

Efficiency of selective solar absorber in high vacuum flat solar thermal panels: The role of emissivity

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Abstract: This study refers to the optimization of a Selective Solar Absorber to improve the Sun-to-thermal conversion efficiency at mid temperatures in high vacuum flat thermal collectors. Efficiency has been evaluated by using analytical formula and a numerical thermal model. Both results have been experimentally validated using a commercial absorber in a custom experimental set-up. The optimization procedure aimed at obtaining Selective Solar Absorber is presented and discussed in the case of a metal dielectric multilayer based on Cr_2O_3 and Ti . The importance of adopting a real spectral emissivity curve to estimate high thermal efficiency at high temperatures in selective solar absorber is outlined. Optimized absorber multilayers can be 8% more efficient than the commercial alternative at 250 °C operating temperatures and up to 27% more efficient at 300 °C. Once the multilayer has been optimized the choice of a very low emissivity substrate such as copper allows to further improve efficiency and to reach stagnation temperature higher than 400 °C without Sun concentration.

Keywords: Thermal emittance; conversion efficiency; selective solar absorber; thermal energy; evacuated flat panel; solar energy

1. Introduction

Solar energy plays a key role in the energy transition from fossil fuels to renewable energy [1]: several works showed that the adoption of energy-efficient and clean energy resources is crucial in reducing greenhouse gas emissions and pollution [2,3]. More than one fourth of the energy resources in the developed countries is nowadays used for heating and cooling [4,5], and industry represents a promising area of application [6]. Such a large fraction of energy can be provided by solar thermal collectors converting solar energy directly into heat with high efficiency. The core component of a solar thermal collector is the Selective Solar Absorber (SSA). An ideal SSA should perfectly absorb solar radiation (solar absorptance $\alpha=1$), whereas its thermal emission should be minimal (thermal emittance $\varepsilon=0$). Its spectral emissivity is assumed to be a step function which flips from 1 to 0 [7] and the wavelength at which the transition happens is commonly named cut-off wavelength ($\lambda_{cut-off}$) [8,9]. The formal definition of $\lambda_{cut-off}$ leads to energetic considerations: it is the wavelength that maximizes the absorber thermal performance and it depends on the working temperature and on the solar incoming power (i.e. solar concentration ratio) [10]. It was generally verified that $\lambda_{cut-off}$ is the wavelength at which the blackbody emission curve crosses the solar radiation spectrum [8,11].

At low temperature, blackbody emission and solar spectrum barely overlap, and the optimization of the SSA limits to maximize the solar absorption, since the demanded emissivity transition (from high absorptance in solar range and low thermal emittance in black body emission spectrum) is easily

reached in a wide wavelengths range. When the operating temperature increases over 200 °C, the blackbody emission starts to overlap the solar spectrum and the sharpness of the transition assumes a greater importance. The SSA idea was introduced at the end of '50, and thenceforward several works have been devoted to SSA optimization. [7,12].

To realize an SSA with an emissivity curve close to the ideal one, different designs have been analyzed by several authors in the past years [13,14]: nanomultilayer [15], ceramic and metal structures (known as cermet) [11], multilayers [16–18], photonic designs [19], structured graphene metamaterial [20], multi-layered cermets [10].

However, a very sharp transition was never obtained and recently Yang et al.[21] studied the effect of non-ideal SSA properties on the overall performances in a Concentrated Solar Power (CSP) system: their simulated SSA has a finite constant slope in the cut-off transition (instead of the ideal step function) and a not ideal SSA emissivity.

Dealing with a real SSA, the relative importance of solar absorptance and thermal emittance to calculate the absorber efficiency has to be taken into account. Cao [11] introduced a Weighting Factor, (w), that indicates the relative weight of α and $\varepsilon(T)$ in the efficiency of a solar absorber. In Fig. 1 w is reported as a function of the absorber temperature and solar concentration.

All the previous selective absorbers, in literature as in commerce, were optimized for concentrated collectors or flat plate collectors without vacuum insulation: in this conditions $w < 1$ and hence α weights more than $\varepsilon(T)$. The only exception is [22], which obtained a stagnation temperature of about 230°C under vacuum that could be increased to about 300°C with further optimization.

