Integration of Antennas and Solar Cells for Autonomous Communication Systems

Maria Jose Roo Ons
Technological University Dublin

Follow this and additional works at: https://arrow.tudublin.ie/engdoc

Part of the Systems and Communications Commons

Recommended Citation

This Theses, Ph.D is brought to you for free and open access by the Engineering at ARROW@TU Dublin. It has been accepted for inclusion in Doctoral by an authorized administrator of ARROW@TU Dublin. For more information, please contact yvonne.desmond@tudublin.ie, arrow.admin@tudublin.ie, brian.widdis@tudublin.ie.

This work is licensed under a Creative Commons Attribution-Noncommercial-Share Alike 3.0 License
INTEGRATION OF ANTENNAS AND SOLAR CELLS FOR AUTONOMOUS COMMUNICATION SYSTEMS

María José Roo Ons
Ingeniero de Telecomunicación

Doctor of Philosophy

Supervisors:
Dr. Max J. Ammann
Prof. Brian Norton
Dr. Sarah J. McCormack

DUBLIN INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRONIC & COMMUNICATIONS ENGINEERING

September 2010
ABSTRACT

Solar energy is becoming an attractive alternative for powering autonomous communication systems. These devices often involve the use of separate photovoltaics and antennas, which demand a compromise in the utilization of the limited space available.

This thesis deals with the design, analysis, fabrication and validation of different techniques for the integration of antennas and solar cells in a single multifunctional device. Four different photovoltaic technologies are considered within this work, namely, polycrystalline silicon (poly-Si), monocrystalline (mono-Si) emitter-wrap-through (EWT) rear contact solar cells, amorphous silicon (a-Si) thin film on glass substrate, and bifacial solar cells.

The use of a poly-Si solar cell was investigated as ground plane for a microstrip patch antenna as well as reflector for a half-wave dipole antenna. Looking forward to further minimize the shade of the solar element on the solar cell and to increase the smart appearance, a film that is both transparent and conductive, the AgHT-4, was evaluated as an antenna radiating element for the integration with an a-Si thin film photovoltaic module on glass substrate. A different approach involves the use of EWT solar cells as a folded dipole for integration with solar concentration. The solar cells in this structure are used both for power generation and as radiating element, and a parabolic trough is employed as well with a double function as solar concentrator for the PV cells as well as reflector for the folded dipole antenna.
Abstract

Numerical simulation results obtained with CST Microwave Studio were validated experimentally with the construction of the corresponding prototypes. The performance of these prototypes is thoroughly evaluated in an anechoic chamber.

The approaches proposed in this work for integration of antennas and PV technology will help to reduce the marginal cost of renewable energy, improving its economic viability due to the possibility of an integrated production and easier maintenance. It also reduces the need for cable deployment and leads to compact reliable systems with decreased exposure to natural disasters and vandalism.
DECLARATION

I certify that this thesis which I now submit for examination for the award of PhD, is entirely my own work and has not been taken from the work of others save and to the extent that such work has been cited and acknowledged within the text of my own work.

This thesis was prepared according to the regulations for postgraduate study by research of the Dublin Institute of Technology and has not been submitted in whole or in part for an award in any other Institute or University.

The work reported on in this thesis conforms to the principles and requirements of the Institute’s guidelines for ethics in research.

The Institute has permission to keep, to lend or to copy this thesis in whole or in part, on condition that any such use of the material of the thesis be duly acknowledged.

Signature: __________________________ Date ________
María José Roo Ons
ACKNOWLEDGMENTS

First and foremost, I would like to express my sincere gratitude to Dr. Max Ammann, for giving me the opportunity to pursue this PhD and for all his support, encouragement and guidance throughout this work. Thank you very much Max for your patience and great mentoring. I also would like to thank Dr. Sarah McCormack and Prof. Brian Norton for their valuable assistance and advice.

Thanks to all my colleagues from the Antennas High Frequency & Research Centre (AHFR) at the DIT, Antoine, Shynu, Sergio, Adam, Pádraig, Matthias, Xiulong and Giuseppe, for all the help and lively chats during lunch breaks. I am specially in debt with Shynu S.V. Nair for fruitful collaboration and discussion; with Antoine Dumoullin for always being there for me at the desk next to mine, always helpful no matter when asked; with Giuseppe Ruvio for providing me a great amount of insight and advice; and with Matthias John for the LaTeX template and aid in the final text processing of this document.

I am very grateful as well of my Dublin famaily. I feel fortunate of the friends I met here in Dublin along this almost four years. Through several barbecues, warming and leaving parties, birthdays, weddings, cinema nights and weekend trips, we’ve become a big family. Thanks too to my friends and family back in Spain and Germany. To all of you, thanks for your inspiration and companionship.

Special thanks go to my parents, María and Matías, and to my husband David, for their invaluable encouragement and love. Thanks David for sharing this journey with me, for your never ending support during all this
years together and specially for your patience during the busy periods.

Finally I wish to acknowledge and thank the financial support of Science Foundation Ireland (SFI), who funded this work through their Research Frontiers Program.
## Nomenclature

\( \alpha_m \)  
\[ \text{solar absorptance of a material} \ (0 \leq \alpha_m \leq 1) \]

\( BW \)  
\[ \text{impedance bandwidth} \]

\( c_0 \)  
\[ \text{speed of light in vacuum, 299,792,458 m/s} \]

\( C_m \)  
\[ \text{specific heat capacity of a material} \ (\text{kg \ m}^{-3}) \]

\( C \)  
\[ \text{capacity} \ (\text{F}) \]

\( d \)  
\[ \text{distance} \ (\text{m}) \]

\( D \)  
\[ \text{directivity} \ (\text{dBi}) \]

\( d_m \)  
\[ \text{thickness of a material} \ (\text{m}) \]

\( e \)  
\[ \text{radiation efficiency} \ (0 \leq e \leq 1) \]

\( \Gamma \)  
\[ \text{microwave reflection coefficient} \ (0 \leq \Gamma \leq 1) \]

\( f \)  
\[ \text{frequency} \ (\text{Hz}) \]

\( f_0 \)  
\[ \text{fundamental resonant frequency of an antenna} \ (\text{Hz}) \]

\( g \)  
\[ \text{feed gap} \ (\text{m}) \]

\( G \)  
\[ \text{gain} \ (\text{dBi}) \]

\( h_c \)  
\[ \text{convection heat transfer coefficient} \ (\text{W \ m}^{-2} \ \text{K}^{-1}) \]

\( I \)  
\[ \text{current} \ (\text{A}) \]

\( k_m \)  
\[ \text{thermal conductivity of a material} \ (\text{W \ m}^{-1} \ \text{K}^{-1}) \]

\( L \)  
\[ \text{inductance} \ (\text{H}) \]

\( l \)  
\[ \text{length of an element} \ (\text{m}) \]

\( \lambda \)  
\[ \text{wavelength} \ (\text{m}) \]

\( \rho_m \)  
\[ \text{density of a material} \ (\text{kg \ m}^{-3}) \]

\( R_i \)  
\[ \text{input resistance of antenna} \ (\Omega) \]

\( RL \)  
\[ \text{return loss} \ (\text{dB}) \]

\( S_{11} \)  
\[ \text{input reflection coefficient in the scattering matrix} \]
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{21}$</td>
<td>transmission coefficient in the scattering matrix</td>
</tr>
<tr>
<td>$t$</td>
<td>time (s)</td>
</tr>
<tr>
<td>$TCK'$</td>
<td>thermal coefficient of the dielectric constant ($K^{-1}$)</td>
</tr>
<tr>
<td>$\tan \delta$</td>
<td>loss tangent of a dielectric material</td>
</tr>
<tr>
<td>$v$</td>
<td>sinusoidal wave’s velocity of propagation (m/s)</td>
</tr>
<tr>
<td>$V$</td>
<td>voltage (V)</td>
</tr>
<tr>
<td>$\varepsilon_r$</td>
<td>relative dielectric constant of a dielectric material</td>
</tr>
<tr>
<td>$w$</td>
<td>width of an element (m)</td>
</tr>
<tr>
<td>$X_i$</td>
<td>input reactance of antenna (\Omega)</td>
</tr>
<tr>
<td>$Z_i$</td>
<td>input impedance of antenna (\Omega)</td>
</tr>
<tr>
<td>$Z_o$</td>
<td>characteristic impedance of antenna feed line (\Omega)</td>
</tr>
<tr>
<td>$\theta, \phi$</td>
<td>angular coordinates in spherical coordinate system (°)</td>
</tr>
<tr>
<td>$x, y, z$</td>
<td>numerical coordinates in a cartesian coordinate system (m)</td>
</tr>
</tbody>
</table>
## Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag</td>
<td>Silver</td>
</tr>
<tr>
<td>Al</td>
<td>Aluminium</td>
</tr>
<tr>
<td>a-Si</td>
<td>Amorphous Silicon</td>
</tr>
<tr>
<td>AUT</td>
<td>Antenna Under Test</td>
</tr>
<tr>
<td>B</td>
<td>Boron</td>
</tr>
<tr>
<td>BSF</td>
<td>Back Surface Field</td>
</tr>
<tr>
<td>BJ</td>
<td>Back Junction</td>
</tr>
<tr>
<td>c-Si</td>
<td>Crystalline Silicon</td>
</tr>
<tr>
<td>CST</td>
<td>Computer Simulation Technology GmbH</td>
</tr>
<tr>
<td>CZ</td>
<td>Czochralski</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>EWT</td>
<td>Emitter Wrap Through</td>
</tr>
<tr>
<td>ESR</td>
<td>Enhanced Specular Reflector</td>
</tr>
<tr>
<td>FD</td>
<td>Finite Difference</td>
</tr>
<tr>
<td>FIT</td>
<td>Finite Integration Technique</td>
</tr>
<tr>
<td>FZ</td>
<td>Float Zone</td>
</tr>
<tr>
<td>GaAs</td>
<td>Gallium Arsenide</td>
</tr>
<tr>
<td>GaInP</td>
<td>Gallium Indium Phosphide</td>
</tr>
<tr>
<td>Ge</td>
<td>Germanium</td>
</tr>
<tr>
<td>GSM</td>
<td>Global System for Mobile Communications</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
</tr>
<tr>
<td>ITO</td>
<td>Indium Tin Oxide</td>
</tr>
<tr>
<td>MIC</td>
<td>Microwave Integrated Monolithic</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------</td>
</tr>
<tr>
<td>MF</td>
<td>Medium Frequency</td>
</tr>
<tr>
<td>MM</td>
<td>Moment Method</td>
</tr>
<tr>
<td>mono-Si</td>
<td>Monocrystalline Silicon</td>
</tr>
<tr>
<td>MPA</td>
<td>Microstrip Patch Antenna</td>
</tr>
<tr>
<td>MWT</td>
<td>Metallization Wrap Through</td>
</tr>
<tr>
<td>NREL</td>
<td>National Renewable Energy Laboratory (US)</td>
</tr>
<tr>
<td>P</td>
<td>Phosphor</td>
</tr>
<tr>
<td>PCB</td>
<td>Printed Circuit Board</td>
</tr>
<tr>
<td>PEC</td>
<td>Perfect Electrical Conductor</td>
</tr>
<tr>
<td>PIFA</td>
<td>Planar Inverted F Antenna</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic</td>
</tr>
<tr>
<td>poly-Si</td>
<td>Polycrystalline Silicon</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>Se</td>
<td>Selenium</td>
</tr>
<tr>
<td>SGH</td>
<td>Standard Gain Horn</td>
</tr>
<tr>
<td>SMA</td>
<td>SubMiniature Type A</td>
</tr>
<tr>
<td>SSFIP</td>
<td>Strip Slot Foam Inverted Patch</td>
</tr>
<tr>
<td>TCO</td>
<td>Transparent Conductive Oxide</td>
</tr>
<tr>
<td>VNA</td>
<td>Vector Network Analyser</td>
</tr>
<tr>
<td>UHF</td>
<td>Ultra High Frequency</td>
</tr>
<tr>
<td>UWF</td>
<td>Ultra Wide Band</td>
</tr>
<tr>
<td>WLAN</td>
<td>Wireless Local Area Network</td>
</tr>
<tr>
<td>ZnO</td>
<td>Zinc Oxide</td>
</tr>
</tbody>
</table>
CONTENTS

Abstract ii
Declaration iv
Acknowledgments v
Nomenclature vii
Abbreviations ix
List of Figures xv
List of Tables xix

1. Introduction 1
   1.1. Evolution of the Photovoltaic Energy and Solar Cell Technology 2
   1.2. Evolution of Radio and Antenna Technology 4
   1.3. Motivation for the Integration of Antennas and Solar Cells 6
   1.4. Past Reported Approaches for Combined Photovoltaics and Antennas 8
   1.5. Outline of This Thesis and Novelty 11

2. Background on Microstrip and Dipole Antenna Technology 14
   2.1. Fundamental Antenna Parameters 14
      2.1.1. Radiation Pattern 14
## Contents

4.4. Electric Field Vector Analysis ........................................... 56  
4.5. Radiation Properties ..................................................... 58  
4.6. Conclusion ................................................................. 59  

5. Polycrystalline Silicon Solar Cell as Reflector for Dipole Antenna 60  
5.1. Inhomogeneous Reflector Surface .................................... 60  
5.1.1. Current Analysis ..................................................... 62  
5.1.2. Simulated Radiation Pattern with Ag-Lattice as Reflector .... 65  
5.1.3. Simulated Impedance Bandwidth and Gain ..................... 66  
5.2. Printed Dipole with Integrated Balun and Poly-Si Solar Cell as Reflector ..................................................... 68  
5.2.1. Antenna Design ..................................................... 68  
5.2.2. Impedance Characteristic and Gain Results ................... 70  
5.2.3. Radiation Properties ................................................. 74  
5.3. Conclusion ................................................................. 74  

