

# **Optical filters for spectral splitting photovoltaic-thermal collectors**

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# Statement of Originality

I hereby certify that, to the best of my knowledge, the content of this thesis is original and the result of my own work. All of the assistance I received and the sources I used have been properly acknowledged.

Joy Masilo-Kumi,

April 2025

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# Abstract

Solar energy technologies, such as photovoltaic cells for electricity and solar thermal collectors for heat, have garnered significant research interest. Combining these technologies results in a hybrid photovoltaic-thermal (PVT) collector that simultaneously generates electricity and heat. Only low to medium-temperature heat (up to 80 °C) can be generated because high-temperature heat (above 80 °C) reduces the efficiency of the PV cells. To address this, optical filters are incorporated into the collector to achieve a thermally decoupled design that separates the PV cells from the thermal absorber.

The optical filters investigated include dielectric-metal-dielectric (DMD) films and metasurfaces. The DMDs used consist of titanium dioxide (TiO<sub>2</sub>) as the dielectric layer and silver (Ag) as the metallic layer. The metasurfaces consist of nanostructured material arrays, particularly nanodisks. These optical filters operate by splitting the solar spectrum into wavebands. The waveband transmitted or reflected to the PV cells matches PV cells' spectral response, and the rest is directed to the thermal absorber. Incorporating optical filters results in a spectral splitting photovoltaic-thermal (SSPVT) collector. When coupled with concentrators such as mirrors or lenses, a spectral splitting concentrating photovoltaic-thermal (SSCPVT) collector is produced.

A parabolic trough SSCPVT collector with two fluid channels was used in this study. One is a PV cooling channel, and the other is for the thermal absorber. A coupled optical-electrical-thermal model of the SSCPVT collector was developed in COMSOL Multiphysics. The SSCPVT collector achieved an overall (electrical and thermal) efficiency of 55% without an optical filter. The simulated metasurface filter increased the overall efficiency to 63%, while the simulated DMD filter reached 68%. In comparison, the fabricated DMD filter only reached 60%. This discrepancy can be attributed to the fabricated filter's lower transmittance compared to the simulated one, due to optical losses from defects such as surface roughness.

# Dedication

*To my amazing husband, Dr David O. Kumi.*

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Thank You my Lord and Saviour, Jesus Christ, for Your abundant grace that sustains me.

# Nomenclature

## *Abbreviations*

|        |                                         |
|--------|-----------------------------------------|
| AM     | Air mass                                |
| AFM    | Atomic force microscopy                 |
| ALD    | Atomic layer deposition                 |
| DC     | Direct current                          |
| DMD    | Dielectric-metal-dielectric             |
| EBL    | Electron beam lithography               |
| FEM    | Finite element method                   |
| FIB    | Focused ion beam                        |
| FF     | Fill factor                             |
| IPA    | Isopropyl alcohol                       |
| LSCM   | Laser scanning confocal microscopy      |
| NIR    | Near-infrared                           |
| OLED   | Organic light-emitting diode            |
| PEVA   | Poly(ethylene-vinyl acetate)            |
| PV     | Photovoltaic                            |
| PVD    | Physical vapour deposition              |
| PVT    | Photovoltaic-thermal                    |
| QD     | Quantum dot                             |
| RF     | Radio frequency                         |
| RMSE   | Root mean square error                  |
| SEM    | Scanning electron microscopy            |
| SR     | Spectral response                       |
| SSPVT  | Spectral splitting photovoltaic-thermal |
| THM    | Transparent heat mirror                 |
| UV-Vis | Ultraviolet-visible                     |
| XRD    | X-ray diffraction                       |
| XPS    | X-ray photoelectron spectroscopy        |

## ***Symbols***

|                 |                                                           |
|-----------------|-----------------------------------------------------------|
| $A'$            | Ideality factor                                           |
| $A_c$           | Aperture area of the collector                            |
| $A_{PV}$        | Area of the photovoltaic cells                            |
| $c_p$           | Specific heat capacity                                    |
| $C_{geo}$       | Geometric concentration ratio                             |
| $D_o$           | Outer diameter of the glass cover                         |
| $e$             | Unit charge of an electron                                |
| $E$             | Electric field                                            |
| $f$             | Focal length                                              |
| $F$             | Force                                                     |
| $G_{abs}$       | Solar irradiance absorbed by the thermal absorber         |
| $G_{AM1.5}$     | Solar irradiance at AM 1.5                                |
| $G_{PV}$        | Solar irradiance absorbed by the PV cells                 |
| $h_w$           | Heat convection coefficient                               |
| $J_{sc}$        | Short-circuit current                                     |
| $k_B$           | Boltzmann constant                                        |
| $k_0$           | Wavenumber in a vacuum                                    |
| $L_c$           | Collector length                                          |
| $\dot{m}_{pri}$ | Mass flow rate of the fluid through the primary channel   |
| $\dot{m}_{sec}$ | Mass flow rate of the fluid through the secondary channel |
| $q$             | Heat flux by conduction                                   |
| $q_{loss}$      | Heat loss                                                 |
| $q_r$           | Heat flux by radiation                                    |
| $Q$             | Boundary heat sources                                     |
| $Q_{PV,abs}$    | Solar energy absorbed by the photovoltaic cell            |
| $Q_{PV,h}$      | Heat generated in the photovoltaic cell                   |
| $T_a$           | Ambient temperature                                       |
| $T_{in}$        | Inlet temperature                                         |
| $T_{m\_pri}$    | Mean temperature of the primary channel                   |
| $T_{m\_sec}$    | Mean temperature of the secondary channel                 |
| $T_{pri}$       | Outlet temperature secondary channel                      |

|              |                                              |
|--------------|----------------------------------------------|
| $T_{PV}$     | Photovoltaic cell temperature                |
| $T_{ref}$    | Reference temperature                        |
| $T_{r\_pri}$ | Reduced temperature of the primary channel   |
| $T_{r\_sec}$ | Reduced temperature of the secondary channel |
| $T_{sec}$    | Outlet temperature secondary channel         |
| $T_{sky}$    | Sky temperature                              |
| $T_w$        | Outer wall temperature                       |
| $V_{max}$    | Maximum voltage                              |
| $V_{oc}$     | Open-circuit voltage                         |
| $V_w$        | Wind speed                                   |
| $u$          | Velocity vector                              |
| $V_{oc}$     | Open-circuit voltage                         |
| $V_w$        | Wind speed                                   |
| $W_c$        | Collector width                              |
| $W_{i,pri}$  | Primary channel inner width                  |
| $W_{o,pri}$  | Primary channel outer width                  |
| $W_{sec}$    | Secondary channel width                      |

### ***Greek***

|                  |                                                  |
|------------------|--------------------------------------------------|
| $\alpha_{PV}$    | Absorptivity of the PV cell                      |
| $\beta$          | Temperature coefficient of the photovoltaic cell |
| $\eta_{el}$      | Electrical efficiency                            |
| $\eta_{el,0}$    | Electrical efficiency at a reference temperature |
| $\eta_{th\_pri}$ | Thermal efficiency of the primary channel        |
| $\eta_{th\_sec}$ | Thermal efficiency of the secondary channel      |
| $\rho$           | Density                                          |
| $\rho_{mirror}$  | Reflectance of the mirror                        |
| $\rho_{filter}$  | Reflectance of the filter                        |
| $\sigma$         | Stefan-Boltzmann constant                        |
| $\tau_{filter}$  | Transmittance of the filter                      |
| $\tau_g$         | Transmittance of glass                           |

# Table of Contents

|                                             |      |
|---------------------------------------------|------|
| Statement of Originality.....               | i    |
| Copyright Declaration.....                  | ii   |
| Abstract .....                              | iii  |
| Dedication .....                            | iv   |
| Acknowledgements.....                       | v    |
| Nomenclature .....                          | vi   |
| List of Figures .....                       | xiii |
| List of Tables.....                         | xvii |
| Chapter 1: Introduction and motivation..... | 1    |
| 1.1. Introduction.....                      | 2    |
| 1.2. Motivation.....                        | 3    |
| 1.3. Aim.....                               | 5    |
| 1.4. Objectives .....                       | 5    |
| 1.5. Outline of the thesis .....            | 6    |
| 1.6. References.....                        | 6    |
| Chapter 2: Literature review .....          | 11   |
| 2.1. Overview .....                         | 12   |
| 2.2. SSCPVT collector designs .....         | 12   |
| 2.3. Configuration of PVT collectors.....   | 14   |
| 2.3.1. Flat plate.....                      | 14   |
| 2.3.2. Parabolic trough.....                | 16   |
| 2.3.3. Linear Fresnel .....                 | 17   |
| 2.3.4. Parabolic dish.....                  | 17   |
| 2.4. Optical filters .....                  | 19   |

|                                                                       |    |
|-----------------------------------------------------------------------|----|
| 2.4.1. Nanofluids as optical filters .....                            | 19 |
| 2.4.2. Nanocomposite-based optical filters.....                       | 23 |
| 2.4.3. Thin film based optical filters for SSPVT collectors .....     | 24 |
| 2.4.4. Metasurfaces as optical filters.....                           | 29 |
| 2.5. Literature gap and thesis novelty .....                          | 31 |
| 2.6. References.....                                                  | 32 |
| Chapter 3: Methodology .....                                          | 43 |
| 3.1. Overview.....                                                    | 44 |
| 3.2. Modelling of DMD and metasurface optical filters .....           | 44 |
| 3.3. Fabrication of DMD films .....                                   | 45 |
| 3.3.1. Characterisation of the fabricated DMD optical filters.....    | 46 |
| 3.4. Collector design .....                                           | 47 |
| 3.5. SSPVT model outline.....                                         | 49 |
| 3.5.1. Optical sub model .....                                        | 49 |
| 3.5.2. PV electrical sub model .....                                  | 50 |
| 3.5.3. Heat transfer and fluid dynamics sub model.....                | 50 |
| 3.5.4. PV-weighted average transmittance of the optical filters ..... | 52 |
| 3.5.5. Flow diagram of the SSPVT model .....                          | 53 |
| 3.6. Summary.....                                                     | 53 |
| 3.7. References.....                                                  | 54 |
| Chapter 4: Simulation and fabrication of DMD optical filters .....    | 55 |
| 4.1. Introduction.....                                                | 56 |
| 4.2. Comsol simulation results.....                                   | 57 |
| 4.2.1. Model validation using the literature results.....             | 57 |
| 4.2.2. Effect of changing the metal layer .....                       | 58 |
| 4.2.3. Effect of varying the TiO <sub>2</sub> thickness .....         | 59 |
| 4.2.4. Effect of varying the Ag thickness .....                       | 60 |

|                                                                                                         |    |
|---------------------------------------------------------------------------------------------------------|----|
| 4.3. Experimental results.....                                                                          | 61 |
| 4.3.1. Atomic force microscopy (AFM).....                                                               | 62 |
| 4.3.2. X-ray diffraction (XRD) .....                                                                    | 62 |
| 4.3.3. X-ray photoelectron spectroscopy .....                                                           | 63 |
| 4.3.4. Model validation using experimental data .....                                                   | 64 |
| 4.3.5. Optical properties of fabricated DMD films .....                                                 | 65 |
| 4.4. Summary .....                                                                                      | 66 |
| 4.5. References.....                                                                                    | 67 |
| Chapter 5: The influence of DMD optical filters on the performance of the SSCPVT collector .....        | 70 |
| 5.1. Introduction.....                                                                                  | 71 |
| 5.2. DMD optical filter selection for PV cells .....                                                    | 72 |
| 5.3. Performance evaluation of the SSCPVT.....                                                          | 76 |
| 5.3.1. Electrical model validation .....                                                                | 76 |
| 5.3.2. Thermal model validation .....                                                                   | 77 |
| 5.3.3. Effect of mass flow rate on the electrical and thermal efficiencies of the SSCPVT collector..... | 78 |
| 5.3.4. Performance curves of the SSCPVT collector using DMDs .....                                      | 79 |
| 5.4. Summary .....                                                                                      | 81 |
| 5.5. References.....                                                                                    | 82 |
| Chapter 6: A parametric study on metasurfaces as potential optical filters in SSCPVTs .....             | 84 |
| 6.1. Introduction.....                                                                                  | 85 |
| 6.2. Metasurface optical filter simulation results.....                                                 | 85 |
| 6.2.1. Simulated regular Ag thin film and metasurfaces consisting of Ag nanodisk arrays .....           | 86 |
| 6.2.2. Simulated metasurfaces consisting of nanodisk arrays of Ag and DMD.....                          | 87 |
| 6.2.3. Simulated metasurfaces consisting of nanodisk arrays of Ag with a hexagonal arrangement.....     | 91 |

|                                                                                                             |     |
|-------------------------------------------------------------------------------------------------------------|-----|
| 6.3. Modelling of the SSCPVT performance using metasurface optical filters.....                             | 92  |
| 6.3.1. Evaluation of the PV modules' system level efficiencies using metasurfaces.....                      | 93  |
| 6.3.2. Performance curves of the SSCPVT collector using a metasurface filter .....                          | 96  |
| 6.3.3. Comparison in the efficiencies resulting from using the DMD and metasurface<br>optical filters ..... | 97  |
| 6.4. Summary .....                                                                                          | 98  |
| 6.5. References.....                                                                                        | 98  |
| Chapter 7: Conclusions and future recommendations .....                                                     | 100 |
| 7.1. General conclusions .....                                                                              | 101 |
| 7.2. Recommendations.....                                                                                   | 103 |
| Appendix A .....                                                                                            | 104 |

# List of Figures

## Chapter 1

|                                                                              |   |
|------------------------------------------------------------------------------|---|
| Figure 1.1: Spectral response of c-Si and CdTe PV cell materials [21]. ..... | 3 |
|------------------------------------------------------------------------------|---|

## Chapter 3

|                                                                                                                               |    |
|-------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 3.1: Schematic representation of: a) DMD films, and b) metasurface unit cell. ....                                     | 44 |
| Figure 3.2: Schematic representation of the optical filter simulation on COMSOL Multiphysics®.....                            | 45 |
| Figure 3.3: (a) Uncoated substrate, (b) TiO <sub>2</sub> film (20 min.), b) Ag film (37 s) and (c) DMD-e1. ....               | 46 |
| Figure 3.4: a) Schematic diagram of the SSCPVT collector, and the cross-section of the b) primary channel and c) SSCPVT. .... | 48 |
| Figure 3.5: Flow diagram of the SSCPVT collector. ....                                                                        | 53 |

## Chapter 4

|                                                                                                                                                                                                                                                 |    |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 4.1: a) The refractive index of Ag, Au, and Cu by Johnson and Christy [14] and b) schematic diagram of the TiO <sub>2</sub> -Ag-TiO <sub>2</sub> DMD. ....                                                                               | 57 |
| Figure 4.2: Transmittance and reflectance spectra of ZnS (31 nm)-Ag(18 nm)-ZnS (34 nm) DMD obtained using our model and the spectra obtained in the literature [11]......                                                                       | 58 |
| Figure 4.3: a) Transmittance, b) reflectance and c) absorptance of DMD films consisting of TiO <sub>2</sub> as the dielectric material and the metallic material is varied between Ag, Au and Cu. ..                                            | 59 |
| Figure 4.4: a) Transmittance, b) reflectance and c) absorptance spectra, and d) contour plot of TiO <sub>2</sub> -Ag-TiO <sub>2</sub> DMDs with Ag thickness fixed at 10 nm while TiO <sub>2</sub> thickness is varied between 10 – 70 nm. .... | 60 |

|                                                                                                                                                                                                                           |    |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 4.5: a) Transmittance spectra, b) reflectance spectra and c) absorptance spectra and d) contour plot of DMDs with TiO <sub>2</sub> thickness fixed at 40 nm while Ag thickness is varied between 10 and 25 nm..... | 61 |
| Figure 4.6: a) AFM and b) SEM images of Ag film, c) AFM and d) SEM images of TiO <sub>2</sub> film. ....                                                                                                                  | 62 |
| Figure 4.7: XRD patterns of Ag, TiO <sub>2</sub> and DMD films with varying Ag thickness deposited on a glass substrate.....                                                                                              | 63 |
| Figure 4.8: XPS spectra of (a-b) TiO <sub>2</sub> , and c) Ag. ....                                                                                                                                                       | 64 |
| Figure 4.9: Transmittance, reflectance and absorptance spectra of the simulated (DMD-s) and fabricated (DMD-e) DMD filters.....                                                                                           | 65 |
| Figure 4.10: Transmittance spectra of a glass substrate, Ag, TiO <sub>2</sub> and DMD-e7, and Transmittance spectra of the fabricated DMD filters.....                                                                    | 66 |

## Chapter 5

|                                                                                                                                                                                                              |    |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 5.1: Parabolic trough SSCPVT collector with primary and secondary channels and a DMD optical filter.....                                                                                              | 72 |
| Figure 5.2: The c-Si PV module electrical efficiency at T <sub>ref</sub> 25 °C of the DMD-s filters.....                                                                                                     | 74 |
| Figure 5.3: CdTe PV module electrical efficiency at T <sub>ref</sub> 25 °C of the DMD-s filters. ....                                                                                                        | 75 |
| Figure 5.4: CdTe and c-Si PV module electrical efficiency at T <sub>ref</sub> 25 °C of the DMD-e filters. ....                                                                                               | 75 |
| Figure 5.5: Spectral irradiance of AM1.5, spectral responses of c-Si and CdTe cells, and bounds of the optical filter.....                                                                                   | 76 |
| Figure 5.6: Comparison of our model to the manufacturers' a) c-Si and b) CdTe data. ....                                                                                                                     | 77 |
| Figure 5.7: Comparison of the overall efficiency of the collector as a function of reduced temperature for the developed model and experiments performed by Cabral et al. [17]. ....                         | 77 |
| Figure 5.8: Thermal and electrical efficiencies against mass flow rate of the primary channel including a) c-Si PV cells using DMD-s6 b) CdTe PV cells using DMD-s6, and c) c-Si PV cells using DMD-e1. .... | 79 |

Figure 5.9: Thermal and electrical efficiencies against reduced temperature of the primary channel including a) c-Si PV cells using DMD-s6 b) CdTe PV cells using DMD-s6, and c) c-Si PV cells using DMD-e1.....80

Figure 5.10: Thermal efficiencies against reduced temperature of the secondary channel of a) c-Si SSPVT collector using DMD-s6 b) CdTe SSPVT collector using DMD-s6, and c) c-Si SSPVT collector using DMD-e1.....81

## Chapter 6

Figure 6.1: Schematic representation of a) regular Ag film, b) Ag nanodisk array. ....86

Figure 6.2: Optical properties of 20 nm a) Ag film, and b) Ag nanodisk. ....86

Figure 6.3: a) Transmittance, b) reflectance and c) absorptance spectra of Ag metasurfaces with a square pattern arrangement with different thicknesses and d) unit cell of the optical filters. ....89

Figure 6.4: a) Transmittance, b) reflectance and c) absorptance spectra of Ag metasurfaces with a square pattern arrangement with different thicknesses and d) unit cell of the optical filters. ....90

Figure 6.5: a) Transmittance, b) reflectance, c) absorptance of DMD nanodisks with square arrangement and d) unit cell of the optical filters. ....91

Figure 6.6: a) Transmittance, b) reflectance, c) absorptance of Ag nanodisks with hexagonal arrangement and d) unit cell of the optical filters. ....92

Figure 6.7: SSPVT collector with the PV cells placed at the bottom. ....93

Figure 6.8: The c-Si and CdTe PV module electrical efficiencies at  $T_{\text{ref}} = 25\text{ }^{\circ}\text{C}$  of the Ag nanodisk metasurfaces with a square arrangement. ....94

Figure 6.9: The c-Si and CdTe PV module electrical efficiencies at  $T_{\text{ref}} = 25\text{ }^{\circ}\text{C}$  of the DMD nanodisk metasurfaces with a square arrangement. ....95

Figure 6.10: The c-Si and CdTe PV modules' electrical efficiencies at  $T_{\text{ref}} = 25\text{ }^{\circ}\text{C}$  of the Ag nanodisk metasurfaces with a hexagonal arrangement. ....96

|                                                                                                                                                                                                                                                                          |    |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| Figure 6.11: a) Thermal and electrical efficiencies of c-Si PV primary cooling channel, and b) thermal efficiency of the secondary channel against reduced temperature using the simulated hexagonal Ag nanodisk metasurface filter, $\text{met}_{\text{Ag\_hx4}}$ ..... | 97 |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|

## Chapter 7

|                                                                                                                          |     |
|--------------------------------------------------------------------------------------------------------------------------|-----|
| Figure A.1: Thickness of $\text{TiO}_2$ measured using AFM and the step height obtained using the Gwyddion software..... | 104 |
|--------------------------------------------------------------------------------------------------------------------------|-----|

|                                                                                                              |     |
|--------------------------------------------------------------------------------------------------------------|-----|
| Figure A.2: Thickness of Ag measured using AFM and the step height obtained using the Gwyddion software..... | 105 |
|--------------------------------------------------------------------------------------------------------------|-----|

# List of Tables

## Chapter 2

|                                                                                            |    |
|--------------------------------------------------------------------------------------------|----|
| Table 2.1: Comparison of non-concentrating and concentrating PVT collectors [22-24]. ..... | 14 |
| Table 2.2: Comparison of different CPVT collectors. ....                                   | 18 |
| Table 2.3: Factors that affect the stability duration of nanofluids. ....                  | 23 |
| Table 2.4: Summary of the DMD fabrication techniques used by other authors.....            | 27 |
| Table 2.5: Summary of the deposition parameters used by other authors. ....                | 28 |
| Table 2.6: Metasurface fabrication techniques [110, 122-124].....                          | 30 |

## Chapter 3

|                                                                  |    |
|------------------------------------------------------------------|----|
| Table 3.1: Optical filter names and their deposition times. .... | 46 |
| Table 3.2: Parameters used in the SSCPVT model.....              | 49 |

## Chapter 4

|                                                                              |    |
|------------------------------------------------------------------------------|----|
| Table 4.1: Fabricated optical filters and their respective thicknesses. .... | 66 |
|------------------------------------------------------------------------------|----|

## Chapter 5

|                                                                                       |    |
|---------------------------------------------------------------------------------------|----|
| Table 5.1: Simulated optical filters used in the electrical and thermal models.....   | 73 |
| Table 5.2: Fabricated optical filters used in the electrical and thermal models. .... | 74 |

## Chapter 6

|                                                                                                |    |
|------------------------------------------------------------------------------------------------|----|
| Table 6.1: Simulated optical filters and their dimensions.....                                 | 88 |
| Table 6.2: Simulated metasurface optical filters used in the electrical and thermal models. .. | 93 |

|                                                                                              |    |
|----------------------------------------------------------------------------------------------|----|
| Table 6.3: Comparison of the efficiencies of the SSCPVT collectors with and without filters. | 97 |
|----------------------------------------------------------------------------------------------|----|

## Chapter 7

|                                                                           |     |
|---------------------------------------------------------------------------|-----|
| Table A.1: Thickness of Ag and TiO <sub>2</sub> films measured using AFM. | 105 |
|---------------------------------------------------------------------------|-----|

# Chapter 1: Introduction and motivation

## Table of contents

|                                  |   |
|----------------------------------|---|
| 1.1. Introduction.....           | 2 |
| 1.2. Motivation.....             | 3 |
| 1.3. Aim.....                    | 5 |
| 1.4. Objectives .....            | 5 |
| 1.5. Outline of the thesis ..... | 6 |
| 1.6. References.....             | 6 |

## 1.1. Introduction

Meeting the rising global energy demands sustainably is one of the greatest challenges of this era. Fossil fuels which have been utilised extensively to meet these energy demands over the years are rapidly diminishing and contributing to global warming [1-3]. In response to this, renewable energy technologies have been widely considered in the academic literature and in sizable global markets. Among these technologies are solar energy technologies that can meet the growing energy demands sustainably because solar energy is abundant, and its harvesting does not involve carbon emissions [4, 5].

Solar energy technologies that are commonly employed include photovoltaic (PV) cells which produce electricity, and thermal absorber for the provision of useful heat. While thermal absorbers use the entire solar spectrum, PV cells only use a specific range of the solar spectrum due to the bandgap of the PV cells [6]. Photons with energies corresponding to the bandgap of a PV cell are efficiently used. For instance, the most commercially employed PV cell, crystalline silicon (c-Si) PV cell, has a bandgap of about 1.1 eV. Photons with energies lower than the bandgap of the PV cell are not absorbed by it, as a result they increase the temperature of the back of the PV cell.

Although the photons with higher energy than the bandgap of the PV cell are absorbed by it, they result in excess heat that causes an increase in the temperature of the PV cell. Therefore, PV cells have a predetermined spectral response (Figure 1.1) at which their efficiencies are optimal. The photons with energies outside the spectral response of these PV cells tend to increase the temperature of the PV cell resulting in the attenuation of their efficiency. PV cells and thermal absorber can be combined to produce hybrid photovoltaic-thermal (PVT) collectors that cool the PV cell while also producing useful heat [7-9]. There are various types of PVT collectors [10]. Concentrators can be added to PVT collectors, resulting in concentrating PVT (CPVT) collectors, to enhance the electrical and thermal efficiencies [11, 12]. PVT collectors have higher overall efficiencies compared to the standalone PV or thermal absorber [13-15]. Hamdy et al. [16] demonstrated that higher electrical efficiencies can be achieved from the PVT collector than the standalone PV cell due to the reduction in the temperature of the PV cell. The PVT collector uses the solar spectrum by splitting the solar spectrum into wavelengths that will be efficiently used by the PV cell and thermal absorber using an optical filter. The optical filter can take the form of an optical coating or filter that uses the principles of reflection or absorption to separate the sunlight [17]. In absorption-based optical filters [18-20], photons with energy corresponding to the spectral response of the PV

cell pass through the optical filter and are converted into electricity by the PV cells. However, photons with lower or higher energy than those sent to the PV cells are absorbed by the optical filter and sent to the thermal absorber, resulting in useful heat.

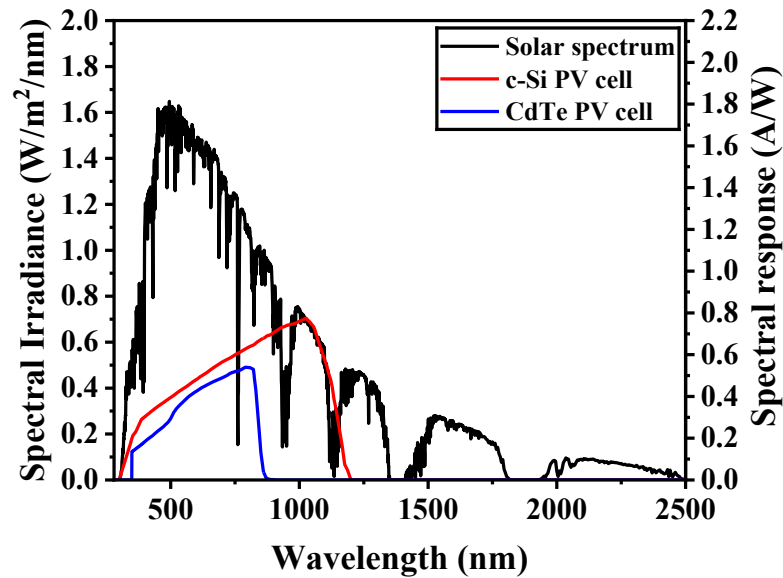


Figure 1.1: Spectral response of c-Si and CdTe PV cell materials [21].

## 1.2. Motivation

Conventionally, PVT collectors operate by recovering waste heat using a heat transfer fluid. The heat transfer fluid is usually in direct contact with the PV cell, flowing underneath or on top of it to remove the excess heat from it. However, this results in low to medium temperature heat (up to 80 °C) applications of the PVT collectors since high temperatures, such as 120 °C, are detrimental to the efficiency of the PV cell [6]. This can be mitigated by thermally decoupling the PV cell and thermal absorber enabling them to operate at different temperatures [22]. This is achieved by using an optical filter to achieve a spectral splitting PVT (SSPVT) or CPVT (SSCPVT) collector. The optical filter operates by dividing the solar spectrum into different wavelength bands and directing them to the suitable receiver. The optical filters can either be solids or liquids. Optical filters can be made of interference thin films. Thin films consist of several layers of different refractive indices. Combining these layers to achieve the appropriate transmittance and reflectance is a complex and expensive process. Consequently, absorptive fluids have garnered increasing research interest as optical filters due to their potential to be less expensive. Conventionally, water, inorganic liquids, glycols and oils are used, but they mostly absorb the infrared part of the spectrum and are mostly transparent in the visible light part of the solar spectrum, which is outside the spectral response of PV cells [23].

To enhance the optical properties of the fluid optical filters, nanoparticles are suspended in them resulting in ‘nanofluids’. The optical properties of the nanofluids can be easily tailored by changing their volume fraction, nanoparticle material, shape, and size. However, nanoparticle suspensions (nanofluids) are susceptible to agglomeration and sedimentation. This is due to the Brownian motion of the nanoparticles as a result of the constant nanoparticle-nanoparticle collisions. This motion results in the agglomeration of the nanoparticles which then settle out of the solution. This process occurs more rapidly when the nanofluids are pumped through tubes as is the case when they are used in SSCPVT collectors and other industrial applications [24]. The methods used to stabilise nanoparticles in a nanofluid reported in the literature include ultrasonication and the use of surfactants or stabilising agents [25, 26]. Some surfactants may improve the stability of nanofluids but hinder heat transfer between the nanoparticles [27]. Despite the nanofluids’ potential benefits, and efforts by researchers to enhance their stability [28-30], their use in SSCPVT collectors remains a challenge.

Therefore, we propose the use of thin film optical filters whose stability can be tailored to last for years [31, 32]. However, the thin film optical filters selected consist of fewer layers, i.e. a maximum of three layers. These thin film optical filters include dielectric-metal-dielectric (DMD) materials, and metasurfaces. DMDs are tri-layer thin films achieved by using a metal layer sandwiched between two dielectric layers deposited on a substrate. DMDs function by transmitting the visible region of the solar spectrum and reflecting NIR region. The metal layer selected should have a very high reflectance and low absorbance in the visible region, which means that the metal should have a very low refractive index. For instance, Ag, Au and Cu have refractive indices of 0.052, 0.28, and 0.64, respectively. These metals are the most used metal layers in DMDs, and of the three, Ag exhibits the highest reflectance. The dielectric layers on both sides of the highly reflective metal act as anti-reflective layers that enhances overall transparency of the DMD optical filter. DMDs consisting of dielectric materials such as  $\text{WO}_3$  [33], ITO [33],  $\text{ZnS}$  [34], and  $\text{TiO}_2$  [35] have been reported. Although DMD optical filters have been widely used in smart windows [36, 37], they can also be used as optical filters in SSCPVT collectors. This is because their high transparency in the visible region results in the transmittance of visible region of the solar spectrum to PV cells, most of which have a spectral response corresponding to visible wavelengths. The NIR region that is reflected by the DMD optical filters can be directed to the thermal absorber component of the SSCPVT collector. The dielectric and metal layers of the DMD optical filters used in this study are  $\text{TiO}_2$  and Ag respectively.  $\text{TiO}_2$  enhances visible light transmittance, while the Ag enhances NIR reflectance.

