



Final report

SolarClean

Intelligent Active Self-Cleaning of CSP Concentrators (Mirrors)





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CleanFIZZ

SolarClean R&D Project

Intelligent Active Self-Cleaning CSP Concentrators (Mirrors)

Developing intelligent self-cleaning mirrors to maximize efficiency and minimize operation and maintenance costs of Concentrated Solar generation

By: George McKarris

01.12.2014

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Abstract

The world is adopting solar energy as a sustainable renewable and eco-friendly alternative to fossil fuel or nuclear energy.

The installation of solar systems for optimum yield is primarily dictated by its geographic location (latitude and available solar insolation) and installation design (tilt, orientation and altitude) to maximize solar exposure. However, once these parameters have been addressed appropriately, there are other depending factors that arise in determining the system performance (efficiency and output).

Dust and ice are acknowledged factors that significantly influence the performance of the solar installations primarily in high to very high sun irradiation regions. It can significantly degrade the efficiency of concentrated solar by 60-80%.

Cleaning solar installations requires infrastructures such as equipment, water, solvents and personnel.

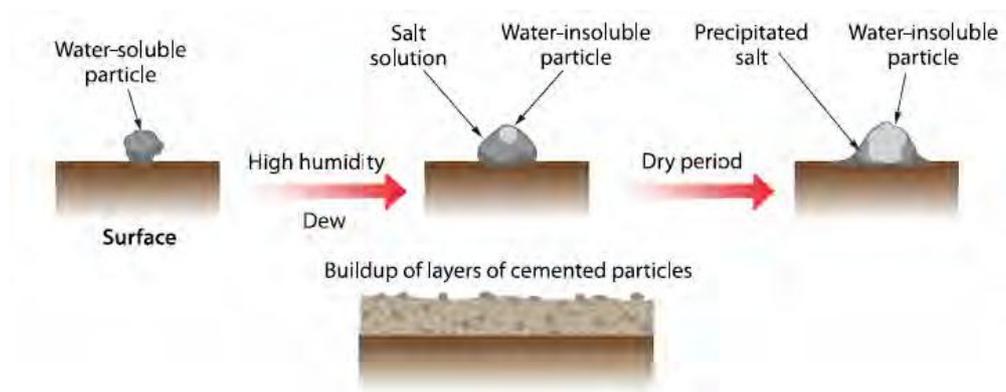


Figure 1 - Dust particles adhesion (DLR 2013)

1. Introduction

The target areas for concentrating solar thermal power projects are moving ever more to regions with high aerosol loads at ground level. Aerosol particles cause soiling of the plant components. Especially the soiling of the mirrors is of relevance as it implies noticeably reduced efficiency of the power plants and/or higher cleaning costs. Therefore, new solutions for soiling mitigation and cleaning are demanded for application in such harsh environments.

CleanFizz has been working on the development of a novel approach for cleaning glass surfaces and has shown the general possibility of applying the technology to CSP mirrors. The technology makes use of the fact that dust particles are partly charged and thus can be repelled from surfaces by the application of strong electric fields. Travelling waves are used to remove the dust particles that are already settled on the glass surface and transport them outside the surface of the mirror. Hence, this cleaning approach reestablishes the high reflectance of the mirror without the need of cleaning personnel or water.

CleanFizz has developed an active self-cleaning technology for de-soiling and de-icing of solar reflectors (mirrors) and glass surfaces using **electrostatic field**.

2. Objectives

Installed capacity for electricity generation from solar energy, both Photovoltaic and CSP, has been growing strongly over the last years. CSP has shown a more than 9-fold increase from below 500 MW in 2008 to 4.5 GW in 2015.

The site selection for CSP plants is basically driven by the available solar resource to maximize economic yield. However, once these parameters have been addressed appropriately, there are other site dependent factors that arise in determining the system performance.

One of the most important of these parameters is the soiling of the mirror surfaces. Dust, dirt, condensation and ice on the mirror surfaces significantly reduce the performance of the solar installations. Accordingly, solar installations have to be cleaned regularly to maintain high efficiency.

Current cleaning procedures make use of one or more vehicles operated by solar field workers that subsequently clean the collectors of the solar field consuming water, fuel, solvents and manpower, as well as creating the need of additional infrastructure in the power plant.

The main objectives of the SolarClean project are:

- Identify and develop intelligent self-cleaning reflector material that is relatively low cost and maintain high optical reflectance
- To optimize the electrostatic waves dust removal technology and bring it to market
- Ensure durability of the reflectors to last the lifetime of the CSP plant under harsh environmental conditions
- Industrial process development of intelligent active self-cleaning mirrors including their application in the solar industry
- The establishment of an ecological concept, under different environmental conditions, that saves water, reduces operating cost, avoids human interventions in very difficult conditions, saves the hassles of equipment and logistics and last but not least a huge reduction in CO₂ emission

3. The concept

The technology consists of parallel electrodes embedded into the surface of the mirror, connected to a DC source that pulses electrostatic fields generating travelling waves¹⁻⁵. The electrostatic forces, induced by the fields, overcome the Van der Waals forces responsible for adhesion of the dust to the surface of the glass, levitate the dust particles and remove them off the surface (Fig. 2). Once removed, the particles follow gravitation on the inclined surfaces and are hence removed from the mirror.

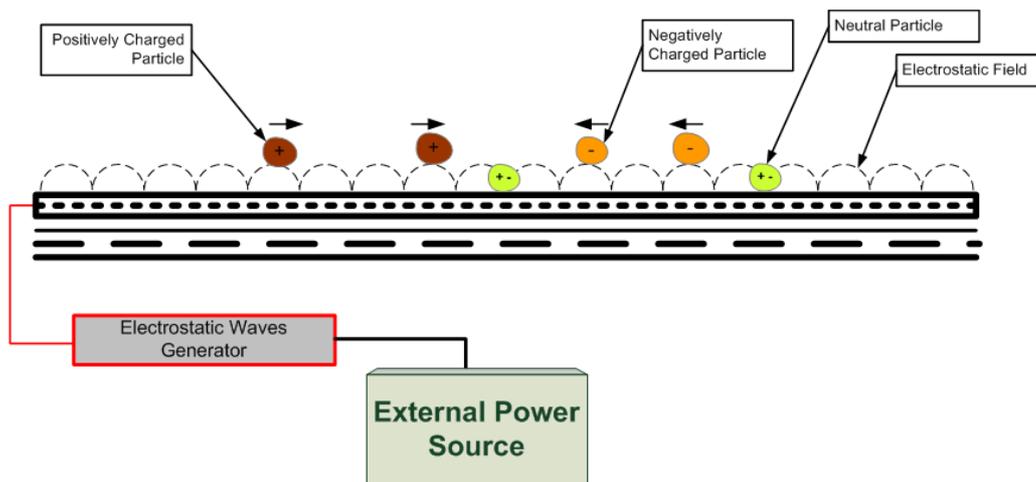


Figure 2 – Particles interaction with electrostatic field

Earlier developments have proven the concept using transparent coating (TCO) for the electrodes such as ITO. TCO material absorbs light and reduces reflectivity of the mirror.

