Visual Characterization of Anti-Reflective Coating on Solar Module Glass

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***Abstract*—Anti-reflection coatings (ARCs) are widely used on photovoltaic (PV) module glass to increase light transmission. The PV community is increasingly concerned with how long these coatings last in the field and would benefit from a simple method for quantifying performance on fielded modules. In this work, we demonstrate how a straightforward visual inspection of the color of reflected light can identify the presence of an interference-based ARC. By tracking the color shift over time a qualitative measurement of ARC degradation can be made. This method is applicable in full-sun outdoor conditions and only requires a flashlight and a standard RGB camera. We demonstrate how the physics of thin-film coating interference and color theory accurately predict the color the reflected light. This technique could gain widespread use for inspecting PV modules in the field because it is easy to perform and requires no specialized equipment.**

I. Introduction

ANTI-REFLECTION coatings (ARCs) on the air-glass interface of photovoltaic (PV) modules are widely used to improve module performance. The most common variety of ARC used on PV glass is a thin layer of porous silica deposited by the sol-gel method with a thickness around ∼120 nm, and can improve power output by up to 3% [1]. These coatings reduce reflection both because they have an index of refraction between that of glass and air and because the thickness is tuned to provide destructive interference of reflected light at the wavelengths most important for the solar absorber.

Recently, there has been increasing concern as to how long ARCs last in the field [2]–[4]. Visual inspection is a widely-used and powerful technique for assessing PV module health [5]. Presently, it is not recognized that visual inspection can also be used to assess the presence and quality of a ∼100 nm thick ARC. In fact, reflected light from interference-based ARCs have a characteristic color shift that varies with the angle of incidence (AOI) and is observable to the trained eye. Similarly, an inexpensive RGB color camera can detect these color shifts.

In this paper, we describe how to characterize ARCs on outdoor modules using simple equipment: a low-power flashlight, white card and either the human eye or a camera. By comparing to broadband spectral reflectivity measurements, we demonstrate that these simple methods can accurately qualify interference-based ARCs without specialized equipment. Further we provide a detailed description of the optical physics that creates this effect and explore opportunities for quantitative ARC characterization using similar methods.

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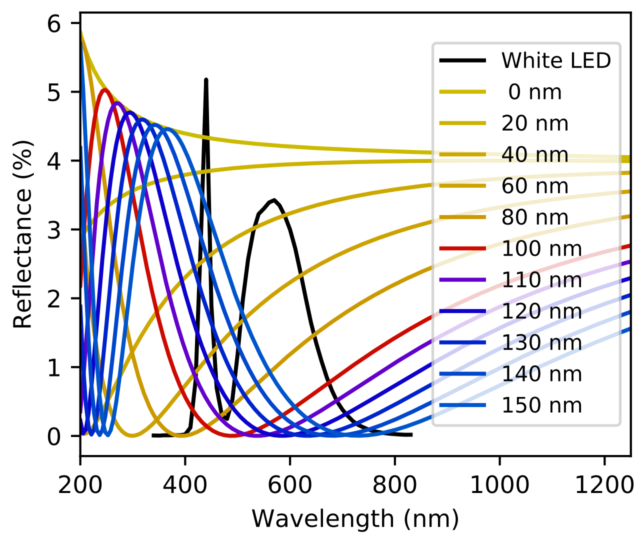

Fig. 1. Dependence of spectral reflectivity on the physical thickness of a porous silica ARC (effective index of refraction 1.23) on BK7 glass at 8 degrees angle of incidence. Also shown is a spectrum of the relative irradiance from a white LED source (iPhone X LED). Units of white LED spectrum are proportional to W/cm^2/nm. Color of plot is a saturated version of the color observed if a white LED were reflected from the sample.

II. Interference-based ARCs

An interference-based ARC is a thin film that causes destructive interference of light reflected from the top and bottom surface of the film. The film optical thickness is chosen to be one-quarter of the wavelength where minimum reflection is desired. At each location, the reflection properties can be calculated using the complex-matrix form of the Fresnel equation [6].

