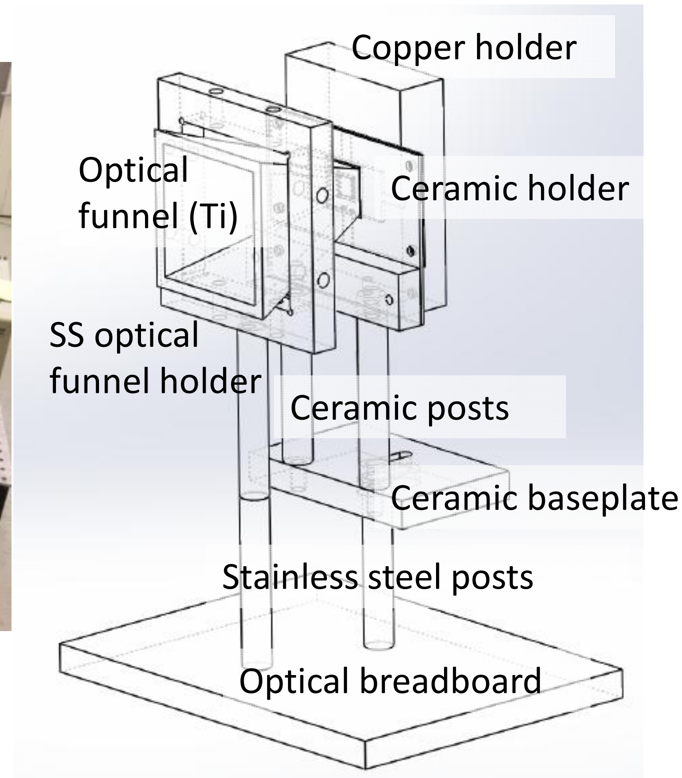


P. Bermel *et al.*, *Opt. Express* **18**, A314 (2010)

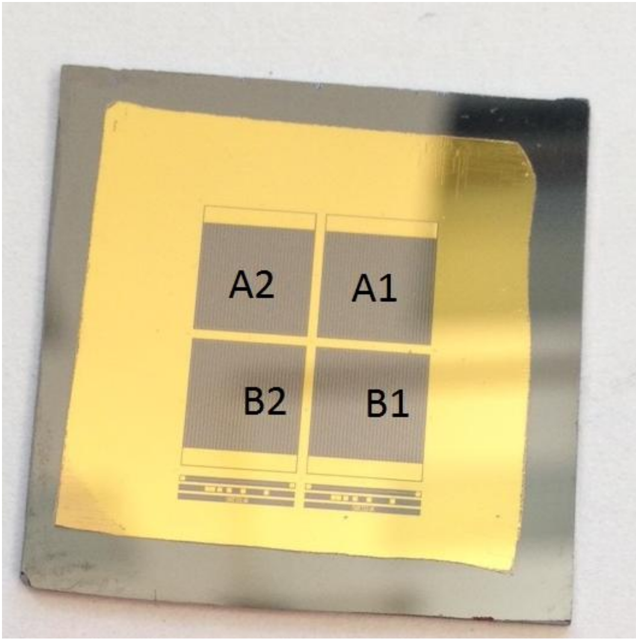
- Optimize selective surface coating
- Select photonic crystal (PhC) emitter and filter
- Assemble cell and validate performance
- Assess receiver/TES options and model-integrated design

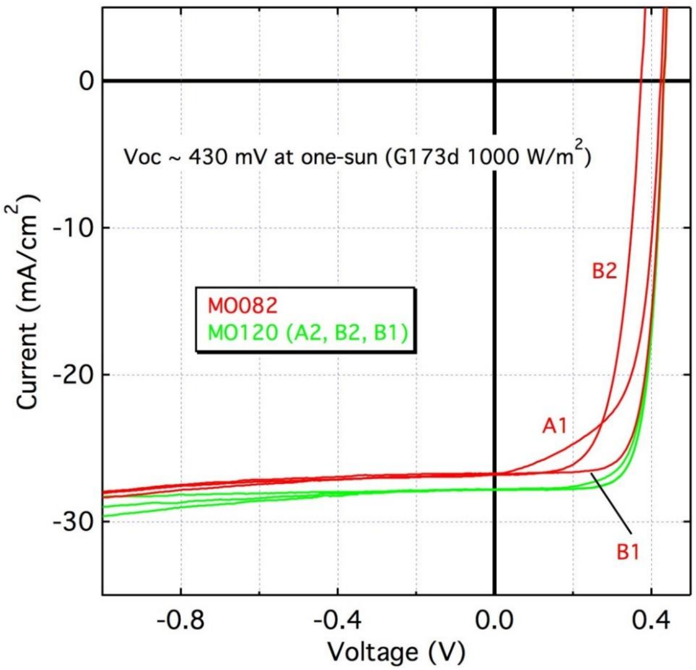
High-Temperature Solar TPV Experiments





InGaAs PV diode



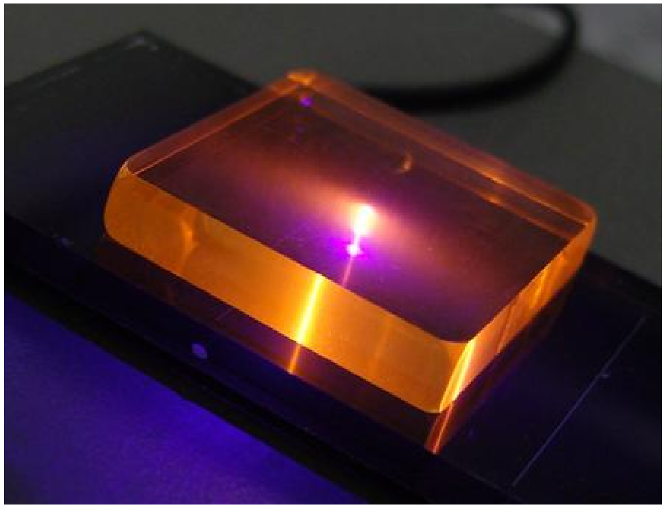


- InGaAs bandgap: $E_g = 0.72{\sim}0.74\ eV$; $EQE_{max} \approx 0.7$
- Devices and I-V characterizations provided by Myles Steiner (NREL)