6. Transparent Antenna on Amorphous Silicon Thin Film Module 76  
6.1. A-Si Thin Film on Glass Substrate .................................. 77  
6.2. AgHT-4 Transparent Conductive Film ................................ 78  
6.3. Antenna Design ........................................................... 78  
6.4. Impedance Characteristic and Gain Results ....................... 80  
6.5. Radiation Properties ..................................................... 81  
6.6. Power Output ............................................................. 81  
6.7. Conclusion ................................................................. 82  

7. Photovoltaic Dipole Antenna with Solar Concentrator 84  
7.1. Use of EWT Rear Contact Solar Cell ............................... 85  
7.2. Antenna and Solar Concentrator Design ......................... 86  
7.3. Impedance Characteristic and Gain Results ..................... 91  
7.4. Radiation Properties ..................................................... 91
## List of Figures

2.1. Coordinate system used for radiation patterns.......................... 15
2.2. Input impedance of an antenna........................................... 16
2.3. Reflected wave from a mismatched load (antenna)......................... 17
2.4. Rectangular microstrip patch antenna....................................... 20
2.5. Coaxial probe fed microstrip patch antenna.................................. 22
2.6. Inset fed microstrip patch antenna........................................... 23
2.7. Proximity coupled fed microstrip patch antenna.......................... 24
2.8. Centre-fed dipole antenna: Ideal layout and horizontal printed implementation........................................... 26
2.9. Folded dipole........................................................................... 28
2.10. Direct connection coaxial cable to dipole antenna......................... 29
2.11. Measurement setup in anechoic chamber................................... 32
3.1. Basic solar cell structure......................................................... 36
3.2. P-N junction............................................................................ 37
3.3. Best research solar cell efficiencies up to date............................ 39
3.4. Cross section of standard wafer based crystalline silicon solar cell.......................... 42
3.5. Cross section of BSF bifacial solar cell and and finger grid electrodes............................................... 44
3.6. Two Silver strips in transparent encapsulate film.......................... 45
4.1. Photo of the developed poly-Si solar MPAs showing both parallel and perpendicular Ag-lattice electrode alignment with respect to the microstrip feed line........................................... 51
4.2. Microscope photo of transversal section of poly-Si solar cell with dimensions. ........................................ 52
4.3. Exploded layout of the poly-Si solar MPA antenna geometry with coordinate system. ............................. 53
4.4. Simulated and measured $S_{11}$ for the solar MPA configurations. ....................................................... 54
4.5. Simulated and measured $Gain(dBi)$ for the solar MPA configurations. ................................................. 55
4.6. Electric field vector in the silicon for both parallel and perpendicular Ag-lattice of solar MPA. ................ 57
4.7. Measured radiation patterns for the solar MPA configurations. Co-polar and cross-polar components are shown for both E-plane and H-plane. ....................................................... 58

5.1. Simulated half-wave ideal dipole antenna with poly-Si solar cell as reflector. Side perspective and front view. 61
5.2. Simulated RF current density in the front Ag-lattice of the cell for both parallel and perpendicular orientation. 63
5.3. Simulated RF current density as a contour plot in copper reflector and aluminium layer of the poly-Si solar cell for both parallel and perpendicular orientation of the Ag-lattice. 64
5.4. Simulated radiation pattern of dipole over a copper reflector and without reflector. ................................. 65
5.5. Simulated radiation pattern of dipole over the 57 thin electrodes of the Ag-lattice for both parallel and perpendicular orientation. ................................................................. 66
5.6. Simulated radiation pattern of dipole over the Ag-lattice for both parallel and perpendicular orientation. 67
5.7. Exploded layout of the proposed printed dipole antenna with poly-Si solar cell reflector and detailed geometry of the dipole and integrated balun. ............................................. 69
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.8</td>
<td>Perspective view of the solar dipole antenna for parallel orientation of the Ag-lattice and front view of the solar dipole antenna for perpendicular orientation of the Ag-lattice.</td>
<td>71</td>
</tr>
<tr>
<td>5.9</td>
<td>Simulated and measured $S_{11}$ for the dipole with poly-Si solar cell as ground plane. Comparison of copper reflector with two possible orientations of the Ag-lattice.</td>
<td>72</td>
</tr>
<tr>
<td>5.10</td>
<td>Measured radiation patterns for the dipole antenna with poly-Si solar cell as reflector. Co-polar and cross-polar components for both E-plane and H-plane.</td>
<td>73</td>
</tr>
<tr>
<td>6.1</td>
<td>Cross-sectional view of a-Si thin film on glass substrate</td>
<td>77</td>
</tr>
<tr>
<td>6.2</td>
<td>Layout and photo of the proposed transparent antenna.</td>
<td>79</td>
</tr>
<tr>
<td>6.3</td>
<td>Simulated and measured $S_{11}$ and gain for a-Si thin film antenna with transparent patch.</td>
<td>80</td>
</tr>
<tr>
<td>6.4</td>
<td>Simulated and measured $S_{11}$ and gain for a-Si thin film antenna with copper patch.</td>
<td>81</td>
</tr>
<tr>
<td>6.5</td>
<td>Measured radiation pattern for both copper and transparent antenna on a-Si thin film glass module. Co-polar and cross-polar components are for both E-plane and H-plane.</td>
<td>82</td>
</tr>
<tr>
<td>7.1</td>
<td>Cross-sectional representation of an Emitter-Wrap-Through (EWT) solar cell.</td>
<td>85</td>
</tr>
<tr>
<td>7.2</td>
<td>Experimental setup to analyze the S-parameter response of EWT back contacted solar cell.</td>
<td>87</td>
</tr>
<tr>
<td>7.3</td>
<td>Comparison of the measured transmission coefficient $S_{21}$ for EWT solar cell and brass strip, as well as for simulated PEC strip.</td>
<td>88</td>
</tr>
<tr>
<td>7.4</td>
<td>Detailed view of the EWT solar folded dipole: Layout and photo image.</td>
<td>89</td>
</tr>
<tr>
<td>7.5</td>
<td>Detailed view of RF-DC decoupling network and balun: Layout-out and photo image.</td>
<td>90</td>
</tr>
</tbody>
</table>
### List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.6</td>
<td>General view of the proposed EWT solar folded dipole antenna with parabolic reflector. Dimensions and photo image.</td>
<td>92</td>
</tr>
<tr>
<td>7.7</td>
<td>Simulated and measured $S_{11}$ for the EWT solar folded dipole with parabolic reflector.</td>
<td>93</td>
</tr>
<tr>
<td>7.8</td>
<td>Measured and simulated radiation pattern for the EWT solar dipole with parabolic reflector. Co-polar and cross-polar components for both E-plane and H-plane.</td>
<td>93</td>
</tr>
<tr>
<td>7.9</td>
<td>Comparison of measured direct current extracted from the folded dipole with reflector and for the dipole alone directly exposed insolation.</td>
<td>94</td>
</tr>
<tr>
<td>8.1</td>
<td>Antenna with poly-Si solar cell as groundplane: Front view and back view.</td>
<td>98</td>
</tr>
<tr>
<td>8.2</td>
<td>Conventional microstrip patch antenna with copper ground plane: front and back view.</td>
<td>99</td>
</tr>
<tr>
<td>8.3</td>
<td>Cross-sectional view of the antenna structure for both standard microstrip patch antenna with copper ground plane and microstrip patch antenna with poly-Si solar cell as ground plane.</td>
<td>101</td>
</tr>
<tr>
<td>8.4</td>
<td>Lighting set-up.</td>
<td>102</td>
</tr>
<tr>
<td>8.5</td>
<td>Set-up for $S_{11}$ measurement under 30 min continue insolation.</td>
<td>104</td>
</tr>
<tr>
<td>8.6</td>
<td>Set-up for temperature measurement under 30 min continue insolation.</td>
<td>105</td>
</tr>
<tr>
<td>8.7</td>
<td>Variation of measured antenna $S_{11}$ parameter for prolonged irradiation with 1,000 W/m², for both copper and solar based MPAs. Results presented for the laminates FR4, RF45 and RO4003.</td>
<td>106</td>
</tr>
<tr>
<td>8.8</td>
<td>Temperature variation for the FR4 based prototypes with prolonged insolation with 1,000 W/m², for both copper and poly-Si solar antenna.</td>
<td>109</td>
</tr>
</tbody>
</table>
# List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>Simulated and measured antenna parameters for various MPA configurations</td>
<td>55</td>
</tr>
<tr>
<td>5.1</td>
<td>Simulated antenna parameters for ideal half-wave dipole with copper and solar cell reflector</td>
<td>67</td>
</tr>
<tr>
<td>5.2</td>
<td>Simulated and measured antenna parameters for microstrip dipole with copper and solar cell reflector</td>
<td>70</td>
</tr>
<tr>
<td>8.1</td>
<td>Description of the laminates FR4, RF45 and RO4003</td>
<td>98</td>
</tr>
<tr>
<td>8.2</td>
<td>Comparative antenna parameter values and maximum deviation with temperature for an insolation of 1,000 W/m$^2$ for the laminates FR4, RF45 and RO4003</td>
<td>107</td>
</tr>
<tr>
<td>8.3</td>
<td>Thermal description of materials involved in FR4 based poly-Si solar MPA antenna</td>
<td>108</td>
</tr>
</tbody>
</table>
1. **Introduction**

The history of solar cell technology dates back to 1839 when Becquerel, while experimenting with electrolytic cells, found that certain material would produce small amounts of electric current when exposed to light [1]. He had just discovered the photovoltaic effect, a phenomenon in which a current (or a corresponding voltage) is created in a material upon exposure to electromagnetic radiation.

The existence of electromagnetic waves was predicted by Maxwell, while synthesizing in a single theory all previously unrelated observations, experiments and equations of electricity, magnetism and optics [2]. In this work, published in 1865, Maxwell showed that the equations predict the existence of electric and magnetic fields travelling through space in the form of waves and proposes for the first time the electromagnetic nature of the visible light.

It was 22 years later in 1887, when Hertz satisfactorily demonstrated the existence of the electromagnetic waves predicted by Maxwell [3]. He built an apparatus to produce and detect ultra-high frequency (UHF) radio waves by creating an electrical spark in the gap of a dipole-like antenna. He observed that the spark was brighter when the apparatus was exposed to visible or ultraviolet light; witnessing the photoelectric effect by which electrons are ejected from matter as a consequence of their absorption of energy from very short wavelength electromagnetic radiation. Both the photoelectric and the photovoltaic effect were later explained by Einstein in 1905 [4] in terms of light being composed of discrete “quanta” (now called photons) containing various amounts of energy corresponding to
the different wavelengths.

The history written by these four men laid the foundations for the development of both solar cells and antennas. These two technologies would follow different paths up to the present day, where there is an increasing interest in combining photovoltaics and antennas.

In the first section of this chapter the evolution of the photovoltaic energy and solar cell technology will be briefly summarized. Section two will guide us through the history of the radio and antenna technology. The motivation for the integration of photovoltaics and antennas is proposed in the third section. The fourth chapter reviews the past reported approaches for the integration, and the fifth section outlines the content of the following chapters of the thesis, and highlights the achieved innovations through the novel designs proposed.

1.1. Evolution of the Photovoltaic Energy and Solar Cell Technology

Ohl patented the first modern solar cell in 1946 [5]. He discovered the p-n junction and the mechanism by which it works. While measuring the properties of a doped silicon crystal containing a “crack” (p-n junction), he noticed a marked change in electric voltage depending on the illumination of the crystal. In 1954, three other researchers at the Bell Laboratories, Pearson, Chapin, and Fuller, designed a silicon solar cell capable of 6% energy conversion efficiency with direct sunlight, which was an improvement by more than an order of magnitude compared with alternative designs, although their cost was as high as $1,000/W (USD per peak Watt). They also created the first solar panels by connecting several strips of silicon in array, and confirmed the increase in power output due to additive voltages [6]. These first solar cells were developed in crystalline silicon, and it continues to be the dominant technology nowadays.
Four years later, in 1958, came the first significant application of solar cells as a back-up power source to the Vanguard I satellite, which allowed it to continue transmitting for over a year after its chemical battery exhausted [7]. The successful operation of solar cells on this mission was duplicated in many other Soviet and American satellites, and by the late 1960s, photovoltaic (PV) technology had become their established source for power, and it remains so.

A fundamental understanding of solar-cell performance was reached in 1961 by Shockley and Queisser, who determined the maximum theoretical light-conversion efficiency of semiconductor solar cells, which for silicon cells is around 30% [8].

After the successful employment of solar panels in satellites, the oil crisis of 1970s drove interest in the terrestrial application of photovoltaics. Significant efforts began to develop PV power systems for residential and commercial uses. Improvements in manufacturing, performance and quality of PV modules helped to reduce costs by 80%, opening up a number of opportunities for applications such as portable consumer electronics (particularly portable calculators), navigational buoys, railroad crossings, critical low-power telecommunication equipment and other remote terrestrial applications where utility-grid connections were too costly [9, 10]. Research interest begins in thin film solar cell technologies, which promised to reduce manufacturing costs by drastically reducing the amount of semiconductor needed in each cell [11, 12]. Other compound semiconductors apart from the silicon, like GaAs or CdS began to be investigated [13, 14].

The 1970s was also the decade of the establishment of large photovoltaic companies (Solar Power in 1972, Solarex Corporation in 1973, and Solec International and Solar Technology International in 1975). And by the end of the decade, PVs started to be installed on buildings and homes although in very limited numbers, due to the still high cost of approximately $80/Watt [15].