The importance of vacuum insulation in solar thermal panel has been already highlighted [23], however only recently TVP Solar [24] presented a new High Vacuum insulated Flat plate solar thermal Panel (HVFP) [25]. High vacuum insulation reduces the internal gas convective and conductive losses to a negligible level, keeping high conversion efficiency at high working temperature. In this case the thermal radiation is the main loss mechanism and the radiative properties of SSA are an aspect of primary importance. It is worth to note that thermal emittance gains weight over the absorptance as the working temperature increases (green arrow in Fig. 1) and that HVFPs represent the only commercial product with $w > 1$. Several absorbers are commercially available [26,27]. Currently HVFPs include the absorber Mirotherm® from Alanod, a commercial SSA optimized for low working temperatures (up to about 150 °C). It results in excellent performance up to 180°C, but at higher temperatures the low selectivity of the absorber increases the thermal radiation losses, affecting the panel efficiency and limiting the stagnation temperature at about 320°C with an illumination of 1000W/m². The increased panel efficiency due to high vacuum has been studied also from other researchers [28] and the superior performance up to 250°C have been predicted [29], if an optimized SSA was mounted in HVFP. However, the authors did not give any indication on how to produce such optimized SSA. In this work, we develop a new absorber coating optimized to work at mid temperature in a high-vacuum system without concentration. As reported above this is a quite peculiar case, not yet analyzed in literature, in which the thermal emittance is expected to be more relevant than absorptance. We developed multilayer absorbers, since their optical properties can be easily simulated and they allow to control thermal emission while guaranteeing high solar absorption and excellent thermal stability. [30]. We deposited several thin layers of different materials to precisely determine the complex refractive index of each material. The optical response of a SSA based on a $Cr_2O_3/Ti/Cr_2O_3$ multilayer on a smooth Aluminium substrate has been studied as function of the thickness of each layer.

A single SiO_2 layer is used as antireflective coating to improve absorptance. The simulated spectral emissivity curves are used to evaluate the temperature dependent spectrally averaged emissivity which in turn allows to evaluate the radiative losses and the SSA efficiency. The efficiency of the new absorber is discussed in comparison with the efficiency of commercially available absorber currently used in HVFPs, taking in to account the non-ideal cut-off in the emissivity curve of both SSAs.

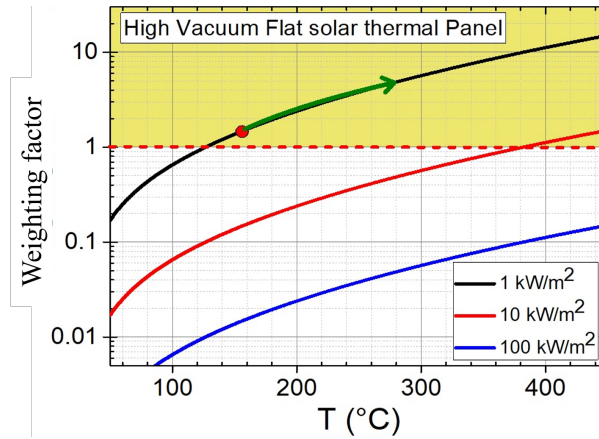


Figure 1. Weighting factor versus Absorber temperature $T(^{\circ}\text{C})$ for different solar concentration ratios. The red dot indicates the operating temperature (160°C) of HVFP equipped with commercial absorber and the green arrow the increasing importance of thermal emittance with working temperature (adapted from [11]).

2. Results and discussion

Several layers have been deposited by ebeam deposition technique. The refractive index measured by ellipsometric measurements are described in the Material and Methods section. The experimental refractive indices have been used to simulate the optical response of a multilayer and the good agreement between simulations and experimental deposited multilayer has been verified. Then the optimization procedure described in the Materials and Methods section has been repeated for four working temperature from 200°C up to 350°C , corresponding to different optimal $\lambda_{cut-off}$. Table 1 sums up the values of $\lambda_{cut-off}$, layer thicknesses, solar absorptance α_S , and thermal emittance $\varepsilon(T)$ for each selective coating, as resulting from the optimization procedure. Fig. 2a shows the spectral emissivity of the four different multi-layer absorbers obtained as the result of the optimization process and the emissivity curve resulting from the optimization process obtained for $\lambda_{cut-off} = 1.5 \mu\text{m}$.

