Optical Transmission Losses of a TiO$_2$-based Anti-soiling Coating for Use in Outdoor Photovoltaic Applications

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**Abstract:** Background: Soiling can be a major challenge for photovoltaic (PV) installations, depending on their location, as it reduces transmission and can lead to significant losses. Anti-soiling coatings have been demonstrated to reduce soiling losses and thereby increase PV power production. 

Objective: This article investigates the applicability of a titanium-dioxide-based anti-soiling coating developed by Photocat under the name “ShineOn” for use with PV installations. The main parameter examined is the optical transmission losses, as this directly translates to performance losses during non-soiled operations.

Methods: Measurements of transmittance are carried out using both indoor laboratory setups as well as outdoor PV installations, including measurements of the short-circuit current ($I_{sc}$), incidence angle modifier (IAM) and spectral transmittance. Investigated samples include both full-sized modules and custom-made mini-modules containing a single solar cell.

Results: Both indoor and outdoor measurements show minor transmission losses in the range of 0.3 to 0.6 % and negligible effects on the IAM. Additionally, observations indicate that samples should be coated after lamination, as losses for samples coated before lamination are slightly higher.

Conclusion: As the transmission losses due to the ShineOn coating are small and no additional angular-dependent losses were observed, the coating is deemed not to be detrimental for PV applications. Proper assessment of the usefulness requires investigations of the anti-soiling properties, for example, through test installations in regions with high soiling rates.

**Keywords:** TiO$_2$, photovoltaics, anti-soiling, transmission, field measurements, incidence angle modifier.

1. INTRODUCTION

1.1. Soiling of PV Devices

Soiling on photovoltaic (PV) modules is caused by organic and/or inorganic particles accumulating on the module surface and thus obstructing light from reaching the solar cells. This in turn, leads to power losses and reduces the energy yield and revenue of PV plants.

Soiling is highly location-dependent and depends on a multitude of environmental factors. Mineral dust intensity has been mapped out on a global level according to the PM10 concentrations [1, 2]. Soiling from organic sources, such as pollen, plant debris, biofilms, mosses and bird droppings as well as air pollution caused by industry and combustion engines, vary on a significantly smaller scale and have to be assessed on a case-by-case basis [3].

As the regions with more intense dust soiling usually present strong solar energy yields, the mitigation of soiling losses becomes increasingly important and makes it worthwhile to invest in anti-soiling measures. In 2018, global annual revenue losses due to this effect were estimated as 3-5 billion €, and they are expected to grow even higher in the future [3].

Soiling can be mitigated through frequent cleaning of the PV modules, usually by mechanical solutions such as dry brushing, using compressed air or washing with water, either under pressure or combined with mechanical brushes [2]. These mechanisms are either labor-intensive or require expensive automated equipment, which limits their cost-effectiveness. Additionally, scarcity of water in soiling-prone areas can limit the available anti-soiling solutions.

As an alternative to these cleaning solutions, an increased focus on self-cleaning PV modules using anti-soiling coatings has arisen in recent years. These coatings are effective, inexpensive and maintenance-free, making them suitable for large PV arrays, for example, in PV power plants.
1.2. Anti-soiling Coatings

In recent years, several studies have investigated the cleaning properties of various anti-soiling coatings. Long-term field tests of anti-soiling coatings under various climates have shown significant reductions in soiling losses of 20-50 % compared to non-coated PV modules [3-8].

A factor significantly affecting the self-cleaning properties of anti-soiling coatings is the contact angle of water droplets on the surface. On the one hand, hydrophilic coatings are characterized by high surface energy and low contact angles, which uniformly spread liquid droplets, pulling out pollutants from the surface. On the other hand, hydrophobic surfaces present low surface energy and higher contact angles, leading to the formation of spherical droplets, which concentrate the dirt particles before running off.

Diverging conclusions on the ideal properties of anti-soiling coatings can be found in the literature. An experimental study performed in different climates showed considerably worse performance for a hydrophobic SiO2 coating compared to hydrophilic TiO2 and TiO2/SiO2 coatings [8]. In a laboratory-based study of fluorinated ethylene propylene (FEP) coatings, however, significantly lower soiling losses were found for hydrophobic coatings compared to hydrophilic coatings [9].

The overall effectiveness of anti-soiling coatings is highly dependent on the local weather conditions, especially the frequency and amount of rain [8]. Additionally, the local environment can affect the performance and durability of the coatings, for instance, due to the presence of salt in coastal locations [10].