Highly Selective Emitter: 2 mm thick Sm-doped glass

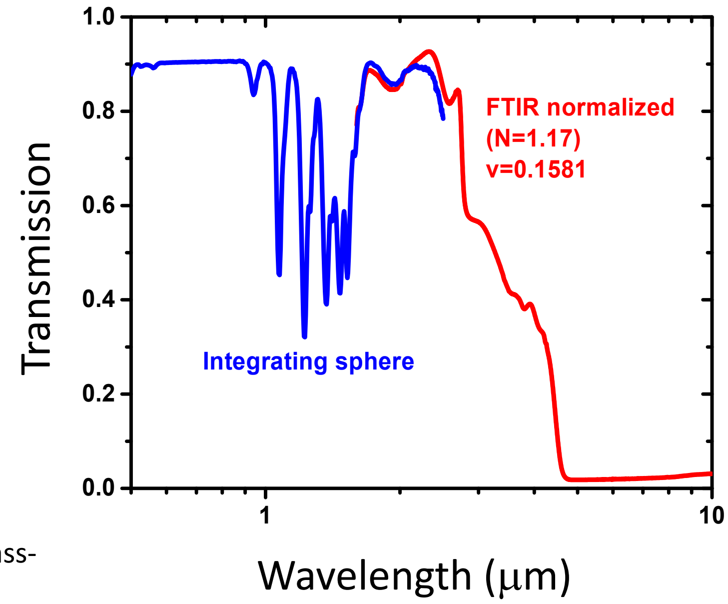
Broadband measurements from integrating sphere and FTIR indicate naturally selective emission, which can be enhanced via Q-matching

Sm-doped glass on PV cell

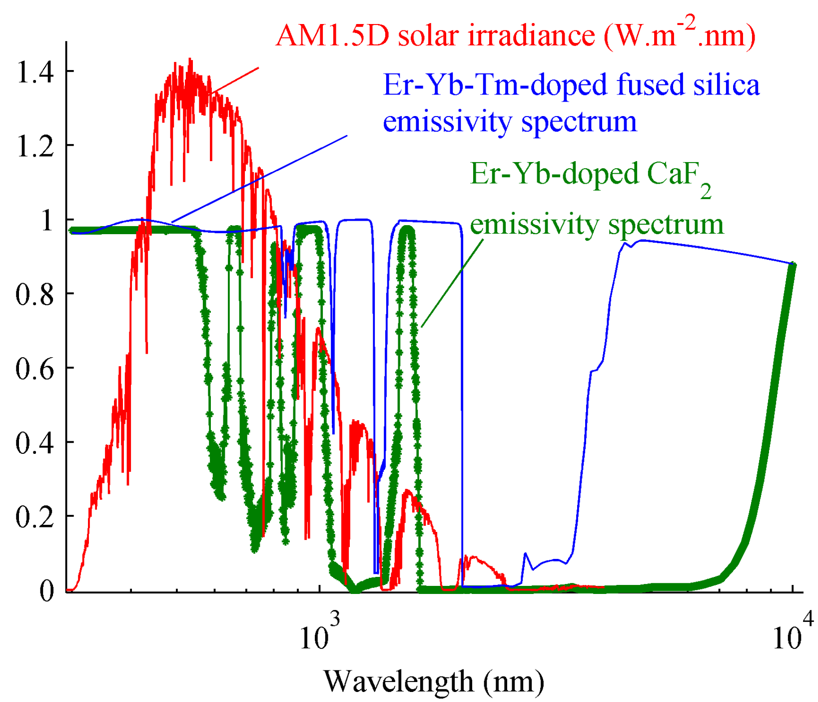


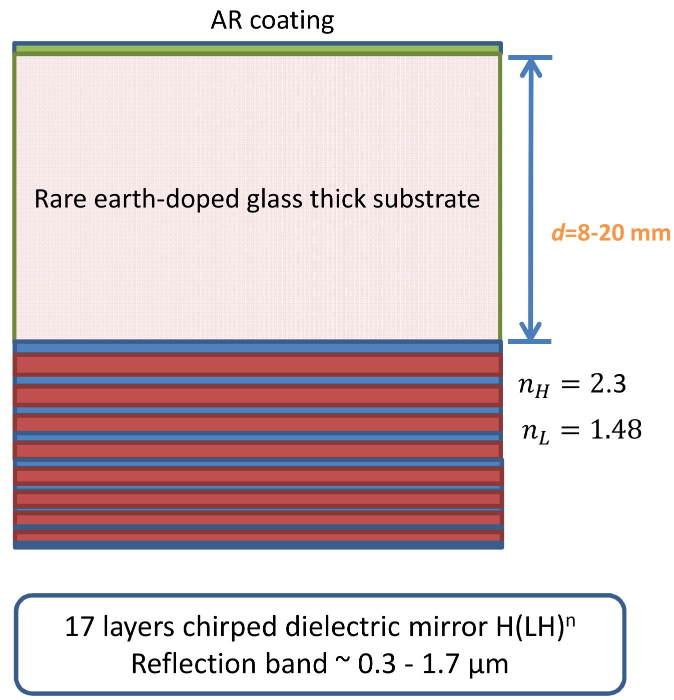
http://spie.org/newsroom/4235-fluorescent-borate-glass-enhances-cadmium-telluride-solar-cells