Table 1. Optimization temperature, $\lambda_{cut-off}$ for desired operating temperature, layer thickness obtained from the optimization process, solar absorptance α_S and thermal emittance $\varepsilon(T)$ at 200°C , 250°C , 300°C and 350°C calculated from eq. 4 and 5, for 5 multilayer absorbers. Sample E was obtained for $\lambda_{cut-off} = 1.5 \mu\text{m}$

Sample	A	B	C	D	E
Optimization Temperature ($^{\circ}\text{C}$)	200	250	300	350	-
$\lambda_{cut-off}$ [11] (μm)	2.47	2.37	2.19	1.79	1.5
Top dielectric layer thickness (nm)	110	98	81	59	46
Metal layer thickness (nm)	16	16	15	13	12
Bottom dielectric layer thickness (nm)	42	38	32	25	20
Anti-Reflective Coating	70	67	63	60	52
Solar absorptance α_S	0.91	0.91	0.91	0.89	0.86
Thermal Emittance ε (200°C)	0.056	0.050	0.041	0.031	0.026
Thermal Emittance ε (250°C)	0.067	0.060	0.048	0.035	0.029
Thermal Emittance ε (300°C)	0.080	0.071	0.057	0.041	0.034
Thermal Emittance ε (350°C)	0.094	0.083	0.066	0.047	0.038

The results of the optimization process show that the SSA $\lambda_{cut-off}$ can be adjusted by varying the layer thicknesses, preserving a high solar absorption and a low thermal emission. In Fig. 2b, the temperature dependent thermal emittance of multi-layers, calculated according to eq. 5 (see Materials and Methods), is compared with the commercial coating currently used in high-vacuum solar collectors

(dashed line). Multi-layers with lower $\lambda_{cut-off}$ can reduce the room temperature thermal emittance and, more important, its temperature dependence, resulting in a more than 50% emittance reduction at all temperature values. In turn this results in an increased efficiency, as it will appear clear in the following.

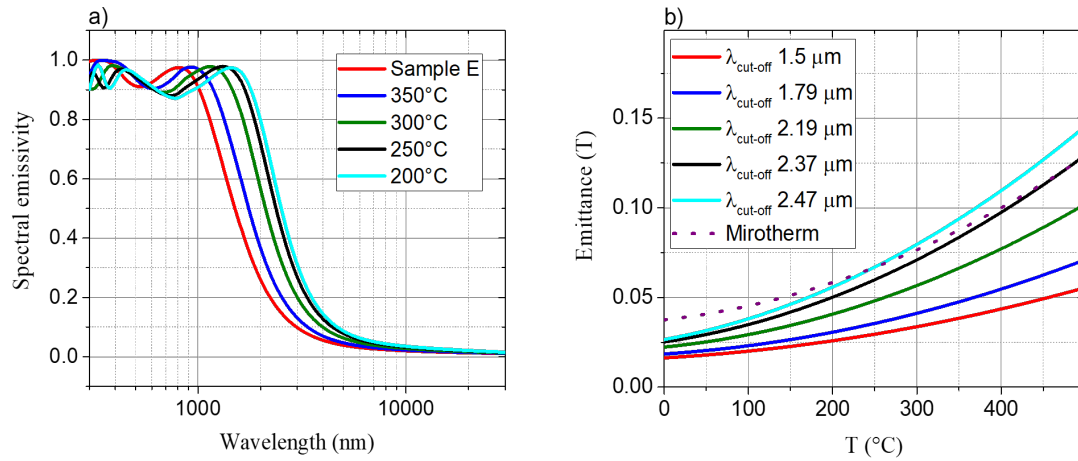


Figure 2. (a) Spectral emissivity of multilayer selective absorbers optimized for different temperature and consequent $\lambda_{cut-off}$. (b) Temperature dependent emittance for different $\lambda_{cut-off}$ calculated using eq.5.

