1. Introduction

New antireflection coatings offer advantages of both broadband antireflection and wide angle antireflection.

Recently, we utilized Bayesian learning optimization to determine the optimized antireflection properties of single layer thin film, nanowire arrays, and nanocone arrays, which are shown in Fig. **??** [**?**]. The single layer thin film consists of a single dielectric with an an index of refraction of the geometric mean of glass and air or $n_1 = 1.21$ and thickness $t = 120$ nm. The nanowire array has a pitch $a = 390$ nm, a diameter of $d = 290$ nm, and a height of $h = 150$ nm. The nanocone has a pitch $a = 400$ nm, bottom diameter $d_{bot} = 400$ nm, top diameter $d_{top} = 90$ nm, and height $h = 640$ nm.

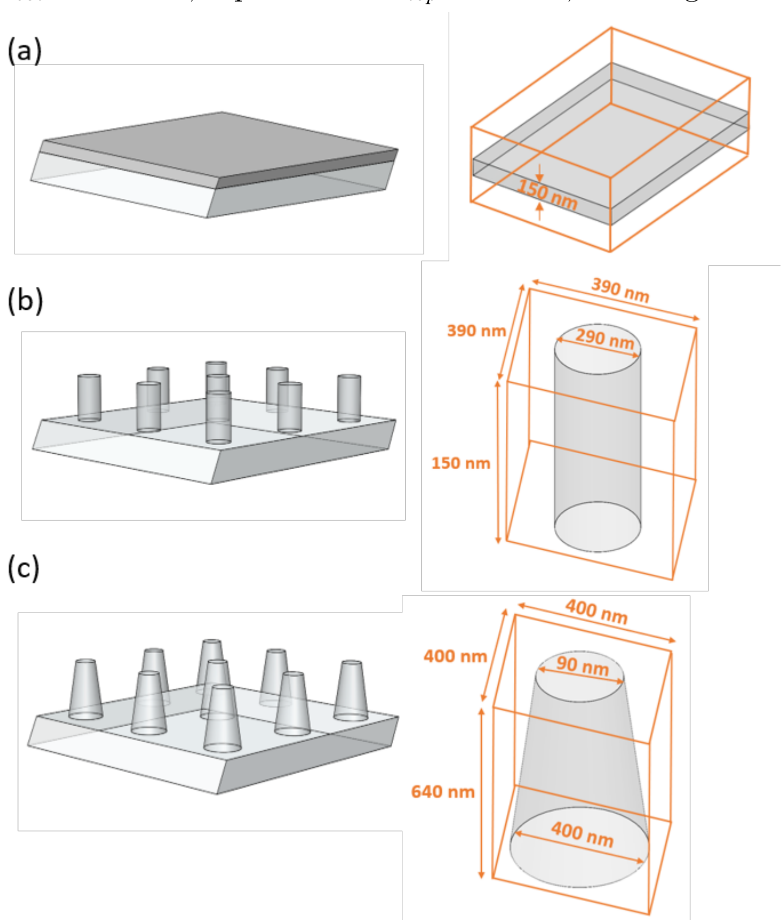

Figure 1: Structures and dimensions of the (a) thin film, (b) nanowire, and (c) nanocone simulated in this study.

We combine this with a simple model for studying available solar irradiance for different module orientations and latitudes [?] to determine the annual enhancement of available solar irradiance with different types of antireflection coatings.

where Φ_{bn} is the photon flux of the direct beam radiation and Φ_d is the diffuse isotropic sky photon flux. θ is the angle between the direct beam radiation on the module and the normal to the module surface. β is the solar module tilt. We assume the irradiance of the diffuse radiation is 10% that of the direct beam radiation as is the case with the AM1.5G and AM1.5D standard spectra.