The era of the large standalone photovoltaic systems started in the 1980s.
1. Introduction

In 1980 ARCO Solar became the first company to produce more than 1 Megawatt of photovoltaic modules in one year and by 1983, they would dedicate a 6 Megawatt photovoltaic substation in Central California. The worldwide photovoltaic production in 1983 exceeded 21.3 Megawatts, and sales topped $250 million. By 1985, the world price of photovoltaic modules fell below $10/ W [16].

Since mid-1990s, leadership in the PV sector has shifted from the US to Japan and Europe due to the strength of the national programs developed by the member states [17–19]. In 1994 Japan began a subsidiary PV program to install nearly “70,000 Solar Roofs” by 2010 and Germany launched a similar “100,000 Solar Roofs” program in by the year 2000, providing low-interest loans for the installation of PV systems [20]. Nowadays Germany, Spain and increasingly China, dominate photovoltaic markets and average module price for reasonable volume orders in Europe was 2.9€/ W during 2008 [17, 21].

Although since late 2008 Europe has suffered a difficult period for the financial economic system, the European Institutions have made legislative and financial commitments to support the future development of sustainable energy technologies and to accelerate their penetration into European and global markets [22, 23].

1.2. Evolution of Radio and Antenna Technology

In 1887, Hertz built the first transmitting and receiving antenna as part of an apparatus to demonstrate the production and detection of electromagnetic radiation [3]. The spark-gap dipole transmitter designed could be located up to a few meters away from the spark-gap loop wire detector in order to work, but Hertz saw no practical use for his discovery, so radio was left to others to be implemented into a practical form.

In 1896 Tesla transmitted signals over a distance of about 48 km, and one
1. Introduction

year later filed the first patent on radio technology [24], where transformer coils were wound in the form of a flat spiral and connected to what will later be known as a magnetic loop antenna.

The word “antenna” as we use it today for wireless receiving and transmitting terminals, relates to Marconi back in 1895, while experimenting with a 2.5 m long tent pole (in Italian, “l’antenna centrale”) with a wire alongside as a radiating/receiving aerial element [25]. In 1901 he performed the first transatlantic transmission between Canada and England using Morse code in the medium frequency (MF) band. Striving for greater transmission distance and improved signal reception, he kept building larger antenna systems, usually massive structures comprising various dozens or hundreds of wires or suspended by wooden towers of about 60 m, which lowered the operating frequency. By late in 1907 he was using a frequency of 45 kHz [26].

At the same time as Marconi’s telegraphy transmissions, Fessenden was working on a new type of continuous wave detector for the transmission of audio signals and by 1906 he had demonstrated the heterodyne principle’s utility for point-to-point wireless telephony [27]. He also made what appears to be the first ever audio radio broadcast that year on Christmas Eve with entertainment and music [28].

From Marconi’s invention until the 1940s, antenna technology was developed for frequencies up to about UHF and was primarily centered on wire radiating elements like dipoles, monopoles or antenna systems the Yagi-Uda and [29, 30] consisting of an array dipoles.

The invention of microwave sources such as the klystron in 1939 [31] and the magnetron in 1940 [32], started the era of the microwaves with frequencies of 1 GHz and above and the centimetre-band radar. This technology developed rapidly during World War II, leading to a decrease in size of the associated antenna radiators, and the introduction of new elements such as waveguide apertures, horns, reflector, etc [33, 34].

The advances made in computer architecture during WWII had a major
impact on the advance of modern antenna technology. Numerical methods such as Method of Moments (MoM) or Finite Difference (FD), were introduced in the study and development of antennas, allowing accurate analysis and design of previously complex antenna systems \[35\text{–}37\]. In fact, while in the first half of the 20th century antenna design may have been considered almost a cut and try operation, today many antenna designs proceed directly from the initial design stage to prototype without intermediate testing with the consequent reduction in production costs.

Although the concept of “microstrip” radiators was first proposed by Deschamps as early as 1953 \[38\] and first patented by Gutton and Baissnot in 1955 \[39\], it was not until the early 1970s when the first practical microstrip or patch antennas were developed \[40, 41\]. They have received a lot of attention since then and remain to be one of the most popular radiators due to their simplicity, versatility, robustness, lightweight, low cost, low profile and the possibility to be conformal to either planar or non-planar surfaces. They can be found today in high-performance aircraft, spacecraft, satellite and missile applications and in many other commercial applications such as mobile and wireless communications. They have been extensively studied as reported in a large number of papers and books \[42\text{–}44\].

While wire antennas and microstrip patches are used widely today, the introduction of the phased array architecture microwave integrating monolithic (MIC) technology \[45\] and new materials such as metamaterials \[46\], artificial magnetic conductors and soft/hard surfaces \[47\] present new challenges for the antenna engineering.

### 1.3. Motivation for the Integration of Antennas and Solar Cells

Most current government policies worldwide seek to increase the use of renewable energy displacing the use of grid-supplied electricity to reduce
carbon dioxide emissions, and so contribute to the alleviation of climate change. With increasing fossil fuel prices solar energy becomes an attractive alternative for powering communication systems and it is actually the primary choice when it comes to powering equipment in space or remote areas where grid power either is not available or it is too expensive to extend to. As an energy source, solar photovoltaic systems are highly reliable and incur minimal maintenance.

The surface space on satellites is scarce, and this is actually most critical for modern mini- and microsatellites [48]. Antennas for communication and solar cells for energy are competing for the available surface area which can be saved by suitably integrating both technologies.

Standalone terrestrial communication systems and sensor networks that communicate environmental data, tracking, telemetry or control information via a wireless microwave link are preferably powered with solar energy [49–56]. Also consumer electronics entertainment systems such as wireless headphones or mobile phones are increasingly powered with photovoltaics (PV) [57, 58]. In these devices, the communications antenna is typically displaced from the panel of photovoltaic cells.

Furthermore, urban mobile cellular communications use an increasingly large number of limited-range building-mounted antennas operating at low power. The installation of microcell antennas on buildings often requires expensive and time-consuming retrofitting of electrical supply cables, which can lead to concern over visual amenity, vandalism and maintenance. Photovoltaic powered microcell transceivers with integrated batteries offer a high inherent reliability and are insusceptible to grid-supply interruptions [59–62]. Vertical façade PV panels for building integration are designed usually with a flat external profile [63, 64] which allows integration with planar antennas.

The integration of photovoltaic solar cells with microwave antennas in a single multifunctional device potentially gives a wide range of advantages in terms of volume, weight, smart appearance and electrical performance to
many applications when compared with a simple juxtaposition of antennas and solar cells. Additionally, it can reduce the marginal cost of renewable energy, improving its economic viability.

1.4. Past Reported Approaches for Combined Photovoltaics and Antennas

The first reported approach to integrate solar cells and antennas dates back to 1996, and it was intended for a microsatellite application [65]. In this case, commercial solar cells were merely placed next to a 2.225 GHz microstrip patch antenna. The solar cells had to be placed at a reasonable distance from the radiating edges of the microstrip patch to avoid performance degradation.

In 1998 the “SOLANT” project for the integration of antennas and solar cells started at the LEMA-EPFL (Lausanne, Switzerland). The selected technology for the development of the first SOLANT antennas was amorphous silicon cells on polymer substrate developed at the University of Neuchâtel (Switzerland) [66]. These cells, although having low power efficiency, appear to be thin, light and flexible films that could be cut to fit structures with complex shapes. They were first glued over an array of Strip-Slot-Foam-Inverted-Patch (SSFIP) antennas [67–69]. In terms of footprint saving there was not much of an improvement in this design over first attempt, but computer simulations were used to study cases of partial or total overlapping of solar cells and the radiating patches [65] providing guidelines for the identification of the antenna regions which could not be covered by cells.

The research on the SOLANT antennas was later oriented to slot antennas, as they offered a larger metallic surface where the solar cells could be glued or even directly deposited. The first experiment in this direction was the direct growth of amorphous silicon solar cells on the ground plane
where the slot antenna is cut [70]. Stainless steel was used for the ground plane to facilitate the deposition of the solar cells as other conductors like copper could easily diffuse into the silicon. The solar cells proved to have negligible effects on the antenna behaviour, but the use of stainless steel introduced a small reduction in antenna efficiency. They then glued fabricated amorphous silicon solar cells onto the ground plane of a cross slot antenna [71]. The a-Si:H thin film could be laser trimmed to conform to the cross slot antenna shape. This solution could be applied to any conductor material in the ground plane, solving the previous observed loss in gain due to the stainless steel, and significantly reducing the cost of customized growth of solar cells into a individual antenna. The variation of the antenna gain due to the solar cell was less than 1 dB over the useful frequency band, and the differences were attributed to the measurement setup instability.

Nevertheless, the power efficiency of a-Si:H solar cell could hardly surpass 10% [72], and the possibility of using Gallium Arsenide (GaAs) solar cells as conductor instead of standard copper patches was also explored [73]. GaAs solar cells can reach very high efficiencies (up to 25%). The antenna was based on a standard commercial cell with size 41 mm × 42.6 mm, so to increase the surface of the solar cells two extra solar patches have been added as parasitic radiators at both sides of the main patch.

The use of solar cells as a radiating element was further investigated at the Institute for Solar Energy Supply Technology (ISET e.V., Kassel, Germany). They presented a “Solar Planar Antenna - SOLPLANT” concept, where crystalline Silicon solar cells were use as planar antennas [74]. They showed that from the RF point of view this type of solar cell acts like a homogeneous metallic plate, due to its rear side contact [74]. The two first realizations of a SOLPLANT antenna were, a four-element planar array with poly-Si solar cells, and an aperture coupled single antenna element with poly-Si solar cells and thin film cells [75]. In the first case the antenna array was excited by a microstrip feeding network on the rear side of the cells. As the solar cells act at the same time as power element and RF ra-
diantor, a DC-RF decoupling network was needed. In the second case, the aperture coupled single antenna element was based on the SSFIP principle (Strip-Slot-Foam-Inverter-Patch) [67]. Due to the aperture coupling in this case there is no galvanic contact between the RF and DC current, thus the RF source does not need to be protected from the DC power [75]. The gain of the antenna with poly-Si patch was found to be 1 dB lower than the copper equivalent, although it is claimed that this discrepancy was in the range of measurement uncertainty.

One of the first SOLPLANT product developments was a wireless monitoring system in the GSM 900 band. The solar module consists of many solar cell strips in order to increase the output voltage. This solar antenna was based on an E-antenna as described in [76]. The antenna is fed via a coaxial cable where the inner and outer conductor is directly connected to one DC port of the solar module. With this construction RF and DC signals are available on the same lines, and the RF-DC separation was carried out by means of a Bias-T at the end of the coaxial cable [75].

The second SOLPLANT product was a GPS antenna for automotive applications [77]. The antenna consisted of a solar cell array where several monocrystalline Silicon (mono-Si) cells were used as radiating elements, excited with a feeding network with Wilkinson power dividers through a ground plane with crossed slots. Other SOLPLANT products based on the same principle that were developed include a GSM antenna for automotive applications and an antenna for a Worldspace Digital Satellite Receiver [78].

The Jet Propulsion Laboratory in Pasadena (California, USA) also investigated on the integration of antennas with solar panels for spacecraft applications. The first antenna/solar array integration solution they developed back in 1999 was a low-gain UHF crossed-slot microstrip antenna integrated with solar cells for the Mars Rover [79]. The cross-slot patch is a microstrip antenna element that consists of four 1/4-wavelength-long sub-patches, of square or slightly rectangular shape, and shorted to the ground
1. Introduction

plane at four sequentially located edges [80]. The solar cells were placed on top of the sub-patches and around them, avoiding the radiating edges, without significantly disturbing the radiation characteristics of the antenna [79].

The second antenna/solar array integration solution developed was an X-band high-gain antenna [81]. The antenna selected was a printed microstrip reflectarray with crossed dipoles laid on the top of a standard solar array which acted as ground plane. While the solar array results were very good, the antenna measurements showed an impaired efficiency. They attributed this to the fact that the electrical characteristics of the overall dipole structure and the inhomogeneous ground plane were not well understood or not well considered in the design, mainly because of the fine and inhomogeneous silver grid on the top surface of the solar cells, which was difficult to characterize [81].

1.5. Outline of This Thesis and Novelty

In Chapter 2 the fundamental antenna parameters involved in this thesis are introduced and a theoretical background on the operation principle of microstrip and dipole antennas is provided.

A background on the different solar cell technologies available is given on Chapter 3. The photovoltaic effect, that is, the phenomena behind the power generation in a solar cell, is also described. Emphasis is placed in characterizing the solar cell technologies considered in this work.

The main contribution of this thesis are Chapters 4 to 8. In Chapter 4 a first solution to integrate solar cells and antennas in a single multifunctional device is presented. This involves the use of a polycrystalline silicon (poly-Si) solar cell as ground plane for a microstrip patch antenna (MPA). The use of the same solar cell as reflector for a half-wave dipole antenna is investigated in Chapter 5. This thesis provides for the first time a com-
plete characterization of the poly-Si solar cell as an inhomogeneous ground plane for MPAs and as reflector for dipole antennas. The electrical properties of the different parts of the cell were established. The proposed antennas have been evaluated numerically with the electromagnetic simulator CST Microwave Studio and experimentally verified for different orientations of the front silver lattice of the solar cell. The influence of the different orientations of the solar cell were thoroughly studied with the analysis of currents, electric fields, impedance and radiation properties, providing a solid analysis for future development of different solar antennas based on poly-Si solar cells.

