Polyhedral Specular Reflector Design for Ultra-High Spectrum Splitting Solar Module Efficiencies (>50%)

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ABSTRACT

One pathway to achieving ultra-high solar efficiencies (>50%) is employing a spectrum splitting optical element with at least 6 subcells and significant concentration (100-500 suns). We propose a design to meet these criteria, employing specular reflection to split and divide the light onto appropriate subcells. The polyhedral specular reflector incorporates a high index parallelepiped with seven subcells. The subcells are placed around the parallelepiped such that light entering at normal incidence encounters the subcells in order from highest to lowest bandgap, with the ray path reflecting at a 90° angle until the light is fully absorbed. Previous studies of the design have shown that concentration and filters are necessary to achieve high efficiencies and thus the current iteration of the design employs shortpass filters and two stages of concentration. Ray tracing of the current iteration shows exceeding 50% efficiency is possible for current subcell qualities with perfect shortpass filters while 50% module efficiencies are only possible for very high quality (>6% ERE) subcells with commercially available shortpass filters. However, even with commercially available filters and achievable subcell quality, ray tracing results show very high (>43%) module efficiency.

Keywords: spectrum splitting, multijunction solar cell, solar concentrator

1. INTRODUCTION

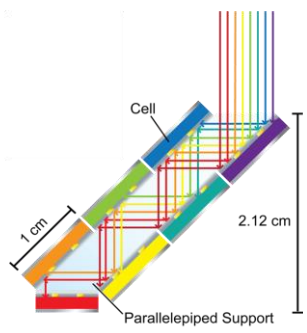
Solar cell efficiency is increased through the incorporation of multiple bandgaps to reduce losses from thermalization and lack of absorption.[1, 2] While significant progress has been made for multijunction cells, ultra-high efficiencies (>50%) have yet to be achieved in isolated cells or upon incorporation into modules.[3, 4] The efficiency in current multijunction cells is largely limited by their fabrication: a monolithic epitaxial growth such that the system is constrained in both lattice- and current-matching. However, these limitations can be avoided by designing an external optical element to split and distribute the solar spectrum onto an array of electrically isolated subcells. Such a design allows for each subcell to be designed for independently, yielding a more ideal set of bandgaps not constrained by lattice- or current-matching.[5] Here we present a polyhedral specular reflector (PSR) design for a spectrum splitting optical architecture and discuss pathways to ultra-high efficiencies.

2. SUMMARY OF RESULTS

The optical design is shown in Figure 1. The PSR, similar to previous spectrum splitting designs, operates based on ordered specular reflection.[6-8] In its most basic design (Figure 1a), incident light enters a parallelepiped and is directed via the inherent optical path of the geometry onto each subcell from highest to lowest bandgap. High energy light is absorbed by the first subcell while only the lowest energy light makes it to the last subcell. This design includes seven subcells (Figure 1a) that were optimized using modified detailed balance calculations.[5] The quality of the subcells is determined by two parameters. The external radiative efficiency (ERE) of the subcells accounts for nonradiative recombination in the subcells and primarily affects the voltage.[9] The percent ideal short circuit current (% ideal Jsc) accounts for incomplete absorption and carrier collection and modifies the maximum current the subcells can achieve. These qualities will be used to survey the efficiencies possible with this optical architecture.

Because the most basic design shown in Figure 1a will not exceed 50% efficiency, the design was further improved with the incorporation of shortpass filters and concentration as shown by Figure 1b.[10] The inclusion of shortpass filters in front of each subcell prevent parasitic losses, such as free carrier absorption, which would be detrimental to subcell efficiency.[10] Concentration was also necessary to boost subcell performance to produce 50% conversion efficiency.[5]

However the inclusion of concentration can greatly decrease the optical efficiency of the design by misallocating photons away from the designed light path.[10] Thus we have chosen to include concentration in two stages to minimize these losses. In this approach, light enters through a primary concentrator, imagined here as a square compound parabolic concentrator (CPC), with a low degree of concentration (2-4x) before entering the solid, high index parallelepiped support. For this study, we consider the support to be made of fused silica. Because the parallelepiped has a higher index than air, the concentrated light will refract slightly upon entering the slab, making the light path closer to normal. The concentrated light is then split by reflection off of and transmission through shortpass filters, and the transmitted light is further concentrated by a secondary CPC onto the designated subcell. A wide range of total concentrations (100x-1000x) are possible.



E_g (eV)	III-V Alloy
2.15	$Al_{0.20}Ga_{0.32}In_{0.48}P$
1.84	$Ga_{0.51}In_{0.49}P$
1.58	$Al_{0.1}Ga_{0.9}As$
1.42	GaAs
1.15	$In_{0.87}Ga_{0.13}As_{0.28}P_{0.72}$
0.94	$In_{0.71}Ga_{0.29}As_{0.62}P_{0.38}$
0.74	$In_{0.53}Ga_{0.47}As$

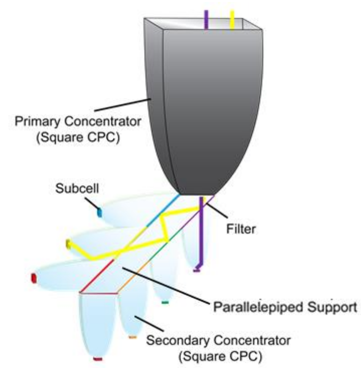


Figure 1. (a) A schematic of the polyhedral specular reflector with corresponding subcell bandgaps. Cells are mounted on the surface of a solid dielectric parallelepiped and light is specularly reflected through the structure until it is absorbed. The cell thicknesses are not to scale. (b) Schematic of the current PSR design, with two stages of concentration and filters to prevent parasitic absorption.

