

Article

Solar Selective Absorber Coating with Ag Infrared Reflector for Receiver Tubes Operating at 550 °C

Salvatore Esposito ¹, Antonio D'Angelo ¹, Claudia Diletto ¹, Gabriella Rossi ¹, Raffaele Volpe ¹,
Antonio Guglielmo ¹, Anna De Girolamo Del Mauro ¹, Claudia Prestigiacomo ² and Michela Lanchi ^{3,*}

¹ Portici Research Centre, Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), P.le E. Fermi 1, 80055 Portici, Italy; anna.degirolamo@enea.it (A.D.G.D.M.)

² Dipartimento di Ingegneria, Università degli Studi di Palermo, Viale delle Scienze Ed. 6, 90128 Palermo, Italy; claudia.prestigiacomo01@unipa.it

³ Casaccia Research Centre, Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), Via Anguillarese 301, S. Maria di Galeria, 00123 Rome, Italy

* Correspondence: michela.lanchi@enea.it; Tel.: +39-(0)6-3048-3292

Abstract: The present work introduces a new solar selective absorber coating (SSAC) for the receiver tube of Concentrated Solar Power (CSP) systems, proposing silver as an infrared reflector for application at 550 °C. In the past, the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) has developed SSACs suitable for applications at 550 °C, featuring solar absorbers based on graded multilayer cermet of WN-AlN and W-Al₂O₃ and an infrared reflector of tungsten. Although these coatings ensured properly stable photothermal performance at 550 °C, due to the low tungsten diffusivity, their hemispherical emittance could be reduced by using metals with higher reflectance in the infrared region, like silver. However, the high diffusivity of silver compromises its use at high temperatures. This last drawback has been addressed by foreseeing two stabilizing layers enclosing the Ag infrared reflector. One W stabilizing layer was placed between the substrate and the Ag infrared reflector, whereas a second stabilizing layer, selected among aluminum nitride deposited with a low and high nitrogen flow and aluminum oxide deposited at a low oxygen flow, was placed between the Ag infrared reflector and the solar absorber. Accelerated aging tests revealed a negligible (not detectable) degradation of the solar absorptance for the new SSACs. Furthermore, the hemispherical emittance at 550 °C increased by 0.75% and 0.42% for solar coatings with aluminum nitride stabilizing layers deposited through a high and low nitrogen flow, respectively. Differently, the increase was evaluated as being equal to 0.08% for the solar coating with an aluminum oxide stabilizing layer deposited through a low oxygen flow. The manufactured solar coating with a stabilizing layer of aluminum nitride deposited with a low nitrogen flow exhibited a solar absorptance of 95%, comparable to ENEA coatings incorporating a W infrared reflector for applications at 550 °C, whereas the estimated hemispherical emittance at 550 °C was 2% lower than that of the best ENEA coating with a W infrared reflector for the same temperature.

Keywords: solar coating; infrared reflector; stabilizing layer; thermal stability; hemispherical emittance; concentrated solar thermal technology



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1. Introduction

CSP technology is widely regarded as a key player in the future of clean energy. Indeed, CSP plants with storage are particularly promising thanks to their inherent generation dispatchability and flexibility, which are not attainable with other renewable energy

technologies. These advantages enable CSP technology to support the penetration of higher shares of renewables in the European energy system despite currently facing higher generation costs than other renewable technologies [1,2]. According to the International Energy Agency (IEA), CSP technology could cover 11.3% of global electricity demand by 2050, with appropriate government support [3]. Extensive research on various technical aspects has been conducted using CSP technology over the years. Currently, the research effort is mainly devoted to the improvement of the overall plant efficiency and to the reduction of costs; in this regard, the increase in stability and durability of each plant component (at least 25 years) is a crucial requirement to limit the impact of operating/maintenance and investment [4]. The broad spectrum of CSP encompasses four primary technologies: parabolic trough collectors (PTCs), linear Fresnel reflectors (LFRs), solar power towers (SPTs), and parabolic dish collectors (PDCs) [5]. Particularly, in PTCs and LFRs plants, linear focusing collectors utilize large mirrors to reflect and concentrate sunlight onto a linear receiver tube. The SSACs deposited on the receiver tube significantly affect the overall efficiency of the system. An ideal SSAC should exhibit a high solar absorptance (α_s), low hemispherical emittance (ϵ_h), and high thermal stability at the operating temperature [6]. Typically, an SSAC comprises a multilayer structure incorporating one or more solar absorber layers positioned between a metallic layer (infrared reflector) and one or more ceramic layers (anti-reflection filter). To minimize thermal losses and protect metallic components from oxidation at operating temperatures typically below 400 °C in commercial applications, SSAs operate under vacuum (10^{-2} Pa). In these systems, thermal oil typically serves as the heat transfer fluid (HTF).

A significant advancement was achieved in the early 2000s with ENEA's introduction of molten salt technology for linear CSP plants. This technology was subsequently scaled up through the Archimedes project [7], enabling the achievement of an HTF working temperature of 550 °C at the solar field outlet. The increase in the plants' operating temperatures has resulted in the enhancement of the heat-to-electricity conversion efficiency, consequently leading to a reduction in the electricity cost [8–10]. Furthermore, the plants' capability to store large amounts of thermal energy within low-cost molten salt tanks enables generating electricity on demand, overcoming the dependence of renewable sources on intermittent source availability.

Over the past two decades, ENEA's research effort has been focused on improving the photothermal efficiency and thermal stability of SSACs operating at 550 °C. The solar absorbers of these SSACs are produced using metal–ceramic (cermet) composite materials, following a widely employed approach to obtain SSACs for medium- and high-temperature applications [11–16]. Among the deposition technologies of the cermet-based SSACs, magnetron sputtering has proven particularly well-suited for fabricating SSACs with the desired requirements [17–27]. This technology allows highly accurate control over the size and quantity of metallic and ceramic particles within the composite materials. Furthermore, this technology is particularly suitable for industrial production thanks to its capability to deposit on a large area at a high rate and low cost [28,29].

The first SSAC with relevant photothermal performance and good durability was patented by ENEA in 2011 [28]. The solar absorber of this SSAC was deposited using ENEA's double nitride cermet technology: specifically, a graded multilayer cermet of tungsten nitride and aluminum nitride (WN-AlN) was placed between an infrared reflector of tungsten (W) and an anti-reflection filter of aluminum nitride (AlN), silica (SiO₂) and WN-AlN cermet with low content of WN. Tungsten was selected as the infrared reflector for high-temperature SSACs thanks to its good infrared reflectance, structural and chemical–physical stability under vacuum, strong adhesion to stainless steel (SS) substrates, low elemental diffusion toward the neighboring layers and effective barrier property

against the diffusion of elements from SS substrates. The photothermal parameters of this SSAC, namely α_s and ϵ_h at 550 °C, were equal to 95% and 10.5%, respectively, whereas the degradation after 25 years of service at 550 °C was equal to 1.65% for α_s and not detectable for ϵ_h at 550 °C [30]. Further improvements of the SSAC for high-temperature applications were obtained in the framework of the Italian “National Electric System Research” Program, Project 1.9 “CSP/CST technology”, 2019–2021 implementation plan. The solar absorber of the SSAC developed in this project comprised a graded multilayer cermet of tungsten and alumina (W-Al₂O₃), positioned between an infrared reflector of W and an AR filter of Al₂O₃, SiO₂, and W-Al₂O₃ cermet with a low metallic content [31]. In this case, the enhancement of the photothermal parameters was very limited: α_s was practically unchanged, while ϵ_h was slightly reduced from 10.5% to 9.9%. However, a more significant improvement was observed in thermal stability. This can be attributed to the confirmed invariance of ϵ_h and a degradation of α_s equal to 0.48% after a lifetime of 25 years [32]. This SSAC can be considered the reference ENEA SSAC for applications at 550 °C, featuring a W infrared reflector and a cermet-based solar absorber.

To improve the photothermal performance of high temperatures SSACs with cermet-based solar absorbers, metals exhibiting higher infrared reflectance than tungsten were investigated to minimize SSAC hemispherical emittance. In 2011, ENEA developed the first SSAC with a silver (Ag) infrared reflector capable of operating under vacuum up to 463 °C [33]. The Ag infrared reflector was grown on a W layer to exploit the tungsten barrier property and improve the structural and chemical–physical stability of the Ag layer, as well as its adhesion on the SS substrate [34]. Solar energy absorption was maximized by a graded multilayer cermet of WN-AlN, whereas solar radiation reflection was minimized by a filter composed of AlN, SiO₂, and WN-AlN cermet with low content of WN. In 2021, ENEA developed a second SSAC design, with a Ag infrared reflector featuring high structural and chemical stability under vacuum up to 514 °C [33]. This new SSAC was deposited using high-energy processes, enabling the growth of compact and uniform W and W-AlN cermet layers beneath and above the Ag infrared reflector, respectively. The SSAC was completed with an anti-reflection filter based on AlN, SiO₂, and W-AlN cermet with low metallic content.

The aim of the present work is to increase the long-term thermal stability of SSACs with Ag infrared reflectors up to 550 °C while maintaining excellent photothermal performance. To further raise the operating temperature of the SSAC up to 550 °C, two stabilizing layers were placed beneath and above the Ag infrared reflector. One stabilizing layer of W was positioned between the substrate and the Ag infrared reflector, whereas eight stabilizing materials were considered and tested between the Ag infrared reflector and the solar absorber. Specifically, six of the eight stabilizing layers were selected from ceramic materials known for their proven structural stability under vacuum at 550 °C and their transparency in the relevant spectral range. These included two AlN_x deposited using a low and high nitrogen (N₂) flow; three silicon nitrides (SiN_x) deposited using a low, medium, and high N₂ flow; and one Al_xO_y deposited using a low O₂ flow. Moreover, two W-AlN cermet layers were added as stabilizing layers on the Ag infrared reflector, the first and second one with low and medium metal content, respectively. The SSACs were completed with a graded multilayer cermet of W-AlN and an anti-reflection filter based on AlN and SiO₂ ceramics in combination with a W-AlN cermet material with a low metal content. The thermal stability of the eight SSACs was experimentally evaluated through accelerated aging tests conducted in a programmable oven capable of operating up to 1000 °C and at a pressure of 2×10^{-2} Pa [33]. Finally, a single SSAC was selected and fabricated from those demonstrating stability at 550 °C for a projected 25-year service life.

2. Materials and Methods

2.1. Magnetron Sputtering System

Metallic, ceramic, and cermet films of SSACs were deposited on planar glass or SS substrates by magnetron sputtering using a planar magnetron sputtering system equipped with a load lock chamber and a process chamber. The substrates were fixed inside housings on the external surface of an SS tube ($L = 60$ mm, $D = 7$ mm), which was mounted on a tube holder in the load lock chamber. Plasma and heating pre-treatments were carried out on substrates in the load lock chamber by rotating the tube with an adjustable spin velocity (ω).

After the pre-treatments, the tube holder was transferred into the process chamber for the deposition of the SSAC materials. Six cathodes were arranged in pairs on two opposite sides of the process chamber. Specifically, a Genco unbalanced magnetron cathode and two standard magnetron cathodes were used to deposit the metallic materials on the substrates. This was achieved by oscillating the tube holder back and forth in front of the cathodes with an adjustable sweep velocity (v) and simultaneously rotating the tube holder with an adjustable spin velocity. Similarly, the ceramic materials were deposited by three dual magnetron cathodes mounted on the opposite side of the previous three cathodes. Finally, the simultaneous deposition of metallic and ceramic materials by co-sputtering mode enabled the fabrication of cermet materials. The deposition plant was also equipped with a Plasma Emission Monitoring (PEM) system (PLASUS, GmbH Company equipment, Mering, Germany) featuring six independent spectrometric channels. The complete spectrum of the plasma light emission was continuously acquired by optical fibers within the wavelength range of 200–1100 nm. Each dual magnetron cathode was monitored by two optical fibers, one for each plasma region facing the two cathodes of the dual magnetron. The PEM system had a rapid feedback control, effectively mitigating sputtering process instabilities.

