Ben-Gurion University
of the Negev

Ray optics light trapping beyond the Lambertian limit

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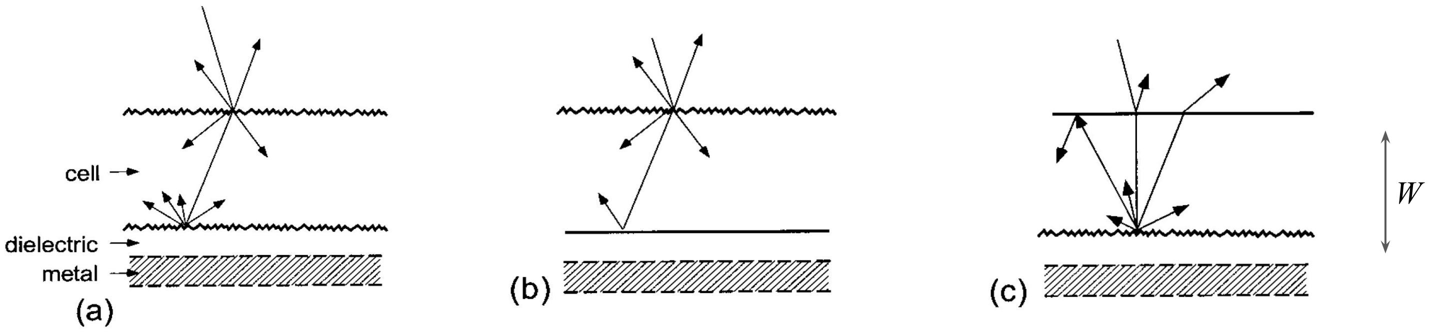
20th Sede Boqer Symposium on Solar Electricity Production jointly with the IKI Annual Nano-Day and the BGU-ENEA WORKSHOP

September 26-28, 2016

The lambertian limit to light confinement



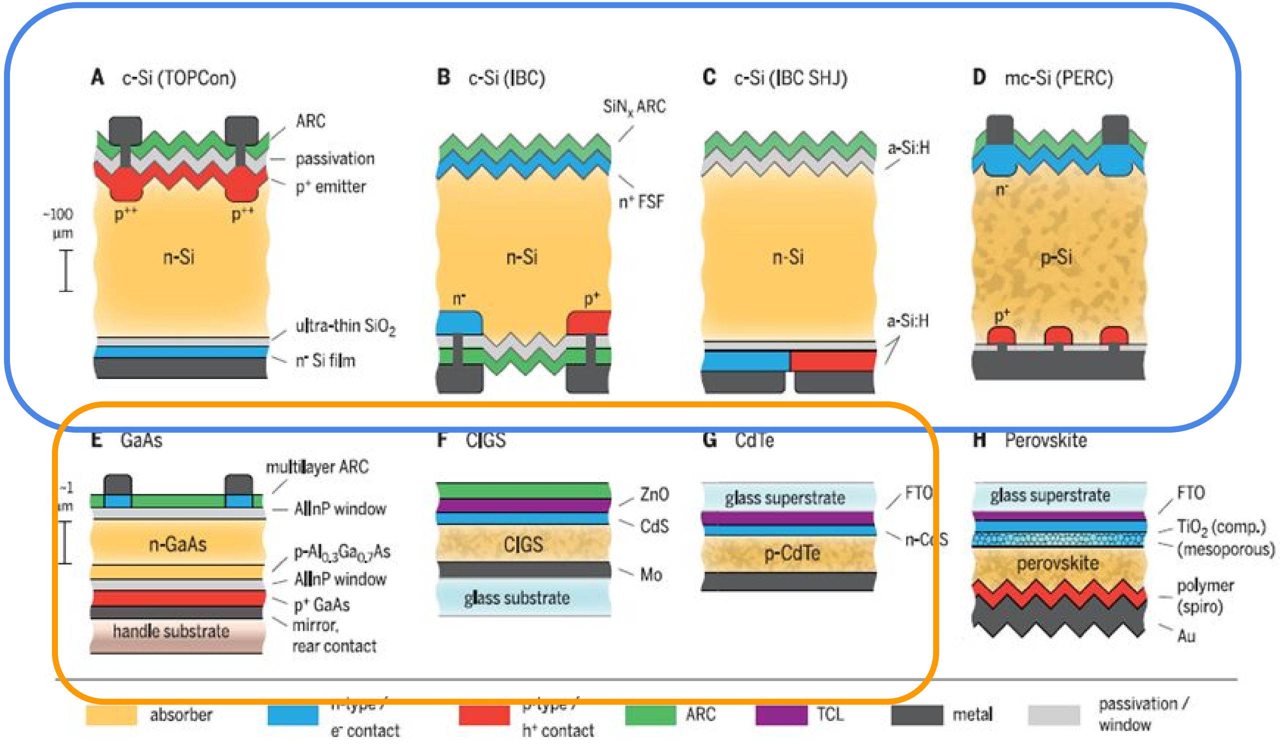
$$A_T = \frac{4n^2\alpha W}{1 + 4n^2\alpha W - 4\alpha W} \simeq \left.\frac{4n^2\alpha W}{1 + 4n^2\alpha W}\right|_{\alpha W < 1} \approx \left. 4n^2\alpha W \right|_{\alpha W \ll 1}$$

