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# State of the art of radiation-matter interaction models applied for the optical characterization of concentrating solar collectors

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**Abstract**

The optical modelling of concentrating solar collectors is nowadays of great importance for a variety of applications. In this study two major goals have been achieved: First, the current market of materials for solar thermal applications was reviewed; and second, the most commonly used optical models for radiation-matter interaction were summarized. In the future, the study could be interesting for ray tracing implementations in order to adequately simulate solar concentrating or PVT collectors, which employ innovative materials and show more sensitive behavior towards incidence angle and wavelength dependent input.

Keywords: *Monte-Carlo Ray Tracing, Optical Modelling, Solar Concentrating Collectors, PVT, Coatings*

## Nomenclature

| Quantity | Symbol | Unit |
|---|---|---|
| Absorptance | $A$ | - |
| Superposition factor | K | - |
| Depolarization factor | $L$ | - |
| Complex refractive index | $N$ | - |
| Reflectance | $R$ | - |
| Transmittance | $T$ | - |
| Optical admittance of a stack | $Y$ | S |
| Optical impedance of free space | $Z_0$ | $S^{-1}$ |
| Empirical constant | $b_0$ | - |
| Empirical constant | $c$ | - |
| Thin-film thickness | $d$ | m |
| Volume fraction | $f$ | - |
| Real refractive index | $n$ | - |
| Porosity | $p$ | - |

| Quantity | Symbol | Unit |
|---|---|---|
| Absorption coefficient | $\alpha$ | - |
| Solar weighted absorption coefficient | $\alpha_{SW}$ | - |
| Permittivity of free space | $\varepsilon_0$ | $Fm^{-1}$ |
| Optical admittance | $\eta$ | - |
| Incidence angle | $\theta_i$ | rad |
| Extinction coefficient | $\kappa$ | - |
| Wavelength | $\lambda$ | m |
| Permeability of free space | $\mu_0$ | $Hm^{-1}$ |
| Variance of specular reflection | $\sigma$ | rad |
| Phase factor of plane wave | $\varphi$ | - |

## 1. Introduction

The optical characterization of concentrating solar collectors is of paramount importance. To mention only some of possible applications, such simulations are nowadays irreplaceable for designing and optimizing conventional or even completely new collector concepts; they allow to economically determining the error tolerance margins for real operating collectors or they could serve to complement testing procedures where laboratory settings cannot reproduce real conditions. Apart from these most common applications, optical modelling might gain even more importance with the increasing success of photovoltaic-thermal (PV/T) applications, which on the one hand have a wavelength sensitive receiver (PV-cells), but at the same time often have complex designs such as concentration collectors.

Undeniably, the core part of each optical simulation is the underlying mathematical radiation-matter interaction models. During the last decades a remarkable progress has been experienced in the field of solar


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materials research. New types of polymers, tailor designed coatings or surface structures are only some indicators for an increasingly changing market. The question is raised whether state-of the art models for radiation-matter interaction are still suitable to describe newly developed materials.

For this reason, a literature review has been conducted in order to first make a comprehensive list of commonly used solar materials and materials that show great potential to be used in the near future. The focus will be on solar thermal concentrating technologies, but the analysis applies to reflective and transparent materials used in PV and PVT collectors as well. The outcome of this review about solar materials will be presented in section 2. Section 3 will be related to section 2 describing physical models for radiation-matter interaction as they are often applied in order to simulate different materials.

A problem that was observed in this regard was to obtain reliable information about incidence angle dependent data of the material or material compounds that could serve as an input to optical models. It is not clear, what parameters a manufacturer or research group should provide in order to allow accurate simulations. We consider this a necessary debate in order to bring together the field of solar material research and development and the field of optical modelling.

## 2. Solar thermal material for concentrating applications

This section will provide a general overview on materials which are nowadays commonly used and such materials that show great potential to be used in the near future. Since the focus will be on concentrating solar collectors, materials are divided into the following groups: “transparent and semi-transparent”, “reflective”, “absorptive materials” and “coatings”.

### 2.1. Transparent and Semi-Transparent

Transparent and semi-transparent materials are mainly used as covers for protection and heat loss reduction. Doubtlessly, such covers come at the cost of a lower optical efficiency, which makes it even more important to model this part of the collector adequately.