The present study is carried out near Roskilde in Denmark, characterized by a temperate oceanic climate. As this region is characterized by relatively low soiling rates, this article focuses on the optical transmission properties of the anti-soiling coating since high transmittance is crucial for PV applications.

1.3. ShineOn Anti-soiling Coating

ShineOn is a thin anti-soiling coating based on a nanocrystal layer of TiO2 which provides the surface with hydrophilic properties. It can easily be applied to the cover glass of PV modules using a manual or semi-automated spray coating process. Additionally, photocatalysis can take place on the coating surface under illumination to aid the removal of organic pollutants. The ShineOn coating is already used commercially on windows and glass façades, for which it has proven self-cleaning properties [11].

2. EXPERIMENTAL METHODOLOGY

Several experiments are carried out to determine the optical transmission properties of the ShineOn coating, including both indoor and outdoor measurements. Prior to the measurements, custom mini-modules are laminated in the PV lab at DTU Fotonik using a 20x30 cm PV-grade, low-iron tempered float glass as cover, EVA as encapsulant, single, 156x156 mm, 2-busbar mono-crystalline PV cell (Motech Virgo 2.0 XS156B2) with 19.6 % efficiency and a white polymeric back sheet.

One group of samples is manually spray-coated by Photocat A/S after lamination, while a secondary group of samples is assembled using glass coated prior to lamination. In addition, uncoated reference samples are laminated using the same components.

2.1. Spectral Transmission

One of the main parameters concerning the suitability of the Shine-On coating for PV applications is a low transmission loss over the entire PV-relevant spectrum. For crystalline Silicon, this includes the entire solar spectrum up to approximately 1150 nm. UV absorption by the glass cover is often encouraged, however, as it protects the encapsulant from degradation. Therefore, high transmission is required mainly in the region between 400-1100 nm.

Transmission of the ShineOn coating is determined on coated samples of the 20x30 cm cover glass used to assemble the mini-modules. Measurements are carried out for both linear and total transmission on two identical samples as well as an uncoated reference glass.

For linear transmittance measurements, a Varian Cary-50 UV-Vis spectrophotometer is used, resulting in transmission spectra between 190 and 1100 nm.

For total transmittance measurements, samples are mounted in front of a Labsphere 6" integrating sphere with a reduced aperturing of 1.5" in diameter. The samples are illuminated using collimated light from an Energetiq EQ99X laser-driven light source (LDLS). Collimation is achieved via 3 off-axis parabolic (OAP) mirrors, resulting in a beam of 1.5" in diameter. To compensate for back-reflection, a so-called correction light source (CLS) is used [12], in this case, an OceanOptics DH-2000 Deuterium-Halogen fiber-coupled light source, which is connected to the top port of the integrating sphere. The side port of the sphere outputs light to a fiber-coupled OceanOptics QE65000 spectrometer for analysis of the transmitted light between 200 and 1000 nm. A representation of the measurement setup is shown in Fig. (1).

![Fig. (1). Setup for total transmission measurements. (A higher resolution / colour version of this figure is available in the electronic copy of the article).](image-url)

Transmittance is measured with and without samples in place and alternating the light sources, which results in the measurements listed in Table 1. Additionally, for every measurement configuration, a dark baseline measurement is acquired and subtracted to compensate for ambient light.
2.3. Outdoor Coupon Tests

Two samples from each sample group – coated before and after laminations as well as uncoated references – are mounted outdoors on a test stand oriented due south with a tilt of 25°. The test stand is situated in close proximity to a solar resource measurement tower, measuring global horizontal irradiance (GHI), direct normal irradiance (DNI), and diffuse horizontal irradiance (DHI) with class A (ISO 9060:2018) radiometers.

One of the reference samples is cleaned once a week to assess the soiling rate, while the remaining samples remain uncleared. Short circuit current and temperature on the samples are measured every 10 seconds. The entire setup was in operation for over two months in July-September 2020, however, including a few periods where no data was recorded.

The measured current values are first filtered to exclude non-physical values as well as measurements with low irradiance values (GHI < 40 Wm\(^{-2}\)). Subsequently, the remaining data is aggregated into hourly averages and further filtered to contain only measurements during overcast periods with diffuse ratios above 0.9. This is done to exclude unwanted reflections on the test stand from buildings in its vicinity.