- W is the slab thickness
- α is the slab absorptivity

Lambertian confinement limit

M. Green, *Prog. Photovolt: Res. Appl. 2001; 10:235:241*

Best in Class



Si Based cells

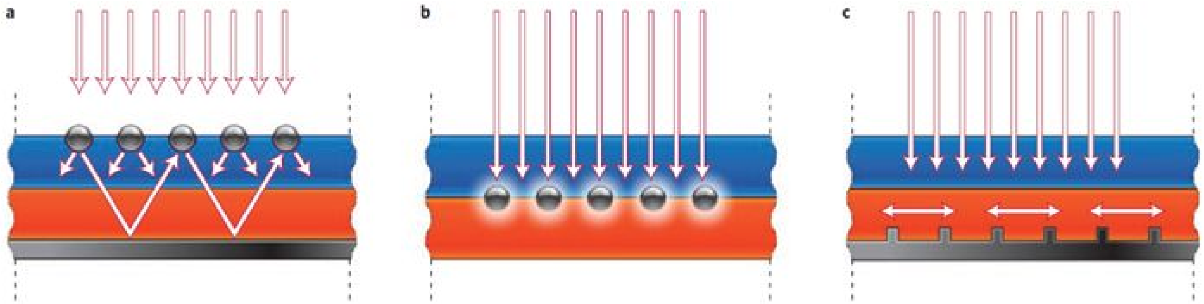
$$n_{Si} = 3.5 \Rightarrow 4n^2 = 49$$

Thin Films

Not within ray optics!