In addition to the DMDs, metasurfaces have attracted immense research attention as the easier to fabricate two-dimensional (2D) counterpart of the 3D metamaterials [38-40]. Metasurfaces are flat nanostructured arrays that can be used for applications such as imaging [41] and optical computing [42] due to their ability to control the amplitude, phase and polarisation of light. This can be achieved by exploiting the nanoarray structure of the metasurfaces to tune the localised surface plasmon resonance (LSPR). As a result, the transmittance, reflectance and absorbance of materials can be tuned. The optical properties of metasurfaces depend on their nanostructured array geometry, and arrangement in addition to their material properties. Of particular interest in this research project, is the use of metasurfaces that can either reflect or transmit the solar spectrum to the PV cell and to the thermal absorber. Materials used in the DMDs were also used in the metasurfaces to further tune the selectivity of the optical filters.

### **1.3. Aim**

The aim of the research is to design and fabricate optical filters to enhance the overall efficiency of SSCPVT collectors. These optical filters will be tailored to the specific PV cell material used. For a c-Si PV cell with a spectral response corresponding to the wavelength range of 300 – 1100 nm, the optical filters will direct this wavelength range of the solar spectrum to the c-Si PV cell, and the rest of the solar spectrum will be directed to the thermal absorber.

### **1.4. Objectives**

- a) To simulate the optical properties of the DMD and metasurface optical filters and optimise them such that they are suitable for use as optical filters for different PV materials.
- b) To fabricate DMD optical filters using a physical vapour deposition method, magnetron sputtering.
- c) To characterise the fabricated materials using atomic force microscopy (AFM), X-ray diffraction (XRD), X-ray photoelectron spectroscopy (XPS), scanning electron microscopy (SEM), and UV-Vis-NIR spectroscopy.
- d) Modelling of an SSCPVT collector efficiency, and testing of the fabricated DMD filters under a solar simulator.

## 1.5. Outline of the thesis

**Chapter 1:** The chapter gives a brief introduction to the study and the associated aims, objectives, and the rationale.

**Chapter 2:** The chapter gives a detailed literature review on the spectral splitting photovoltaic-thermal (SSCPVT) collectors and the types of optical filters used.

**Chapter 3:** The chapter provides a detailed description of the experimental procedures and characterisation techniques used in the synthesis and analysis of the optical filters.

**Chapter 4:** The chapter focuses on the simulation and fabrication of dielectric-metal-dielectric (DMD) materials as potential SSCPVT optical filters.

**Chapter 5:** The chapter reports on the results obtained from SSCPVT modelling using DMD optical filters.

**Chapter 6:** The chapter reports on the results obtained from using metasurfaces as potential optical filters in the SSCPVT model.

**Chapter 7:** The chapter provides the overall conclusions of the study and future recommendations.

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# Chapter 2: Literature review

## Table of contents

|                                                                  |    |
|------------------------------------------------------------------|----|
| 2.1. Overview.....                                               | 12 |
| 2.2. SSCPVT collector designs .....                              | 12 |
| 2.3. Configuration of PVT collectors.....                        | 14 |
| 2.3.1. Flat plate.....                                           | 14 |
| 2.3.2. Parabolic trough .....                                    | 16 |
| 2.3.3. Linear Fresnel .....                                      | 17 |
| 2.3.4. Parabolic dish.....                                       | 17 |
| 2.4. Optical filters .....                                       | 19 |
| 2.4.1. Nanofluids as optical filters .....                       | 19 |
| 2.4.2. Nanocomposite-based optical filters.....                  | 23 |
| 2.4.3. Thin film based optical filters for SSPVT collectors..... | 24 |
| 2.4.4. Metasurfaces as optical filters.....                      | 29 |
| 2.5. Literature gap and thesis novelty .....                     | 31 |
| 2.6. References.....                                             | 32 |

## 2.1. Overview

As global energy demand continues to soar, it is important to meet it efficiently and sustainably while limiting carbon footprint. This has fuelled research on renewable energy technologies which include solar energy technologies. As mentioned earlier, combinations of the two main solar energy technologies, photovoltaic (PV) and solar thermal, have garnered great research attention. This has given rise to immense research on hybrid photovoltaic-thermal collectors, especially the spectral splitting photovoltaic-thermal (SSPVT) collectors. SSPVT collectors produce electricity and useful heat which is not limited by the PV material used. This is because the PV and thermal absorber can be thermally decoupled in an SSPVT collector. One of the important components of an SSPVT collector is the optical filter. The optical filter is used to split the incident solar spectrum to the PV and thermal absorber. A comprehensive overview of PVT collectors, including SSPVT collectors, and optical filters will be provided in this chapter.

## 2.2. SSPVT collector designs

PVT collectors can utilise the solar spectrum more efficiently than standalone single-junction PV cells [1, 2]. Standalone single-junction PV cells have a specific bandgap which limits the photons that the PV cells can absorb and convert effectively to electricity. The limit was first reported by Shockley and Queisser [3] to theoretically be about 33%. This results in a PV cell with a specific quantum efficiency or spectral response which is the ratio of the charge carriers generated to all the photons incident on a PV cell. Although they may be used interchangeably, the spectral response refers to the power instead of the photons incident on a PV cell. The spectral response is usually referred to as a ‘window’ of a PV cell outside of which photons tend to result in thermalization losses instead.

One of the most common commercial PV cells, Si PV cell, has an efficiency between 16 – 25%. The operating temperature of a PV cell is among the factors that affects its efficiency. Different PV cells respond differently to the operating temperature. Generally, an increase in the temperature of a PV cell results in a decrease in its efficiency [4-6]. An increase in temperature has an impact on the charge carrier mobility in a PV cell. As the temperature increases, the charge mobility increases while the recombination process also increases, ultimately resulting in a decrease in charge carriers.

Theoretically, some authors [7, 8] have shown that for every 10 °C increase in the temperature of a crystalline Si (c-Si) PV cell, its efficiency decreases by about 4.5%. Manufacturers’ datasheets and the literature have reported a c-Si PV cell temperature coefficient to be between

-0.37 and -0.52%/°C. For instance, Radziemska et al. [9] demonstrated through their experimental results that for every 10 °C increase in the temperature of the c-Si PV cell, there is a 6.5% decrease in its efficiency. The temperature of the PV cell can reach up to 70 – 80 °C on hot days during summer, resulting in a significant decrease in the efficiency of the PV cell [10-12].

However, the temperature coefficient of thin film PV cells, such as CdTe PV cells, is less affected by a temperature increase. For instance, Virtuani et al. [13] conducted a study on the temperature coefficients of different PV cells. They reported that the CdTe PV cell's temperature coefficient was -0.24%/°C which was within the range often reported by CdTe manufacturers and other authors which is between -0.18%/°C and -0.36%/°C. Therefore, PVT collectors are employed as a method of cooling the PV cell not only to enhance the electrical efficiency but also to generate heat. The heat can be used for water or space heating [14, 15]. This makes PVT collectors attractive and cost-effective because they can meet, simultaneously, both the electrical and thermal demands of industry and residential areas.

Several PVT configurations have been reported. The most common conventional PVT collectors involve the PV cell and the heat transfer (working) fluid in direct contact. These type of collectors have a limitation in their application because an increase in the temperature of the heat transfer fluid (HTF) results in an increase in that of the PV cell [16]. As a result, their operating temperatures can only go up to 100 °C [17]. Therefore, in order to achieve an even higher thermal output without compromising the PV cell efficiency, a spectral splitting PVT collector is employed. This is a type of PVT collector where the PV cell and thermal collector are thermally decoupled [5, 18-20]. It is achieved by splitting the solar spectrum into different wavelength bands before they reach the PV cell and thermal collector [21]. The SSPVT collector can either be non-concentrating or concentrating (Table 2.1).

Table 2.1: Comparison of non-concentrating and concentrating PVT collectors [22-24].

| Property          | Non-concentrating PVT                                                                                                              | Concentrating PVT                                                                                                                                                         |
|-------------------|------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Design            | Typically involve collectors whose aperture and absorber area are the same. For example, flat plate and evacuated tube collectors. | Consist of lenses or mirrors that focus the incident solar radiation onto a smaller absorber area. For example, parabolic trough, linear Fresnel lens and parabolic dish. |
| Temperature range | Lower temperatures (<120 °C).                                                                                                      | Can go beyond 400 °C.                                                                                                                                                     |
| Cost              | Cheaper as they are less complex. They are easy to install and do not require tracking systems.                                    | Higher installation and maintenance costs. Tracking systems required.                                                                                                     |
| Applications      | Residential and commercial applications where low to moderate temperatures are required.                                           | Industrial applications where higher temperatures are required.                                                                                                           |

## 2.3. Configuration of PVT collectors

Typically, PVT collectors consist of the PV cells, heat transfer fluid channel and solar thermal collector. The thermal collectors most commonly employed include, flat-plate, evacuated tube, parabolic trough, linear Fresnel reflector and parabolic dish collectors [25]. The design of PVT collectors is adapted from the configuration of the thermal collectors.

### 2.3.1. Flat plate

The most commonly used PVT collector is the flat-plate type [26]. Flat plate PVT collector designs involve a thermal absorber being directly connected to the PV cell and they can have different designs. This is done to achieve removal of heat from the PV cell and simultaneously generate electricity and heat. This results in higher overall efficiencies than would be achieved with only a standalone PV cell or thermal absorber [27]. However, a limitation of this design is that only temperatures up to 80 °C can be achieved. This is due to the detrimental effect high temperatures have on the PV cell. To mitigate this, spectral splitting designs have been implemented in flat plate PVTs.

Spectral splitting can be achieved in flat plate PVTs by incorporating a liquid or solid filter. The filter works by directing certain wavelengths of the solar spectrum to the PV cells particularly the ones that correspond to the spectral response of the PV cell. The filter then directs the rest of the wavelengths to the thermal absorber. This results in maintaining cooler temperatures for the PV cells while achieving higher temperature output from the thermal absorber [28]. The PV cells and thermal absorber are thermally decoupled. Liquid filters are commonly used in this flat plate type of SSPVT collector. Great emphasis is placed on the optical and thermal properties of the liquid filters because they must be able to filter the solar spectrum and be used as a heat transfer fluid. Regarding their optical properties, liquid filters must be selectively absorptive. They must absorb photons with wavelengths outside the spectral response wavelengths of the PV material used. In most cases, the liquid filters must absorb the NIR wavelengths of the solar spectrum not used by the PV cell. In some cases, they must be able to absorb the UV part as well. This depends on the wavebands selected to be transmitted to the PV cells. Commonly used liquid filters include heat transfer fluids that can absorb photons with NIR wavelengths such as water [29], glycols [30] and oils [31].

Instead of having a single heat transfer channel through which the heat transfer fluid flows, a second heat transfer channel is introduced to achieve a flat plate SSPVT collector. The second heat transfer channel is placed between the incident solar radiation and the PV cell and is the optical filter of the collector. It only transmits photons corresponding to the spectral response of the PV cell, and there is a gap between the PV cell and the optical filter channel. Huang et al. [32] reported on this type of flat plate SSPVT collector, however, they coupled it with a parabolic mirror concentrator making it an SSCPVT collector. They were able to achieve both a high temperature output of 400 °C and low temperature output of 50 °C. The electrical efficiency was 17.5% and the thermal efficiency of both channels combined was 69%.

Hassani et al. [33] used nanofluids with different base fluids for the top (high temperature) and bottom (low temperature) channel. The top channel contained Ag nanoparticles suspended in Therminol VP-1 and was optimised to act as an optical filter. The bottom channel was optimised to enhance the cooling of the PV cells and contained Ag nanoparticles suspended in water instead. Water has better thermal conductivity than Therminol VP-1, while Therminol VP-1 can withstand higher temperatures (up to 400 °C) than water. They observed an enhancement in their electrical efficiency and overall efficiency of 9% and 5.8%, respectively. Huang et al. [34] were able to demonstrate that semi-transparent PV cells can be used as a solid optical filter and to generate electricity simultaneously in a flat plate SSPVT collector. The

electrical efficiency was 13.8% while the overall thermal efficiency was 43.6% with low temperature and high temperature output of 50 °C and 150 °C, respectively.

### **2.3.2. Parabolic trough**

Parabolic trough collectors (PTCs) contain a parabolic mirror, which focuses sun rays onto an absorber or receiver tube that is along its focal line. The absorber converts solar radiation to useful thermal energy through a heat transfer fluid while a glass cover around the absorber reduces heat loss through vacuum space. PTCs are one of the most studied and mature concentrated solar power (CSP) collectors. Several studies have been conducted to predict the performance of a PTC numerically. For instance, Forristal et al. [35] created both one and two-dimensional models of SEGS LS-2 module, which was experimentally investigated by Dudley et al. [36]. Xiong et al. [37] developed a two-dimensional model to investigate heat loss characteristics of a PTC under different annulus pressures, selective coatings, and wind velocities. He et al. [38] developed a method that employs a Monte Carlo Ray Tracing (MCRT) routine to calculate the non-uniform heat flux around the receiver and coupled the result to a Finite Volume Element (FVM) routine through a commercial Computational Fluid Dynamics (CFD) code to simulate the thermal behaviour of PTCs and studied effects of different concentration ratios on thermal efficiency.

Calise et al. [39] focused on the design and simulation model of a concentrating photovoltaic-thermal (CPVT) collector, utilising a parabolic trough reflector and a triangular receiver on which the PV cells are attached. The triangular receiver consisted of a tubular heat transfer fluid channel. A parametric study was conducted by varying the length of the collector and the diameter of the heat transfer channel. An increase in the length of the collector and the heat transfer fluid channel diameter results in a decrease in the electrical and thermal efficiencies. This was attributed to an increase in the outlet temperature if the collector which is detrimental to the electrical efficiency. As the temperature of the heat transfer fluid channel increased, there was an increase in the convective and radiative losses due to lack of insulation.

Generally, by utilising the CPVT configuration, higher electrical efficiencies can be achieved using a smaller PV area because the incident solar radiation reaching it is concentrated i.e. of high intensity. High temperature output can also be achieved which can be used for a wider range of applications. The introduction of the spectral splitting phenomenon in CPVTs has attracted great research attention and led to higher overall efficiencies. Before the introduction of spectral splitting in CPVTs, the NIR part of the solar spectrum would be reflected and not

efficiently utilised. The spectral splitting is achieved using an optical filter which reflects or transmits to the incident radiation to the receivers.

Authors such as Raush and Chambers [40] incorporated an optical filter into their parabolic trough PVT collector, in the form of a dichroic mirrors. The mirrors reflected part of the concentrated radiation from the parabolic concentrator to the PV cells while the rest of the concentrated radiation not intercepted by the dichroic mirrors reached the thermal absorber. They were able to achieve electrical efficiencies of about 30%. To an existing parabolic solar thermal collector Wingert et al. [41] also incorporated dichroic mirrors and PV cells. Through these modifications to the collector, they were able increase its power output by at least 13%.

### **2.3.3. Linear Fresnel**

Linear Fresnel PVT collectors consist of a linear Fresnel reflector (LFR) that has been segmented into several smaller reflectors which still maintain the optical effects as the large one. This allows the PVT collector to be more compact resulting in less land space being occupied. The LFR can either be flat or curved, with the flat one being more common due to its low cost although it is associated with low optical losses [42, 43]. Assembly of the LSR mirrors requires consideration of shading and blocking that may occur from placing the mirrors next to each other. Therefore, Montes et al. [44] conducted a parametric study by placing the mirrors at different inclinations. The results they obtained revealed that careful consideration must be made when changing the inclinations because the mirrors may be too far from the receiver causing poor focus of the sun rays.

### **2.3.4. Parabolic dish**

The parabolic dish PVT collector generally consists of a reflector and a receiver at the focus that contains the PV cells. The solar irradiance incident on the parabolic dish reflector is concentrated and directed toward the receiver. Like the other PVT collectors that consist of reflectors for concentration of the incident solar radiation, the area of the PV cells is much smaller than is required in a conventional PV module. This encourages utilisation of multi-junction solar cells which are more expensive but result in higher efficiencies. Bamroongkhan et al. [45] also developed a parabolic dish PVT collector. Their collector consisted of the reflector, PV and thermoelectric modules. A temperature difference of at least 160 °C was achieved using this collector.

Table 2.2: Comparison of different CPVT collectors.

| Collector type            | Author                | Optical filter                                                                  | HTF<br>temp<br>°C | Electrical<br>(%) | Thermal<br>(%) |
|---------------------------|-----------------------|---------------------------------------------------------------------------------|-------------------|-------------------|----------------|
| Linear Fresnel reflectors | Han et al.[46]        | Propylene glycol + HB650                                                        | 48.9              | 6.0               | 40.7           |
|                           | Wang et al.[47]       | Multiple layers of $\text{Na}_3\text{AlF}_6$ , $\text{Nb}_2\text{O}_3$ , and Ge | 300               | 30.8              | 25.8           |
|                           | Stanley et al. [48]   | Semiconductor-doped glass and propylene glycol                                  | 120               | 31.0              | 3.8            |
|                           | Jiang et al. [49]     | Ag- $\text{CoSO}_4$ /Water Nano-Fluid                                           | -                 | 13.7              | 42.6           |
|                           | Mojiri et al. [50]    | Semi-conductor doped glass and propylene glycol                                 | -                 | 3.9               | 44.0           |
| Parabolic trough          | Widyolar et al. [51]  | InGaP/GaAs back-reflecting solar cells                                          | 600               | 52.0              | 4.0            |
|                           | Wang et al. [52]      | Multi-layer film                                                                | 356               | 30.5              | 26.6           |
|                           | Guo et al. [53]       | Hyperbolic secondary concentrator                                               | -                 | 24.3              | 36.7           |
|                           | Buonomano et al. [54] | -                                                                               | 180               | 19.0 – 25.0       | 60.0           |
| Parabolic dish            | Jiang et al. [55]     | Multilayer films of $\text{Nb}_2\text{O}_5$ and $\text{SiO}_2$                  | -                 | 18.0              | -              |
|                           | Houcine et al. [56]   | Bandpass filter with reflectivity between 380 – 1100 nm                         | 170               | -                 | -              |

## **2.4. Optical filters**

Optical filters can be incorporated into PVT collectors to enhance their efficiencies as mentioned previously. the solar spectrum is usually first split at the wavelength that corresponds to the bandgap energy level of the PV cell [18]. This is because the photons with energy corresponding to the bandgap of the PV cell can efficiently produce electricity. However, the photons with energy less than that of the PV cell's bandgap cannot be used by it to produce electricity [57]. They rather pass through the PV cell without being absorbed and are dissipated as heat. The photons with energy higher than that of the bandgap of the PV cell can be absorbed by it but not without resulting in excess heat [20]. Therefore, the solar spectrum should then be split according to how efficiently the PV cell and the thermal collector will utilise it. As a result, the solar spectrum is split at two wavelengths generating three wavebands. The wavebands including the shortest and longest wavelengths are directed to the thermal collector, while the waveband including the bandgap of the PV, which is the 'PV window', is directed to the PV cell. This splitting can be achieved using an optical filter. Optical filters have been reported to promote a more efficient utilisation of the solar spectrum by solar energy technologies [17, 58].

The optical properties of a material should be taken into consideration when designing an optical filter [35]. The optical filter can either be selectively absorptive or reflective, and also be transmissive. For selectively absorptive filters, the optical filter should have an absorption that is not only within the solar spectrum wavelengths, but it must not absorb the region that is to be transmitted to the PV cell. Otanica et al. [59] illustrated the absorption spectra of different materials. They focused on the factors that affect the absorption of spectra of materials and their tunability. Materials that exhibit plasmonic resonance are widely used because their absorption peaks are easy to tune depending on the wavelengths of interest. These materials include Au, Ag, Cu, Al, and Li. The absorption of Ag can be tuned over a broader wavelength range than all of these materials, from UV to near-infrared, making it suitable to employ as an optical filter for different PV cell materials [58]. The optical properties of nanoparticles can be tuned by varying the shape, size, concentration, and the refractive index surrounding the nanoparticles [60] [61].

### **2.4.1. Nanofluids as optical filters**

Heat transfer fluids, especially the selectively absorbing liquids, can also function as optical filters in PVT collectors. They are a much cheaper alternative to the thin film-based optical filters, and exhibit efficient heat absorption and transfer [62, 63]. These liquid optical filters

filter the solar spectrum depending on their optical properties such as their absorption and transmittance of wavelengths. Ideally, the liquid filter should transmit the wavelengths corresponding to the spectral response of the PV cell and absorb the rest of the wavelengths for thermal output. The liquid optical filters that have received great research attention are water, glycols, and oils.

For instance, Joshi et al. [64] investigated liquid optical filters such as, water, silicone oil and coconut oil. These optical filters were used for a silicon PV cell with a spectral response of 750 – 1125 nm. The authors used a UV-Vis-NIR spectrophotometer for their optical property measurements with a range of 200 – 2500 nm which represents the terrestrial solar spectrum. From their results they observed that the coconut oil performed better than the other filters because it resulted in the highest overall efficiency of 59% while water and silicone oil resulted in overall efficiencies of 33% and 54%, respectively. Furthermore, Christosomo et al. [2] synthesized Ag nanodiscs of different concentrations. They were able to tune the absorption peaks of the Ag nanodiscs from 440 nm to 530 nm. The absorption of IR radiation >1100 nm can be achieved using the conventional liquid filters such as inorganic aqueous salts, water, oils and glycols [65]. Liquids such as CoSO<sub>4</sub> solution, propylene glycol, and Valvoline oil have garnered great research interest as liquid IR absorbers.

To enhance the thermal conductivity, heat transfer, and optical properties of the pure liquid optical filters (base fluid), a small volume fraction of nanoparticles is incorporated into them. This results in liquids known as ‘nanofluids’ [66]. Nanofluids have attracted great research interest over the years due to the nanoparticles’ ability to tune the optical properties of base fluids, at low concentration, in PVT collectors [17, 66]. For instance, Taylor et al. [17] used nanofluids to thermally decouple the PV cell and thermal collector in an SSPVT collector. They used nanofluid filters to match the spectral response of five different PV cells, which include Si, Ge, CdTe, InGaAs, and InGaP. The nanofluid They concluded that using the nanofluid filter is an easier and economical method of achieving tuned optical properties than the conventional thin film-based optical filter. The optical properties can be tuned by varying the nanoparticle type, size, shape, and mass fraction [17, 67]. Cui and Zhu [68] used a MgO-water nanofluid filter for their PVT collector. They performed an experiment to study the effect of the mass fraction and thickness of the nanofluid on the optical properties of the nanofluid. They concluded that the PVT collector using a nanofluid filter with a smaller mass fraction of 0.02% produced ~4.5 W more power than one using a nanofluid with a mass fraction of 0.1%. The nanofluid layer with a thickness of 2 mm performed better than that 4 mm, resulting in a higher overall efficiency

of 61.9% compared to just 46% for the 4 mm. This is because an increase in the mass fraction of the nanofluid and the thickness of the nanofluid layer results in a decrease in the transmittance of visible light to the PV cell, reducing the collector's efficiency.

To further tune the optical properties of the nanoparticles, dielectric materials can be added to them in the form of a core/shell morphology. This was demonstrated by Taylor et al. [67] when they used a dielectric core/shell configuration in which the dielectric core was encapsulated by a noble metal shell. This core/shell configuration results in a more pronounced plasmonic resonance absorption, they observed, which can be tuned by varying the core-to-shell ratio. The core/shell configuration was also employed by Hjerrild et al. [58] by depositing a layer of SiO<sub>2</sub> around Ag nanoparticles which were then dispersed in water. This was done to maintain the spherical shape of the Ag nanoparticles and, consequently, their optical properties. They observed an increase in the combined efficiency of 30%.

More recently PVT collectors that contain both liquid and solid filters have been reported in the literature. For instance, Stanley et al. [48] combined both types of filters to achieve a more efficient spectral splitting PVT collector. They used a bandpass solid optical filter and propylene glycol as their heat transfer fluid. Their collector was thermally decoupled and they achieved a high output temperature. Their electrical efficiency was about 3.8% and their total efficiency was 50% but they expect total efficiencies of more than 75% after applying minor modifications to their collector. Han et al. [65] also used a combination of a liquid, CoSO<sub>4</sub> solution, and solid, HB650 glass, as optical filters. However, they obtained an electrical efficiency of 9.1% and total efficiency of 49%. This shows that more work needs to be done to enhance the efficiency of this type of collector, but it shows great potential.

#### **2.4.1.1. Stability of nanofluid optical filters**

The stability of nanofluids plays a significant role in the nanofluids' ability to maintain their optical and thermophysical properties, without aggregation and sedimentation. The factors that affect the nanofluids' stability include nanoparticle properties, base fluid properties, and nanoparticle synthesis techniques. These factors can be tuned to improve the nanofluids' stability for a certain period, however for long term use between 20 – 30 years, which is the lifetime of most PVT collectors [69], this remains an issue.

#### **2.4.1.2. Nanoparticle properties**

The size, shape and concentration of nanoparticles have a significant effect on the stability and thermophysical properties of nanofluids. For instance, the size of the nanoparticles determines

the how rapidly sedimentation occurs in the nanofluid. This is because nanoparticles in a fluid are constantly in collision with each other due to Brownian motion [70]. Brownian motion contributes to the stability of nanofluids by preventing sedimentation of nanoparticles due to gravity. Larger nanoparticles tend to settle out of the suspension faster than smaller nanoparticles. This is due to the reduced effect of Brownian motion in nanofluids containing larger nanoparticles. Nanofluids containing spherical particles tend to be more stable than those of other shapes. Non-spherical shapes tend to experience increased drag which reduces their sedimentation rate [71]. An increase in nanoparticle concentration leads to an in nanofluids results in agglomeration of nanoparticles because of the enhanced van der Waals forces [72].

#### **2.4.1.3. Base fluid properties**

The choice of the base fluid in which the nanoparticles are dispersed is crucial as it also affects the nanofluid's stability. The properties often considered when selecting an appropriate base fluid are its viscosity and dielectric constant. Base fluids with high viscosity tend to have higher stability because they slow down nanoparticle aggregation and sedimentation [73]. A high dielectric constant strengthens the repulsive force between the nanoparticles in the nanofluid which maintains the particle spacing and keeps the nanoparticles dispersed. Additionally, the pH of the base fluid affects the zeta potential. The zeta potential is used to determine the stability of a nanofluid which is a colloidal solution by the degree of repulsion between the particle charges indicated by the zeta potential numbers. At higher pH values, the zeta potential is also high and the higher the zeta potential is whether positive or negative, the more stable the nanofluid is [74].

#### **2.4.1.4. Nanoparticle synthesis techniques**

The addition of surfactants and stabilisers to nanofluids helps achieve high stability in them by either steric or electrostatic stabilisation or both combined [73]. Steric stabilisation involves creating steric hindrance using polymers to prevent the nanoparticles from adhering to each other. Electrostatic stabilisation involves adding charges to the surface of the nanoparticles resulting in an electrostatic repulsive force between similarly charged nanoparticles. These stabilisation techniques prevent the nanoparticles from adhering to each other or aggregating. However, electrostatic stabilisation may not be effective in highly concentrated nanofluids, and steric stabilisation may not work when the poor solvent is used. Ultrasonication is another method used to achieve stable nanofluids. It involves dispersing the nanoparticles in the base fluid, but the dispersed nanoparticles may not remain that way for an extended period.

Despite the efforts reported in the literature to enhance the stability of nanofluids. Their viability economically remains hindered by their stability and lifespan, especially for PV collectors whose lifespan is about 25 years [75]. An estimate of the stability duration of some nanofluids is summarised in Table 2.3.

Table 2.3: Factors that affect the stability duration of nanofluids.

| Author                | Nanofluid                                                                  | Concentration<br>(wt%) | Surfactant                      | Sonication | Stability<br>duration |
|-----------------------|----------------------------------------------------------------------------|------------------------|---------------------------------|------------|-----------------------|
| Mehrali et al. [76]   | N <sub>2</sub> -doped graphene nanoparticles in water                      | 0.1 – 0.6              | Triton X-100                    | 1h         | 180 days              |
| Witharana et al. [77] | Al <sub>2</sub> O <sub>3</sub> ZnO in propylene glycol and ethylene glycol | 1 – 9                  | -                               | 16h        | >60 days              |
| Albert et al. [78]    | CuO in water                                                               | 0.5                    | Polyvinyl alcohol               | 1h45       | 1 year                |
| Li et al. [79]        | Ag, Au in water                                                            | -                      | Cationic gemini                 | -          | 60 days               |
| Wusiman et al. [80]   | Multi-walled carbon nanotubes in water                                     | 0.5                    | Sodium dodecylbenzene sulfonate | 20min      | 30 days               |
| Mousavi et al. [81]   | MoS <sub>2</sub> in diesel oil                                             | 0.1 – 0.7              | Triton X-100                    | 45min      | >14 days              |

#### 2.4.2. Nanocomposite-based optical filters

Alternatively, nanoparticles can be employed by embedding them in a polymer matrix, resulting in a nanoparticle-polymer nanocomposite. The optical properties of the nanocomposite can be tuned by varying the nanoparticle size, surface modification, concentration, and the dielectric constant of the polymer. Polymers such as poly(methyl methacrylate) (PMMA) have been used to embed nanoparticles in a wide range of applications such as photonics and optics that require transparent materials. Of interest is the use of PMMA as a transparent UV absorbing film with

nanoparticles embedded in its matrix. The nanoparticles, especially the ones with a wide bandgap, enhance the UV absorption of PMMA. The nanoparticle sizes are kept below 40 nm to retain the optical transparency of PMMA because nanoparticles of that size hardly scatter visible light. Nanoparticles such as TiO<sub>2</sub>, ZnO, CdS, and ZnS have been used. For instance, Koziej et al. [82] synthesized a UV filtering TiO<sub>2</sub>-PMMA nanocomposite. The TiO<sub>2</sub> nanoparticles were an average of 14.6 nm in size, resulting in a transparent TiO<sub>2</sub>-PMMA film. The weight percentage of TiO<sub>2</sub> was varied from 1.1 – 9.3wt% and UV-Vis analysis was performed on each film to show that the transmission and absorbance can be tuned.