The use of reflective electrodes is primarily to enhance the reflectance of the mirror, use lower cost material than ITO and respectively reduce manufacturing cost by applying only one material. The electrodes optimum material selected is silver based which is deposited under vacuum using the proven sputtering technique.

The width of the electrodes can vary between 100 to 500 μm and 200 to 500 nm in thickness. The dimensions of the electrodes are adjusted depending upon the thickness of the front glass layer and the desired electric field strength.

The concept of the SolarClean electrostatic based self-cleaning mirror solution consists of the following components (Fig 3):

- Mirrors with embedded electrodes
 - Anti-humidity system will be developed and added in the second stage of this project
- Electronics:
 - Main control unit
 - Wave generator
 - Sensors and environmental detection
 - Communication
- Power source and storage
- Software
- Online shared data collection and analysis platform

3.1. Complete self-cleaning mirror concept

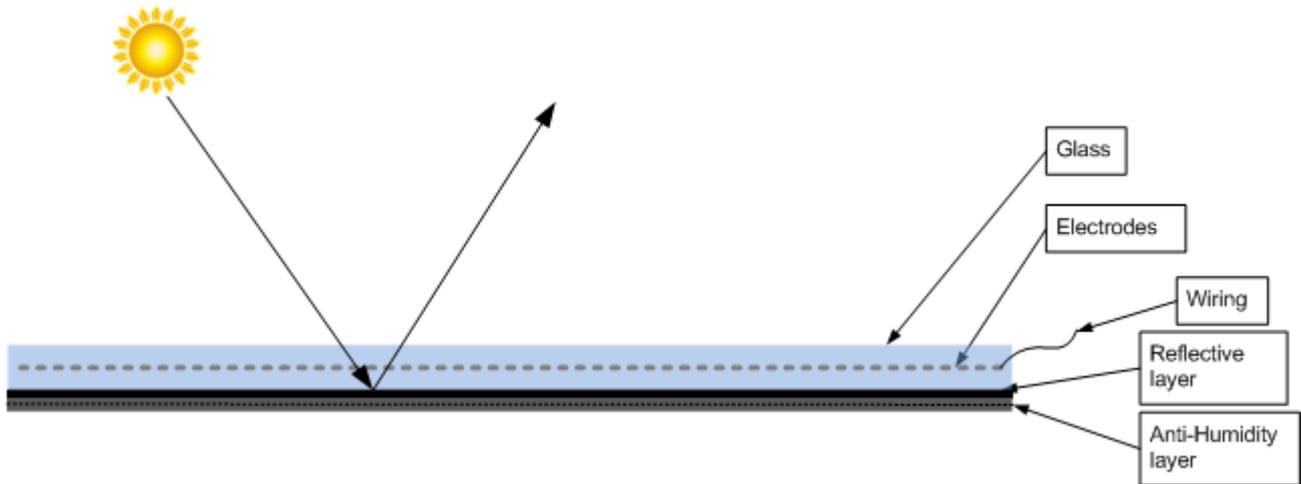


Figure 3 - Self-Cleaning mirror

3.2. Block diagram

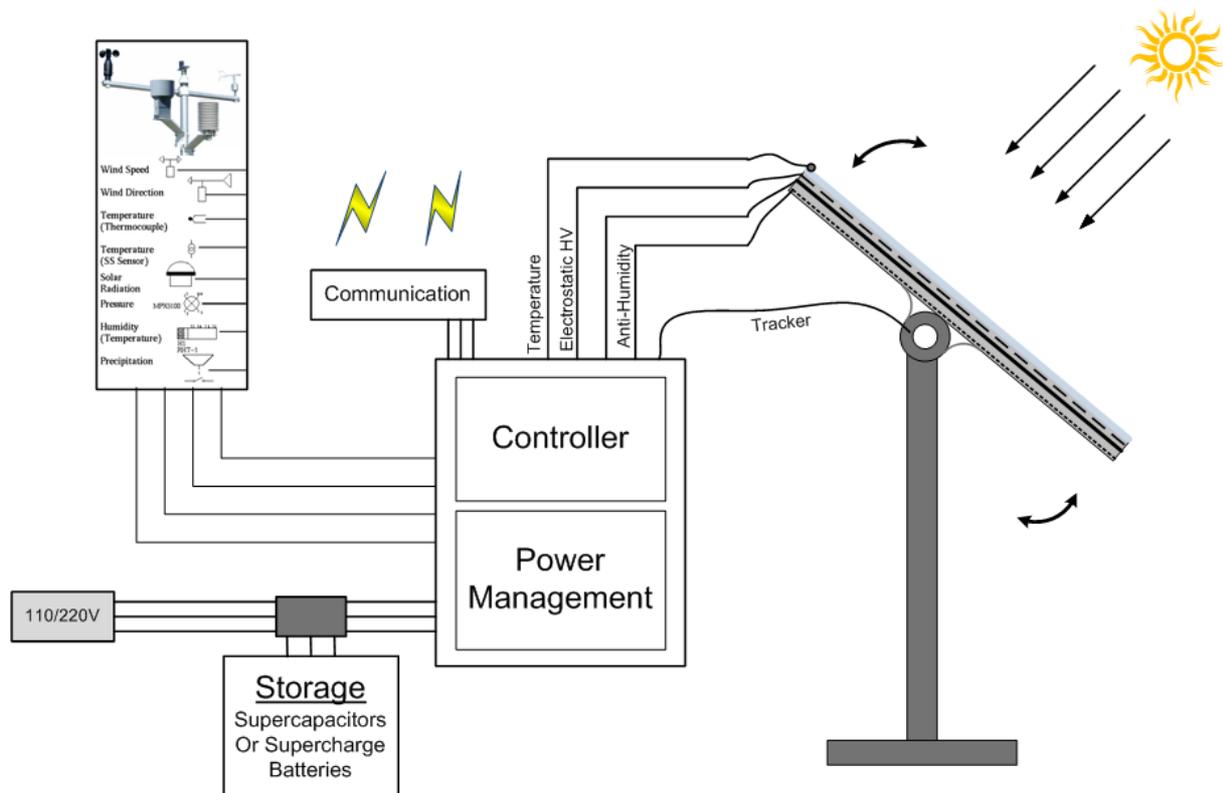


Figure 4 - SolarClean complete experimental setup

4. Materials and Methods

4.1. Glass Type

The Extra White low iron glass (Table 1) has been selected from the various types researched due to its clarity, surface roughness⁶ and higher light transmission.

General chemical and physical properties of 0.8 mm glass		
Silicon Dioxide	SiO ₂	72.20%
Sodium Oxide	Na ₂ O	14.30%
Potassium Oxide	K ₂ O	1.20%
Calcium Oxide	CaO	6.40%
Magnesium Oxide	MgO	4.30%
Aluminum Oxide	Al ₂ O ₃	1.20%
Ferric Oxide	Fe ₂ O ₃	0.03%
Sulfur Trioxide	SO ₃	0.30%
Mean Coefficient of Expansion	20° - 300°	90.6 x 10 ⁻⁷ /C°
Stain Point log n 14.5	513° C	
Softening Littleton Point	720°C	
Reflectance second surface mirror	Total solar reflection (M = 2) Proportion of normally incident solar energy reflected from a second surface mirror when solar elevation is 30°	95.3%
Light transmission	Total solar reflection (M = 2) Proportion of normally incident solar energy transmitted when solar elevation is 30°	91.5%
Refractive index	At λ = 546.07 nm	1.5171
	Specific gravity	2.479

Table 1 – Extra white glass properties

4.2. Coating material

The following investigations between a TCO and metallic electrodes material will determine the best performance or the best candidate electrode material for this project.

