Inverse Optimization of Plasmonic and Antireflective Grating in Thin Film PV Cells

Shima Hajimirza and John Howell
The University of Texas at Austin
Department of Mechanical Engineering
Austin, Texas, USA
Email: Shima@ices.utexas.edu

Abstract. This work addresses inverse optimization of three dimensional front and back surface texture grating specifications, for the purpose of shaping the absorptivity spectrum of silicon thin film cells in targeted ways. Periodic plasmonic gratings with dimensions comparable or less than the incident light wavelength are known to enhance light absorption. We consider surface patterning of amorphous silicon (a-Si) thin films using front and/or back metallic nanostrips and ITO coatings, and show that wideband enhancement in unpolarized absorptivity spectrum can be achieved when back reflectors are used. The overall short circuit current enhancement using such structures is significant and can be as high as 97%. For TM-polarized wave it can be even higher as reported in previous work. In this work however, we focus on the optimization for the more realistic unpolarized radiation which is of significantly higher complexity. In addition, optimization is done with respect to two objective functions independently: spectral absorptivity and gain-bandwidth product of the absorptivity spectrum.

Keywords: Thin film solar cells, Inverse optimization, Spectral absorptivity

1. Introduction

Light trapping is very important in improving efficiencies of thin film solar cells, especially modern cells which are transparent or reflective to most of the solar radiation due to very thin absorber layers (~100nm to 1 micron) and use of indirect band-gap material (Silicon). Nanoscale patterning is a light trapping technique that can greatly enhance PV efficiency in amorphous Silicon (a-Si) thin film cells [1-4], and has become practical with the aid of modern thin film deposition techniques. Precise characterization of such effects is however not trivial, as several physical mechanisms are independently responsible for absorption enhancement across the visible and near infrared spectrum. Thin antireflective coatings introduce gradual change of refractive index on the thin film interface and reduce surface reflectivity. These effects are mostly modelled by Fresnel’s equations. In addition, Sub-wavelength dimensions of thin film cells result in physical mechanisms that are not modelled by conventional ray tracing radiation; Small structures on the same order of size as incident wavelengths can produce forward scattering and localize light below the diffraction limit, effects which both lead to enhanced absorption. Metallic gratings and particles of even smaller nanoscale dimensions can use optical wavelengths to trigger surface plasmon polariton (SPP) waves or localized surface plasmon resonances (LSPR) as investigated in [5-10]. These free-electron mobilizations represent focused electromagnetic fields that absorb evanescently into an adjacent a-Si medium. Long periodic metallic structures (nanostips) create waveguide modes that can resonate with the incident light, and result in peaks in spectral absorptivity at those eigen-modes. Further, nanoscale patterns (such as gratings, coating or cladding) provide different mechanisms when present on the back surface of the cell. Coatings designed to change the refractive index on the rear side of a device can reflect energy back through the silicon for an additional round of absorption.
When independent light trapping mechanisms are combined in a poly-process design, the cumulative absorption effects can be coupled and/or non-linear, complicating analytical studies. Variations of source angle, polarization and solar irradiance add to the challenge. Scant work exists in the literature that theoretically analyzes the limits of light trapping in nanoscale thin films [19, 20], and even those are subject to many simplifications and assumptions.

Numerical and experimental methods have been favourable for investigating discrete solutions to nanostructured PV cells. A few of such recent results studying the effects of plasmonic nanoparticles or gratings, and ITO are given in [2-17]. These studies were forced to use an exhaustive search method to access a small number of flexible parameters in two-dimensional device geometries. The exhaustive search approach involves calculation of the complete parameter map, which is intensely time consuming for problems with large number of flexible parameters and/or wide numerical ranges. Computational expense is a formidable challenge, with convergence times bottlenecked by extraordinarily small time steps and/or element sizes required to resolve the light/structure interaction accurately. Therefore, the addition of merely a few more flexible parameters makes an exhaustive search scheme intractable on even the fastest machines. Given the size of the available design space, the ability to conduct accurate and comprehensive analysis would be extremely valuable, precluding the need for expensive trial and error fabrication. One way to achieve this goal is through inverse optimization.