Zhang et al. [83] embedded ZnO quantum dots (QDs) into the matrix of a PMMA film, ZnO-PMMA, for UV shielding. About 2wt% ZnO QDs were used which had an average size of 4.6 nm which exhibited good dispersion and resulted in a transparent ZnO-PMMA film. The UV-Vis spectra of the film showed that the film had very high absorption (almost zero transmission efficiency) up to 400 nm. The bandgap of the ZnO QDs is 3.58 eV, while that of bulk ZnO is 3.37 eV. This is because of quantum confinement. Mumin et al. [84] used poly(ethylene-vinyl acetate) (PEVA) instead to embed nanoparticles in it. CdS and CdS-ZnS QDs were embedded with high dispersion inside the PEVA film. The dispersion of the nanoparticles was studied using laser scanning confocal microscopy (LSCM).

#### **2.4.3. Thin film based optical filters for SSPVT collectors**

Interference optical filters in the form of thin films have been used significantly in spectral splitting PVT collectors [57]. They consist of thin multilayers of high and low refractive index materials that are transparent [85]. These multilayers split the solar spectrum by constructive/destructive interference of the solar spectrum wavelengths [62]. They are able to transmit and reflect wavelengths as required [57]. The materials usually used are either metal-dielectric materials or exclusively dielectric materials. Soule et al. [86] used metal-dielectric films, one including Au between dielectric layers and the other, Sn-doped In<sub>2</sub>O<sub>3</sub>. They discovered that the metal-dielectric films exhibit significant absorptive losses due to the presence of the metals. Hence, most of the thin films used in spectral splitting PVT collectors usually consist of dielectric materials such as titania/silica [85], niobium pentoxide/silica [55].

For instance, Chrisostomo et al. [87] demonstrated the use of thin films as optical filters by incorporating 16 layers of silicon nitride and silica into their PVT collector. The films reflect the wavelengths that correspond to the spectral response of the PV cell towards the PV cell, and transmit the rest of the wavelengths to the thermal collector. Shou et al. [57] utilised an 82-

layer titania/silica film filter. However, achieving the desired reflectance and transmittance requires many layers of the materials which makes the fabrication of the thin-films expensive to be used in commercial spectral splitting PVTs.

#### **2.4.3.1. Dielectric-metal-dielectric coatings**

The incidence of a light or electromagnetic (EM) wave on a material results in an interaction with the material based on the wavelength of the incident EM wave and the material's atomic structure. The interaction could result in transmittance, reflectance or absorptance. Absorptance can be defined as the ratio of radiation that is absorbed by a material to the radiation incident on the material. The sum of transmittance ( $\tau$ ), reflectance ( $\rho$ ) and absorptance ( $\alpha$ ) is equal to 100 % or unity. This can be represented using the equation,  $\tau + \rho + \alpha = 1$ . This obeys the law of conservation of energy because the incident EM wave can either be transmitted, reflected or absorbed.

Thin film coatings have been utilised as optical filters for a wide variety of applications including in SSCPVT collectors as demonstrated in Section 2.2. Achieving the desired optical properties with less films has always been of utmost importance. This can be seen in the development of tri-layer films such as transparent heat mirrors which consist of metal layers sandwiched between dielectric layers also known as dielectric-metal-dielectric (DMD) films. Metals are chosen due to their high reflectance in the NIR region while transmitting light in the visible light region.

The dielectric materials, due to their anti-reflectivity abilities, enhance the visible light transmittance of the sandwiched metal layer. This is due to their plasma frequency being in the UV region because of d-d transitions [88]. To better understand the interaction of these layers with light, surface plasmons are used. Surface plasmons occur as a result of the coherent oscillations of electrons at the metal-dielectric interface when an electromagnetic wave is incident on the material [89]. They can be described as surface plasmon polaritons (SPP) which involve coherent oscillations of free electrons in a wave-like manner at the interface of two media such as a dielectric-metal interface.

In order for the DMDs to transmit the visible part of the solar spectrum, the dielectric materials selected should have a high refractive index. Numerous studies have been conducted on the effect of the dielectric and metallic materials used, as well as their thicknesses on the optical properties of the DMDs. As far back as 1982, a study was conducted by Kostlin and Frank [90] using ZnS as the dielectric material on both sides of the metal, Ag. They optimised their DMDs

such that the thickness of ZnS was kept constant at 30 nm while the thickness of Ag was varied between 3 nm and 40 nm. When Ag was 3 nm, considered too thin, the resulting spectra revealed that there was rather IR absorptance rather than the desired reflectance. When Ag was 40 nm, considered too thick, the resulting spectra revealed that there was significant reflectance in the visible region instead of the desired high transmittance.

#### **2.4.3.2. Fabrication techniques of DMD optical filters**

Fabrication of DMD optical filters involves the deposition of a dielectric material, followed by a metal and another dielectric material onto a substrate. Vacuum deposition methods are amongst the common thin film deposition methods. Chemical vapour deposition (CVD) and physical vapour deposition (PVD) are the two main types of vacuum deposition methods. CVD forms thin films chemically due to the reaction of a precursor gas on a heated substrate, while PVD forms thin films physically due to the transfer of atoms to a substrate from a solid material in a vacuum. Typically, techniques such as thermal evaporation [91-93], magnetron sputtering [94], ion beam sputtering [95] and atomic layer deposition (ALD) [96] are used (Table 2.4). For instance, Idriss et al. [97] fabricated  $\text{TiO}_2$ -Cu- $\text{TiO}_2$  DMD films using magnetron sputtering. The dielectric material was selected to be  $\text{TiO}_2$  which was deposited using RF power while the metal layer was selected to be Cu which was deposited using DC power. The thicknesses of the layers were varied. The top  $\text{TiO}_2$  layer varied between 445 nm and 252 nm, the Ag layer varied between 14.2 nm and 68.0 nm and the bottom  $\text{TiO}_2$  layer varied between 130 nm and 167 nm. Fouad et al. [98] combined ALD and magnetron sputtering to fabricate DMD films. The ALD method was used to deposit the  $\text{TiO}_2$  layers titanium tetrachloride ( $\text{TiCl}_4$ ) and  $\text{H}_2\text{O}$  were used as precursors, while magnetron sputtering was used to deposit the Cu layer using a Cu sputter target. Magnetron sputtering is of particular interest in this study.

Table 2.4: Summary of the DMD fabrication techniques used by other authors.

| Author             | Metasurface                                                       | Fabrication technique         | Application                                                                              |
|--------------------|-------------------------------------------------------------------|-------------------------------|------------------------------------------------------------------------------------------|
| Fouad et al. [98]  | TiO <sub>2</sub> -Cu-TiO <sub>2</sub>                             | Atomic layer deposition (ALD) | Transparent electrode in commercial applications, including display and lighting devices |
| Singh et al. [95]  | TiO <sub>2</sub> -Ag-TiO <sub>2</sub>                             | Ion beam sputtering           | -                                                                                        |
| Kim and Lee [99]   | WO <sub>3</sub> -Ag-WO <sub>3</sub>                               | -                             | Flexible transparent electrode in organic light-emitting diodes (OLEDs)                  |
| Lopéz et al. [100] | MoO <sub>3</sub> -Cu-MoO <sub>3</sub>                             | Thermal evaporation           | Anode in organic photovoltaic cells                                                      |
| Kwon et al. [101]  | Al <sub>2</sub> O <sub>3</sub> -Ag-Al <sub>2</sub> O <sub>3</sub> | ALD and thermal evaporation   | Fluorescent OLEDs                                                                        |
| Butt et al. [102]  | TiO <sub>2</sub> -Ag-TiO <sub>2</sub>                             | Magnetron sputtering          | Smart windows                                                                            |

#### 2.4.3.3. Fabrication of DMDs using magnetron sputtering

Magnetron sputtering is a technique widely used for thin film fabrication. It involves the bombardment of a target material, to be deposited on a substrate, by energetic ions of a gas. Magnetic and electric fields are used to confine the ions to the surface of the target material. This causes the atoms of the target to escape from the target to the surface of the substrate. The gas often used is Ar because of its high sputter yield and low cost [103]. There are mainly two types of magnetron sputtering, direct current (DC) sputtering and radio frequency (RF) sputtering [104]. In DC sputtering, the Ar<sup>+</sup> ions bombard the target which acts as a cathode due to the high negative voltage applied to it. The collision dislodges atoms from the target which are then deposited onto the surface of a substrate forming a thin film on it.

DC sputtering is only suitable for conducting targets because it causes a positive ion buildup on the surface of non-conducting targets which repels further ions and stops the sputtering

process [105]. RF sputtering is used instead for non-conducting targets. This is because RF sputtering uses alternating RF power to produce  $\text{Ar}^+$  ions that bombard and dislodge atoms from the target that are then deposited onto a substrate. This alternating current causes a periodic reversal of polarity of the target which prevents ion buildup on the target. RF sputtering can also be used for conductive targets. The parameters (Table 2.5), that are considered in the sputtering process include, gas flow rate, RF or DC power, deposition rate and process pressure.

Table 2.5: Summary of the deposition parameters used by other authors.

| Author                | Material         | Sputtering process | Sputtering gas and flow rate              | Process pressure (mTorr) | Deposition rate | Thickness (nm) |
|-----------------------|------------------|--------------------|-------------------------------------------|--------------------------|-----------------|----------------|
| Idriss et al. [97]    | TiO <sub>2</sub> | RF (150 W)         | Ar (16 sccm)                              | 6.76                     | 1 – 2           | 150            |
|                       |                  | DC (40 W)          | Ar (10 sccm)                              |                          | nm/min          |                |
|                       | Cu               |                    |                                           | 6.61                     |                 | 5 – 50         |
| Nawade et al. [106]   | TiO <sub>2</sub> | RF (50 – 400 W)    | Ar (25 sccm)                              | 3.3                      | -               | 40 – 50        |
|                       | Cu               | DC (100 W)         |                                           |                          |                 | ~12            |
| Hasan et al. [107]    | WO <sub>3</sub>  | RF (200 W)         | Ar (40 sccm) and O <sub>2</sub> (20 sccm) | -                        | 0.052 nm/s      | 50             |
|                       | Ag               | DC (50 W)          | Ar (46 sccm) and O <sub>2</sub> (10 sccm) |                          | 0.093 nm/s      | 20             |
|                       | TiO <sub>2</sub> | RF (250 W)         | sccm)                                     |                          | 0.39 nm/min     | 35             |
| Spinelli et al. [108] | ITO              | RF (60 W)          | Ar and O <sub>2</sub>                     | -                        | 0.06 nm/s       | 65             |
| Ionescu [109]         | ZnO              | RF (40 W)          | Ar                                        | 7.5                      | -               | 20 – 60 nm     |

#### **2.4.4. Metasurfaces as optical filters**

Metasurfaces are 2D materials that consist of arrays of nanostructures with different materials such as dielectric, metallic or a combination of both. Metasurfaces can control the phase, amplitude, polarization, absorptance, reflectance and transmittance of light. The design of these nanostructures involves tuning their geometry to achieve the desired interactions with electromagnetic waves [110]. Application of metasurfaces results in miniaturization of devices, multifunctionality and higher efficiency. They have been applied in the fabrication of metalenses [111], optical computing [112], holography [113] and biosensing [114].

##### **2.4.4.1. Fabrication of metasurfaces**

Metasurfaces are fabricated using different types of lithographic techniques such as photolithography [115-117], electron beam lithography (EBL) [118, 119], focused ion beam (FIB) lithography and colloidal lithography. These techniques involve forming a pattern using a mask or without a mask on a material of interest which could be a coated or uncoated substrate. Photolithography and colloidal lithography involve patterning substrates by transferring the pattern from a mask. EBL and FIB lithography involve forming a pattern without using a mask. A more detailed description of the techniques is included in Table 2.6.

For instance, Park et al. [120] fabricated metasurfaces with SiO<sub>2</sub> pillar arrays using photolithography. The fabrication process involved transferring a pattern of spherical nanoarrays from a mask using deep ultra visible light onto an SiO<sub>2</sub> substrate coated with Cr and a photoresist. The photoresist was then developed to obtain the nanoarray pattern on the Cr layer. The sample was then dry etched using Cl<sub>2</sub> which resulted in selective etching of Cr layer having the same shape as the photoresist since SiO<sub>2</sub> resistant to Cl<sub>2</sub> plasma etching. Therefore, to obtain the SiO<sub>2</sub> pillar arrays under the Cr nanodisks, fluoride plasma was used instead. Further Cl<sub>2</sub> plasma etching was used resulting in only the SiO<sub>2</sub> pillar arrays.

Yamasaki et al. [121] fabricated Ag metasurfaces consisting of nanodisk arrays using EBL. This involved transferring a nanodisk pattern designed using a software by Autodesk to a substrate coated with an electron beam resist, ZEP520A, and a charge dissipating agent, Espacer 300Z. The transfer of the pattern was achieved using an EBL system. Following the pattern transfer, the Espacer 300Z was removed using ultrapure water. The patterned substrate was developed using xylene and rinsed using isopropyl alcohol. Ni was then deposited on the patterned substrate so that it can be used for adhesion of the Ag films which was deposited on

top of the Ni layer. This was followed by the lift-off process using 2-butanone and an isopropyl alcohol rinse. Finally, the resulting Ag nanodisk patterned substrate was annealed.

Table 2.6: Metasurface fabrication techniques [110, 122-124].

| Type of lithography | Photolithography                                 | Colloidal lithography                                                      | Electron beam lithography (EBL)                                                                    | Focused ion beam (FIB)                                              |
|---------------------|--------------------------------------------------|----------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------|---------------------------------------------------------------------|
| Process             | Uses a mask and photoresist for pattern transfer | Uses self-assembled colloidal particles as a mask to create a pattern from | Uses a computer-aided design (CAD) file to directly draw the pattern, and an electron beam resist. | Uses a focused ion beam to draw the pattern directly on a material. |
| Throughput          | High                                             | High                                                                       | Low                                                                                                | Low                                                                 |
| Resolution          | 10 – 100 nm                                      | <100 nm                                                                    | <10 nm                                                                                             | <10 nm                                                              |
| Cost                | Moderate                                         | Low                                                                        | High                                                                                               | High                                                                |

#### 2.4.4.2. Stability of thin film optical filters

The thin film optical filters discussed should ideally be able to maintain their optical properties throughout the lifetime of the solar energy technologies they are applied to. However, their exposure to various conditions, because of their application, will cause them to degrade over time. The degradation results in changes in the optical, chemical and structural properties of the filters. The selective transmittance and reflectance of the filters will be altered and cause the filter to perform poorly. The degradation of the filters may occur due to the deposition of soil on their surfaces, surface reactions with environmental compounds, temperature, humidity, cracks and delamination of the films [125]. While degradation due to the deposition of soil may be reversed through cleaning, degradation due to the other factors is irreversible. There are several mechanisms through which degradation of thin films may occur.

To study the degradation of thin films due to exposure to high temperatures, Zhang et al. [126] conducted thermal stability tests on DMDs, specifically AZO-Ag-AZO. The temperature was varied up to 600 °C. High temperatures resulted in the diffusion of Ag to replace the  $\text{Zn}^{2+}$  in AZO. This was observed using the XRD data. A significant reduction in the Ag peak was

observed from 300 °C. As the temperature increased the Ag peak reduced even more, until it completely disappeared at 600 °C. To inhibit this, a layer of Ni was deposited onto Ag. Because  $\text{Ni}^{2+}$  is smaller than  $\text{Ag}^{2+}$ ,  $\text{Ni}^{2+}$  would diffuse and protect Ag from oxidation. Dalapati et al. [127] annealed a  $\text{TiO}_2\text{-Cu-TiO}_2$  coating at different temperatures. For temperatures up to 500 °C an improvement in the coating's optical performance was observed due to the enhancement of the coating's transmittance in the region of interest for the study. However, at 600 °C degradation of the coating occurred due to the partial oxidation of Cu, and the inter-diffusion of Cu and oxygen at the metal-dielectric interface. This was reflected in the XRD data by the reduction in the Cu peaks' intensity and the appearance of CuO peaks. The partial oxidation of Cu was attributed to the inter-diffusion.

## **2.5. Literature gap and thesis novelty**

Optical filters play a pivotal role in SSPVT collectors to selectively transmit, absorb or reflect the solar spectrum depending on the collector design and the end-user's needs. DMDs and metasurfaces, based on their optical properties, have great potential to be used as optical filters in SSPVTs. Sibin et al. [128] reported on the ITO-Ag-ITO DMD as a potential material for spectral splitting in a photovoltaic-thermoelectric collector. They focused on the design, fabrication and characterisation of the DMD's optical properties, but their work did not extend to integration or performance evaluation within a collector model. To the best of our knowledge, DMDs and metasurfaces have not been used in SSPVTs, especially in a parabolic trough SSPVT collector, which is our collector design. DMDs were selected because they exhibit transmittance in the visible region and part of the near-infrared region of the solar spectrum, which correspond to the spectral response of most commercial PV cells. The rest of the solar spectrum is then reflected by the DMDs. Metasurfaces, on the other hand, can exhibit either transmittance or reflectance in the visible region. However, unlike DMD films, their optical properties are structure dependent, and their selectivity can be tuned even more. This work involves simulating, fabricating and characterising the DMDs. This is followed by using the DMDs' optical properties as input in our comprehensive coupled optical-electrical-thermal SSPVT collector model to evaluate the collector's efficiency. Metasurfaces as optical filters are also evaluated.

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# Chapter 3: Methodology

## Table of contents

|                                                                       |    |
|-----------------------------------------------------------------------|----|
| 3.1. Overview.....                                                    | 44 |
| 3.2. Modelling of DMD and metasurface optical filters .....           | 44 |
| 3.3. Fabrication of DMD films .....                                   | 45 |
| 3.3.1. Characterisation of the fabricated DMD optical filters.....    | 46 |
| 3.4. Collector design .....                                           | 47 |
| 3.5. SSCPVT model outline.....                                        | 49 |
| 3.5.1. Optical sub model .....                                        | 49 |
| 3.5.2. PV electrical sub model .....                                  | 50 |
| 3.5.3. Heat transfer and fluid dynamics sub model.....                | 50 |
| 3.5.4. PV-weighted average transmittance of the optical filters ..... | 52 |
| 3.5.5. Flow diagram of the SSCPVT model .....                         | 53 |
| 3.6. Summary .....                                                    | 53 |
| 3.7. References.....                                                  | 54 |

### 3.1. Overview

This chapter includes a detailed description of the simulation and experimental methods used in the design and fabrication of the optical filters. The optical simulations were used to optimise the optical properties of the optical filters and allow the useful part of the solar spectrum to reach the PV cells. The resulting optical filter design was then coupled to an electrical, heat transfer and fluid mechanics model to estimate the performance of the collector.

### 3.2. Modelling of DMD and metasurface optical filters

The DMD optical filters were simulated using the COMSOL Multiphysics® [1] wave optics module. The DMD films consisted of an Ag layer sandwiched between TiO<sub>2</sub> layers as shown in Figure 3.1. All simulations were performed using the electromagnetic wave frequency domain physics and the wavelength domain study. The American Society for Testing of Materials (ASTM), air mass (AM1.5), Global (ASTM G-173) solar spectrum [2, 3], which is commonly used for testing solar energy technologies, was selected as the reference spectrum. The wavelengths considered were between 280 – 2500 nm which include ultraviolet, visible light and near infrared wavelengths of the solar spectrum. The governing equation was the time-harmonic equation for an electric field, which is given as:

$$\nabla \times (\nabla \times \mathbf{E}) - k_0^2 n^2 \mathbf{E} = 0 \quad (3.1)$$

where  $\mathbf{E}$  is the electric field,  $k_0$  is the wavenumber in a vacuum,  $n$  is the refractive index of the materials. The  $n$  values, of Ag and TiO<sub>2</sub> were imported from the COMSOL Multiphysics® database.

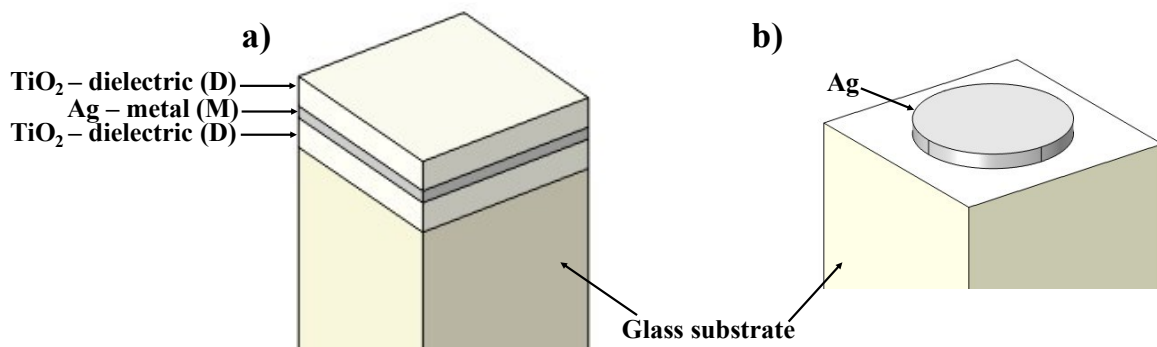


Figure 3.1: Schematic representation of: a) DMD films, and b) metasurface unit cell.

The simulation domain was set up as shown in Figure 3.2. Floquet periodic boundary conditions were applied on the side walls of the DMD or metasurface optical filters and the glass substrate (highlighted in blue). This was done to represent the laterally infinite films, DMDs, and the infinite arrays of metasurfaces. Periodic ports boundary conditions, inlet and

outlet, were also applied to the top and bottom of the physics domains to measure the reflected and transmitted spectra as a function of wavelength. Above and beneath the physics domains, perfectly matched layer (PML) boundary conditions were applied to ensure that the outgoing waves from the physics domains were strongly absorbed to ensure that they would not be reflected back inside. All the domains were then meshed, followed by a computation of a parametric sweep of the wavelengths.

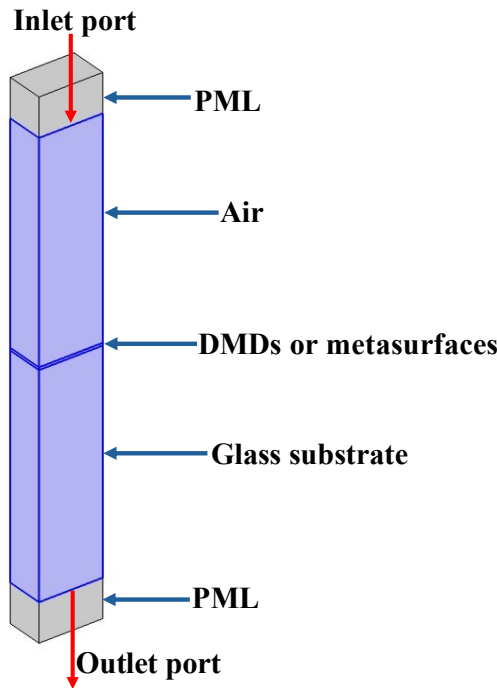


Figure 3.2: Schematic representation of the optical filter simulation on COMSOL Multiphysics®.

### 3.3. Fabrication of DMD films

The DMD ( $\text{TiO}_2\text{-Ag-TiO}_2$ ) films were fabricated using a physical vapour deposition (PVD) system (Hex-L, Korvus Technology Ltd). Prior to the deposition, the glass substrates onto which the films were deposited were cleaned by ultrasonication for 10 min in acetone, isopropanol and deionised water, consecutively. The  $\text{TiO}_2$  layer was deposited using a  $\text{TiO}_2$  target (99.9% pure, Kurt J. Lesker Company®) and RF sputtering power of 150 W at room temperature and process pressure of  $5 \times 10^{-3}$  mbar in an Argon (Ar) gas atmosphere (50 SCCM). This was followed by the deposition of the Ag layer without breaking the vacuum using an Ag target (99.99% pure, Kurt J. Lesker Company®) and DC power of 38 W at room temperature and process pressure of  $4 \times 10^{-3}$  mbar in an Ar gas atmosphere (40 SCCM). Then finally, another layer of  $\text{TiO}_2$  was deposited without breaking the vacuum using the same

conditions as the first TiO<sub>2</sub> layer. The deposition time for TiO<sub>2</sub> was fixed at 20 min while that of Ag was between 20 – 50 s. The parameter used for each filter is outlined in Table 3.1 and images of the fabricated filters are shown in Figure 3.3 below.

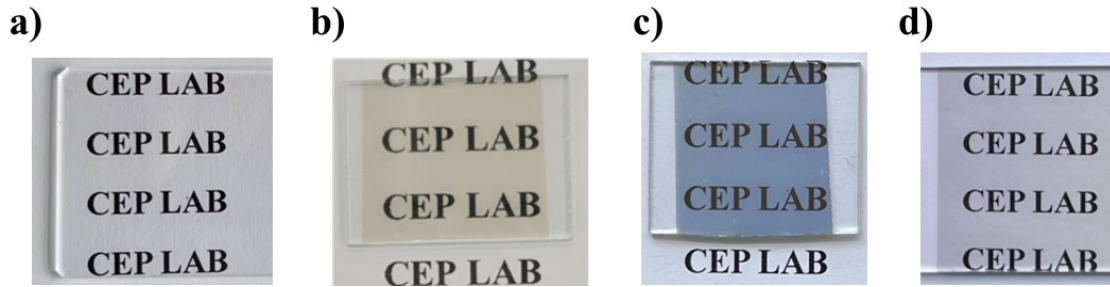


Figure 3.3: (a) Uncoated substrate, (b) TiO<sub>2</sub> film (20 min.), (c) Ag film (37 s) and (d) DMD-e1.

Table 3.1: Optical filter names and their deposition times.

| Optical filter   | Thickness (nm) | Deposition time      |
|------------------|----------------|----------------------|
| Ag               | 22             | 40 s                 |
| TiO <sub>2</sub> | 40             | 20 min.              |
| DMD-e1           | 40-10-40       | 20 min.-20 s-20 min. |
| DMD-e2           | 40-13-40       | 20 min.-25 s-20 min. |
| DMD-e3           | 40-16-40       | 20 min.-30 s-20 min. |
| DMD-e4           | 40-18-40       | 20 min.-35 s-20 min. |
| DMD-e5           | 40-21-40       | 20 min.-40 s-20 min. |
| DMD-e6           | 40-24-40       | 20 min.-45 s-20 min. |
| DMD-e7           | 40-27-40       | 20 min.-50 s-20 min. |

### 3.3.1. Characterisation of the fabricated DMD optical filters

Various characterisation techniques were used to determine the morphology and topography of the DMD films. The composition of the films was also verified.

#### 3.3.1.1. Atomic force microscopy (AFM)

Atomic force microscopy (AFM, Oxford Instrument Asylum – MFP-3D) was used to investigate the surface topography of the films and their thickness. Silicon AFM probes (NuNano, Scout 70) consisting of sharp tips with a resonant frequency of 70 kHz were used in the analysis. The mode used to obtain the sample topography was the tapping mode. The thickness of the thin films was determined by measuring the height difference between the

coated part (thin film surface) and the uncoated part of the substrate. Part of the substrate was masked during the thin film deposition.

#### **3.3.1.2. X-ray diffraction (XRD)**

XRD (Malvern Panalytical – Aeris) analysis was used to determine the phase composition of the films. Because the sample analysed consisted of nanometres-thin films deposited on a glass substrate, the angle of incidence needed to be much smaller i.e. less than  $1^\circ$ . This causes the X-rays to interact with the nanofilms and not mainly with the substrate. To perform this analysis, grazing incidence XRD analysis was performed the angle of the incident beam was fixed on a low angle, specifically  $0.5^\circ$ . The software, Highscore, was used to identify the peaks and phases present in the measured patterns.

#### **3.3.1.3. UV-Vis-NIR spectroscopy**

UV-Vis-NIR spectroscopic analysis of the samples was performed using the Agilent Cary 5000 UV-Vis-NIR spectrophotometer. Transmittance and reflectance were measured using the solid sample holder and integrating sphere, respectively.

#### **3.3.1.4. X-ray photoelectron spectroscopy (XPS)**

XPS (Thermo Scientific K-Alpha) analysis was carried out to determine the sample composition, specifically the chemical and electronic state of the samples. The spectra obtained were analysed using the KherveFitting software.

### **3.4. Collector design**

A parabolic trough spectral splitting concentrating photovoltaic-thermal (SSCPVT) collector design was used. The parabolic trough SSCPVT collector used consists of two channels, primary (top) and secondary (bottom) channels (Figure 3.4). The primary channel consists of PV cells attached to the absorber. The heat transfer fluid (HTF) inside the absorber can cool the PV cells while generating low temperature heat. The primary channel consists of water in the HTF channel and the secondary channel consists of Therminol VP-1, which has high thermal stability, in the HTF channel. The secondary channel does not consist of PV cells and can generate high temperature heat. The optical filter is placed directly under the primary channel to selectively split the solar radiation that reaches it. The solar radiation is first incident on the parabolic mirror and then reflected by the parabolic mirror to the optical filter. Depending on the type of optical filter used, the optical filter transmits or reflects the solar radiation wavebands that correspond to the spectral response of the PV cells. The rest of the solar spectrum is then reflected or transmitted to the thermal absorber. This makes the

secondary channel thermally decoupled from the PV cells, allowing high temperature heat generation. The parameters are outlined in Table 3.2.