4.2.1. Transparent Coating

Transparent Conductive Oxides (TCO) coatings have been investigated. ITO (Indium Tin Oxide) will be used initially as it has a long and proven track record in flat monitors and thin film photovoltaic manufacturing.

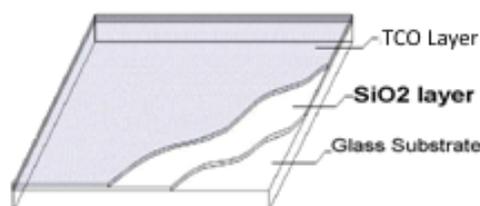


Figure 5 - Glass coated with ITO

4.2.2. TCO Coating Specifications:

SiO ₂ Thickness		ITO Thickness		Sheet resistance		Transmittance (at 550 nm)		Heat resistance (at 300°C)
Normal	Typical	Normal	Tolerance	Specified	Typical	Specified	Typical	
nm	nm	nm	nm	Ω/□	Ω/□	%	%	Ω/□
≥20	25	125	15	≤15	12	≥87	89	≤30

Table 2- ITO specifications

4.2.3. Patterning TCO

Three methods of patterning TCO have been investigated and tested:

- Photo Lithography
- Screen Printing
- Laser Scribing

Photo Lithography will be used at this stage of the research due to the availability and the proximity of service providers.

Electrode width		Spacing	Absorption (at 550 nm)
Normal	Coverage	Specified	Specified
μm	%	mm	%
500	15	3	≤1.5

Table 3 – Selected ITO specifications

4.2.4. Reflective coating thickness and reflectivity

Three reflective coating have been investigated to find an ideal candidate for the electrodes material:

- Aluminium (Al) is the lowest cost and most common coating. It yields a reflectivity of around 88%-92% over the visible spectrum.
- Silver (Ag) has a reflectivity of 95%-99% even into the far infrared, but suffers from decreasing reflectivity (<90%) in the blue and ultraviolet spectral regions.
- Gold (Au) which gives excellent (98%-99%) reflectivity throughout the infrared, but limited reflectivity at wavelengths shorter than 550 nm, resulting in the typical gold colour.

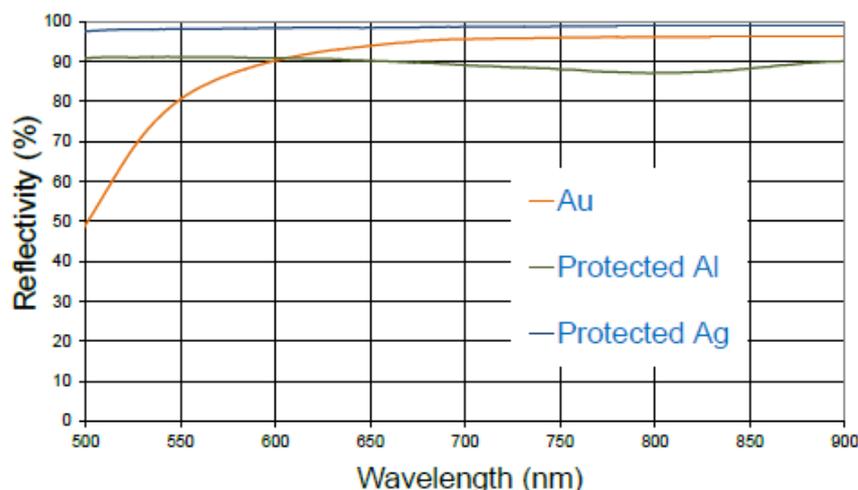


Figure 6 - Reflective coatings performance

Silver (AG), due to its properties and cost, has been selected as the best performance coating for the electrodes material (Fig. 3). Furthermore, silver has a better sheet resistance rate allowing for much thinner electrodes.

4.2.4.1. Preparation

Glass sheets of 40x50 cm and 0.8 thick have been prepared, washed and controlled inside a clean room until the quality of the surface was sufficient for the deposition process.

4.2.4.2. Deposition Process

The glass sheets were coated using a sputtering process (PVD) under vacuum. A protective layer of Silicon Oxide (SiO₂) was applied first to ensure adherence of Silver to the Glass. Followed by a layer of Silver applied as well under vacuum in a reverse coating method.