2.2. Sputtering Mode

The new SSAC structure incorporates a Ag infrared reflector placed between two stabilizing layers, which block the Ag elemental diffusion to and from the adjacent layers. A first stabilizing layer of W was deposited between the substrate and the Ag infrared reflector, whereas a second stabilizing layer was grown on the Ag infrared reflector. On the second stabilizing layer, a graded multilayer cermet of W-AlN was grown to absorb solar radiation, and then an anti-reflection filter composed of AlN, SiO₂, and W-AlN cermet with low metal content was deposited to minimize solar radiation reflection.

A Genco unbalanced magnetron cathode in Direct Current (DC) sputtering mode was used to deposit a compact structure and low defects W layer [33]. A standard magnetron cathode in DC sputtering mode was employed for the deposition of the Ag infrared reflector on the W layer.

Hence, eight stabilizing materials were deposited on the Ag layer: two AlN_x layers, three SiN_x layers, one Al_xO_y ceramic layer, and two W-AlN cermet layers with low and medium metal content, respectively. Dual magnetron cathodes were used to deposit the ceramics with Medium Frequency (MF) reactive sputtering in transition or poisoned mode [35]. The two W-AlN cermet layers were deposited in co-sputtering mode; specifically, the unbalanced magnetron cathode was employed for the W deposition in DC mode, while the dual magnetron cathodes arranged on opposite sides were employed to deposit AlN with MF reactive sputtering in transition mode. The graded multilayer cermet of W-AlN and the cermet of the anti-reflection filter were deposited using the same mode adopted for the fabrication of the stabilizing cermet layers. Finally, AlN and SiO₂ of the anti-

reflection filter were deposited by dual magnetron cathodes with MF reactive sputtering in transition mode.

2.3. Materials Preparation and Methods for Thermal Stability Analysis

Two different sets of samples were deposited. The first set was used for the optical design of eight SSACs and subsequent thermal stability studies. The second set was used for the optical design of a single SSAC, which was selected from those demonstrating stability at 550 °C for a projected 25-year service life, with optimized photothermal performance. The first set of samples consists of single layers of materials deposited on Eagle XG glass substrates. These materials were grown under conditions significantly different from those employed during the coating deposition. Consequently, the estimation of their optical parameters was not accurate enough to fabricate SSACs with optimized photothermal performance. Considering that SSACs with good photothermal performances are sufficient for thermal stability studies, this procedure was preferred due to its simplicity and rapidity in sample preparation and optical characterization. Conversely, for the second set of samples, each material was deposited under conditions closely replicating those employed in the coating fabrication. This approach, though experimentally demanding and time-consuming, was essential for achieving the accuracy required to fabricate SSACs with optimal photothermal performance.

In this section, the procedure developed to prepare samples of the first set is described. The first structure was deposited on a glass substrate for the estimation of the optical parameters of the infrared reflector. Three consecutive pre-treatments were carried out on the glass substrate in the load lock chamber, namely ionic etching, heating, and electronic etching, whose process parameters are reported in Table 1. The ionic and electronic etching were carried out in argon (Ar) plasma, whereas the heating was carried out under vacuum by means of thermal radiation from three electrical resistances.

Table 1. Process parameters for the substrate pre-treatments.

Parameter	Ionic Etching	Heating	Electronic Etching
DC voltage (V)	3000		
Temperatures of the three resistances (°C)		480, 490, 490	
DC current (mA)			3000
Ar flow (sccm)	200		200
Ar plasma pressure (Pa)	2.5		1.5
Spin velocity of tube (rpm)	20	60	60
Process duration (min)	10	30	10

After the pre-treatments, the tube holder was transferred into the process chamber for the materials deposition. The W layer was grown in Ar plasma generated by a gas flow (Φ) of 100 sccm injected into the process chamber from the gas ring around the W target. Process pressure (p) was fixed at about 0.4 Pa, and the power density (S) applied to W target was 13.33 W/cm². For this deposition, v was fixed at 50 cm/min, while ω was fixed at 15 rpm. On the W layer, a Ag infrared reflector was grown in Ar plasma generated by a gas flow of 200 sccm and injected into the process chamber from the gas ring around the Ag target. The deposition was carried out with power density applied to Ag target of 4.13 W/cm² and at Ar pressure of 1 Pa. V and ω were fixed at 200 cm/min and 30 rpm, respectively.

Hence, six ceramic and two cermet stabilizing materials were deposited onto glass substrates for the estimation of their thicknesses and optical parameters. The process parameters adopted for the fabrication of each stabilizing layer are reported in Table 2. Two AlN_x stabilizing layers were deposited in Ar + N₂ plasma. The first AlN_x stabilizing

layer, named AlN_{HF} , was deposited using MF reactive sputtering in poisoned mode [35]. During the deposition of the ceramic sample, a nitrogen flow of 50 sccm was injected into the process chamber to poison the surfaces of the Al targets. This deposition process was characterized by a low sputtering rate, and the ceramic produced was nitrogen-rich. The second AlN_x stabilizing layer, named AlN_{LF} , was deposited on glass substrate with MF reactive sputtering in transition mode. Since the optical properties of the AlN_{LF} layer strongly depend on the target conditions, which in turn are extremely sensitive to the quantity of reactive gas injected in the process chamber, the PEM system controlled the intensity of the emission spectral line of the element selected as representative of the target conditions, increasing or decreasing the N_2 gas flow injected in the process chamber [33]. In order to obtain the AlN film with the expected stoichiometry, the Al emission spectral line was accurately controlled by adjusting the N_2 flow rate around 25 sccm, and the voltage measured at the Al targets was equal to 327 V.

Table 2. Process parameters for the deposition of the eight stabilizing materials.

Parameter	AlN_{HF}	AlN_{LF}	SiN_{HF}	SiN_{MF}	SiN_{LF}	Al_xO_y	$\text{W}_{\text{LS-AIN}}$	$\text{W}_{\text{MS-AIN}}$
S_{W} (W/cm^2)							0.67	1.56
S_{Al} (W/cm^2)	5.16	2.58				2.58	2.58	2.58
S_{Si} (W/cm^2)			1.29	1.29	1.29			
Φ_{Ar} (sccm)	400	400	400	400	400	400	400	400
Φ_{N_2} (sccm)	50	~25	~60	~40	~20		~30	~30
Φ_{O_2} (sccm)						22		
p (Pa)	1	1	1	1	1	1	1	1
ω (rpm)	60	60	60	60	60	60	60	60
v (mm/min)	1000	1000	1000	1000	1000	500	1000	1000

Three SiN_x stabilizing layers were deposited in Ar + N_2 plasma with low, medium, and high nitrogen content and named SiN_{LF} , SiN_{MF} , and SiN_{HF} , respectively. These stabilizing layers were grown on glass substrate using MF reactive sputtering in transition mode. The control was performed on the N emission spectral line by adjusting the N_2 flow rates around 20, 40, and 60 sccm for the SiN_x layers, with low, medium, and high nitrogen content, respectively.

Finally, the Al_xO_y stabilizing layer was deposited on a glass substrate using MF reactive sputtering in transition mode. The control was performed on the Al emission spectral line by adjusting the O_2 flow rate to around 22 sccm. In this case, low oxygen flow was used to avoid degradation of the Ag reflective properties.

Two W-AlN cermet layers with low and medium metal content were also added as stabilizing layers. These cermet layers were deposited using the same power density employed for depositing the AlN_x stabilizing layer in transition mode and low and medium power densities for depositing the metallic components of W. The N_2 gas was introduced in the process chamber from the gas ring around the Al targets and controlled by the PEM system to maintain unchanged the Al emission spectral line at the value that guaranteed a voltage at the Al targets equal to 327 V. This voltage was the same measured at the Al targets during the deposition of the AlN_{LF} stabilizing layer. In this case, the cermet layer with low power density was named $\text{W}_{\text{LS-AIN}}$, whereas the cermet layer with medium power density was named $\text{W}_{\text{MS-AIN}}$.

Five cermet materials were used to design the solar absorber. These materials were deposited on glass substrates for the estimation of their thicknesses and optical parameters. The materials were grown in Ar + N_2 plasma by using the process parameters in Table 3. The cermet materials were deposited with a sampling step of the power densities applied to the W target equal to $0.89 \text{ W}/\text{cm}^2$, whereas the other process parameters were equal to

those adopted for the deposition of the two W-AlN cermet stabilizing layers with low and medium metal content.

Table 3. Process parameters for the deposition of the W-AlN cermet layers used to design the solar absorbers of the SSACs for the study of thermal stability.

Parameter	W-AlN Cermet				
	C1 _{Glass}	C2 _{Glass}	C3 _{Glass}	C4 _{Glass}	C5 _{Glass}
S_W (W/cm ²)	4.00	3.11	2.22	1.33	0.44
S_{Al} (W/cm ²)	2.58	2.58	2.58	2.58	2.58
Φ_{Ar} (sccm)	400	400	400	400	400
Φ_{N_2} (sccm)	~30	~30	~30	~30	~30
p (Pa)	1	1	1	1	1
ω (rpm)	60	60	60	60	60
v (mm/min)	1000	1000	1000	1000	1000

As layers of the anti-reflection filter, the stabilizing layers of AlN_{LF} and W_{LS}-AlN were used, whereas a layer of SiO₂ was deposited on glass substrate to be optically characterized. This layer was grown in Ar + O₂ plasma by using the process parameters reported in Table 4. The O₂ gas was introduced in the process chamber from the gas ring around the Si targets, and the control was performed on the O emission spectral line by adjusting the O₂ flow rate to around 18 sccm.

Table 4. Process parameters for the deposition of the SiO₂ layer used to design the anti-reflection filter of the SSACs for the study of thermal stability.

Parameter	SiO ₂
S_{Si} (W/cm ²)	3.88
Φ_{Ar} (sccm)	200
Φ_{O_2} (sccm)	~18
p (Pa)	1
ω (rpm)	60
v (mm/min)	500

Refractive indexes n and extinction coefficients k of all materials were collected in a database for the successive step of SSAC design. The resulting design consisted of a sequence of layers with assigned thickness values and with a specific metal content profile for the graded multilayer cermet. Eight SSACs, one for each stabilizing layer, were manufactured according to the respective optical designs on SS substrates with a surface roughness closely matching that of the receiver tube and subsequently optically characterized to evaluate α_s and ε_h at 550 °C.

Finally, the SSACs were subjected to three accelerated aging tests, conducted under the operative conditions reported in Table 5, to estimate their structural and chemical stability through the modifications of α_s and ε_h at 550 °C, computed at regular intervals for each annealing temperature.

Table 5. Temperatures and durations of accelerated aging tests on SSACs.

Accelerated Aging Test	T [°C]	Duration [h]
#1	620	7344
#2	650	1632
#3	690	384

2.4. Materials Preparation for the SSAC Fabrication with Optimized Photothermal Performance

The second set of samples for the optical design and fabrication of the optimized SSAC were deposited on SS substrates with a surface roughness closely matching that of the receiver tube. Each SS substrate was subjected to the three consecutive pre-treatment processes in the load lock chamber described in Table 1. After the pre-treatments, the tube holder was transferred into the process chamber to deposit the SSAC layers. The sputtering technologies adopted for the deposition of the SSAC layers were the same as for the first set, as well as the process parameters, except for the sequence of the power densities applied to the W target for the deposition of the W-AlN cermet layers of the solar absorber and the power density applied to the W target for the deposition of the W-AlN cermet layer of the anti-reflection filter. On the pre-treated SS substrate, a W layer and a Ag layer were grown in sequence; subsequently, a stabilizing layer with a thickness expected to effectively stabilize the Ag infrared reflector was deposited to complete the structure. This structure was used to estimate the thickness of the stabilizing layer and the optical parameters of the Ag infrared reflector and the stabilizing layer. Next, the SS/W/Ag/stabilizing layer/C1_{SS} structure was manufactured to estimate the thickness and optical parameters of the C1_{SS} cermet layer. C1_{SS} was the first cermet layer of the solar absorber deposited with a thickness of a few nanometers, typical of a cermet layer in a graded solar absorber. Three different C1_{SS} cermet layers were deposited on the stabilizing layer to identify the W power density required to fabricate a solar absorber, with the first cermet layer exhibiting a higher metal content than the second. In this case, in order to obtain a first cermet layer with a higher metal content than the second one, it was not sufficient to apply a higher power density to the W target, as performed for the first set of samples: the metal content of the first cermet layer was lower near the interface with the stabilizing layer due to the initial interaction of the non-metal atoms of this layer with the metal atoms involved in the growth of the first cermet layer. The power densities applied to the W and Al targets to deposit the three C1_{SS} cermet layers are reported in Table 6.