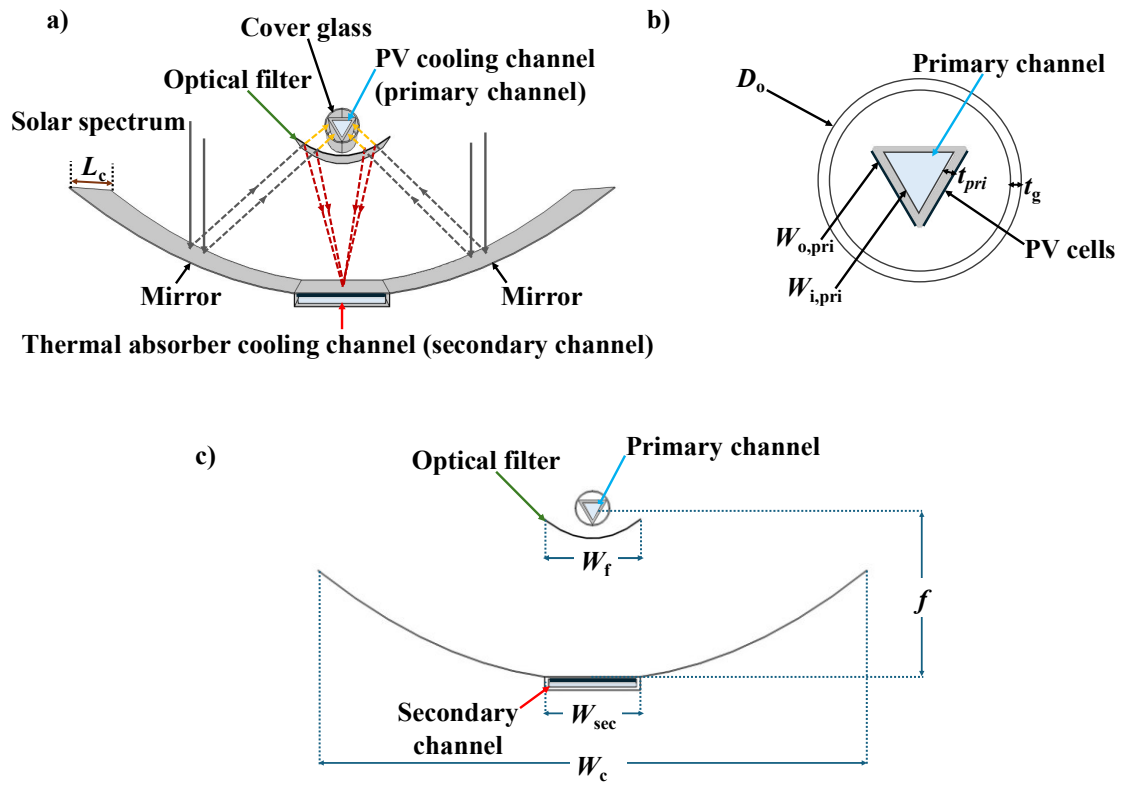


Figure 3.4: a) Schematic diagram of the SSCPVT collector, and the cross-section of the b) primary channel and c) SSCPVT.

Table 3.2: Parameters used in the SSCPVT model.

| Parameters                     | Symbol          | Value (m) |
|--------------------------------|-----------------|-----------|
| Collector length               | $L_c$           | 2 m       |
| Aperture width                 | $W_c$           | 1 m       |
| Focal length                   | $f$             | 1.3 m     |
| Cover glass outer diameter     | $D_o$           | 70 mm     |
| Cover glass thickness          | $t_g$           | 2.5 mm    |
| Primary channel inner width    | $W_{i,pri}$     | 39 mm     |
| Primary channel outer width    | $W_{o,pri}$     | 51 mm     |
| Primary channel wall thickness | $t_{pri}$       | 2.5 mm    |
| Width of secondary channel     | $W_{sec}$       | 170 mm    |
| Thickness of secondary channel | $t_{sec}$       | 14 mm     |
| Cover glass transmittance      | $\tau_g$        | 0.95 [4]  |
| Mirror reflectance             | $\rho_{mirror}$ | 0.95 [5]  |
| PV absorptivity                | $\alpha_{PV}$   | 0.92 [6]  |

### 3.5. SSCPVT model outline

The SSCPVT model developed in this work is composed of optical, heat-transfer, and PV sub-models. These sub models are then coupled to form a Multiphysics model in COMSOL to assess the suitability of the modelled and fabricated optical filters within an SSCPVT collector and to evaluate the resulting impact of the filters on overall collector performance.

#### 3.5.1. Optical sub model

The optical model was developed to determine the solar irradiance that is transmitted to the PV cells using the following equation:

$$G_{PV}(\lambda) = G_{AM1.5}(\lambda) \cdot C_{geo} \cdot \tau_g \cdot \tau_{filter}(\lambda) \cdot \rho_{mirror} \quad (3.2)$$

where  $G_{AM1.5}(\lambda)$  is the spectral irradiance, AM1.5 global (ASTM G-173) solar spectrum.  $C_{geo}$  is the geometric concentration ratio ( $A_c/A_{PV}$ ),  $\tau_g$  is the glass transmittance,  $\tau_{filter}(\lambda)$  is the transmittance of the optical filter, and  $\rho_{mirror}$  is the mirror reflectance. The solar irradiance that is reflected to the thermal absorber is given as:

$$G_{abs}(\lambda) = G_{AM1.5}(\lambda) \cdot C_{geo} \cdot \tau_g \cdot \rho_{filter}(\lambda) \cdot \rho_{mirror} \quad (3.3)$$

where  $\rho_{\text{filter}}(\lambda)$  is the reflectance of the optical filter.

### 3.5.2. PV electrical sub model

The electrical model was used to determine the electrical efficiency of the PV at an operating temperature,  $T_{\text{PV}}$ . The electrical efficiency is given by:

$$\eta_{\text{el}} = \eta_{\text{el},0} [1 - \beta(T_{\text{PV}} - T_{\text{ref}})] \quad (3.4)$$

$$\eta_{\text{el},0} = \frac{V_{\text{oc}} I_{\text{sc}} FF}{G_{\text{AM1.5}} A_{\text{c}}} \quad (3.5)$$

where  $\eta_{\text{el},0}$  is the electrical efficiency at a reference temperature,  $T_{\text{ref}}$  (25 °C),  $\beta$  is the temperature coefficient of the PV cell,  $V_{\text{oc}}$  is the open circuit voltage,  $I_{\text{sc}}$  is the short circuit current,  $FF$  is the fill factor [6],  $G_{\text{AM1.5}}$  is the solar irradiance at AM 1.5 equal to 1000 W/m<sup>2</sup> (integral of the spectral irradiance),  $A_{\text{c}}$  is the aperture area of the collector. The short-circuit current is calculated as follows [7]:

$$I_{\text{sc}} = J_{\text{sc}} A_{\text{PV}} \quad (3.6)$$

$$J_{\text{sc}} = \int_{280 \text{ nm}}^{2500 \text{ nm}} SR(\lambda) G_{\text{PV}}(\lambda) d\lambda \quad (3.7)$$

where  $J_{\text{sc}}$  is short circuit current density,  $A_{\text{PV}}$  is the area of the solar cell, and  $SR(\lambda)$  is the spectral response of the PV cell. The open circuit voltage of the solar cells is given as [8]:

$$V_{\text{oc}} = \frac{A' k_{\text{B}} T_{\text{ref}}}{e} \ln \left( \frac{J_{\text{sc}}}{J_{\text{ds}}} + 1 \right) \quad (3.8)$$

where  $A'$  is the ideality factor,  $k_{\text{B}}$  is the Boltzmann constant, and  $e$  is the unit charge.  $J_{\text{ds}}$  dark saturation current density which is calculated by [9]:

$$J_{\text{ds}} = k_1 T_{\text{ref}}^{3/z} \exp \left( \frac{-E_{\text{bg}}}{b k_{\text{B}} T_{\text{ref}}} \right) \quad (3.9)$$

where  $k_1$ ,  $z$ , and  $b$  are empirical parameters that are equal to 0.03, 1.25, and 0.98, respectively.  $E_{\text{bg}}$  is the bandgap of a PV cell.

### 3.5.3. Heat transfer and fluid dynamics sub model

A three-dimensional steady-state model was developed in COMSOL Multiphysics® using the finite element method (FEM). The energy balance equation for the collector is given as:

$$\rho c_p \mathbf{u} \cdot \nabla T + \nabla \cdot (\mathbf{q} + \mathbf{q}_r) = Q \quad (3.10)$$

where  $\rho$  is the density,  $c_p$  is the specific heat capacity,  $T$  is the absolute temperature,  $\mathbf{u}$  is the velocity vector,  $\mathbf{q}$  is the heat flux by conduction,  $\mathbf{q}_r$  is the heat flux by radiation and  $Q$  contains heat sources. In addition, for the fluid domain, the mass and momentum equations were solved, which are as follows [6]:

$$\rho \nabla \cdot \mathbf{u} = 0 \quad (3.11)$$

$$\rho(\mathbf{u} \cdot \nabla) \mathbf{u} = -\nabla P + \nabla \tau + \mathbf{F} \quad (3.12)$$

where  $P$  is pressure,  $\tau$  is shear stress and  $\mathbf{F}$  is external force per unit area.

Boundary conditions were applied at the interface between the walls of the primary and secondary channels and their respective heat transfer fluids. A no slip boundary condition was applied for the walls of the fluid. The inlet had temperature and mass flow boundary conditions applied to it. The outlet was set to be a pressure outlet with 0 Pa reference pressure.

To the outer surface of the glass of the primary channel, convection and radiation heat losses were applied. For convection between the tubular glass cover and the ambient, the correlation for the heat convection coefficient was estimated using [5]:

$$h_w = 4V_w^{0.58} \cdot D_o^{-0.42} \quad (3.13)$$

where  $V_w$  is the wind speed ( $V_w = 1$  m/s) and  $D_o$  is the outer diameter of the glass cover. The convective heat transfer coefficient at the secondary thermal absorber is given as [10]:

$$h_w = 4.5 + 2.9V_w \quad (3.14)$$

The total heat loss from the glass cover to the ambient is given by:

$$q_{\text{loss}} = h_w(T_w - T_a) + \varepsilon\sigma(T_w^4 - T_{\text{sky}}^4) \quad (3.15)$$

where  $T_a$  and  $T_w$  are ambient (298 K) and outer wall temperatures, respectively, while  $\varepsilon$  and  $\sigma$  are emissivity and Stefan-Boltzmann constant, respectively.  $T_{\text{sky}}$  is the equivalent sky temperature for radiation, which is equal to  $0.0522T_a^{1.5}$  [11].

The heat generated in the PV is calculated from:

$$Q_{\text{PV,h}} = Q_{\text{PV}} - \eta_{\text{el},0} \cdot C_{\text{geo}} \cdot G_{\text{AM1.5}} \quad (3.16)$$

where  $Q_{PV}$  is the solar energy absorbed by the PV. The solar irradiance that is transmitted to the PV cell is absorbed by it and is given as:

$$Q_{PV} = \int_{280 \text{ nm}}^{2500 \text{ nm}} \alpha_{PV}(\lambda) G_{PV}(\lambda) d\lambda \quad (3.17)$$

where  $\alpha_{PV}(\lambda)$  is the absorptivity of the PV cell.

The thermal efficiencies of the primary and secondary channels are then calculated as:

$$\eta_{th\_pri} = \frac{\dot{m}_{pri} c_{p,pri} (T_{pri} - T_{in})}{A_c \cdot G_{AM1.5}} \quad (3.18)$$

$$\eta_{th\_sec} = \frac{\dot{m}_{sec} c_{p,sec} (T_{sec} - T_{in})}{A_c \cdot G_{AM1.5}} \quad (3.19)$$

where  $\dot{m}_{pri}$  and  $\dot{m}_{sec}$  are mass flow rates of the fluid through the primary and secondary channels, respectively, while  $c_{p,pri}$  and  $c_{p,sec}$  are the specific heat capacity through the primary and secondary channels, respectively.  $T_{pri}$  is the outlet temperature of the primary channel and  $T_{sec}$  is the outlet temperature of the secondary channel.  $T_{in}$  is the inlet temperature (303.15 K) of the primary and secondary channels. The reduced temperatures of the primary and secondary channels are then calculated as follows:

$$T_{r\_pri} = \frac{T_{m\_pri} - T_a}{G_{AM1.5}} \quad (3.20)$$

$$T_{r\_sec} = \frac{T_{m\_sec} - T_a}{G_{AM1.5}} \quad (3.21)$$

where  $T_{m\_pri}$  is the mean temperature of the primary channel,  $T_{m\_sec}$  is the mean temperature of the secondary channel and  $T_a$  is the ambient temperature.

#### 3.5.4. PV-weighted average transmittance of the optical filters

The PV-weighted average transmittance,  $\tau_{avg,PV}$  of the optical filters quantifies the amount of solar irradiance that is transmitted to a PV cell that corresponds to the spectral response of the PV cell and accounts for the solar spectrum.

$$\tau_{avg,PV} = \frac{\int_{\lambda_1}^{\lambda_2} \tau_{filter}(\lambda) G_{AM1.5}(\lambda) SR(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} G_{AM1.5}(\lambda) SR(\lambda) d\lambda} \quad (3.22)$$

where  $\lambda_1$  and  $\lambda_2$  are the lower bound and upper bound, respectively, of the spectral response of a PV cell.

### 3.5.5. Flow diagram of the SSCPVT model

The SSCPVT model consists of optical, electrical and thermal sub models which are shown in Figure 3.5. COMSOL Multiphysics® and MATLAB were used to calculate the equations outlined in Section 3.4. The optical properties, reflectance and transmittance, of the optical filters that were simulated and fabricated were among the parameters used as inputs to determine the part of the solar spectrum that reaches the PV cells. This solar spectrum that reaches the solar spectrum was then used in the electrical model to determine the systemic electrical efficiency. The parameters from the optical and electrical models were then used in the thermal model to calculate the temperature output of the channels and overall performance of the SSCPVT collector.

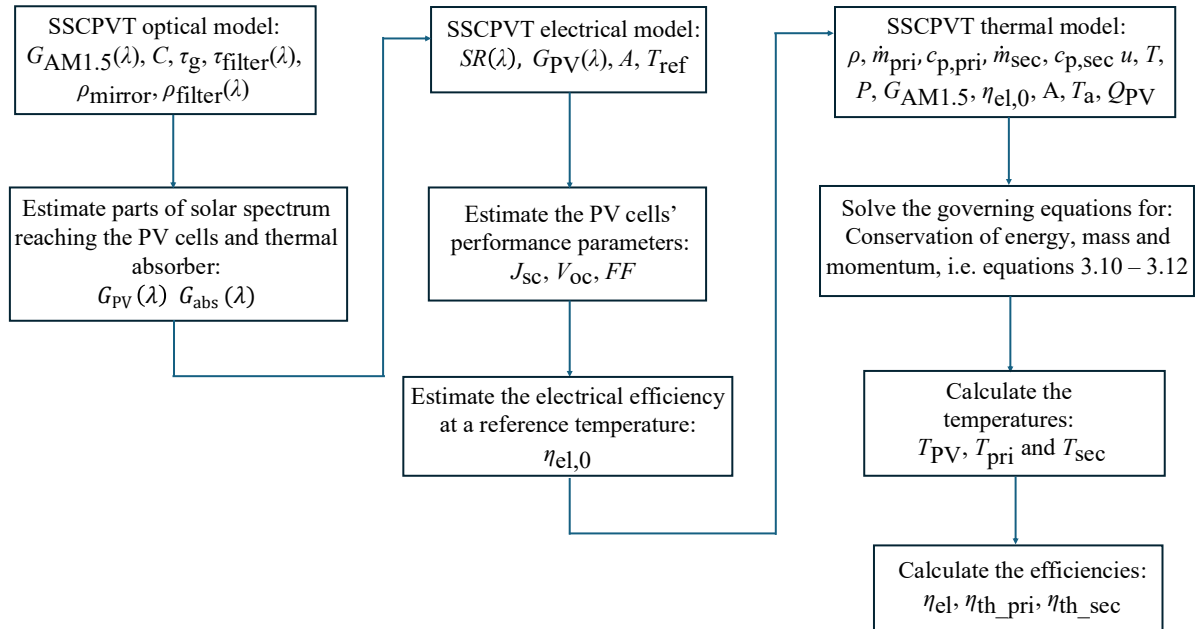


Figure 3.5: Flow diagram of the SSCPVT collector.

### 3.6. Summary

This chapter involved a detailed outline of the methodologies used to achieve the optical filters for an SSCPVT collector and evaluate the collector's performance. The DMD and metasurface optical filters were simulated using COMSOL Multiphysics® to determine the suitable optical properties for the application. The DMD optical filters were fabricated using magnetron sputtering and characterised using various techniques such as AFM, XRD, UV-Vis-NIR spectroscopy, and XPS. The SSCPVT collector's performance was modelled using COMSOL Multiphysics® and MATLAB. The model included optical, electrical and thermal sub models, and all the equations used were included.

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# Chapter 4: Simulation and fabrication of DMD optical filters

## Table of contents

|                                                               |    |
|---------------------------------------------------------------|----|
| 4.1. Introduction.....                                        | 56 |
| 4.2. Comsol simulation results.....                           | 57 |
| 4.2.1. Model validation using the literature results.....     | 57 |
| 4.2.2. Effect of changing the metal layer .....               | 58 |
| 4.2.3. Effect of varying the TiO <sub>2</sub> thickness ..... | 59 |
| 4.2.4. Effect of varying the Ag thickness .....               | 60 |
| 4.3. Experimental results.....                                | 61 |
| 4.3.1. Atomic force microscopy (AFM).....                     | 62 |
| 4.3.2. X-ray diffraction (XRD) .....                          | 62 |
| 4.3.3. X-ray photoelectron spectroscopy .....                 | 63 |
| 4.3.4. Model validation using experimental data .....         | 64 |
| 4.3.5. Optical properties of fabricated DMD films .....       | 65 |
| 4.4. Summary .....                                            | 66 |
| 4.5. References.....                                          | 67 |

## 4.1. Introduction

The design and optimisation of optical filters for spectral splitting concentrating photovoltaic-thermal (SSCPVT) collectors have garnered great research interest. Commonly used optical filters in SSCPVT collectors include selectively absorptive liquid filters [1] and interference thin film filters [2]. Selectively absorptive liquid filters split the incident solar radiation by selectively transmitting the solar radiation to the PV module and absorbing the rest of the solar radiation, while thin film interference filters selectively transmit or reflect the solar radiation. Nanofluid filters which comprise of nanoparticles dispersed in a liquid are the most widely reported selectively absorptive liquid filters in the literature. These nanofluid filters are reported to be suitable for use due to the ease with which their optical properties can be varied and their low cost [3]. However, their stability especially for long term use remains an issue [4]. The thin film filters that have been reported, such as interference filters, tend to involve many layers which may be costly to fabricate [5].

Therefore, in this study a tri-layer thin film optical filter will be used, which is less costly to fabricate, and its optical properties are easy to vary while mitigating the issue of the stability of nanofluids. The tri-layer thin film optical filter consists of dielectric-metal-dielectric (DMD) layers. These DMD optical filters have been widely used in smart windows applications [6]. DMD optical filters are also known as transparent heat mirrors (THMs) in the literature [7]. DMDs function by transmitting the visible region of the solar spectrum and reflecting NIR region. This is achieved by using a metal layer sandwiched between two dielectric layers of the same material. The metal layer selected should have a very high reflectance and low absorbance in the visible region, which means that the metal should have a very low refractive index in the region (Figure 4.1). Because of their low refractive index in the visible region, Ag, Au and Cu are the most used metal layers in DMDs. The dielectric layers on both sides of the highly reflective metal act as anti-reflective layers that enhances overall transparency of the DMD optical filter. DMDs consisting of dielectric materials such as  $\text{WO}_3$  [8], ITO [9], ZnS [7], and  $\text{TiO}_2$  [10] have been reported. DMDs have been used in smart windows [11], electrodes [12] and they have also been proposed as potential optical filters for spectral splitting in a photovoltaic-thermoelectric collector [13]. However, they were not simulated or tested within an actual photovoltaic-thermoelectric collector to evaluate its performance. DMDs, specifically  $\text{TiO}_2\text{-Ag-TiO}_2$ , were proposed as optical filters for SSCPVTs in this research. This is because of their high transparency in the visible region enables transmittance of the visible region of the solar spectrum to the PV cells. The PV cells studied in this research have a spectral response

that includes visible light wavelengths. DMDs, in addition to their visible light transmittance, can reflect the NIR region. The NIR region that is reflected by the DMDs can be directed to the thermal absorber component of the SSCPVT collector. The  $\text{TiO}_2$  layer enhances visible light transmittance, while the Ag layer enhances the NIR reflectance. This chapter focuses on the simulation, fabrication and characterisation of the DMDs.

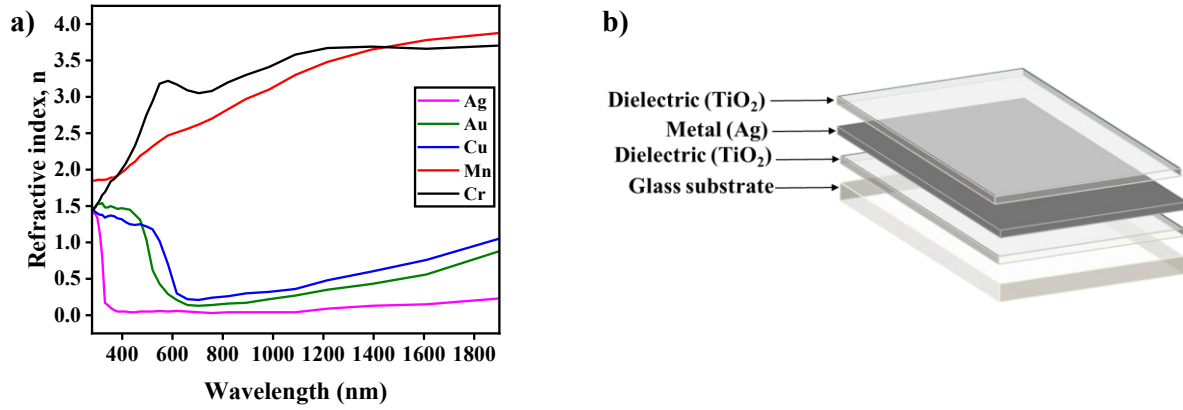


Figure 4.1: a) The refractive index of Ag, Au, and Cu by Johnson and Christy [14] and b) schematic diagram of the  $\text{TiO}_2$ -Ag- $\text{TiO}_2$  DMD.

## 4.2. Comsol simulation results

A model was developed in COMSOL Multiphysics® as outlined in Section 3.2 to simulate the optical properties of the DMD optical filters. Validation of the model was also conducted using results obtained from the literature and the experimental results. A parametric study was conducted by varying the thickness of the DMD layers, i.e. dielectric and metal layers, both of which greatly affect the resulting optical properties.

### 4.2.1. Model validation using the literature results

The optical properties of a DMD consisting of ZnS (31 nm)-Ag (18 nm)-ZnS (34 nm) layers were simulated using the model outlined in Section 3.2 were validated against the results reported in the literature [11] (Figure 4.2). The root mean square errors (RMSE) were calculated. The RSME for transmittance and reflectance were under 4%. The literature and simulated spectra were similar in appearance, based on the RSME values calculated, they were in good agreement.

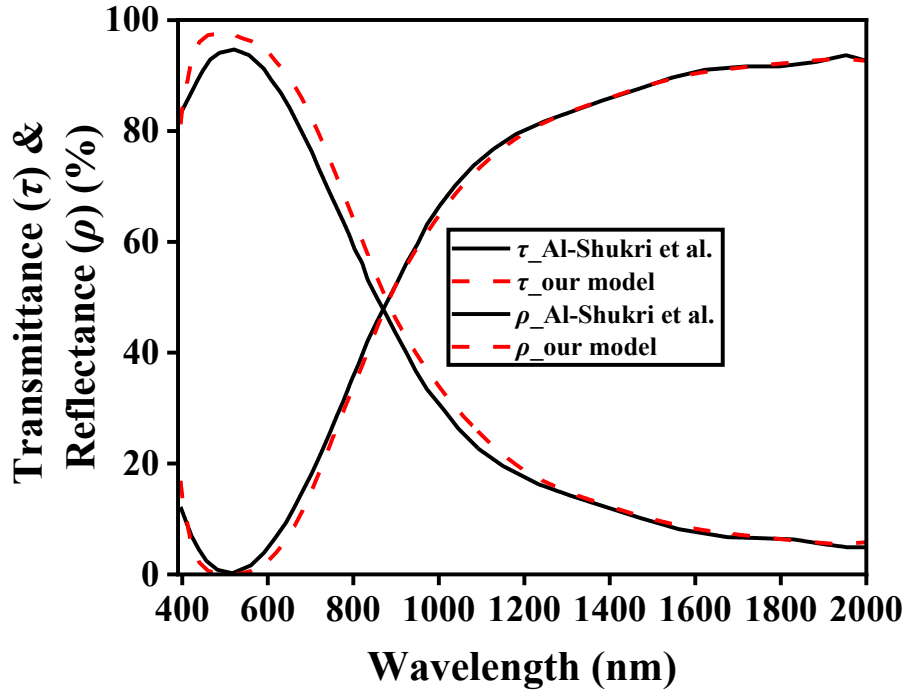


Figure 4.2: Transmittance and reflectance spectra of ZnS (31 nm)-Ag(18 nm)-ZnS (34 nm) DMD obtained using our model and the spectra obtained in the literature [11].

#### 4.2.2. Effect of changing the metal layer

The optical properties of DMD optical filters depend on the optical properties of the materials used. A comparison between different metals of the DMD, Ag, Au and Cu, was performed while keeping the dielectric materials, which are both  $\text{TiO}_2$ , constant (Figure 4.3). DMD\_Ag denotes a DMD material with Ag sandwiched between dielectric materials,  $\text{TiO}_2$ . The thickness of Ag, Au and Cu was kept at 10 nm and the thickness of the  $\text{TiO}_2$  layers was 50 nm. The thickness of all the layers was kept constant since the comparison was only based on the metallic materials. This comparison was performed to show the effect of changing the metal layer on the DMDs' optical properties, i.e. transmittance, reflectance and absorptance. The transmittance of DMD\_Ag in the visible region (400 nm – 700 nm) is higher than that of DMD\_Au and DMD\_Cu. This is because of the low absorptance of DMD\_Ag in comparison to DMD\_Au and DMD\_Cu as a result of the low refractive index of Ag. A high transmittance in the visible region is required due to the application of the DMD optical filters in this study. The DMD optical filter should be able to transmit the region of the solar spectrum corresponding to the spectral response of the PV materials, Si and CdTe, which a significant part of is in the visible region.

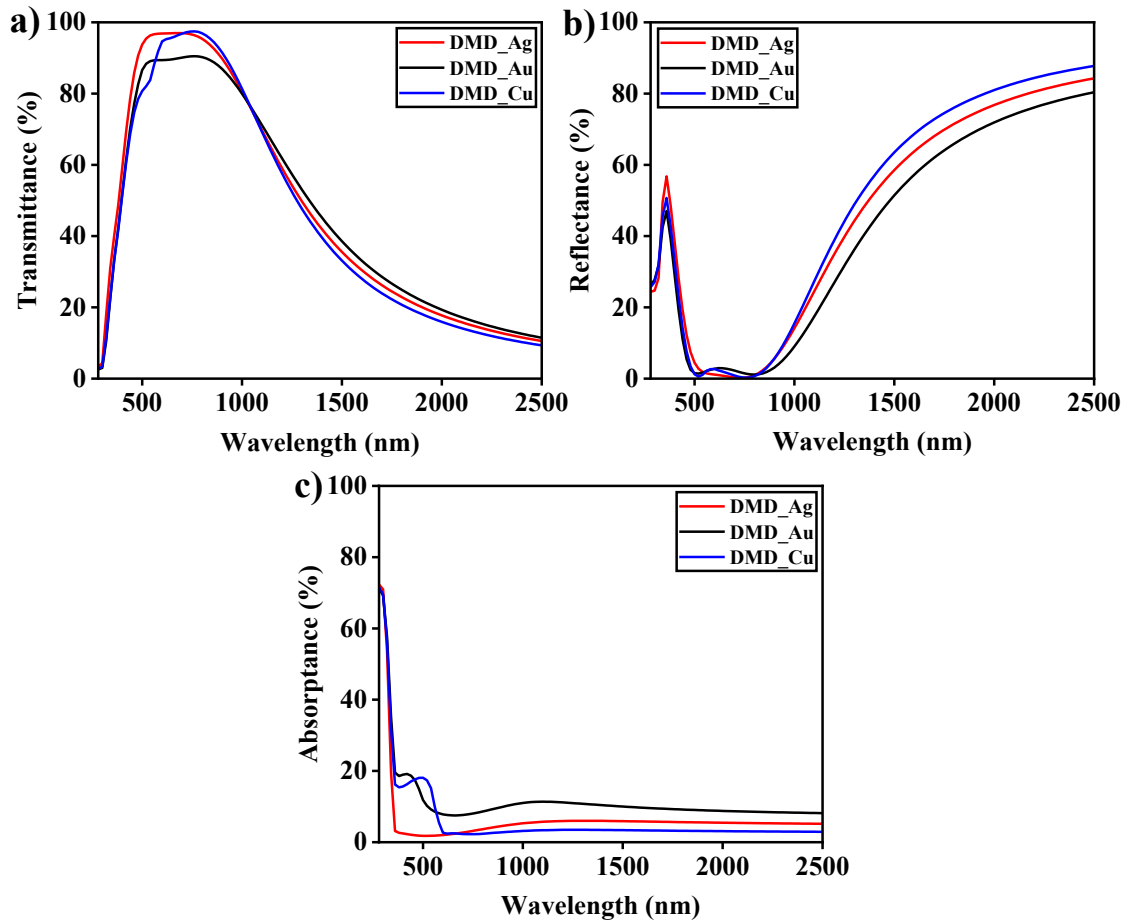


Figure 4.3: a) Transmittance, b) reflectance and c) absorbance of DMD films consisting of TiO<sub>2</sub> as the dielectric material and the metallic material is varied between Ag, Au and Cu.

#### 4.2.3. Effect of varying the TiO<sub>2</sub> thickness

The simulated optical properties including reflectance, transmittance and absorbance of the TiO<sub>2</sub>-Ag-TiO<sub>2</sub> DMD films were plotted as shown in Figure 4.4. The 10nm-10nm-10nm optical filter name corresponds to the layer thickness of each material in the TiO<sub>2</sub>-Ag-TiO<sub>2</sub> DMD films. The DMD optical filters' transmittance spectra can be tuned by varying the thickness of the Ag or TiO<sub>2</sub> layers. Generally, the DMDs exhibit transmittance in the visible light region and reflectance in the NIR region. TiO<sub>2</sub> layers result in the DMDs' high transmittance in the visible region. This is because TiO<sub>2</sub>, being a dielectric material, acts as an anti-reflective layer on top of the Ag by creating a Fabry-Pérot resonance effect, where reflected waves at the dielectric-metal interface destructively interfere with each other, maximising transmittance while minimising reflectance in the visible region [15]. Redshifted broad peaks were observed when the Ag layer thickness was fixed at 10 nm (Figure 4.4 a), while the thickness of TiO<sub>2</sub> was increased from 10 nm to 70 nm.