4.2.4.3. Patterning Silver

Three methods of patterning TCO have been investigated and tested:

- Photo Lithography
- Screen Printing
- Laser Scribing

Chemical etching in the Photo Lithography process was unsuccessful for patterning silver on a 40x50 cm samples.

A small sample of 10x10 cm was prepared, using a metallic mask, with silver electrodes having properties shown in Table 4 below.

Coating material	Electrode width		Electrode Thickness	Spacing	Reflectivity
	Normal	Coverage	Ideal	Specified	Specified
Silver (AG)	μm	%	Nm	Mm	%
	200	6	100	3	≥ 95

Table 4 - Silver based electrodes specifications

5. Electronics and control system

The electronics and control consist of the following modules:

- Main control unit
- Electrostatic waves controller
- Power management and supply
- WiFi and GSM communication

All the above modules are designed for reliable operation under difficult to extreme conditions. All the above electronics will be housed in a double wall cabinet delivering higher thermal insulation in a tough climate conditions.

5.1. Electronics Architecture

This architecture design (Figure 7) enables the control of a pilot installation or rather a solar plant from anywhere in world with the collected data being available from anywhere as well.

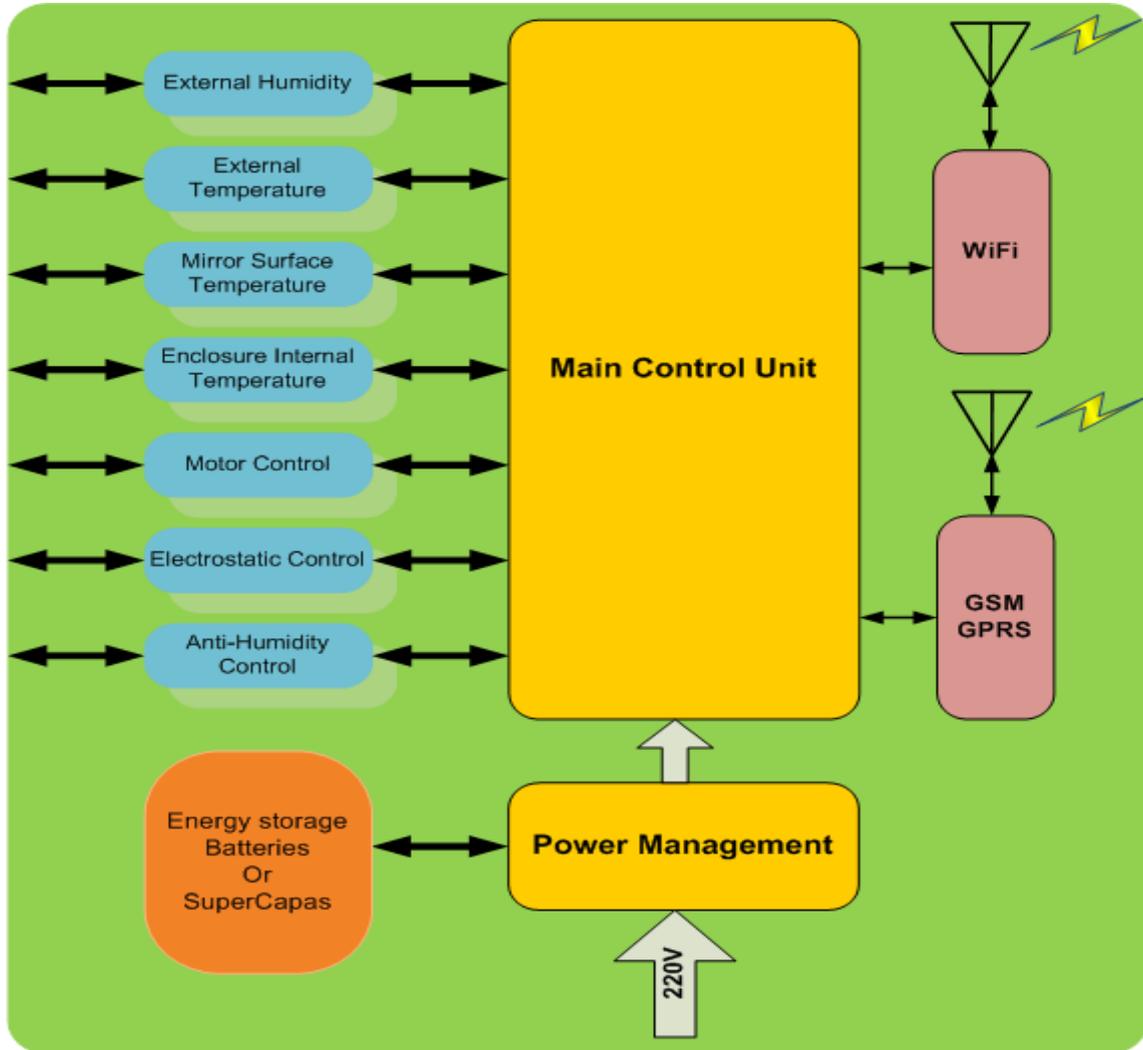


Figure 7 - Electronics Block Diagram

5.2. Measured Parameters and data flow

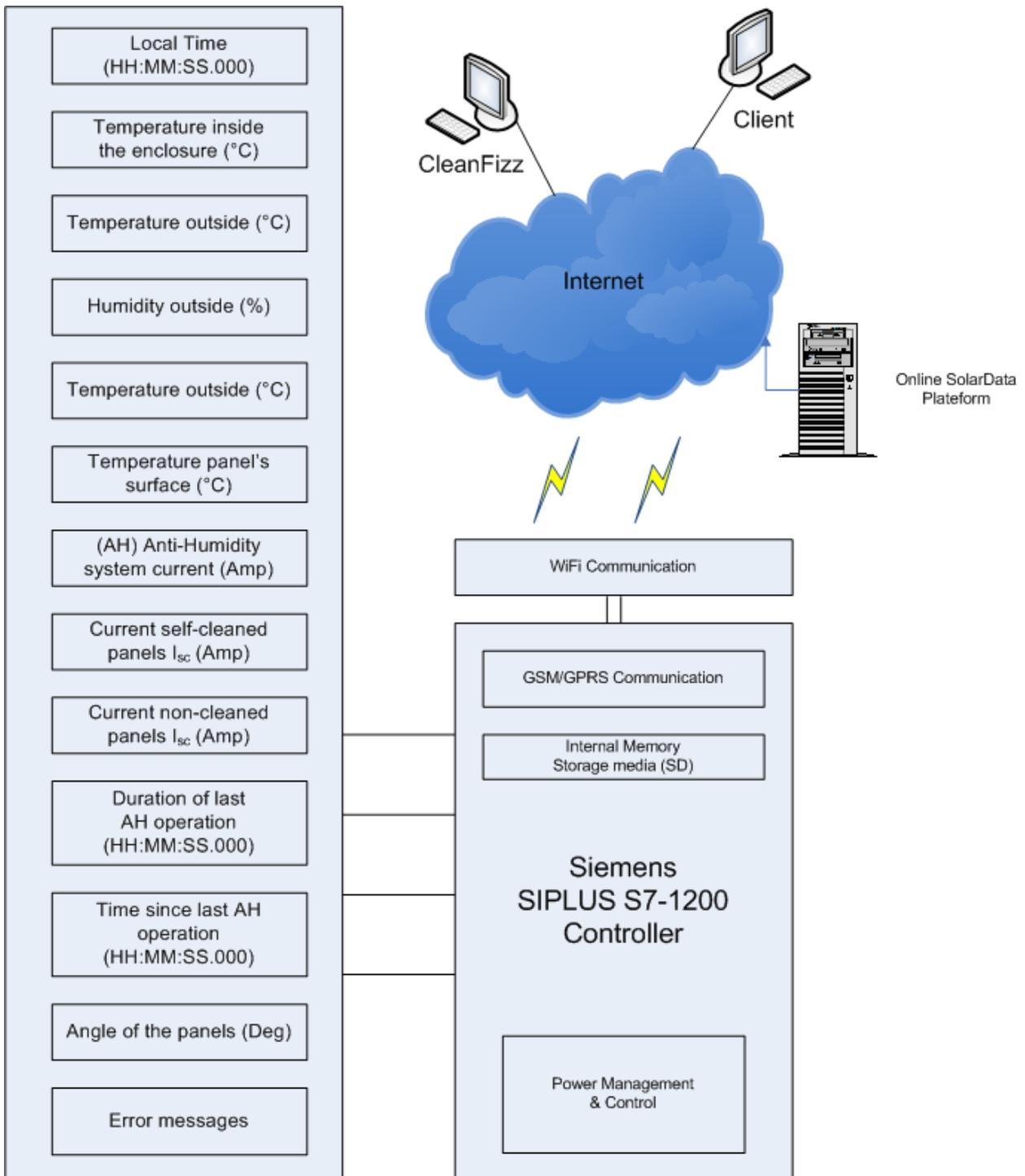


Figure 8 – Data flow and storage

6. Anti-Humidity and De-Icing system

6.1. Implementation of the Anti-Humidity layer