Sm-doped glass measurements



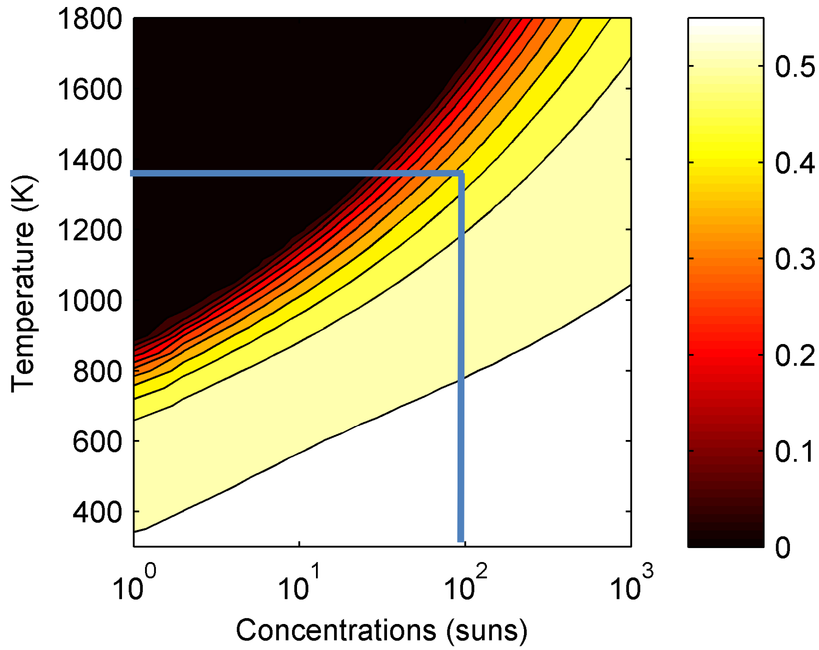
Rare-earth doped selective structure: absorption



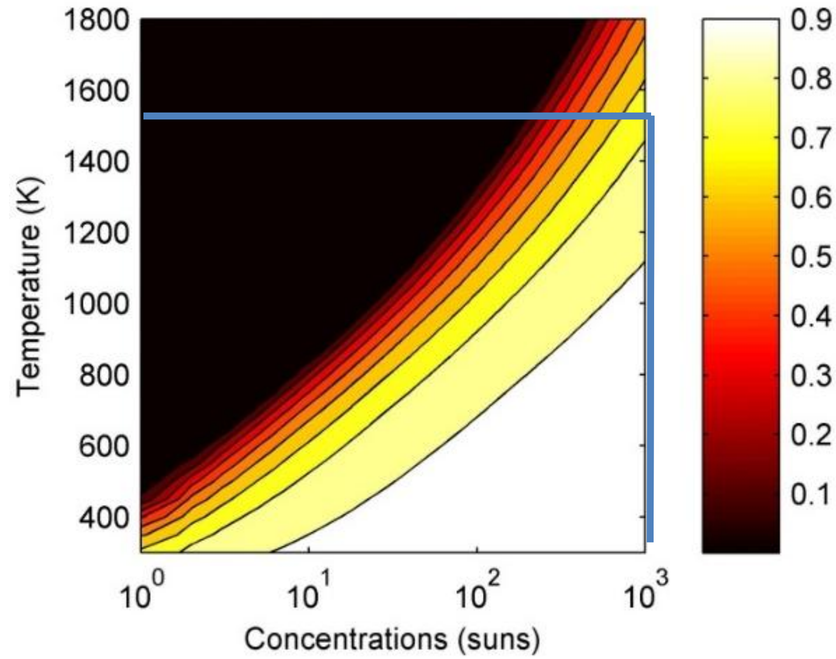


cf. Ilic, Bermel *et al.*, *Nature Nanotechnol.* (2016)

Rare-earth doped selective structure: thermal transfer efficiency



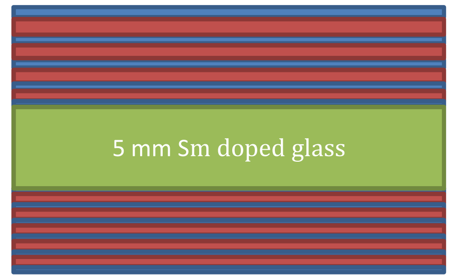
Er-Yb doped CaF_2
$\eta_t = 44\%$ at 1350 K under 100 suns



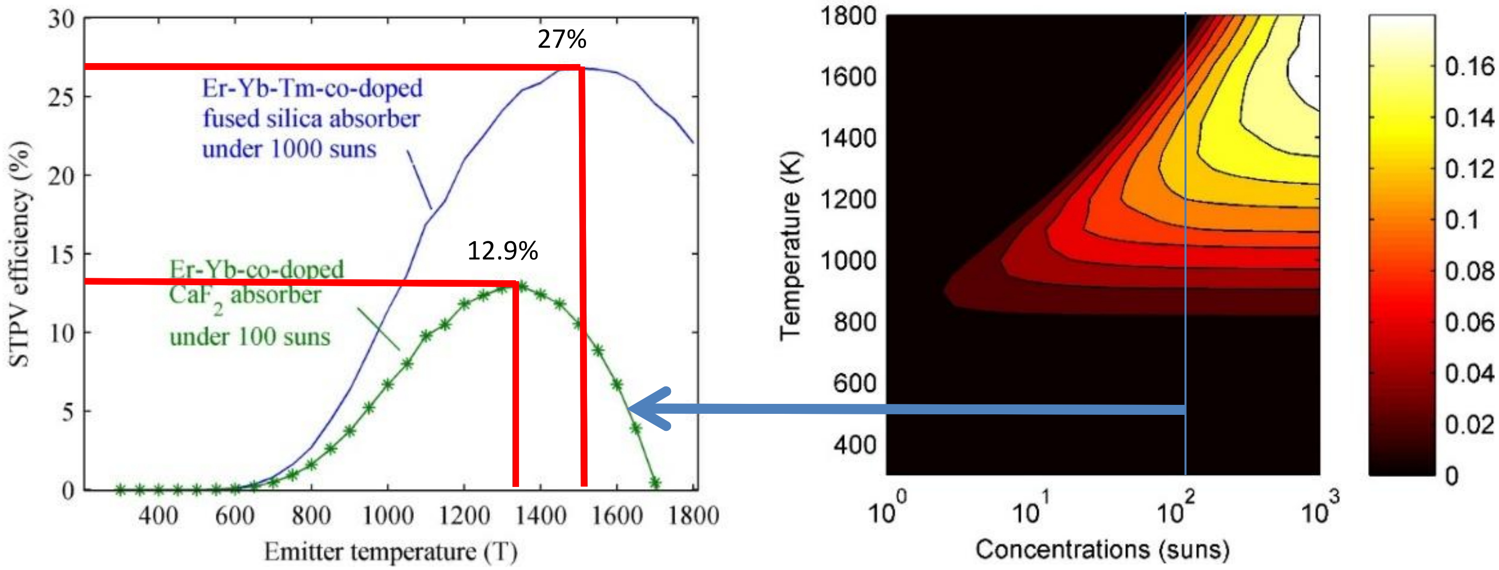
Er-Yb-Tm doped fused silica absorber
$\eta_t = 78\%$ at 1500 K under 1000 suns