Furthermore, double peaks on the transmittance spectra were observed and the splitting of the peaks became more pronounced as the thickness of the TiO<sub>2</sub> films increased. The double peaks could be attributed to the splitting of the surface plasmon wave modes into symmetric and antisymmetric when Ag is sufficiently thin [16, 17]. A redshift was also observed in the reflectance peaks as the thickness of TiO<sub>2</sub> increased. As the thickness of the TiO<sub>2</sub> films increases, the width of the reflectance peak at lower wavelengths also increases. Consequently, reflectance in the visible light region increases (Figure 4.4 d). While a high reflectance in the NIR region is required for the intended application, reflectance in the visible light region is not.

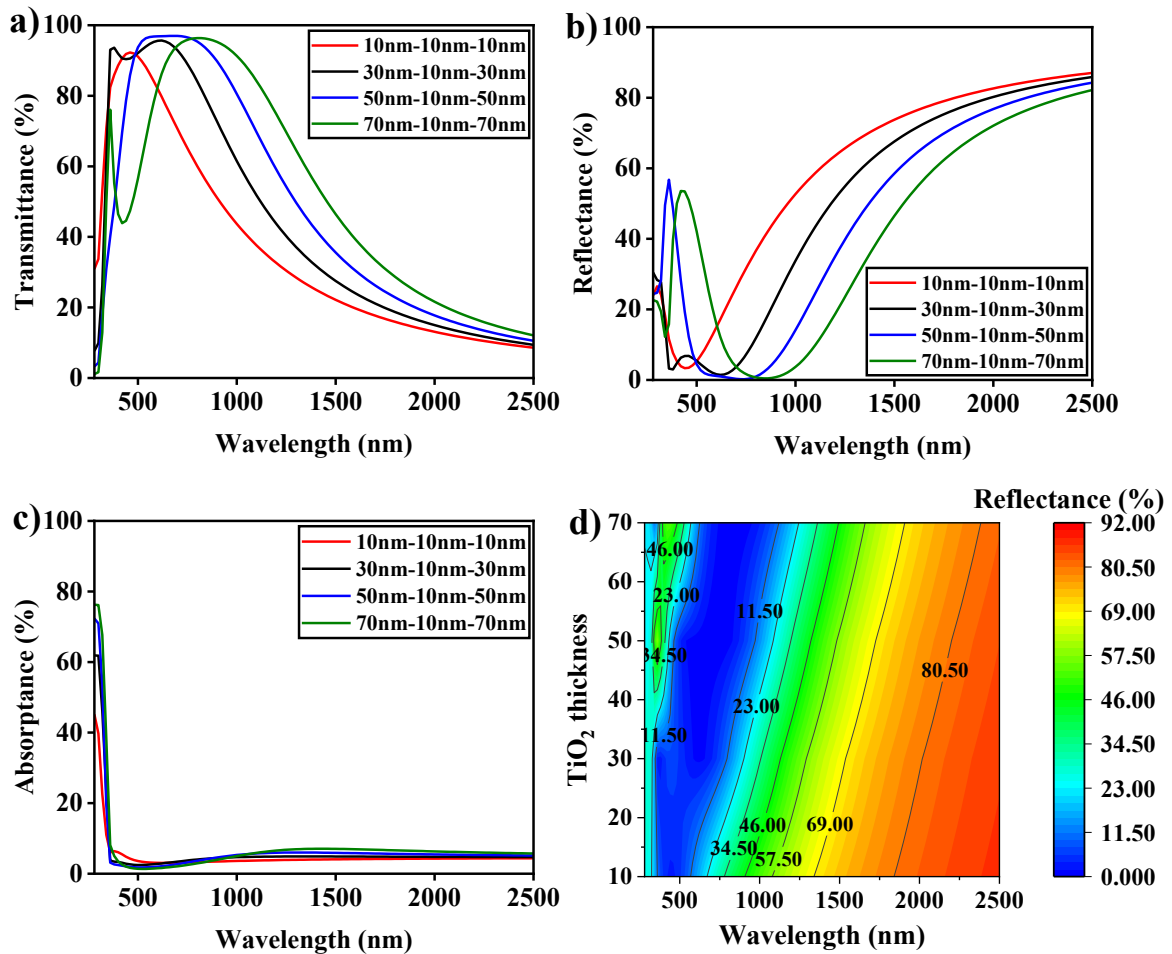


Figure 4.4: a) Transmittance, b) reflectance and c) absorptance spectra, and d) contour plot of TiO<sub>2</sub>-Ag-TiO<sub>2</sub> DMDs with Ag thickness fixed at 10 nm while TiO<sub>2</sub> thickness is varied between 10 – 70 nm.

#### 4.2.4. Effect of varying the Ag thickness

Ag is responsible for the high reflectance of the DMDs in the NIR region. The thickness of the Ag layer affects the balance between NIR reflectance and visible transmittance, i.e. as one increases, the other typically decreases (Figure 4.5). A reduction in the transmittance of visible

light was observed as the thickness of the Ag increased. This can be observed in Figure 4.5 where the thickness of both TiO<sub>2</sub> layers was kept constant and equal to 40 nm, while the thickness of the Ag layer was varied between 10 nm and 25 nm at intervals of 5 nm. The increase in thickness of Ag results in an increase in NIR reflectance and visible light absorptance. This is due increase in the free electrons of Ag as its thickness increases [13, 18].

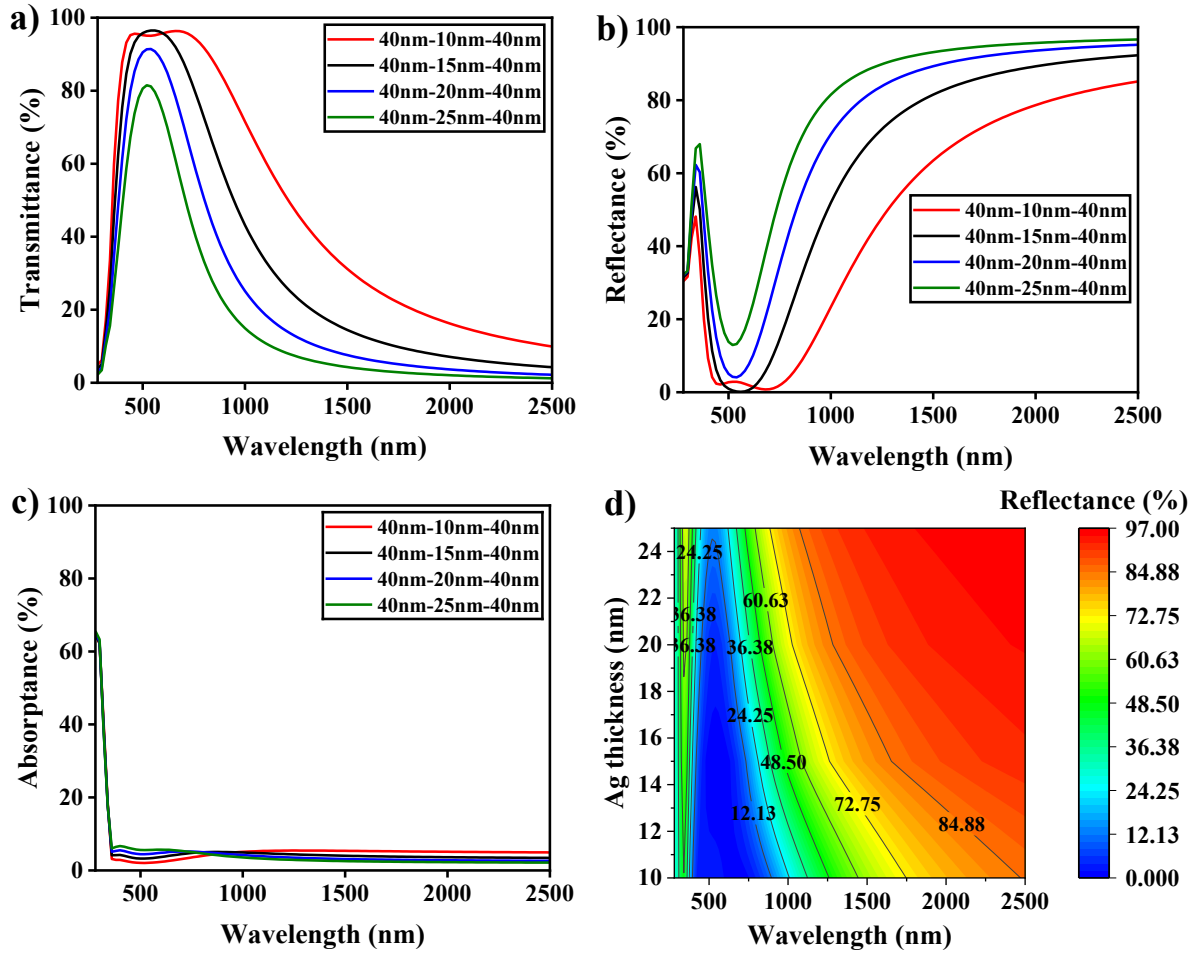


Figure 4.5: a) Transmittance spectra, b) reflectance spectra and c) absorptance spectra and d) contour plot of DMDs with TiO<sub>2</sub> thickness fixed at 40 nm while Ag thickness is varied between 10 and 25 nm.

### 4.3. Experimental results

The experimental results section includes the morphology, chemical composition, and optical properties of the fabricated DMDs. The DMDs were fabricated by depositing TiO<sub>2</sub>, Ag and TiO<sub>2</sub> thin films, subsequently, onto a glass substrate using magnetron sputtering. The procedure is outlined in Section 3.5. The optical properties of the DMDs obtained experimentally were also used in the modelling of the electrical efficiency of the PV cells.

#### 4.3.1. Atomic force microscopy (AFM)

The morphology of the DMD films was studied using AFM and the resulting 3D topography shows that it has a rough surface (Figure 4.6). Ag has a roughness that is 3× that of TiO<sub>2</sub>. This is due to the growth mode of the Ag film following the Volmer-Weber mode during the sputtering process starting first as clusters of islands [19, 20]. The thicknesses of the TiO<sub>2</sub> and Ag films were also determined using AFM (Appendix, Figure A.1, A.2 and Table A.1). The thickness of the thin films was determined by measuring the height difference between the coated part (thin film surface) and the uncoated part of the substrate. Part of the substrate was masked during the thin film deposition.

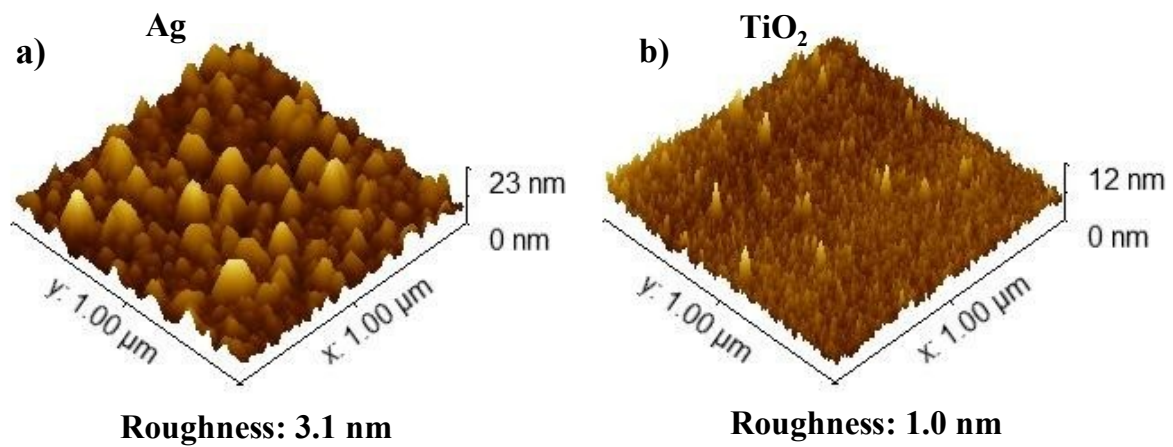


Figure 4.6: a) AFM and b) SEM images of Ag film, c) AFM and d) SEM images of TiO<sub>2</sub> film.

#### 4.3.2. X-ray diffraction (XRD)

The XRD data show (Figure 4.7) diffracted peaks of Ag at  $2\theta$  values 38.3°, 44.5°, 64.9° and 77.7° in all the DMD films. These peaks correspond to (111), (200), (220) and (300) planes, respectively (ASTM.Ag, no:00-004-0783) [20]. The peaks positions are in good agreement with the literature [21]. As the Ag thickness increases, the intensity of peaks increases along with improved crystallinity of multilayer films. However, the TiO<sub>2</sub> peaks are not visible, there is a hump at  $2\theta$  value of about 25° which is characteristic of that of a glass substrate. The absence of TiO<sub>2</sub> peaks is due to TiO<sub>2</sub> being in an amorphous phase following its deposition at room temperature [22] and another technique was used to confirm its successful deposition.

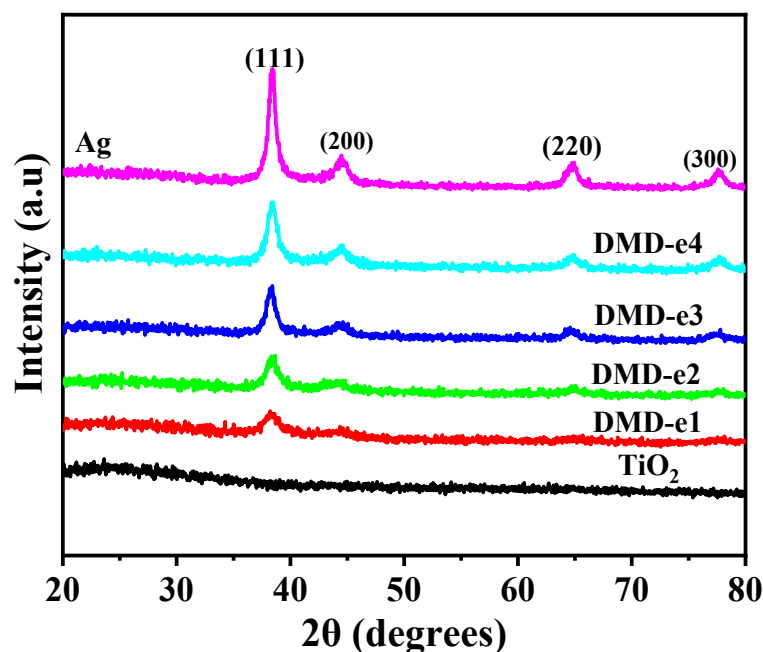


Figure 4.7: XRD patterns of Ag, TiO<sub>2</sub> and DMD films with varying Ag thickness deposited on a glass substrate.

#### 4.3.3. X-ray photoelectron spectroscopy

XPS analysis was conducted on the TiO<sub>2</sub> and Ag films. Peak fitting of the data obtained was achieved using the KhurveFitting software. XPS analysis of TiO<sub>2</sub> resulted in Ti2p and O1s spectra (Figure 4.8). The Ti2p spectrum revealed Ti2p<sub>3/2</sub> and Ti2p<sub>1/2</sub> peaks at binding energies of 458.9 eV and 464.6 eV respectively, which are characteristic of Ti<sup>4+</sup> oxidation state in TiO<sub>2</sub> [23]. The peaks at 458.1 and 463.8 eV indicated the presence of Ti<sup>3+</sup> species. The O1s spectrum revealed the presence of the lattice oxygen (O<sup>2-</sup>) peak of TiO<sub>2</sub> at 530.4 eV. The peak at 532.3 eV is assigned to basic Ti-OH groups. This confirmed the presence of TiO<sub>2</sub> in our sample. The Ag XPS spectrum included Ag3d<sub>5/2</sub> and Ag3d<sub>3/2</sub> peaks positioned at 368.2 eV and 374.2 eV respectively, which confirmed the deposition of Ag [24].

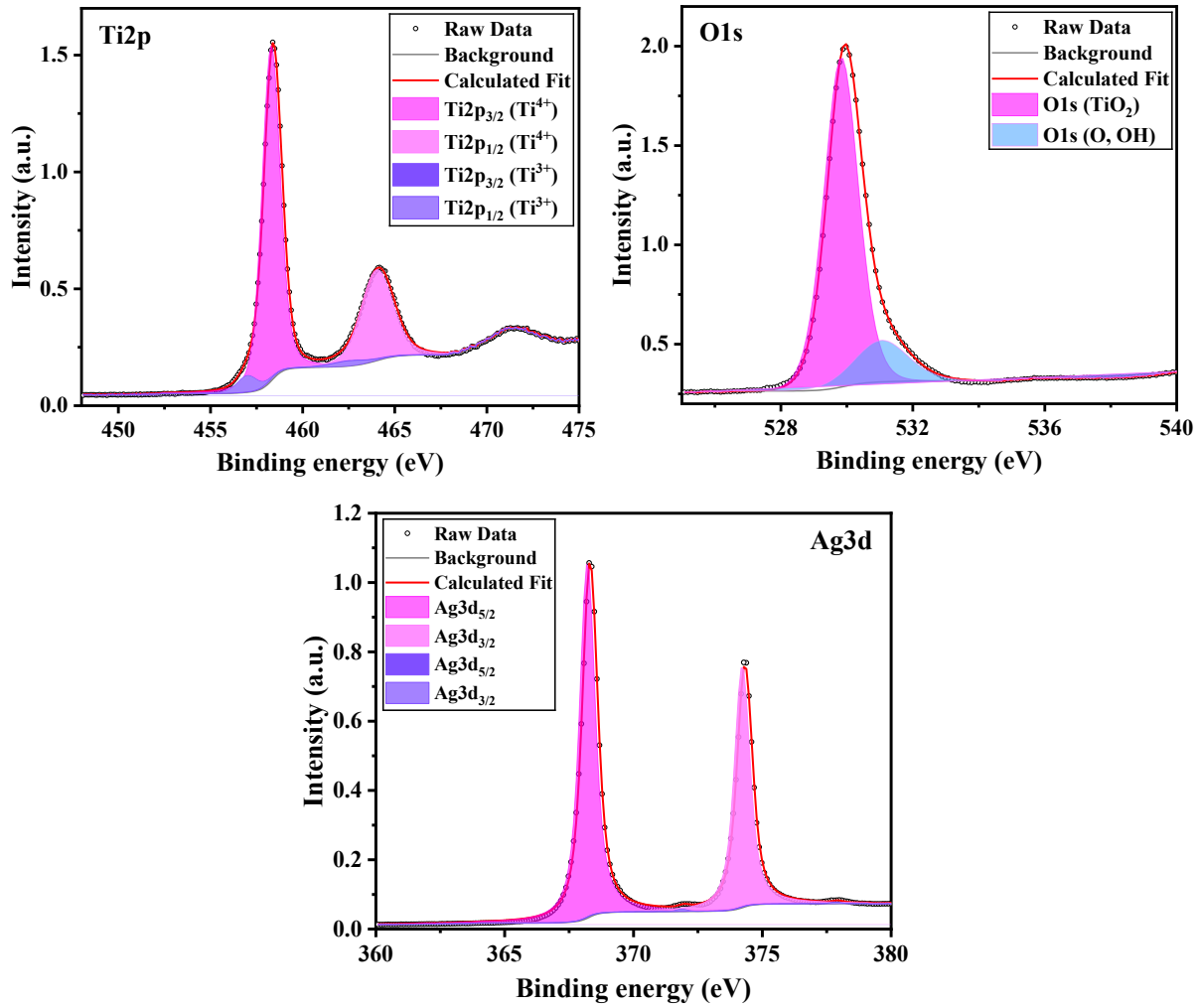


Figure 4.8: XPS spectra of (a-b)  $\text{TiO}_2$ , and c) Ag.

#### 4.3.4. Model validation using experimental data

The experimental data of the DMD optical filter (DMD-e) was compared with the simulated data (DMD-s). These optical filters both thickness of 40 nm for both  $\text{TiO}_2$  layers, and 10 nm for Ag to compare the spectra obtained in both cases. The transmittance, reflectance and absorbance spectra of the experimental and simulated samples had a similar appearance (Figure 4.9). They both had higher transmittance in the visible region, and higher reflectance in the NIR region, although those of the simulated data were much higher. The absorbance of the experimental data was much higher than that of the simulated data. This can be attributed to the features of the surfaces of the deposited layers, which may result in increased scattering and absorbance of light. Features such as surface roughness at the dielectric-metal interfaces affect the optical properties of the DMD optical filters, while simulations are usually more simplified by considering surfaces to be smooth. The Ag forms islands during the initial stages of its deposition and as the process continues it grows into a more uniform and smoother layer

the thicker it becomes especially when using a physical vapour deposition (PVD) method. The roughness of the surface of the Ag layer increases the absorbance which is surface plasmon induced [25]. The reflectance, transmittance and absorbance RSME were all equal to 0.08.

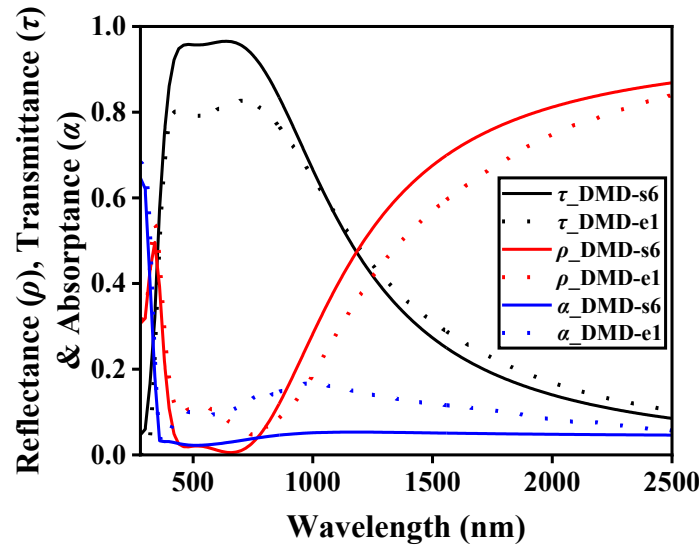


Figure 4.9: Transmittance, reflectance and absorbance spectra of the simulated (DMD-s) and fabricated (DMD-e) DMD filters.

#### 4.3.5. Optical properties of fabricated DMD films

The optical properties of the glass substrate, TiO<sub>2</sub> film, Ag film and DMD (TiO<sub>2</sub>-Ag-TiO<sub>2</sub>) films were measured using UV-Vis-NIR spectroscopy and the results are shown in Figure 4.10. The thickness of the TiO<sub>2</sub>, Ag and DMD films is detailed in Table 4.1. The glass substrate and the TiO<sub>2</sub> film exhibit high transmittance in the visible and NIR regions, but TiO<sub>2</sub> has a lower transmittance than glass due to a more significant reflectance than glass when light is incident on it. Both glass and TiO<sub>2</sub> have a low reflectance in the visible and NIR regions. Ag however, has a significantly lower transmittance and a high reflectance in the visible and NIR regions.

The transmittance of DMD-e1 was the highest (Figure 4.10) while that of DMD-e7 was the lowest. This is due to an increase in the thickness of Ag from 10 nm to 27 nm. All the fabricated DMDs exhibit transmittance in the visible light, reflectance in the NIR region and absorbance in the UV region.

The Ag film was varied between 10 nm and 27 nm while the TiO<sub>2</sub> layer was fixed at 40 nm. This was conducted to observe the effect of varying the Ag thickness on the transmittance of the DMDs experimentally (Figure 4.10). Similar to the simulated results, the transmittance of the DMDs decrease with an increase in the thickness of the Ag. The anti-reflection role of the

TiO<sub>2</sub> layers weakens due to an increase in the reflectance and absorptance of Ag as the thickness of Ag increases [15].

Table 4.1: Fabricated optical filters and their respective thicknesses.

| Optical filter   | Thickness (nm) |
|------------------|----------------|
| Ag               | 22             |
| TiO <sub>2</sub> | 40             |
| DMD-e1           | 40-10-40       |
| DMD-e2           | 40-13-40       |
| DMD-e3           | 40-16-40       |
| DMD-e4           | 40-18-40       |
| DMD-e5           | 40-21-40       |
| DMD-e6           | 40-24-40       |
| DMD-e7           | 40-27-40       |

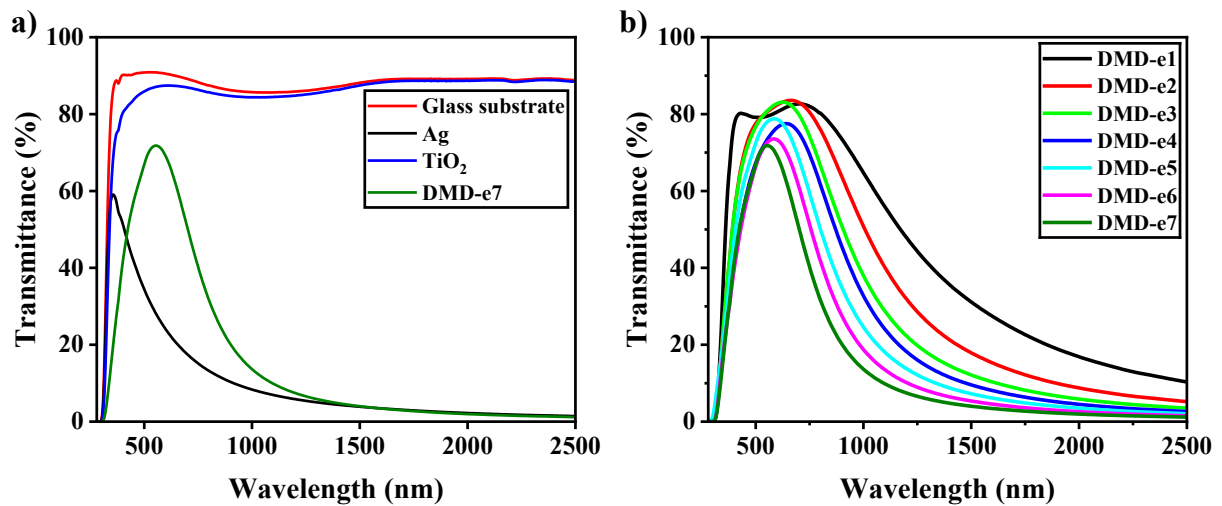


Figure 4.10: Transmittance spectra of a glass substrate, Ag, TiO<sub>2</sub> and DMD-e7, and Transmittance spectra of the fabricated DMD filters.

#### 4.4. Summary

A study on the optical properties of DMD materials was conducted, particularly TiO<sub>2</sub>-Ag-TiO<sub>2</sub>. The optical properties play an important role in identifying materials' potential to be used as optical filters. At first the optical properties of the DMD materials were simulated using COMSOL Multiphysics®. The results from the simulation were validated against the results obtained in the literature by other authors which were in reasonable agreement with each other. The DMD materials were then fabricated using magnetron sputtering onto a glass substrate. The results obtained were validated against the simulated results. The spectra were similar, but

the fabricated DMD materials' spectra were lower with an RSME value of 0.08 compared to the simulated data. This was attributed to the surface features of the fabricated DMD materials which were characterised using AFM. AFM results confirmed that Ag had a rough surface while in the simulations the surface of Ag was considered to be smooth. The roughness of Ag results in the enhancement of SPPs which enhance the absorptance of Ag leading to a much lower transmittance. Based on their optical properties, these DMD materials display a potential to be used as optical filters for SSCPVT collectors, which will be studied in the next chapter

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# **Chapter 5: The influence of DMD optical filters on the performance of the SSCPVT collector**

## **Table of contents**

|                                                                                                         |    |
|---------------------------------------------------------------------------------------------------------|----|
| 5.1. Introduction.....                                                                                  | 71 |
| 5.2. DMD optical filter selection for PV cells .....                                                    | 72 |
| 5.3. Performance evaluation of the SSCPVT.....                                                          | 76 |
| 5.3.1. Electrical model validation .....                                                                | 76 |
| 5.3.2. Thermal model validation .....                                                                   | 77 |
| 5.3.3. Effect of mass flow rate on the electrical and thermal efficiencies of the SSCPVT collector..... | 78 |
| 5.3.4. Performance curves of the SSCPVT collector using DMDs .....                                      | 79 |
| 5.4. Summary .....                                                                                      | 81 |
| 5.5. References.....                                                                                    | 82 |

## 5.1. Introduction

Solar energy technologies such as photovoltaic and solar thermal collectors have garnered immense research interest over the years [1-4]. This resulted in researchers combining the two to produce a hybrid photovoltaic-thermal (PVT) collector that can meet the end-user's electrical and thermal demands. Conventionally, the PVT collector involves the PV and solar thermal collector in contact with each other and are therefore not thermally decoupled. This is detrimental to the PV module's electrical efficiency due to its dependency on the operating temperature which is between  $-0.3\%/^{\circ}\text{C}$  and  $-0.5\%/^{\circ}\text{C}$  for c-Si [5] and  $-0.2\%/^{\circ}\text{C}$  and  $-0.3\%$  for CdTe [6] PV modules. However, they can be thermally decoupled by separating them and using an optical filter to split the incident solar radiation according to their spectral response resulting in a spectral splitting PVT (SSPVT) collector [7-10]. In SSPVT collectors, part of the solar radiation which corresponds to the spectral response of the PV collector is directed to it while the rest of the solar radiation is directed to the solar thermal collector. This is achieved using an optical filter to make efficient use of solar radiation. Concentrators can be added to the SSPVT collectors, resulting in spectral splitting concentrating PVT (SSCPVT) collectors, to enhance the electrical and thermal efficiencies [11, 12].

The optical filters, dielectric-metal-dielectric (DMD) films, studied in the previous chapter will be used in modelling the performance of an SSCPVT collector in this chapter. As demonstrated previously, the optical properties of these tri-layered DMD filters can be tuned by changing the dielectric or metallic materials used or by varying the DMDs' thicknesses. The dielectric material selected was  $\text{TiO}_2$ , and the metallic material, Ag, as mentioned in detail in chapter 4. Since PV cells have a particular spectral response, it is important to develop optical filters that either transmit or reflect wavebands that correspond to the PV cell's spectral response. For instance, c-Si PV cells have a bandgap of about 1.12 eV [13] which corresponds to a cutoff wavelength of about 1100 nm. The bandgap of CdTe is about 1.45 eV which corresponds to a wavelength of about 854 nm [14]. The cutoff wavelength of c-Si is in the NIR region, therefore its optical filter should exhibit NIR transmittance up to or a little beyond the cutoff wavelength.

DMDs can exhibit transmittance in this region, which can be achieved by varying the thickness of its layers. The rest of the NIR region is reflected by the DMDs to the thermal absorber. When applied to an SSCPVT collector, particularly a parabolic trough SSCPVT collector, the DMD filter is placed in such a way that it can transmit and reflect the incident solar radiation appropriately. The parabolic trough SSCPVT collector used in this study consists of two channels, primary (top) and secondary (bottom) (Figure 5.1). The filter is placed under the

primary channel so that the solar radiation that first incident on the parabolic mirror and then reflected by the parabolic mirror does not reach the PV cells in its entirety. The filter transmits the solar radiation wavebands that correspond to the spectral response of the PV cells. The primary channel consists of PV cells attached to the absorber. The heat transfer fluid inside the absorber can cool the PV cells while generating low temperature heat. The secondary channel does not consist of PV cells, it only consists of a thermal absorber, and is thermally decoupled from the PV cells because it is meant for high temperature heat generation.