Table 6. Power densities for the deposition of the W-AlN cermet layers used to design the solar absorber of the SSAC with optimized photothermal performance.

Cermet Layer of the Solar Absorber	S _W (W/cm ²)	S _{Al} (W/cm ²)
C1 _{SS}	6.67	2.58
C1 _{SS}	5.33	2.58
C1 _{SS}	4.00	2.58
C2 _{SS}	3.11	2.58
C3 _{SS}	2.67	2.58
C4 _{SS}	1.33	2.58
C5 _{SS}	0.89	2.58
C6 _{SS}	0.44	2.58

Three SS/W/Ag/stabilizing layer/C1_{SS}/C2_{SS} structures were deposited, one for each C1_{SS} cermet layer, and the power densities applied to the W and Al targets for the deposition of the C2_{SS} cermet layers are reported in Table 6. These structures were used to estimate the thicknesses and optical parameters of the three C2_{SS} cermet layers. By iterating the procedure, the structures for the estimation of thicknesses and optical parameters of the other cermet layers reported in Table 6 were fabricated. These cermet layers were deposited on the structure with C1_{SS} and C2_{SS} cermet layers that enabled the fabrication of a solar absorber composed of cermet layers with a graded metal content profile, progressively decreasing from the stabilizing layer toward the anti-reflection filter.

The anti-reflection filter of SSAC was fabricated by combining AlN and SiO₂ ceramics with a W-AlN cermet layer deposited using the same process parameters as the C6_{SS} cermet layer and

named C7_{SS}. The SS/W/Ag/stabilizing layer/C1_{SS}/C2_{SS}/C3_{SS}/C4_{SS}/C5_{SS}/C6_{SS}/AlN structure was fabricated for the estimation of thickness and optical parameters of the AlN layer. Hence, the SS/W/Ag/stabilizing layer/C1_{SS}/C2_{SS}/C3_{SS}/C4_{SS}/C5_{SS}/C6_{SS}/AlN/C7_{SS} structure was carried out for the optical characterization of the C7_{SS} cermet layer. Finally, the estimation of thickness and optical parameters of SiO₂ was performed by using the SS/W/Ag/stabilizing layer/C1_{SS}/C2_{SS}/C3_{SS}/C4_{SS}/C5_{SS}/C6_{SS}/AlN/C7_{SS}/SiO₂ structure.

2.5. Materials Characterization

The thickness of the samples deposited on glass substrate was mechanically measured using a Tencor P-7 surface profiler (KLA company, Milpitas, CA, USA).

The optical parameters of the materials of the first set, except for those of the Ag infrared reflector, were estimated by inversion method applied to the experimental optical reflectance and transmittance of the structures produced as specified in Section 2.3 [33]. Specifically, reflectance and transmittance were measured in the wavelength range 300–2500 nm by using a double-beam LAMBDA 1050+ UV/VIS/NIR spectrophotometer (PerkinElmer, Shelton, CT, USA) equipped with a 15 cm diameter integrating sphere.

The ellipsometric technique was used to estimate the optical parameters of the Ag layer of the first set and to estimate the optical parameters and thickness of each material of the second set. The ellipsometric measurements were acquired from the structures produced as specified in Sections 2.3 and 2.4 by a Variable Angle Spectroscopic Ellipsometer (J. A. Woollam Company, Lincoln, NE, USA), which is able to operate in the wavelength range 300–2500 nm.

The reflectance of the SSACs for the photothermal performance estimation was measured in the wavelength range 300–2500 nm by the LAMBDA 1050+ UV/Vis/NIR spectrophotometer and in the wavelength range 1700–16,000 nm by an INVENIO X FTIR (Fourier Transform Infrared) spectrometer (Bruker, Ettlingen, Germany) equipped with an MCT detector and a 7.5 cm diameter integrating sphere, coated with diffuse reflecting gold.

SEM and EDX analyses were carried out using an LEO mod.1530 (Carl Zeiss SMT GmbH, Oberkochen, Germany) equipped with an INCA EDX analyzer (Oxford Instruments, Halifax, UK) including a PentaFET precision laboratory equipment. Cross-sectional SEM analysis was carried out through a QUANTA 200 (FEI, Hillsboro, OR, USA).

X-ray diffraction (XRD) analysis was carried out using a X' PERT PRO MRD diffractometer (Philips Panalytical, Almelo, Netherland) working with CuK α radiation ($\lambda = 1.54059 \text{ \AA}$). The measurements were collected through the glancing incidence configuration to obtain high sensitivity to the film structure and using a scan range of 10–90° (2 θ).

Finally, the lifetime prediction of the SSACs was estimated by subjecting them to three accelerated aging tests in a programmable furnace (Carbolite, Hope, UK) capable of operating up to 1000 °C at a pressure of 2×10^{-2} Pa.

3. Results and Discussion

The experimental work described here was finalized to manufacture SSACs with Ag infrared reflectors thermally stable up to 550 °C and with excellent photothermal performance. Although Ag infrared reflectors can effectively reduce the hemispherical emittance at high temperatures of SSACs, their adhesion to SS substrate and their ability to mitigate the diffusion of elements from the SS substrate significantly degrade increasing temperature. Moreover, Ag is subject to structural modifications such as crystalline reorientation and grain coalescence, which are strongly dependent on temperature and can compromise the structural stability of SSACs. Finally, the high diffusion coefficient of the Ag atoms causes variation in the composition of the adjacent layers with consequent deterioration of the optical properties of the infrared reflector and solar absorber. This chemical–physical

instability intensifies with increasing temperature. Despite these limitations, silver can be used as an infrared reflector in high-temperature SSACs for extended periods when placed between two stabilizing layers. One W stabilizing layer was positioned between the SS substrate and the Ag infrared reflector, whereas eight materials were tested as stabilizing layers between the Ag infrared reflector and the cermet-based solar absorber. The multilayer structure proposed for a high-temperature SSAC is the following:

SS/W stabilizing layer/Ag/stabilizing layer/graded cermet (W-AlN)/AR filter (AlN, W-AlN cermet with low metal content, SiO₂).

Eight SSAC multilayer structures were designed and deposited according to the method described in the previous section. These structures were subsequently subjected to accelerated aging tests to evaluate their structural and chemical stability. Subsequently, among the SSACs demonstrating thermal stability up to 550 °C for at least 25 years, only one SSAC was selected to be manufactured with optimized photothermal performance.

3.1. Durability Study

In this section, the activity carried out to predict the lifetime at 550 °C of eight SSACs is described. The eight SSACs were manufactured and subjected to accelerated aging tests in a programmable oven for the estimation of photothermal parameter degradation. The infrared reflector of these SSACs was a 120 nm thick Ag layer deposited according to the operative conditions specified in Section 2 on a W stabilizing layer of equal thickness. The W layer was chosen due to its good structural and chemical–physical stability, strong adhesion to the SS substrate, low elemental diffusion toward the neighboring layers, and effective capacity to block the diffusion of migrant elements from the SS substrate, especially when used as an infrared reflector at the operating temperature of 550 °C [30]. Moreover, the adhesion on the SS substrate, as well as the structural and chemical stability of the Ag layer, are improved when it is deposited on the W stabilizing layer [34]. The optical characterization, performed by the ellipsometric technique applied to the Ag layer deposited on the glass/W structure, provided spectral *n* and *k* values by applying the equation of the pseudo-dielectric function [36] coincident with the actual dielectric function. This approach is valid when the Ag thickness is sufficiently high to neglect the optical reflection at the W/Ag interface.

Eight layers were placed between the infrared reflector and the cermet-based solar absorber to test their ability to improve the structural and chemical–physical stability of the Ag layer by blocking the diffusion of the Ag atoms toward the upper layers and acting as an adhesion layer for the cermet-based solar absorber. Six ceramics and two cermet layers were deposited as stabilizing layers on glass substrates and optically characterized according to the operative conditions specified in Section 2. Figure 1 displays the thickness and deposition rate of the eight stabilizing layers, whereas Figure 2 shows the corresponding optical parameters.

Regarding the selection of stabilizing materials, the ceramics were selected for their proven structural stability under vacuum at high temperatures and preferred as barrier layers since they form dense and compact layers with minimal defects when deposited through reactive sputtering. As a drawback, thermo-mechanical stresses can arise in the SSAC structure due to the insertion of ceramic layers with thermal expansion coefficients lower than those of the adjacent metal and cermet layers. A possible alternative solution to mitigate this thermo-mechanical mismatch is represented by the use of two W-AlN cermet layers to be added as stabilizing elements, the first and second one with low and medium metal content, respectively. These stabilizing layers could ensure better thermomechanical compatibility with the adjacent metallic and cermet layers thanks to their higher thermal expansion coefficients than those of the ceramic layers. Moreover, the low metal content

of these cermet layers results in properties very close to that of ceramics, with benefits in terms of compactness and low defect density.

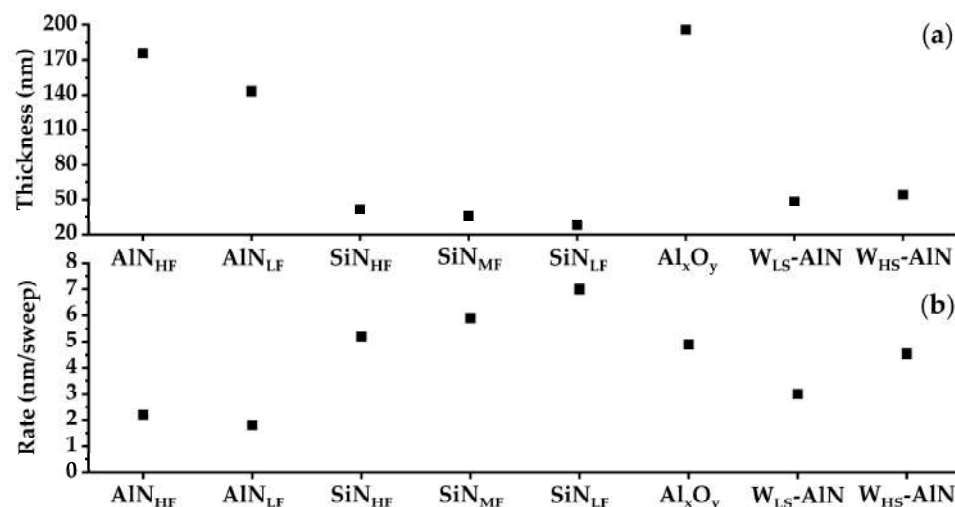


Figure 1. Thickness (a) and deposition rate (b) of the eight stabilizing materials used to design the SSACs for the study of thermal stability.

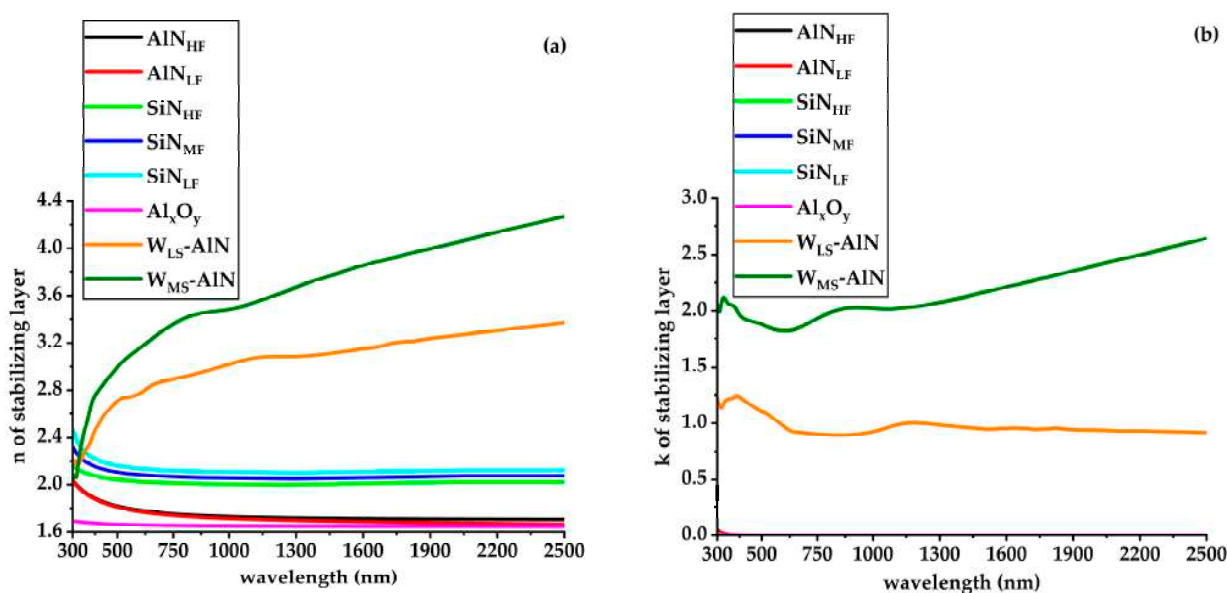


Figure 2. Optical parameters of the eight stabilizing layers used to design the SSACs for the study of thermal stability: (a) refractive index; (b) extinction coefficient.