In Chapter 6 the radiation performance of a material that is both optically transparent and electrically conductive, comprising a clear polyester film coated with nano-layers of metal oxides, was evaluated on the glass cover of an amorphous silicon thin film solar module. Even though a number of transparent antennas had been previously studied, gain data was not reported or was between 5 and 10 dB lower than its copper counterpart, and therefore of no practical use, due to the inherent low conductivity of the transparent film. In the structure presented in this chapter a total transparent antenna is used for the first time in combination with a solar panel. A proximity coupled feed configuration and perspex superstrate is used for improved performance, providing a gain of 3.9 dBi, just 1.85 dB below its copper equivalent.

An innovative technique illustrating how emitter-wrap-through rear contact solar cells can be used as a folded dipole antenna which is located in the focal line of a parabolic solar concentrator, to provide high solar efficiency as well as high antenna gain, is presented in Chapter 7. This represents a unique multifunctional approach to solar antenna design, where the solar cells connected in series act both as radiating element and for power generation, and the metallic solar concentrator is simultaneously reflector for the dipole. The solar concentration increases the flux on the solar cell’s surface, thus reducing the amount of PV material required, and the antenna
reflector functions allows for improved gain, exceeding 11 dBi at 3.5 GHz.

Solar antennas incorporated into building facade will experience diurnal temperature variation. Chapter 8 characterizes for the first time the influence of solar heating on the radiation properties of a solar antenna, in this case, a MPA with polycrystalline silicon solar cell as ground plane. The study compares experimental device performance for MPAs printed on three commercial laminates with different thermal coefficients of the dielectric constant, and suggest which materials should be employed in this type of integration to avoid performance degradation under prolonged insolation.

Chapters 9 gives conclusions and outlines possibilities for future work. A novel idea for the use of bifacial solar cells as a frequency selective surface is proposed given the periodicity of the silver grid contacts, and the lack of homogeneous rear metalization, following the principle of operation of a wire grid polariser. This technology used in front of a radiating element would power the antenna system and at the same time, the frequency selective behaviour may help to reduce the constraint on the transceiver’s filter.
2. BACKGROUND ON MICROSTRIP AND DIPOLE ANTENNA TECHNOLOGY

The aim of this chapter is to introduce the fundamental antenna parameters and antenna structures used in this thesis, namely, microstrip patch antennas and dipoles. The fundamental antenna parameters are covered in the first section. The second section describes the microstrip antenna structure and feed techniques. This is followed by an introduction to dipole antennas.

2.1. Fundamental Antenna Parameters

2.1.1. Radiation Pattern

According to the IEEE Standard Definitions of Terms for Antennas [82] an antenna radiation pattern (or antenna pattern) is defined as a mathematical function or a graphical representation of the radiation properties of the antenna as a function of space coordinates. In most cases, the radiation pattern is measured in the far-field region, on a sphere surrounding the antenna and it is represented in a 3- or 2-dimensional space as function of two angular coordinates (θ, φ) in a spherical coordinate system. The standard coordinate system used in this work is described in Figure 2.1.

Usually 2-dimensional cuts of the radiation pattern are plotted to visualize the two main planes of the pattern containing the direction of maximum radiation, elevation (E-plane) and azimuth plane (H-plane).
2. Background on Microstrip and Dipole Antenna Technology

2.1.2. Directivity and Gain

Both directivity and gain quantify how an antenna focuses radiated energy in a particular direction. The directivity ($D$) of an antenna is defined as the ratio of the radiation intensity in a given direction, to the radiation intensity averaged over all directions; the average radiation intensity being the total radiated power radiated by the antenna divided by $4\pi$ [82]. In this thesis we will normally refer to the directivity in the direction of maximum radiation.

$$D(\theta, \phi) = 4\pi \frac{\text{radiated power intensity}(\theta, \phi)}{\text{total radiated power}}$$

(2.1)

The realized gain of an antenna ($G$), which will be referred simply as “gain” in this thesis, is linearly related to the directivity measurement through the antenna radiation efficiency ($e$), which takes into consideration ohmic losses, dielectric losses and mismatch losses at the input terminals of the antenna [34]. In this thesis, if the direction of the gain is not indicated, the direction of maximum gain is assumed.
2. Background on Microstrip and Dipole Antenna Technology

Transmission Line \( Z_o \) Antenna

\[ Z_i = \frac{V}{I} \]

\[ Z_i(f) = R_i(f) + jX_i(f) \]

\( X_i(f) = 0 \), resonant antenna

\[ G(\theta, \phi) = e^D(\theta, \phi) \quad (2.2) \]

The gain is usually expressed in dBi as an improvement over a theoretical isotropic antenna which has equal radiation in all directions.

2.1.3. Input Impedance

An antenna must be connected to either a transmitter that provides the energy to radiate or to a receiver where the arriving energy is processed. This is made through a feeding circuit, usually a transmission line for which the antenna is seen as a load, as seen from Figure 2.2. \( Z_o \) is the impedance of the feeding transmission line. The feeding transmission lines used in this work are designed to have a characteristic impedance of 50 \( \Omega \) to match the coaxial cable coming from the transmitter/receiver which in this case is the \textit{Rohde & Schwarz ZVB24} Vector Network Analyser (VNA) [83, 84] operating at that impedance.

The input impedance \( Z_i \) can be defined as the ratio of voltage to current at the antenna terminals. It has a real part \( R_i(f) \), and an imaginary part \( X_i(f) \), both of which are frequency dependent.
2. Background on Microstrip and Dipole Antenna Technology

2.1.4. \( S_{11} \) Parameter and Bandwidth

If the load impedance (i.e. the antenna) \( Z_l \) differs from the characteristic impedance \( Z_o \) of the transmission line, a fraction of the voltage will be reflected, as shown in Figure 2.3.

The \( S_{11} \) parameter of the scattering matrix is equivalent to the reflection coefficient \( \Gamma \), and it can be calculated as [34]

\[
S_{11} = \frac{Z_l - Z_o}{Z_l + Z_o}
\]  

A perfect impedance match would be indicated by \( S_{11} = 0 \), that is when \( Z_l = Z_o \). In this state, the power transmission between antenna and source is maximal. The worst impedance match is given by \( S_{11} = -1 \) or 1, corresponding, respectively, to a short or an open circuit as the load impedance.

The \( S_{11} \) parameter at the input of the antennas under test (AUT) is measured with a Rohde & Schwarz ZVB24 Vector Network Analyser (VNA) [83, 84] and represented as a magnitude in dB,

\[
S_{11}(dB) = 20 \log_{10} |S_{11}|.
\]  

The \( S_{11} \) is related with the return loss RL and the reflection coefficient \( \Gamma \),

\[
RL(dB) = -S_{11}(dB) = -20 \log_{10} |\Gamma|.
\]
The antenna impedance bandwidth BW can be defined between two frequency limits between with the $S_{11}$ dB remains below an acceptable value. A value of $-10$ dB is commonly used. With respect to power, that means that 90% of the input power is sent and only 10% is reflected back. The fractional bandwidth of an antenna is given by

$$%BW = \frac{2(f_u - f_l)}{f_u + f_l} \times 100\%$$

where $f_u$ and $f_l$ are the upper and lower frequency limits.

### 2.1.5. Polarization

The polarization of the wave radiated by an antenna is the property of the electromagnetic wave that describes the time varying direction of the electric-field vector, specifically, the figure traced as function of time by the extremity of the vector at a fixed location is space, as observed along the direction of propagation [82]. Antenna polarization indicates the polarization of the radiated wave of the antenna in the far-field region and it is typically measured in the direction of maximum radiation. When the radiated electric-field vector follows a line, the antenna is linearly polarized. If it follows a circle, it is circularly polarized (either with a left hand sense or right hand sense). Any other orientation is said to represent an elliptically polarized antenna. The antennas developed for this thesis are all linearly polarized.

To determine the gain and the radiation pattern of the antenna, a reference antenna of known gain was selected to be a Standard Gain Horn antenna (SGH) [85] in the measurement setup described at the end of this chapter. We will refer to the co-polar component of the radiation pattern to the radiation obtained when both antenna under test (AUT) and SGH are polarized in the same plane. The cross-polar component is the result of measuring the radiation pattern of the AUT with the SGH’s electric field oriented orthogonal to that of the AUT. Ideally, the AUT cross-polar com-
ponent should be as low as possible. We would consider it acceptable for the antennas investigated in this work to have cross-polar discrimination higher than -15 dB because that means the 97% of the spurious cross-polar component of incident electromagnetic field is rejected.

2.1.6. Wavelength

Wavelength ($\lambda$) is the distance in the space travelled in the interval of time corresponding to one cycle of a wave. The wavelength $\lambda$ (m) of a sinusoidal waveform (at it is an electromagnetic wave) travelling at a constant speed ($v$) is given by [86],

$$\lambda = \frac{v}{f} \tag{2.7}$$

where $v$ (m/s) is the speed of propagation (magnitude of the phase velocity), and $f$(Hz) is the frequency.

The speed of a wave depends upon the medium in which propagates. In the case of electromagnetic radiation in free space the speed $v$ is the speed of light in free space $c_0$, about $3 \times 10^8$ m/s.

There is an inherent relation between antenna dimensions and the frequency it is able to radiate/receive and actually most antennas are often made to be about one quarter or half wavelength [34]. Accordingly, as the size of the antenna increases (wavelength $\lambda$ increases) the frequency $f$ decreases. If the antenna size is less than $\lambda/4$, then the antenna efficiency may be reduced but various miniaturisation techniques can be used to improve performance [87].

2.2. Microstrip Patch Antennas

In its most basic form, a microstrip patch antenna (MPA) consists of a very thin ($d_{cu} \ll \lambda_0$, $\lambda_0$ being the free space wavelength) radiating metallic patch (normally copper) on one side of a dielectric substrate with a thickness
2. Background on Microstrip and Dipole Antenna Technology

The microstrip antenna is composed of a dielectric substrate, a patch, and a ground plane. The patch thickness $d_{cu}$ is generally a small fraction of a wavelength ($0.003\lambda_0 < d_{sus} < 0.05\lambda_0$), and a continuous metal layer bonded to the opposite side of the dielectric substrate acting as ground plane for the radiofrequency (RF) signal [34, 88] as seen in Figure 2.4. The microstrip patch is designed so its maximum radiation is normal to the patch (broadside radiator). This is accomplished by properly choosing the mode (field configuration) of excitation beneath the patch through the appropriate feeding system [88].

Although the patch can take almost any possible shape, square, rectangular and circular are the most common because of simplicity of analysis and their attractive radiation characteristics, especially low cross-polarization radiation [34, 88]. A rectangular MPA is illustrated in Figure 2.4. The radiating patch is usually photo etched on common circuit board laminates [89]. The radiation occurs primarily because of the fringing fields between the patch edge and the ground plane.

MPAs are in general half-wavelength structures and are operated at the fundamental resonant mode $TM_{01}$ or $TM_{10}$. Based on the cavity model approximation [88], the fundamental or first resonant frequency of the rectangular patch with a thin substrate as presented in Figure 2.4 is inversely proportional to the substrate thickness.
2. Background on Microstrip and Dipole Antenna Technology

proportional to the patch length ($l_p$) and the square-root of the dielectric constant ($\varepsilon_r$) of the substrate, with an approximated value given by,

$$f_{01} = \frac{c_0}{2l_p\sqrt{\varepsilon_r}}$$  \hspace{1cm} (2.8)

where $c_0$ is the speed of light in free space. Analyses are available that introduce the effects of the substrate thickness ($d_{sus}$), the patch width ($w_p$), and the copper thickness ($d_{cu}$) [88].

Microstrip antennas are inherently narrowband, with typical bandwidths in the range of 2 – 4% of the centre frequency. They can be used to satisfy the special requirements of certain applications by properly selecting the feed method, the thickness and dielectric constant of the substrate, and various techniques such as the use of coplanar parasitic elements [88], slot loading technique [90], and stacked elements [44].

2.2.1. Feeding Techniques

A coaxial cable with characteristic impedance ($Z_o$) of 50 $\Omega$ [91] is the most widespread transmission line used to feed an antenna. The actual connection of the coaxial cable to the laminate where the MPA is printed is usually done with an SMA connector grounded to the ground plane metal layer of the MPA. From there, the energy from the inner connector of the SMA can be transferred to the radiating patch by different methods [92].

These can be classified into contacting methods, where the RF power is fed directly to the radiating patch using a connecting element such as the SMA coaxial probe itself or a microstrip line, and non-contacting methods where the power transfer is done by electromagnetic field coupling between microstrip feed line and radiating patch.

Three of the most popular feed techniques are described below: the coaxial probe, the microstrip line (both contacting schemes), and proximity coupling (non-contacting scheme).
2. Background on Microstrip and Dipole Antenna Technology

![Diagram of Coaxial Probe Fed Microstrip Patch Antenna]

**Figure 2.5.** Coaxial probe fed microstrip patch antenna with patch length $l_p$, patch width $w_p$, patch thickness $d_{cu}$ and thickness of the substrate $d_{sus}$.

### Coaxial Probe Feed

The coaxial feed or probe feed is a very common technique used for feeding microstrip patch antennas where the inner conductor of the coaxial SMA connector extends through the dielectric and is connected to the radiating patch, while the outer conductor is connected to the ground plane as seen in Figure 2.5. The feed probe can be placed at any appropriate location inside the patch in order to match with its input impedance [34, 88].

This type of feeding was not selected to feed any of the antenna structures presented in this work as it would necessitate the perforation of the solar cell when used as ground plane. Such perforation would impair the operation of the solar cell.

### Inset Microstrip Line Feed

In this type of feed technique, the inner conductor of the SMA connector is attached to a conducting strip (feed line) generally etched on the same substrate as the radiating patch as shown in Figure 2.6. The conducting strip is smaller in width as compared to the patch, typically designed to
match the $50\,\Omega$ impedance of the coaxial cable. The purpose of the inset feed as seen in Figure 2.6 is to match the impedance of the feed line to the patch without the need for any additional matching element. This is achieved by properly controlling the inset position [92].