A. Polman et al., Science **352**, aad4244 (2016)

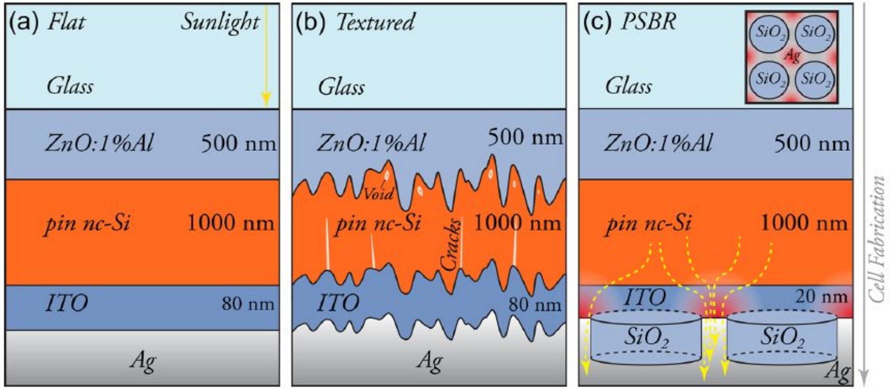
Other approaches: Plasmonic Enhancement

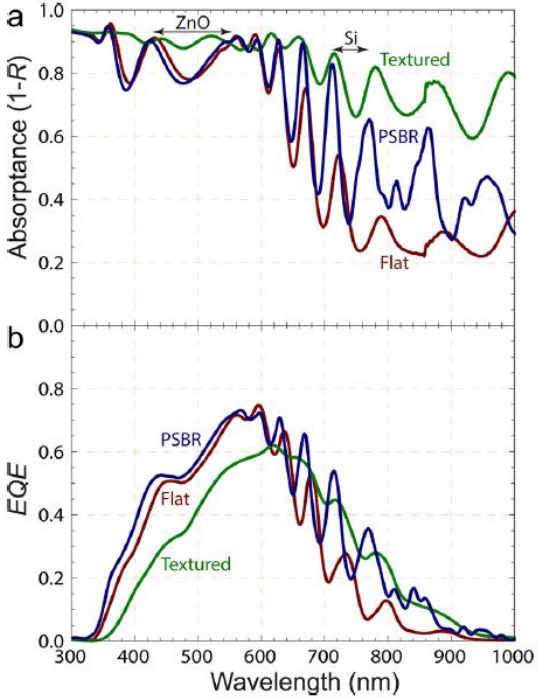


Superfluous absorption ends as metal losses!!!

H. Atwater and A. Polman, Nat. Mat. 9, 205 (2010)

Other approaches: Photonic Enhancement





Resonant nature inadequate for broadband sources like the sun!

Lourens van Dijk and A. Polman et al., ACS Photonics 2016, 3, 685−691

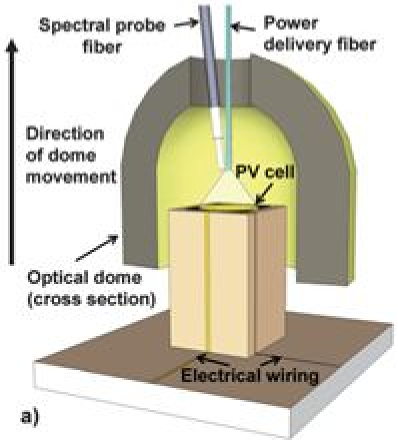
What we are looking for...

A ray based approach that surpasses the Lambertian limit

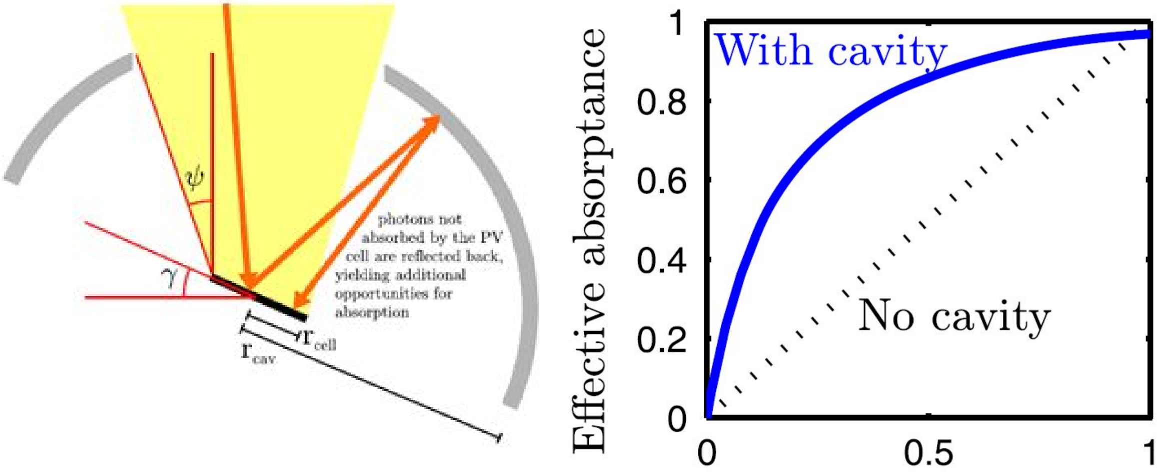
How we are going to do so...

