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Design, fabrication, and measurement of a polymer-based anti-reflection coating for improved performance of a solar panel under a specific incident angle

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ABSTRACT

Solar panels are usually covered with anti-reflection coatings (ARCs) that operate optimally for normal light incidence. Thus, ARCs effectiveness declines with increasing incident angles. In this contribution, we propose and design a polymer-based ARC that can be customized to operate optimally under a specific incident angle. It finds its application in building-applied photovoltaic (BAPV) and building-integrated PV (BIPV) systems where solar panels are installed on various building facets at arbitrary angles. A sample of the designed coating is fabricated using Polyurethane (PU) as a transparent polymer in a low-cost process. Our experiments show a 5.6% enhancement in the real outdoor conversion efficiency of a glass-covered Si solar cell equipped with the designed ARC under the targeted incident angle, wherein it is compared with a case in which our designed ARC is substituted by a plain PU-based sheet ARC of an equal thickness.

1. Introduction

Anti-reflection Coatings (ARCs) have been utilized in diverse optical and optoelectronic devices. In the field of Photovoltaics (PV), ARCs are applied on the front glass cover of solar panels to reduce reflection from the panel surface, thus to increase the short-circuit current (I_{sc}), and to improve the conversion efficiency of the solar panels. Different types of ARCs have been proposed in the literature for application in solar panels. Porous coatings of low refractive index materials on glass [1], textured glasses [2], multilayer graded-index ARCs [3], and polymer-based ARCs [4] are commonly used for this purpose. Among various technologies, there is a growing investment in the polymer-based ARCs [5–8]. Polymer-based coatings are lightweight, adhere to the substrate readily, show mechanical flexibility, and can be mass produced while being cost-effective. Polydimethylsiloxane (PMMA), Polycarbonate (PC), Polyethylene terephthalate (PET), Polycycloolefin, Polysulfone (PSU), Polyethersulfone (PES), and Polyamide (PA) are some of the previously used transparent polymers for fabrication of ARCs in various applications [9].

ARCs are usually optimized for minimum reflectance at normal incidence (zero incident angle) while maintaining low reflection for larger incident angles, to the extent possible. Nevertheless, there are some applications in which solar panels cannot be aligned to receive incident light vertically at noon. For instance, this can be due to various installation constraints imposed on a building. this condition is encountered in BAPV and BIPV applications, where solar panels are installed on various building facets at arbitrary angles [10]. In such cases, using ARCs optimized for a specific incident angle corresponding to the light at noon improves the energy generated by the panel over 24 h. The angle of incidence is dependent on the geographical location of the intended building and the installation angle of solar panels. Fig. 1 illustrates a typical case. In this figure, the reception pattern of solar panel 3 equipped with the ARC introduced in this work is changed from 4 to 5. This obviously increases power generation of panel 3 due to improved alignment towards the sun.

In this research, we design, fabricate and measure a polymer-based ARC which can be customized for a specific incoming light angle. This coating is stacked on the constituting layers of a solar panel to improve electric power generation when the incident light rays arrive obliquely. The ray-tracing method is used for calculation of transmission patterns of the designed ARCs. This method is verified by a full-wave numerical technique. Also, the fabrication process of a sample of the designed coatings is explained in Section 3. Finally, results of the PV performance measurements are presented in Section 4.

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1,2,3: Solar panels
4: Reception pattern of the solar panel 3 without ARC
5: Reception pattern of the solar panel 3 with ARC

Fig. 1. Role of the ARC in changing the reception pattern of a solar panel on a building facet under a specific incident angle.

2. Design

The constituting layers of a typical commercial solar panel are depicted in Fig. 2. The first layer is made of low iron glass with a typical 3- to 4- mm thickness. This top layer provides mechanical stability and protection for the module. Two polymer layers are added to both sides of the cell matrix for encapsulation. In silicon (Si) solar panels, these polymer sheets are usually made of copolymer Ethylene Vinyl Acetade (EVA). The third layer shown in the figure is composed of solar cells including their top anti-reflective layers. Note that in Si solar cells, a thin-film silicon nitride (Si_3N_4) is commonly used as the anti-reflection layer. Finally, the back layer is a composite plastic sheet for preventing moisture from entering the module. As will be explained in what follows, an additional ARC can be utilized on top of the shown layers.