The design was simulated in a ray tracing software (LightTools) to determine the spectral fluxes incident upon each subcell. This was done for both ideal shortpass filters (perfect performance and omnidirectional) and for commercially available shortpass filters matching the cutoff wavelengths needed. These represent the upper and lower bounds for the optical efficiency, respectively. These spectra are then input into the modified detailed balance model described elsewhere to calculate the overall efficiency of the module.[5] Figure 2 shows efficiency maps for these two cases as a function of subcell ERE and % ideal Jsc. For single junction subcells, 90% ideal Jsc and ERE's of 1-2% have been demonstrated for III-V alloys.[5, 11] Thus 50% efficiency is readily achievable for ideal filters but will require higher efficiency subcells in this case of the commercially available filters. However, very high efficiencies (>43%) are achievable with commercially available filters and show promise for high efficiency spectral splitting module architectures.

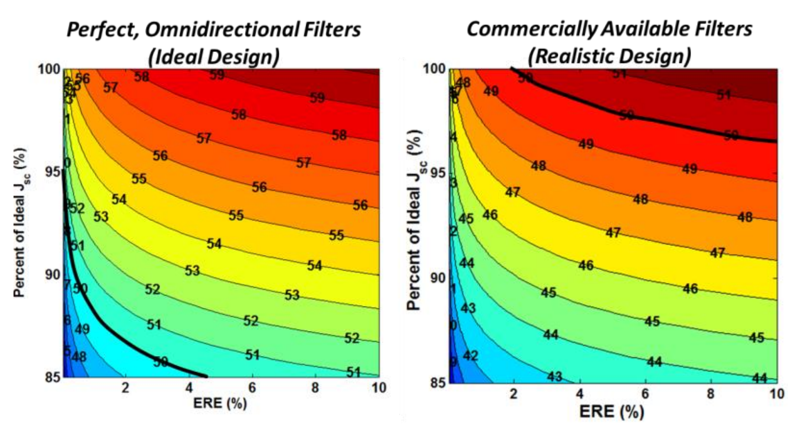


Figure 2. Efficiency maps as a function of ERE and % Ideal Jsc for the current iteration of the PSR with perfect, omnidirectional filters (left) and commercially available filters (right).

3. CONCLUSIONS

We have designed and modeled a spectrum splitting design based on specular reflection. The current iteration of the design includes 7 single junction subcells, filters to prevent parasitic absorption, and two stages of concentration to boost subcell performance while minimizing optical losses. We show through ray tracing simulations that high efficiencies are with both perfect, ideal filters and non-custom, commercially available filters. With current subcell quality, >50% is possible with perfect filters and 42-45% is possible with currently available filters.

REFERENCES

[1] A. Marti, G. L. Araujo, Solar Energy Materials and Solar Cells 1996, 43, 203.

[2] M. A. Green, Third Generation Photovoltaics: Advanced Solar Energy Conversion, Springer-Verlag, Berlin, Heidelberg 2003.

[3] A. Polman, H. A. Atwater, Nat. Mater. 2012, 11, 174.

[4] M. A. Green, K. Emery, Y. Hishikawa, W. Warta, E. D. Dunlop, Progress in Photovoltaics: Research and Applications 2013, 21, 1.

[5] E. C. Warmann, C. N. Eisler, E. D. Kosten, M. Escarra, H. A. Atwater, "Spectrum Splitting Photovoltaics: Proposed Band Gaps and Materials to Achieve 50% System Efficiency", presented at Photovoltaic Specialists Conference (PVSC), 2013 39th IEEE, 2013.

[6] M. Ellion, Edmund, United States of America Patent, 1987.

[7] A. Barnett, C. Honsberg, D. Kirkpatrick, S. Kurtz, D. Moore, D. Salzman, R. Schwartz, J. Gray, S. Bowden, K. Goossen, M. Haney, D. Aiken, M. Wanlass, K. Emery, "50% Efficient Solar Cell Architectures and Designs", presented at Photovoltaic Energy Conversion, Conference Record of the 2006 IEEE 4th World Conference on, May 2006, 2006.

[8] B. Mitchell, G. Peharz, G. Siefer, M. Peters, T. Gandy, J. C. Goldschmidt, J. Benick, S. W. Glunz, A. W. Bett, F. Dimroth, Prog. Photovoltaics 2011, 19, 61.

[9] M. A. Green, Progress in Photovoltaics: Research and Applications 2012, 20, 472.

[10] C. N. Eisler, E. D. Kosten, E. C. Warmann, H. A. Atwater, in Photovoltaic Specialists Conference (PVSC), 2013 39th IEEE, 2013.

[11] J. F. Geisz, M. A. Steiner, I. Garcia, S. R. Kurtz, D. J. Friedman, Applied Physics Letters 2013, 103, 041118.