Combining external cavities with a novel passive tracking scheme

External cavities



A. Braun et al., Energy Environ. Sci. **6**, 1499 (2013)



L. A. Weinstein et al., J. Opt. **17**, 055901 (2015)

Pros and cons of external cavities

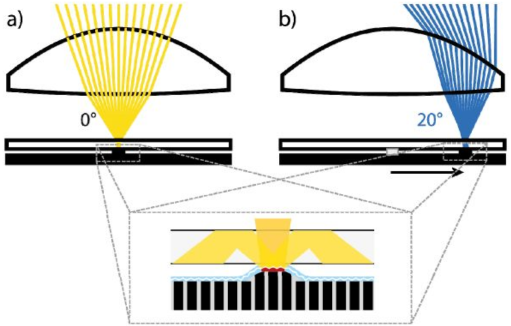
Pros

- Higher confinements then Lambertian approaches
- Removes optical constraints from the cell
- Diffused illumination on the active material
- Reduces recombination current in high luminescence materials (perovskites, GaAs)

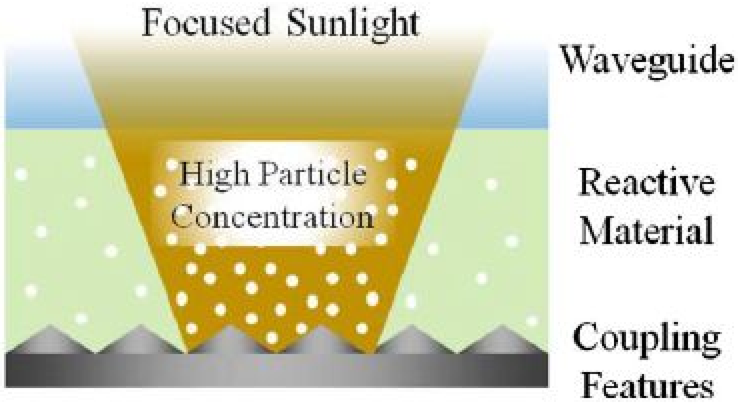
Cons

- Requires tracking
- Bulkier construction

Passive tracking

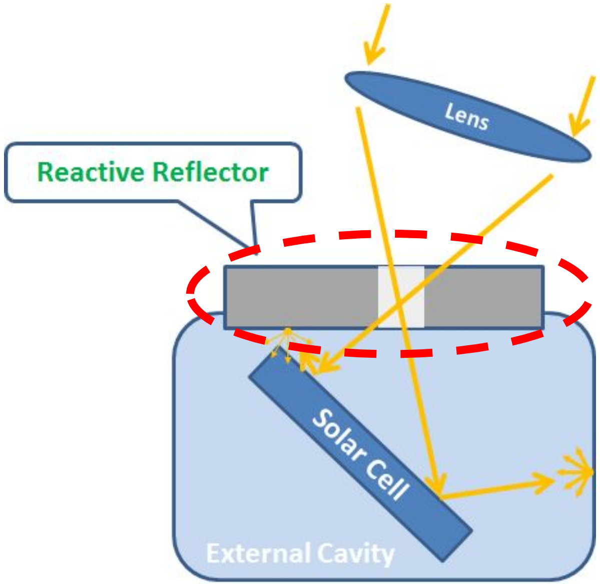


Opt. Expr. **22**, A498 (2014)

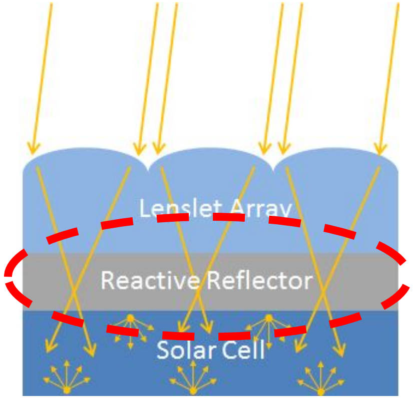


Appl. Opt. 51, 186 (2012)