In previous work, we applied hybrid optimization techniques to solve for optimal front and back surface metallic gratings as well as indium tin oxide (ITO) antireflective layers to achieve maximum enhancement factor in the absorption of solar energy, and reported preliminary results for the case of two-dimensional simulations [18]. In this work, we generalize the previous preliminary results in several ways. We consider three-dimensional PV cells invoking more intense computational loads for numerical optimization. We allow for the front and back surface grating structures to be misaligned, giving more degrees of freedom to locations of resonated waveguide modes. In addition, we consider optimization for the case of unpolarized incident light which is an improvement over most existing numerical results. Furthermore, we consider the optimization of the texture morphology against an alternative objective function of gain-bandwidth product in addition to the short circuit current. In addition, we also analyse the sensitivity of the optimal designs to structural variations that might occur in the geometry vector as a result of numerical or fabrication error, and compare the results for different texture models.

The conclusions obtained from numerical simulations are similar to the case of 2D simulations previously studied. In particular, we observe that antireflective effect of the thin ITO layer on the absorption spectrum superimposes with the waveguide resonance created by back surface metallic grating, and creates a more productive coupling than with front surface gratings. In general, metallic structures on the back surface are less sensitive to structural and light incident angle variations and couple better with the antireflective coating than the front surface metallic gratings.

2. Structures for Metal Grating and ITO Coating

We study three different light trapping mechanisms based on periodic arrays of infinitely long metallic nanostrips and anti-reflective ITO coatings on the front and/or rear sides of a thin a-Si layer of a fixed thickness. Since these structures and the thin film absorber have sub-wavelengths dimensions, the study of light trapping in these cases extends beyond conventional ray tracing techniques, and require solving near field Maxwell’s equations as will be discussed in the next section [19,21].

The studied structures are shown in Figure 1-3. The structure of Figure 1 consists of a periodic array of silver nanostrips and a thin layer of ITO mounted on top the silicon absorber, and is parameterizes
with four variables: period $\Lambda$, silver height $h_{Ag}$, silver width $w_{Ag}$ and ITO thickness $h_{ito}$. Front metallic gratings contribute to the absorption enhancement by various means; they produce forward scattering and excite evanescent surface plasmon polariton (SPP) waves that absorb in the underlying layers. This phenomenon is only present in thin film layers with smaller (or comparable) dimensions than incident photons wavelengths and is not characterized by the ray tracing models. In addition periodic nanostrips are waveguide-slots that create guided modes of electromagnetic energy. The electric field components of these modes peak at the centre of the slot, and due to the continuity of the electromagnetic field at the interface, create excitation in the absorber layer. However, the refractive index of silver is small compared to a-Si, thus a large fraction of the resonated energy is reflected. The reflection of incident energy at the interface is governed by Frensel equations [21]. A thin ITO layer in between silicon and nanostrips helps reduce reflectivity by smoothening the refractive index contrast between a-Si and Ag. ITO is a relatively transparent material with low absorption (small $k$ index) with a refractive index between that of Ag and a-Si.

![FIGURE 1: Front surface silver nanostr玩意 grating and ITO coating structure.](image)

The second structure is that of Figure 2, consisting of metallic nanostrampoline gratings on the back surface and ITO coating on the front of silicon. The parameters are the same as those of Figure 1. Unlike the front surface grating, metallic structures on the back are sought to be good reflectors, scattering light back into the cell. In addition they also create guided optic modes that couple with the incident light at certain wavelengths and create resonances, leading to increased absorptivity. Multiple peaks in the absorptivity spectrum are justified by the presence of such waveguide modes.

![FIGURE 2: Back surface silver nanostrampoline grating and front ITO coating structure.](image)

Finally, Figure 3 shows a third structure we study, which is a combination of both of the structures in Figures 1 and 2, with an additional thin ITO coating on the back. This geometry is characterized by 8 parameters: period $\Lambda$, height and width of front nanostrips $h_{Ag}^f, w_{Ag}^f$, height and width of back nanostrips $h_{Ag}^b, w_{Ag}^b$, and height of front and back ITO layers $h_{ito}^f$ and $h_{ito}^b$. In addition, we allow for
spacing δ between the centres of the front and back nanostrips. Such spacing potentially helps compensate the phase shifts due to light refraction on the front surface and higher of coupling with the guided modes on the back.

![FIGURE 3](image-url) Front and back surface silver nanostrip gratings and ITO coating structure.