The anti-humidity system consists of a layer of low resistance conductive metal deposited on the back side of the main reflective layer (Figure 9).

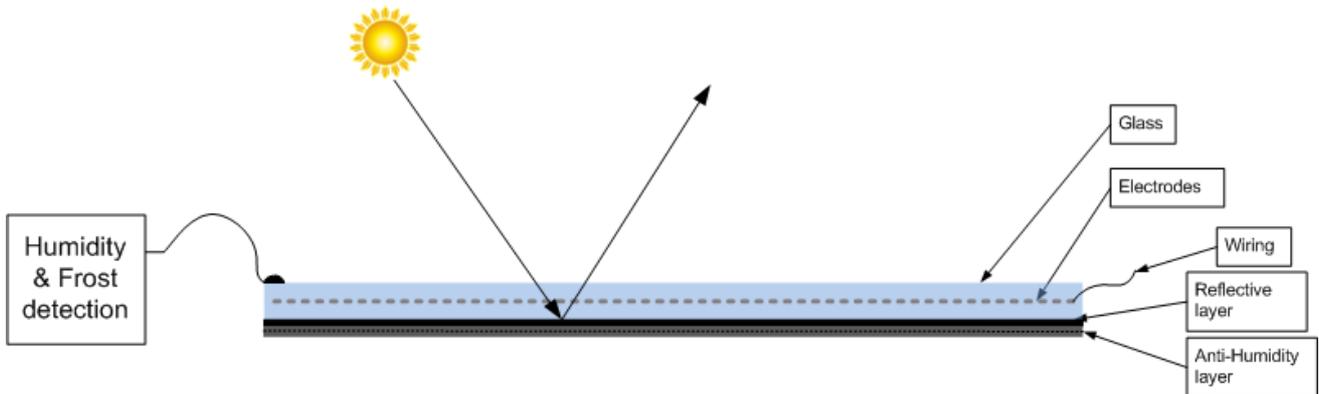


Figure 9 – Self-cleaning mirror with anti-humidity layer

As the anti-humidity system, being assembled on the back of the mirror, has no effect on the reflectivity nor on the performance of the electrostatic dust removal system. Two samples of 50x40 cm mirrors have been manufactured, mounted on a pilot setup (Figure 10), without tracking mechanism and at an angle of 45°. The pilot was tested outside in nature for 3 months during the winter time locally in Geneva.



Figure 10 - Anti-Humidity & De-Icing setup

7. Accomplishments and Tests

Three mirror samples have been produced and tested. One without electrodes to be used as a reference, the second with transparent electrodes and the third with reflective electrodes.

7.1. Silver adhesion test

The silver coating adhesion to the glass was tested using the ASTM D3359 scotch tape method giving a result of 5B.

7.2. Transmittance and reflectance

As light can be absorbed, scattered, transmitted and reflected depending on the material properties used, two types of coating technologies were researched and experimented in order to select the least absorbant and to obtain the highest reflectance possible.

When light interacts with the matter it intercepts the material properties associated with these behaviours are absorptance (α), transmittance (τ) and reflectance (ρ).