External cavity + Passive tracking



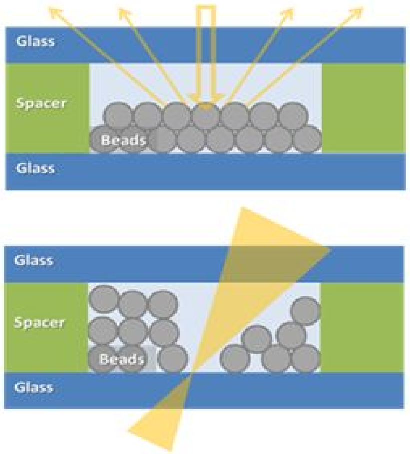
Flat panel arrangement



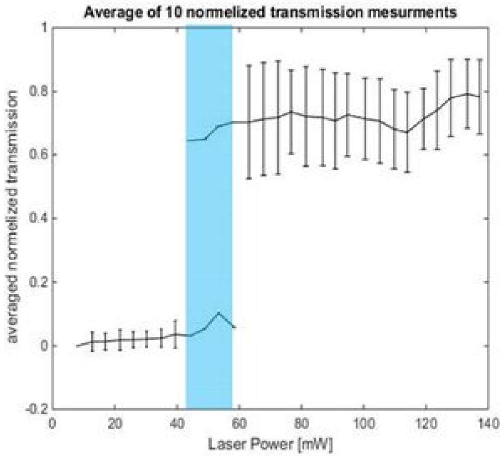
The key is an efficient Reactive Reflector