IV-curve measurements from the laboratory (measured at STC) are then used in conjunction with the solar resource measurements to normalize current ratios to the GHI according to the following Equation:

\[
\delta_{GHI} = \frac{I_{meas}}{I_{sc,STC}C_{t}} \frac{C_t}{C_{ref}} \frac{C_{ref}}{GHI}
\]

Here, \(C_{t}\) refers to the temperature correction coefficient to 20°C, the average operating temperature during the measurement period. Finally, a statistical analysis is performed on the normalized current ratio, and a comparison of the mean values is translated to optical losses.

2.4. Farm Test

In order to assess the influence of the ShineOn coating on the performance of PV panels, it is applied at DTU's Risø campus solar farm. The solar farm, located in Roskilde, Denmark (55.6 °N, 12.1 °E), is a kilowatt-scale PV system including both bifacial and monofacial PV modules. These modules are split into 8 Horizontal Single Axis Trackers (HSATs) and 8 south-facing fixed tilt (25°) structures 45 m long, as shown in Fig. (2).

Substructure number 16 is chosen for the testing of the ShineOn coating. It is equipped with 88 PV modules (Trina 60-cell mono facial p-PERC) with a 305 Wp rating, wired into 4 parallel strings. The strings are connected to the same inverter onto the same Maximum Power Point Tracking (MPPT) input and the DC operation parameters (voltage and current) are measured every minute for each of the strings. Additionally, meteorological and solar radiation measurements are acquired at the solar resource measurement tower aforementioned, as well as the plane of array (POA) irradiance measured by a class C (ISO 9060:2018) pyranometer on site.

In the first phase, the performance of all four strings is assessed by analyzing each string current within a 3 months period prior to the application of the ShineOn coating (April 1st 2020 – July 7th 2020). This analysis gives the relative performance between the strings and sets the reference for comparisons once the coating is applied. Subsequently, the ShineOn coating is sprayed on the eastern strings after cleaning and polishing the glass surface of the PV modules and the variations on the strings relative performance is analyzed until the start of the rainy season in the studied location (July 9th 2020 – September 15th 2020). The glass surface of the uncoated PV modules is also cleaned at the time of coating application for consistency in the results. Fig. (3) shows one of the substructures with a superposed diagram stating which strings are coated, as well as the nomenclature used in this project to refer to each of the strings as a reference.

This setup configuration ensures that the evaluation of the ShineOn performance is carried out under relatively homogeneous irradiance conditions for all the strings.

All the data recorded within this period goes through a quality control assessment to remove all corrupted or unreliable data points. First, the Baseline Surface Radiation Network (BSRN) quality control filters [13] are applied to the solar irradiance measurements. Besides, as shown in previous studies [14], the uncertainty in irradiance measurements acquired by pyranometers using glass domes can be noticeable high during instances when the angle of incidence of the direct beam irradiance is higher than 85°, and therefore, such instances have been removed as well.
Additionally, every data point with a measured plane of array irradiance lower than 30 W/m² is removed with the intention of only considering data points with non-negligible irradiance conditions. Moreover, the analyzed data is filtered for instances when the inverter is operating in normal maximum power point to ensure comparable data.

The remaining dataset shows a total measured POA insolation equal to 965 kWh/m², which represents 75% of the total POA insolation received in 2020, and an angle of incidence ranging between 7°-80° with an average value of 37°.

In order to evaluate the performance variations derived from the ShineOn coating, a current ratio between the coated strings and the uncoated strings is defined, and its difference between both described phases analyzed. This current ratio is calculated for hourly averages of currents, after proper filtering of the data, and is defined as follows:

\[ R_{imp} = \frac{(I_{NE} + I_{SE})}{(I_{NW} + I_{SW})} \]  

2.5. Angular Dependent Transmission

While common transmission measurements are concerned only with normal incidence, angular-dependent transmission is also relevant for PV applications. While PV modules mounted on 2-axis trackers achieve almost normal incidence at all times, 1-axis trackers and fixed-tilt installations experience widely changing lighting conditions depending on installation location, time of day and time of the year. Additionally, diffuse light can be approximated to an effective incidence angle of 50°-65° [15], making transmission at high incidence angles relevant regardless of installation.

Angular dependent transmission is commonly described using the incidence angle modifier (IAM), which corresponds to the relative transmission at different incidence angles. The IAM already includes compensation for geometric effects through cosine correction and is given by the following Equation:

\[ IAM(\theta) = \frac{I_{sc}(\theta)}{I_{sc}(0^\circ)} \cos \theta \]  

For measurements of the IAM, the samples investigated in the IV curve measurements section are mounted vertically on a rotary stage and illuminated by the same light source and collimation setup used for the total transmission measurements. Both short-circuit current (I_s) and device temperature (T_{DUT}) are measured to ensure temperature stability over the measurement period. Further details of the measurement setup, as shown in (Fig. 4), have been presented in previous publications [16].