Z. Zhou *et al.*, *MRS Advances* **1** (2015)

Rare-earth doped selective structure: STPV efficiency

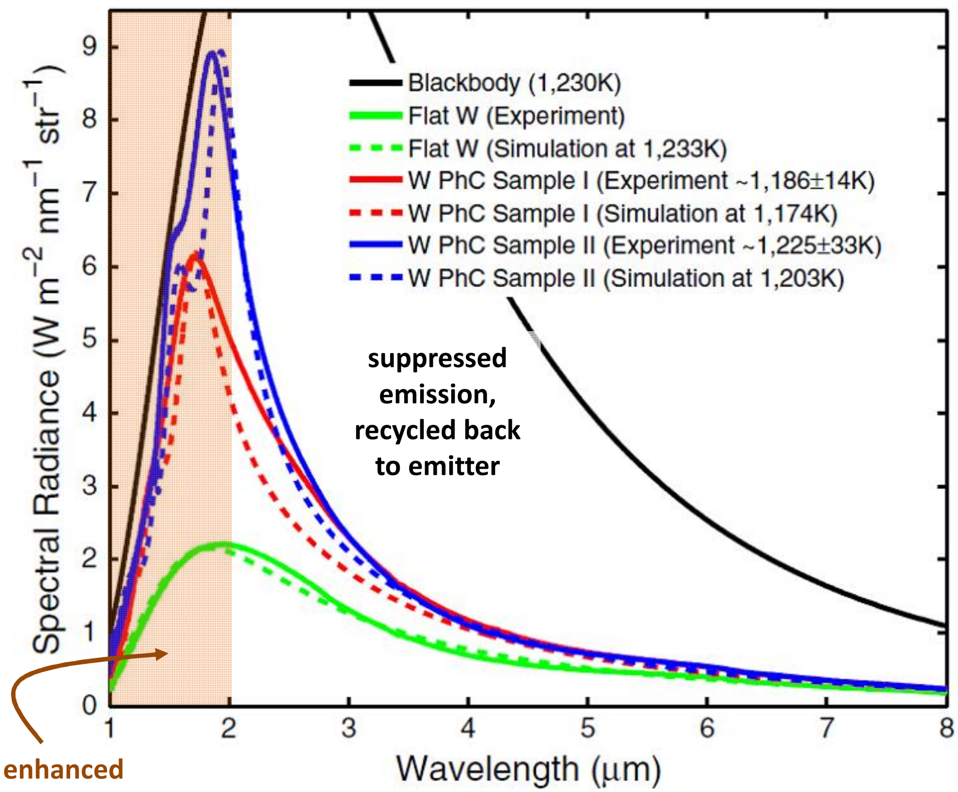


Combining with a Q-matched Sm-doped glass emitter*



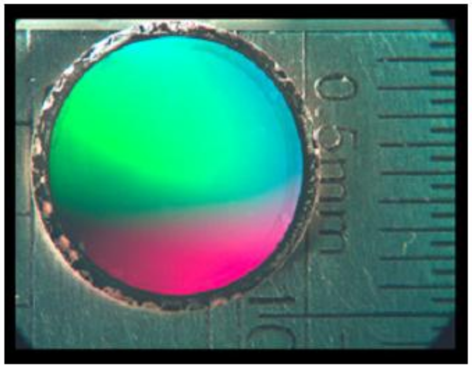
*Sakr, Bermel *et al.*, in *SPIE Opt. Eng. + Appl.*, p. 960819 (2015)

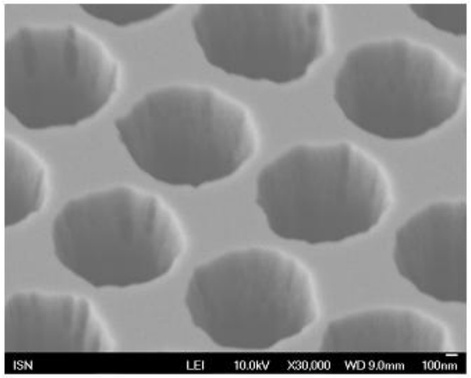
2D Tungsten Emitters Are Also Quite Selective at High Temperatures