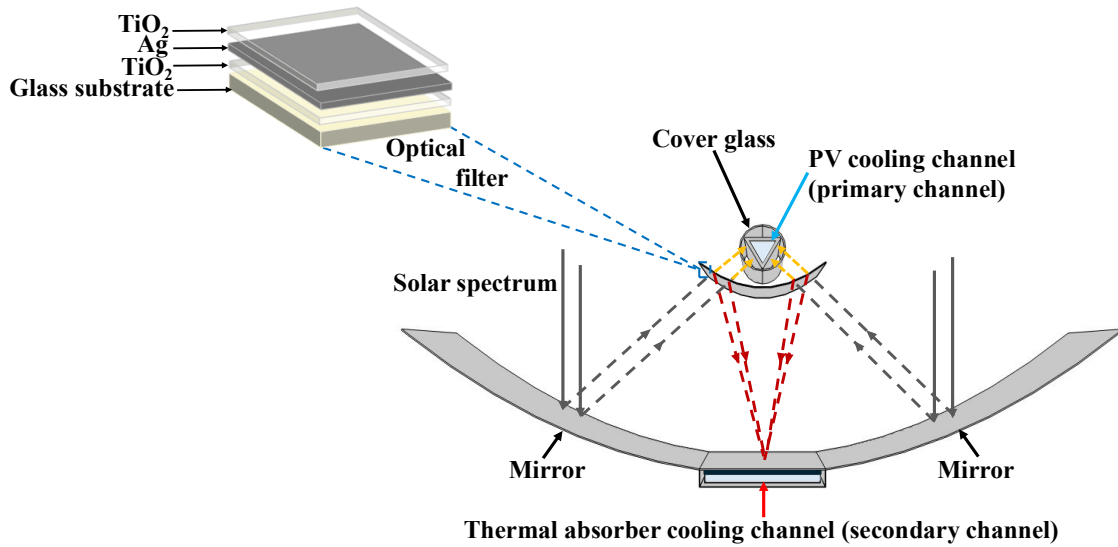


Figure 5.1: Parabolic trough SSCPVT collector with primary and secondary channels and a DMD optical filter.

## 5.2. DMD optical filter selection for PV cells

The optical filters, both simulated (DMD-s) and fabricated (DMD-e), were used in the modelling of the c-Si PV and CdTe module electrical efficiencies module at 25 °C. This was done to quantitatively demonstrate the suitability of the optical filters. The system level electrical efficiencies were calculated using equation (3.6) and shown in Figure 5.2 and Figure 5.3 for the simulated DMD optical filters, and Figure 5.4 for the fabricated DMD optical filters. The highest system level electrical efficiency was achieved for the c-Si PV cell using the simulated DMD-s3 and DMD-s6, and for the CdTe PV cell, DMD-s6. This is due to their high PV-weighted average transmittance which quantifies the amount of solar irradiance that is transmitted to a PV cell and is useful (Table 5.1). Similarly, the fabricated optical filter that resulted in the highest system level efficiency is DMD-e1, for both c-Si and CdTe PV cells (Figure 5.4) because of DMD-e1's high PV-weighted transmittance that is shown in Table 5.2.

Table 5.1: Simulated optical filters used in the electrical and thermal models.

| <b>Varied parameter</b>                                                      | <b>Optical filter</b> | <b>Thickness (nm)</b> | <b>c-Si PV-weighted average transmittance (%)</b> | <b>CdTe PV-weighted average transmittance (%)</b> |
|------------------------------------------------------------------------------|-----------------------|-----------------------|---------------------------------------------------|---------------------------------------------------|
| Thickness of both TiO <sub>2</sub> layers while Ag is kept at 10 nm          | DMD-s1                | 10-10-10              | 64                                                | 76                                                |
|                                                                              | DMD-s2                | 30-10-30              | 75                                                | 88                                                |
|                                                                              | DMD-s3                | 50-10-50              | 76                                                | 86                                                |
|                                                                              | DMD-s4                | 70-10-70              | 75                                                | 77                                                |
|                                                                              | DMD-s5                | 90-10-90              | 70                                                | 68                                                |
| Thickness of Ag while TiO <sub>2</sub> is kept constant at 40 nm             | DMD-s6                | 40-10-40              | 76                                                | 89                                                |
|                                                                              | DMD-s7                | 40-15-40              | 62                                                | 80                                                |
|                                                                              | DMD-s8                | 40-20-40              | 48                                                | 66                                                |
|                                                                              | DMD-s9                | 40-25-40              | 37                                                | 52                                                |
|                                                                              | DMD-s10               | 40-30-40              | 27                                                | 40                                                |
| Thickness of both TiO <sub>2</sub> layers while Ag is kept constant at 20 nm | DMD-s11               | 20-20-20              | 45                                                | 59                                                |
|                                                                              | DMD-s12               | 30-20-30              | 47                                                | 64                                                |
|                                                                              | DMD-s13               | 50-20-50              | 48                                                | 62                                                |
|                                                                              | DMD-s14               | 70-20-70              | 47                                                | 53                                                |
|                                                                              | DMD-s15               | 90-20-90              | 46                                                | 47                                                |

Table 5.2: Fabricated optical filters used in the electrical and thermal models.

| Varied parameter                                                     | Optical filter | Thickness (nm) | c-Si PV-weighted average transmittance (%) | CdTe PV-weighted average transmittance (%) |
|----------------------------------------------------------------------|----------------|----------------|--------------------------------------------|--------------------------------------------|
| Thickness of both TiO <sub>2</sub> layers while Ag is kept at 10 nm. | DMD-e1         | 40-10-40       | 65                                         | 77                                         |
|                                                                      | DMD-e2         | 40-13-40       | 57                                         | 70                                         |
|                                                                      | DMD-e3         | 40-16-40       | 51                                         | 67                                         |
|                                                                      | DMD-e4         | 40-18-40       | 45                                         | 60                                         |
|                                                                      | DMD-e5         | 40-21-40       | 43                                         | 58                                         |
|                                                                      | DMD-e6         | 40-24-40       | 37                                         | 51                                         |
|                                                                      | DMD-e7         | 40-27-40       | 32                                         | 47                                         |

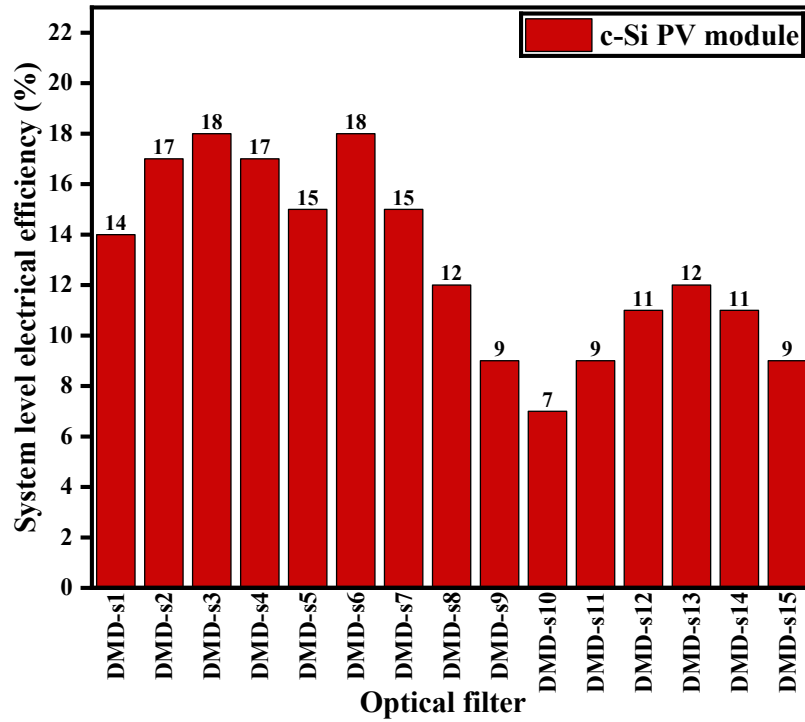


Figure 5.2: The c-Si PV module electrical efficiency at  $T_{ref}$  25 °C of the DMD-s filters.

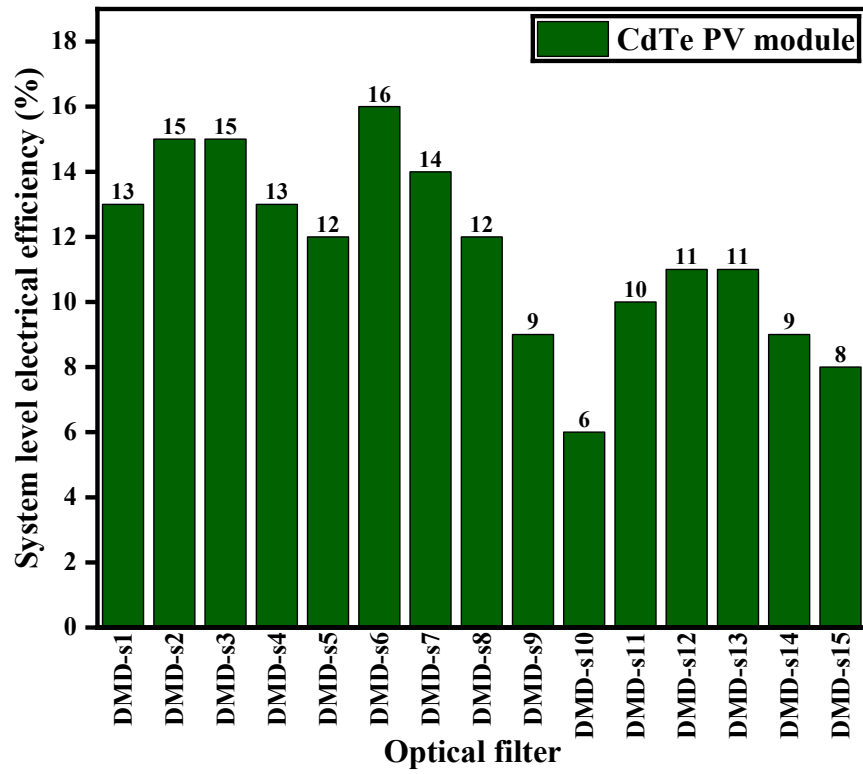


Figure 5.3: CdTe PV module electrical efficiency at  $T_{ref}$  25 °C of the DMD-s filters.

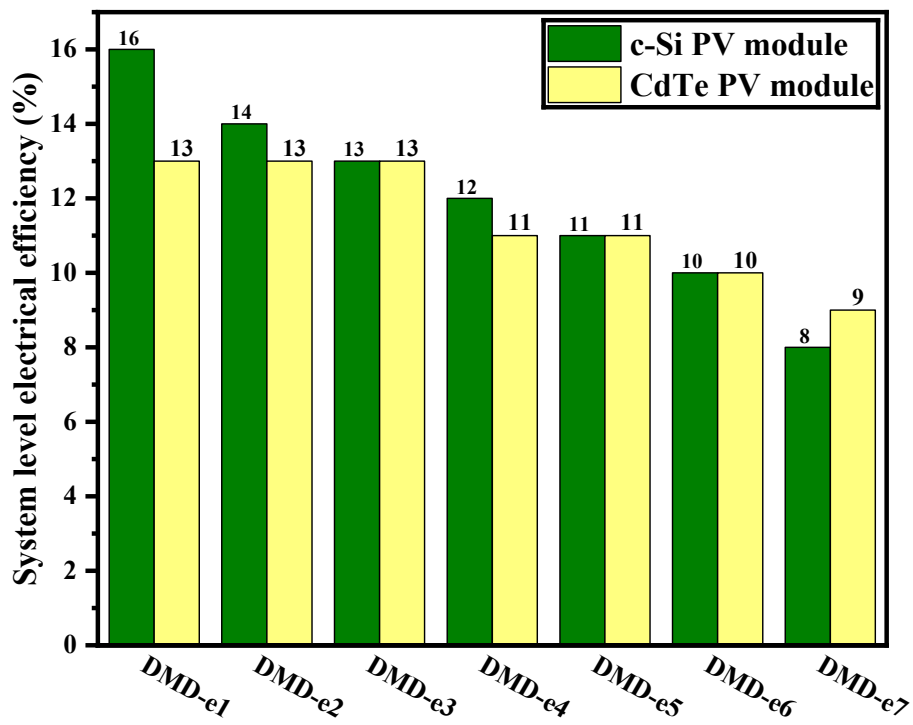


Figure 5.4: CdTe and c-Si PV module electrical efficiency at  $T_{ref}$  25 °C of the DMD-e filters.

### 5.3. Performance evaluation of the SSCPVT

The SSCPVT collector consists of two heat transfer channels, i.e. primary and secondary channels. It also consists of an optical filter in between the channels, and a parabolic trough reflector. The primary channel is triangular with PV cells attached to it, while the secondary channel is rectangular. The primary channel is located at the focus of the parabolic trough reflector and the secondary channel is located at the bottom, in the middle of the parabolic trough reflector. The solar radiation is first incident on the reflector and the concentrated solar radiation is reflected on to the optical filter. The optical filter, in this case DMD-s, transmits part of the solar radiation to the PV cells attached to the primary channel and reflects part of the solar radiation to secondary channel (Figure 5.5).

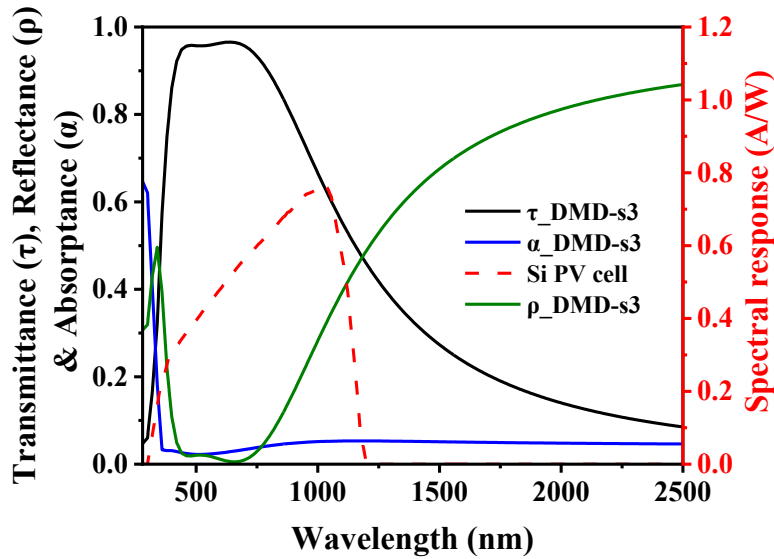


Figure 5.5: Spectral irradiance of AM1.5, spectral responses of c-Si and CdTe cells, and bounds of the optical filter.

#### 5.3.1. Electrical model validation

The SSCPVT model is divided into sub-models. To validate the electrical model, commercial PV module datasheets were used for both c-Si [15] and CdTe [16]. The electrical efficiencies of c-Si The electrical efficiency results from this study's model were compared with the results obtained from the datasheets (Figure 5.6). The maximum percentage errors of the c-Si and CdTe PV cell electrical efficiencies were both under 2%, which indicates that the data is in reasonable agreement with each other.

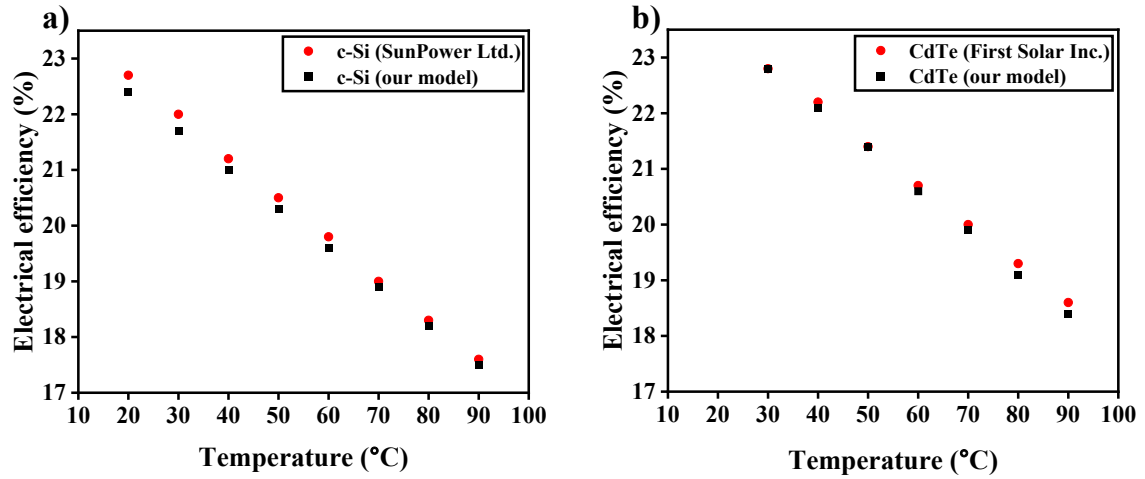


Figure 5.6: Comparison of our model to the manufacturers' a) c-Si and b) CdTe data.

### 5.3.2. Thermal model validation

To validate the thermal model, experimental results obtained by Cabral et al.[17] and results from our numerical model were compared against each other (Figure 5.7). The same operating conditions were used. The maximum percentage error in the thermal efficiency results was under 6%, indicating good agreement.

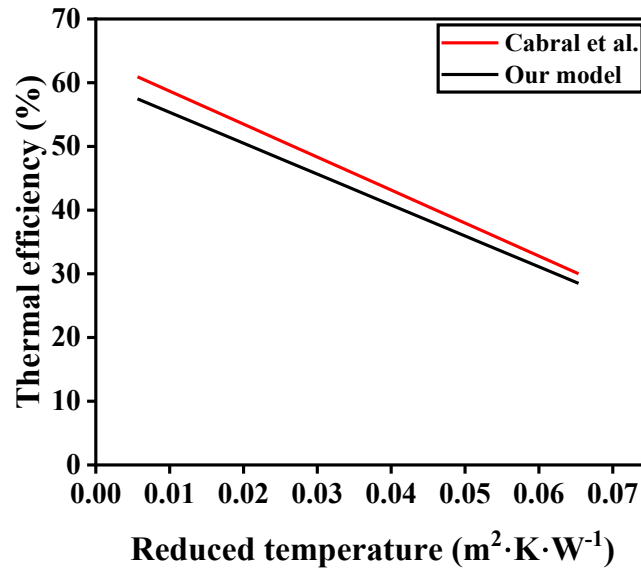


Figure 5.7: Comparison of the overall efficiency of the collector as a function of reduced temperature for the developed model and experiments performed by Cabral et al. [17].

### 5.3.3. Effect of mass flow rate on the electrical and thermal efficiencies of the SSCPVT collector

A parametric study was conducted to investigate the effect of the mass flow rate,  $\dot{m}$ , (0.005 – 0.25 kg/s) on the electrical and thermal efficiencies. Optical filters, DMD-s6 and DMD-e1 were used in the SSCPVT collector. For a c-Si SSCPVT collector using DMD-s6, an increase in the electrical and thermal efficiencies from 16 to 18% and 24 to 28%, respectively, were observed as  $\dot{m}$  increased (Figure 5.8 a). For a CdTe SSCPVT collector using DMD-s6, an increase in the electrical and thermal efficiencies from 14 to 15% and 28 to 32%, respectively, were observed as  $\dot{m}$  increased (Figure 5.8 b). For a c-Si SSCPVT collector using DMD-e1, an increase in the electrical and thermal efficiencies from 12 to 15% and 22 to 27%, respectively, were observed as  $\dot{m}$  increased (Figure 5.8 c). The output temperatures decreased with an increase in the mass flow rates. A higher mass flow rate facilitates better heat transfer, leading to cooler operating temperatures for the photovoltaic cells which improves their electrical efficiency while also maximising heat extraction for thermal efficiency. At  $\dot{m} = 0.1$  kg/s the efficiency curves have reached their asymptotic limit. This  $\dot{m}$  value of 0.1 kg/s was selected as the mass flow rate to generate the performance curves in the next section because beyond this point a further increase in the  $\dot{m}$  value will result in unnecessary energy consumption.

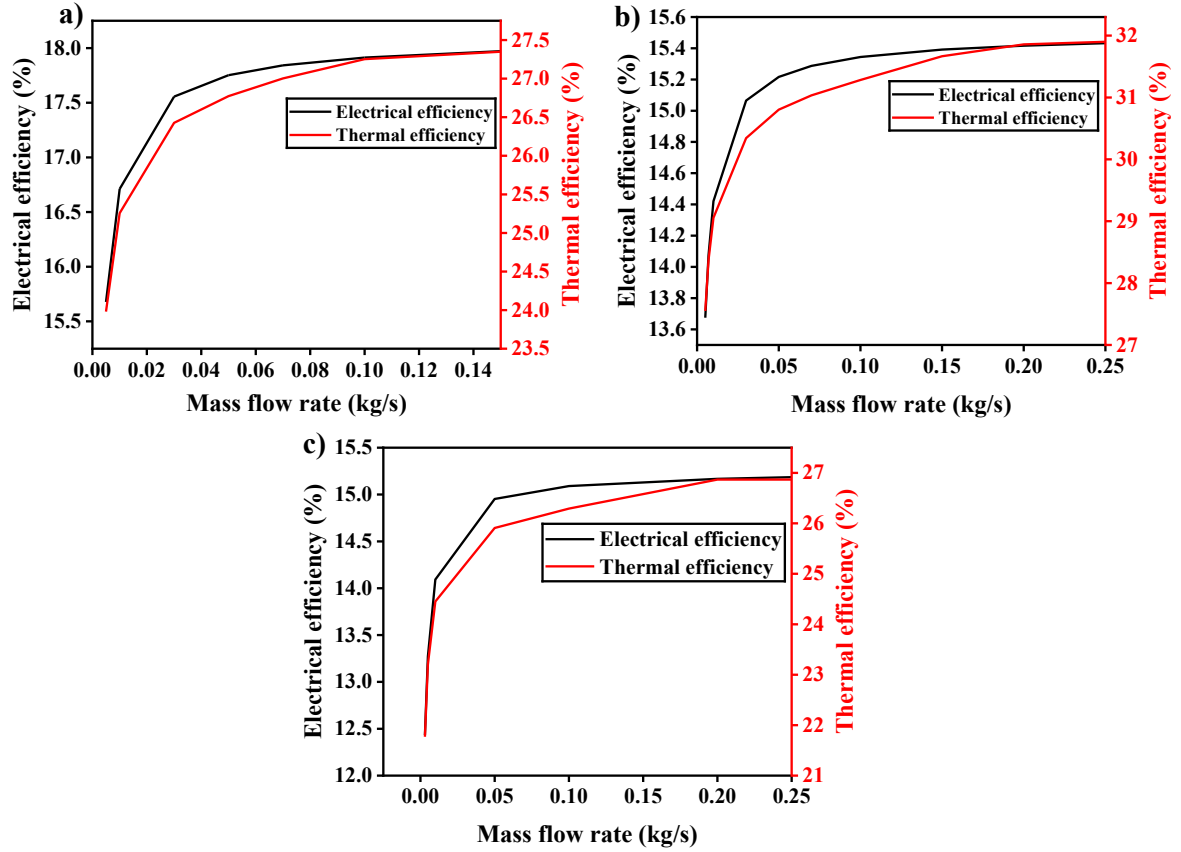


Figure 5.8: Thermal and electrical efficiencies against mass flow rate of the primary channel including a) c-Si PV cells using DMD-s6 b) CdTe PV cells using DMD-s6, and c) c-Si PV cells using DMD-e1.

#### 5.3.4. Performance curves of the SSCPVT collector using DMDs

Performance curves were plotted against reduced temperatures of the primary and secondary channels,  $T_{r\_pri}$  and  $T_{r\_sec}$ , respectively (Figure 5.9). The mass flow rate was kept constant at 0.1 kg/s as explained in Section 5.3.2. Results of the primary and secondary channels of the c-Si SSCPVT using DMD-s6 are shown in Figure 5.9 a and Figure 5.10 a, respectively. For the CdTe PV c-Si SSCPVT using DMD-s6, the results are shown in Figure 5.9 b and Figure 5.10 b, and for the c-Si SSCPVT using DMD-e1 the results are shown in Figure 5.9 c and Figure 5.10 d. The efficiencies decreased with an increase in the reduced temperatures. The decrease in the efficiencies can be attributed to thermal losses as the temperature of the channel increases [18]. The  $T_{r\_pri}$  and  $T_{r\_sec}$  at which the thermal efficiencies are equal zero are referred to as the stagnation temperatures, where the primary and secondary channels of the SSCPVT collectors have reached their maximum temperatures. The maximum values of the SSCPVT collectors' efficiencies were observed when  $T_{r\_pri}$  and  $T_{r\_sec}$  were equal to zero. Maximum temperatures  $>120^\circ\text{C}$  were achieved from the thermal absorber.

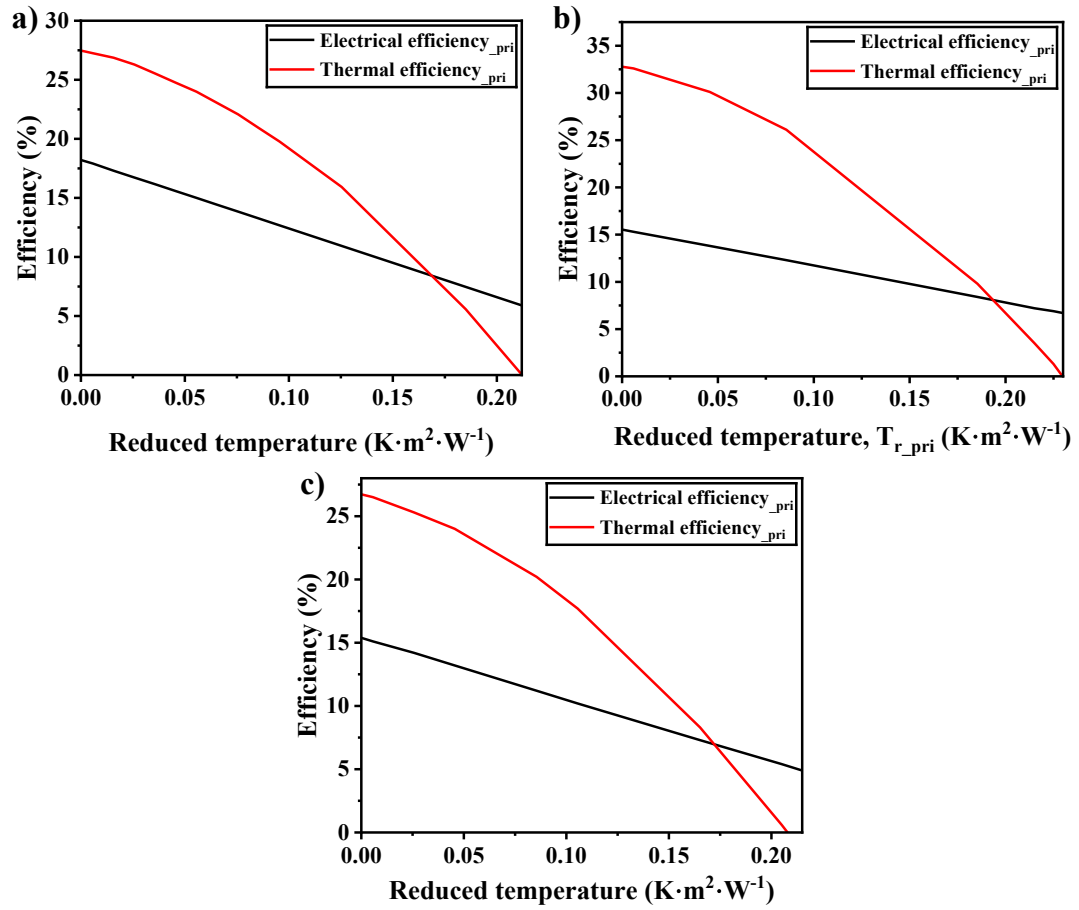


Figure 5.9: Thermal and electrical efficiencies against reduced temperature of the primary channel including a) c-Si PV cells using DMD-s6 b) CdTe PV cells using DMD-s6, and c) c-Si PV cells using DMD-e1.

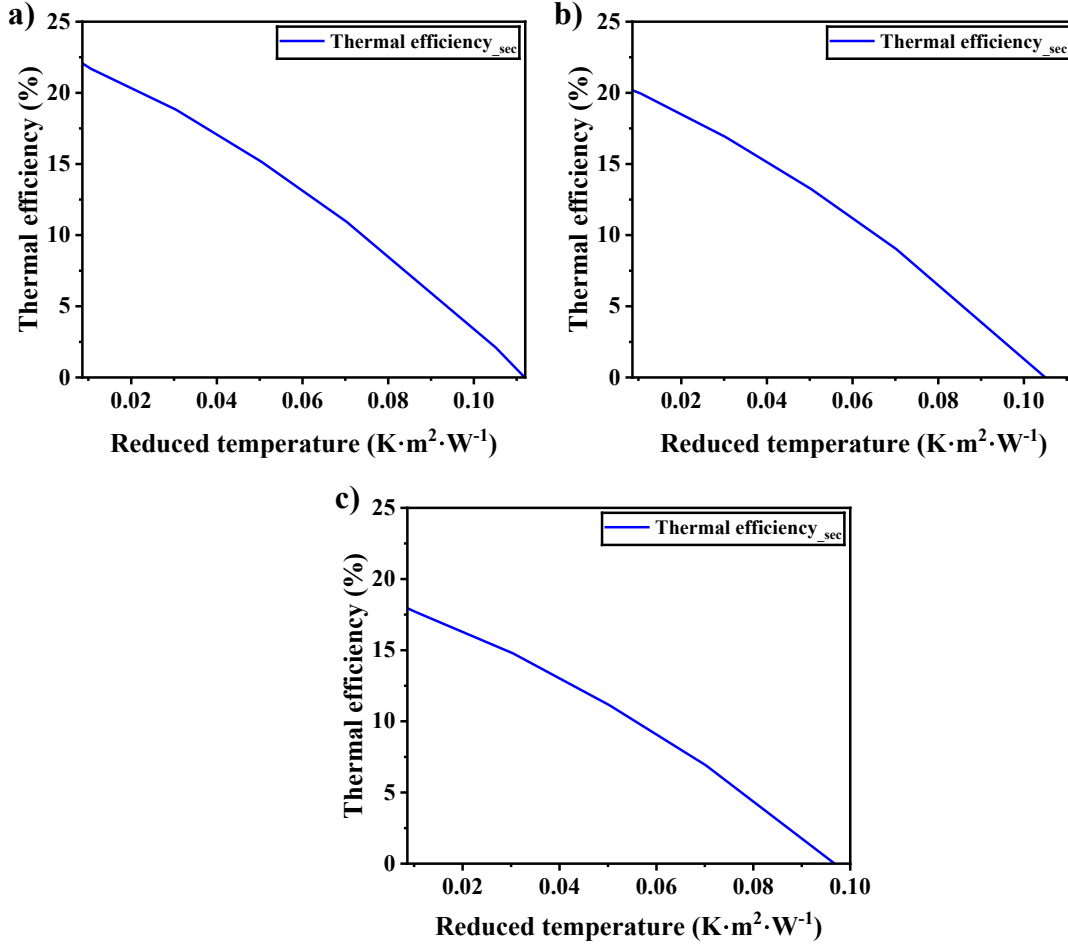


Figure 5.10: Thermal efficiencies against reduced temperature of the secondary channel of a) c-Si SSCPVT collector using DMD-s6 b) CdTe SSCPVT collector using DMD-s6, and c) c-Si SSCPVT collector using DMD-e1.