In a previous work [18] we reported optimization of similar structures using a simplified 2D model restricted to TM polarized sources only. An interesting observation made was that unlike front grating structures, back surface Ag gratings result in a modification of the absorptivity spectrum which superimposes with that of ITO, leading to wide-band absorption enhancement. Consequently, improvements as large as 100% in the short circuit current were reported. Furthermore, back surface structures are less sensitive to changes in the source polarization. We study these issues for the 3D nanostrip grating structures and consider unpolarized incident wave in this paper.

3. Details of Forward and Inverse Solvers

Here we discuss how numerical optimization is used to find a geometry structure with maximum absorption enhancement. Suppose that a general light trapping scheme is considered, which could be parameterized with a geometry vector $\mathbf{x}$. This can represent the positions and dimensions of metallic grating or antireflective coating on the front or back surface of the a-Si layer (as discussed in Section 2). An inverse optimization involves finding appropriate values for the coefficients of the unknown $\mathbf{x}$. To understand how this is done, we first discuss the forward problem of finding absorptivity characteristics for a given $\mathbf{x}$.

3.1. Forward Problem

For a known PV structure, the most accurate way of determining the spectral absorptivity of the thin film absorber is through solving near field Maxwell’s equation. Once the Maxwell’s equations are solved assuming a source with 1 Watt/m$^2$ radiation power, the spectral absorptivity of the silicon slab is found numerically by:

$$\alpha(\lambda) = \int_{V} -\left(\frac{\pi}{\lambda}\right)|\mathbf{E}|^2\epsilon'' dV$$  \hspace{1cm} (1)$$

where $\epsilon''$ is the imaginary part of the electric permittivity of the absorbing material (a-Si), $\mathbf{E}$ is the electric field vector, and $V$ is the volume of integration which encompasses a-Si slab. Furthermore, for unpolarized radiation (such as that of solar) the unpolarized absorptivity $\bar{\alpha}(\lambda)$ shall be considered:
where $\alpha_\phi(\lambda)$ is the absorptivity for a plane wave source with polarization angle $\phi$. The spectral reflectivity of a PV cell tells a lot about its conversion efficiency. If the irradiation air-mass spectrum is $I(\lambda)$, then the total number of absorbed photons in a spectral range $\Omega$ can be computed from a weighted expectation over the spectral absorptivity as follows:

$$N_a = \int_\Omega \lambda I(\lambda) \tilde{\alpha}(\lambda) d\lambda$$

Note that the above quantity is also proportional to the short circuit current of an ideal PV cell, neglecting the recombination effects within the semiconductor. Therefore, the photo-electric conversion of a cell is derived from the solution of Maxwell’s equations. The forward solution therefore includes solving Maxwell’s equations for sources with various polarization angles, and then numerically evaluating (2) and (3). Finite Difference Time Domain (FDTD) method is often used in solving partial differential equations such as Maxwell’s.

### 3.2. Inverse Problem

The goal of the inverse problem is to find a PV structure that maximizes an objective function related to the spectral absorptivity. When the mapping between the geometry and material properties to the resulting objective function is not analytically tractable and is complex, numerical optimization methods should be used. Most global optimization techniques call on the forward problem many times as they try to find the best combination of free parameters in the geometry. Furthermore, forward problems can be considerably time consuming to converge, not to mention that multiple simulations are necessary to account for an unpolarized source. Therefore an inverse optimization can last a very long time for such problems. This motivates the use of very efficient global optimization algorithms.

The objective function is a goodness measure for a geometry vector $x$. A useful choice of the objective function is the enhancement factor in the number of absorbed photons defines by:

$$f_{EF}(x) = \frac{N_{a-Si}^{x}(x)}{N_{a-Si}}$$

where $N_{a-Si}^{x}(x)$ is the number of absorbed photons in the a-Si layer equipped with the light trapping scheme with geometry vector $x$, and $N_{a-Si}$ is the number of absorbed photons in the bare a-Si. For a vector, these quantities are computed by equation (3) in the forward solution. Note that $N_{a-Si}$ needs only be computed once, since we consider an absorber layer of fixed thickness.

