Inverse Electromagnetic Design for Subwavelength Light Trapping in Solar Cells

Vidya Ganapati, Owen D. Miller, and Eli Yablonovitch
University of California, Berkeley, USA

ABSTRACT

In the subwavelength regime, the optimal surface texture for light trapping in solar cells remains to be found. We use computational inverse electromagnetic design to find the optimal nanoscale surface texture.

INTRODUCTION

Texturing of solar cell surfaces allows for absorption enhancement, due to the ability of incident light rays to couple to modes that are totally internally reflected within the cell (see Fig. 1). It is well known that in the ray-optics regime (where the thickness of the solar cell is much greater than the wavelength of light), that the maximum enhancement of optical path length in a medium is $4n^2$ times the single pass absorption of αd, where n is the refractive index of the material, α is the absorption coefficient, and d the thickness [1]. This maximum enhancement occurs when the light rays are ergodic in the medium, and can occur when there is a random surface texture on the solar cell.

However, in recent years, light trapping has seen renewed interest due to the problem of light trapping in the subwavelength regime. Currently, this is an important question as increasingly thin materials are being utilized for increased efficiency and lower cost. In this regime, traditional ray optics does not hold, and two fundamental questions are of great importance: (1) What is the maximum absorption enhancement available in this regime, and (2) what surface texture allows us to realize this maximum? We show how to find the optimal surface texture in the subwavelength regime through inverse electromagnetic design. Though Yu and co-workers [2] show a texture in the subwavelength regime that exceeds $4n^2$ light trapping, they utilize a low-index material for the absorber layer. In our work, we find the optimal texture for a typical semiconductor with refractive index of n = 3.5.

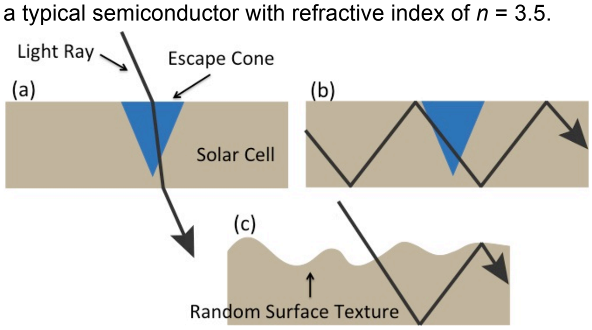

Figure 1 (a) An external light mode, (b) an internal mode, and (c) coupling from an external to an internal mode with the aid of a randomly textured surface.

INVERSE DESIGN ALGORITHM

We call our approach "inverse" design, because instead of "forward solving" by creating textures and then using an electromagnetic solver to find the absorption enhancement, we start with some arbitrary initial conditions, calculate the "shape derivative" of our texture, and iterate to the optimal final shape (see Fig. 2). We optimize a Figure of Merit (FOM) that accounts for absorption over a frequency range of ω_2 to ω_1.

$$FOM \equiv \frac{\frac{1}{\omega_2 - \omega_1}\int_{\omega_1}^{\omega_2} a(\omega)\,d\omega}{\alpha d}, \quad (1)$$

where $a(\omega)$ is the angle-averaged absorptivity, α is the absorption coefficient, and d is the average thickness.

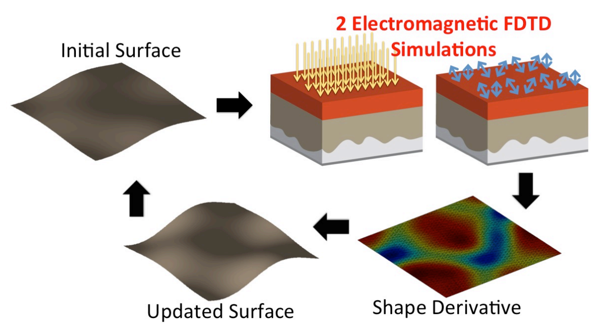

Figure 2 The steps in one iteration of our "inverse design" algorithm.

SURFACE TEXTURE OPTIMIZATION

With our inverse design algorithm, we optimized the surface texture of our absorbing material, also finding the optimal periodicity and antireflection coating thickness (see Fig. 3).

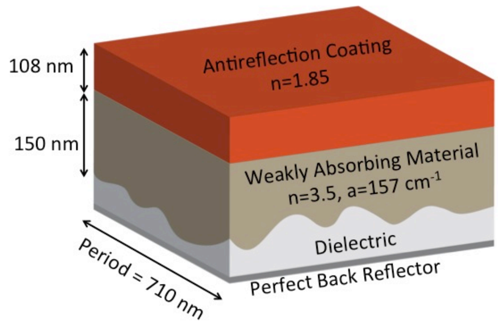

Figure 3 A schematic of the solar cell structure.