At this point, the most employed material for covers is solar/optical glass, which is made of borosilicate with a low content of iron. One conventional example for such glass is the Schott BK-7 type (Schott, 2014). But there are also more innovative approaches to give glass more favorable properties for the use in solar applications, such as introducing gas bubbles to reduce the thermal conductivity and increase the transmittance (Cai et al., 2016).

While for a long time solar glass was the only choice for solar covers it has become more popular recently to employ semi-transparent polymeric materials. The advantages are manifold: low costs, less weight and almost no restrictions on the design. When it comes to essential optical properties such as the transmittance, polymers perform still poor in comparison to glass. However, due to its good mechanical properties polymer covers can be made extremely thin, which makes this drawback less significant. A good example for such an application is the parabolic trough collector (PTC) prototype of (Bader et al., 2011), which has a pressurized chamber with an ETFE-membrane as top-cover.

(French et al., 2011) and (Köhl et al., 2012) give an overview of polymeric materials which are promising for the use in solar thermal applications (ST). Some of them are:

- Fluoropolymers: ETFE, FEP
- Ethylene backbone polymers: PV1400 EVA
- Polyimides: Kapton H

### 2.2. Reflective

Reflective material is used for mirrors. To be interesting for the use in concentrating solar collectors, they need to be stable, stretch- and soil-resistant, durable and highly reflective in the wavelength range of the solar spectrum. Three types of mirrors are commercially available:

**Glass mirrors**

Glass mirrors are the most used type of mirrors. They usually have a 4mm thick solar glass layer with a thin reflective silver layer beneath. A paint layer protects the silver from environmental impacts such as corrosion. This type of mirror is very resistant and durable but rather expensive and heavy. Moreover, the 4 mm glass substrate reduces the mirror's reflectance. To improve optical performance there are versions with a 1mm thick substrate, which, however, comes at the cost of reduced rigidity. An additional metal sheet on the back side of this mirror can compensate this loss.

**Polymer mirrors**

This type of mirror comes as a thin foil. The core part of the mirror is a reflective silver or aluminum layer protected by a copper layer at the backside. Finally, a thin polymer film at the front and the back side further protects the metal stack from environmental impacts. Polymer mirrors are extremely light, flexible and cheap, but also less durable and resistant than glass mirrors. For the parabolic trough collector in (Bader et al., 2011) MyLar polymer mirrors are used.

**Aluminum mirrors**

Aluminum mirrors start from an anodized aluminum substrate that has either a pure aluminum or silver layer on top for reflection. To protect the reflection layer from corrosion and abrasion the mirror is also provided with a reflectance enhancing, protective coating. The advantage of aluminum mirrors is a comparably low weight at a still high rigidity. The overcoat of the mirror plays an important role for the optical performance and will be explained more in detail in the following.

### 2.3. Absorptive

Solar absorbers are mostly made of stainless steel, copper or ceramics (solar tower) or less common of polymeric material (pool collector or flat plate collector) (Köhl et al., 2012). The substrate of the absorber has to guarantee a high heat transfer coefficient. The most important part of the absorber is, however, its selective overcoat. This one should show high absorption in the short wavelength region (UV-Vis region), but low absorption/emission in the long wavelength region (Infra-red thermal radiation (IR)). According to Kirchhoff's law, a low absorption is equivalent to a low emission, which allows making use of most of energy of the incident radiation. The other main requirements to a selective coating are thermal stability at the operating range, good adhesion to the absorber substrate and resistance to corrosion. In fact, commercially available coatings are only designed for a specific temperature range (Selvakumar and Barshilia, 2012).

### 2.4. Coatings

As already mentioned in the previous sections, coatings or thin-films are single or multi-layers placed on top of a substrate with the purpose of giving a material certain optical properties. Today's processing methods allow designing coatings with a high degree of accuracy which give a lot of freedom for property design. Their importance for solar thermal technologies is paramount. In fact, nowadays coatings are employed in basically all parts of a solar thermal collector: Absorbers have a selective overcoat to allow better exploitation of energy of the incident solar spectrum; anti-reflective layers on covers reduce their reflectance and simultaneously enhance transmittance while mirrors have a high-reflectance coating to improve reflectance further sometimes to an even higher extent than the pure metal and at the same time protect the reflective layer.