In addition, we briefly discuss an alternative choice of objective function called the gain-bandwidth product. This is equivalent to the product of the maximum spectral absorptivity and the bandwidth, defined by:

$$f_{GBP}(x) = \Delta B \times \max_{\lambda \in \Omega} \tilde{\alpha}(\lambda)$$

Where $\Delta B$ is the spectrum bandwidth defined as the difference between the two frequencies where the absorption drops by a factor $p$ from its peak value. Such criterion is commonly used in the design of

---

1 $\phi = 0$ means TM polarized and $\phi = \pi/2$ means TE polarized.
wideband amplifiers in electronics, and might not have a trivial physical interpretation for PV cells considered here. However, we suggest that gain-bandwidth product can be a measure of the stability of the light conversion efficiency of the PV cell to variations in the solar irradiance. Specifically, different realizations of solar radiation have different spectral irradiances. A cell with wideband absorptivity has therefore less sensitivity to such variations.

3.3. Optimization Algorithms

We have successfully adopted a combination of random and deterministic optimization algorithms such as Simulated Annealing and Quasi-Newton, and have created a tuneable hybrid optimization package that can solve the inverse geometry problems for thin films cells with considerable efficiency. Many of the details follow the descriptions given in previous work [15-18], so we skip them here to avoid repetition. We emphasize that our optimization algorithms are constrained, meaning that only sub-ranges of values for $x$ are acceptable. This is considered with the motivation of narrowing down the search space and also for finding light trapping mechanisms that are feasible to fabricate. For a more comprehensive discussion on this, please consult with [17].

4. Results

We optimized geometry parameters of different structures using simulated annealing and an iterative coordinate-wise optimization. FDTD simulations of the forward problem were run in the Lumerical FDTD software [22]. The thickness of silicon is fixed 80nm, and spectral range of $\Omega = (300,700)\text{nm}$ is considered. Solar irradiance is assumed to be the statistically averaged AirMass1.5 [23], and radiation is normal to the surface with a polarization angle that varies uniformly between 0 and $\pi/2$. For the case of back surface gratings and front ITO (Figure 2), we tried two different objective functions: unpolarized enhancement factor (UEF) and gain bandwidth product (GBW) with 90% peak bandwidth definition. For all other cases, only UEF objective is considered. The search regions for the optimum $x$ are constrained by upper and lower bounds: $50\text{nm} \leq h_{Ag}, w_{Ag} \leq 200\text{nm}, 10\text{nm} \leq h_{ito} \leq 100\text{nm}$ and $0 \leq \delta \leq 50\text{nm}$. In addition, a minimum spacing of $50\text{nm}$ between adjacent nanostrips is imposed to assure that the resulting structures are feasible to fabricate. Note that even with these limitations, an exhaustive search method takes a very long time to find the best solution, especially for the case of both front and back patterns.

Numerical values of the optimization solutions are provided in Table 1. Figure 4 shows the evolution of the objective function (enhancement factor) during the course of SA optimization for the case of rear surface grating and front ITO, which has been included as an example. Note that only selected candidates are represented in this plot (for more details about SA, please refer to [15]). In addition, the unpolarized absorptivity spectrums of the optimal structures of Table 1 are plotted in Figure 5, where they are compared with the bare a-Si spectrum. Also, the enhancement factor in the number of absorbed photons of the optimized structures is plotted for varying source polarization angles in Figure 6.

| Case                                  | Geometry(x)                                           |
|---------------------------------------|-------------------------------------------------------|
| Front Grating & ITO                  | $[\lambda, w_{Ag}, h_{Ag}, h_{ito}] = [167,54,100,37]\text{nm}$ |
| Back Grating & Front ITO (UEF)       | $[\lambda, w_{Ag}, h_{Ag}, h_{ito}] = [196,82,198,50]\text{nm}$ |
| Back Grating & Front ITO (GBW)       | $[\lambda, w_{Ag}, h_{Ag}, h_{ito}] = [148,75,160,30]\text{nm}$ |
| Back & Front Gratings and ITO’s      | $[\lambda, w_{Ag}, h_{Ag}, h_{ito}, w_{ito}, h_{ito}, h_{ito}, \delta] = [190,52,50,60,100,173,20,24]\text{nm}$ |
FIGURE 4: Evolution of the objective function (enhancement factor) during SA optimization for the case of rear surface gratings and front ITO layer.