Figure 3 shows the thickness and deposition rate of the five cermet materials that were deposited on a glass substrate and optically characterized for the optical design of solar absorbers. The process developed by ENEA for the deposition of W-AlN cermet samples employs different power densities to grow the metallic component and the same power density to deposit the ceramic component. An interpolation method was used to compute the deposition rate and optical parameters of the non-deposited cermet materials, which had an intermediate W power density between the values in Table 3. These additional cermet materials completed the database to design the solar absorbers of the SSACs for the thermal stability study.

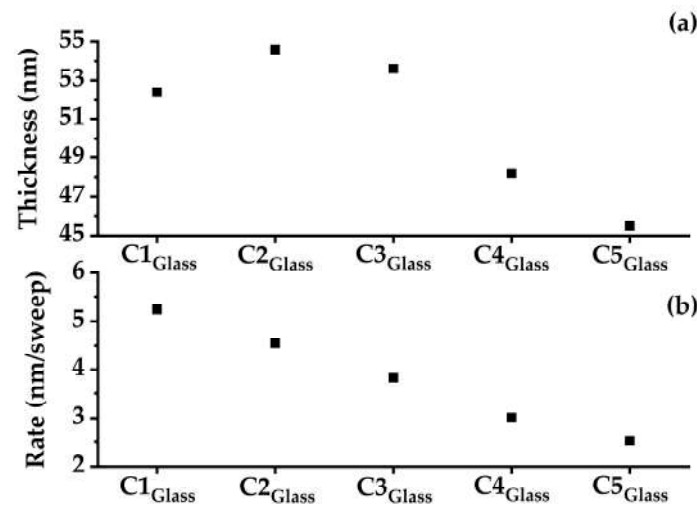


Figure 3. Thickness (a) and deposition rate (b) of the five cermet layers deposited to design the solar absorbers of the SSACs for the study of thermal stability.

Finally, the deposition rate and optical parameters of AlN, SiO₂, and W-AlN cermet material with low metal content were estimated for the optical design of the anti-reflection filter. Specifically, only a 168.4 thick SiO₂ layer was grown on a glass substrate with an 8.4 nm/sweep deposition rate and was optically characterized according to the operative conditions specified in Section 2. Regarding the other two materials, the deposition rate and optical parameters of the stabilizing layers of AlN_{LF} and W_{LS}-AlN cermet material were used for the optical design of the anti-reflection filter.

The refractive Index and extinction coefficient of each material were used to create a database that was imported into Essential Macleod (Version 9.9.457/Manufacturer Thin Film Center Inc., Tucson, AZ, USA), a commercial software for the optical analysis of multilayer structures. This software was used to design two distinct SSACs, one for the six ceramic stabilizing layers and the other for the two cermet stabilizing layers. Table 7 reports the optical designs formulated to fabricate the SSACs with the ceramic stabilizing layers, whereas Table 8 shows the optical designs developed to fabricate the SSACs with the cermet stabilizing layers.

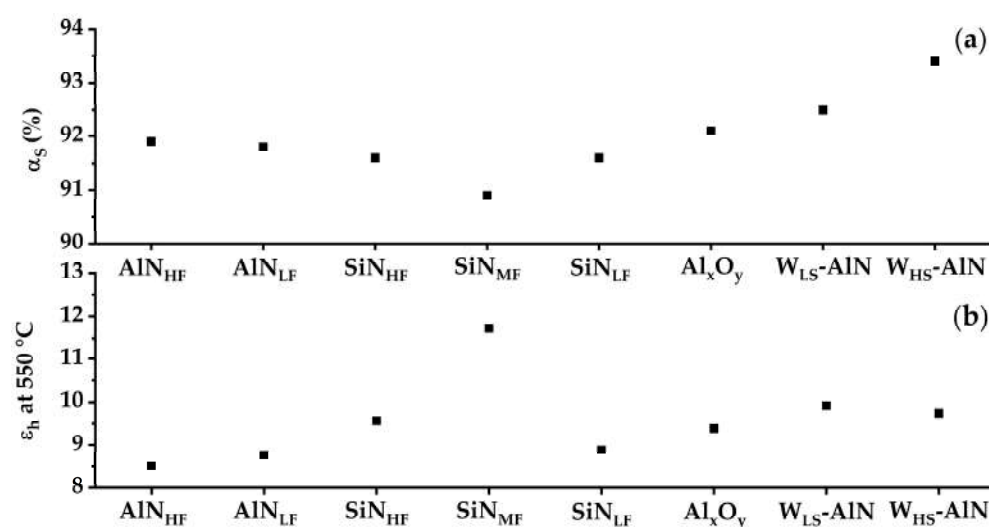
Table 7. Optical design of the six SSACs with ceramic stabilizing layers for the study of thermal stability.

Material	Power Density (W/cm ²)	Thickness (nm)
W	13.33	120
Ag	4.13	120
AlN _{HF} , AlN _{LF} , SiN _{HF} , SiN _{MF} , SiN _{LF} , Al _x O _y	5.16, 2.58, 1.29, 1.29, 1.29, 2.58	22.0, 21.6, 20.8, 23.6, 21.0, 19.6
Cermet 1 (W, AlN)	(2.67, 2.58)	8.38
Cermet 2 (W, AlN)	(2.44, 2.58)	8.01
Cermet 3 (W, AlN)	(2.22, 2.58)	7.66
Cermet 4 (W, AlN)	(1.78, 2.58)	6.84
AlN	2.58	28.8
Cermet 5 (W, AlN)	(0.67, 2.58)	10.6
SiO ₂	3.88	100.8

The eight structures in Tables 7 and 8 were manufactured on SS substrate with a surface roughness closely matching that of the receiver tube. The reflectance of each structure was measured for the photothermal performance estimation as specified in Section 2. Figure 4 reports α_s and ϵ_h at 550 °C for each fabricated SSAC sample.

Table 8. Optical design of the two SSACs with cermet stabilizing layers for the study of thermal stability.

Material	Power Density (W/cm ²)	Thickness (nm)
W	13.33	120
Ag	4.13	120
W _{LS} -AlN, W _{MS} -AlN	(0.67, 2.58), (1.56, 2.58)	21.07, 22.75
Cermet 1 (W, AlN)	(2.22, 2.58)	7.66
Cermet 2 (W, AlN)	(2.00, 2.58)	7.25
Cermet 3 (W, AlN)	(1.78, 2.58)	6.84
Cermet 4 (W, AlN)	(1.33, 2.58)	6.01
AlN	2.58	28.8
Cermet 5 (W, AlN)	(0.67, 2.58)	10.6
SiO ₂	3.88	100.8

**Figure 4.** α_s (a) and ϵ_h at 550 °C (b) of the eight SSACs with stabilizing layers fabricated for the study of thermal stability.

For the subsequent evaluation of the long-term thermal stability of the eight SSACs, ENEA has developed an investigation method derived from the main guidelines of the standard procedure to assess the thermal stability of hot water systems [30]. This method correlates the chemical, physical, and structural modifications of SSAC with the degradation of some parameters, such as solar absorptance, hemispherical emittance, and photothermal conversion efficiency [33]. As a first step, the method involves the identification of the predominant modification mechanisms activated by temperature that contribute to the degradation of photothermal parameters in solar coatings. In SSCs with Ag infrared reflectors, the predominant modification mechanism that degrades the SSAC photothermal parameters is the diffusion of Ag atoms toward the neighboring solar absorber. The rate r of this mechanism can be expressed through the Arrhenius law:

$$r \propto e^{-\left(\frac{E_a}{RT}\right)}$$

where E_a is the activation energy, R is the universal gas constant, and T is the absolute temperature. To reduce the time to failure, this mechanism is accelerated by increasing the temperatures of aging tests. Assuming that no additional predominant degradation mechanisms are activated at higher temperatures beyond those observed during operation, the lifetime prediction of SSACs can be estimated with high accuracy.

The eight SSACs with stabilizing layers were subjected to three accelerated aging tests, as specified in Section 2. The total duration of three annealing tests was sufficient to observe an initial linear degradation of photothermal parameters and a subsequent rapid accelera-

tion of degradation. The E_a estimation was performed for each SSAC in correspondence with the linear degradation of ε_h at 550 °C, as the observed α_s variations were negligible compared to the accuracy of the measurement instruments. Regarding ε_h at 550 °C, the difference between the measured and the corresponding value on the interpolation line was lower than the accuracy of the measurement instruments for all SSACs; thus, the $\Delta\varepsilon_h$ at 550 °C/ Δt ratio was assumed constant for each SSAC in correspondence with the linear degradation, according to the Arrhenius law. The E_a values were used to predict the lifetime of the SSACs and the degradation of ε_h at 550 °C during the lifetime. The results showed that only the SSACs with stabilizing layers of AlN_{HF} , AlN_{LF} , and Al_xO_y had a lifetime of 25 years (8 h/day) at the operating temperature of 550 °C with an ε_h increase by 0.75%, 0.42%, and 0.08%, respectively. These data highlight the excellent thermal stability of the new SSACs with stabilizing layers of AlN_{HF} , AlN_{LF} , and Al_xO_y after 25 years of service at 550 °C. Figure 5 shows the Arrhenius plot of the three SSACs with the linear interpolation used to determine the ratio E_a/R . The E_a values of the SSACs with stabilizing layers of AlN_{HF} , AlN_{LF} , and Al_xO_y were 281 kJ/mol, 310 kJ/mol, and 462 kJ/mol, respectively.