**Anti-reflectance and high-reflectance coating**

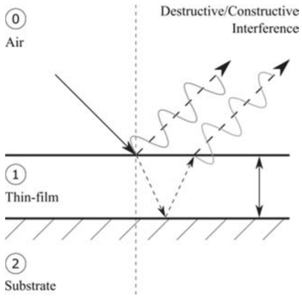


**Fig. 1.** Single layered optical coating: Controlled destructive or constructive interference by multiple reflections.

While anti-reflectance (AR) coatings are applied to reduce surface reflectance and enhance transmittance of covers such as e.g. the envelope of a PTC, high-reflectance (HR) coatings try to achieve exactly the contrary and are used on mirrors. Even though the effect of both coatings is exactly the opposite, their underlying principle is the same. These coatings consist of one or multiple layers. As an electromagnetic wave is propagating through the thin-film assembly it is partially reflected at the layer interfaces according to Fresnel's equations (Eq. 2). Given a specific refractive index for each layer, their thickness can be adjusted for a specific wavelength such that interference of the reflected light is either destructive (AR coating) or constructive (HR coating), as illustrated in Fig. 1. The resulting overall reflectance of the stack is then low or high. Absorption within the thin-film assembly is not desired which is why they consist of dielectrics.

The simplest version of an AR coating is a single $MgF_2$ of the thickness of a quarter of the target wavelength. When constructing a single HR layer on a metal surface it has to be taken into account that the substrate material has a complex refractive index (Macleod, 2010).

Coatings only perform well at the range around the wavelength and incidence angle they were designed for. In order to enable broadband AR or HR behavior for a coating, it is common practice to use multiple quarter-wavelength layers of alternating low (L) and high (H) refractive indices. In this sense, LHL…LHL would form an anti-reflective and HLH…HLH a highly-reflective structure. Commonly used dielectric materials are: $MgF_2$, $SiO_2$, $TiO_2$ (Choi et al., 2014; Jeong et al., 2004; Sutter et al., 2012), $HfO_2$, $Si_3N_4$, $Al_2O_3$ or ZnO (Macleod, 2010; Mazur et al., 2015).

Other increasingly popular low-refractive materials are sol-gels. The sol-gel process allows manufacturing porous layers with an almost tailor-designed refractive index (Atkinson et al., 2015; Prado et al., 2010; Sutter et al., 2010; Xin et al., 2013).

**Selective coating**

Selective coatings show low reflectance in the short wavelength range and high reflectance (low emission) in the long wavelength range. Most coatings incorporate metal which functions as an infra-red reflector, while the dielectric matrix substrate mainly absorbs in the UV-Vis spectrum. It can be distinguished between four types basic of selective surfaces: Intrinsic, metal-semiconductor tandem, metal-dielectric composite (e.g. cermets) or textured surfaces (Atkinson et al., 2015; Selvakumar and Barshilia, 2012; Soum-Glaude et al., 2013). To reduce reflection losses, selective coatings often also have an AR coating on top. The principle of textured surfaces differs from the other methods in such a way that short wavelength radiation is "trapped" in a complex structure and finally absorbed after multiple reflections (see Fig. 2).

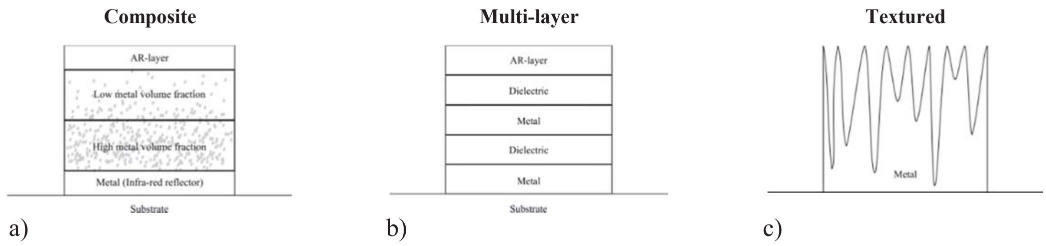


**Fig. 2.** Structures of selective coatings: a) dielectric-metal-composites b) dielectric-metal multi-layers c) textured surface.

