OPTICAL MODELLING AND SIMULATION OF PV MODULE ENCAPSULATION TO IMPROVE STRUCTURE AND MATERIAL PROPERTIES FOR MAXIMUM ENERGY YIELD

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ABSTRACT

This paper presents a simulation tool to investigate the optical transmission of any encapsulation of PV modules under real-word conditions in order to test various types of encapsulation materials and front covers, with and without anti-reflective-coatings. While standard test conditions are using a fixed spectrum at perpendicular incidence only, real world performance is more complex to determine. The model developed is consequently linked with a precise simulation of the actual irradiance condition for each moment of a clear day considering incidence angles, spectra, dispersion and multiple internal reflections inside and among the layers. To calculate and compare life-cycle yields, several of those "snapshots" (each 15 minutes) of transmittance, actual irradiance, efficiency and electrical power output. The model is an appropriate tool to optimize the optical layout of the encapsulation, including new materials, not just within the standard test conditions but also for real world applications at different locations.

OPTICAL MODELLING OF ENCAPSULATION

In order to achieve a precise representation of the actual optical conditions in the module, a model for the encapsulation of the cell was developed that extracts the insolation reaching the cell from sun and sky irradiance. This was done by modeling the optical processes involved (reflection, absorption) outside and inside the encapsulation.

Optical interface at boundary layers

Perpendicular incidences: At the transition when radiation from a material of a given optical density (n_0) enters into another (n_1), the radiation is split up into a reflected component (R) and a transmitted one (T) at the optical interface, R is also called “reflectance“ and T, “transmittance“. Irradiance (E) of the incoming radiation is normalized to $E = 1$.

$$R = \frac{(n_1 - n_0)^2}{(n_0 + n_1)^2} \qquad T = 1 - R \tag{1}$$

Non-perpendicular incidences: More realistic is the case of non-perpendicular incidences of insolation (Fig. 1). Here the reflectance could be calculated by the FRESNEL formula [1] for a certain incidence angle θ_{in}.

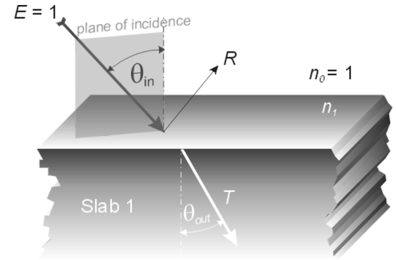

Fig. 1. Transmittance and reflectance at an optical boundary for non-perpendicular incidence ($\theta_{in} \neq 0°$).

The components of the direction of polarization parallel (∥) to or perpendicular (⊥) toward the angle of incidence are to be calculated separately from each other. The normalized reflections ($R_\parallel$ and $R_\perp$) are given as follows (neglecting the imaginary part of a complex refractive index - the treatment of those is described in [2]):

$$R_\parallel = \frac{\tan^2(\theta_{in} - \theta_{out})}{\tan^2(\theta_{in} + \theta_{out})} \qquad R_\perp = \frac{\sin^2(\theta_{in} - \theta_{out})}{\sin^2(\theta_{in} + \theta_{out})} \tag{2}$$

$$T_\parallel = 1 - R_\parallel \qquad T_\perp = 1 - R_\perp \tag{3}$$

$$\text{angle of refraction: } \theta_{out} = \arcsin\left(\frac{n_0}{n_1}\sin\theta_{in}\right) \tag{4}$$

Optical transmittance of a plane slab

Incident insolation has to pass through two optical boundaries layers and the attenuation by absorption inside the material. Reflection at the lower boundary is not lost completely, but bounced up and forward through the slab at decreasing intensity (see Fig. 2).

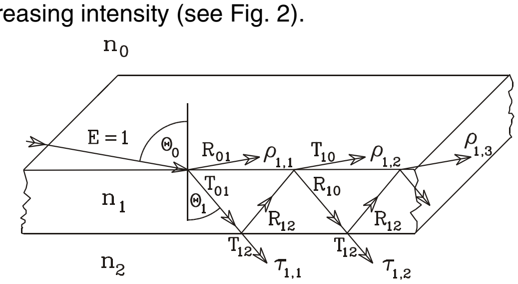

Fig. 2. Transmittance through a plane optical slab.