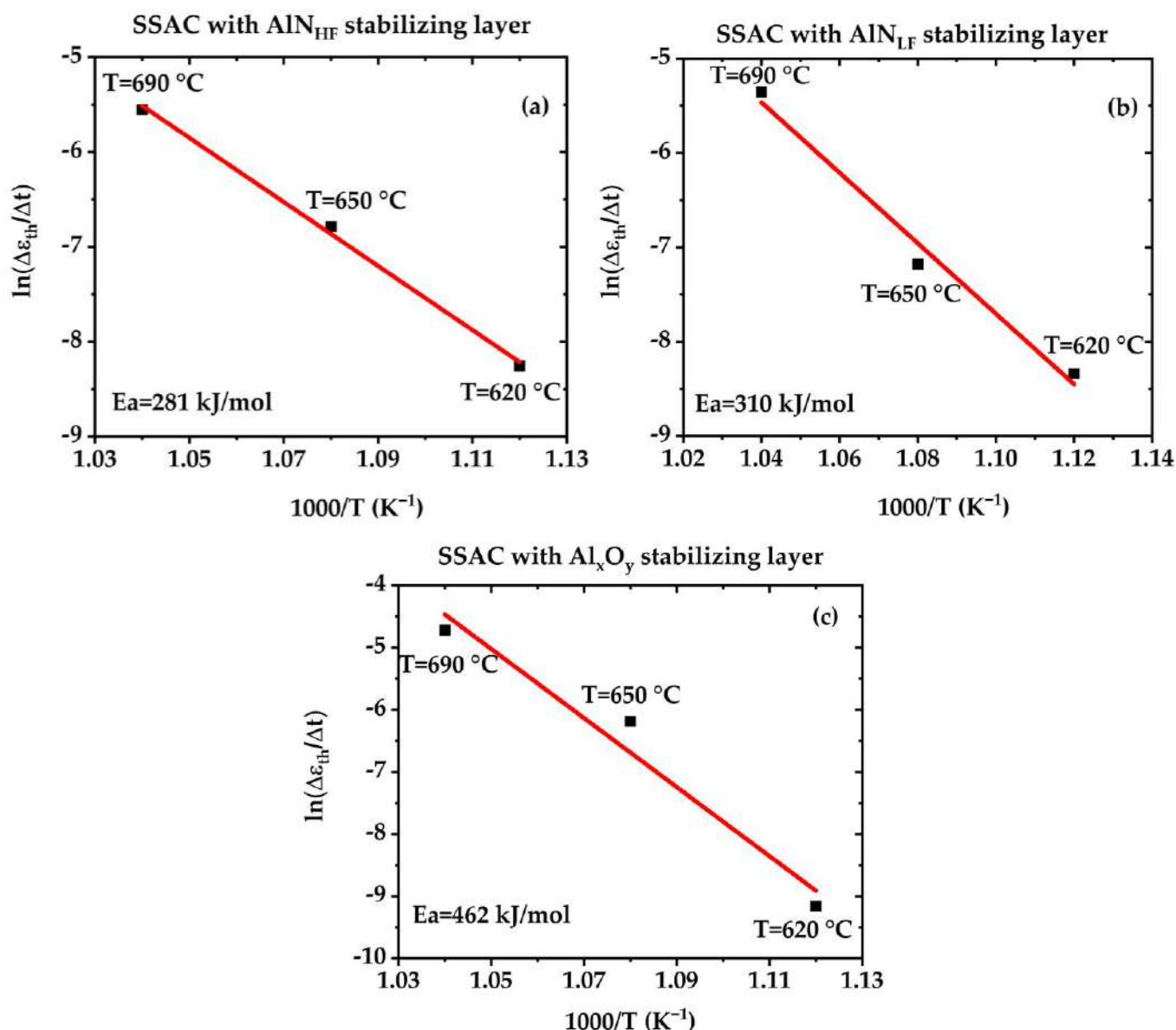


Figure 5. Arrhenius plot: $\ln(\Delta\varepsilon_h/\Delta t)$ vs. $1/T$ of the SSAC with stabilizing layer of AlN_{HF} (a), the SSAC with stabilizing layer of AlN_{LF} (b), and the SSAC with stabilizing layer of Al_xO_y (c).

In summary, the results of the thermal stability analysis clearly demonstrate the key role played by tungsten coupled with one of the stabilizing layers of AlN_{HF} , AlN_{LF} and Al_xO_y in mitigating the effects of silver diffusion. This diffusion mechanism, triggered at high temperatures, is the primary cause of the severe performance loss observed in previously developed SSACs operating under these specific and more challenging operative conditions.

3.2. SSAC Design and Manufacturing

In this section, the activity of designing and manufacturing a single SSAC with optimized photothermal performance is described. Among the three SSACs stable at 550°C for a lifetime of 25 years, the SSAC with the Al_xO_y stabilizing layer exhibited the best thermal stability at the operating temperature of 550°C , but its deposition process was particularly complex to be controlled through the PEM system due to the high reactivity of the oxygen in plasma [31]. Consequently, the SSAC with the AlN_{LF} stabilizing layer was selected. This choice was based on two key factors: it exhibited the second-highest thermal stability among the tested configurations, and its deposition process was readily controllable through the PEM system [37]. Thanks to this choice, the same deposition process was used for the deposition of the stabilizing layer, the ceramic component of the solar absorber, and the nitride ceramic of the anti-reflection filter.

On a pre-treated SS substrate with a surface roughness closely matching that of the receiver tube, a W layer of 120 nm, a Ag layer of 120 nm, and an AlN_{LF} layer of about 20 nm were grown in sequence according to the operative conditions specified in Section 2. The optical characterization of the Ag and AlN_{LF} layers was conducted using ellipsometry on an SS/W/Ag/ AlN_{LF} structure, closely replicating the deposition conditions employed in the fabrication of the optimized SSAC. This analysis enabled the determination of the optical parameter modifications of the Ag infrared reflector induced by the deposition of the AlN_{LF} layer. The comparison between the optical parameters of the Ag layers before and after the deposition of the AlN_{LF} layer is reported in Figure 6. This figure shows an absorption peak of the Ag infrared reflector in the wavelength range of 350–500 nm that can be explained by the formation of a very thin interlayer of Ag-N-Al clusters between the infrared reflector and the stabilizing layer. However, this interlayer is so thin that it does not degrade the high reflectance of the Ag layer in the infrared region.

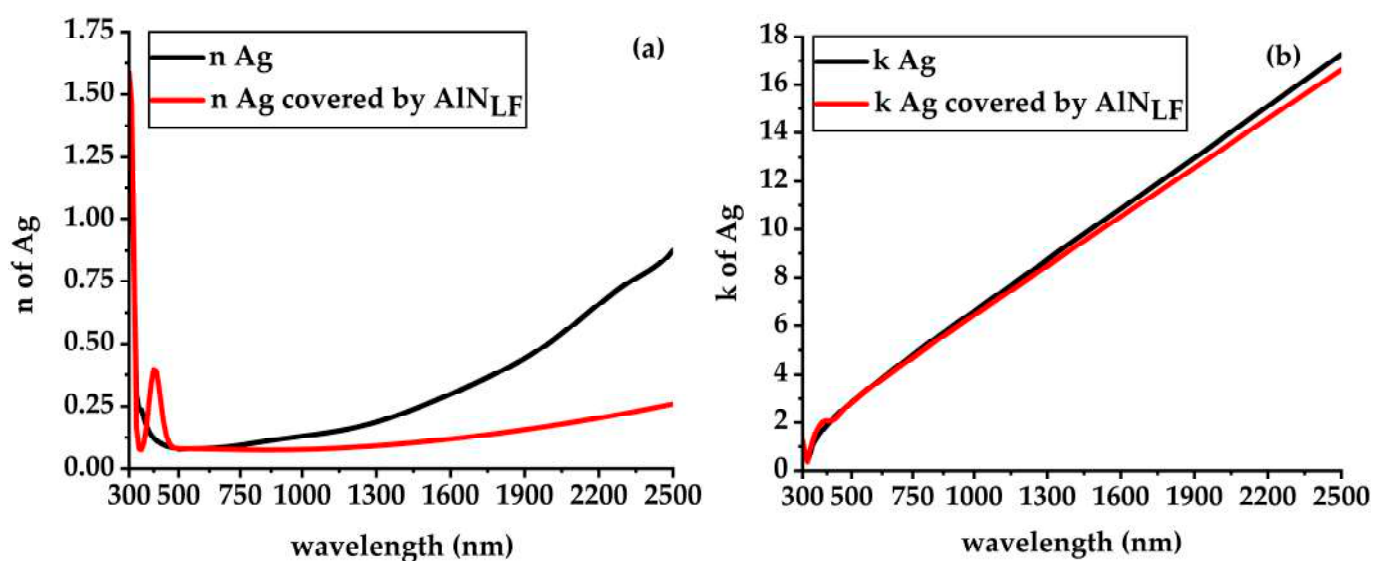


Figure 6. Optical parameters of the Ag layers with and without covering layer of AlN_{LF} : (a) refractive index; (b) extinction coefficient.

In order to exclude the formation of a thick interlayer of Ag-N-Al, XRD analysis was conducted on a glass/W/Ag structure, and the same structure was covered with a layer of AlN_{LF} . X-ray diffraction patterns, shown in Figure 7, were collected with an incidence angle to the sample of 0.5° ; the very low incidence angle enhanced the sensitivity to the thin film structure, especially to the last deposited layers.

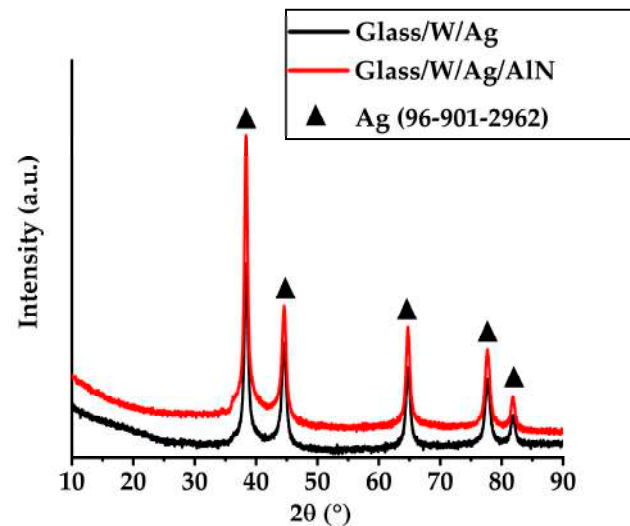


Figure 7. Comparison among the XRD spectrum of the Glass/W/Ag structure, the XRD spectrum of the Glass/W/Ag/ AlN_{LF} structure, and the standard PDF card of $\text{Ag}_{4.00}$.

The XRD spectra of the two structures in Figure 7 are very similar and related to the typical structure of $\text{Ag}_{4.00}$ identified by the standard PDF card no. 96-901-2962. This structure displays the symmetry of the Fm-3m space group (No. 225) of the cubic crystal system. Furthermore, the preferential growth orientations of the Ag grains in the two structures are in a crystalline plane (111). Since no additional peaks are visible in the diffraction pattern of the structure coated with AlN_{LF} , the formation of a thick intermediate layer resulting from the chemical interaction among Ag, Al, and N can be excluded, so confirming the initial hypothesis.

Regarding the stabilizing layer, the estimated thickness was equal to 22.2 nm, whereas the estimated optical parameters are shown in Figure 8.

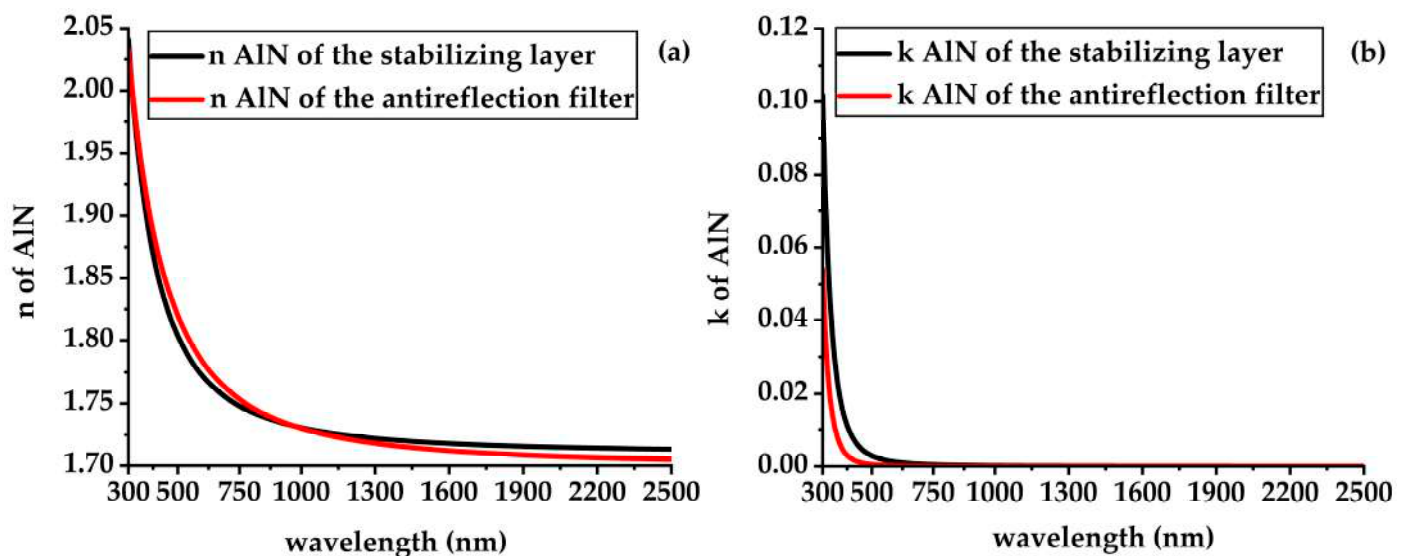


Figure 8. Optical parameters of the AlN layers of the stabilizing layer and anti-reflection filter: (a) refractive index; (b) extinction coefficient.

In order to optically characterize the C1_{SS} cermet layers, three SS/W/Ag/stabilizing layer/C1_{SS} structures were deposited according to the operative conditions specified in Section 2. The first C1_{SS} cermet layer was deposited using a power density applied to the W target of 4.00 W/cm². The thickness and deposition rate of this layer are shown in Figure 9, whereas the optical parameters are displayed in Figure 10.