The most widely used concepts nowadays are the composites or dielectric-metal multi-layers (Selvakumar and Barshilia, 2012). Selective coatings are designed for a narrow operation range. High temperature coatings are often based on $Al_2O_3$ as dielectric due to its high thermal resistance. Other dielectric matrix materials are: AlN, SiO and MgO (Selvakumar and Barshilia, 2012). Also possible for high-temperature resistant selective coatings is the assembly of the metallic-like TiAlN with the semiconductor TiAlON on top of a metallic IR reflective layer or directly on the substrate (An et al., 2015; Barshilia et al., 2008; Rebouta et al., 2012) or composites of $MoSi_2$ (conductor) and $Si_3N_4$ (dielectric)(Hernández-Pinilla et al., 2016).

**Anti-soiling coating (AS)**

Another positive effect of coatings is to make materials more resistant against soiling. In this light, TiO2 needs to be highlighted as a dielectric material with a couple of additional favorable properties. Not only does $TiO_2$ show high scratch resistance, its photocatalytic properties accelerate the decomposition of organic particles, which leads to a self-cleaning effect (Atkinson et al., 2015; Mazur et al., 2015).

## 3. Optical models for solar materials

After having summarized some of the most important materials and new structural concepts that are employed in concentrating solar collector nowadays, we will discuss some of the optical models in order to simulate material response on incident radiation. It will be distinguished between surface, volume and thin-film (coating) effects.

The propagation of an electromagnetic wave (radiation) through a medium is described by the Maxwell equations and the Lorentz force law. Where complex optical devices are used and results with a high degree of accuracy are needed, it is necessary to employ computational methods to solve these equations. However, if the properties of a medium are approximately constant and its dimensions are several times larger than the considered wavelength, the wave front can be represented by rays (geometrical optics). As a ray is passing through a solar thermal collector and interacting with different materials the finally absorbed energy is subject to a complex coupling of different physical correlations. The overall optical performance of a collector is then best approached by tracing an arbitrary number of rays separately according to the Monte Carlo method until the result is statistically stable. This is the principle description of how ray tracing work, the most commonly applied method for simulation of solar concentrating collectors.

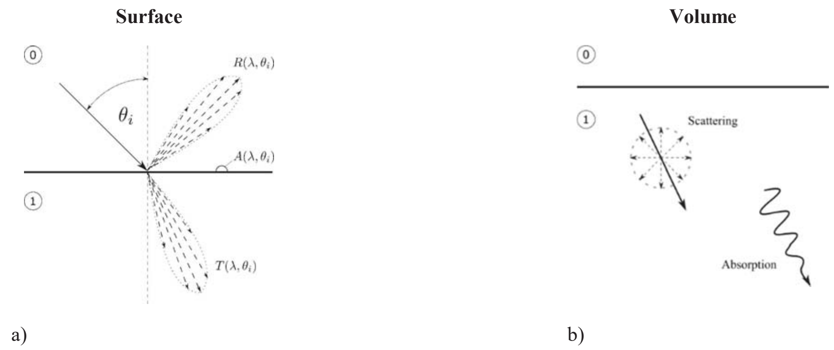


**Fig. 3.** Radiation-matter-interaction phenomena: a) Reflection, transmission and absorption on surfaces. b) Scattering and absorption within volume.

### 3.1. Surface effects:

In ray tracing, when a ray hits a surface there are only three possible ways it can interact with it. It can be either reflected, transmitted or absorbed (Fig. 3). According to the law of energy conservation all fractions over the incident energy add up to 1.

$$R(\theta_i,\lambda) + T(\theta_i,\lambda) + A(\theta_i,\lambda) = 1 \quad (1)$$

All coefficients depend on the wavelength, the incidence angle and the polarization of the incident light. Making some approximations regarding Eq. 1, helps to group the previously presented materials into different categories according to their surface type. Fig. 4 illustrates these categories. It is valid to assume zero transmission for absorptive and reflective materials such as receivers and mirrors. On the other hand, transparent materials like covers can be assumed to have zero absorption, since even if they are coated they only employ dielectric materials. This only goes for the surface itself. In the volume there will be absorption. The main advantage of this simplification is that a material is optically fully characterized when determining its reflectance beside its scattering properties, which will also be discussed.