This feeding scheme provides ease of fabrication and simplicity in modelling. However, as the substrate size increases, surface waves and spurious feed radiation also increase and can lead to undesired cross polarized radiation [34, 88]. This type of feed was implemented in the antennas proposed in Chapter 3 and Chapter 8.

**Proximity-Coupled Feeding**

This is also called the electromagnetic coupling scheme. As shown in Figure 2.7, two dielectric substrates are used such that the feed line is between the two substrates and the radiating patch is on top of the upper substrate.

This scheme allows the choice of two different dielectric media, one for the patch and one for the feed line to optimize the individual performances. Normally a thinner substrate is used for the feed and a thicker one for the patch in order to achieve increased gain. This feed technique eliminates spurious feed radiation and provides very high bandwidth (as high as 13%) [44, 88]. It also provides several degrees of freedom for matching/tuning.
2. Background on Microstrip and Dipole Antenna Technology

![Proximity coupled fed microstrip patch antenna](image)

**Figure 2.7.** Proximity coupled fed microstrip patch antenna with patch length \( l_p \), patch width \( w_p \), patch thickness \( d_{cu} \), thickness of lower substrate \( d_{slow} \) and thickness of the upper substrate \( d_{sup} \).

However, there is an increase in the overall thickness of the antenna, which can be a drawback for some applications. This feed scheme is used for the transparent antenna of Chapter 5.

### 2.3. Dipole Antennas

A dipole antenna is a radiating element that can be made by a simple wire, straight or curve, with a feedpoint usually in the centre. The “dipole” gets its name from a Greek word meaning “two poles”, which obviously refers to the two parts of the antenna, one on each side of the fed element somewhere in the middle, in contrast to a “monopole” antenna which is made of a single element usually fed against ground [34, 93]. The feed element is often in the centre of the wire, configured in a symmetrical fashion with two equal-length arms. There are also versions of dipoles that are not centre-fed [93].

The centre-fed \( \lambda/2 \)-long dipole is a fundamental type of antenna that is electrically a little bit less than \( \lambda/2 \) if the operating frequency is \( f = c/\lambda \). It is by far the most widely used type of dipole because it is relatively easy to construct, match and has high radiation efficiency. It is also a basic
building block for many other antenna systems, including beam antennas such as the popular Yagi Antenna [30, 93].

The solar antenna structure presented in Chapter 4 and Chapter 6 will involve a centre-fed \( \lambda/2 \)-long dipole and a folded dipole respectively. These two types of dipoles and the balun structure needed to feed them from an unbalanced transmission line are introduced in the following subsections.

### 2.3.1. Centre-Fed Half-Wave Dipole

A centre-fed half-wave dipole consists of a two quarter wavelength conductors placed in a symmetric fashion and extended in opposite directions from the feed point as depicted in Figure 2.8. It has been experimentally verified that the current in a centre-fed wire antenna has sinusoidal form with nulls at the end points [34, 93]. This is coherent with the theory of transmission lines, where a standing wave on an element of a approximately \( \lambda/4 \) length yields the greatest voltage differential, as one end of the element is a node while the other is an antinode of the wave [91]. So for a total length \( l = \lambda/2 \), the current amplitude reaches a maximum at the centre [34] as seen in Figure 2.8a. The larger the differential voltage at the centre feed point, the greater the current flow between the elements. Assuming a sinusoidal distribution, the current impressed by this voltage differential can be approximated by [34],

\[
I = I_0 e^{j\omega t} \cos(kz) \tag{2.9}
\]

where \( I_0 \) is the maximum current amplitude, \( \omega = 2\pi f \) (rad/s) is the angular frequency, \( k = 2\pi/\lambda \) is the wave number, and \( z \) a spatial coordinate along the dipole \((-1/2 \leq z \leq 1/2)\).

For the case of the far-field, the formula for the electric field of the radiating electromagnetic wave in free space emitted by the centre-fed half-wave
2. Background on Microstrip and Dipole Antenna Technology

Figure 2.8. Centre-fed dipole antenna: (a) ideal layout and (b) horizontal printed implementation.

A dipole can be approximated by [34, 35],

$$E(\theta, r) = \frac{-j I_0}{2 \pi \varepsilon_0 c_0 r} \frac{\cos(\pi/2 \cos \theta)}{\sin \theta} e^{j(\omega t - kr)}$$

being \((\theta, r)\) coordinates of the spherical system and \(\varepsilon_0\) the permittivity of vacuum.

The resulting radiation pattern is slightly flattened doughnut-like torus [34], as can be seen from Figure 5.4(b).

For free space, the theoretical input impedance of a physically half-wave long dipole antenna made of an infinitely thin conductor is \(Z_i = 73 + j 42.5 \, \Omega\). This antenna, exhibiting both resistance and reactance is slightly long electrically compared to the length necessary for exact resonance, where the reactance is zero. A small segment of wire can be therefore cut away them from the original length \((0.5 \times \lambda)\), until the reactance vanishes (at approximately \(0.48 \times \lambda\)), leading the dipole to resonance [34, 93]. This also provides an almost ideal match for widely used 50Ω transmission lines. The input impedance of the dipole, and therefore the matching and resonant frequency, is affected by the wire radius, the feed gap, and the presence of metallic objects like reflectors in the near field [34, 93], as it will be seen in the next subsections.
2. Background on Microstrip and Dipole Antenna Technology

Effect of Wire Radius and Feed Gap

The input resistance does not change significantly for different wire radii, but the input reactance slightly increases as the wire diameter gets thicker [34, 93], so a larger segment from the \( \lambda/2 \)-length dipole has to be removed to achieve resonance. A broadening of the impedance bandwidth is also observed with the increasing thickness of the wire.

The gap spacing at the feed does play a significant role. The input reactance, for a fixed wire diameter increases with increase of the feed gap. This means that, for a given length of the dipole, the resonant frequency decreases with increasing feed-gap. This effect is more pronounced as the wire diameter gets thicker [34, 93].

Effect of a Conductor Plane below a Horizontal Half-Wave Dipole

The presence of a metallic reflector near the dipole also affects the input impedance: it is decreased as the dipole gets closer to the reflector [94]. Other aspects of the radiation characteristics (pattern, gain, efficiency) of a half-wave dipole horizontally placed above a conductor plane change with the distance dipole-reflector. When the metallic reflector is at a \( \lambda/4 \)-distance from the dipole, the reflected electric field interference is additive, and therefore enhanced gain and maximum radiation is achieved in the direction normal to the reflector plane [34, 94] as it can be seen from Figure 5.4(a).

2.3.2. Folded Dipole

A folded dipole is a variation of the single dipole element, where the two ends of the dipole arms are connected with an additional wire forming a thin rectangular loop \( s < 0.05\lambda \) as shown in Figure 2.9. When \( l_d = \lambda/2 \), impedances in the order of about 300\( \Omega \) are achieved, which is ideal for
connections to “twin-lead” transmission lines, widely used for TV applications [34, 93, 95].

The input reactance of the folded dipole antenna varies less rapidly with frequency changes away from resonance than a single wire antenna. Therefore, it is possible to operate over a wider range of frequencies while maintaining a low $S_{11}$ on the line compared with a simple dipole. This is partly explained by the fact that the two conductors in parallel form a single conductor of greater effective diameter [93, 95].

2.3.3. Baluns

In a perfectly operating balanced two-terminal system like a centre-fed dipole, or a transmission line like a twisted pair or a stripline, we have a symmetrical system consisting of two conductors of the same type, each of them carrying equal and opposite currents, as well as having equal impedances to the ground along their lengths. On the other hand, in an unbalanced system such as the coaxial cable or a microstrip line, there is a significantly different voltage from each conductor to the ground. Actually, in a perfectly working coaxial line one terminal (the shield) has zero voltage to the outside world, that is, it is the ground, even while the currents there and in the inner conductor are equal and opposite. In a perfectly working coaxial line, the current on the centre conductor is balanced by an
equal but opposite flowing current on the inner surface of the outermost shield [34, 91, 93].

Figure 2.10 shows what happens when a centre-fed dipole is fed directly with a coaxial cable (inherent unbalance transmission line). Currents $I_1$ and $I_2$ from the transmitter flow on the inside of the coax ($I_1$ flows on the outer surface of the coaxial’s inner conductor and $I_2$ flows on the inner surface of the shield, both having equal magnitudes but 180° out of phase with respect to each other). The currents flowing on the antenna itself are labelled $I_1$ and $I_4$, and both flow in the same direction at any instant in time for a resonant half-wave dipole. On Arm 1 of the dipole, $I_1$ is shown going directly into the centre conductor of the feed coaxial. However, on the other side of this dipole once current $I_2$ reaches the end of the coaxial, it will split into two: $I_4$ going directly into Arm 2 of the dipole and $I_3$ flows down the outer surface of the coaxial shield. $I_3$ (also called common-mode current) not only causes an imbalance in the amount of current flowing in each arm of the otherwise symmetrical dipole, but it also radiates by itself. This imbalance in the dipole will cause a distortion in the radiation pattern and a modification of the input impedance [93]. In order to avoid this undesired effect, we need a special type of electrical arrangement called a
“balun” (balanced-to-unbalanced) in between in order to balance the termination of an unbalanced transmission line like a coaxial or a microstrip line, connected to a balanced antenna like a centre-fed dipole.

The balun used in Chapter 5, a quarter-wave open balun implemented in microstrip technology, is a variation of the classical quarter-wave coaxial balun or so-called Pawsey stub [34, 93], adapted particularly to balance our horizontal microstrip dipole [96] from the feeding microstrip line, using the solar cell as ground plane.

For the case of the folded dipole presented in Chapter 7, a split-coaxial-balun [97] was selected. This has the advantage of being implemented directly on the outer shell of the feeding coaxial, while also providing the 4:1 impedance transformation needed to match the 50 Ω impedance of the coaxial cable to the high input impedance of the folded dipole.

2.4. Modelling and Simulation

The design and analysis of an antenna requires both extensive calculations and the fabrication and measurement of prototypes. Until the second half of the 20th century, the design of antennas was based mainly in a trial and error operation, and the built of many prototypes was needed until the desired performance was achieved, with the consequent increase in the production costs. The underlying electromagnetic equations governing the behaviour of antennas was at that time either poorly known or too complex to be manually calculated. With the advances made in computer architecture during the second World War, the calculation power of the machines started to be enough to support the computation of numerical methods. These numerical methods would be applied to approximate efficiently the Maxwell equations, either in its integral or differential form, and therefore to evaluate the exact current, electric and magnetic field distribution for a given antenna geometry and given electrical properties of the materials.
involved \cite{98}. Furthermore, the development of computer aided design (CAD) technology \cite{99} made it easier to input and modify complex antenna geometries.

Integral equation solvers such as the Method of Moments (MoM) has become very popular since the 1980s. It expands the currents in an antenna in a linear sum of simple basis functions, making the approximate solutions a finite series of these base functions. The coefficients are then computed by solving integral equations to satisfy boundary conditions on the surface of the antenna. Because it requires calculating only boundary values, rather than values throughout the space, it is quite efficient in terms of computational resources for problems with a small surface/volume ratio. Conceptually, it works by constructing a “mesh” over the modeled surface \cite{100}.

However, for many problems, this method is significantly less efficient than volume-discretization methods like the Finite Element Method (FEM) or the Finite Integration Technique (FIT), which are differential equation solvers \cite{101}. The store requirements and computational time for the boundary element formulations like MoM tend to grow according to the square of the problem size. By contrast, the storage requirements for the system matrices in the finite element methods like FEM and FIT typically grow linearly with the problem size.

CST Microwave Studio (MWS) \cite{102,103} is the commercial electromagnetic design software used for the design, modelling and optimization of the antennas presented in this work. It provides a computer aided design (CAD) environment to create antenna geometries, define materials, surrounding space properties and excitation sources. The MWS solver is based on the Finite Integration Technique (FIT) which was first proposed by Weiland in 1977 and has been enhanced continually over the years \cite{104}. Results can be visualised and postprocessed in various different ways. Most used in this work are plots of S-parameter information, farfield pattern, electric fields as well as surface currents.
2. Background on Microstrip and Dipole Antenna Technology

2.4. Measurement Setup

In order to obtain accurate and repeatable measurement of the antennas developed in this thesis, a partially anechoic chamber was set up in the Antenna and High Frequency Research Centre (AHFR Centre) of the Dublin Institute of Technology [105], in order to obtain accurate and repeatable measurement of the antennas developed in this thesis. The setup comprises of the Antenna Under Test (AUT) and a Standard Gain Horn antenna (SGH) in a partially anechoic chamber. The Antenna Under Test (AUT) is mounted on top of a fibreglass mast which is mounted on a turntable positioner. The turntable allows for 360° rotation. Both antennas are connected to a Vector Network Analyser and a PC is connected to control the turntable and the network analyser. Software has been developed to control both devices and automate the measurement.

The anechoic chamber is ideally free of reflections, which otherwise could impair the accuracy of the measurements. The absorbing material used in this chamber is Emerson\&Cuming Eccosorb VHP-18 pyramidal carbon loaded urethane foam absorber of 45 cm height [107], placed in strategic positions on the walls, where first order reflections occur between the antenna under test and the standard gain horn. By absorbing energy that would otherwise be reflected of the walls it is ensured that radiation...
occurs mainly in the line of sight.

