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Durability analysis of the [Eu(bphen)(tta)$_3$] down-shifter on Si-based PV modules exposed to extreme outdoor conditions

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ABSTRACT

In this work, the ageing of [Eu(bphen)(tta)$_3$]/PMMA down-shifters (DS) placed on top of photovoltaic (PV) modules exposed to extreme outdoor conditions is reported for first time. The PV modules have been placed in a defined location in Tenerife, Canary Island, where extreme outdoor conditions exist. The [Eu(bphen)(tta)$_3$]/ PMMA DSs have been directly exposed to the outdoor conditions or covered with a low iron glass. The results reveal an improvement of the total power of the modules with [Eu(bphen)(tta)$_3$]/PMMA down-shifters, 7.06% for the DS directly exposed to outdoor conditions, and a 3.95% for the encapsulated DS during the first operation day, in comparison with a reference module. However, the improvement vanishes after 20 days when the DS is not encapsulated.

1. Introduction

During the last decade, dramatic cost reductions and substantial improvements in fabrication procedures have risen photovoltaic (PV) energy as the main generating actor in future power grids [1]. The cumulative PV power capacity installed worldwide has overtaken 235 GW, mainly dominated by bulk silicon technologies [2], reaching more than 90% of the market [3,4].

However, the predominant technology, based on silicon single junctions, is limited by the Shockley–Queisser limits to values below 30% in efficiency [5]. To continue the PV expansion worldwide, the industry needs to forward beyond the standard single-junction solar cells, and offer new cost-effective alternatives increasing the efficiency values [6].

To enhance the solar efficiency, several techniques have been addressed and tested in the last decade [7,8]. One of the most promising strategies to improve the PV module efficiency is the cost-effective increase of its external quantum efficiency (EQE) in the UV spectral range, where the losses are high [9,10].

Among the different techniques to produce the EQE enhancement in the UV range, down-conversion [11–13] and down-shifting of UV photons to longer wavelengths in the visible range [6,14] where the EQE is closer to 100%, can be the most profitable routes applied to commercial solar cells.

To obtain down-converting and down-shifting layers, different materials and methods have been used in the last decade, as glass [15], glass-ceramic [16], sol-gel [17], or polymeric materials [18], among others [19–21]. Our group has reported a significant enhancement of the EQE in the 280–400 nm spectral range [9] in the laboratory applying a low-cost down-shifter (DS) synthesized from commercial chemicals and placed on top of PV cells and modules, offering a cost-effective procedure to increase the energy efficiency of these devices.

Then, the expected next step is to test the PV device with the low-cost DS in outdoor conditions and check the reliability and the evolution of the power output with aging. Therefore, it is necessary to establish a testing procedure in order to obtain accurate PV parameters, their relations with the components, a degradation analysis of the DS layer, and the influence on the behaviour of the PV module under outdoor conditions.

In addition, it is important to select a proper location of the testbed for testing the durability of the DS. As it has been reported elsewhere [22], the durability of the PV modules is strongly influenced by the location because of temperature cycles, humidity, salinity and dust, differentiating between tropical, desert and mild weather. As it will be described in the experimental section, our

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devices have been placed in a coastal and windy area in the South of Tenerife, where high irradiation, humidity, salinity and dust coming from the Sahara Desert produce extreme outdoor conditions.

In this work, first total power results for PV modules covered by Eu^{3+}-based DS and tested under extreme outdoor conditions are presented. Firstly, a description of the active species and the different procedures to place the DS on the PV module is included. Secondly, a description of the testbed and the outdoor conditions are exposed in order to show the extreme climatic conditions prevalent in the area. Finally, first results in terms of power output for the different PV modules just after the deposition of the DS, and after submission to the extreme outdoor conditions for several days are reported. Finally, the durability of the DS film under ambient conditions is discussed.

2. Materials and methods

2.1. Monitoring system

To carry out the outdoor the analysis of the DS layers, a batch of eight one-cell PV modules were laminated in the Instituto Tecnológico y de Energías Renovables (ITER) in Tenerife, Spain.

Each module was designed with a standard 156 mm × 156 mm multicrystalline silicon solar cell from ETON manufacturer, encapsulated in a conventional structure composed by low iron glass with cerium oxide antireflection coating, ethylene vinyl acetate (EVA), solar cell, EVA and tedlar-polyester-tedlar. Due to the environment conditions in Tenerife, anodized aluminium profiles were used to frame the modules. Finally, large four-terminal class junction boxes were joined at the backside of the module. Inside the junction box, an acquisition card with an rs485 profibus connector was installed. The acquisition card allows monitoring the typical electrical parameters of the solar cells as current, voltage, radiation and temperature.

Before the exposure of the DS layers to the outdoor conditions, a set of modules was characterised in the laboratory according to IEC 61853 part one and part two [23,24]. Eight modules with similar I-V characteristics at standard test conditions (STC) and under low irradiance were selected.

According to the EN 60904 procedure [25], the system was designed to acquire the most relevant values every minute. In addition, a current-voltage (IV) measurement system was performed to obtain the open circuit voltage and the short current density values. The acquisition cards from the eight modules were connected to a master electronic card, which records the values from each module and sends the data to a server, allowing a real-time monitoring of the PV modules thru a Supervisory Control and Data Acquisition (SCADA) system, managed by ITER.

The eight modules were installed in an anodized aluminium structure, in two rows of four modules (Fig. 1).

The structure allows the manual adjustment of the azimuth and inclination angles. The monitoring system of commercial PV modules with DS layers was designed and installed on the roof of one of the 25 bioclimatic buildings in the Instituto Tecnológico y de Energías Renovables (ITER), in the south of Tenerife (28°04′16.48″N 16°30′48.15″W). Tenerife is a Spanish island from the Canary Island Archipelago in front of the Morocco coast. The average daily global horizontal irradiation reaches 4.822 kW h/kW·day (1761 kW h/kW yr), and an average temperature of 19.8 °C is registered. Average wind speed in the area is 7.58 m/s (80 m in height) [26].

Several times per year Saharan dust hazes reach the area where the testbed is located showing these events variable duration, from several hours to some weeks. As the Sahara Desert is the world's largest source of aeolian soil dust [27], it affects air temperatures around the testbed through the absorption and scattering of the solar radiation. In addition, abrasion effects are expected on glass surfaces when a combination of dust and wind is produced. Aerosol optical thicknesses at 550 nm up to 0.8, haze dust densities up to

Fig. 1. Outdoor setup: tilting head (up-left), exchangeable pillar (up-right) and modules attached with clamps (down).