Measurements are performed for all angles between -80° and 80°, with the incident light spot contained within the cell area between the bus bars. Since all light is contained within the active area, cosine correction becomes unnecessary, and the IAM can be expressed as a simple ratio between currents.
Finally, the measured IAM for coupons coated with the ShineOn coating is compared to reference coupons without coating, resulting in a relative IAM according to the following Equation:

\[
IAM_{rel}(\theta) = \frac{IAM_{sample}(\theta)}{IAM_{reference}(\theta)}
\]

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1. Spectral Transmission

The transmission spectra for both linear transmittance and total transmittance relative to the reference glasses are shown in Fig. (5). At higher wavelengths, the transmittance loss for the ShineOn coating is negligible, while the minimum transmission can be observed around 380 nm. This corresponds well to the known absorption spectrum of TiO$_2$ [17]. The observed high relative transmittance at lower wavelengths can be attributed to the already high absorption of UV light in the glass sample, which leads to reduced overall transmissions.

In general, the overall transmission loss over the PV-relevant spectrum is relatively low, especially in the near-infrared region, which promises good suitability for PV applications. The noticeable difference between the two samples can be attributed to the manual application process of the coating, which can lead to variations in thickness and homogeneity.

3.2. IV-curve Measurements

IV-curves were measured on the post-lamination samples both before and after coating. This resulted in the short circuit current measurements and relative current losses shown in Table 2. While a low average loss in $I_{sc}$ of approximately 0.6% can be observed, the high spread in loss between samples indicates varying coating thickness and/or homogeneity on the samples due to the manual coating process.

The measured loss in short-circuit current corresponds well to the earlier transmission measurements, again indicating good suitability for use as an anti-soiling coating for PV modules in the field.

3.3. Outdoor Coupon Tests

The GHI-normalized current ratios are shown in Fig. (6), where no significant difference can be observed between the cleaned reference sample and the soiled reference, meaning no resulting soiling rate. This conforms well with expectations due to the generally low soiling intensity in Denmark.

Regarding the coated samples, losses of around 0.7-0.9% compared to the reference sample can be observed for the post-lamination sample. The pre-lamination samples show higher losses of 1.2-1.3%. For all these measurements, there is a large spread in data, however, which, combined with the complex irradiance conditions at the site, leads to high uncertainty in the results.
Table 2. Measured current loss for the ShineOn coating on coupon-sized PV modules.

<table>
<thead>
<tr>
<th>Sample</th>
<th>(I_{sc} ) (initial)</th>
<th>(I_{sc} ) (coated)</th>
<th>rel. (I_{sc} ) loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample #1</td>
<td>9.316 A</td>
<td>9.282 A</td>
<td>0.37 %</td>
</tr>
<tr>
<td>Sample #2</td>
<td>9.268 A</td>
<td>9.213 A</td>
<td>0.59 %</td>
</tr>
<tr>
<td>Sample #3</td>
<td>9.328 A</td>
<td>9.221 A</td>
<td>1.15 %</td>
</tr>
<tr>
<td>Sample #4</td>
<td>9.330 A</td>
<td>9.294 A</td>
<td>0.39 %</td>
</tr>
<tr>
<td>Average</td>
<td>9.311 A</td>
<td>9.253 A</td>
<td>0.62 %</td>
</tr>
</tbody>
</table>

While these measurements show a significantly higher average transmission loss for the ShineOn coating than both the direct transmittance measurements and IV-curves, this can most likely be attributed to the non-ideal surroundings of the test stand and the connected irradiance conditions. More interesting is, therefore, the observed difference between samples coated before and after lamination, with the latter showing significantly lower losses. While the proper effects of the lamination process on the coating would have to be studied separately, this indicates at least some change in its optical properties affecting the transmittance.

3.4. Farm Test

The strings’ current ratio, as defined in Section 2.4, is shown in Fig. (7) for both studied periods: under normal operation (reference) and after the application of the ShineOn coating on the NE and SE strings (anti-soiling phase).