In order to establish a common nomenclature, a layer is marked by an index "k," the upper medium by the index "k-1" and the lower medium by "k+1". The angle of incidence at the transition from medium "k-1" to the medium "k" is marked by θ_k, the angle of refraction by θ_{k+1}. The optical transitions are denoted by the indices of media in the order of the radiation passing through them $k,k\pm1$ (e.g. T_{01}). The transmitted parts i of the irradiance on slab k are marked as $\tau_{k,i}$, the reflected ones as $\rho_{k,i}$. A distinction between the planes of polarization is not made any more to keep the formulas simple. So, for the generally used variables R and T, the specific components $R_\parallel$, $R_\perp$ and $T_\parallel$, $T_\perp$ are to be inserted. The incident irradiance is also normalized to E=1. The absorptive attenuation of a ray after a passage through the slab 1 for example, is determined by the coefficient of absorption $\alpha_1(\lambda)$ of the material, its thickness d_1 and the incidence angle θ_1 on the considered slab 1:

$$\frac{\Delta E_1}{E_1} = \exp\left(-\alpha_1 \frac{d_1}{\cos\theta_1}\right) \tag{5}$$

If the imaginary part of the complex refractive index $\hat{n} = n - j\,k$ is known, α could also be computed from $\alpha(\lambda) = 4\,\pi\,k\,\lambda^{-1}$. Therefore reflection loss R_{01} occurs at the incident boundary surface of slab 1 and R_{12} on its lower surface, while the remaining transmitted part consists of:

$$\tau_{1,1} = T_{01}\,T_{12}\exp\left(-\alpha_1\frac{d_1}{\cos\theta_1}\right) \tag{6}$$

The internal reflection R_{12} is computed the same as R_{01} using (31), as well, the new angle of incidence θ_2 for the lower layer 2 according to (32). The internal reflection at the boundary 1-2 passes through layer 1 again, and is attenuated accordingly. At the boundary 0-1 this ray is refracted once more, while a component T_{10} passes into medium 0. The reflected component R_{10} reaches boundary 1-2 under attenuation, where another part T_{12} enters slab 2.

$$\tau_{1,2} = T_{01}\,R_{12}\,R_{10}\,T_{12}\exp\left(\frac{-3\,\alpha_1 d_1}{\cos\theta_1}\right) \tag{7}$$

Summing up all transmitted fractions of the layer 1:

$$\tau_1 = T_{01}\,T_{12}\exp\left(\frac{-\alpha_1 d_1}{\cos\theta_1}\right)\sum_{i=1}^{\infty}\left[R_{12}\,R_{10}\exp\left(\frac{-2\,\alpha_1 d_1}{\cos\theta_1}\right)\right]^{i-1} \tag{8}$$

$$\tau_{1,i} = T_{01}\,T_{12}\,R_{12}^{i-1}\,R_{10}^{i-1}\exp\left(\frac{-(2i-1)\,\alpha_1 d_1}{\cos\theta_1}\right) \tag{9}$$

This infinite series is a geometrical one and can be summarized as follows:

$$\tau_1 = \frac{T_{01}\,T_{12}\exp\left(\frac{-\alpha_1 d_1}{\cos\theta_1}\right)}{1 - R_{12}\,R_{10}\exp\left(\frac{-2\,\alpha_1 d_1}{\cos\theta_1}\right)} \tag{10}$$

Because radiation is being absorbed in the slab, the reflectivity ρ of a slab has to be computed explicitly, because $\rho \neq 1 - \tau$. The reflected components $\rho_{1,i}$ of a slab 1 are to be calculated as follows:

$$\rho_{1,1} = R_{01} \tag{11}$$

$$\rho_{1,2} = T_{01}\,R_{12}\,T_{10}\exp\left(\frac{-2\,\alpha_1 d_1}{\cos\theta_1}\right) \tag{12}$$

$$\rho_{1,3} = T_{01}\,R_{12}^2\,R_{10}\,T_{10}\exp\left(\frac{-4\,\alpha_1 d_1}{\cos\theta_1}\right) \tag{13}$$

$$\rho_{1,i>1} = T_{01}\,R_{12}^{i-1}\,R_{10}^{i-2}\,T_{10}\left(\exp\left(\frac{-2\,\alpha_1 d_1}{\cos\theta_1}\right)\right)^{i-1} \tag{14}$$

The sum of all reflected components ρ_1 of the layer 1:

$$\rho_1 = R_{01} + T_{01}R_{12}T_{10}e^{\frac{-2\alpha_1 d_1}{\cos\theta_1}}\sum_{m=1}^{\infty}\left(R_{10}R_{12}e^{\frac{-2\alpha_1 d_1}{\cos\theta_1}}\right)^{m-1} \tag{15}$$

This infinite series is again a geometrical series and can be summarized:

$$\rho_1 = R_{01} + \frac{T_{01}\,R_{12}\,T_{10}\exp\left(\frac{-2\,\alpha_1 d_1}{\cos\theta_1}\right)}{1 - R_{10}\,R_{12}\exp\left(\frac{-2\,\alpha_1 d_1}{\cos\theta_1}\right)} \tag{16}$$