As an example, Fig. 1 shows the dependence of the reflection spectrum on coating thickness for a typical ARC on a silicon solar cell. This simulation considers a layer of porous silica with an effective index of refraction of 1.23 on

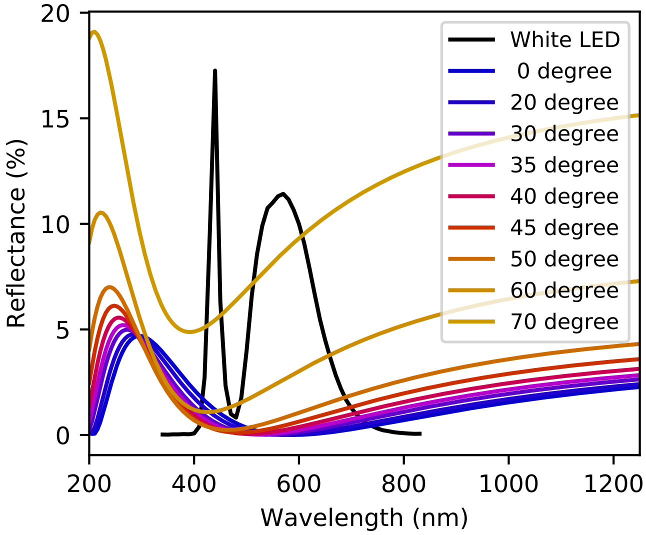

Fig. 2. Angle dependence for a porous silica ARC (effective index of refraction 1.23) on BK7 glass with 120 nm thickness. Also shown is a spectrum of the relative irradiance from a white LED source (iPhone X LED). Units of white LED spectrum are proportional to W/cm^2/nm. Color of plot is a saturated version of the color observed if a white LED were reflected from the sample. Color variation is similar if sunlight is used instead of a white LED.

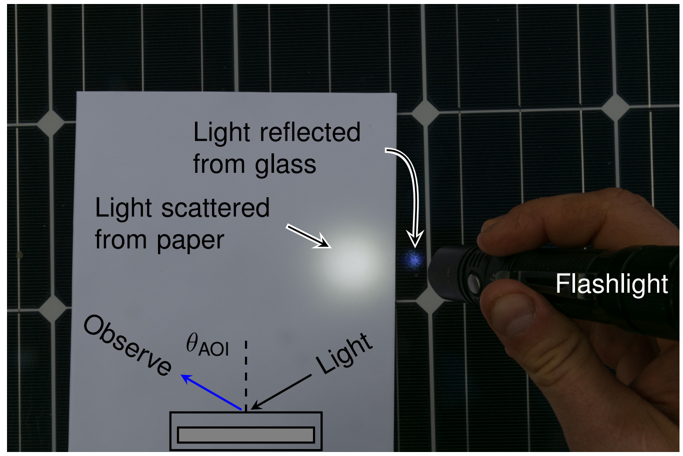

Fig. 3. Demonstration of simple identification of ARC on outdoor PV module. A flashlight is reflected from the module glass, a significant blue shift indicates that an ARC is present. Image is taken on a PV module with an ARC (Panasonic n330) outdoors with overcast conditions. The flashlight spreads light over a large range of angles, leading to diffuse reflection observed from the paper and specular reflection observed from the glass, and s specular reflection observed from the glass.

a thick slab of BK7 glass. The coating provides broadband anti-reflection where the wavelength of minimum reflectivity is related to the coating thickness. The ARC is most effective for normally incident light.

The spectral shift at different coating thicknesses or angles causes an observable color shift in the reflected light. Perceived color is a complex subject, but can be calculated based on the CIE color functions and translated into an RGB value. In Fig. 1, we also show the relative irradiance from a white LED. This spectrum was taken by calibrating a spectrometer (Ocean Insight HDX) using a 2500 K blackbody spectrum (Ocean Insight HDX) and finding the relative irradiance from a white LED (iphone X). Fig. 1 displays each spectrum with the color a human would observe from the reflection spectrum. To do this, we calculate the CIE hsv color value from the reflection spectrum and the white LED light source [7], increase the saturation to 1 and value to 0.8 (in order to show the more saturated color). The resulting plots show that a significant color shift should be observable for different coating thicknesses. The color shift is similar if 6000 K blackbody radiation is used instead.

Similarly a coating color shift from blue to magenta to yellow is observed as the angle-of-incidence increases from 0 (normal) to 60 degrees, see Fig. 2.

III. Visual Characterization of ARC

Several simple methods are available for detecting the presence of an ARC by the color shift of white light reflected from the glass surface. In these methods, shown schematically in the inset of Fig. 3, a broadband white light source (flashlight or sunlight) is reflected from the PV glass and the reflected light is collected. The reflected light can be observed using an RGB camera, a white card or directly by eye if a low-intensity light source is used.