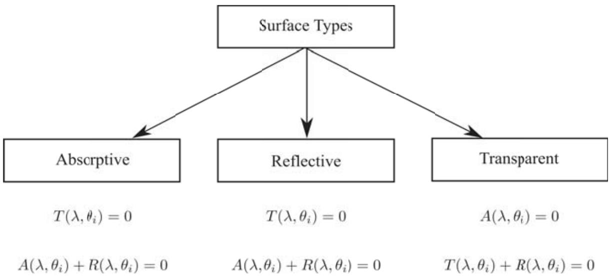


**Fig. 4.** Classification of typical solar thermal material: absorptive material (receiver), reflective material (mirrors) and transparent material (covers, envelopes)

**Reflectance - $R(\theta_i,\lambda)$**

One solution of Eq. 11 is given by the Fresnel equations, which result from the boundary condition of a balance of the electric and magnetic fields across the surface. The Fresnel equations therefore present a solution of the simplified Maxwell equations (Macleod, 2010).

$$R = \left(\frac{\eta_0 - \eta_1}{\eta_0 + \eta_1}\right)\left(\frac{\eta_0 - \eta_1}{\eta_0 + \eta_1}\right)^* \quad (2)$$

$$T = \frac{4\eta_0 Re(\eta_1)}{(\eta_0 + \eta_1)(\eta_0 + \eta_1)^*} \quad (3)$$

$\eta$ is the optical admittance of the material and depends on the polarization of the incident light. It is also common to use a modified “tilted” version of the optical admittance that also incorporates the angle of propagation $\theta$ of the particular medium.

$$\eta_i = \begin{cases} \frac{N_i \cos\theta_i}{Z_0} & \text{, for s-polarization (TE)} \\ \frac{N_i}{Z_0 \cos\theta_i} & \text{, for p-polarization (TM)} \end{cases} \quad (4)$$

with $Z_0$ the optical impedance of free space. TE refers to a plane wave with the electric field vector perpendicular to the plane of incidence and TM with the magnetic field vector perpendicular to the plane of incidence.

$$Z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} \quad (5)$$

And $N$ the complex refractive index

$$N = n + i\kappa \tag{6}$$

It should be noted that the refractive index can be complex as is the case for non-dielectric matter such as metals. This becomes important for the analysis of mirrors. The refractive index and the angle of incidence are also the only non-Natural constants and hence fully describe the reflectance at an interface.

The angle of propagation of each medium $\theta_i$ is related to the angle of incidence $\theta_0$ by Snell's law:

$$n_0 \sin\theta_0 = n_i \sin\theta_i \tag{7}$$

In the case of dielectric materials ($\kappa \neq 0$) Schlick proposed an approximation of the incidence angle dependence of the reflectance given by Eq. 2 (Schlick, 1994). Schlick's alternative equation is computationally less expensive.

$$R(\theta) = R_0 + (1 - R_0)(1 - \cos\theta)^5 \tag{8}$$

**Scattering**

Beside de Fresnel effect, scattering is another important phenomenon of radiation-matter interaction on a surface. While the former is the result of an energetic balance, the latter is instead due to surface texture. The microscopically random surface structure has influence on the direction of the reflected photon and disperses the energy flux spatially (see Fig. 5).