Internal transmission and reflection

Knowledge of the internal transmission $\bar{\tau}$ is necessary to determine the transmission of multiple layer systems, for example $\bar{\tau}_1$: the transmittance of slab 1, when it is illuminated from reflections coming out of slab 2. To distinguish internal transmittance and internal reflectance from the external ones, a bar over the variable is used.

$$\bar{\tau}_1 = T_{10}\exp\left(\frac{-\alpha_1 d_1}{\cos\theta_1}\right)\sum_{i=1}^{\infty}\left[R_{10}R_{12}\exp\left(\frac{-2\,\alpha_1 d_1}{\cos\theta_1}\right)\right]^{i-1} \tag{17}$$

$$\bar{\tau}_1 = \frac{T_{10}\exp\left(\frac{-\alpha_1 d_1}{\cos\theta_1}\right)}{1 - R_{10}R_{12}\exp\left(\frac{-2\,\alpha_1 d_1}{\cos\theta_1}\right)} \tag{18}$$

At the boundary between slab 2 and slab 1, T_{21} is neglected because it has been already accounted for by the net reflectivity of the lower slabs. The internal reflectivity $\bar{\rho}_1$ is set up the same way:

$$\bar{\rho}_1 = R_{10}T_{12}\exp\left(\frac{-2\alpha_1 d_1}{\cos\theta_1}\right)\sum_{i=1}^{\infty}\left[R_{12}R_{10}\exp\left(\frac{-2\alpha_1 d_1}{\cos\theta_1}\right)\right]^{i-1} \tag{19}$$

$$\bar{\rho}_1 = \frac{R_{10}\,T_{12}\exp\left(\frac{-2\,\alpha_1 d_1}{\cos\theta_1}\right)}{1 - R_{12}R_{10}\exp\left(\frac{-2\,\alpha_1 d_1}{\cos\theta_1}\right)} \qquad (20)$$

The transition from slab 2 to slab 1 (T_{21}) is also neglected.

Transmittance through two slabs

Now an optical system consisting of slab 1 and slab 2 will be examined. In addition to the internal reflections inside each slab there are also reflections over two slabs (between the upper boundary of the other slab and the lower boundary of the lower slab) to be considered. In order to keep the picture simple, the rays and their infinite series are summed up as slab transmittances τ and slab reflectances ρ. This is done in Fig. 3 and is marked by bold arrows. The following fraction outlines the most direct way into slab 3:

$$\tau_{12,1} = \frac{\tau_1\tau_2}{T_{12}} \qquad (21)$$

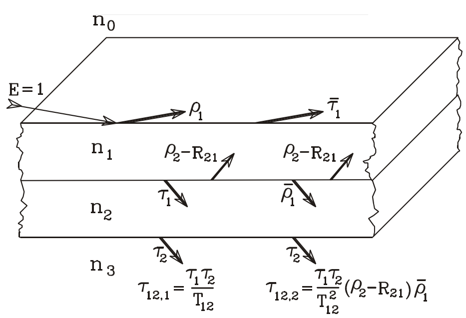

Fig. 3. Transmittance of an optical system consisting of two optical slabs.

It should be mentioned that for the combination of the slab transmittances τ_1 and τ_2 the reflection at the boundary 1-2 has been taken into account in τ_1 as well as in τ_2. So T_{12} has to be compensated once by τ_{12}. Accordingly this has to be done for further combinations of slabs τ_{k+1}. The reflected part $\tau_1 \cdot (\rho_2 - R_{21}) \cdot T_{12}^{-1}$ from inside layer 2 enters slab 1 and is reflected at the boundary 1-0 back into slab 1 by losing $\bar{\tau}_1$. From slab 1 the fraction $\bar{\rho}_1$ reaches slab 2:

$$\bar{\rho}_1 = \frac{R_{10}\,T_{12}\exp\left(\frac{-2\,\alpha_1 d_1}{\cos\theta_1}\right)}{1 - R_{12}R_{10}\exp\left(\frac{-2\,\alpha_1 d_1}{\cos\theta_1}\right)} \qquad (22)$$

The fraction $\bar{\rho}_1$ can be treated in the same way as the direct incoming part and therefore has the same attenuation $\tau_2 \cdot T_{12}^{-1}$ as that in slab 2 when it enters slab 3. This results in:

$$\tau_{12,2} = \frac{\tau_1(\rho_2 - R_{12})\bar{\rho}_1\tau_2}{T_{12}^2} \qquad (23)$$