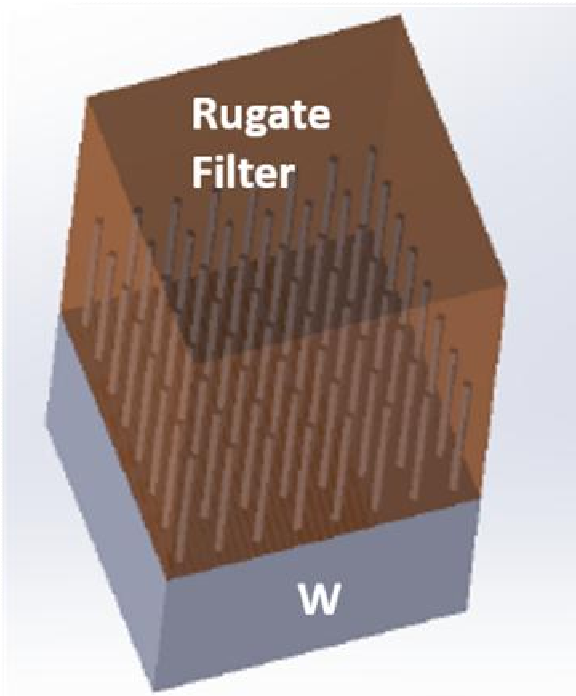
enhanced emission, converted to electricity

Y.X. Yeng et al., *PNAS* **109**, 2280 (2012)



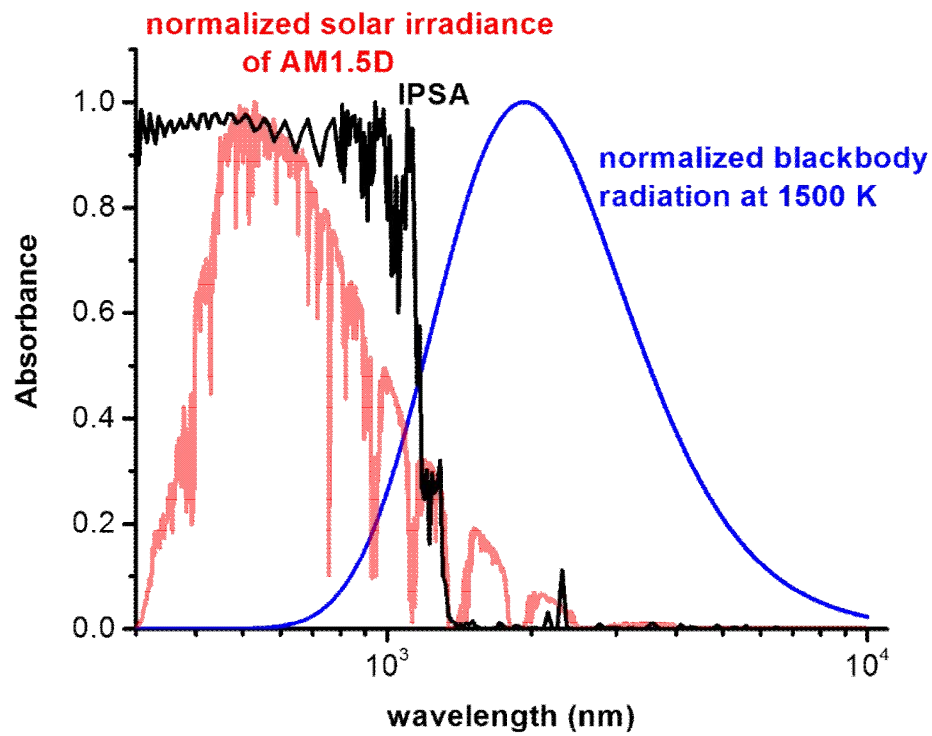


Integrated PhC selective structure: absorption



$a = 0.470\ \mu m;\ r = 0.293\ \mu m;\ d = 2.386\ \mu m$

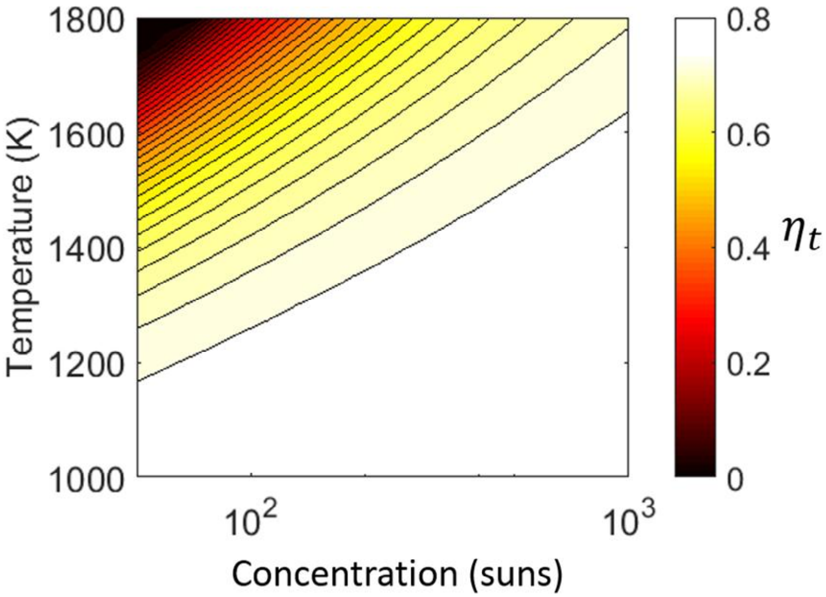
Integrate filter directly into selective emitter structure!