## 5.4. Summary

The DMD optical filters were used to model the electrical and thermal efficiencies of c-Si and CdTe PV cells. The SSCPVT collector used was a parabolic trough collector with the PV cells attached to the primary channel at the top. At the bottom was the thermal absorber i.e. the secondary channel. DMD-s was used as the optical filter to model the electrical and thermal efficiencies of the c-Si and CdTe SSCPVT collectors. The DMD filters functions by transmitting the visible region of the solar spectrum and part of the NIR region to the c-Si and CdTe PV cells attached to the primary channel. Part of the NIR region was transmitted because the bandgap of c-Si is about 1.12 eV which corresponds to a wavelength of 1100 nm and that of CdTe is about 1.45 eV which corresponds to a wavelength of about 854 nm. The mass flow rate,  $\dot{m}$ , was varied between 0.005 – 0.25 kg/s. The  $\dot{m}$  value used to obtain the performance

curves was determined from the efficiencies' plot as a function of  $\dot{m}$  to be 0.1 kg/s. Electrical and overall thermal efficiencies of 18% and 50% were achieved using c-Si SSCPVT and DMD-s6, 15% and 33% were achieved using CdTe and DMD-s6, and 15% and 45% were achieved using c-Si and DMD-e1.

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# Chapter 6: A parametric study on metasurfaces as potential optical filters in SSCPVTs

## Table of contents

|                                                                                                          |    |
|----------------------------------------------------------------------------------------------------------|----|
| 6.1. Introduction.....                                                                                   | 85 |
| 6.2. Metasurface optical filter simulation results.....                                                  | 85 |
| 6.2.1. Simulated regular Ag thin film and metasurfaces consisting of Ag nanodisk arrays .....            | 86 |
| 6.2.2. Simulated metasurfaces consisting of nanodisk arrays of Ag and DMD.....                           | 87 |
| 6.2.3. Simulated metasurfaces consisting of nanodisk arrays of Ag with a hexagonal arrangement.....      | 91 |
| 6.3. Modelling of the SSCPVT performance using metasurface optical filters.....                          | 92 |
| 6.3.1. Evaluation of the PV modules' system level efficiencies using metasurfaces.....                   | 93 |
| 6.3.2. Performance curves of the SSCPVT collector using a metasurface filter .....                       | 96 |
| 6.3.3. Comparison in the efficiencies resulting from using the DMD and metasurface optical filters ..... | 97 |
| 6.4. Summary .....                                                                                       | 98 |
| 6.5. References.....                                                                                     | 98 |

## 6.1. Introduction

In addition to the dielectric-metal-dielectric (DMD) regular thin film optical filters, metasurfaces have attracted immense research attention as the easier to fabricate two-dimensional (2D) counterpart of the 3D metamaterials [1-3]. Metasurfaces are flat nanostructured arrays consisting meta-atoms (repeating unit) that can be used for a vast range of applications such as imaging [4], biosensing [5], and optical computing [6] due to their ability to control the amplitude, phase and polarisation of light. This can be achieved by exploiting the nanoarray structure of the metasurfaces to tune the localized surface plasmon resonance (LSPR). LSPR occurs due to the collective oscillations of the free electrons in the materials upon excitation by an electromagnetic wave [7, 8]. As a result, the transmittance, reflectance and absorbance of materials can be tuned. The optical properties of metasurfaces depend more on their structural properties than their material properties. Of particular interest in this research project, is the use of metasurfaces that can either reflect or transmit the solar spectrum to the PV cell and to the thermal absorber.

So far, the interest in transparent metasurfaces has been because of their potential use in smart windows to reflect the near-infrared (NIR) region while transmitting visible light. Materials used in the DMDs were also used as metasurfaces to further tune the selectivity of the optical filters. The optical properties of the metasurfaces, such as that of the DMDs, can be tuned by varying the thickness of the structures. Additionally, due to the nanoarrays of the metasurfaces, the optical properties of the metasurfaces can be further tuned by varying the geometry of the nanoarrays [9]. The tunability of the optical properties results in a wide range of optical filters to select from to enhance the electrical and thermal efficiencies of SSCPVT collectors. Metasurfaces consisting of Ag and DMD nanodisk meta-atom arrays were used as the optical filter in the spectral splitting concentrating photovoltaic-thermal (SSCPVT) collector. By tuning the thickness, materials and arrangement of the meta-atoms, the optical filters of the metasurfaces were tuned such that they exhibit reflectance in the visible light region and part of the NIR region of the solar spectrum.

## 6.2. Metasurface optical filter simulation results

The model used for the DMD optical filters simulations which was validated in chapter 4 was also used for the metasurface optical filters. The metasurface optical filters simulated involved arrays of nanodisks. A parametric study was conducted to find suitable metasurface optical filters for the SSCPVT collector. The diameter, thickness, arrangement and interparticle distance of the arrays were varied and the results are discussed in this section.

### 6.2.1. Simulated regular Ag thin film and metasurfaces consisting of Ag nanodisk arrays

The optical properties of regular thin films were compared with those of Ag nanodisk metasurfaces with different geometries. The metasurfaces consist of arrays of nanodisks patterned from the regular Ag thin film with a thickness of 20 nm (Figure 6.1). The simulated reflectance ( $\rho$ ), transmittance ( $\tau$ ) and absorptance ( $\alpha$ ) of the Ag regular thin film, and Ag nanodisks are shown in Figure 6.2. The Ag nanodisks displayed enhanced selectivity in their reflectance and transmittance compared to the regular Ag thin film.

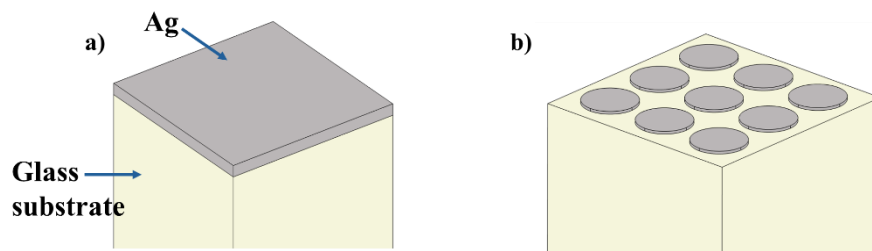


Figure 6.1: Schematic representation of a) regular Ag film, b) Ag nanodisk array.

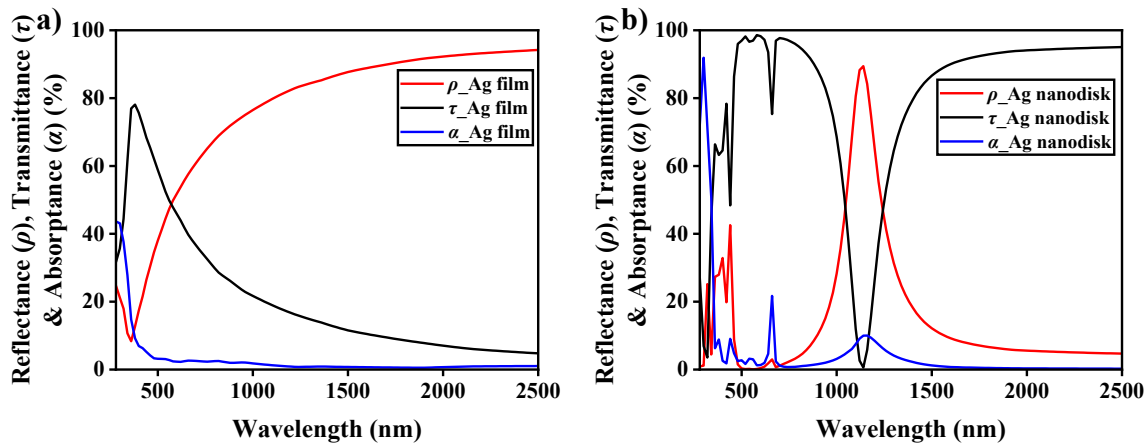


Figure 6.2: Optical properties of 20 nm a) Ag film, and b) Ag nanodisk.

Generally, metallic nanostructures have optical properties that are dependent on their structure and their surrounding medium. Most specifically their absorption is due to the surface plasmon resonance phenomenon. This occurs as a result of the collective oscillation of surface electrons when an electromagnetic field is incident on the metallic nanostructure particularly at the metal-dielectric interface. These oscillations are referred to as plasmons and the confinement of these plasmons at the surface of a metal is referred to as localised surface plasmon resonance.

### 6.2.2. Simulated metasurfaces consisting of nanodisk arrays of Ag and DMD

The optical properties of the metasurfaces were simulated using the model outlined in Section 3.4. These metasurfaces consist of an array of Ag or DMD nanodisks and are detailed in Table 6.1 which includes the names of the optical filters and the dimensions of the nanodisks. A parametric study was conducted in order to select a suitable metasurface optical filter for selective reflectance of visible light and part of the NIR regions of the solar spectrum. This was achieved by varying the nanodisk metasurfaces' pattern arrangement (square and hexagonal), diameter between 50 nm and 200 nm while the thickness of Ag was kept constant, and varying the thickness of Ag was varied between 10 nm and 70 nm. The thickness of TiO<sub>2</sub> was also varied. This parametric study revealed the changes in the optical properties of the materials as the dimensions of the nanodisks changed. This effect is attributed to the LSPR phenomenon which results in a change in the resonance peaks as the dimensions of the nanodisk change.

A decrease in the diameter of the Ag nanodisks results in the narrowing of the peaks of the optical filters, met<sub>Ag\_sq1</sub> – met<sub>Ag\_sq4</sub>, (Figure 6.3). This is due to an increase in the quality factor (Q-factor) which quantifies energy losses and is inversely proportional to the total energy loss coefficient [10, 11]. Smaller nanodisks also result in a strong electric field localisation which leads to peak narrowing [12]. Increasing the thickness of the Ag nanodisks results in a blueshift in the transmittance and reflectance peaks of the optical filters, met<sub>Ag\_sq5</sub> – met<sub>Ag\_sq8</sub>, (Figure 6.4). This can be attributed to the increase in the Ag absorptance at lower wavelengths as the thickness increases due to the high extinction coefficient of Ag [13]. Addition of dielectric layers, TiO<sub>2</sub>, to the top and bottom of the Ag nanodisk, results in the DMD nanodisk optical filters, met<sub>DMD\_sq1</sub> – met<sub>DMD\_sq4</sub>. These optical filters result in a redshift in the reflectance peaks and a decrease in the peak widths as the thickness of the TiO<sub>2</sub> layers increases (Figure 6.5). This is due to the increased dispersion because of material permittivity [11, 14].

Table 6.1: Simulated optical filters and their dimensions.

| Optical filter properties                                 | Optical filter | Thickness (nm) | Diameter of the nanodisk (nm) |
|-----------------------------------------------------------|----------------|----------------|-------------------------------|
| Ag nanodisk with a square lattice arrangement.            | metAg_sq1      | 20             | 50                            |
|                                                           | metAg_sq2      | 20             | 100                           |
|                                                           | metAg_sq3      | 20             | 150                           |
|                                                           | metAg_sq4      | 20             | 200                           |
|                                                           | metAg_sq5      | 10             | 200                           |
|                                                           | metAg_sq6      | 30             | 200                           |
|                                                           | metAg_sq7      | 50             | 200                           |
|                                                           | metAg_sq8      | 70             | 200                           |
| DMD nanodisk metasurface with square lattice arrangement. | metDMD_sq1     | 10-10-10       | 200                           |
|                                                           | metDMD_sq2     | 30-10-30       | 200                           |
|                                                           | metDMD_sq3     | 50-10-50       | 200                           |
|                                                           | metDMD_sq4     | 70-10-70       | 200                           |
| Ag nanodisk metasurface with hexagonal arrangement.       | metAg_hx1      | 20             | 50                            |
|                                                           | metAg_hx2      | 20             | 100                           |
|                                                           | metAg_hx3      | 20             | 150                           |
|                                                           | metAg_hx4      | 20             | 200                           |

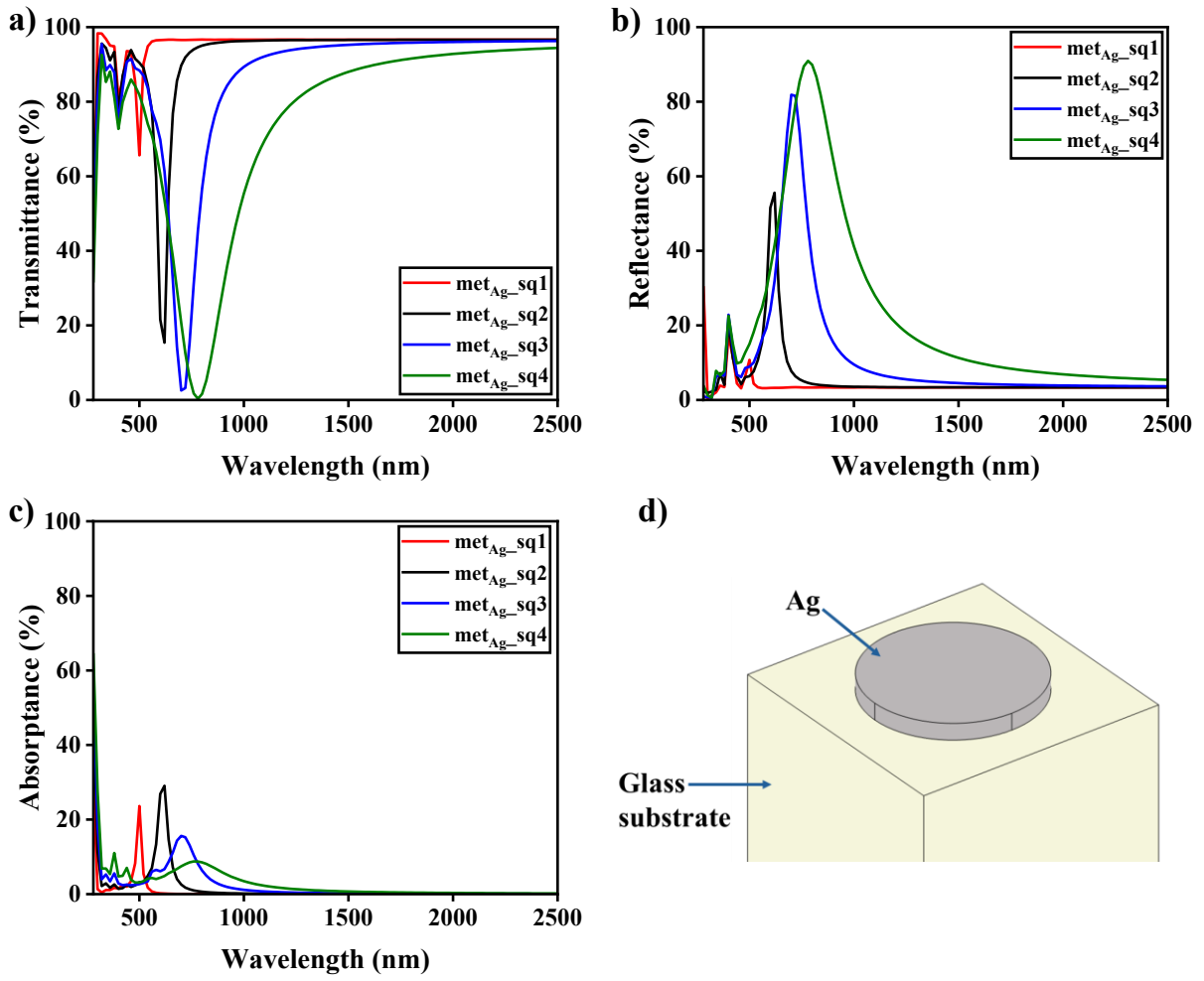


Figure 6.3: a) Transmittance, b) reflectance and c) absorbance spectra of Ag metasurfaces with a square pattern arrangement with different thicknesses and d) unit cell of the optical filters.

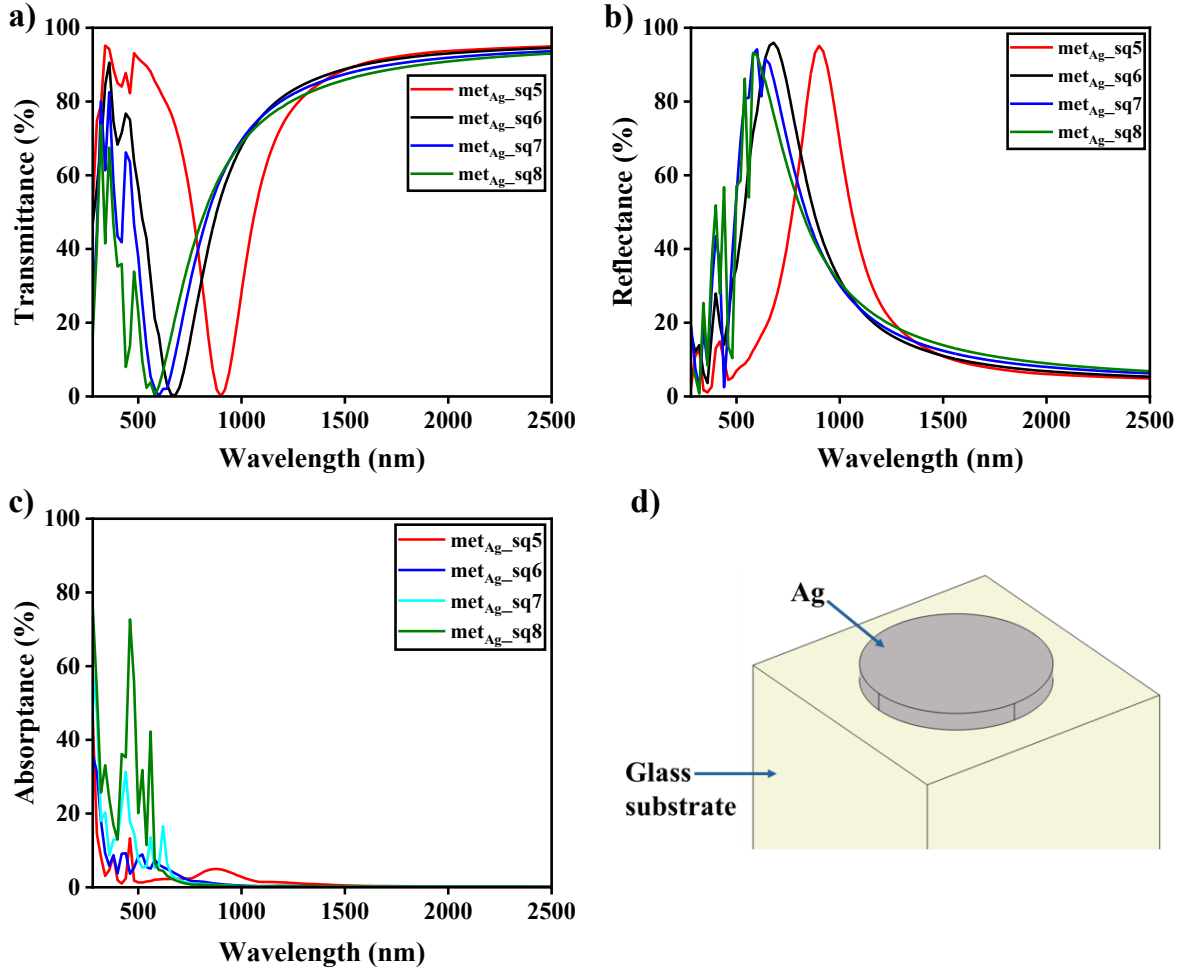


Figure 6.4: a) Transmittance, b) reflectance and c) absorptance spectra of Ag metasurfaces with a square pattern arrangement with different thicknesses and d) unit cell of the optical filters.

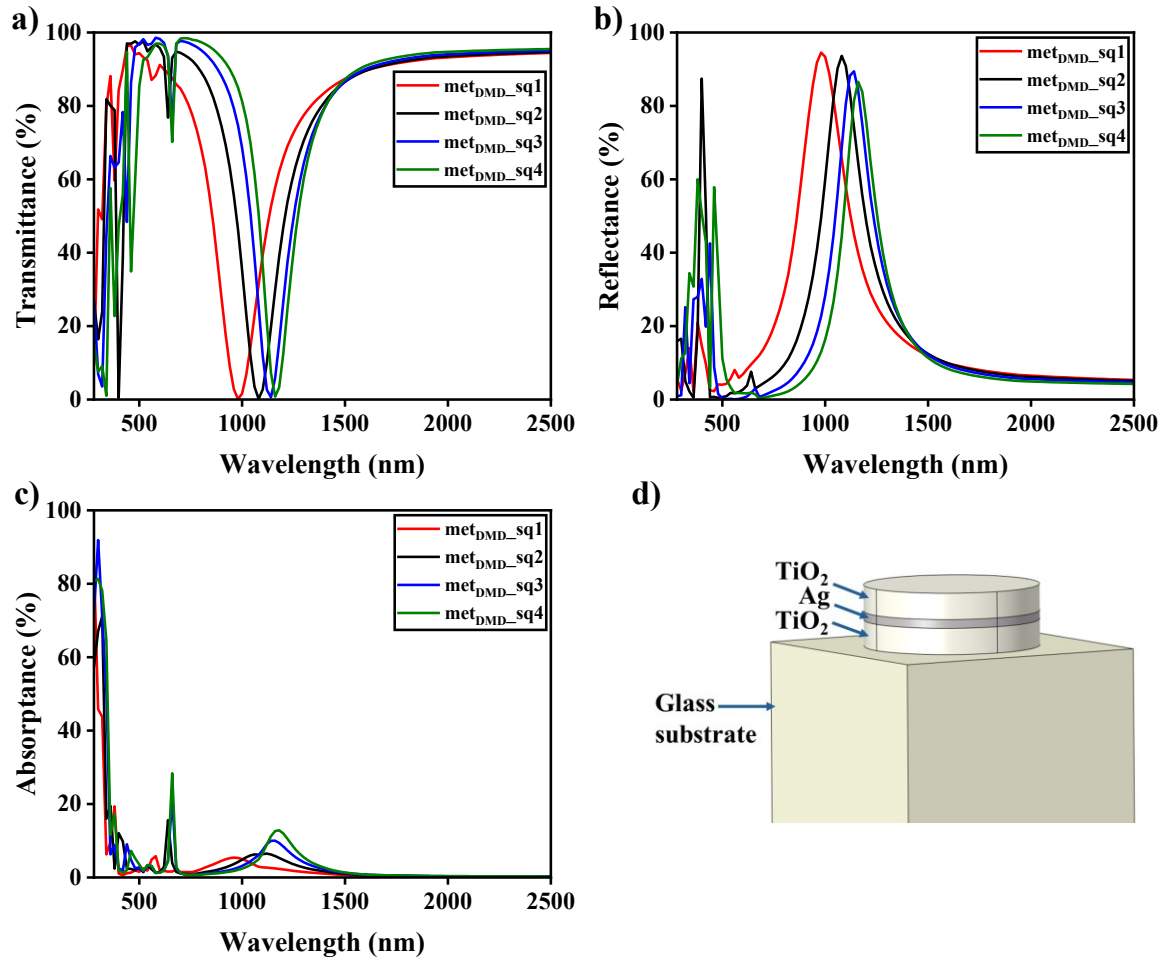


Figure 6.5: a) Transmittance, b) reflectance, c) absorptance of DMD nanodisks with square arrangement and d) unit cell of the optical filters.

### 6.2.3. Simulated metasurfaces consisting of nanodisk arrays of Ag with a hexagonal arrangement

The optical properties of metasurfaces are also dependent on their pattern arrangement. To investigate the effect of the pattern arrangement, a study was conducted to compare the optical properties of Ag metasurfaces with a square arrangement in comparison to the one with a hexagonal arrangement. The meta-atoms were maintained as nanodisks. In particular, Ag nanodisk arrays with different arrangements were studied. The diameter was varied up to 200 nm for the optical filters, met<sub>Ag\_hx1</sub> – met<sub>Ag\_hx4</sub> (Figure 6.6).

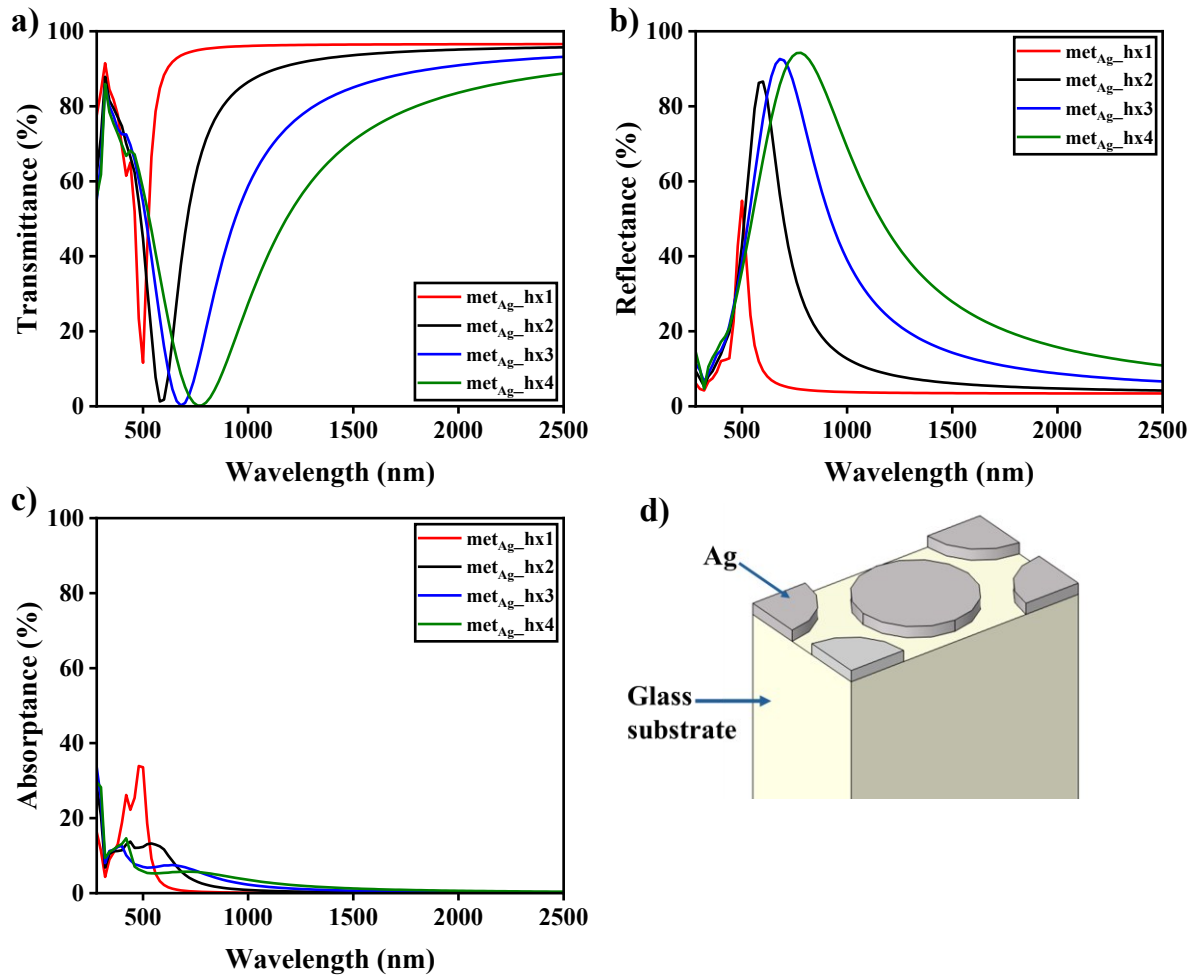


Figure 6.6: a) Transmittance, b) reflectance, c) absorbance of Ag nanodisks with hexagonal arrangement and d) unit cell of the optical filters.

### 6.3. Modelling of the SSCPVT performance using metasurface optical filters

The SSCPVT collector simulated was similar to that used to model the electrical and thermal efficiencies using DMD optical filters. However, due to the differences in the optical properties of DMDs and metasurfaces the PV cells were placed at the bottom (Figure 6.7). Instead of transmitting the visible light to the PV modules which was the case with DMDs, they reflect it, but the region reflected is narrower. This shows that enhanced selectivity in the wavebands directed to the PV modules could be achieved using metasurfaces. The metasurfaces reflect the region of the solar spectrum, i.e. visible region, to be directed to the PV cells and transmits the NIR wavelengths to the thermal absorber. All other parameters are the same as the ones in Chapter 5. The resulting efficiencies are discussed in this section.