The direct beam spectral irradiance $F(\lambda)$ of arbitrary airmass AM is

$$F\_bn(\lambda) = F\_AM0(\lambda)\left[\frac{F\_AM1.5D(\lambda)}{F\_AM0(\lambda)}\right]^{(AM/1.5)^{0.678}} \tag{1}$$

where $F_{AM0}(\lambda)$ and $F_{AM1.5D}(\lambda)$ are the spectral irradiance of the AM0 and AM1.5D spectrum [?], respectively and λ is the wavelength in vacuum. The power relationship is a fit to empirical data [?]. The direct beam irradiance of particular air mass may be obtained by integrating the spectral irradiance

$$I\_bn = \int F\_bn(\lambda)d(\lambda)d(\lambda). \tag{2}$$

The AM1.5G spectrum is assumed to follow the same scaling as AM1.5D and the diffuse radiation can be obtained from the difference between the two gobal spectral irradiance and the direct beam spectral irradiance:

$$F_d(\lambda) = F_{AM0}(\lambda)\left[\frac{F_{AM1.5G}(\lambda)}{F_{AM0}(\lambda)}\right]^{(AM/1.5)^{0.678}} - F_{bn} \tag{3}$$

$$I_d = \int F_d(\lambda)d\lambda. \tag{4}$$

The direct beam photon flux density is related to the spectral irradiance by

$$b_{bn}(\lambda) = \frac{F_{bn}(\lambda)\lambda}{hc}. \tag{5}$$

$$b_d(\lambda) = \frac{F_d(\lambda)\lambda}{hc}. \tag{6}$$

The photon flux is

$$\Phi_{bn} = \int b_{bn}(\lambda) d\lambda \tag{7}$$

$$\Phi_{d} = \int b_{d}(\lambda) d\lambda \tag{8}$$

The total photon flux incident on a module is the sum of the direct beam and diffuse components

$$\Phi_{Tm} = \Phi_{bn} \cos\theta + \frac{(1+\cos\beta)}{2}\Phi_d \tag{9}$$

The annual module incident photon flux is

$$B_{mA} = \frac{12}{\pi} \times 3600 \int_0^{365} \int_{-\omega_s}^{\omega_s} \Phi_{Tm} d\omega dn \tag{10}$$

ω_s is the sunset hour angle,

$$\omega_s = \cos^{-1}\left(-\tan\phi\tan\delta\right) \tag{11}$$

and $-\omega_s$ is the sunrise hour angle.

The number of photons not reflected by the module is

$$b_{Tc} = b_{bn}\left[1 - R(\lambda,\theta,\gamma_i)\right] + b_d \frac{1}{2\pi} \int_0^{2\pi} \int_0^{\pi/2-\beta} \left(\frac{1+\cos\theta}{2}\right)\left[1 - R(\lambda,\theta,\gamma_i)\right] d\theta d\gamma \tag{12}$$

where $R(\lambda,\theta,\gamma_i)$ is the reflection spectra of the module/interface is a function of angle of incidence θ, and injection azimuth angle γ_i. $\gamma_i = \gamma - \gamma_s$, where γ is the module azimuth angle and γ_s is the solar azimuth angle. The azimuth angle is defined so $0°$ is south, negative is east, and positive is west [**?**]. The total photon flux transmitted through the top glass is

$$\Phi_{Tc} = \int b_{Tc}(\lambda) d\lambda \tag{13}$$

The annual solar cell flux is

$$B_{cA} = \frac{12}{\pi} \times 3600 \int_0^{365} \int_{-\omega_s}^{\omega_s} \Phi_{Tc} d\omega dn \tag{14}$$

The annual module reflection is the portion of photons over an entire year that are lost due to reflection is

$$R_{mA} = \frac{1 - B_{cA}}{B_{mA}}. \tag{15}$$

The reflection spectra of various antireflection structures is shown in Fig. **??**. The reflection is shown as a function of wavelength along the radius and incidence angle θ in the circumferential direction. The reflection is shown for (a) bare glass, (b) thin film, (c) nanowire array, and (d) nanocone array. The reflection spectra shown is averaged for both TE and TM polarized light and over the incident azimuth angles γ_i. The integrated reflection as a function of incidence angle θ is shown in Fig. **??**(b). The reflection spectra is integrated over wavelengths from 280 to 1200 nm.