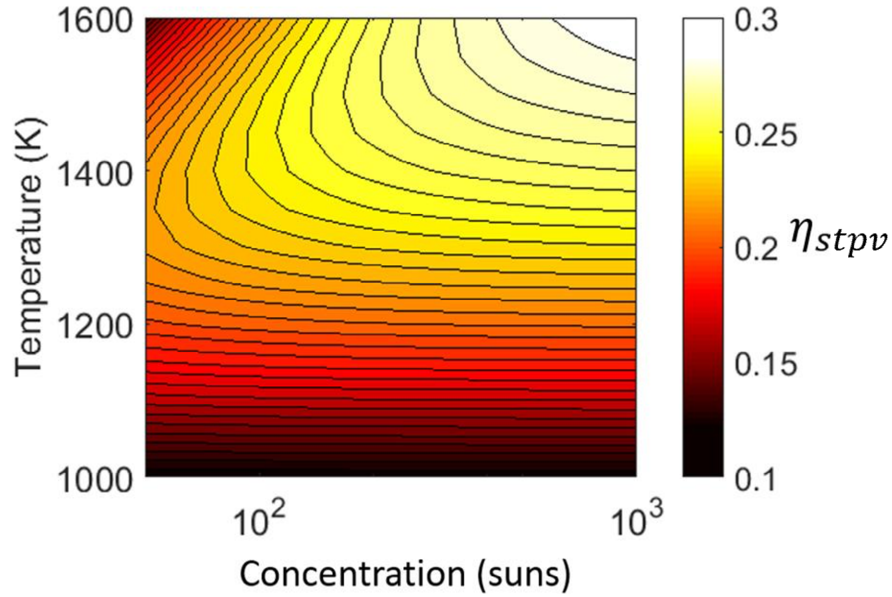
$\eta_t = 68\%$ and $\eta_{STPV} = 24.3\%$
@100 suns and 1450 K

Z. Zhou *et al., MRS Advances* **1** (2015)

Integrated PhC selective structure: efficiency



Solar transfer efficiency approaches theoretical limits

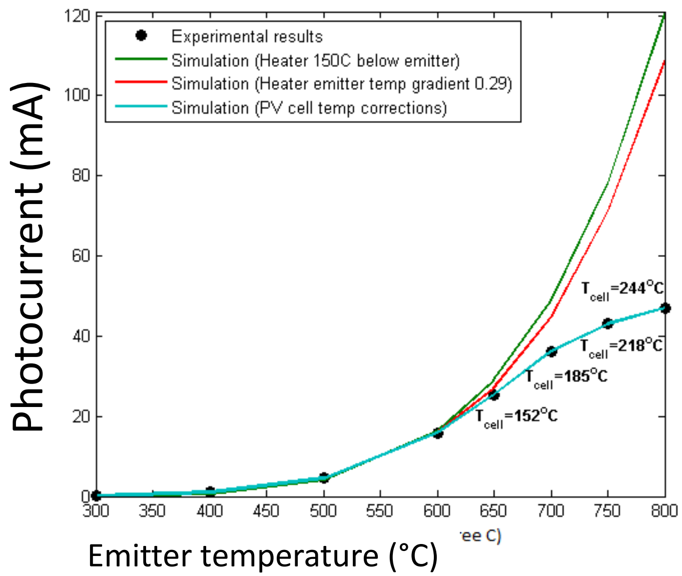


STPV efficiency limited by highest achievable temperatures

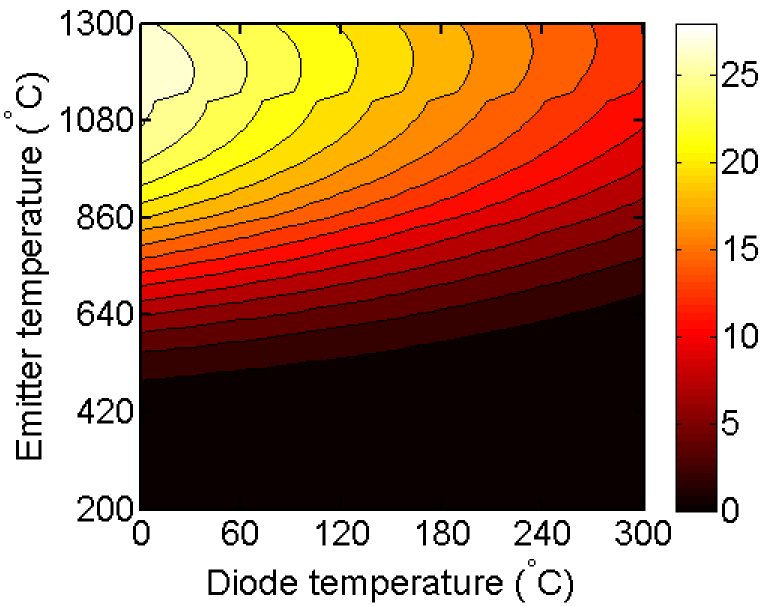
Z. Zhou *et al., MRS Advances* **1** (2015)

TPV Power Production: Thermal Management Challenges

Generated photocurrent and PV cell temperature vs. emitter temperature

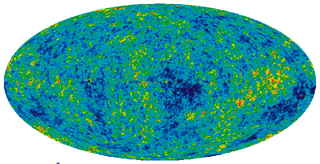


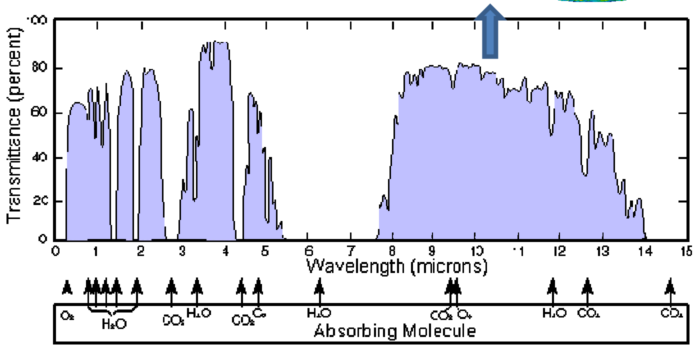
STPV efficiency vs. emitter and diode temperatures