2.1. ARC in the form of a plain polymer layer

For a Si solar panel, the main reflection losses occur at the interfaces of EVA/Si_3N_4/Si and air/glass. Since the refractive index of glass is slightly greater than 1.5, a transparent polymer sheet with the typical refractive index between 1.4 and 1.5 can be placed on the glass layer as an ARC for the panel. Fig. 3 compares the transmission pattern through the surface of a typical Si solar panel (without ARC) with a case in which a plain polymer sheet is applied on the glass layer (with ARC). The results have been calculated by the Transmission-Line Formulation (TLF) which is a Fourier-based numerical technique [11,12]. We observe that using this ARC improves the transmittance for a wide range of incident angles. Nevertheless, the design is not angle selective.

Note that throughout this paper, transmission values at different incident angles have been calculated as the average transmission rate of incident light through the ARC weighted by the standard solar spectrum AM1.5G ($F(\lambda)$) over the wavelength range between 300 nm and 1100 nm. In addition, since the sunlight is not polarized, the transmission values are the average of the transmission for TE and TM-polarized incident light as given by:

$$T = \frac{\int_{300nm}^{1100nm} (\frac{T_{TE} + T_{TM}}{2}) F(\lambda) d\lambda}{\int_{300nm}^{1100nm} F(\lambda) d\lambda}, \quad (1)$$

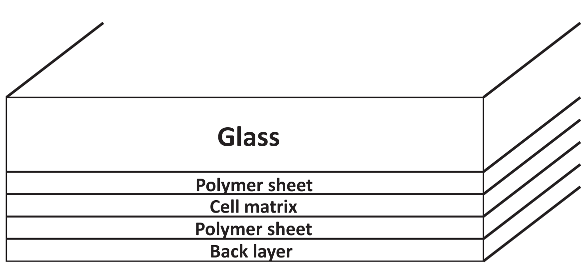

Fig. 2. Constituting layers of a typical solar panel.

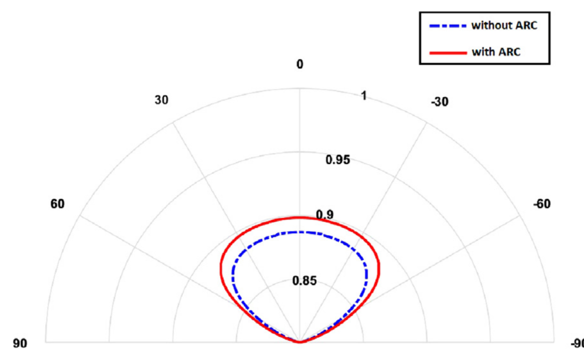

Fig. 3. Transmission patterns through the surface of a typical Si solar panel with/without a plain polymer layer as the ARC. (Transmission values and incident angles are shown along radial and angular directions, respectively.).

2.2. ARC in the form of a polymer-based periodic structure

As discussed in the previous Section, we are interested in a design for the ARC that can be optimized for a specific incident angle. For this purpose, we propose an ARC in the form of a periodic structure with blazed grooves to be stacked on a Si solar panel. This periodic structure changes the light acceptance angle of a solar panel towards a specific incident angle. At the same time, it is designed in such a way that multi-reflection at the facets of its grooves results in an increase in transmittance especially for the incident angle. Therefore, the designed structure works like an ARC which operates optimally under a specific incident angle. This structure shows improved performance compared to symmetric periodic structures as will be explained in what follows.

For the calculations, we study a typical Si solar panel equipped with the designed ARC (Fig. 4). In this figure, the angle of incidence is

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