It took approximately 75 iterations to reach the optimal texture. The progression of the surface texture is shown in Figure 4.

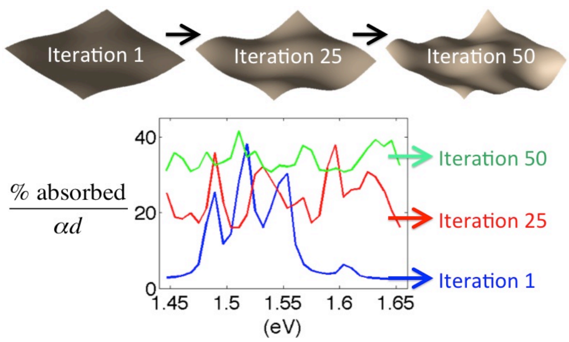

Figure 4 The evolution of the surface texture as the algorithm is iterated. The absorption enhancement is shown for normal incidence, one polarization.

The final surface texture is shown in Fig. 5. Though we only applied normally incident light at one polarization while optimizing the structure, we were able to achieve a high angle-averaged result, an enhancement of 40 times the single pass absorption (see Fig. 6). This angular robustness arises because in every iteration of our algorithm, we modify the surface in order to enhance the worst absorbing frequency, ignoring the behavior of the other frequencies. Thus, we eliminate resonances that are very sensitive to changes in incident angle and frequency. We can see the effect of this approach in Fig. 4. In the first iteration of our algorithm, there are some peaks in absorption enhancement at a few frequencies. However, this washes out by iteration 50, where the enhancement as a function of frequency is much more uniform.

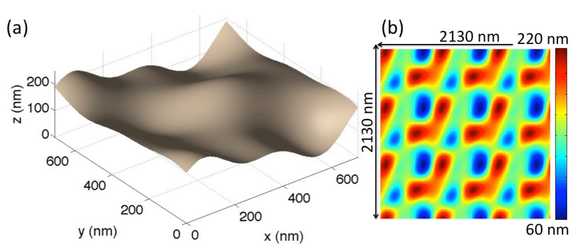

Figure 5 (a) One unit cell of the final surface texture and (b) a top-down view of multiple periods of the texture.

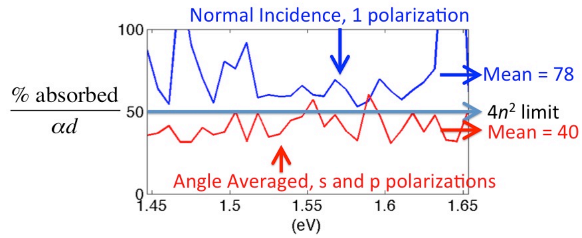

Figure 6 The absorption enhancement for normally incident and angle-averaged light.

We optimize a surface texture for a weakly absorbing material (as the $4n^2$ factor from ray optics assumes a weak absorber [1]), and assume an absorption coefficient that is the same for all frequencies. However, to demonstrate that this texture is applicable to real solar cell materials, which have frequency-dependent absorption coefficients, we show that we achieve close to the full enhancement factor for larger absorption coefficients. For αd = 50%, our structure gives 99% absorption (see Fig. 7).

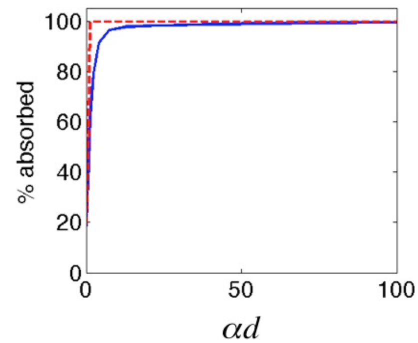

Figure 7 The absorptivity (frequency averaged, at normal incidence) as a function of the single pass absorption, αd. The blue line shows the actual absorptivity and the red dashed line shows the ideal case of achieving an enhancement factor of 78 (as we obtain in normal incidence for the case where α = 157 cm^{-1}) at every value of α.

REFERENCES

[1] E. Yablonovitch, "Statistical Ray Optics", *J. Opt. Soc. Am.* **72**, 1982, pp. 899-907.

[2] Z. Yu et al., "Fundamental limit of nanophotonic light trapping in solar cells", *Proc. Nat. Acad. Sci.* **107**, 2010, pp. 17491-6.