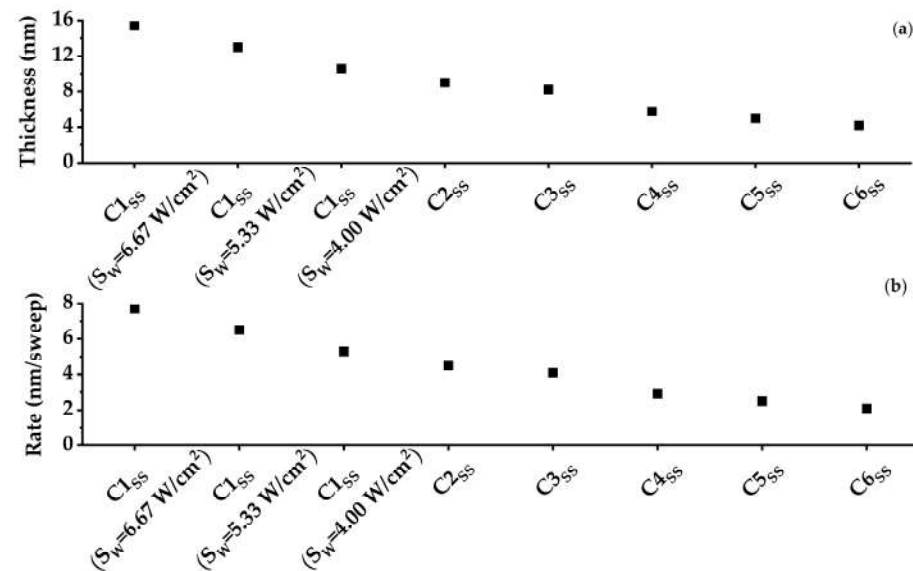


Figure 9. Thickness (a) and deposition rate (b) of the cermet materials deposited to design the solar absorber of the SSAC with optimized photothermal performance.

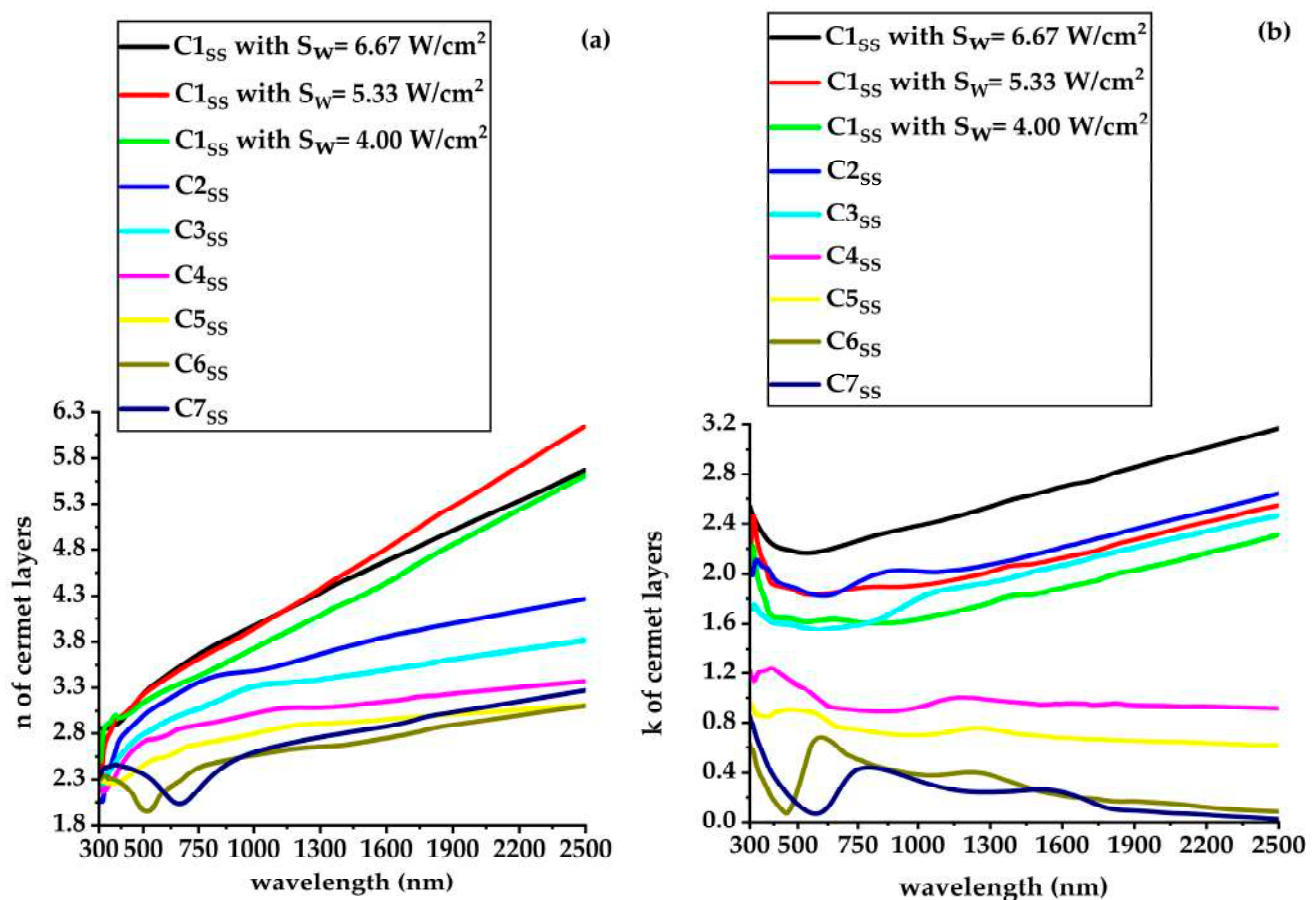


Figure 10. Optical parameters of the cermet layers deposited to design the SSAC with optimized photothermal performance: (a) refractive index; (b) extinction coefficient.

Figure 11 reports the optical parameters of the C1_{SS} cermet layer deposited with thicknesses of 10.6 nm and 31.8 nm on the stabilizing layer compared with the optical parameters of the same cermet layer grown with a thickness of 10.6 nm directly on the Ag infrared reflector. This figure highlights that the extinction coefficient of the C1_{SS} cermet layer depends strongly on its thickness. It is plausible to assume that the metal content of this cermet layer increases with thickness, as the metal atoms involved in its growth had a decreasing probability of interacting with the non-metal atoms of the stabilizing layer. Figure 11 also shows that the extinction coefficient of the C1_{SS} cermet layer with a thickness of 31.8 nm grown on the stabilizing layer approaches the extinction coefficient of the C1_{SS} cermet layer with a thickness of 10.6 nm grown directly on the Ag infrared reflector, which is free from non-metal atoms. Therefore, it can be concluded that the metal content within the C1_{SS} cermet layer increases rapidly as the distance from the stabilizing layer increases.

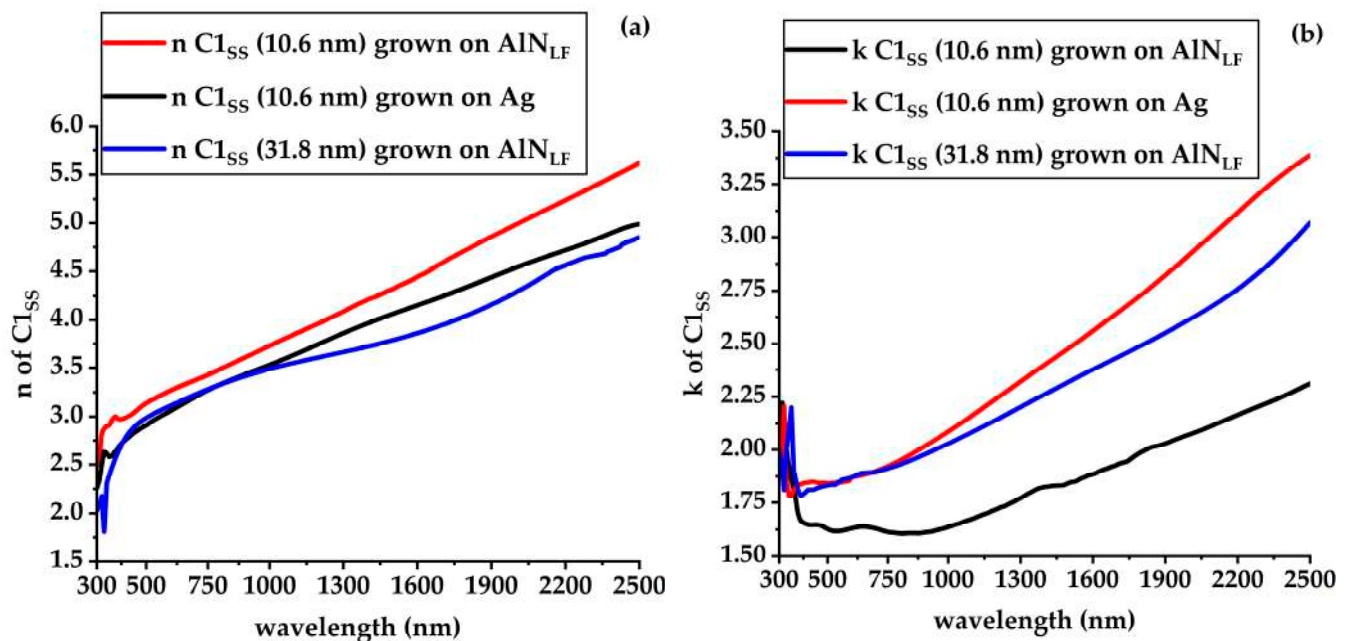


Figure 11. Optical parameters of the C1_{SS} cermet layer deposited with a power density of 4.00 W/cm² on the Ag infrared reflector compared with the optical parameters of the C1_{SS} cermet layers deposited with the same density power but different thicknesses on the AlN_{LF} layer: (a) refractive index; (b) extinction coefficient.

The second and third C1_{SS} cermet layers were deposited using a power density applied to the W target of 5.33 W/cm² and 6.67 W/cm², respectively. The thickness and deposition rate of these layers are shown in Figure 9, whereas the optical parameters are shown in Figure 10. The following step was the deposition of the C2_{SS} layer on the three C1_{SS} cermet layers according to the operative conditions specified in Section 2. In this case, the estimated thickness and optical parameters of the three C2_{SS} cermet layers were very similar, and Figures 9 and 10 show the thickness and optical parameters of the C2_{SS} cermet layer grown on the C1_{SS} cermet layer, which was deposited using a W target power density of 6.67 W/cm². Notably, as can be seen in Figure 10, only this specific cermet material enabled the fabrication of a solar absorber with a graded metal content profile, progressively decreasing from the stabilizing layer toward the anti-reflection filter.

The other cermet layers in Table 6 with indexes from 3 to 6 were deposited according to the operative conditions specified in Section 2 and optically characterized using the same procedure as the previous cermet layers. The thickness and optical parameters of these cermet layers are shown in Figures 9 and 10, respectively. Also, in this case, an

interpolation method was used to compute the deposition rate and optical parameters of the not deposited cermet materials having an intermediate W power density between 3.11 W/cm^2 and 0.44 W/cm^2 (see Table 6), thus completing the database to design the SSAC solar absorber with optimized photothermal performance.

Finally, AlN, SiO_2 , and a W-AlN cermet material with low metal content were carried out for the design of an anti-reflection filter. As mentioned in Section 2, the SS/W/Ag/stabilizing layer/ C1_{SS} ($S_W = 6.67 \text{ W/cm}^2$)/ C2_{SS} / C3_{SS} / C4_{SS} / C5_{SS} / C6_{SS} /AlN structure was fabricated for the estimation of thickness and optical parameters of AlN by the ellipsometric technique. The thickness and deposition rate of AlN were 14.8 nm and 1.85 nm/sweep, respectively, whereas the AlN optical parameters are shown in Figure 8. Similarly, the SS/W/Ag/stabilizing layer/ C1_{SS} ($S_W = 6.67 \text{ W/cm}^2$)/ C2_{SS} / C3_{SS} / C4_{SS} / C5_{SS} / C6_{SS} /AlN/ C7_{SS} structure was fabricated for the estimation of thickness and optical parameters of the C7_{SS} cermet layer. The thickness and deposition rate of this layer were 25.2 nm and 2.1 nm/sweep, respectively, whereas the C7_{SS} optical parameters are shown in Figure 10. Finally, the SiO_2 layer was fabricated according to the operative conditions specified in Section 2 and optically characterized. The thickness and deposition rate of SiO_2 were 80.0 nm and 8.0 nm/sweep, respectively, whereas Figure 12 reports the SiO_2 optical parameters.