Combination of these parameters which are subject to the following law of conservation of energy:

$$\alpha + \tau + \rho = 1$$

Reflectance ρ is defined as the ratio of the radiant flux ϕ_r , reflected from a surface to that of the incident flux ϕ_i (Figure 9).

$$\rho = \frac{\phi_r}{\phi_i}$$

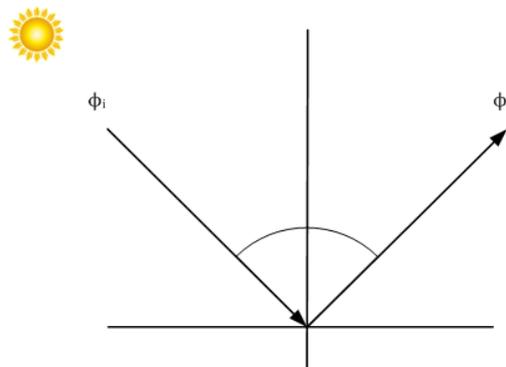


Figure 11 - Reflectance

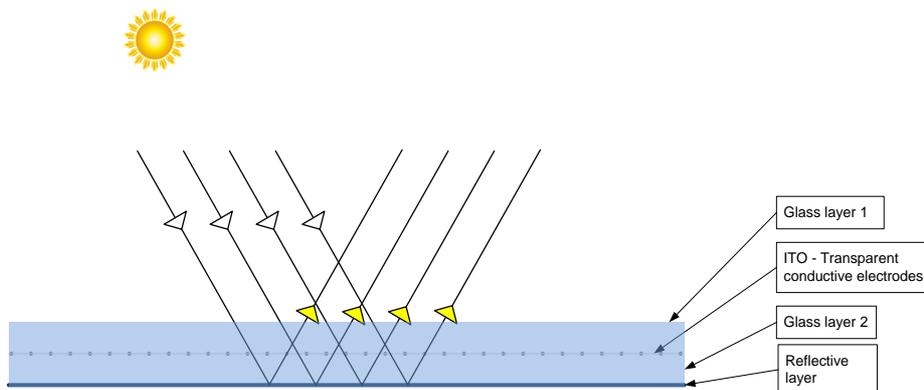


Figure 12 - Reflectance with ITO transparent electrodes

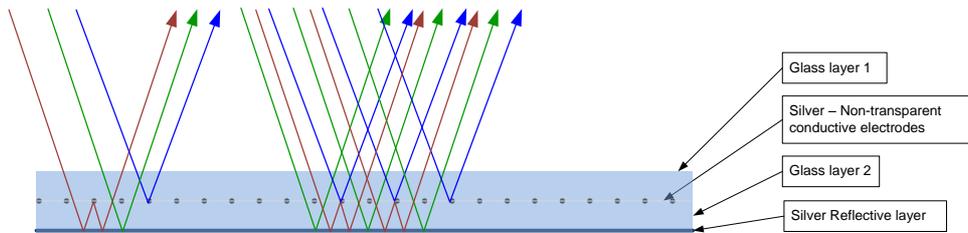


Figure 13 - Reflectance with silver non-transparent electrodes

7.3. Lab tests and validation

An Integrating Sphere optical measurements instrument (Figure 14) with an HeNe Laser has been used to measure the reflectance quality of the samples. A beam diameter of ~ 1.5 mm at an incident angle of 45° has been reflected off the samples and measured inside the Integrating Sphere. Reference measurements have been taken on a known target.



Figure 14 - Integrating Sphere optical test instrument

7.4. Reflective sample without electrodes

The first measurements were made on a sample mirror without the electrodes layer.

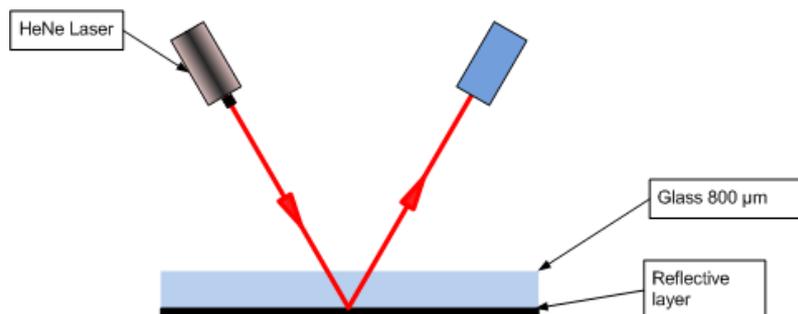


Figure 15 - Reference measurement without electrodes layer

Measurement	Reflectance %
1	94.8 %
2	95.2 %
Average	95.0%

Table 5 - Reference measurements

7.5. Reflective sample with ITO transparent electrodes

Measurements were then made on a sample multilayer mirror with ITO transparent electrodes.