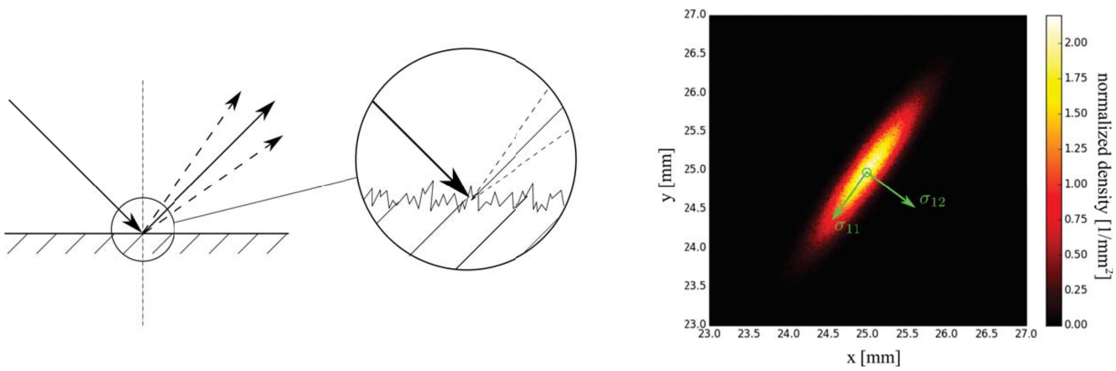


**Fig. 5.** Microscopic surface errors lead to narrow-angle dispersion of specular reflection (left). Right: reflection pattern on target. Due to systematic errors brought into by e.g. processing methods of the material, dispersion can have a preferred direction.

In general, it can be distinguished between two ideal cases of reflection: isotropic reflection (maximum dispersion) and specular reflection (no dispersion). In reality, the reflection pattern is a combination of both cases and is described by a bidirectional reflectance distribution function (BRDF). Many different BRDFs have been proposed to meet the variety of many different surface types (Montes and Ureña, 2012).

From the perspective of Monte Carlo ray tracing, it is necessary to express the direction of reflection in terms of probabilities. Isotropic or Lambertian reflection in this regard is the simplest case, since the probability for each reflection direction on the surface hemisphere is the same. This is the case for highly rough or matte surfaces.

Most of BRDF models are based on a Gaussian distribution. Especially when it comes to modelling the specular reflection of mirrors for solar thermal collectors, this is a well-established probability function (Gee et al., 2010; Good et al., 2016; Pettit, 1977; Sutter et al., 2016).

$$f = Ke^{\left(-\frac{\varphi^2}{2\sigma_{21}^2} - \frac{\varphi^2}{2\sigma_{22}^2}\right)} + (1 - K)e^{\left(-\frac{\varphi^2}{2\sigma_{11}^2} - \frac{\varphi^2}{2\sigma_{12}^2}\right)} \tag{9}$$

Eq. 9 essentially incorporates four basic forms of Gaussian specular reflection (Gee et al., 2010):

- Single univariate ($K = 0, \sigma_{11} = \sigma_{12}$ )

- Single bivariate ($K = 0, \sigma_{11} \neq \sigma_{12}$ )
- Double univariate ($K \neq 0, \sigma_{11} = \sigma_{12}$ , $\sigma_{21} = \sigma_{22}$)
- Double bivariate ($K \neq 0, \sigma_{11} \neq \sigma_{12},\ \sigma_{21} \neq \sigma_{22}$ )

The multivariate Gaussian function accounts for a preferred reflection direction, which in reality appears on reflective material. It is caused by the respective processing method, so for example the rolling process in the manufacturing of aluminum mirrors. The superposition of two Gaussian distributions better represents the combined effect of microscopic and macroscopic surface errors. In practice, as long as macroscopic errors (slope, shape, alignment, tracking) are considered random, they are all summed up to a total surface variety $\sigma_{tot}$ (Rabl, 1985).

$$\sigma_{tot}^2 = \sum_{i=1}^{n} \sigma_i^2 = \sigma_{spec}^2 + 4\sigma_{slope}^2 + 4\sigma_{shape}^2 + 4\sigma_{align}^2 + 4\sigma_{track}^2 \tag{10}$$

It is important to state that the dispersion itself depends on the wavelength and the angle of incident light as well ($\sigma = \sigma(\lambda, \theta)$). This dependency significantly depends on the material type (Good et al., 2016; Sutter et al., 2016). Since there is still no standardized experimental method for the complete spectral assessment of specular material (SolarPACES, 2013), little can be found on wavelength and incidence angle dependency of $\sigma$. One relation is the power law that can be derived from (Good et al., 2016) is given by Eq. 11.

$$\sigma(\lambda, \theta) = \sigma(\lambda_{ref}, \theta_{ref}) \cdot \left(\frac{\lambda}{\lambda_{ref}}\right)^p \cdot \left(\frac{\cos\theta}{\cos\theta_{ref}}\right)^q \tag{11}$$

### 3.2. Volume effects:

When an electromagnetic wave is propagating through a medium it will experience both scattering and absorption (Fig. 3). Scattering can be important if the medium contains particles or inclusions as for example in the case of (Cai et al., 2016). Volume scattering can also play an important role in polymeric material (French et al., 2011) or atmospheric calculations such as for solar tower applications. If the medium is mainly homogeneous, however, volume scattering in comparison to surface scattering is rather small and absorption will have most influence on the radiation intensity (Wallner et al., 2005).

