Light Management Optimization of Upconversion-Based Solar Cells using Genetic Algorithms

J. A. Bork, M. F. Doty, J. M. O. Zide
Depart. of Mater. Sci. and Eng., University of Delaware, Newark, Delaware, USA

Background: A major contributor to the efficiency limit of single-junction solar cells is the lack of absorption of below-bandgap light.[1] By converting this below-bandgap light into above-bandgap light, upconversion-based solar cells (UBSCs) expand the spectral region accessible for solar energy harvesting, thereby increasing the solar cell's efficiency limit.[2]

The Goal: Through genetic algorithm-based optimization of UBSCs using COMSOL Multiphysics®, realizable gains can be estimated, the efficiency limit can be maximized, and design rules of UBSCs can be better understood.

Model Approach: The Wave Optics Module is used to model two fundamental optical processes in a UBSC (figure 1-left):

1) Absorption of below-bandgap light in the upconverter layer (figure 1-middle, figure 2-left)
2) Emission of upconverted, above-bandgap light in the upconverter layer and its reabsorption in the host solar cell (figure 1-right, figure 2-right)

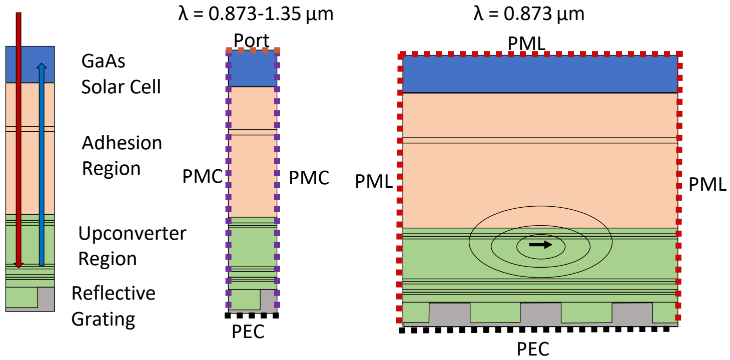

Figure 1. (left) Illustration of a GaAs UBSC. Red arrow represents absorption of below-bandgap light. Blue arrow represents emission of upconverted, above-bandgap light. (middle) Model geometry for model of absorption of incident light. (right) Model geometry for emission of upconverted light. Arrow with circles represent electric dipole source. Both perpendicular dipole orientations are independently modeled.

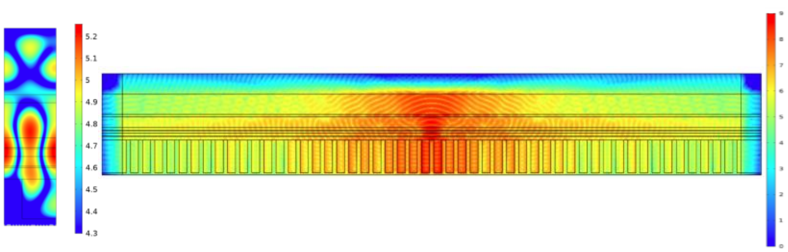

Figure 2. Typical modeled E-fields for the absorption of below-bandgap light in the upconverter (left) and dipole emission (right). Color scales are logarithmic.

LiveLink™ for MATLAB® allows for the combination of these two models to account for

- Solar cell efficiency
- Purcell enhancement
- Photon recycling
- Genetic algorithm optimization for maximum performance

UBSCs are tested as different geometries, including flat layers, square grating back reflector, and photonic crystal geometries. Each geometry is tested with varying numbers of upconverting layers.

Definitions:

n_{UP} : Number of upconverted photons generated
$n_{UP\rightarrow SC}$: Number of upconverted photons delivered to solar cell
$f_{UP\rightarrow SC}$: Fraction of upconverted photons delivered to solar cell
$f_{SS\rightarrow UP}$: Fraction of incident solar spectrum photons converted to upconverted photons

Results:

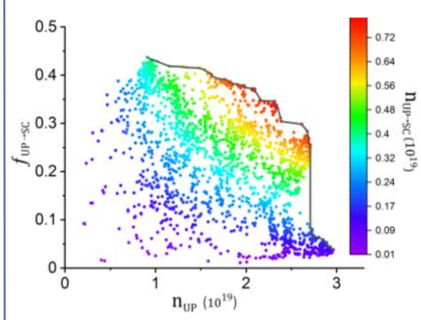

Figure 2. Pareto front (line of best solutions, grey line) calculated through multiobjective genetic algorithm. Demonstrates a compromise between n_{UP} and $f_{UP\rightarrow SC}$ for maximum UBSC performance.

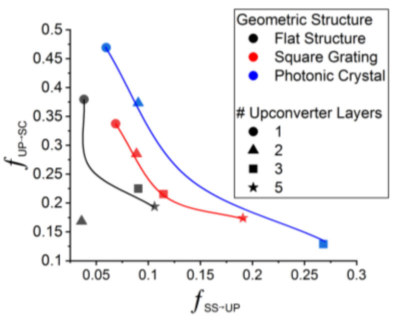

Figure 3. $f_{UP\rightarrow SC}$ versus $f_{SS\rightarrow UP}$ for multiple geometric configurations. Lines are guides to the eye.

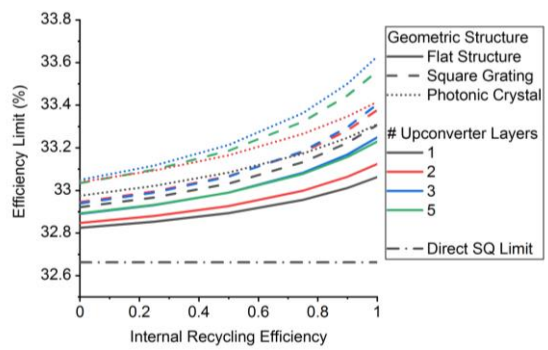

Figure 4. Efficiency limit of UBSC in comparison to the direct Shockley-Queisser limit.

Conclusion:

- Demonstrates an inherent compromise between $f_{SS\rightarrow UP}$ and $f_{UP\rightarrow SC}$ necessary for maximizing performance of a UBSC
- Photonic crystal configurations perform better than a simple grating, while both are improvements on a completely flat structure.
- ~1% efficiency increases to the efficiency limit are possible (which is considerable for a competitive technology operating near the existing efficiency limit)

Acknowledgments: This project is supported by the Delaware Energy Institute and W. M. Keck Foundation.

References:

1. Trupke, T., et al. Improving solar cell efficiencies by up-conversion of sub-band-gap light. *Journal of Applied Physics*, *92*(7), 4117–4122 (2002)
2. Chen, E. Y., et al. A Kinetic Rate Model of Novel Upconversion Nanostructures for High-Efficiency Photovoltaics. *IEEE Journal of Photovoltaics*, *6*(5), 1183–1190 (2016)