FIGURE 5: Spectral absorptivity of the inverse optimization solutions for different structures. Back grating and front ITO optimizations are done for two objective functions: Unpolarized Enhancement Faactor (UEF) and Gain Bandwidth product (GBW).
4.1. Discussion

As indicated by Figure 5, using back surface waveguides enhancement factors as large as 1.85 in the conversion efficiency of a-Si can be achieved for unpolarized radiation. Front nanopatterns only enhance the TM polarized light absorption and are not very effective for unpolarized sources. When both back and front surface structures are used, a very stable enhancement factor over all variations of polarization angles is achieved. However, the net absorption in this case is not as high as back reflectors and front coating. These conclusions are in agreement with the results previously observed for the 2D model [18].

Note that the spectral absorptivity of the solution obtained from optimization using the GBW objective has a higher 90% bandwidth than the UEF objective, but its peak occurs at shorter a wavelength. AM1.5 spectrum peaks at around 460nm, and thus the UEF optimum solution has an overall higher photon absorption.

Referring to the numerical values of Table 1, we observe that back surface nanostrips are considerably wider and thicker than front surface gratings. Wider metallic structures are better reflectors and, when on the rear, are constructive light trapping mechanisms. Furthermore, very thick metallic gratings on the front are highly absorbent, and are thus to be avoided.

4.1.1. Sensitivity to Structural Variations

For the solutions obtained using inverse optimization, we perform a sensitivity analysis to evaluate the effect of geometry deviations on the absorptivity of the cell. This is a measure of stability of the design. In [17] a statistical analysis of efficiency robustness was reported using Monte Carlo simulations. Here, we use a different metric for measuring sensitivity. For a geometry vector \( \mathbf{x} \), we define relative average sensitivity of absorption to geometry deviations as the normalized mean of the derivative of spectral absorptivity with respect to the coefficients of \( \mathbf{x} \).
We numerically calculated $\mu(\lambda)$ for the optimum structures obtained by inverse optimization (for the UEF objective). The resulting curves are plotted in Figure 7. Note that front grating structures have a highly geometry-sensitive spectrum. In contrast, rear surface structures are fairly robust to average structural deviations.

$$\mu(\lambda) = \frac{1}{\bar{\alpha}(\lambda)} \left( \frac{1}{n} \sum_{i=1}^{n} \left| \frac{\partial \bar{\alpha}(\lambda)}{\partial x_i} \right| \right)$$

(6)

We numerically calculated $\mu(\lambda)$ for the optimum structures obtained by inverse optimization (for the UEF objective). The resulting curves are plotted in Figure 7. Note that front grating structures have a highly geometry-sensitive spectrum. In contrast, rear surface structures are fairly robust to average structural deviations.

![Figure 7: Average spectral sensitivity to geometry deviations for different structures.](image)

5. Conclusion

We used inverse optimization algorithms to optimize combinations of back and/or front surface gratings and ITO coating to maximize photon absorption of thin film a-Si cells for unpolarized radiation. The problem is of a significant computational load and thus, locating optimal geometries for the nanoscale patterns require efficient numerical optimizations. We concluded that nanostrip back reflectors are significantly more effective in enhancing the spectral absorptivity of thin film silicon than front structures, and are less sensitive to variations in source polarization and structural deviations. Our optimization framework allows for tuneable light trapping which can maximize arbitrary objective functions. For instance, we demonstrated the gain-bandwidth product maximization of absorptivity spectrum using back surface gratings. Future work shall report experiments with other forms of physically meaningful objectives.