The absorption coefficient $\alpha$ is correlated with the extinction coefficient $\kappa$ – the complex part of the refractive index of a material (Eq. 6).

$$\alpha(\lambda) = \frac{4\pi\kappa}{\lambda} \tag{12}$$

A rough relation between a material's absorbance and the wavelength can be obtained by an exponential Urbach fit. However, this approximation is not accurate in all cases (French et al., 2011).

In order to get from experimental data to usable input for ray tracing, one challenge is to separate between volume and surface effects, as in reality they can only be measured together. This was also pointed out by the work of (Good et al., 2016) and (Wallner et al., 2005).

### 3.3. Thin-film effects (coatings):

The most common approach to model the reflectance, transmittance and absorptance of a thin-film assembly (coating) is the transfer-matrix method (TMM). Within a layer the electric and magnetic field is the sum of the total forwards and backwards (reflected) waves propagating according to a phase factor. This assumption is described by $M_p$, the characteristic matrix of a thin-film. Since the continuity condition of the electric and magnetic field across the boundary of the layer p and its adjacent layer is also applies here, the characteristic matrices can be multiplied. Theoretically, this can be done for an infinite number of layers. The result correlates the electric and magnetic field on top and at the bottom of the assembly (see Eq. 13) (Macleod, 2010).

$$\begin{pmatrix} B \\ C \end{pmatrix} = \left\{ \prod_{p=1}^{q} \underbrace{\begin{bmatrix} \cos\varphi_p & (i\sin\varphi_p)/\eta_p \\ i\eta_p \sin\varphi_p & \cos\varphi_p \end{bmatrix}}_{M_p} \right\} \begin{pmatrix} 1 \\ \eta_q \end{pmatrix} \tag{13}$$

with the phase factor $\varphi_i$ (Eq. 14), the number of layers q (including the substrate) and the optical admittance of the substrate $\eta_q$

$$\varphi_i = \frac{2\pi N_i d_i \cos\theta_i}{\lambda} \tag{14}$$

From Eq. 13 an optical admittance of the assembly can be derived.

$$Y = C/B \tag{15}$$

And in the same way as done for the Fresnel equations, the reflectance, transmittance and absorptance of the stack can be calculated.

$$R = \left(\frac{\eta_0 - Y}{\eta_0 + Y}\right)\left(\frac{\eta_0 - Y}{\eta_0 + Y}\right)^* \tag{16}$$

$\eta_0$ is the optical admittance of the incidence medium.

$$T = \frac{Re(\eta_q)(1-R)}{Re(BC^*)} \tag{17}$$

$$A = 1 - R - T \tag{18}$$

The transmittance of the assembly is always independent of the direction of the propagation (propagation from the incidence medium to the substrate or from the substrate to the incidence medium (Abelés, 1950)). For the reflectance, however, this is only the case if there is no absorption in any of the layers (only dielectric material), which is usually satisfied for AR coatings, since here absorption is not desired.

Eqs. 13 to 18 present the basis for all thin-film performance simulations and design.

**AR/HR coatings**

There are many ways to design AR and HR coatings. One possibility is to make them out of multiple quarter wavelength layers. In this case the quarter wavelength condition $\varphi = \pi/2$ has to be satisfied for each layer, so that

$$d_p = \frac{\lambda}{4n\cos\theta_p} \tag{19}$$

and with a successively increasing refractive index according to

$$N_p = \sqrt[p+1]{\frac{n_0}{n_{sub}}} \tag{20}$$

It is however more common, in practice, to use layers with alternating refractive indices. Some examples for the analytical assessment of such layers are (Choi et al., 2014; Mazur et al., 2015; Sahouane and Zerga, 2014) for ST and (Saylan et al., 2015; Sikder and Zaman, 2016) for PV applications.