Radiative Cooling for Passive Thermal Management

3 K microwave background



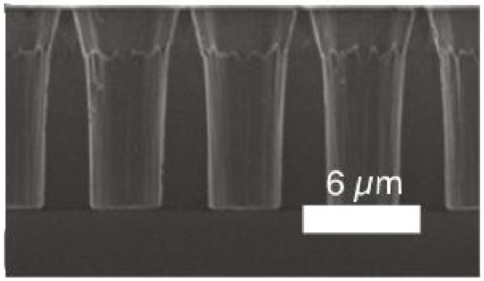


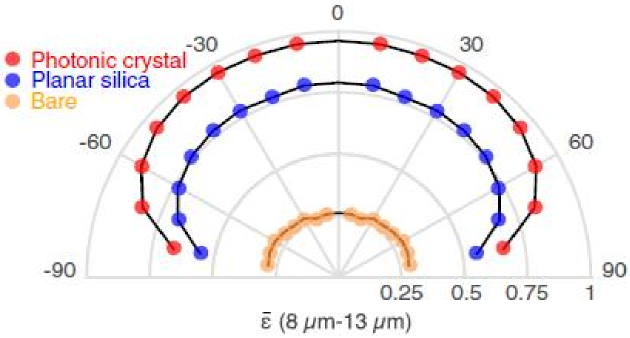
The sky transparency window allows radiative cooling outdoors

<u>Questions:</u>

1. Any alternative coolers to PhCs?
2. What is the temperature reduction and performance improvement by applying radiative cooling to hybrid or STPV systems?

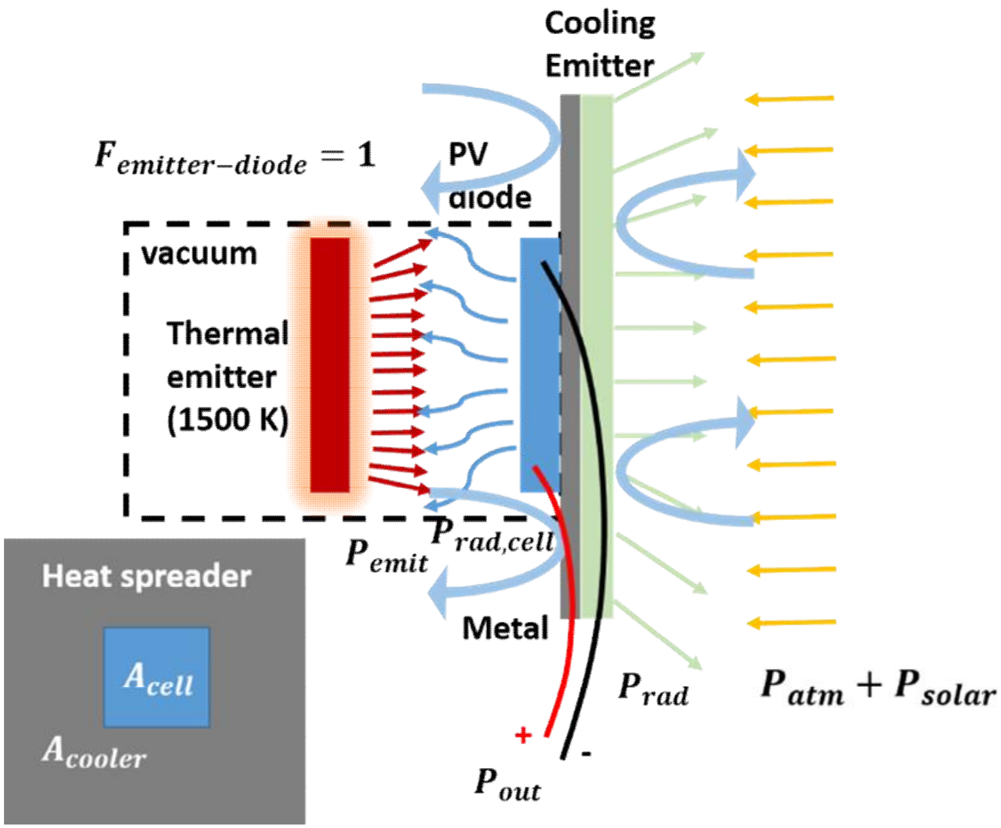
Photonic Crystal





Zhu, Linxiao *et.al Proceedings of the National Academy of Sciences* 112.40 (2015): 12282-12287.

Self-Consistent Modeling of Radiative Cooling for Passive Thermal Management



P_{emit}: emission power from thermal emitter at T_E

$P_{rad,cell}$: radiative recombination of the PV diode at T_C

P_{out}: electrical output power from PV diode (**SQ Limit**)

P_{rad}: radiation power from the cooling emitter at T_C

P_{atm}: radiation power from atmosphere (300 K)