To highlight the differences between both periods, and despite the high deviation of the results, a linear fit curve for both periods is also plotted in Fig. (7). These curves remark the differences in the current ratio average as a consequence of the ShineOn coating application that results in transmission losses of 0.3 % as shown in Fig. (8). This reduction is associated to transmission losses due to the added layer of anti-soiling coating, since the soiling losses in the studied location are rather negligible.

The lower observed current losses due to the ShineOn coating on the solar farm modules compared to the outdoor coupons could be explained by differences in the application process for full-sized PV modules (performed outdoors) compared to coupon-sized samples (performed indoors).

3.5. Angular Dependent Transmission

Three samples coated before and four samples coated after lamination are measured in addition to two uncoated reference samples. For each sample, five individual measurements are performed, over which IAM measurements are averaged. Subsequently, sample measurements are compared to the reference sample measurement, as described in section 2.5.

As can be observed in Fig. (9), the average reduction in IAM relative to the uncoated samples is significantly below 0.5 % for all measured angles, with no visible losses at angles smaller than ±45°. The error bars show the propagated error according to the standard deviation of measurements, highlighting a higher measurement uncertainty at higher incidence angles. It can be concluded in general that the effect of the ShineOn coating on the IAM losses is negligible and should not impact PV performance in the field in a significant way. If glass with a special anti-reflective coating is used, however, this assessment may change since glass texture or index-matched coatings can significantly impact the IAM.

![Fig. (6). Current normalized to GHI for coupons samples. Crosses mark mean values.](image-url)
Fig. (7). Current ratio before and after coating of PV modules in the solar farm. (A higher resolution / colour version of this figure is available in the electronic copy of the article).

Fig. (8). Distribution of current ratios in different periods. (A higher resolution / colour version of this figure is available in the electronic copy of the article).
CONCLUSION

In this article, the optical transmission properties of a TiO₂-based anti-soiling coating for PV applications, called ShineOn, were investigated. Relative transmission measurements showed transmission spectra with generally high transmittance (above 99%) in the near-infrared region, and reduced transmission of 95-98% near the TiO₂ absorption edge at 380 nm. Indoor IV-curve measurements showed current losses of 0.6% for silicon PV cells, while outdoor measurements showed losses of 0.75-2% (mini-modules) and 0.3% (full-size modules). Additionally, no significant angular-dependent transmission losses could be observed, with a relative IAM loss below 0.5% for all angles.

Due to the variation in experimental parameters and external influences, such as variations in irradiance conditions, the outdoor coupon test showed a large variation in current ratios over time and should not be considered an accurate measure of the optical transmission of the ShineOn coating. For the remaining measurements, average losses of 0.3-0.6% were observed, indicating good suitability of the coating for use in PV applications in soiling-prone areas. The remaining differences in transmission can be attributed to the manual coating process, resulting in different coating thicknesses for full-sized modules and mini-modules.

Due to the low soiling rate at the measurement location in Denmark, no proper evaluation of the anti-soiling properties could be made in this article. Literature indicates, however, that TiO₂-based anti-soiling coatings can be effective alternatives to expensive cleaning solutions. With the base point for the optical transmission of the coating established, future work should include documentation of the anti-soiling effect on installations in soiling-prone regions.

LIST OF ABBREVIATIONS AND SYMBOLS

\begin{align*}
\text{DHI} & = \text{Diffuse Horizontal Irradiance} \\
\text{DNI} & = \text{Direct Normal Irradiance} \\
\text{DUT} & = \text{Device Under Test} \\
\text{EVA} & = \text{Ethylene Vinyl Acetate} \\
\text{GHI} & = \text{Global Horizontal Irradiance} \\
\text{IAM} & = \text{Incidence Angle Modifier} \\
\text{Isc} & = \text{Short-Circuit Current} \\
\text{LDLS} & = \text{Laser-Driven Light Source} \\
\text{OAP} & = \text{Off-Axis Parabolic Mirror} \\
\text{Pmp} & = \text{Power at the Maximum Powerpoint} \\
\text{POA} & = \text{Plane Of Array} \\
\text{PV} & = \text{Photovoltaic} \\
\text{STC} & = \text{Standard Test Conditions} \\
\text{Voc} & = \text{Open-Circuit Voltage} \\
\theta & = \text{Angle of Incidence} \\
\phi(\lambda) & = \text{Spectral Flux} \\
\end{align*}

CONSENT FOR PUBLICATION

Not applicable.

AVAILABILITY OF DATA AND MATERIALS

Not applicable.

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CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

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REFERENCES