First, we demonstrate ARC identification by visually inspecting the color of a flashlight as it reflected from the glass. Fig. 3 shows that light reflected from the glass is much more blue than the light scattered from a sheet of white paper. This agrees with how a typical interference-based ARC at low AOI reflects more blue light than green or red, see Fig. 1, thus making the reflection appear blue. This is a remarkable demonstration that a simple measurement can detect the presence of a 100-nm thick coating.

The blue reflection for a full-thickness coating is also easily visible by eye. When directly observing the reflected light by eye, it is important to use a flashlight with the ability to give a very low output intensity ($\sim$ 1-10 lumens). If the flashlight is too bright then the human observer can no longer distinguish color and the measurement could pose a safety hazard. Because the reflection from the glass is predominantly specular, the measurement can be performed in full sunlight. It is only important to align the flashlight and observer so that the the specular reflection from the sun does not overlap with the flashlight reflection. Incidentally, if a camera is used, it is possible to use the sun as a light source instead of the flashlight.

Next, we inspect in more detail the color of the reflected light and how it depends on angle, see Fig. 4(a). Images were taken using a consumer RGB camera (Canon 5DS R, Canon 100 mm f/2.8L lens) on a PV module with an interference-based ARC (Panasonic n330) outdoors (overcast conditions) and a white LED keychain flashlight (Nitecore TIP, lowest intensity setting). The camera settings were set to a white balance color temperature of 6000 K, aperture f/32, ISO 100

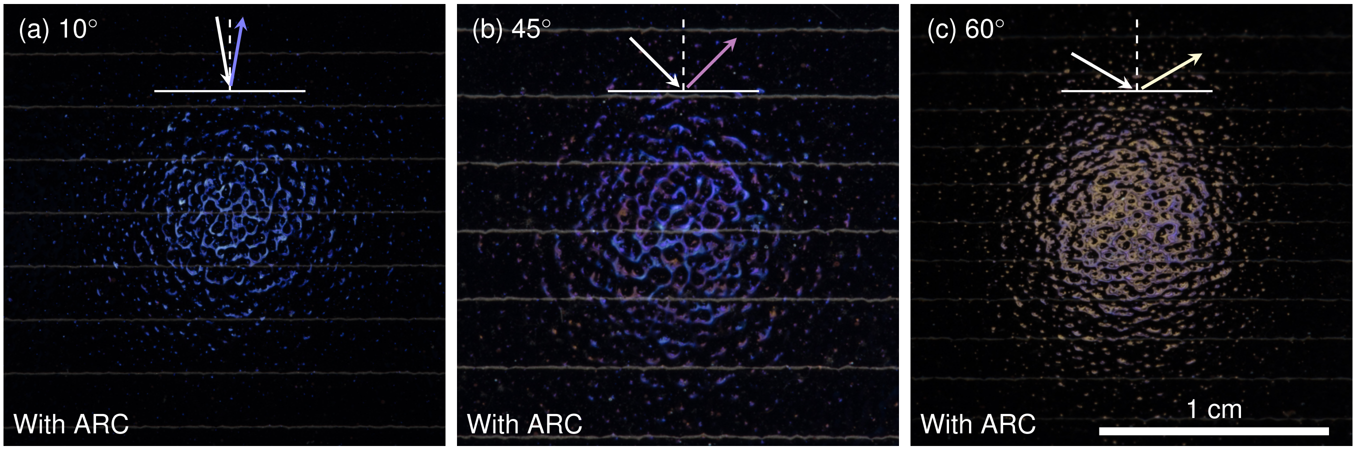

Fig. 4. Dependence of reflected LED (nitecore TIP) light on angle of incidence for a PV module with ARC (Panasonic n330). As the angle of incidence increases, reflected light goes from blue to more violet to yellow. The grid lines are lightly visible.

and 1 second exposure. The small aperture setting was chosen in order to increase the depth of field so the full reflected spot is in focus even at higher angles-of-incidence.

The 0.1 mm scale roughness in Fig. 4(a) is visible as a non-uniform surface glitter. A similar phenomenon of ocean glitter has been studied extensively [8], finding that the spatial extent and highlight distribution is related to the angular distribution of surface normals and solid angle of the light source. These glitter images could be analyzed in detail to determine the local surface normal at each point in the image. Since the distribution of surface normals affects the spectral reflectivity and local color, a more-precise understanding of the surface normal distribution can lead to a better prediction of how averaged spectral reflectivity relates to coating performance.