The SSA efficiency can be written as following:

$$\eta_{coat} = \frac{q_h}{H_{abs}} = \alpha_s - \frac{\varepsilon(T) \cdot \sigma_{SB}(T^4 - T_{amb}^4)}{H_{abs}} \quad (1)$$

where η_{coat} is the coating efficiency, α_s the solar absorptance, $\varepsilon(T)$ the temperature dependent thermal emittance, q_h the heat flux to the thermal system (Wm^{-2}), H_{abs} the Solar Irradiance on the absorber (Wm^{-2}), T the absorber temperature (K), T_{amb} the environmental temperature (K), and σ_{SB} the Stefan-Boltzmann constant ($Wm^{-2}K^{-4}$).

The SSA efficiency for the simulated multilayers and the commercial absorber, calculated from eq. 1, is plotted in Fig. 3. The graph shows how temperature dependent thermal emittance shapes the selective absorber performance curves. Mirotherm® commercial absorber is optimized for standard flat-plate solar collectors: it shows the highest efficiency for lower values of operating temperature because of its higher solar absorption coefficient and a relatively low spectrally averaged emissivity (see Fig. 2b). Multilayers A and B are good options for mid temperature applications: although these two coatings have a lower solar absorptance α_s with respect to the commercial absorber, the improvement in thermal emittance (Fig. 2b, table 1) results comparable performances for high working temperatures. Multilayer C and D offers the highest stagnation temperatures thanks to the lowest spectrally averaged emissivity, but a slightly lower efficiency in low to mid temperatures range. This is due to the low cut-off that reduces the power achievable from the Sun spectrum, resulting in a lower absorptance. However, starting from 200 °C, they present a coating efficiency higher than the other absorbers, including the Mirotherm ®.

In Fig. 3 we also report the efficiency calculated using an emissivity curve obtained for sample E, which has a $\lambda_{cut-off} = 1.5\mu m$. Its cut-off is outside the typically explored wavelength interval, since it corresponds to a region of zero intensity in the Sun spectrum, one of the so-called *hidden regions*[11]. Despite its lower absorptance, starting from 300 °C, it has the highest efficiency thanks to its lower thermal emittance.

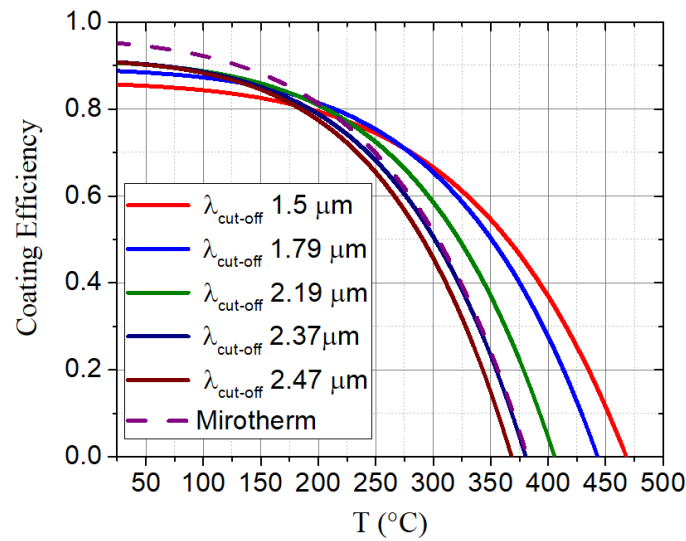


Figure 3. Absorber efficiency versus operating temperature for five multilayer absorbers with different $\lambda_{cut-off}$ optimized for different temperatures (continuous lines), and Mirotherm® commercial absorber (dashed line).

A further reduction in $\lambda_{cut-off}$ below $1.5 \mu\text{m}$ can result in a further increase in the stagnation temperature, but drastically reduces the efficiency at lower temperatures (the curves are not reported here). This is due to the specific features of the solar irradiance spectrum, which rises very fast when wavelength reduces below $1.4 \mu\text{m}$.