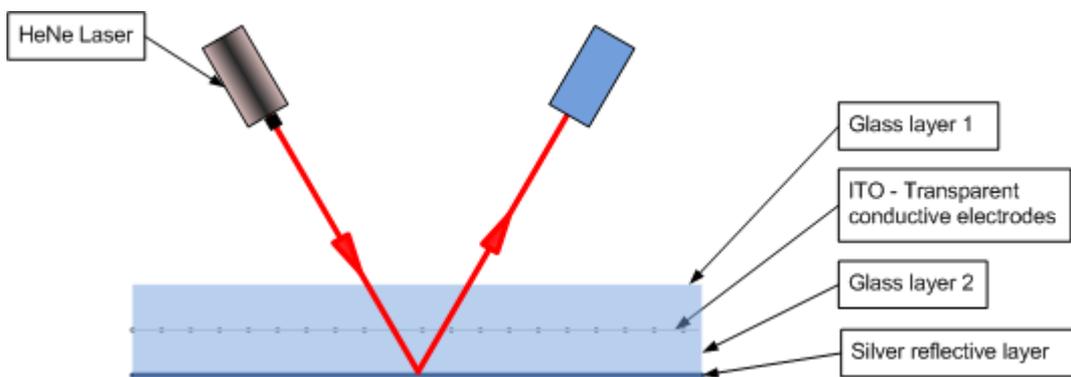


Figure 16 - Measurements with ITO transparent electrodes

Reflectance with ITO electrodes

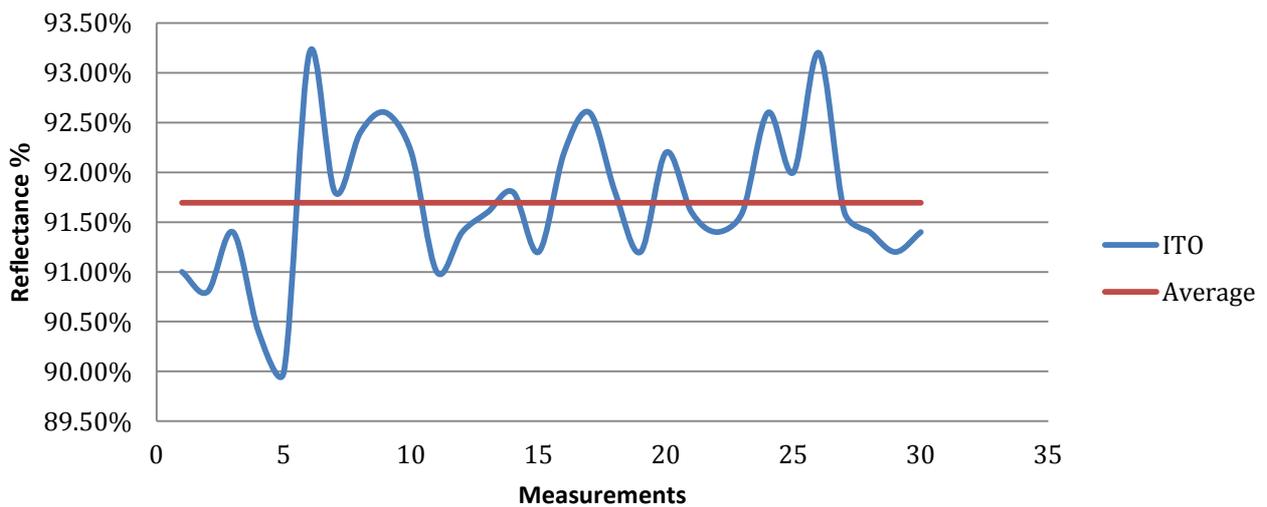


Figure 17 – Reflectance test of ITO sample

7.6. Reflective sample with Silver electrodes

Measurements were made on a sample multilayer mirror with silver non-transparent electrodes.

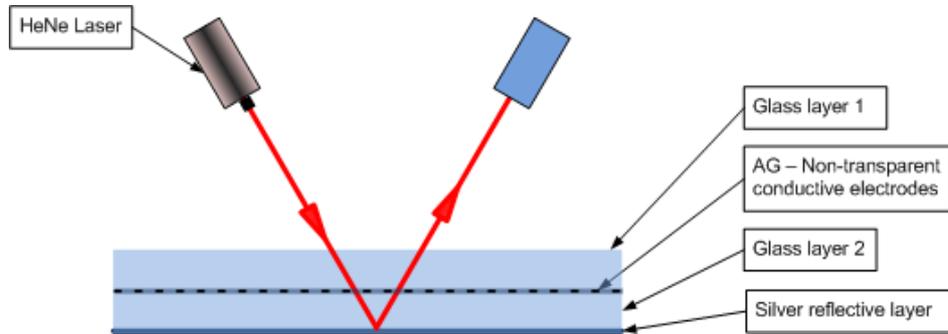


Figure 18 - Measurements with silver non-transparent electrodes

Due to the opacity of Silver, the laser beam has scattered off the back of the electrodes producing various effects as shown in figure 19 below.

The reflectance efficiency was not tested correctly with this apparatus due to the fact that the laser beam diameter is only around 1.5 mm and it will not represent the same effect produced by the much larger sunrays shining uniformly on the whole surface at once.