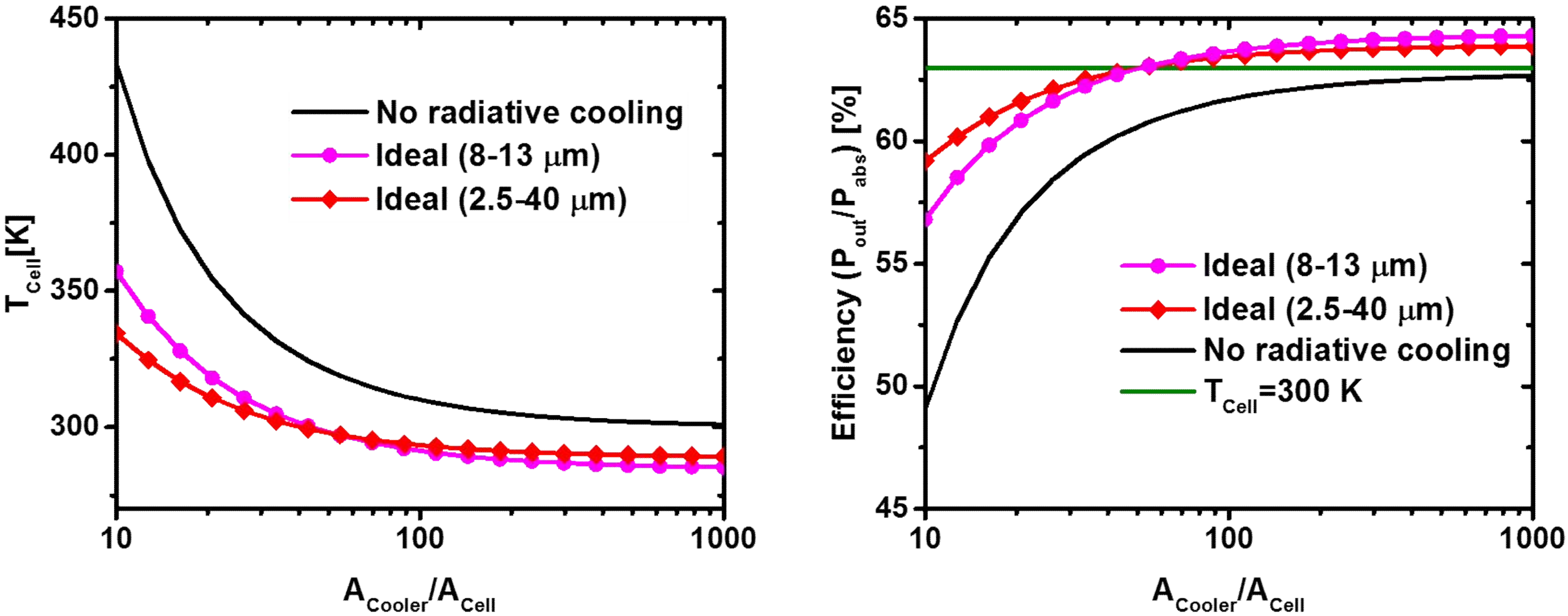
P_{conv}: convection power at the exposed surface

$R = A_{cooler}/A_{cell}$ (Area ratio)

$$P_{emit}(T_E, E > E_g) + R \cdot P_{atm} = P_{out}(T_C) + P_{rad,cell}(T_C) + R \cdot P_{rad}(T_C) + (2R - 1) \cdot P_{conv}$$

Z. Zhou *et al.*, *SPIE Conf. Proc.* (submitted).

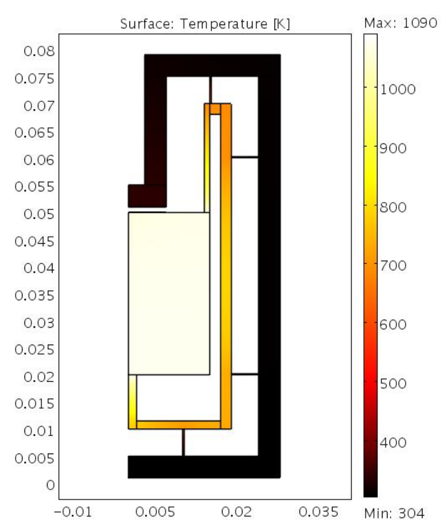
Radiative Cooling Reduces Temperature and Improves Performance Substantially



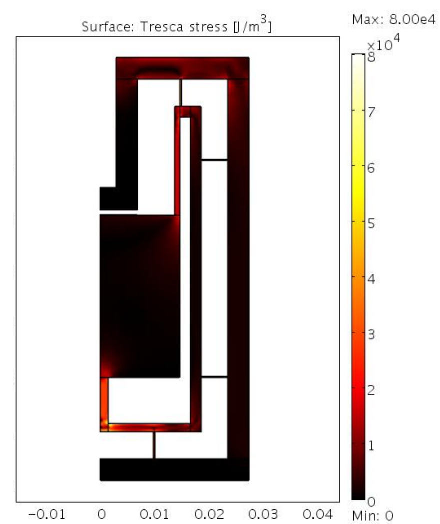
Z. Zhou *et al.*, *SPIE Conf. Proc.* (submitted).

Key Research Challenges in TPV

- Integrate new high-performance components: selective solar absorbers, selective thermal emitters, filters, and TPV cells
- Characterize and model materials degradation under operating conditions
- Demonstrate long-term reliability and reproducibility of system performance
- Incorporate radiative cooling where needed

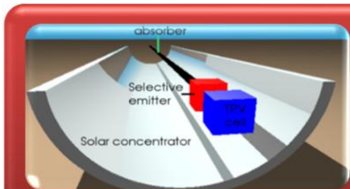


Surface temperature distribution

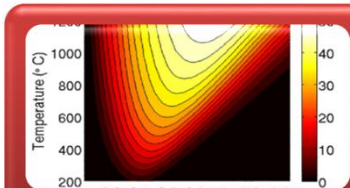


Mechanical stress distribution

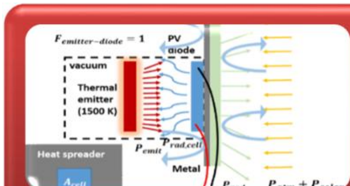
Conclusions



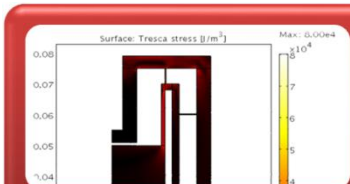
Selective solar thermophotovoltaics can enable highly efficient systems with storage & dispatchability



Overall system efficiencies can approach 52% at reasonable temperatures, with up to 100% dispatchability



Radiative cooling can maintain reasonable temperatures without efficiency penalties



Further demonstrations of higher performance, greater reliability, and reduced costs now needed

Next Class

- Next time: we will continue finite-difference time domain techniques, as applied to radiative cooling