Reactive Reflector Prototype

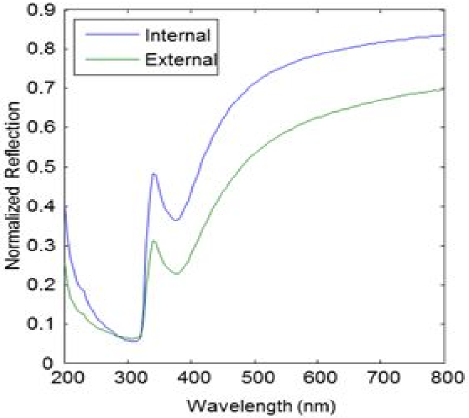
Concept



Transmission

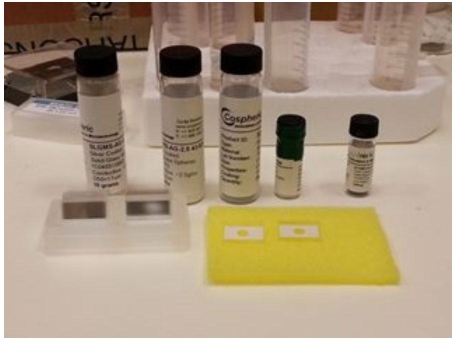


Reflection

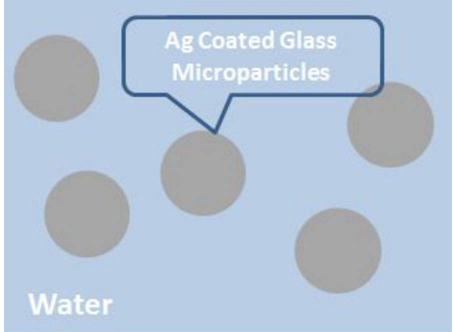


Preparation of the reactive reflector

1



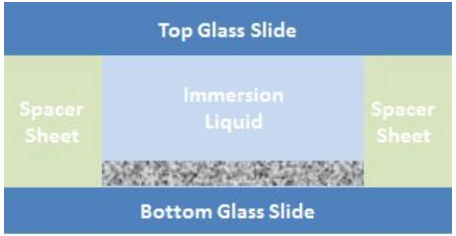
2



Ag Coated Glass Microparticles

Water

3



Top Glass Slide

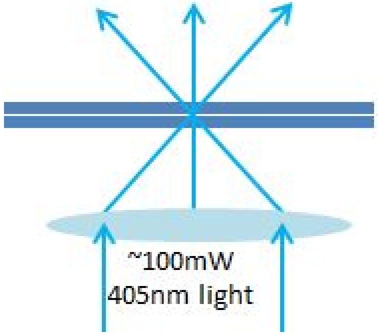
Spacer Sheet

Immersion Liquid

Spacer Sheet

Bottom Glass Slide

4



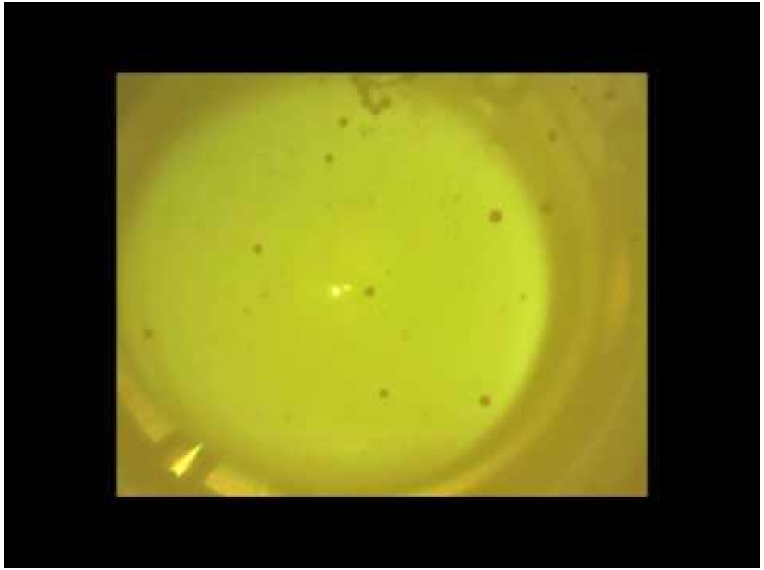
Sample

10X Objective

~100mW 405nm light

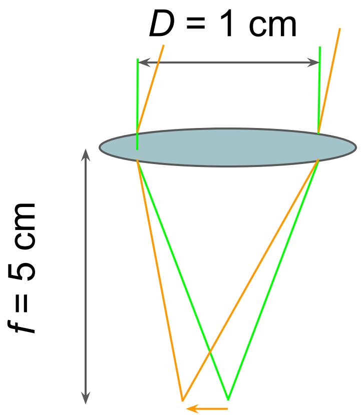
Optical forces on microparticles

Optical forces on a single bead



Rearrangement of beads around focused light beam

Predicted performance



Ω = 0.5 deg:

(ang. spread of the sun)

$$PSF = \Omega f = 0.5mm$$

Let’s be practical: PSF = 1mm

Confinement factor:

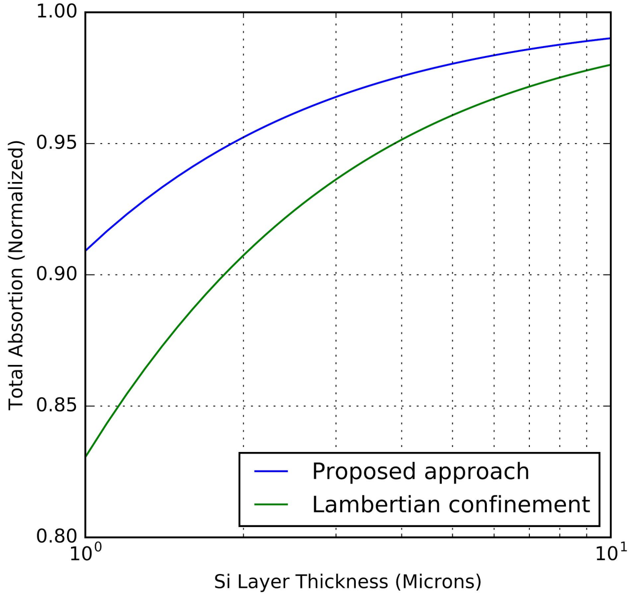
$$F = \frac{A_{in}}{A_{out}} = \left(\frac{D}{PSF}\right)^2 = 100$$

