

Artificial Photonic Materials to Challenge Conventional Limits to Light Trapping and Solar Energy Conversion

Harry A. Atwater, Jeremy N. Munday, Dennis M. Callahan, Emily Kosten
Kavli Nanoscience Institute and Thomas J. Watson Laboratories of Applied Physics,
California Institute of Technology, Pasadena, CA,

Solar energy is currently enjoying substantial growth and investment, owing to worldwide sensitivity to energy security and climate change, and this has spurred basic research on light-matter interactions relevant to solar energy. Artificial photonic materials can enhance light-trapping and absorption, as well as increase the open circuit voltage and enhance quantum efficiency in solar photovoltaic structures. We describe photonic approaches for designing thin film and wire array solar cells that have light-trapping intensity and absorption enhancements that can exceed the conventional ergodic light-trapping limit using both wave optics and ray optics methods.

From thermodynamic arguments, Yablonovitch and Cody in 1982 determined the maximum absorption enhancement in the ray optics limit for a bulk material to be $4n^2$, where n is the index of refraction of the absorbing layer [1]. Stuart and Hall in 1997 expanded this approach to study a simple waveguide structure; however, for the waveguide structures they considered, the maximum absorption enhancement was $<4n^2$ [2]. Using a combination of analytical and numerical methods, we describe why these structures do not surpass the conventional ergodic limit, and show how to design structures that can.

We present here a physical interpretation in terms of the waveguide dispersion relations and describe the necessary criteria for surpassing the conventional limit. In particular, the wavevector β needed for a mode to surpass the ergodic limit is given by $\beta > (2n^2h\alpha^2)/(\alpha c^2)$, where α is the waveguide confinement factor and h is the waveguide thickness.

Another perspective on this issue is that the conventional light trapping limit can be exceeded in waveguide-like structures when the active region has an elevated local density of optical states (LDOS) compared to that of the bulk, homogeneous material. Additionally, to practically achieve light trapping exceeding the ergodic limit, the modes of the structure must be appreciably populated via an appropriate incoupling mechanism. We find using full wave simulations that ultrathin solar cells incorporating a plasmonic back reflector can achieve spatially averaged LDOS enhancements of 1 to 3, and a metal-insulator-metal (MIM) structure can achieve enhancements over 50 at a wavelength of 1100 nm, the bandedge of Si. Interestingly, incorporating the active solar cell material within a localized metallodielectric plasmonic or metamaterial resonator can lead to nearly spatially uniform LDOS enhancements above 1000 within the active material. We also have examined the possibility of structuring and combining ultrathin solar cells with dispersive dielectric structures such as photonic crystals to exceed the ergodic light trapping limit. We find that LDOS enhancements of ~ 2 -5 inside an untextured, planar solar cell can be achieved by simply placing a photonic crystal above or below the active material.

We have also developed a ray optics model for high aspect ratio wire array light trapping that suggests intensity enhancements within the wires can exceed the conventional limit for arrays with low wire area fractions on a Lambertian back reflector. We have applied this model to wire arrays with area fractions from .1% to 90%, and with aspect ratios between 30 and 200. The intensity enhancement at low wire area fraction can increase cell open circuit voltage, but low wire fraction results in a reduced short circuit current per unit area, and we explore optimizing cell efficiency within this parameter space. We compare with experimental Si wire array optical absorption data for wavelengths between 500 and 1100 nm for Si wires of varying sizes. We find reasonable agreement for large Si wires (radius 4 μ m) but the model underpredicts optical absorption for smaller wires (radius 1 μ m), suggesting that wave optics effects are important for the strong absorption observed in the small wire arrays.

Overall, we find many opportunities for exceeding the previously anticipated intensity enhancement and light trapping factor in dispersive dielectric and metallodielectric photovoltaic structures. These results can guide future solar cell designs that incorporate dispersive dielectric structures, plasmonics and metamaterials to achieve unprecedented light trapping.

[1] Yablonovitch and Cody. IEEE Trans. Elect. Dev. 29 300 (1982)

[2] Stuart and Hall J. Opt. Soc. Am A 14 3001 (1997)