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Freeform surface invisibility cloaking of interconnection lines in thin-film photovoltaic modules

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ABSTRACT

The vast majority of conventional photovoltaic (PV) module technologies suffer from inactive areas, for example, due to the front contact finger grids or interconnection lines, which are essential for efficient extraction of the photocurrent. Invisibility cloaking by freeform surfaces is a new concept to guide incident light of the entire solar spectrum and all angles of incidence away from these inactive areas to the active areas of the PV modules. In this work, a freeform surface design is incorporated into a standard encapsulation layer of conventionally front glass covered PV modules. For a copper indium gallium diselenide (CIGS) thin-film PV module, a relative improvement in power conversion efficiency of 6.5% is presented, which demonstrates that the entire optical losses of the inactive area can be recovered. The design of the freeform surface is optimized based on rigorous ray-tracing simulations, which further allow discriminating and quantifying the underlying optical effects. Moreover, in order to demonstrate the scalability of the freeform surface cloak, a prototype CIGS thin-film PV module (comprised of nine monolithically interconnected solar cells) exhibiting fully-cloaked interconnection lines is presented.

1. Introduction

Photovoltaics (PV) plays a major role in the global effort to transform the energy supply from limited fossil fuel sources to renewable energy sources. With regard to the economic competitiveness of PV, the importance of high power conversion efficiencies (PCEs) has increased steadily within recent years [1]. A key optical loss mechanism of the PCE in all PV technologies is the reflection and parasitic absorption of light in inactive areas of PV modules. These so-called "dead areas" mostly originate from the need for an efficient current extraction via front contact fingers and bus bars in conventional crystalline silicon (c-Si) PV modules or alternatively interconnection lines in thin-film PV modules. For both technologies, these dead areas account for a relative loss in PCE of up to 4–10% [2,3].

Bearing in mind that PV modules often are subject to irradiance of oblique incidence — whether, for example, due to diffuse sunlight caused by clouds or simply direct sunlight that is not normally incident on the stationary PV module due to the time of day — a number of optical concepts to recapture the light incident of all angles of incidence on the dead areas of PV modules have been presented in the literature [4–18]. These optical concepts rely on redirecting the incident light into the active area of the PV module by diffractive optics [4,5], reflection [6–9] and refraction [10–12] of incident light as well as recovering the back-scattered light off front contacts via total internal reflection off the inside of the cover glass [13,14]. One disadvantage of any diffractive optics based approach is the strong dependence on the angle of incidence and wavelength, which limits the ability to redirect incident light into the active area of the PV module for the entire solar spectrum and for arbitrary angles of incidence [4,5]. While tailored contacts [6,7,13,14], triangular voids inside the encapsulation of a PV module [8,9], and prismatic covers [10–12] successfully demonstrated the ability to redirect light by geometrical optics in the entire solar spectrum, they either suffer from low performance at large angles of incidence or are not compatible with the conventional combination of an encapsulation layer and a front glass cover. Advanced optical concepts, such as contact grids with subwavelength photonic structures, promise to minimize the reflection losses off the electrical contacts. However, these are regarded as being difficult to fabricate as well as being limited

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to a small area [15,16]. For Si PV modules, dead areas caused by front contact grids can be circumvented in interdigitated back contact (IBC) device architectures [17,18], but to this date this architecture cannot be applied to thin-film PV modules and, furthermore, it involves more complex and expensive process steps.

An alternative approach represents the novel, relatively simple, and straight forward concept of freeform surface (FFS) cloaks [19–21]. Such cloaks render the contacts invisible by refracting the incident light into the active area of the device. Since FFS cloaks rely exclusively on refractive optics, they efficiently redirect the entire incident solar spectrum (see Fig. S1 in the Supplementary material). Furthermore, the FFS can be designed such that it efficiently cloaks contacts for all angles of incidence [21]. For PV, the latter is of uppermost importance, since light often impinges under oblique incidence in real-life operating conditions of PV modules considering that the fraction of diffuse irradiation in Central Europe is > 50% [22]. On solar cell level (24 mm^2 area), it was demonstrated previously that FFS cloaks without a glass cover aligned with the front contact fingers of c-Si solar cells can reduce the optical losses of the front contact grid completely [21].

A key hurdle for FFS cloaks is the development of a suitable FFS for PV module integration. With regard to the application to PV modules, it has to be considered that the standard industrial solar module architecture comprises a polymer encapsulant layer sandwiched between a planar front cover glass and the solar cells. Thus, the key challenge is to incorporate the FFS design into this reference PV module architecture. Moreover, the concept shall also be extended to thin-film PV technologies. While c-Si solar cells exhibit a contacting scheme based on contact fingers and bus bars, thin-film PV modules rely on interconnection lines instead which again induce dead areas. The interconnection lines are essential to divide the total PV module into smaller cells, which are then monolithically connected in series.