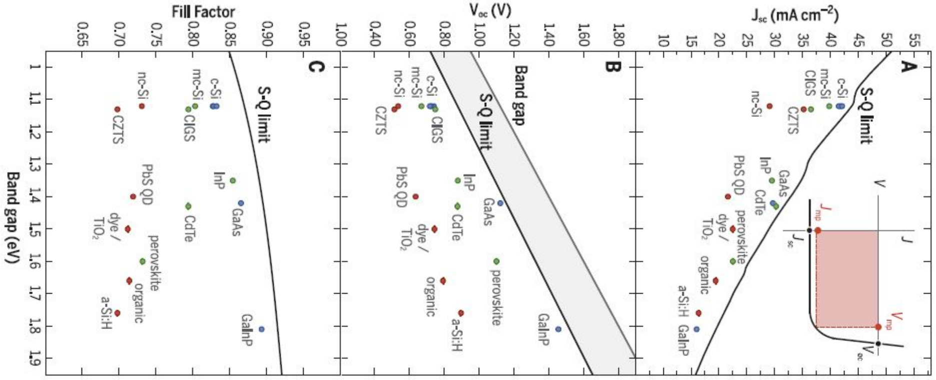
Lambertian confinement:

$$F_{Lamb} = 4n^2 = 49\big|_{n=3.5}$$

For Silicon: $\alpha = 1 \times 10^3 cm^{-1}$

Total Absorption: $A_T \simeq \dfrac{FW}{1 + FW}$



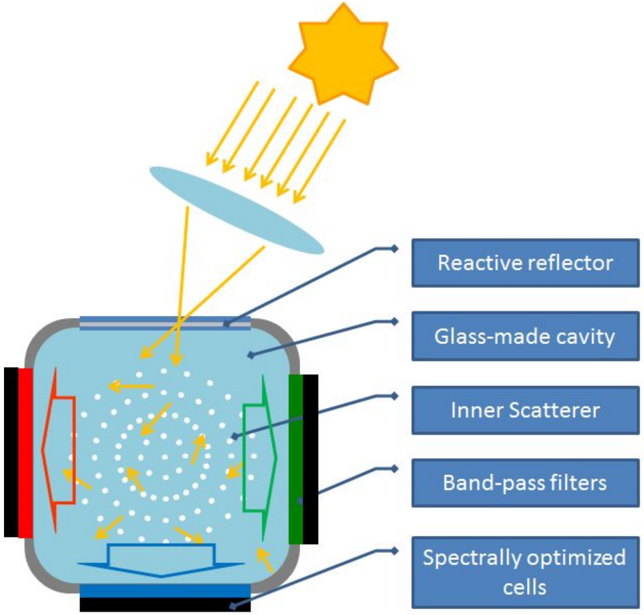


There's room for improvement even for silicon

(25% in Voc and 6% in fill-factor for mc-Si)

A. Polman et al., Science **352**, aad4424 (2016)

Surpassing SQ limit with wavelength splitting



Reactive reflector

Glass-made cavity

Inner Scatterer

Band-pass filters

Spectrally optimized cells

Conclusions

- The combination of external cavities with efficient passive tracking opens up new opportunities for cost-effective solar energy conversion
    - Making simpler cells
    - Confinement beyond the Lambertian limit
- Possibility to surpass SQ limit via wavelength splitting
- Challenges still remains with maximizing transmission, reflection, and concentrator design
- The existence of a new kind of optomechanical force brings opportunities beyond light management

Acknowledgments

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