Combining structures on different length scales in ray tracing: Analysis of optical losses in solar cell modules

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***Abstract*—Solar cell modules consist of optically relevant geometric structures on very different length scales. While the whole module and the solar cells are on a scale of meters and centimeters, the pyramids etched on mono-crystalline Si cells (for enhancing light-trapping) have sizes in the micrometer range. The simulation domain cannot be reduced substantially to still capture module specific effects. Hence, these large differences in length scale have so far prohibited a detailed ray tracing analysis. In this work, we developed a ray tracing approach by separating large and small scale geometries into different simulation domains; the ray tracer automatically switches between the different domains as needed. With this approach, it is possible to simulate whole modules on current desktop computers within reasonable time. We demonstrate the capabilities of this method by analyzing the optical losses in modules from mass production, and also in modules under development, having no encapsulant. For the first time, we are able to assess the optical properties under tilted incidence, and we show that the optical losses of modules are underestimated under standard testing conditions (normal incidence). We derived an average yearly light source from thirteen years of meteorological measurements, and reveal that reflection from the glass cover and absorption in the glass as well as in the encapsulant account for 58–76% of the optical losses in module power—while under normal incidence, these losses account for only 41–47%.**

I. Introduction

Sophisticated geometrical ray tracing was developed in the photovoltaic community throughout the 90ies, resulting in software such as TEXTURE, the model in PC1D, SUNRAYS, RAYN, SONNE, and RAYSIM. Most of these software have not been transferred to modern IT technologies and have not been applied to other optoelectronic devices such as light-emitting diodes and laser diodes, with the exception of RAYSIM, which is still available [1].[1] These software are limited to rather simple simulation domains with a size in the micrometer range. Therefore, we have developed a ray tracing framework called DAIDALOS [3], which is as highly configurable as possible, and we perform in this paper an optical loss analysis of entire modules of crystalline Si solar cells.

[1]In the printed version of this abstract we claimed that the ray tracer RAYN would have been included in SENATURUS [2]. This is not correct, the ray tracer in SENTAURUS was developed independently. We apologize for this error.

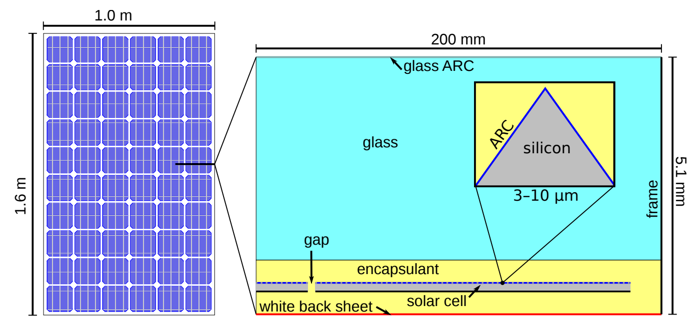

Fig. 1. Schematic of a solar cell module. Left: top view; right: cross section across a solar cell. The inset shows details of the cell's front surface texture.

II. Simulation Setup

The framework DAIDALOS is programmed in the Java language in a strictly modular way. It provides interfaces for incorporating self-written plugins to replace any part of the ray tracing simulation, even the ray tracer itself. This allows the user to add new optical effects at surfaces and in volumes, and to create specific output. The software is not commercially available.

Figure 1 shows the usual dimensions of solar cell modules installed on roofs. The module contains a highly reflective white back sheet, and the cells are laminated between layers of 450 µm thin transparent ethylene vinyl acetate (EVA).

The cells are typically 170 µm thick and 3 mm apart. Light-trapping is enhanced by chemical texture of random pyramids with side lengths of about 3 to 10 µm, and an anti-reflection coating (ARC) made of SiN_x. The cell's back side is typically covered with Al, which acts as back surface reflector and electrical contact. For protection, the module is covered with a 3 to 4 mm thick glass sheet of low Fe content, possibly coated with an ARC as well.

A. Sophisticated ray tracing algorithm

So far, ray tracing simulations of solar cells have been performed in simulation domains restricted to a single pyramid of the texture. In order to cover module effects, the simulation domain must be expanded to include the cell's edge and the

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gaps between neighboring cells. However, such an approach is prohibitive with current computer technology, as there are about 10^{10} pyramids on a cell.