References

[1] Rockstuhl, C., Fahr, S. and Laderer, F. 2008 Absorption Enhancement in Solar Cells by Localized Plasmon Polaritons, *J. Appl. Phys.*, Vol. 104(12).
[2] Beck, F.J., Polman, A. and Catchpole, K. R. 2009 Tunable Light Trapping for Solar Cells Using Localized Surface Plasmons, *J. Appl. Phys.*, Vol. 105.
[3] Wang, W., Wu, S. 2010 Reinhardt, K., Lu, Y. and Chen, S.: Broadband Light Absorption Enhancement in Thin-Film Silicon Solar Cells, *Nano Lett.*, Vol. 10.
[4] Sefunc, M.A., Okyay, A.K. and Demir, H.V. 2011 Volumetric Plasmonic Resonator Architecture for Thin-Film Solar Cells, *Appl. Phys. Letts.*, Vol. 98.
[5] Schaadt, D. M, Feng B. and Yu E. T. 2005 Optical Absorption Via Surface Plasmon Excitation in Metal Nanoparticles, *Appl. Phys. Lett.*, Vol. 86.
[6] Panoiu, N.C. and Osgood, R.M. 2007 Enhanced Optical Absorption for Photovoltaics Via Excitation of Waveguide and Plasmon-Polariton Modes, *Opt. Lett.*, Vol. 32.
[7] Shchegrov, A. V., Joulin, K., Carminati, R. and Greffet, J.J. 2000 Near-Field Spectral Effects due to Electromagnetic Surface Excitations, *Phys. Rev. Letts.*, Vol. 85.
[8] Derkacs, D., Lim, S.H., Matheu, P., Mar, W. and Yu, E.T. 2006 Improved Performance of Amorphous Silicon Solar Cells Via Scattering From Surface Plasmon Polaritons in Nearby Metallic Nanoparticles, *Appl. Phys. Lett.*, Vol. 89.
[9] Pillai, S., Catchpole, K.R., Trupke T. and Green, M. A. 2007 Surface Plasmon Enhanced Silicon Solar Cells. *J. Appl. Phys.*, Vol. 101.
[10] Ferry V.E., Sweatlock L.A., Pacifici D. and Atwater H.A. 2008 Plasmonic Nanostructure Design for Efficient Light Coupling Into Solar Cells, *Nano Lett.*, Vol. 8.
[11] Munday, J. and Atwater, H.A. 2010 Large Integrated Absorption Enhancement in Plasmonic Solar Cells by Combining Metallic Gratings and Antireflection Coatings, *Nano Letters*, Vol. 11.
[12] Muller, J., Rech, B., Springer, J. and Vanecek, M. 2004 TCO and Light Trapping in Silicon Thin Film Solar Cells, *Solar Energy*, Vol. 77.
[13] Ferry, V.E., Verschuuren, M.A., Li, H.B.T., Verhagen, E., Walters, R.J., Schropp, R.E.I., Atwater, H.A. and Polman, A. 2010 Light Trapping in Ultrathin Plasmonic Solar Cells, *Opt. Express*, Vol. 18.
[14] Zhao L., Zuo Y.H., Zhou C.L., Li H.L., Diao H.W. and Wang W.J. 2010 A Highly Efficient Light-Trapping Structure for Thin-Film Silicon Solar Cells, *Sol. En.*, Vol. 84.
[15] Hajimirza, S., El Hitti, G., Heltzel, A. and Howell, J. 2011 Specification of Micro-Nanoscale Radiative Patterns Using Inverse Analysis for Increasing Solar Panel Efficiency, *Proc. ASME/JSME 8th Thermal Eng. Joint Conf. AJTEC2011 (accepted ASME J. Heat Transfer)*.
[16] Hajimirza, S., El Hitti, G., Heltzel, A. and Howell, J. 2011 Using Inverse Analysis to Find Optimum Nano-scale Radiative Surface Patterns to Enhance Solar Cell Performance, *Int. Conf. Ther. & Mat. NanoSci. & NanoTech. TMNN (accepted Int. J. Ther. Sci.)*.
[17] Hajimirza, S. and Howell, J. 2011 Robust Nanoscale Patterns for Thin Film Solar Cells Using Inverse Optimization of Non-Uniformly Sampled Absorption Spectrum, *ASME Int. Mech. Eng. Conf. & Exp.*.
[18] Hajimirza, S., Heltzel, A. and Howell, J. 2012 Broadband Absorption Enhancement in Thin Film Solar Cells Using Inverse Optimization of Light Trapping Mechanisms, *ASME Micro/Nanoscale Heat and Mass Trans. Int. Conf. MNHMT*.
[19] Yu, Z., Raman, A. and Fan, S. 2010 Fundamental Limit of Nanophotonic Light Trapping in Solar Cells, *Proc. Nat. Acad. Sci. USA, doi:10.1073/pnas.1008296107*.
[20] Han, S.E. and Chen, G. 2010 Toward the Lambertian Limit of Light Trapping in Thin Nanostructured Silicon Solar Cells, *Nano Lett.*, Vol. 10 (11).
[21] Howell, R., Siegel R. and Menguc P.M. 2011 Thermal Radiation Heat Transfer, *CRC Press 5th Ed.*
[22] http://www.lumerical.com/fdtd.php
[23] American Society for Testing and Materials, 2003, ASTM standard tables for reference solar spectral irradiances. See also URL http://www.astm.org.