Again a fraction ρ_2-R_{12} is reflected from slab 2 into slab 1. Summarized, the total transmittance is:

$$\tau_{12} = \frac{\tau_1\tau_2}{T_{12}}\sum_{i=1}^{\infty}\left[\frac{(\rho_2 - R_{12})\bar{\rho}_1}{T_{12}}\right]^{i-1} \qquad (24)$$

$$\tau_{12} = \frac{\tau_1\tau_2}{T_{12} - (\rho_2 - R_{12})\,\bar{\rho}_1} \qquad (25)$$

The total reflectance ρ_{12} of the slab system can be derived accordingly:

$$\rho_{12,1} = \rho_1 \qquad (26)$$

$$\rho_{12,2} = \frac{\tau_1(\rho_2 - R_{12})\bar{\tau}_1}{T_{12}} \qquad (27)$$

$$\rho_{12,3} = \frac{\tau_1(\rho_2 - R_{12})^2\,\bar{\rho}_1\,\bar{\tau}_1}{T_{12}^2} \qquad (28)$$

$$\rho_{12} = \rho_1 + \frac{\tau_1\bar{\tau}_1(\rho_2 - R_{12})}{T_{12}}\sum_{i=1}^{\infty}\left[\frac{(\rho_2 - R_{12})\bar{\rho}_1}{T_{12}}\right]^{i-1} \qquad (29)$$

$$\rho_{12} = \rho_1 + \frac{\tau_1\bar{\tau}_1(\rho_2 - R_{12})}{T_{12} - (\rho_2 - R_{12})\bar{\rho}_1} \qquad (30)$$

The inner reflectivity $\bar{\rho}_{21}$ of the slab system is:

$$\bar{\rho}_{21} = \bar{\rho}_2 + \frac{\bar{\tau}_2\bar{\rho}_1\tau_2}{T_{12}}\sum_{i=1}^{\infty}\left[\frac{(\rho_2 - R_{12})\bar{\rho}_1}{T_{12}}\right]^{i-1} \qquad (31)$$

$$\bar{\rho}_{21} = \bar{\rho}_2 + \frac{\bar{\tau}_2\tau_2\bar{\rho}_1}{T_{12} - \bar{\rho}_1(\rho_2 - R_{12})} \qquad (32)$$

with (50):

$$\bar{\tau}_2 = \frac{T_{21}\exp\left(\frac{-\alpha_2 d_2}{\cos\theta_2}\right)}{1 - R_{21}R_{23}\exp\left(\frac{-2\,\alpha_2 d_2}{\cos\theta_2}\right)} \qquad (33)$$

Transmittance through three slabs

The encapsulation is now considered as three slabs of different optical properties. The two upper slabs 1 and 2 are now considered as a system described by its common transmittance and its common reflectance. So interactions as transmittance and internal reflections have to be considered only between slab system 12 and the new slab 3. After the separation of the ray at the module surface (i.e., slab 1) into a reflected and a transmitted part, the latter joins with the fractions being reflected at the inner boundaries at absorptive attenuation toward the boundary layer of slab 2. Accordingly, this is the same for the transmission of slab 2 and 3. Therefore the two upper slabs 1 and 2 are now considered as a system described by its common transmittance and its common reflectance, for the fraction entering slab 4 the following results occur:

$$\tau_{123,1} = \frac{\tau_{12}\tau_3}{T_{23}} \qquad (34)$$

At the boundary 2-3 internal reflections from slab 3 pass to the border of slab system 21. (The reflection R_{23} has been accounted for already in τ_2 and is therefore subtracted.) A fraction passes through slab system 21, but another fraction will be reflected again and reaches slab 4 after passing boundary 2-3 and slab 3:

$$\tau_{123,2} = \tau_{12} \cdot \frac{(\rho_3 - R_{23})}{T_{23}} \cdot \frac{\bar{\rho}_{21}\tau_3}{T_{23}} \tag{35}$$

The sum of all fractions reaching medium 4 is:

$$\tau_{123} = \frac{\tau_{12}\tau_3}{T_{23}} \sum_{i=1}^{\infty} \left[\frac{(\rho_3 - R_{23})\bar{\rho}_{21}}{T_{23}} \right]^{i-1} \tag{36}$$

$$\tau_{123} = \frac{\tau_{12}\tau_3}{T_{23} - (\rho_3 - R_{23})\bar{\rho}_{21}} \tag{37}$$

SIMULATION RESULTS

Actual transmittance as a function of the incidence angle using the three slab model described is plotted in Fig. 4.