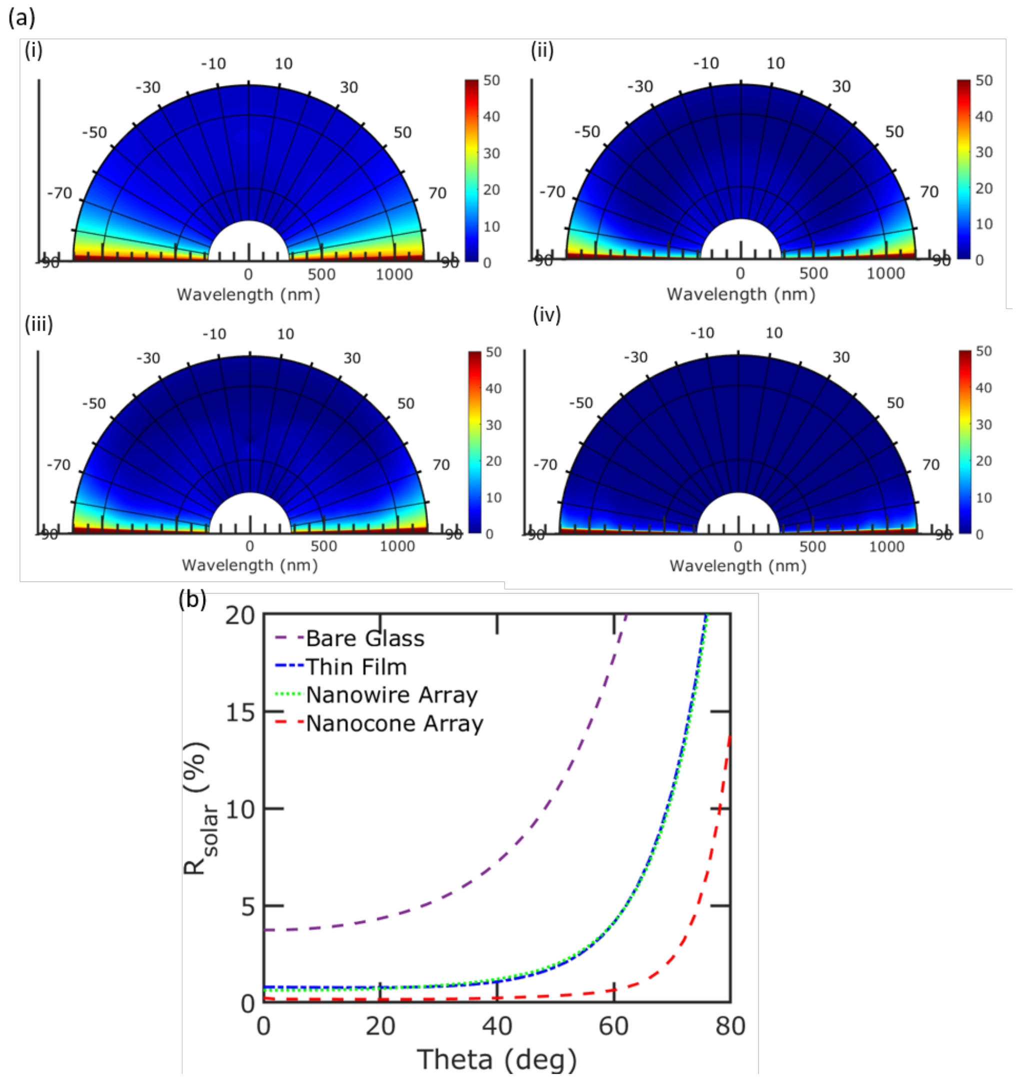

Figure 2: Reflection spectra of different structures. (a) Reflection spectra as a function of incidence angle θ for (i) bare glass, (ii) thin film, (iii) nanowire array, and (iv) nanocone array. (b) Integrated solar reflection as a function of incidence angle.

2. Data Availability

All python code used for the model to generate the figures in the manuscript can be found in the following Github repository: `https://github.com/pleu/LAMPsolar`.

3. Acknowledgements

This work was supported by the National Science Foundation [grant number 1930582].