We therefore introduce a universal method which separates small scale structures, such as the pyramid texture, from large scale structures, such as the solar cells or the glass cover. The inset in Fig. 1 shows that rays hitting the front surface of a cell are transferred to a small cuboidal domain, which covers just a single pyramid of the cell texture. The ray is positioned randomly at the top (or bottom) face of the small domain which is equipped with quasi-periodic side boundary conditions to model the random placement of the pyramids. This boundary condition adds an additional random horizontal displacement to the ray, which is a good approximation to reality [4]. Whenever a ray leaves the small domain through the top or bottom face it is repositioned in the big domain.

III. Optical Losses in Solar Cell Modules

The optical properties directly influence the module's short-circuit current J_{sc}. This value cannot be extracted from ray tracing simulations alone, but two additional entities must be taken into account: (i) the collection efficiency of photo-generated carriers to the metal contacts of the cells (simulated with SENTAURUS [2]), and the fact that the cells are connected in series in the module, so the cell with the smallest J_{sc} limits the J_{sc} of the entire module (calculated with the electrical-circuit simulator SPICE [5]).

Two different light sources were used for the simulation. One to derive the module power under standard testing conditions (normal incidence, 1000 W/m^2 AM1.5g spectrum) and one with an angular and spectral distribution derived from thirteen years of weather data collected at the ISFH in Hamelin, Germany (52.07° N, 9.35° E). To make these simulations better comparable to the standard conditions the illumination of this source was also scaled to 1000 W/m^2.

We simulated two different modules: A standard module represented in fig. 1, and a module without EVA where the cell is placed directly between back sheet and glass cover and hence is surrounded by air. In empty modules, we applied an additional ARC to the inner side of the glass and a second ARC made of SiO_2 on top of the cell. In both cases we included the cell's front metalization,[2] but neglected other electrical contacts in the ray tracing. To define a module without optical losses to compare with, we assume an otherwise identical hypothetical module which manages to couple all light into cells with perfect Lambertian light trapping.

A. Simulation results

The results of our simulations are shown in fig. 2. Losses due to reflection are marked at the furthest interface the light reached in the order of: glass front, frame, glass rear, back sheet, cell front metalization, cell front texture, cell rear.

Under standard testing conditions, the standard (EVA) module loses 48 W and the empty 14 W more. The main contribution to this difference is the reflection from the back sheet and the front metalization. In the EVA module 21% more light gets reflected from the back sheet onto the cell.

[2]This is an update to the printed version of the abstract. With this we also correct an error in the numbers for the yearly average lighting conditions.

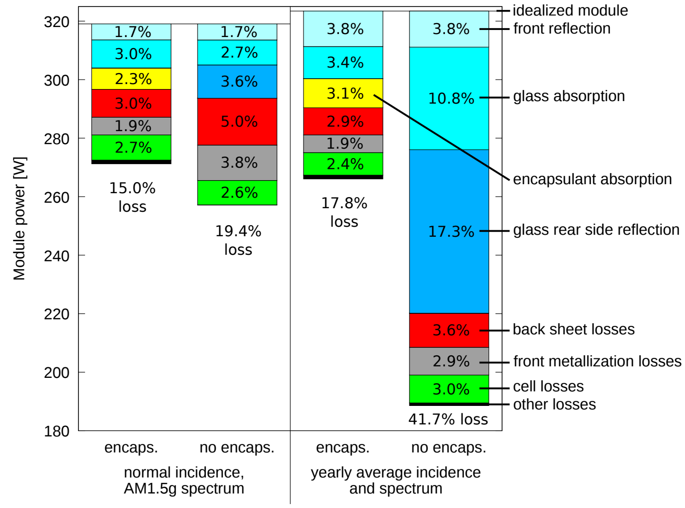

Fig. 2. The optical losses in solar cell modules, expressed as electrical losses in the standard module (cells encapsulated in EVA) and in a module under development (no encapsulant), calculated with ray tracing.

The results obtained with the yearly average light-source show that testing under standard condition may be misleading. When including light at oblique incidence, light that gets reflected repeatedly within the glass travels very long distances leading to high absorption. Thus, the EVA module, which does not suffer from this type of multiple reflections, outperforms the gas encapsulated module by 77 W (with total optical losses of 57 W). However, also in the EVA module the absorption and reflection on glass and EVA dominate the losses with 58% compared to 47% for normal incidence.

These results show that it is important to use light with realistic angular distribution to determine loss mechanisms in solar cells and that the parts covering the cell (glass and EVA) are the most important parts for optical improvements to solar cell module performance.

IV. Application to Other Optical Devices

The approach to separate simulation domains of different length scales can be applied universally. Other possible fields of application include textured light emitting diodes or photo-diodes with corresponding refraction optics. With the demonstrated approach, a single universal ray tracing framework can be used for a unprecedented broad range of applications.

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