Equation 1 allows to evaluate the coating efficiency without taking into account boundary conditions (such as the glass optical losses, conductive losses and substrate radiative losses due to the heat exchange between the back side of the absorber and the collector vessel). In case of negligible conductive and convective losses (as in the case of an absorber suspended in a high vacuum envelope), eq. 1 can be modified in order to evaluate the overall absorber efficiency, η_{all} of a flat absorber as following:

$$\eta_{all} = \tau_{Glass} \cdot \alpha_S - \frac{\varepsilon(T) \cdot \sigma_{SB}(T^4 - T_{amb}^4)}{H_{abs}} - \frac{\varepsilon_{Sub} \cdot \sigma_{SB}(T^4 - T_{amb}^4)}{H_{abs}} \quad (2)$$

where τ_{Glass} is the glass transmittance, and ε_{Sub} is the equivalent thermal emittance relative to the absorber back-side and the vessel and it is assumed to be temperature independent. For Mirotherm®, a previous work [31] has shown that $\varepsilon_{Sub}=0.045$ provides an excellent fit to experimental data; it is in agreement with the spectrally averaged emissivity calculated by Fourier-transform infrared spectroscopy (FTIR) measurement. We validated eq. 2 by using an home-made experimental setup, the so called *Mini-Test-Box* (MTB) [31,32], which allows to evaluate the overall efficiency of the absorber by performing stagnation temperature measurements in high vacuum (see Material and Methods section for further details).

Fig. 4a reports the Mirotherm® overall efficiency (as from eq. 2) when placed in the MTB (blue solid line), the numerical simulation of the experimental setup (orange dash-dot line) and the overall efficiency experimentally measured using eq. 2 (black dots). The excellent agreement between numerical simulations, measured data obtained by eq. 6, and values descending from eq. 2 confirms that, if the conductive losses are negligible and the proper ε_{Sub} is taken in to account, the eq. 2 is a valid instrument to evaluate the overall absorber efficiency. Fig. 4b shows the overall efficiency calculated from eq. 2 for the coating with different cut-off and an equivalent thermal emittance of aluminium substrate of 0.045. The equivalent substrate thermal emittance is assumed to be constant with temperature.

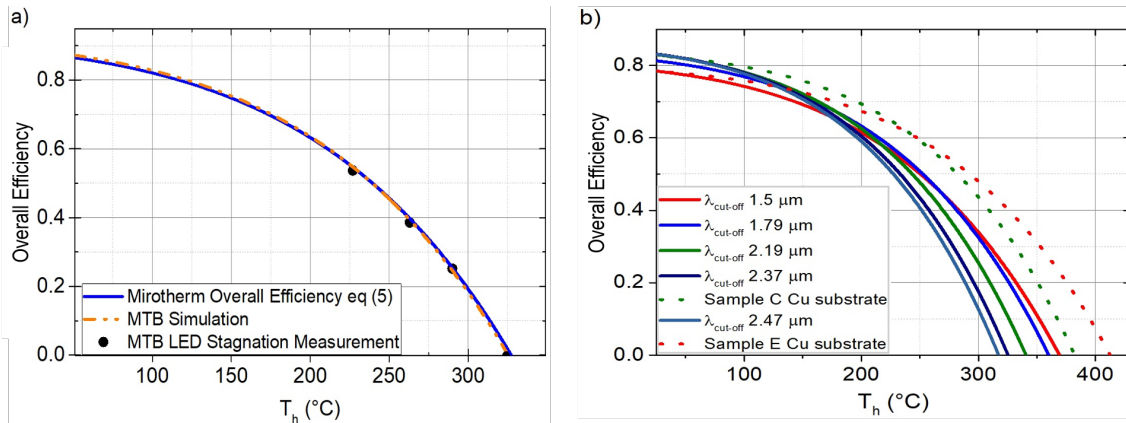


Figure 4. (a) Overall efficiency versus Absorber temperature T_h : MTB simulated efficiency (orange, dash dot), Led Measured MTB efficiency (black dots), Mirotherm® overall efficiency calculated using eq. 2 (blue solid line). (b) Overall efficiency calculated using eq. 2 for coating having different cut-off on aluminium substrate (solid lines) and for coatings with 2.0 μm and 1.5 μm cut-off deposited on copper substrate with $\varepsilon(T)=0.02$ (olive and red dashed line).