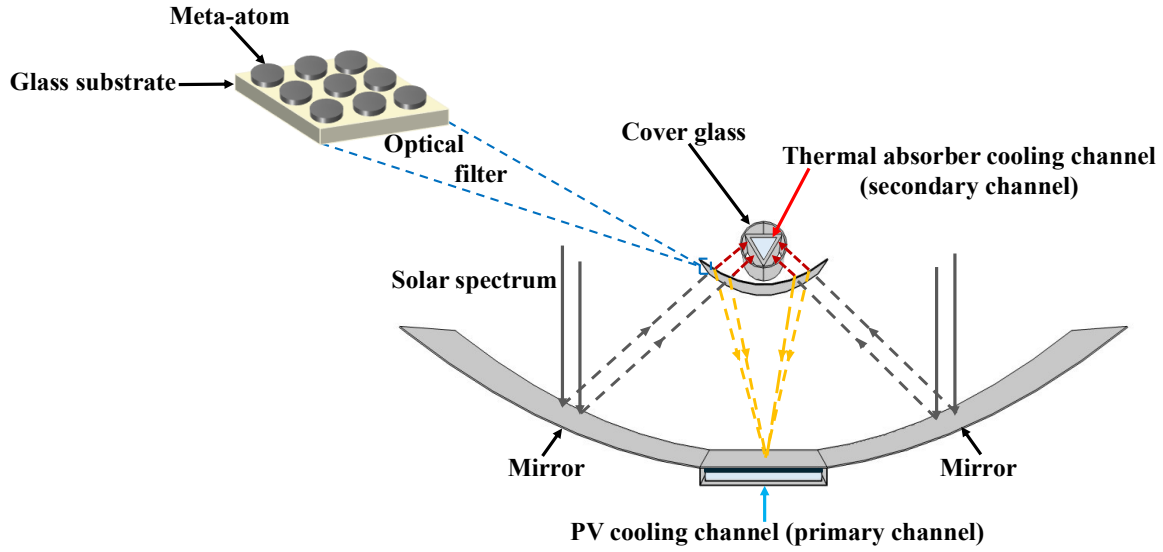


Figure 6.7: SS-CPVT collector with the PV cells placed at the bottom.

### 6.3.1. Evaluation of the PV modules' system level efficiencies using metasurfaces

The simulated metasurface optical filters and their PV-weighted reflectance are included in Table 6.2. These optical filters were used in the modelling of the c-Si PV and CdTe module electrical efficiencies module at 25 °C. This was done to quantitatively demonstrate the suitability of the optical filters.

Table 6.2: Simulated metasurface optical filters used in the electrical and thermal models.

| Optical filter | c-Si PV-weighted<br>average reflectance (%) | CdTe PV-weighted average<br>reflectance (%) |
|----------------|---------------------------------------------|---------------------------------------------|
| metAg_sq1      | 4                                           | 5                                           |
| metAg_sq2      | 9                                           | 12                                          |
| metAg_sq3      | 20                                          | 30                                          |
| metAg_sq4      | 38                                          | 44                                          |
| metAg_sq5      | 32                                          | 20                                          |
| metAg_sq6      | 41                                          | 51                                          |
| metAg_sq7      | 42                                          | 53                                          |
| metAg_sq8      | 40                                          | 50                                          |
| metDMD_sq1     | 32                                          | 17                                          |
| metDMD_sq2     | 27                                          | 12                                          |
| metDMD_sq3     | 22                                          | 9                                           |
| metDMD_sq4     | 23                                          | 15                                          |
| metAg_hx1      | 10                                          | 12                                          |

|                        |    |    |
|------------------------|----|----|
| met <sub>Ag</sub> _hx2 | 28 | 40 |
| met <sub>Ag</sub> _hx3 | 45 | 55 |
| met <sub>Ag</sub> _hx4 | 55 | 58 |

Figure 6.8 – Figure 6.10 show the system level electrical efficiency achieved from integrating the metasurface optical filters into the SSCPVT collector. The Ag nanodisk metasurface optical filter with the square arrangement, met<sub>Ag</sub>\_sq7, resulted in the highest system level electrical efficiencies of 12% and 11% for both c-Si and CdTe PV modules, respectively (Figure 6.8). This shows that the blueshift in the reflectance peaks results in enhanced reflectance in the wavelength region that corresponds to spectral response of the PV cells. However, the reflectance eventually decreases and the system level efficiency because an increase in absorptance also occurs as the Ag thickness increases. The DMD nanodisk metasurface optical filter with the square arrangement, met<sub>DMD</sub>\_sq1, resulted in the highest system level electrical efficiencies of 6% and 2% for both c-Si and CdTe PV modules, respectively (Figure 6.9). The Ag nanodisk metasurface optical filter with the hexagonal arrangement, met<sub>Ag</sub>\_hx4, resulted in the highest system level electrical efficiencies of 14% for c-Si and 11% for CdTe PV modules, respectively. The optical filters with the highest PV-weighted reflectance resulted in the highest electrical efficiencies.

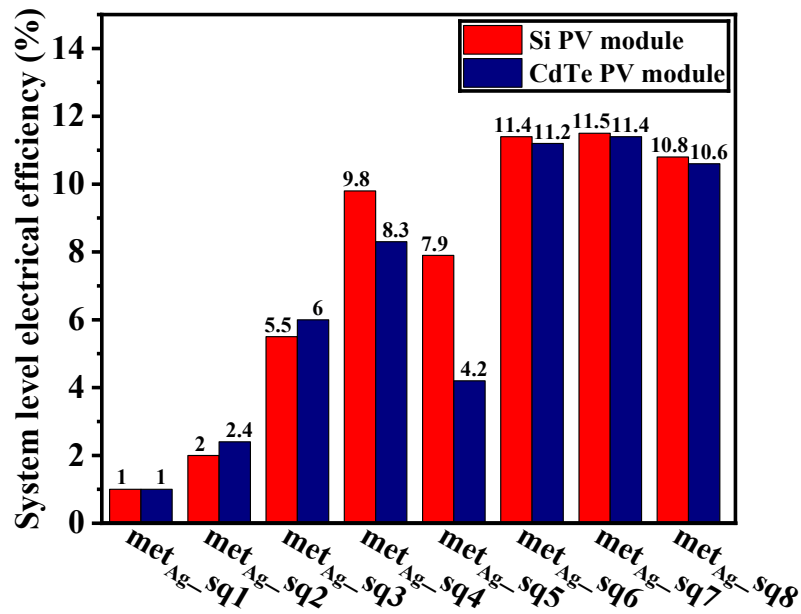


Figure 6.8: The c-Si and CdTe PV module electrical efficiencies at  $T_{\text{ref}} = 25 \text{ }^{\circ}\text{C}$  of the Ag nanodisk metasurfaces with a square arrangement.

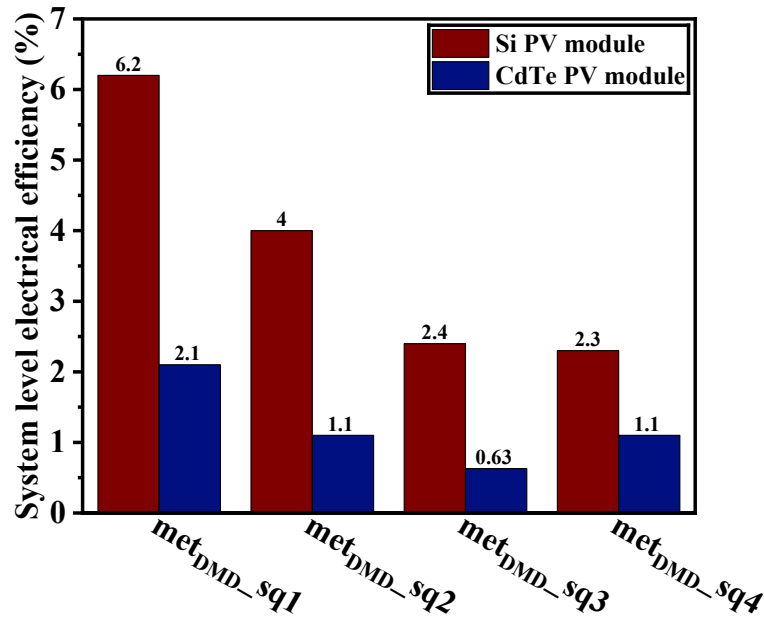


Figure 6.9: The c-Si and CdTe PV module electrical efficiencies at  $T_{\text{ref}} = 25 \text{ }^{\circ}\text{C}$  of the DMD nanodisk metasurfaces with a square arrangement.

The DMD metasurfaces resulted in the lowest PV system level electrical efficiency. As the thickness of  $\text{TiO}_2$  increases, the peaks become narrower and the absorptance increases. Their lower PV reflectance meant significantly less of the visible region wavelengths were reflected to the PV cells, resulting in lower efficiencies. This makes DMD metasurfaces less suitable to be optical filters for the c-Si and CdTe PV modules. The system level electrical efficiency of both c-Si and CdTe PV cells using the Ag nanodisk metasurface with hexagonal arrangement was modelled. The thickness was kept constant at 20 nm and the diameter was varied between 50 – 200 nm. The system level electrical efficiencies of c-Si varied between 2 – 14% while that of CdTe varied between 2 – 11% (Figure 6.10). This can be attributed to the redshift in the peaks and the peak broadening as the diameter of the filters increased from 50 nm to 200 nm (Figure 6.6 b). The reflectance spectra were used because the filters reflect the region of the solar spectrum that corresponds to the spectral response of the PV cells. The  $\text{met}_{\text{Ag\_hx4}}$  filter resulted in the highest efficiency for c-Si and CdTe. It also had the highest

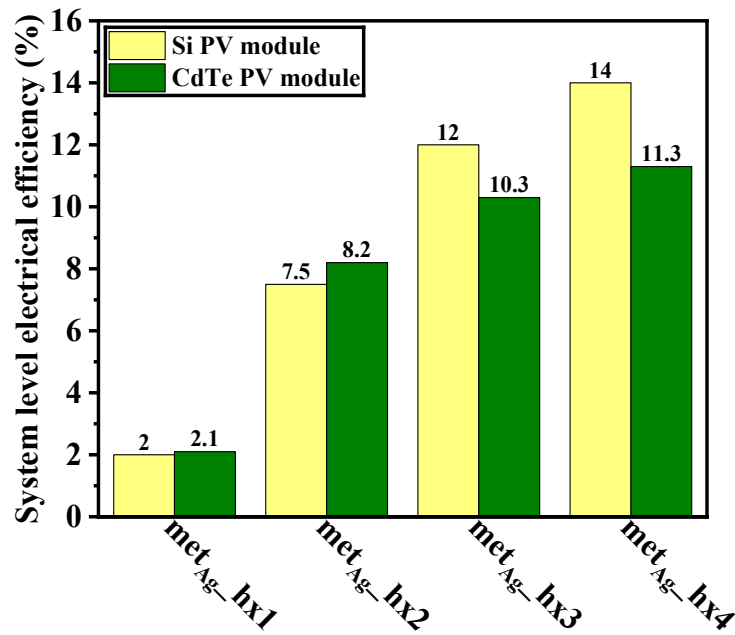


Figure 6.10: The c-Si and CdTe PV modules' electrical efficiencies at  $T_{ref} = 25\text{ }^{\circ}\text{C}$  of the Ag nanodisk metasurfaces with a hexagonal arrangement.

### 6.3.2. Performance curves of the SSCPVT collector using a metasurface filter

The performance curves of the c-Si SSCPVT collector were obtained from the model using the hexagonal array Ag nanodisk metasurface filter, met<sub>Ag</sub>\_hx4 (Figure 6.11). For the primary channel, the electrical and thermal efficiencies decreased from 14 to 6% and from 22 to 0% as the reduced temperature increased. For the secondary channel the thermal efficiency also decreased from 27 to 0%. Both efficiencies decreased as a result of thermal losses as the reduced temperature increased.

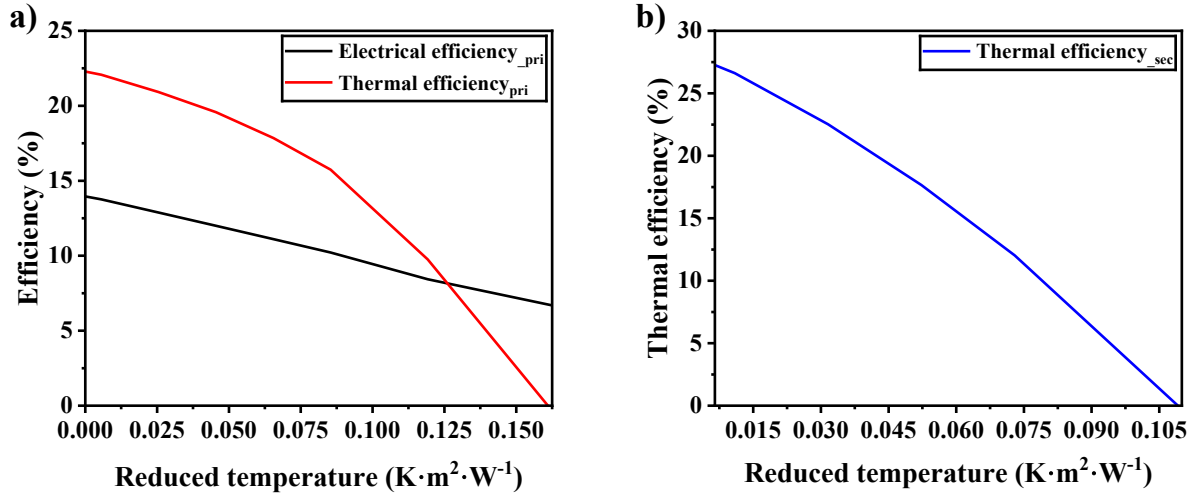


Figure 6.11: a) Thermal and electrical efficiencies of c-Si PV primary cooling channel, and b) thermal efficiency of the secondary channel against reduced temperature using the simulated hexagonal Ag nanodisk metasurface filter,  $\text{met}_{\text{Ag\_hx4}}$ .

### 6.3.3. Comparison in the efficiencies resulting from using the DMD and metasurface optical filters

The electrical and thermal efficiencies of the c-Si SSCPVT collector obtained without a filter, and with the DMD and metasurface filters, are outlined in Table 6.3. The efficiency of the SSCPVT without a filter had the lowest overall (electrical plus thermal) efficiency while the simulated DMD optical filter, DMD-s6, resulted in the highest over efficiency. This is because the optical filters were able to direct the portion of the solar spectrum that is not used by the PV cells to thermal absorber, resulting in a more efficient use of the solar spectrum.

Table 6.3: Comparison of the efficiencies of the SSCPVT collectors with and without filters.

| Optical filter                | Electrical<br>efficiency (%) | Thermal<br>Efficiency<br>(primary<br>channel) (%) | Thermal<br>efficiency<br>(secondary<br>channel) (%) | Overall<br>efficiency (%) |
|-------------------------------|------------------------------|---------------------------------------------------|-----------------------------------------------------|---------------------------|
| No filter                     | 20                           | 35                                                | -                                                   | 55                        |
| DMD-s6                        | 18                           | 28                                                | 22                                                  | 68                        |
| DMD-e1                        | 15                           | 27                                                | 18                                                  | 60                        |
| $\text{Met}_{\text{Ag\_hx4}}$ | 14                           | 22                                                | 27                                                  | 63                        |

## 6.4. Summary

A metasurface optical filter was used in an SSCPVT collector. The metasurfaces are 2D nanostructured arrays of materials. The selection of a metasurface optical filter involved simulating the optical properties of different metasurface materials by performing a parametric study. The parametric study involved varying the geometry of the materials which significantly affect the resulting optical properties. The hexagonal Ag metasurface resulted in the highest system level electrical efficiency while the DMD metasurface resulted in the lowest system level efficiency. The performance of the SSCPVT using the hexagonal Ag metasurface filter,  $\text{met}_{\text{Ag\_hx4}}$ , in the model was evaluated. Electrical and overall thermal efficiencies of 14% and 49%, respectively. A comparison between the filters was conducted, and the simulated DMD optical filter, DMD-s6 (chapter 5), when incorporated into an SSCPVT, resulted in the highest overall efficiency of 68%. The SSCPVT without a filter yielded an overall efficiency of 55%.

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# Chapter 7: Conclusions and future recommendations

**Table of contents**

7.1. General conclusions ..... 101

7.2. Recommendations..... 103

Appendix A ..... 104

## 7.1. General conclusions

The aim of this research was to design and fabricate optical filters for a spectral splitting concentrating photovoltaic-thermal (SSCPVT) collector. Optical filters such as nanofluids and interference thin film filters have commonly been used in SSCPVT collectors. However, the stability of nanoparticles in nanofluids remains an issue especially for long-term use, and interference thin film filters often require many layers to tune their optical properties. In this research project particular attention was placed on designing and fabricating solid optical filters that could potentially be used long-term while taking advantage of nanomaterials. Nanomaterials, due to their features, offer unparalleled opportunities for the manipulation of light because of a phenomenon such as surface plasmonic resonance (SPR). SPR plays a significant role at the nanoscale in tailoring the optical properties of nanomaterials.

Materials such as dielectric-metal-dielectric (DMD) films and metasurfaces were studied. The DMD films involve only three layers to tailor the optical properties. The dielectric and metallic materials used were  $\text{TiO}_2$  and Ag, respectively. Ag was chosen as the metal layer due to its high reflectance and  $\text{TiO}_2$  due to its high transmittance. The role of the  $\text{TiO}_2$  layers at the top and bottom of the Ag layer is to act as an anti-reflective layer by creating a Fabry-Pérot resonance effect. This results in the destructive interference of the reflected waves, maximising transmittance while minimising reflectance of the DMDs, especially in the visible region of the solar spectrum. This results in a selective optical filter with high transmittance in the visible region and reflectance in the NIR region. The design and choice of the filters was based on their optical properties as their function in SSCPVT collectors depends on their optical properties. COMSOL Multiphysics® Wave Optics module was used to simulate the optical properties of the DMD materials. A parametric study was conducted by varying the thicknesses of the films and the materials. The thickness of  $\text{TiO}_2$  was kept constant at 40 nm, while the thickness of Ag was varied between 10 – 25 nm. It was observed that an increase in the thickness of the Ag layer resulted in a decrease in the transmittance of the DMDs. As the thickness of Ag increases, the role  $\text{TiO}_2$  plays diminishes, and reflectance and absorptance of visible light increases.

The thickness of  $\text{TiO}_2$  was then varied between 10 – 70 nm while the thickness of Ag was maintained as 10 nm. A redshift in the peaks was observed as well as a second peak due to the splitting of surface plasmon wave modes into symmetric and antisymmetric when the metal layer, i.e. Ag is sufficiently thin. The DMDs were also fabricated using magnetron sputtering. The simulated and fabricated DMDs had similar profiles although the fabricated DMDs lower

transmittance and absorptance than the simulated DMDs. This can be attributed to features such as the roughness of the materials especially Ag. During the magnetron sputtering deposition process of Ag. The Ag film forms islands first and as the deposition process progresses the Ag becomes a more uniform and smoother layer.

The optical properties of metasurfaces were also simulated. Metasurfaces consist of 2D nanostructured array counterpart of the 3D metamaterials. Unlike the DMDs, their optical properties can be tailored beyond just varying the material used and thickness because the shape of the nanostructured arrays play a significant role in the resulting optical properties. This was observed when the simulated optical properties of a regular Ag thin film on a glass substrate were compared with that of an Ag nanodisk metasurface of the same thickness, 20 nm. The Ag nanodisk metasurface displayed higher selectivity in terms of its reflectance. A narrow reflectance peak was observed between  $\sim 900 - 1300$  nm while for the regular thin film the reflectance accounts for a wider range of the solar spectrum wavebands. A parametric study was conducted to tune the selectivity of the Ag metasurfaces.

The diameter of the Ag nanodisks was varied between 50 – 200 nm. A broadening in the peaks was observed as the diameter increased to include part of the NIR region. For the most part, the Ag nanodisk metasurface was tuned to selectively reflect the visible region of the solar spectrum. The arrangement of the Ag nanodisk arrays was also varied to observe its effect on the optical properties of the metasurfaces. It was selected as square and hexagonal. The hexagonal Ag nanodisk arrays resulted in a higher system level electrical efficiency for both c-Si and CdTe PV cells. The environment around the Ag nanodisk was also varied. The Ag nanodisk was sandwiched between layers of  $\text{TiO}_2$ . The thickness of  $\text{TiO}_2$  was varied between 10 – 70 nm. The peaks were narrower than those of Ag nanodisk metasurfaces without the  $\text{TiO}_2$  layers. As the  $\text{TiO}_2$  thickness increased, the peaks became narrower due to the dispersion phenomenon.

The simulated and fabricated DMD filters, as well as the simulated metasurface filters were used in the Si and CdTe SSCPVT model to evaluate their efficiencies. The SSCPVT modelled was a parabolic trough collector that consisted of primary and secondary channels. When using the DMD filter, the primary channel was placed at the top. The solar radiation was reflected off the parabolic mirror, filtered and transmitted through the DMD filter and concentrated onto the primary channel. The primary channel was triangular with the PV cells attached to its sides and was placed inside an evacuated tube. When using the Ag nanodisk metasurface filter, the

primary channel was at the bottom so that solar spectrum corresponding to the spectral response of the PV cells was reflected to the primary channel with the PV cells. Parametric studies involving the variation of mass flow rate and inlet temperature was conducted. Performance curves were obtained from plotting electrical and thermal efficiencies as a function of reduction temperature. The c-Si SSPVVT, without a filter, resulted in an overall efficiency of 55% (electrical efficiency of 20% and thermal efficiency of 35%). Incorporating the simulated metasurface optical filter (met<sub>Ag</sub>\_hx4) resulted in overall efficiencies of 63%, while that of the simulated DMD optical filter (DMD-s6) was 68%. In comparison, the fabricated DMD optical filter (DMD-e1) resulted in an overall efficiency of 60%. This can be attributed to DMD-e1's lower transmittance than DMD-s6, due to losses from defects such as surface roughness.

## 7.2. Recommendations

Optical filters play a crucial role in SSPVVTs as they perform spectral allocation by directing part of the solar spectrum to the PV cell and the rest to the thermal absorber. In this study DMD and metasurface materials were identified as potential optical filters. However, the fabrication and characterisation of DMD materials revealed that in order to enhance their transmittance in the visible region of the solar spectrum, their absorptance has to be suppressed. The absorptance is intensified by the roughness of the Ag surface. A different Ag deposition technique could be used such as ion beam sputtering for a smoother Ag surface with a very small thickness  $\leq 10$  nm. Etching the glass substrate could also enhance the transmittance of the DMD films. Metasurfaces can be fabricated using a variety of fabrication techniques such as electron beam lithography (EBL), photolithography, and colloidal lithography. The square arrangement can be achieved with more ease using EBL or photolithography, while the hexagonal arrangement can be achieved using colloidal lithography which has a high throughput and is a cheaper option. Degradation studies on the filters to observe the effect of exposure to high temperatures, UV radiation and moisture. A more detailed parametric study on the SSPVVT collector could be conducted involving mesh interdependence studies, angular solar irradiance studies, and a study on transient effects such as thermal inertia. Outdoor testing of the SSPVVT prototype with the optical filters incorporated into it could also be conducted.

## Appendix A

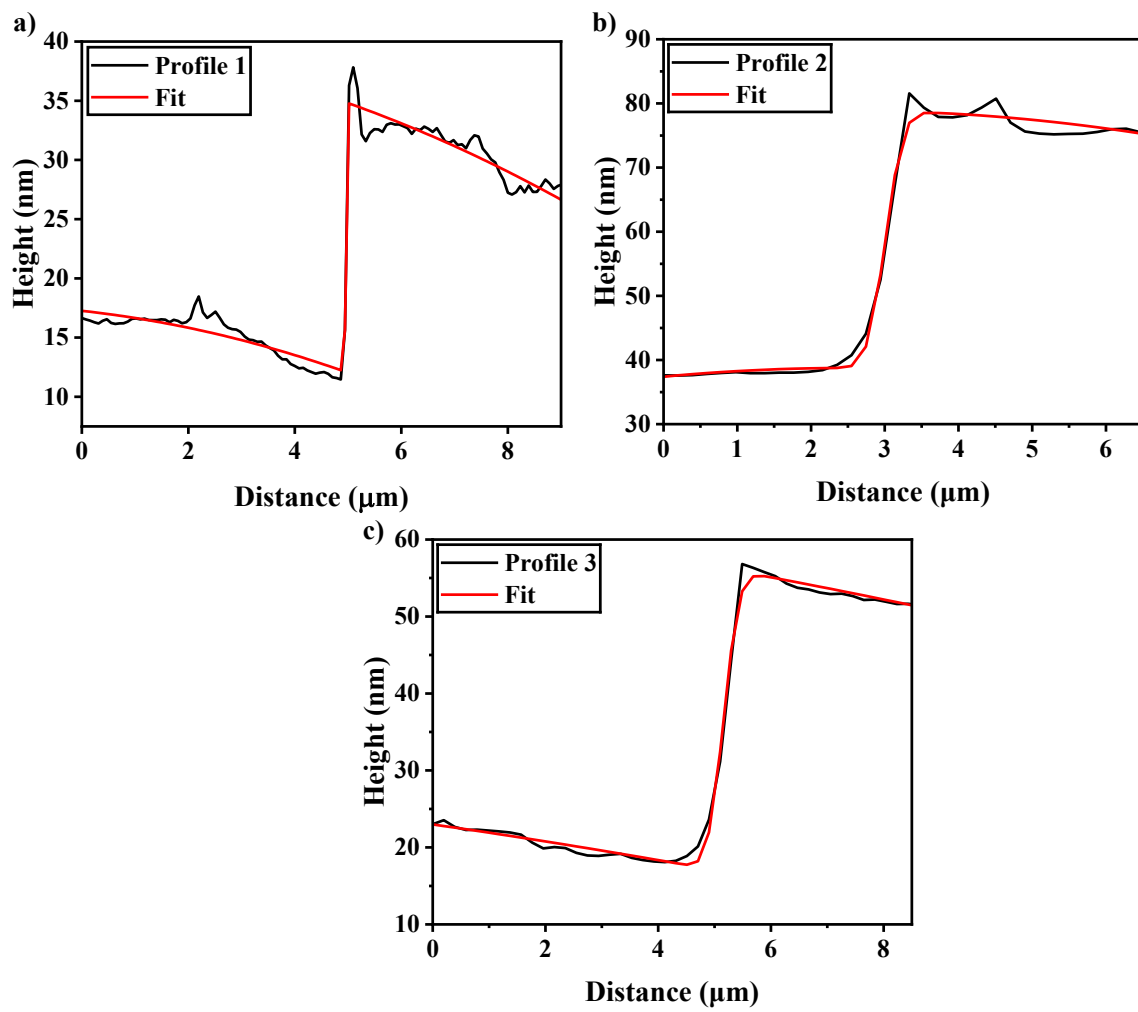


Figure A.1: Thickness of TiO<sub>2</sub> measured using AFM and the step height obtained using the Gwyddion software.

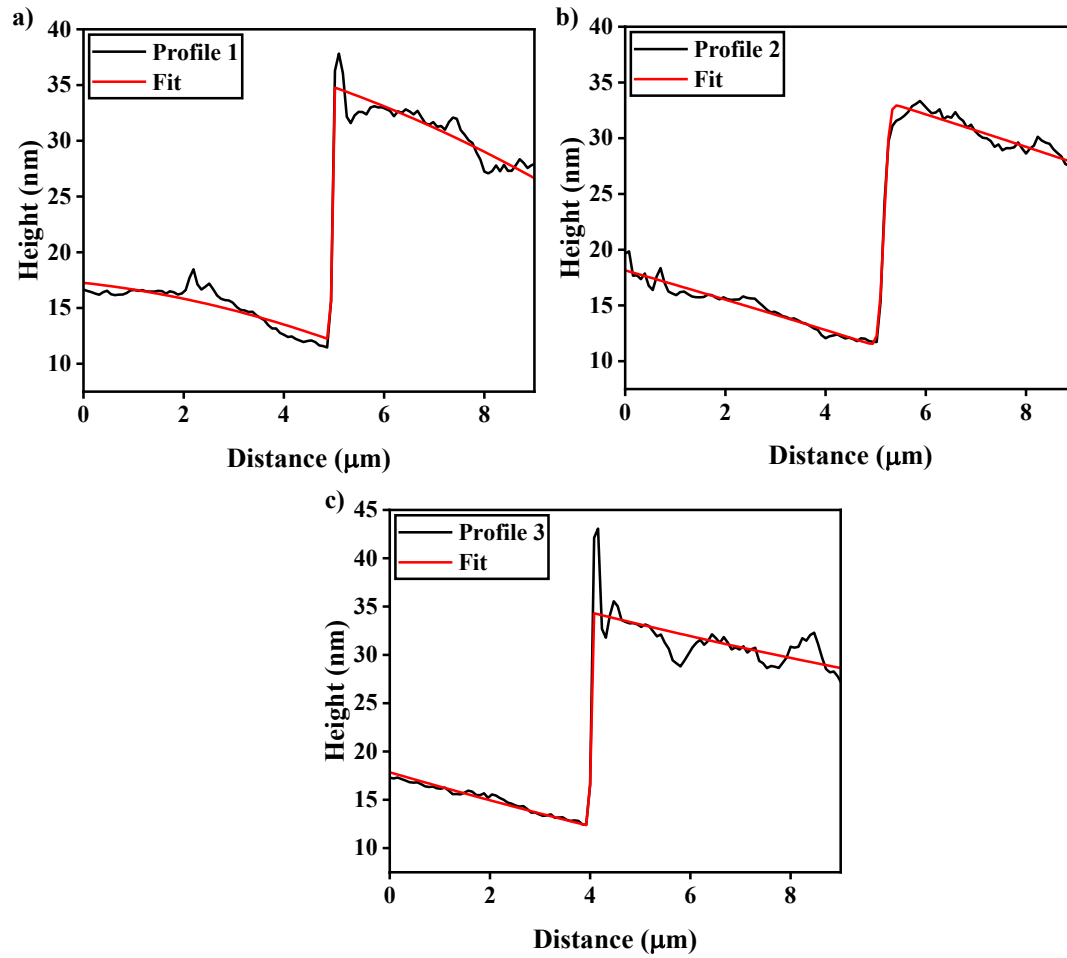


Figure A.2: Thickness of Ag measured using AFM and the step height obtained using the Gwyddion software.

Table A.1: Thickness of Ag and TiO<sub>2</sub> films measured using AFM.

|           | Ag thickness (42 s deposition time) | TiO <sub>2</sub> thickness (20 min deposition time) |
|-----------|-------------------------------------|-----------------------------------------------------|
| Profile 1 | 22.7 nm ± 0.38 nm                   | 39.1 nm ± 1.1 nm                                    |
| Profile 2 | 22.2 nm ± 0.55 nm                   | 40.1 nm ± 1.3 nm                                    |
| Profile 3 | 22.1 nm ± 0.59 nm                   | 39.4 nm ± 1.1 nm                                    |
| Average   | 22.3 nm ± 0.51 nm                   | 39.5 nm ± 1.2 nm                                    |

The deposition rates of Ag and TiO<sub>2</sub> were 0.53 nm/s and 2.0 nm/min, respectively.