In this work, the hurdles outlined above are tackled by designing and developing FFS cloaks for thin-film PV modules that are compatible with the architecture of industrial PV modules. For this purpose, an understanding of the working principle of FFS cloaks for dead areas in thin-film PV modules is established by discriminating the involved optical effects. Rigorous optical ray-tracing simulations are used to optimize these surfaces with regard to the light transmitted through the front glass-covered cloaking layer into the active area of the PV module. The performance of four different prototype architectures of module-integrated FFS cloaks on a CIGS mini-module is analyzed for all angles of incidence and compared to a reference architecture. Furthermore, in order to demonstrate the scalability of the FFS cloak, a prototype CIGS thin-film PV module with fully cloaked interconnection lines of nine monolithically interconnected solar cells is presented.

2. Working principle of freeform surface cloaking

Before designing an FFS cloak compatible with a conventional architecture of front glass-covered thin-film PV modules, the working principle of FFS cloaking is investigated by means of an in-house developed ray-tracing software that considers Fresnel reflection at all interfaces, light absorption in the bulk and dispersion of the involved materials. For simplification, the ideal FFS cloak, referred to as *original cloak* in the following, without a front glass cover is chosen for analysis in this section. The FFS cloak seeks to refract incident light away from the contact grids or interconnection lines for all angles of incidence and distribute it to the active area within the PV module [21]. For this purpose, the FFS (total width $w = 3$ mm) is incorporated into a highly transparent layer with a refractive index of 1.5 and is centered above the dead area of the PV module but extends 1.4 mm into the active area on either side (see illustration in Fig. 1a).

As a starting point, we illustrate the working principle of the FFS cloak in a thin-film PV module for light of normal incidence (see schematic simplification in Fig. 1b). Spatially resolved transmittance of incident light into the active area of the PV module is simulated by ray-tracing. The results are compared for PV modules equipped with the FFS cloak and a conventional architecture, referred to as *reference architecture* in the following, consisting of a planar front cover glass and an encapsulation layer. This reference architecture is represented by a single, highly transparent layer with approximately the same refractive index $n = 1.5$. For the reference architecture, no light is transmitted into the active area of the PV module if incident on the dead area (red region). In contrast, the transmittance of the original FFS cloak in the dead area is high, indicating it efficiently redirects the incident light. In region I, the FFS cloak and the reference architecture exhibit the same transmittance of light into the active area, since the layer stack is almost identical apart from a minor curvature of the FFS. Additionally, as can be seen by the enhanced transmittance into the active area next to the dead area in region II the FFS cloak induces another optical effect, namely enhanced light incoupling.

The contributions of these optical effects: (1) effective matching of refractive indexes (blue), (2) invisibility cloaking of the dead areas (orange), and (3) enhanced light incoupling (yellow) are discriminated in Fig. 2 and quantified below:

1) Starting from a pristine PV module with interconnection lines (case 1), the FFS cloak as well as the reference architecture improve the transmittance into the PV module by matching effectively the refractive index (blue region in Fig. 2) of the TCO top layer ($n \approx 1.95$ at $\lambda = 550$ nm) of the PV module and the ambient air (case 2).
2) Secondly, omnidirectional invisibility cloaking (orange region in Fig. 2) creates a virtual, planar sample with invisible interconnection lines while still allowing for series connection of the cells (case 3). Consequently, the optical losses caused by the dead area can be fully recovered. The investigated CIGS thin-film PV modules show a geometrical fill factor of the interconnection lines of $f_0 = 4.7\%$. Hence, the relative enhancement in current density expected by the FFS cloak compared to the reference architecture is $\zeta = f_0 / (1 - f_0) = 4.9\%$. Note that this value exclusively originates from geometrical considerations [21].
3) The third optical effect, light incoupling (yellow region in Fig. 2), refers to the reduction of reflection by the curvature of the FFS. Around the cloaked region the reflected light is redirected onto the FFS for multiple times, giving it a second chance to be coupled into the cloaking layer (case 4). Consequently, the J_{SC} of CIGS PV modules covered with an FFS cloak can exceed the J_{SC} of the reference architecture even further. Combining the contributions of light incoupling and invisibility cloaking, a relative increase in J_{SC} of $\zeta = 5.4\%$ is the maximum that can be achieved at normal incidence.

Regarding the performance at oblique angles of incidence, omnidirectional invisibility cloaking is ensured by the outer domains of the curvature of the FFS cloak. Furthermore, the light incoupling of the FFS cloak is significantly enhanced at high angles of incidence compared to the reference architecture that features high reflection losses under these conditions. This can be explained by lower Fresnel reflection due to the non-planar FFS.

3. Design of the freeform surface cloak for module integration

Having described the fundamental working principle of the FFS cloaking at the example of the original cloak without a front glass cover, in the following an FFS suitable for the incorporation into the reference architecture is developed. A curved surface as given by the FFS is not acceptable, since its notch is potentially prone to soiling and planar front cover glasses are the industrial standard of commercial PV modules.

The most straightforward approach to integrate the FFS cloak into the reference architecture, and thus providing the module with robustness, simply is to place a conventional front cover glass on top of the original cloaking layer as illustrated in the results of the simulations