When estimating the overall efficiency, we first observe that the reduction in the $\lambda_{cut-off}$ in samples A-D doesn't affect performance at low temperature significantly, being all the values around 0.8. Only the sample E with $\lambda_{cut-off} = 1.5 \mu m$ shows a reduction in α_S (see table 1) which results in an efficiency at low temperature lower than 0.8. However, when the temperature increases, the low thermal emittance plays a major role in preserving efficiency and the sample E shows the best performances with respect to the others at temperature higher than 280 °C.

Moreover it should be noted that for coating with $\lambda_{cut-off} < 2 \mu m$, the coating thermal emittance is lower than the industrial aluminium substrate emissivity. Hence the adoption of a different substrate with a lower thermal emittance can significantly improve efficiency. This result is not surprising: looking at the commercial absorber it is clear that the uncoated side of the absorber has a relative high roughness ($R_a = 1.65 \mu m$) and thermal emittance increases with roughness. The commercial absorbers have been developed for standard flat panels, for which the absorber uncoated side is insulated by rock wool, while the coated side is in air or inert atmosphere and it is not useful to provide a better surface finishing to further reduce aluminium emissivity.

On the contrary, in the HVFPs case, the substrate emittance of the uncoated side can play an important role in determine the radiation losses. Once a proper selective coating minimizes the thermal emittance of the solar absorber, the absorber overall efficiency can be significantly increased by using a very low emittance surface also on the uncoated side. Typical emissivity values for electropolished copper is 0.02 [33,34], whereas silver films have been reported having an emissivity as low as 0.01 [35]. Eq. 6 has been calculated also for an equivalent substrate thermal emittance of 0.02. Results are reported in Fig. 4b as dashed lines, confirming the importance of the uncoated side thermal properties to reach high temperatures with high efficiencies. In particular, choosing the proper cut-off and the proper substrate, it is possible to achieve absorber efficiency higher than 50% at temperature up to 280 °C or a stagnation temperature in excess of 400 °C. In particular, at 300 °C the overall efficiency increase from 20% of Mirotherm to 44 and 48% with optimized coatings on copper with a relative increase more than 100%.

3. Materials and methods

Multilayer SSAs consist of stacks of alternating dielectric layers (high absorptance in the visible range, transparent in the Infrared region) and metal absorption layers (thin enough to allow for partial transparency). Absorption is guaranteed by multiple reflections at interfaces, while spectrally averaged emissivity is mainly due to the low-emissive metal substrate (IR reflector) [17,30,36]. In this study a tri-layered structure has been investigated. A Titanium absorbing layer is sandwiched between two

Chromium Oxide (Cr_2O_3) dielectric layers on an Aluminium substrate acting as IR reflector. Al_2O_3 natural passivation layer of the Al substrate has been included in the numerical simulations model. The multilayer structure is completed by an antireflective coating (ARC) based on SiO_2 to further enhance solar absorption.

The complex refractive index of the materials used to simulate the solar selective absorber have been experimentally determined. The materials were deposited by e-beam evaporation on an aluminum film on glass substrate and their complex refractive index were experimentally estimated by ellipsometry measurement [37].

3.1. Samples preparation

The materials composing the multilayer solar absorber coatings were deposited onto smooth glass substrates (roughness 1 nm) using e-beam evaporation physical deposition technique. The glass slides were cleaned using soapy water and ultrasonic washing in acetone and isopropanol baths. Substrates temperature is monitored during the deposition process and it never exceeds 80 °C. The e-beam system used is equipped with a rotating planetary (Fig.5) that guarantees the samples thickness uniformity.



Figure 5. E-beam deposition system: glass substrates mounted on the rotating planetary

The evaporating materials are Al , (Cr_2O_3) and Ti pellets with a purity of 99.999% . Prior to depositions, the vacuum chamber is pumped down to a base pressure of 10^{-7} mbar and the materials are slowly outgassed to remove unwanted trapped gases (impurities). Evaporation rates were set on 2 Å/s for Al and Ti layers and on 1 Å/s for Cr_2O_3 layer. To facilitate optical studies all coatings have been deposited on aluminum coated glass substrates that have been exposed to air in order to obtain a reproducible Al_2O_3 natural passivation layer similar to that of the commercial aluminium rolls.