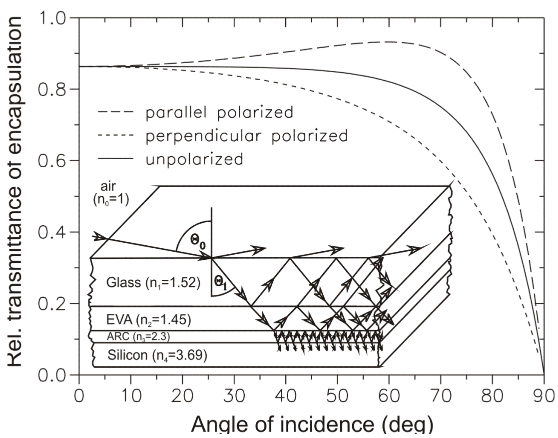

Fig. 4. Transmittance of three optical slabs as a function of the incidence angle.

Refractive indices and absorption coefficients used are given in [2]. Thicknesses used are 2 mm for glass, 0.5 mm for EVA and 0.05 mm for ARC. Fig. 5 shows the transmittance over the time of day (21st of March) for an anisotropic sky hemisphere (applying the DIN 5034 model) using the actual spectra (interpolated from CIE standard spectra) for clear sky conditions. For that case, absorption in the upper three layers was set to zero. The simulation has been carried out for a location 30° South of the Equator at an elevation angle of the module of 30° from horizontal.

A remarkable effect is that optical performance drops significantly after sunrise (at 6 a.m.) and before sunset (at 6 p.m.). These minima can be explained by high reflection losses of the direct component due to flat incidence angels. Before sunrise and after sunset just a diffuse component exists which suffers from relatively small reflection losses. At noon, transmittance is maximal. Effects of simplifications to the model have been evaluated: Relatively small deviations (1%) from the original track could be observed if the internal reflections are neglected. Neglecting optical dispersion results in a yield overestimation of 1.5%. Disregard of lower slabs and the use of perpendicular incidence causes vast overestimations and should not be applied.

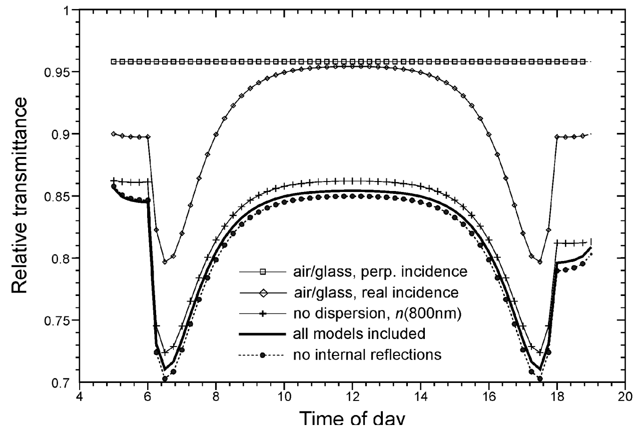

Fig. 5. Transmittance through a PV module during a clear day using different models (no absorption).

Improved matching of the refractive indices

Using the optical model presented above as a simulation for the optical system consisting of front glass, EVA, anti-reflective coating, and silicon solar cell, a parameter variation leads to the following results: A better optical matching of the two upper layers allows an increase optical transmittance by 3.2% for materials with ideal properties, and 1.9% for real materials. Fig. 6 shows the transmittance for perpendicular, unpolarized irradiance for a variation of the parameters n_1 (refractive index of front layer) and n_2 (refractive index of second layer). Also the transmittance of a typical, real PV module is shown.

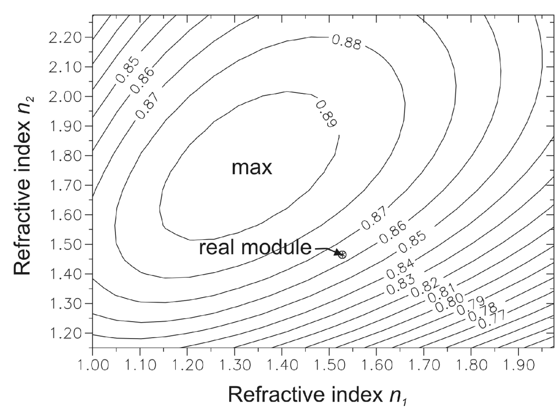

Fig. 6. Optical transmittance of a module encapsulation as a function of the refractive index of the two upper cover sheets for perpendicular incidence of irradiance (θ = 0°).

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[2] S. Krauter, *Solar Electric Power Generation* (1st ed.), Springer: Berlin, Heidelberg, New York 2006.