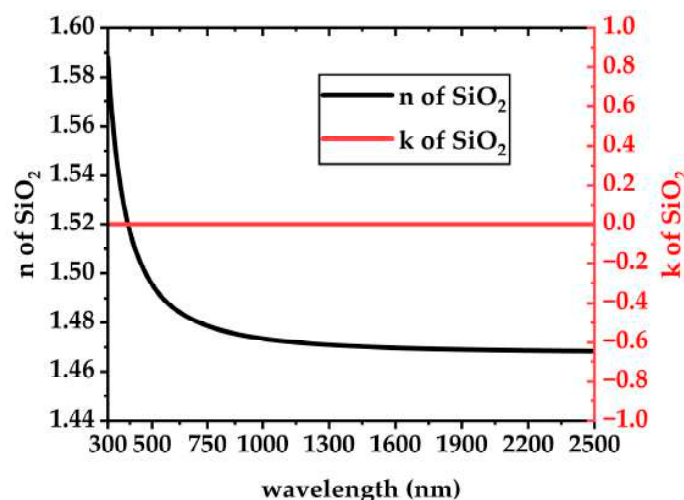


Figure 12. Optical parameters of the SiO_2 layer.

The optical parameters of all materials were collected in a database and imported into Essential Macleod to design the SSAC with optimized photothermal performance [33]. The aim of the optimization procedure was the fabrication of an SSAC with α_s equal to 95% and the lowest ε_h at 550°C . This target was achieved through an optical design involving successive refinements of the metallic profile shape of the graded multilayer cermet and of its thickness, as well as the anti-reflection filter layers' thicknesses. The SSAC with the photothermal parameters target of the optimization procedure was fabricated with the optical design reported in Table 9. In Figure 13, the image of this SSAC deposited on an SS substrate that is 3.5 cm long, 2.5 cm large, and 1 mm thick is shown.

SEM analyses were conducted to thoroughly investigate the surface properties of the optimized SSAC, especially to evaluate the possible change of morphology, such as grain size, during the deposition of the different layers. Figure 14 shows the changes in surface morphology between the SS substrate, the SS/W/Ag, and the optimized SSAC samples. As reported in Figure 14, while the SS substrate is characterized by a surface that does not show a granular distribution (Figure 14a), the SS/W/Ag and optimized SSAC samples exhibit a very homogeneous grain size distribution with an average grain size of about 102 nm, and 150 nm diameters, respectively (Figure 14b,c). These grain sizes are too small

to induce substantial changes in surface morphology, which would significantly impact the photothermal properties of the samples.

Table 9. Optical design of the SSAC with optimized photothermal performance.

Material	Power Density (W/cm ²)	Thickness (nm)
W	13.33	120
Ag	4.13	120
AlN _{LF}	2.58	22.2
Cermet 1 (W, AlN)	(6.67, 2.58)	15.4
Cermet 2 (W, AlN)	(3.11, 2.58)	4.5
Cermet 3 (W, AlN)	(2.67, 2.58)	4.1
Cermet 4 (W, AlN)	(2.22, 2.58)	3.7
Cermet 5 (W, AlN)	(1.78, 2.58)	3.3
Cermet 6 (W, AlN)	(1.33, 2.58)	2.9
Cermet 7 (W, AlN)	(0.89, 2.58)	2.5
AlN	2.58	5.55
Cermet 8 (W, AlN)	(0.44, 2.58)	33.6
SiO ₂	3.88	80



Figure 13. Image of the optimized SACC deposited on an SS substrate that was 3.5 cm long, 2.5 cm large, and 1 mm thick.

An EDX analysis was also carried out on different points of the surface of the optimized SSAC sample to verify the qualitative presence of the different elements within the sample. Table 10 shows the results of this characterization, in which all elements constituting the coating were identified.

Table 10. Results of EDX analyses carried out on the surface of the optimized SSAC sample.

Element	Atomic %
N	9.25
O	36.54
Al	13.36
Si	9.30
Ag	10.33
W	21.22
Total	100.00

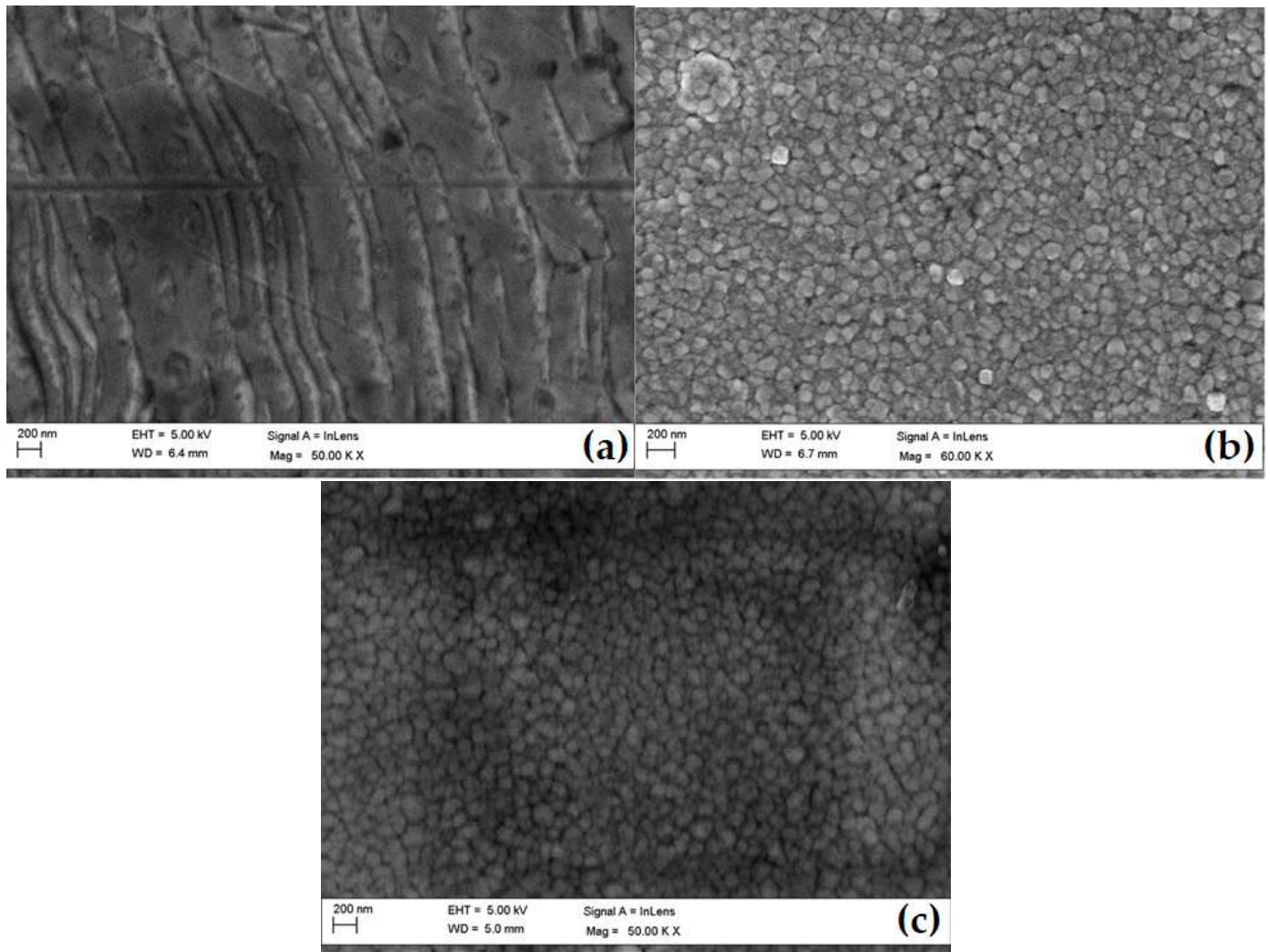


Figure 14. SEM characterization of the SS substrate (a), the SS/W/Ag (b), and the optimized SSAC (c) samples.

Subsequently, the optimized SSAC sample was also subjected to XRD analysis. X-ray diffraction patterns, reported in Figure 15, were collected at very low incidence angles to the sample, 1° and 0.3° . Due to the high resonance density of W, Ag metallic layers, and SS substrate, as well as the poor crystallinity of cermet and AR layers, both patterns exhibit very similar spectrums. Only the peaks of the first metallic layers, including SS, are detected, while no peaks referable to the other layers are visible.

The last morphologic characterization was a cross-sectional SEM analysis carried out on the optimized SSAC deposited on the c-Si substrate; the c-Si substrate is suitable to analyze a very thin layer, thus avoiding damage to the coating itself. Figure 16 shows a clear stratification of materials composing the fabricated SSAC, in which W and Ag layers are well visible and have a thickness of around 125 nm each, which is in agreement with the deposition recipe. The image also highlights that the barrier layer, cermet, and AR filter appear as unique layers due to their very similar morphology, electronic density, and composition. The total thickness was evaluated to be equal to 430 nm.

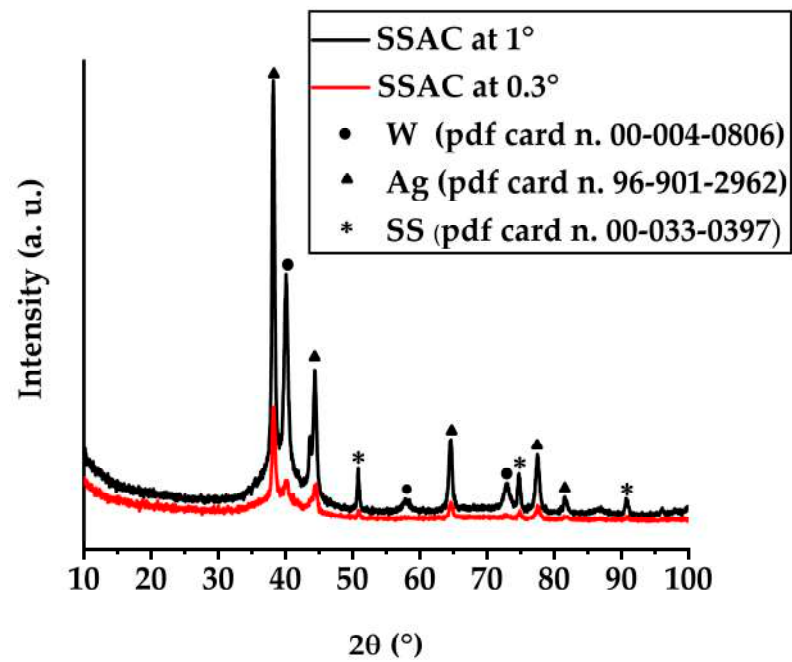


Figure 15. XRD patterns collected at different incident angles on the optimized SSAC sample.