3.2. Samples characterization

Aluminium film thickness has been chosen to be optical opaque and fixed to 250 nm for all produced samples. The Cr_2O_3 and Ti layer thicknesses have been varied from 5 nm up to 200nm to study the possible influence of layer thickness on the optical properties. The film thickness was measured using a profilometer with an uncertainty lower than 2 nm and then confirmed by ellipsometric analysis. The refractive index of the coatings were investigated using a phase modulated spectroscopic ellipsometer (UVISSEL by Jobin Yvon Horiba). In the optical model the dispersion of the Cr_2O_3 was assumed to follow a dispersion relation based on Forouhi-Bloomer formulation [38], while for Titanium a classical Drude dispersion model was used. For Aluminum, Al_2O_3 and SiO_2 layers literature data have been used [39–41] since from optical analysis they proved to fit well experimental data. Fig. 6 a) and b) reports the refractive index obtained by the characterization procedure and used in the numerical simulation of the multilayer solar absorber coating.

Before proceeding with the multilayer optimization we have verified that the measured refractive indices and the numerical simulation program provide the correct multilayer optical response. Numerical simulations have been performed using IMD software [42], which allows to estimate the optical response of a multi-layer structure. We have simulated a multilayer on an aluminium substrate with the following layer thicknesses: 70/10/70nm and we have deposited, by e-beam evaporation, a multilayer with the same layer thicknesses on aluminium on glass substrate. In Fig. 6c) we report the numerical simulation and the experimental measurements showing the good agreement. The experimental optical response of the produced multilayer has been measured using an integrating sphere and an Optical Spectrum Analyzer (OSA) from 400nm up to 1700nm and by a FTIR from 1200nm up to 20μm using a FTIR. The almost perfect agreement in the overlapping region confirms the measurement quality.

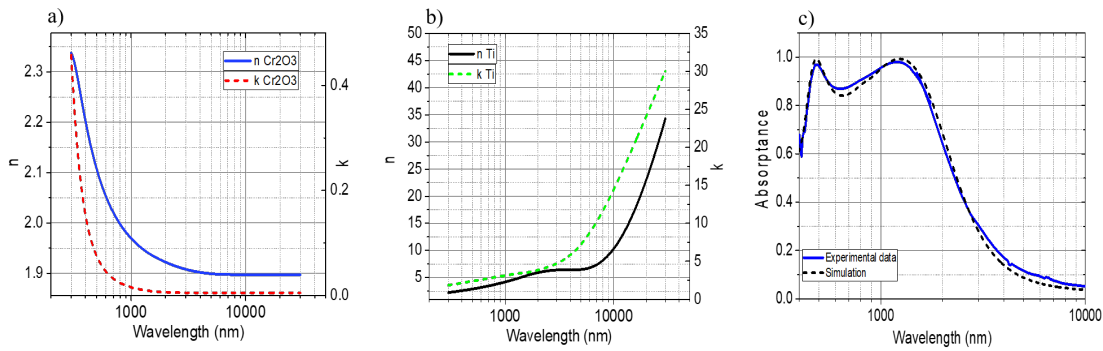


Figure 6. a) and b) Complex refractive index for Cr_2O_3 and Ti respectively: real part n on the left axis, imaginary part k on the right axis. c) Emissivity curve of $Cr_2O_3/Ti/Cr_2O_3$ multilayer: experimentally measured absorbance (blue line) and numerical simulation (black dotted line)

3.3. Optimization procedure

A genetic algorithm is used to adjust layer thicknesses in order to fit a target curve. The genetic algorithm creates a starting population of individuals (in our case multilayers with different layer thicknesses) and a Figure of Merit (FOM) is determined; only individuals with best FOM will be retained. FOM function is defined as follows :

$$FOM = \frac{\sum_{i=1}^{N_{mo}} w[i] \cdot |Y[i] - Y_{mo}[i]|^n}{\sum_{i=1}^{N_{mo}} w[i]} \quad (3)$$

where $w[i]$ is the weighting factor for the i^{th} point, $Y[i]$ is the value of the function being optimized for the i^{th} point, $Y_{mo}[i]$ is the value of the target function for the i^{th} point. $\Delta(FOM)/FOM < \zeta$ (with ζ the convergence tolerance value) determines the convergence of the algorithm. $\Delta(FOM) = < FOM > - FOM$ and the quantity $< FOM >$ corresponds to the average of FOM over the previous X generations of individuals. The exponent n is used to compute the FOM itself and has to be specified: in our simulations we set n to be 2.