The Vector Network Analyzer (VNA) used to evaluate the performance of the prototypes is a Rohde & Schwarz ZVB24 [83, 84]. The VNA allows wave quantities to be displayed in terms of S-parameters or Smith Charts, as well as a range of options for postprocessing, scaling and visualisation of measured data. It can be remote controlled by a PC connected to the Ethernet port. All functions of the analyser are available to the PC via the remote control protocol RSIB [83]. This feature allows for complete automation of the radiation pattern measurement.

To calculate the gain of the Antenna Under Test, a reference antenna of known gain has to be used in the measurement. The system uses a Standard Gain Horn (SGH) from Schwarzbeck covering from 800MHz to 18 GHz [85]. The gain of the AUT can be calculated then from the distance between the antennas and the known gain of the horn using Friis transmission formula [34] which can be written as

\[
(G_{AUT})_{dB} = 20 \log_{10} \left(\frac{4\pi R}{\lambda}\right) + 10 \log_{10} \left(\frac{P_r}{P_0}\right) - (G_{SGH})_{dB}
\] (2.11)

where \(P_0\) and \(P_r\) are the transmitted and received power, \((G_{SGH})_{dB}\) is the known gain of the SGH and \(R\) is the distance between the antennas.

In accordance with the IEEE Standard Test Procedures for Antennas [108], the antenna under test is positioned at the centre of a spherical coordinate system. The measuring point is at a fixed distance \(R\) from the AUT. This makes the radiation pattern only dependant on the two angular coordinates \(\theta\) and \(\phi\). The coordinate system is shown in Figure 2.1. In the chamber, the reference horn is fixed and the AUT is rotated by the positioner. The positioner can only rotate around one axis. In order to obtain the two principal cuts of the radiation pattern, the AUT has to be mounted in a different orientation for each cut. To measure co-polar and cross-polar components, the horn has to be rotated by 90° in order to align the linear
polarisation plane of the horn with the desired polarization plane of the
AUT. In order to get a complete set of radiation patterns, six measurements
are necessary.

Control software was developed to automate measurements and guide
the user through the steps necessary to obtain accurate results. The soft-
ware helps with the initialisation of the system, calibration, measurement
setup and gives hints for mounting the AUT and SGH. After all measure-
ment steps have been completed successfully, the software automatically
computes the gain using the Friis transmission formula (Equation 2.11)
and plots the pattern data in spherical contour plots. This allows for quick
assessment of the results. Raw data is stored in tabular format in Excel files
for further processing.
3. Background on Solar Cell Technology

In this thesis four different solar cell technologies are considered for integration with antennas, namely, polycrystalline silicon (poly-Si) solar cell, monocrystalline silicon (mono-Si) emitter-wrap-trough solar cell (EWT), amorphous silicon (a-Si) thin film on glass substrate, and bifacial solar cells. The aim of this chapter is to review the main features of different solar cell technologies.

The photovoltaic effect is explained in section 3.1. The energy loss mechanism in a solar cell, the concept of energy conversion efficiency, multi-junction solar cells and light concentrators are covered in section 3.2. The technology behind wafer based crystalline silicon solar cells, both mono-Si and poly-Si is presented in section 3.3. Section 3.4 introduces the bifacial solar cell technology, and back-contact solar cell structures are described in section 3.5. Thin-film solar cells are explained in section 3.6 and finally section 3.7 briefly presents emerging new photovoltaic technologies like dye-synthesized and organic solar cells.

3.1. The Photovoltaic Effect

A semiconductor solar cell in its most basic form consists of one p-n junction and back and front metallic electrodes, as depicted in Figure 3.1. The electrode exposed to light is generally metallic thin grid, usually made of silver (Ag), thin enough to let the maximum amount of light reach the
silicon beneath, but at the same time with enough density as to keep the series resistance fairly low. The back contact is a homogeneous metallic layer, usually made of aluminium (Al).

A p-type semiconductor is obtained by doping it with a certain type of atoms in order to create an abundance of holes. In the case of silicon, the material used to create the vast majority of the solar cells, the doping element has to be a trivalent atom, typically boron (B) or aluminium (Al), that would be substituted into the silicon lattice, creating in result one “missing electron” (hole) from one of the four covalent bonds normal for the silicon lattice. An n-type semiconductor is the result of doping a pure intrinsic semiconductor material with atoms capable of providing extra conduction electrons to the host material, such as phosphorus (P) for the silicon [109].

By joining together p-type and n-type semiconductors in very close contact, a boundary depleted of carriers is formed in the p-n junction, as can be seen in Figure 3.2. This “depletion zone” occurs because the electrical charge carriers in doped n-type and p-type (electrons and holes respectively) attract and eliminate each other in a process called recombination. This phenomena leaves positively charged ions in the n-region and negative charged ions in the p-region. The diffusion process that tends to generate a larger depletion zone is opposed by the electric field created by this space charge region itself, so equilibrium will be reached where the electric field separating the two sides, cancels the diffusion forces [13, 109].
When a photon strikes a solar cell, it can be reflected, it can simply pass through the cell as if it were transparent, or it can be absorbed. The absorption occurs when the photon hits and transfers its energy to an electron that would then be able to abandon its normal position in the valence-band of the atom, and “jump” to the conduction-band, where it is able to move freely. By leaving its position in the valence band, the electron causes a hole, in what is called “electron-hole” generation \[109\]. If this happens in the depletion zone, in the range of influence of the electric field generated there by the p-n junction, the electron will be pushed to the n-side, and the hole to the p-side, and they eventually can reach the metallic contacts of the cell, to be driven through an external circuit to an external load (such as a light bulb) as shown in Figure 3.1.

In order to induce electron-hole generation, the photon needs to have enough energy to make the electron overcome the energy “bandgap” separating the valence and conduction band. The energy of this band gap determines what portion of the solar spectrum a particular photovoltaic cell absorbs depending on the semiconductor from which the solar cell is made. For example, at 300 K the energy band gap for crystalline Silicon (c-Si) is around 1.1 eV, 1.7 eV for amorphous silicon (a-Si), 1.74 eV for selenium (Se), 0.67 eV for germanium (Ge) and 1.43 eV for gallium arsenide (GaAs) \[13,109,110\].
3.2. Energy Loss in a Solar Cell and Energy Conversion Efficiency

A solar cell’s energy conversion efficiency is the percentage of the incident solar radiation power that is converted into electrical power by the solar cell, when connected to a circuit. As shown in section 3.1, of all the radiant solar energy incident on a solar cell, only photons with enough energy to “activate” the electrons in the semiconductor are used. When this occurs, there is a surplus of photon energy (with energy exceeding the band gap) that will be transformed into heat rather than into electrical energy. These two effects alone can account for the loss of about the 70% of the radiation energy incident in the cell leading to a theoretical maximum level of efficiency that is around the 30% for a single junction crystal silicon solar cell [8]. This means that from an irradiance of 1,000 W/m² (typical peak insolation value on a clear day [13]), only a maximum of a 300 W/m² will be used.

In addition to that, there are optical losses, such as the shadowing of the cell surface due to the front metal electrode, the front covering glass, or reflections of the incoming rays on the cell surface. Furthermore, not all the generated electron-hole pair reaches the metal electrodes of the cell. The electrical resistance in the semiconductor (crystal defects, material contamination, badly designed p-n junction with long distances to reach the contacts), and the resistance of the ohmic contact with the external electrodes also account for losses.

A summary of the research solar cell efficiencies to date published by the National Renewable Energy Laboratory (NREL, USA) [111] [112] can be seen in Figure 3.3.
3. Background on Solar Cell Technology

Figure 3.3. Best research solar cell efficiencies up to date ([112]).
3. Background on Solar Cell Technology

3.2.1. Multiple-Junction Solar Cells and III-V Compound Semiconductors

A way to circumvent the theoretical maximum efficiency given by Shockley and Queisser [8] are the multiple-junctions (also called tandem or stacked) solar cells. These cells consist of several layers of different semiconductors, arranged one on top of the other, each type of semiconductor having different characteristic band gap energy, carefully chosen to absorb nearly all the solar spectrum [13, 113, 114]. Mostly, the semiconductors chosen to be part of these structures are III-V compounds based on arsenides and phosphides like GaAs, Ge and GaInP [14, 115]. Space remains the main application of these solar cells, as the cost of the device is a minor concern compared to efficiency and reliability [116, 117]. With a maximum efficiency of 41.6%, multiplejunction solar cells are currently the most efficient solar cells [114]. On earth, these materials are primarily being investigated for employment in conjunction with solar concentrators.

Solar Concentrators

Light concentrators are a way to “boost” solar power. By increasing the light intensity, typically more photogenerated carriers are created, resulting in increased efficiency [109, 118]. They are believed to have a great potential to reduce the costs of solar generated electricity using optical devices such as plane mirrors, Fresnel lenses and imaging and non-imaging parabolic reflectors [63, 118, 121], as well as non-optical devices such as luminescent concentrators [122], to collect solar light and concentrate it on a single small area of solar cell. This light concentration boosts the solar cell conversion efficiency and reduces the total cell area an amount proportional to the concentration ratio. Therefore, the cost of the PV system can be decreased by replacing the expensive semiconductor material with a relatively inexpensive solar concentrator. Optical concentrators have inherent
3. Background on Solar Cell Technology

limitations as to the amount of diffuse insolation collected. Luminiscent concentrators can theoretically overcome this limitations \cite{122}.

Both III-V compound semiconductors and silicon based solar cells are being investigated for use with light concentrators, generally implemented in back-contacted structures, with the front surface devoid of any metallization \cite{123}, as it will be seen in Section 3.5.

3.3. Wafer Based Crystalline Silicon Solar Cells

In 1959 Hoffman Electronics created a commercial single crystal silicon solar cell with 10% efficiency. They introduced the use of a grid front contact, significantly reducing the solar cell’s series resistance \cite{124}. Crystal silicon wafer based solar cells continue to be the dominant technology for terrestrial applications today, accounting for more than 80% of the solar cell market \cite{13, 125}.

Two types of crystalline silicon (c-Si) are used in the industry. The first is mono-crystalline silicon (mono-Si), also called single-crystalline, and produced by slicing wafers (typically 200 – 300 mm diameter, and 200 – 400 µm thick) from a high-purity single crystal cylindrical ingot obtained with methods for crystal growth like the Czochralski (CZ) or Float-zone silicon (FZ-Si) processes \cite{13, 125, 128}. The second is the poly-crystalline Silicon (poly-Si), also known as multi-crystalline, made by sawing a cast block of silicon into bars and then wafers with size in the same range of those mono-Si solar cells \cite{13, 129, 130}.

Standard c-Si solar cells in their basic form consist of a front metallization (cathode), usually a grid of thin parallel metallic lines that transport the current to somewhat thicker bus bars. These are the result of a trade-off between having low coverage to limit optical losses and high coverage to limit resistive losses. The bus bars are relatively wide and can be used as solder pads to connect to the external leads. The emitter (usually $n^+$-doped
3. Background on Solar Cell Technology

**Figure 3.4.** Cross section of standard wafer based crystalline silicon solar cell.

Silicon (n-type) is collocated immediately beneath, to provide smooth electrical interface to the front metallization which collects the electrons generated in the internal p-n junction due to the incident photons. The back side (positive polarity) of these conventional cells is not exposed to solar radiation; it is usually fully covered with a homogeneous aluminium-alloyed junction [13], as seen in Figure 3.1 and Figure 3.4.

A key step in increasing the efficiency of crystal silicon solar cells up to 15% came with the introduction of the back-surface-field (BSF) structure in the 1970’s. In the conventional single p-n junction cells used before, the minority carrier recombination velocity at the back surface was very high due to ohmic contact. The addition of a homopolar low-high (L-H) junction near the back surface of the solar cell results in a much lower recombination velocity, and therefore a higher conversion efficiency [131]. Such improvements have been obtained for both n^+ p− p^+ [132] and p^+ n− n^+ [133] BSF solar cell structures. BSF structures on crystalline silicon continue to be today’s prevalent structure. The introduction of the passivation of the cells with silicon nitride in the 1980’s [134] and the later incorporation of the front texturing of the wafers in the 1990’s has produced solar cells with conversion efficiencies exceeding 19% for polycrystalline (also known as multicrystalline) silicon (poly-Si or multi-Si) wafers and 24% for monocrystalline silicon (mono-Si) [135].
Solar cell efficiencies for single-junction crystalline Si solar cells have been increasing very slowly since then as the maximum theoretical limit of around 30% is approached [8]. Poly-Si and Mono-Si solar cells continue to be today the predominant technology for power plants and building façade. Best research cell efficiencies achieved so far for poly-Si and mono-Si are 20.4% and 24.7% respectively [111, 112, 128, 136, 137]. But commercial solar cell efficiencies are significantly lower, around 12%-15% for poly-Si and 18-20% for mono-Si [138–140].

In Chapter 4 and 5 a 13.5% efficient standard polycrystalline solar cell from Solland [141] is used as ground plane for a microstrip patch and as reflector for a dipole antenna, respectively.

### 3.4. Bifacial Solar Cells

Bifacial solar cells are sensitive to light in both sides due to the lack of the rear side complete metallization. A novel promising use for this type of solar cells as a frequency selective surface in radio communication applications is proposed as future work in Chapter 9. In the next subsections the two predominant technologies for producing bifacial cells are introduced.

#### 3.4.1. BSF Bifacial Solar Cells

Today’s prevalent bifacial solar cell structure are Back Surface Field (BSF) solar cells on crystalline silicon having a homopolar p-p+ or n-n+ on the opposite surface where the heteropolar p-n junction is as shown in Figure 3.5a. This technology has seen a progressive increase in its efficiency since the first approaches at the end of the 1970s. These first experimental devices had an efficiency of just 7% [142]. The subsequent incorporation of pyramidal texturing of the wafers and buried contacts has produced front and rear efficiency exceeding 19% and 15% respectively [143, 144]. The passivation of the cells with silicon nitride [145, 146] reported efficiencies exceeding 20%.
Figure 3.5. (a) Cross section of Back Surface Field bifacial solar cell and (b) Front and rear metallic finger grid electrodes.