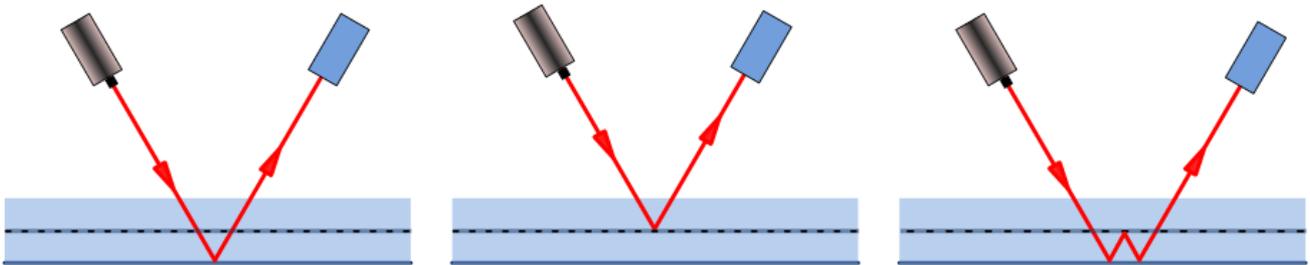


Figure 19 - Effects on beam through silver electrodes

7.7. Results with silver electrodes

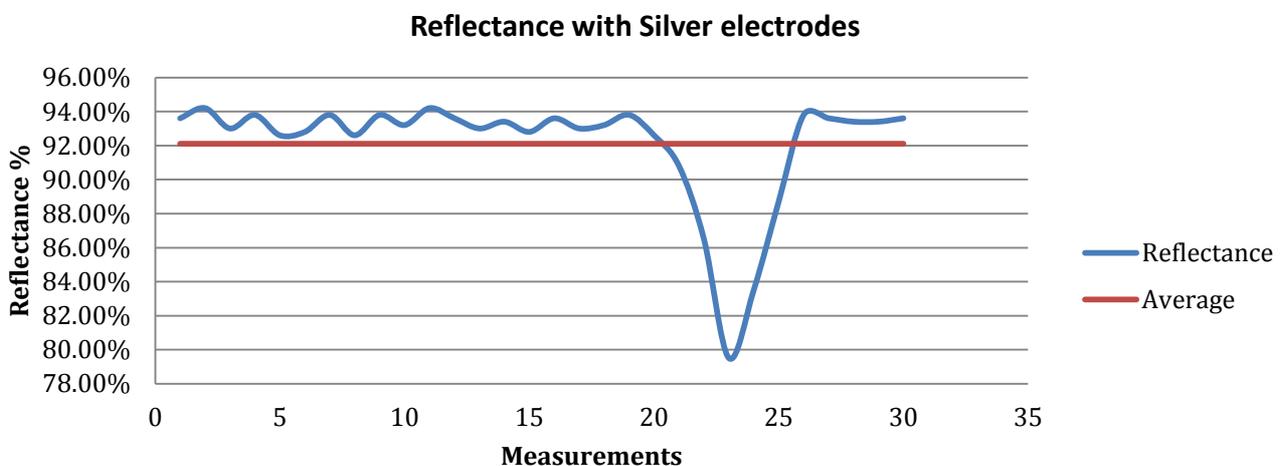


Figure 20 – Reflectance test of non-transparent silver electrodes

7.8. Reflectance comparison of mirrors with and without electrodes

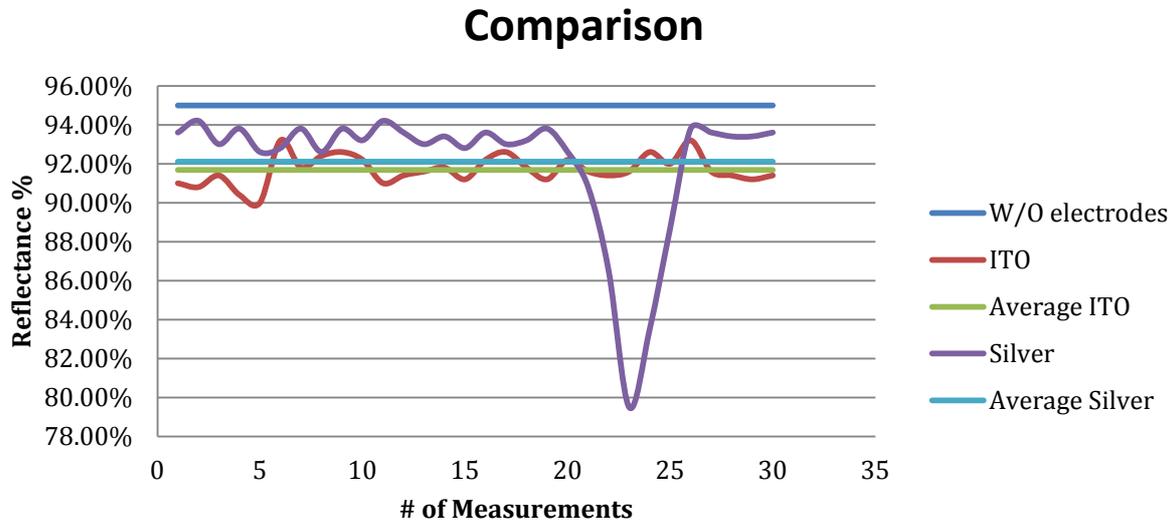


Figure 21 – Reflectance comparison of samples with and without electrodes

7.9. Electrostatic field tests

Four pulsed electric fields were tested and applied to the electrodes on the 10x10 cm. No surface discharge was noticed between the four electrodes due to the highly insulating encapsulant. Also no discharge or leakage towards the other surfaces. Successful and efficient dust particles transport even of particle size greater than 200µm.

7.10. Anti-humidity and de-icing tests

Anti-humidity and de-icing tests were carried out between the month of October and January. The top mirror was equipped with the SolarClean anti-humidity technology and the other mirror was not. During the entire test period the SolarClean mirror remained free of humidity, condensation and frost.



Figure 22 – Anti-humidity and anti-frost test

8. Findings and Conclusion

The main objective of this research project was to develop an Intelligent Active Self-cleaning Reflector to be manufactured and used for Concentrated Solar Power applications.

The first part of the work was focused on identifying materials, processes, coating methods, patterning techniques and assembly solutions.

Glass

- Low iron glass with thickness less than 1 mm for the front and the second layer

TCO electrodes

- Investigation revealed that ITO is better choice than the ZnO since it supports very well the selected adhesive layers

Reflective electrodes

- Silver was selected, among two other candidates Aluminum and Gold, due to its optical performance and cost

Coating methods

- magnetron sputtering, also known as PVD, was researched and selected from many other processes such as CVD, paint, ink jet printing etc.

Patterning techniques

The following patterning techniques have been researched and tested:

- **TCO patterning:** Photo Lithography with chemical etching was successfully used to pattern ITO. Also laser ablation was investigated and revealed successful results but substrate dimensions limitation were a barrier
- **Silver patterning:**
 - Photolithography was unsuccessful for patterning silver. The silver coating on the small patterned sample (10x10 cm) had to be deposited using a metallic mask. The mask was made out of metal favorable to sputtering conditions but could not exceed the above dimensions due to its mechanical instability.
 - For patterning larger samples of silver, many different method were investigated and revealed unsuccessful due to different reasons such as the weakness of the silver being reverse coated, the photoresist was not adapted to PVD process or the chemical etching products attacked the silver electrodes and removed them

Connectivity

- Two researched methods for connecting the electrodes to the wiring were successful, conductive adhesive tape and ultrasound soldering

Assembly

- The multilayer mirrors were assembled using the vacuum lamination process under specific temperature that proved to be most reliable
- Three sample mirrors of 10x10 cm have been assembled to be tested for optical performance and material selection

- Larger dimensions mirror samples of 40x50 cm were assembled, one with transparent electrodes and another one with the anti humidity layer
- An attempt to make a 70x60 cm sample was unsuccessful due to the instability and weakened adherence of silver following the patterning

Summary and Conclusion

Reflectance comparison between a mirror without electrodes, used as a reference, a mirror with TCO electrodes and a mirror with reflective electrodes proved that the reflective silver electrodes delivers higher optical performance than the TCO.

Material	W/O electrodes	ITO	Silver
Average Reflectance	95.00%	91.69%	92.11%

Due to the small diameter of the laser incident beam (~1.5 mm) used for characterizing the silver reflectance, compared to the sun rays, and also due to the separation of 3 mm between the electrodes, the reflected beam hitting the back of the silver electrodes was scattered performing lower reflectance. The average reflectance between the electrodes was measured at 93.38%.

A more realistic measurement should be taken with an incident beam spot of at least 10 mm to cover at least an area wider than 2-3 electrodes or even using sun rays would be the ideal condition.

The anti-humidity layer was successfully assembled to the mirror and the 3 months test showed a great reliability and high efficiency.

Most of the objectives in this phase 1 of the project were met except the reverse silver coating and patterning process. To resolve this barrier additional research, investigation and experimental trials must be carried out through the use of alternative deposition methods and by adding enhancing reflective material.

9. Acknowledgments

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