As a target function (Y_{mo}) we used the spectral emissivity curve of an ideal selective solar absorber with a temperature dependent $\lambda_{cut-off}$ defined as in [11]. Y functions, representing individuals spectral emissivity curves, are calculated by optical simulations once multi-layer materials thicknesses are fixed. Solar absorptance and temperature dependent thermal emittance (also referred as spectrally averaged emissivity) are then calculated from the spectral emissivity curves as in the following eqs. 4 and 5:

$$\alpha_s = \frac{\int \varepsilon(\lambda) \cdot S_{Sun}(\lambda) d\lambda}{\int S_{Sun}(\lambda) d\lambda} \quad (4)$$

$$\varepsilon(T) = \frac{\int \varepsilon(\lambda) \cdot E_{bb}(\lambda, T) d\lambda}{\int E_{bb}(\lambda, T) d\lambda} \quad (5)$$

with S_{Sun} and E_{bb} being the solar spectral irradiance and the blackbody radiation, respectively and the integral is calculated in the wavelength regions where $S_{Sun}(\lambda)$ and $E_{bb}(\lambda, T)$ are different from zero.

3.4. The Mini-Test-Box set-up

The MTB experimental set-up consists of a stainless steel high-vacuum chamber, closed by an extra-clear float glass, which can host a flat absorber suspended by four springs of negligible thermal conductivity. The MTB has been numerically simulated using Comsol Multiphysics [36]. The experimental data were obtained illuminating the absorber with different light power using a calibrated LED illumination system described in [42] and recording the absorber stagnation temperature [32]. In such configuration the power losses are equal to absorbed power $\varepsilon(T_{AS}) \cdot \sigma_{SB}(T_{AS}^4 - T_{amb}^4) + \varepsilon_{Sub} \cdot \sigma_{SB}(T_{AS}^4 - T_{amb}^4) = \tau_{Glass} \alpha_{LED} P_{LED}(T_{AS})$, where α_{LED} is the absorptance α evaluated as in eq. 4, where the solar spectrum is replaced by the spectrum of the LED lump used to illuminate the absorber [42], $P_{LED}(T_{AS})$ is the light power provided by the calibrated LED system and T_{AS} is the absorber stagnation temperature at the given LED power. As consequence, at $T = T_{AS}$ the efficiency can be calculated, as reported below:

$$\eta(T) = \tau_{Glass} \cdot \alpha_S - \frac{\tau_{glass} \cdot \alpha_{LED} \cdot P_{LED}(T_{AS})}{P_{inc}} \quad (6)$$

where P_{inc} is Sun irradiated power set to 1000 Wm^{-2} , $\tau_{glass} = 0.91$, $\alpha_S = 0.95$.

4. Conclusion

We have optimized a selective solar absorber for mid-temperature operations in a high-vacuum flat solar thermal panel based on $\text{Cr}_2\text{O}_3/\text{Ti}/\text{Cr}_2\text{O}_3$ trilayer on metallic substrate. Our results show that a reduction in spectrally averaged emissivity is essential to reach high operating and/or high stagnation temperatures in HVFP. Once the thermal emittance of the selective absorber has been optimized, the overall absorber performances can be further improved using a very low emittance material such as copper (or silver) on the absorber back side, allowing to reach operating temperature up to 300°C , with overall coating efficiency of 48% with a 140% improvement respect to the commercial coating. The stagnation temperature can also be increased from 320°C to more than 400°C without concentration. Such performances confirm that the HVFP can be the most efficient system to convert the solar energy in heat at temperature up to 250°C and they will allow to HVFP to contribute to the energy transition from fossil fuels to renewable energy for efficient heat production.

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Conflicts of Interest: The authors declare no conflict of interest

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