The above described BSF cells are usually implemented in crystalline Si wafers with a thickness of \( \approx 200 \mu \text{m} \) \[147, 148\]. The contact grid metallization is typically a mirrored image for front and rear side and composed of several thin parallel finger electrodes and two perpendicular busbars as shown in Figure 3.5b, that can be buried \[144\] or carried out by screen printing and co-firing using an Ag paste \[147, 148\]. The fine finger electrodes have a width of 110 \( \mu \text{m} \) or less and the busbar electrode is at least 10 times wider than that of the finger electrode (1 to 3 mm) \[149\]. The spacing between the Ag fingers can generally vary for BSF cells between 2 mm and 2.6 mm \[148–150\].

3.4.2. Sliver Solar Cells

Sliver cells are truly bifacial as they respond equally well to light on either surface. For applications facing the dark on one side, a white rear reflective layer formed at the back side of the module, allows collection of 70% of the light that passes through the gaps. Efficiencies exceeding 18.5% have been demonstrated for this technology \[151, 152\].

The recent Sliver cell technology uses a series of individual thin solar
3. Background on Solar Cell Technology

![Diagram of solar cell technology](image)

Figure 3.6. Two Sliver strips in transparent encapsulate film.

Cells (typically 0.5 – 2 mm wide, 50 – 120 mm long and 20 – 200 µm thick) connected in series and spaced in such way that there is a gap between cells generally equal to their width or up to about 1.5 times the width of the cell, so only maximum half of the module is covered with the cells [151][152]. The silicon strips are micro-machined from mono-Si wafers, and prepared as individual working cells where, on the contrary of conventional cells, their electrical contacts are along the two long edges, as shown in Figure 3.6.

3.5. Back-Contacted Solar Cells

As we have seen in Section 3.2.1, concentrating solar energy onto a photovoltaic material can drastically reduce the solar cell area required per peak watt output. However, standard solar cell structures have both contact metallization in both front and rear side to extract the current, and they do not perform efficiently under the high illumination intensities of the concentrators, among other things due to the shadowing of the contacting fingers in the illuminated surface. Furthermore, the conventional way of interconnecting cells by soldering highly conductive tabs to the front and rear of neighbouring cells leads to a very restrained manufacturing process [123].

Schwartz proposed the first back-contacted solar cell in 1975 in order
to overcome the before mentioned issues \[153\]. Back-contacted solar cells have both positive and negative contact pads on the rear side, so the illuminated surface is devoid of any metallization. Besides, moving all interconnection circuitry to the rear of the module allows for the build-up of the contacting fingers to a thickness which reduces the series resistance of the contacting structure to low values, and for optimized module efficiency by increasing the packing density of the cells \[154\].

Back-contacted solar cells are divided into three main classes: back-junction (BJ), emitter wrap-through (EWT) and metallization wrap-through (MWT) \[123\]. The contact wrap-through or metallization wrap-through (MWT) back-contact cell is the concept that is most closely linked to the conventional cell structure. In these cells, the emitter is located near the front surface, but part of the front metallization grid is moved from the front to the rear surface \[123, 155\]. In the emitter wrap-through (EWT) cell concept, the front surface is void of any metallization. Whereas the emitter is still located near the front surface, all contacts are on the rear surface. The connection between the active emitter near the front surface and the emitter contacts on the rear surface is provided by extending the emitter in the walls of holes in the substrate \[123, 156, 157\]. Finally, in the back-junction cell concept (BJ), the emitter is no longer located near the front surface, but together with the contacts moved to the rear surface \[123, 158\].

These three technologies refer to different structural embodiments of the metallization, emitter and base contacts of the solar cells, but can be implemented on different semiconductor materials. The use of back-junction cells with high quality monocrystalline silicon \[157, 159, 160\] is common, but it is also found with polycrystalline silicon \[158\], thin-film silicon \[161\] as well as in multijunction solar cells based on III-V compounds for the bottom cell \[162\]. Their efficiency will depend to a large extend to these materials.

In Chapter 7 mono-Si EWT solar cells are combined with a parabolic through solar concentrator. A cross-sectional representation for this solar cell structure can be seen in Figure \[7.1\]
3.6. Thin-Film Technology

The second generation of photovoltaic materials is based on the use of thin-film deposits of semiconductors, such as amorphous silicon (a-Si), cadmium telluride (CdTe), copper indium gallium diselenide (CIGS) or copper indium sulphide (CIS) [11]. Thin film technologies appear as one of the most promising ways to achieve economical competitiveness of photovoltaics and nowadays account for the 18% – 20% of the market share [12].

The selected materials are all strong light absorbers and only need to be about 1 µm thick, so material costs are significantly reduced. Low-cost backing materials such as ordinary window glass, or alternatively thin, flexible substrates such as metal or polymer foils allow highly automated roll-to-roll deposition processes and the production of large-area modules at once, with potential for additional cost savings [11, 163, 164]. Although the efficiencies of thin film solar cells tend to be lower compared to conventional solar cells, it is anticipated they will increase from current 6% – 12% to 10% – 15% in the upcoming years [165]. Furthermore, thanks to the lower manufacturing cost the price in terms of $/W of electrical output can be reduced [166].

Amorphous silicon (a-Si) is the most developed of the thin film technologies [11, 12]. The deposition and connection of the a-Si thin film is an integrated process where deposition steps are alternated with laser scribing in order to create a series of thin strip-shaped solar cells [167, 168]. In Chapter 6 a module with a-Si thin film technology deposited on glass will be used.
3. Background on Solar Cell Technology

3.7. Emerging PV

A third generation of photovoltaic cells have emerged and are being developed nowadays that do not use the p-n junction. These approaches include dye-synthesized \[13, 169\] and organic solar cells \[170, 171\] among others.

Some consider that these cells will offer lower manufacturing costs in the future because of their simplicity and use of cheap materials. The challenges of scaling up, manufacturing and demonstrating reliable field operation of products lie ahead. The best research efficiencies achieved so far with these technologies is of 11.1\% \[112, 172\] for dye-synthesized solar cell and 9.7\% \[112, 173\] for a organic solar cell.
4. **Polycrystalline Silicon Solar Cell as Ground Plane for MPA**

Various configurations have been suggested recently to address the integration of antennas and solar cells in a multifunctional compact device, as reported in Section 1.4. In a previous approach a metal microstrip ground plane was substituted by silicon standard solar cells underneath a printed microstrip reflect-array of thin crossed-dipoles for an 8.5 GHz horn-reflector antenna \[81\]. This configuration indicates that the implementation of a solar cell based microwave ground plane for a printed antenna is highly feasible and leads to a significant reduction in footprint. Nevertheless, the results of this development showed an impaired RF efficiency that was attributed to difficulties in characterizing the electrical properties of the micron-scale features of the solar cell which is acting as an inhomogeneous ground plane, and the consequent limitation to antenna performance.

Standard polycrystalline silicon (poly-Si) solar cells are available with solar energy efficiencies (>12%) which approach those of monocrystalline silicon (mono-Si) (>15%) but with a considerably lower cost as described in Section 3.3. In this chapter the implementation of a poly-Si solar cell as a microwave ground plane for a 2.2 GHz microstrip square patch antenna is investigated. The inhomogeneous nature of the poly-Si solar cell as microstrip ground plane is characterized in the first section. The second section presents the proposed microstrip patch solar antenna design and both measured and simulated radiofrequency (RF) characteristics are analyzed in sections three, four and five.
4. Polycrystalline Silicon Solar Cell as Ground plane for MPA

4.1. Inhomogeneous Ground Plane

A standard polycrystalline silicon (poly-Si) solar cell from Solland [141], with dimensions 156 mm × 156 mm × 0.26 mm was selected to be used as the ground plane for a printed microwave microstrip antenna. The photosensitive poly-Si wafer is partially masked on the front side by a cathode lattice of silver (Ag) electrodes with orthogonal bus bars and it interfaces with a homogeneous aluminium (Al) anode layer on the rear side. The combination of the anisotropic structure of the Ag-lattice, the doped silicon and the homogeneous Al back contact layer make up an inhomogeneous ground plane for the antenna when compared with the homogeneous metal ground plane conventionally used for microstrip antennas.

For a conventional half-wave microstrip patch design, the resonant electric near-fields radiate from the antenna feed edge, and opposite edge, to the ground plane through the substrate as seen in Section 2.2. The orientation of the anisotropic Ag-lattice, as shown in Figure 4.1, with respect to the electric near-fields, was anticipated to be significant to the integrated radiating performance. The electric field flux lines from radiating edges of the truncated substrate patch are typically parallel with the microstrip feed which is used as an orientation reference. To interpret the impact of the inhomogeneous conducting ground plane below the truncated FR-4 substrate; the antenna feed line was aligned (1) parallel with the Ag electrode lines, (2) perpendicular with the Ag electrode lines, (3) simulated over Si without the Ag-lattice and (4) contrasted with a homogeneous copper (Cu) ground plane.

Measurements were carried out with a Reichert-Jung MeF3 metallurgical microscope to establish the solar cell layer dimensions. A photo of the transversal section of the solar cell is shown in Figure 4.2. On the upper surface, the cathode Ag-lattice layer is 13 µm thick and it comprises 57 electrodes with a line width of 0.1 mm and separation of 2.64 mm respectively, and two orthogonally oriented bus bars that are 2 mm wide and separated...
4. Polycrystalline Silicon Solar Cell as Ground plane for MPA

Figure 4.1. Photo of the developed solar MPAs showing the Ag-lattice electrode alignment with the microstrip feed line: (a) parallel and (b) perpendicular.

by 74.2 mm. On the rear side the solar cell is covered with a thin homogeneous aluminium layer of thickness 36 µm that functions as anode. In between the lattice and the aluminium, a n$^+$ – p – p$^+$ doped poly-Si wafer of about 205 µm thickness is responsible for the inherent electrical potential in the cell when illuminated. The overall solar cell thickness is of 0.0254 cm as it can be derived from Figure 4.3.

The n$^+$ – p – p$^+$ doped regions of the poly-Si substrate were modelled with a bulk permittivity $\varepsilon_r = 15.3$ and conductivities were set in proportion to the ambient light intensity and temperature of the laboratory, 1.4 W/m$^2$ and 293 K respectively. The conductivity values used in simulation are $\sigma = 254,383$ S/m for the light exposed area of the silicon and $\sigma = 310$ S/m for the area in the silicon shaded due to the FR-4 printed antenna [174].

4.2. Antenna Design

The structure, shown in Figure 4.3, comprises a printed microstrip patch antenna (MPA) on single-sided FR-4 substrate, of height $d_{sus} = 1.52$ mm,
$\varepsilon_r = 4.2$, and $\tan\delta = 0.02$ with a $50\,\Omega$ inset feed line in order to avoid piercing the brittle solar cell. It can be observed that the spare substrate around the microstrip patch was eliminated to reduce shade over the cell. The SMA port is grounded to the Al layer of the solar cell. In order to minimize light shadow on the solar cell, the FR-4 substrate is truncated at the edges of the antenna features. The square patch dimensions are $l_p = w_p = 33.6\,\text{mm}$ and the feed-inset parameters of $l_i = 9\,\text{mm}$ and $w_i = 3\,\text{mm}$. The $3\,\text{mm}$ wide feedline has a $61.6\,\text{mm}$ length in order to place the patch over the centre of the poly-Si cell. Patch and feed arrangement shadow is 13.2% of the solar cell area.

The poly-Si solar cell is an inhomogeneous ground plane for the printed microstrip patch. It is depicted in Figure 4.3 as a three layered structure comprising front silver lattice, silicon and aluminium. Fracturing the brittle poly-Si solar cell was prevented by supporting the integrated structure on a $1.52\,\text{mm}$ FR-4 dielectric layer.
4.3. Impedance Characteristic and Gain Results

The proposed antenna has been evaluated numerically with the electromagnetic simulator CST Microwave Studio based on finite integration method [102–104] and experimentally verified. Figure 4.4 shows the simulated and measured $S_{11}$ parameter for both parallel (Para-Ag) and perpendicular (Perp-Ag) orientation of the antenna feed line with respect to the Ag electrodes, for the homogeneous copper (Cu) ground plane, as well as the simulated $S_{11}$ of the patch directly placed over the Si, without the Ag-lattice (Si-No-Ag). Great agreement is achieved.

The homogeneous ground plane reference is resonant at 2.276 GHz and exhibits a $-10\,\text{dB}$ matched bandwidth of 2.42%. In contrast, a Si ground plane with parallel Ag electrode lines tunes lower to 2.190 GHz. The corresponding bandwidth is 3.11%. Similarly, the perpendicular Ag electrode lines produce an even lower resonance at 2.168 GHz and an increase in bandwidth to 3.13%.

Both simulated and measured results for the four configurations are illustrated in Figure 4.5. The gain of the proposed antennas at resonance was found to be 2.60 dBi for the structure with the homogeneous ground plane (Cu), 1.23 dBi for the one with Ag electrode lines parallel (Para-Ag) to the
Figure 4.4. Simulated and measured $S_{11}$ for the solar MPA configurations.
Figure 4.5. Simulated and measured Gain (dBi) for the solar MPA configurations.

feed line and 1.05 dBi in the case of Ag electrodes perpendicular (Perp-Ag). Table 4.1 is a summary comparison of the simulated and measured antenna $S_{11}$ and gain.