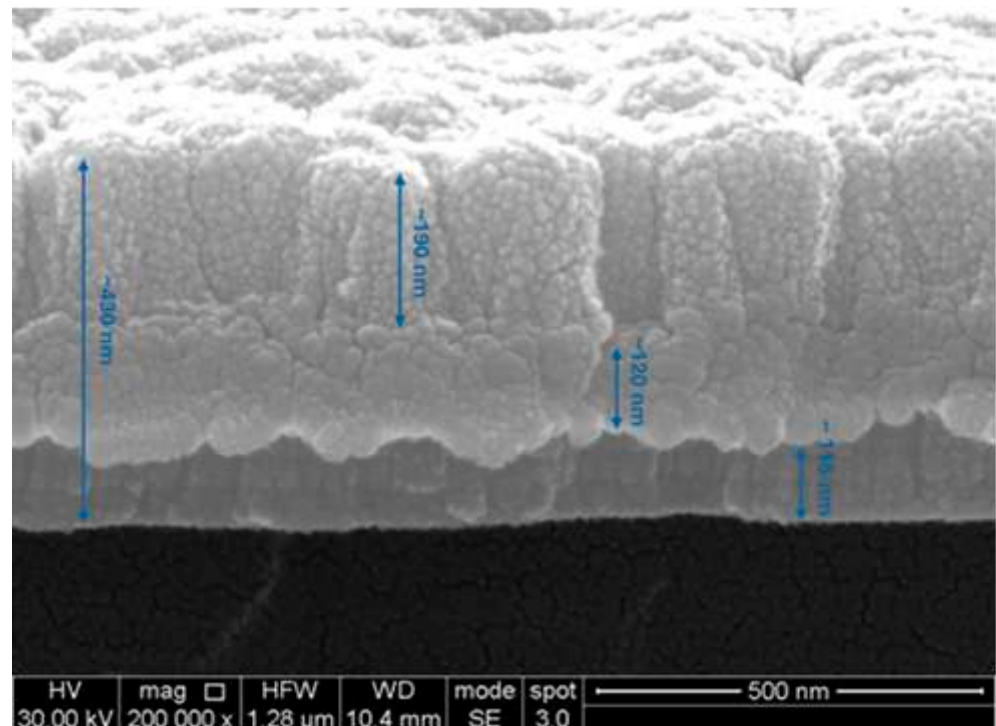


Figure 16. Cross-sectional SEM characterization of the optimized SSAC deposited on c-Si substrate.

The optical characterization of the optimized SSAC deposited on the SS substrate (see Figure 13) was performed by measuring its spectral reflectance as specified in Section 2. Figure 17 reports the comparison between the experimental reflectance of the optimized SSAC sample and the simulated reflectance of the optical design used to fabricate it. The good agreement between these curves highlights the high accuracy of the procedure adopted to estimate the thicknesses and optical parameters of the SSAC layers. Hence, the estimation of the photothermal performance was performed by using the experimental reflectance of the optimized SSAC sample shown in Figure 18. Measured α_s and ε_h at 550°C were equal to 95% and 9.5%, respectively. This result shows a reduction of ε_h at 550°C

of 0.4% compared to the best-performing ENEA coating with a W infrared reflector. This reduction is lower than expected due to the optical mismatch introduced by the stabilizing layer in the SSAC structure. As shown in Figure 18, three different regions can be identified in the SSAC reflectance spectrum: the solar absorption region from 300 to 1100 nm; the transition region from 1100 to 4000 nm; and, finally, the high reflectance region from 4000 to 16,000 nm.

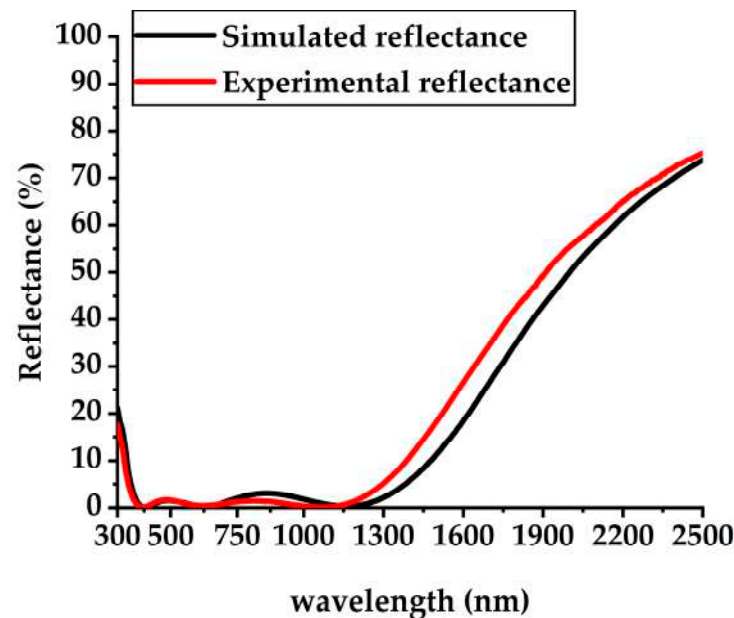


Figure 17. Comparison between the experimental reflectance of the optimized SSAC sample and the simulated reflectance of the optical design used to fabricate it.

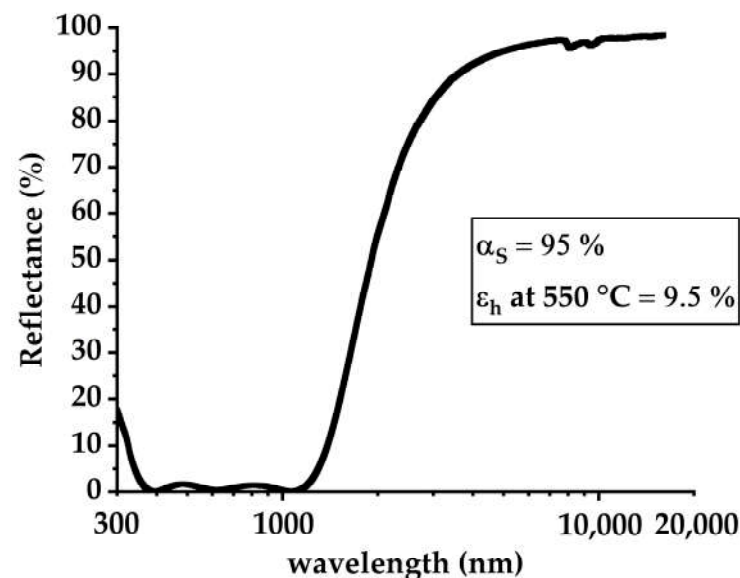


Figure 18. Experimental reflectance of the optimized SSAC sample.

In the first region, the thickness of the stabilizing layer is thick enough to promote constructive and destructive interference between the reflected waves at its interfaces. Although this phenomenon modifies the amplitude and position of the reflectance peaks compared to those of the SSAC without a stabilizing layer, the solar absorbance of these SSACs remains quite similar because the intensity of the interfering waves is very low. In the transition region, the thickness of the stabilizing layer promotes destructive interference between the reflected waves at its interfaces. In this case, the intensity of the interfering

waves begins to increase with wavelength, and consequently, the SSAC reflectance decreases compared to SSAC without a stabilizing layer. Since the reflectance reduction occurs where the irradiance peak of the blackbody at 550 °C is located, ϵ_h at 550 °C of the SSAC with a stabilizing layer increases compared to SSAC without a stabilizing layer. Finally, in the high reflectance region, the thickness of the stabilizing layer is too thin to promote significant interference phenomena. In this case, the combination of the waves reflected at the interfaces of the stabilizing layers produces a negligible modification of the SSAC reflectance, which results in very similar results to that of the SSAC without a stabilizing layer. Therefore, the expected reduction of ϵ_h at 550 °C is almost completely nullified by the introduction of the stabilizing layer in the SSAC structure. Given this limited reduction in ϵ_h , the utilization of Ag infrared reflectors in high-temperature SSACs may not be justified, considering the increased manufacturing complexity and associated costs. However, this analysis does not consider that photothermal performance is systematically underestimated by using the reflectance curve measured at room temperature, which may not accurately represent the reflectance at the operating temperature of 550 °C [38]. In fact, it is well-known that the infrared reflectance of metals decreases with temperature [39,40]. Table 11 reports the difference between ϵ_h at 550 °C computed with the reflectance evaluated at 550 °C and ϵ_h at 550 °C computed with the reflectance evaluated at room temperature for W and Ag in the Mid-Infrared Range (MIR). These estimations were carried out using experimental data [41,42] and the theoretical model proposed by A. G. Maki et al. [43], which computes the reflectance of Ag and W through the knowledge of their DC electrical resistivity at operating temperature [44,45].

Table 11. Difference between ϵ_h at 550 °C computed with the reflectance measured at 550 °C and ϵ_h at 550 °C computed at room temperature.

Reflectance	$\Delta\epsilon_h$ at 550 °C (%) in MIR	
	W	Ag
Experimental data	4.0	1.2
Theoretical model	3.2	1.6

Table 11 highlights that ϵ_h at 550 °C of the SSAC with a W infrared reflector is more underestimated than ϵ_h at 550 °C of the SSAC with a Ag infrared reflector. Therefore, the actual ϵ_h gap at 550 °C between the SSACs with Ag and W infrared reflectors is even larger than 0.4%. In order to estimate this gap, the Ag optical parameters at 550 °C and room temperature were evaluated by the theoretical model proposed by Meng Xu et al. [40] and imported into Essential Macleod to simulate the reflectance at 550 °C and at a room temperature of the SSAC with optimized photothermal performance, whose optical design is reported in Table 9. Regarding the optical parameters of the other layers in the optical design of Table 9, they were extrapolated in the MIR range and assumed invariant with temperature. The difference between ϵ_h at 550 °C, computed with the simulated reflectance at 550 °C, and ϵ_h at 550 °C, computed with the simulated reflectance at room temperature, was equal to 1.5%. The same procedure was applied to simulate the reflectance at 550 °C and at room temperature of the ENEA best SSAC with a W infrared reflector. In this case, the W optical parameters at 550 °C and room temperature were evaluated by the theoretical model proposed by S. X. Cheng et al. [39], whereas the optical parameters of the other layers of the best ENEA SSAC with W infrared reflector [32] were extrapolated in the MIR range and assumed invariant with the temperature. The difference between ϵ_h at 550 °C, computed with the simulated reflectance at 550 °C, and ϵ_h at 550 °C, computed with the simulated reflectance at room temperature, was equal to 3.5%. Therefore, the estimated gap between ϵ_h at 550 °C of the SSAC with a Ag infrared reflector and the SSAC with a

W infrared reflector is equal to 2%. This result highlights that SSACs with Ag infrared reflectors still represent the preferred choice for high-temperature applications.

4. Conclusions

This work describes the development of new SSACs based on a Ag infrared reflector specifically designed to exhibit high structural and chemical stability under vacuum conditions up to 550 °C. Structural and chemical stability at 550 °C of these SSACs was improved by introducing their structures to two stabilizing layers beneath and above the Ag infrared reflector. One W stabilizing layer was positioned between the substrate and the Ag infrared reflector, whereas six ceramic and two cermet layers were tested as stabilizing layers positioned between the Ag infrared reflector and the cermet-based solar absorber. Specifically, a set of SSACs was manufactured for thermal stability evaluation at 550 °C, composed of an SS/W stabilizing layer/Ag/stabilizing layer/graded cermet (W-AlN)/AR filter (AlN, W-AlN cermet with low metal content, SiO₂). An ENEA-developed methodology was employed to assess the degradation of these SSACs at the operating temperature of 550 °C, enabling the prediction of their service lifetime.

As a first finding of this activity, only SSACs with stabilizing layers of aluminum nitride deposited at a high and low nitrogen flow and stabilizing layer of aluminum oxide deposited at a low oxygen flow were stable for 25 years (8 h/day) at the operating temperature of 550 °C. They showed no degradation of the solar absorptance, whereas the hemispherical emittance at 550 °C increased by 0.75% for the SSAC with a stabilizing layer of aluminum nitride deposited through a high nitrogen flow, 0.42% for the SSAC with a stabilizing layer of aluminum nitride deposited through a low nitrogen flow, and 0.08% for the SSAC with a stabilizing layer of aluminum oxide deposited through a low oxygen flow.

Among the three SSACs stable at 550 °C for a lifetime of 25 years, the SSAC with a stabilizing layer of aluminum nitride, deposited using a low nitrogen flow, was manufactured with optimized photothermal performance. This choice was based on two key factors: it exhibited the second-highest thermal stability among the tested configurations, and its deposition process was readily controllable through the PEM system. This SSAC showed a solar absorptance of 95%, similar to ENEA coatings with W infrared reflector for applications at 550 °C, whereas the estimated hemispherical emittance at 550 °C was reduced by 2% compared to that of the best-performing ENEA coating using W infrared reflector for applications at 550 °C.

Given the excellent stability that the tube receiver can achieve through these SSACs, the present results are expected to significantly contribute to the efficient operation and maintenance of solar fields in CSP plants. Furthermore, the significant reduction of hemispheric emittance can relevantly enhance the overall efficiency of the solar field. In fact, depending on the location of the CSP plant in the Mediterranean solar belt, an increase in energy production between 5 and 10% can be estimated for each percentage point reduction in hemispheric emittance at 550 °C.

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