By inspecting Fig. 4(a) more closely, we note that there is some minimal color variability in the highlights. This is explained by comparing with Fig. 2, where there is only minimal perceived color variation as AOI ranges from 0 to 20 degrees. In contrast, Fig. 4(b) shows the reflected spot for an image taken at 45° AOI. In this image, some blue, violet, magenta and orange colors are seen in the glitter highlights, agreeing with the predicted colors for higher AOI.

At 60° AOI, see Fig. 4(c), the overall reflected spot becomes wholly more yellow, while individual highlights are mostly violet and yellow, in agreement with the simulations. This overall shift toward yellow of the reflected light at higher AOI is also clearly visible by eye. We note that some of the color variation could be due to non-uniform coating thickness (this possibility will be explored in detail in the final manuscript).

In contrast, Fig. 5 shows reflected light from a module without an ARC. The reflected light in these images does not show any color compared with a white card, or a color shift with AOI.

IV. Comparison with Spectral Measurements

A broadband spectral reflection measurement can confirm the ARC properties observed using the simple methods. In

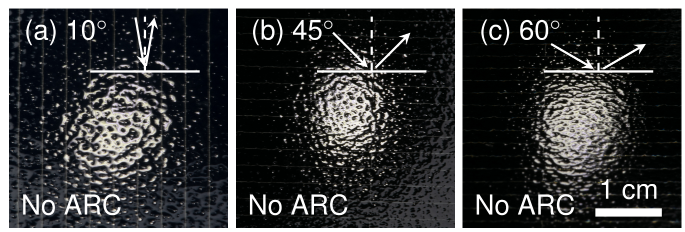

Fig. 5. Reflected light from a PV module without an ARC (Megsun B07PV6HBQ8) is white, regardless of angle. Lightsource: Nitecore TIP.

this measurement, a fiber-coupled (400 μm multimode, 0.22 NA) tungsten-halogen light source (Ocean Insight HL-2000) is directed onto a PV module at a 45 degree AOI (Thorlabs RPH-SMA). Light is analyzed on a compact CCD spectrometer (Ocean Insight HDX).

The reflection spectrum is calculated by comparing the reflected light from the sample of interest to a back-blackened BK7 sample (Filmetrics REF-BK7). The module with ARC (Panasonic n330) shows a broadband dip centered around 600 nm, see Fig. 6. On the other hand, a module without ARC (Megsun B07PV6HBQ8) shows a flat response with a reflection similar to that of glass. The offset between the glass reflection and the reflection from the module without ARC is due to the roughness of the glass, which reduces the light collected. These spectral measurements confirm which modules have ARCs.

V. Conclusion and Outlook

PV module ARCs are widely used for increasing performance. We have described an exceedingly simple method for measuring these ARCs in the field. As the module ages and the ARC thickness is reduced or scratched away, we predict the reflected color will shift in a quantifiable way. This method could easily find widespread use in field inspection of solar modules.

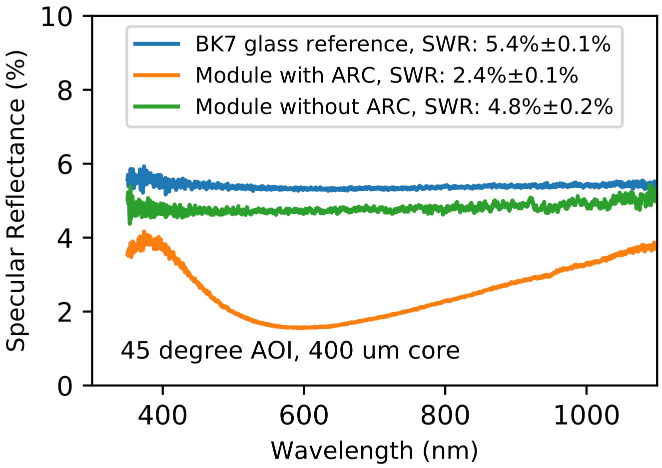

Fig. 6. Reflection spectrum from PV module glass with and without ARC. The module with ARC shows a pronounced dip centered at 600 nm, while the module without ARC has a flat reflectance. The solar weighted reflection (SWR) is calculated using the standard AM1.5 spectrum, the uncertainty quoted in the legend is the standard deviation of the mean SWR for 50 measurements at slightly different locations on the same module. This averages the variable reflection due to the glass roughness.

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