Especially for single layer AR coatings low refractive material are needed. Promising here are porous sol-gels, because the refractive index is related to the porosity (Prado et al., 2010; Xin et al., 2013).

$$n_p = [(1-p)(n^2-1)+1]^{1/2} \tag{21}$$

where $p$ is the porosity volume fraction and $n$ the refractive index of the base material.

**Selective coatings**

As described in the previous section, selective coatings are often based on dielectric-metal composites. Eqs. 13 to 18 are only valid for layers with homogeneous properties. It is therefore necessary to approximate the effective refractive index of the composite from the refractive indices of the base materials. This can be done by the Maxwell-Garnett relation.

$$\frac{\varepsilon_{eff} - \varepsilon_m}{L(\varepsilon_{eff} - \varepsilon_m) + \varepsilon_m} = f \cdot \frac{\varepsilon_i - \varepsilon_m}{L(\varepsilon_i - \varepsilon_m) + \varepsilon_m} \tag{22}$$

with the dielectric constants $\varepsilon_m$ of the matrix, $\varepsilon_i$ of the inclusions and $\varepsilon_{eff}$ of the composite. $f$ is the volume fraction of inclusion and matrix and $L$ the depolarization factor.

Some examples for the analytical analysis and design of high-temperature resistant selective thin-film assemblies using the previously described transfer matrix method are (An et al., 2015; Cardenas, 2015; Hernández-Pinilla et al., 2016; Rebouta et al., 2012; Soum-Glaude et al., 2013; Yang et al., 2016).

Particularly interesting for ray tracing applications is the approach of (Tesfamichael and Wäckelgård, 2000) and (Grena, 2010). In their studies they tried to describe the absorptance (reflectance) of a selective solar receiver as a function of the angle of incidence only. Tesfamichael et al. proposed a modified version of the incidence angle modifier law for solar thermal applications (Duffie and Beckmann, 2006)

$$\alpha_{SW}(\theta_i) = \alpha_{SW}(\theta_0) \cdot b_0 \left(\frac{1}{\cos\theta_i} - 1\right)^c \tag{23}$$

Where $\alpha_{SW}(\theta_0)$ is the absorption coefficient at normal incidence.

$$\alpha_{SW}(\theta_0) = \frac{\int_0^\infty s(\lambda) \cdot \alpha(\lambda, \theta_0)\, d\lambda}{\int_0^\infty s(\lambda)\, d\lambda} \tag{24}$$

This model is able to describe different selective surfaces by adjusting the characteristic parameters $b_0$ and c. Unfortunately, the only available results are those provided by the authors themselves, which were those measured for a $Al_2O_3$-Ni/$Al_2O_3$ assembly and a $NiO_3$-Ni-composite layer.

(Grena, 2010), on the other hand, defines a more general power law based on experimental data from different selective absorption material.

$$\alpha_{SW}(\theta_i) = \alpha_{SW}(\theta_0) \cdot \left[1 - \left(\frac{2\theta}{\pi}\right)^8\right] \tag{25}$$

## 4. Discussion and Outlook

During the last decades significant progress has been experienced in the development of new materials and collector designs. Especially coatings have gained in importance for the use in solar thermal collector technologies due to more sophisticated processing methods and the possibility of application specific design, but also the increasing success of PV and PVT technologies make great demands on optical simulations.

In this study two major goals have been achieved: First, the current market of materials for solar thermal applications was reviewed; and second, the most commonly used optical models for radiation-matter interaction were summarized.

The outcome of this study could be particularly interesting for implementations of ray tracing optical simulation tools. It could be shown that most ray tracing programs do not consider the option of a more accurate spectral analysis. Whether such an analysis is necessary, might depend on the types of material that are employed. Glass mirrors e.g. do not show very strong variations of scattering with the wavelength, but aluminum and polymer mirrors do. It is also noticed that there is a lack of models that reflect incidence angle dependencies, most of all for selective surfaces.

The radiation-matter interaction models that were presented are a summary of what can be found in current literature. A key parameter to optically define materials is their refractive index. There are extensive data bases that contain refractive information based on ellipsometry and dispersion relations for many different materials. Such data bases could provide valuable input to optical simulations. Nevertheless, a general problem one faces when trying to get from experimental data to usable input for ray tracing e.g., is to separate between volume and surface effects. This might be important in order to model compounds such as e.g. glass mirrors.

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