The reductions in gain and the increases in matched bandwidth manifested in the configurations with solar cell as ground plane are evidence for increased losses due to the Si properties.

Table 4.1. Simulated and measured antenna parameters for various MPA configurations.

<table>
<thead>
<tr>
<th>Integrated Configuration</th>
<th>Frequency (GHz)</th>
<th>$-10$ dB Bandwidth (%)</th>
<th>Peak Gain ${\theta = 90^\circ}$ (dBi)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Simulated</td>
<td>Measured</td>
<td>Simulated</td>
</tr>
<tr>
<td>Cu</td>
<td>2.274</td>
<td>2.276</td>
<td>2.43</td>
</tr>
<tr>
<td>Para-Ag</td>
<td>2.190</td>
<td>2.190</td>
<td>3.13</td>
</tr>
<tr>
<td>Perp-Ag</td>
<td>2.169</td>
<td>2.168</td>
<td>3.30</td>
</tr>
<tr>
<td>Si-No-Ag</td>
<td>2.160</td>
<td>n/a</td>
<td>3.40</td>
</tr>
</tbody>
</table>
4.4. Electric Field Vector Analysis

The electric field flux lines radiated from the microstrip antenna patch edges are typically parallel with the microstrip feed line which is used as an orientation reference. This electric field originates from microwave surface currents along its direction on the homogeneous metallic ground plane implemented in ordinary microstrip antennas. The performance of printed antennas over solar cell ground planes will largely depend on the disruption of the microwave surface-currents by the photovoltaic component. When the front parallel Ag-lattice electrode lines are in line with the current flow, the antenna performance is closer to that of the antenna with homogeneous copper as ground plane. Although the perpendicular lines are normal to the current flow, the modes are supported because the periodicity of the lines, \( d = 2.64 \text{ mm} \), is much less than the radiated wavelength, \( \lambda_a = 138 \text{ mm} \), but the reductions in gain and the increases in matched bandwidth are evidence for increased losses due to the Si properties.

Figure 4.6 taken from the CST simulations, shows the Electric Field Vector in the silicon layer of the cell for both parallel and perpendicular orientation of the lattice. While both Ag-lattice orientations mitigate energy lost in the Si, the perpendicular orientation provides the least isolation and so the simulations show a stronger electric field penetrating into the lossy silicon. Similarly, the Si permittivity increases the effective dielectric loading for the patch and the resultant downward shift in resonant frequency shown in the previous section is more notable for the perpendicular Ag-lattice case. Although measurements were not possible, the simulated removal of the Ag-lattice from a solar cell ground plane indicates that additional energy would be lost in the Si layer.
Figure 4.6. Electric field vector in the silicon for (a) parallel and (b) perpendicular Ag-lattice of solar MPA.
4. Polycrystalline Silicon Solar Cell as Ground plane for MPA

The E- and H-plane radiation patterns for each of the Ag-lattice orientations are shown in Figure 4.7. While the parallel and perpendicular orientated poly-Si solar cell ground planes lose small amounts in peak gain values, the radiation patterns are similar to the homogeneous Cu case. Cross-polarization isolation values exceeding 20 dB on boresight are observed for both orientations of the Ag-lattice. The similar gain patterns for each of the measured planes and provisional modeling indicates that circularly polarized antennas would perform well provided the periodicity of the Ag-lattice layer is much smaller than the radiated wavelength.
4.6. Conclusion

The feasibility of using poly-Si solar cells as ground plane for common inset-fed microstrip square patch antennas is demonstrated. The performance of the PV antenna was similar to the ideal conventional antenna with copper as a ground plane but with a slight decrease in gain and increase in bandwidth. The reduction in gain is attributed to increased conductivity losses due to the semiconductor properties of the silicon. The anisotropic electrode lattice of silver mitigates some of the losses when the antenna polarization is suitably aligned. Because the microstrip is low-profile, it provides a promising and low-cost method of integration of PV and antennas for applications in autonomous communications systems in building façades.
5. **Polycrystalline Silicon Solar Cell as Reflector for Dipole Antenna**

The use of polycrystalline silicon (poly-Si) solar cells as a ground plane for microstrip antennas was investigated in Chapter 4 on a single 156 mm × 156 mm cell developed by Solland. Since the radiating element above the solar cell obstructs the incident light, thus reducing the solar cell efficiency, reduced size antennas are more desirable for the integration. The dipole provides the least possible shadow over the solar cell because of its thin profile [34, 93]. In this chapter, the performance of poly-Si silicon solar cells as reflectors for dipole antennas is investigated. The studies were validated with the fabrication of a novel solar antenna design using a printed dipole with an integrated balun.

### 5.1. Inhomogeneous Reflector Surface

The use of a metallic reflector structure behind a dipole antenna is a common technique used to achieve enhanced directivity and gain. If the distance between the reflector and the dipole is approximately a quarter-wavelength, direct and reflected electric fields are in phase and maximum gain is achieved in the broadside direction [34].

The full-wave integral-equation based electromagnetic simulator CST Microwave Studio [102,104] was used to analyse the behaviour of a poly-Si solar cell as a reflector surface for a half-wave dipole antenna in comparison
5. Polycrystalline Silicon Solar Cell as Reflector for Dipole Antenna

![Diagram of dipole antenna with solar cell as reflector]

**Figure 5.1.** Simulated half-wave ideal dipole antenna with poly-Si solar cell as reflector. (a) Side perspective view of the structure with Ag-lattice parallel alignment and dimensions $l_{\text{cell}} = 156$ mm, $l_d = 62$ mm and separation from the dipole to the solar cell $s_d = 30$ mm. (b) Front view for Ag-lattice perpendicular alignment.

with a copper reflector of the same dimensions. The proposed dipole is 62 mm in length with a 1 mm radius and a 3 mm feed gap at its centre for a targeted resonant frequency of around 2 GHz. A plot of the simulated configuration with solar cell as reflector is shown in Figure 5.1. The solar cell selected in this study is of the same nature and dimensions as in Section 4.1, that is, a 156 mm $\times$ 156 mm $\times$ 0.26 mm poly-Si solar cell from [Solland 141]. Compared to the homogeneous metallic structures that are normally used as reflectors for dipole antennas, it was seen in Section 4.1 that this poly-Si solar cell is a hybrid combination of silver grid cathode (Ag-lattice), doped silicon and the aluminium anode on the rear side. On the upper surface, the 57 thin parallel electrodes of the Ag-lattice can be aligned parallel or perpendicular to the electric field radiated by the dipole, which is directed along the dipole itself, and that is used as an orientation reference, as depicted in Figure 5.1.
5.1.1. Current Analysis

Simulations of the radiofrequency (RF) induced current distribution in the conductive parts of the solar cell have been made for both parallel and perpendicular orientations of the Ag-lattice with respect to the radiated field, and are presented as density of arrows in Figure 5.2 for the Ag-lattice itself, and as density contour plot in Figure 5.3 for the back aluminium contact layer.

The electric field radiated by a centre-fed half-wave dipole is linearly polarized and directed along the dipole. Therefore, the currents induced in metals due to the influence of this electric field will tend to flow linearly following the same direction that the electric field. It can be observed in Figure 5.2(a) that for the parallel orientation of the Ag-lattice the current flows smoothly along the parallel thin silver front electrodes, reaching the maximum intensity in the region placed directly below the dipole. For the case of perpendicular orientation of the Ag-lattice with respect with the dipole, and therefore, with respect with the radiated electric field, the front electrodes disrupt the natural flow of the current, which results in the circulation of the current around the perimeter of the thin electrodes, and penetration of the electric field into the lossy silicon towards the aluminium layer. The non linear circulation of the currents in the perpendicular case is evident from Figure 5.2(b). From Figure 5.3(c) it can be seen that the penetration of the electric field for the perpendicular case induces a strong current density in the rear aluminium layer, almost as much as the the current induced in a copper reflector (Figure 5.3(a)). For the parallel case seen in Figure 5.2(a), the electric field is already reflected to a large extended in the front silver grid, where the currents are free to move naturally, and therefore the penetration of the electric field into the lossy silicon towards the aluminium is minimal (Figure 5.3(b)) when compared with the perpendicular case (Figure 5.3(c)).
5. Polycrystalline Silicon Solar Cell as Reflector for Dipole Antenna

For parallel orientation of the Ag-lattice, current intensity is maximal directly below the dipole. Current flows smooth along the thin silver electrodes, aligned with the electric field radiated by the dipole.

For perpendicular orientation of the Ag-lattice, currents are disrupted of their natural flow and circulate around the perimeter of the thin front electrodes.

Figure 5.2. Simulated RF current density in the front Ag-lattice of the cell for (a) parallel and (b) perpendicular orientation.
Figure 5.3. Simulated RF current density as a contour plot in (a) copper reflector and (b) aluminium layer of the poly-Si solar cell for parallel and (c) perpendicular orientation of the Ag-lattice.
5.1.2. Simulated Radiation Pattern with Ag-Lattice as Reflector

The effect of the front Ag-lattice as reflector for the dipole, excluding the other layers of the solar cell, was considered in simulations to gain more knowledge on the internal operation of the poly-Si solar cell as an inhomogeneous reflector surface. For comparison reasons, Figure 5.4 shows the simulated radiation pattern of the half-wave dipole both over a homogeneous copper surface of the same size as the Solland [141] poly-Si solar cell under study, and the classic doughnut shaped radiation pattern of a half-wave dipole without reflector in free space [34].

For the radiation patterns depicted in Figure 5.5 only the 57 thin parallel silver lines (0.1 mm width, 13 µm thickness) of the Ag-lattice were considered. It is observed that the radiation pattern over the structure aligned in parallel to the dipole’s radiated electric field is very similar to that of the homogeneous copper seen as reference in Figure 5.4 while for the perpendicular orientation the pattern resembles that of a dipole in free space.

Finally the complete Ag-lattice (57 thin parallel electrodes plus two orthogonal 2 mm width bus bars) is considered for simulation. It can be
derived from Figure 5.6 that the effect of the two orthogonal bus bars is minimal for the case of the parallel orientation, while it partially reflects the fields in the case of the perpendicular orientation.

5.1.3. Simulated Impedance Bandwidth and Gain

A summary of the resonant frequency, bandwidth and gain obtained with the simulation of the structure shown in Figure 5.1 with the poly-Si solar cell as reflector for an ideal half-wave dipole can be seen in Table 4.1. Comparing these results with those of the microstrip patch with the same poly-Si solar cell as ground plane presented in Chapter 4, we can derive that a dipole with solar cell as reflector not only significantly reduces the shading of the cell, but also provides an important increase in gain and a larger bandwidth.

Furthermore, for the microstrip antenna placed directly over the poly-Si solar cell the difference in the alignment of the front Ag-lattice was enough to cause a shift in frequency and a degradation of gain. In the case of the dipole spaced a quarter-wavelength from the solar cell, the two different orientations of the front silver lattice result in the same performance
Table 5.1), and very close to that of an ideal copper reflector. Key factor for this behaviour is that, even if the front Ag-lattice does not behave as a perfect reflector by itself as seen from Figure 5.5 and Figure 5.6, the distance to the homogeneous rear aluminium layer of the solar cell can be considered negligible when compared to the distance of the dipole to the solar cell.

**Table 5.1.** Summary of simulated antenna parameters for half-wave dipole (1 mm radius, 62 mm length) with copper reflector and both parallel and perpendicular orientation of polar-Si solar cell.

<table>
<thead>
<tr>
<th>Reflector Configuration</th>
<th>Frequency (GHz)</th>
<th>$-10$ dB Bandwidth (%)</th>
<th>Peak Gain ${\theta = 90^\circ}$ (dBi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>2.060</td>
<td>6.2</td>
<td>9.06</td>
</tr>
<tr>
<td>Para-Ag</td>
<td>2.062</td>
<td>6.4</td>
<td>9.06</td>
</tr>
<tr>
<td>Perp-Ag</td>
<td>2.068</td>
<td>6.4</td>
<td>9.05</td>
</tr>
</tbody>
</table>
5.2. Printed Dipole with Integrated Balun and Poly-Si Solar Cell as Reflector

The simulation analysis undertaken in Section 5.1 for an ideal half-wave dipole antenna suggests that the use of a poly-Si solar cell as reflector will give a large improvement in gain and bandwidth when compared to the microstrip antenna of Chapter 4, while providing a considerable reduction in shadow of the radiating element over the solar cell. Furthermore, when compared with a copper reflector, the two possible different orientations of the front Ag-lattice of the cell result in the same performance.

In this section, the prototyping of a dipole antenna with poly-Si solar cell as reflector is described. This encompasses the design of the printed dipole antenna along with a feed system with integrated balun to balance the current in the dipole arms. The impossibility of creating a hole in the brittle solar cell complicates this design.

5.2.1. Antenna Design

The geometry of the proposed printed dipole solar antenna and microstrip balun is shown in Figure 5.7. The radiating element consists of a half-wave dipole with length \( l_d = 47 \text{ mm} \), width \( w_d = 5 \text{ mm} \) and feed gap of \( g = 3 \text{ mm} \), printed on an FR4 substrate of thickness \( d_{sus} = 1.52 \text{ mm} \), \( \varepsilon_r = 4.2 \), and \( \tan\delta = 0.015 \).

A detailed diagram of the printed dipole and the balun is shown in Figure 5.7b. One of the arms is fed by a vertically bent continuation of the feed microstrip line. The other arm is shorted from an offset distance of \( s_x = 2.5 \text{ mm} \), down to the solar cell via a stripline carefully adjusted to achieve a better dipole antenna performance.

A 50 \( \Omega \) microstrip line with solar cell as RF ground plane connects the dipole with the SMA connector. CST Microwave Studio was used for the full wave optimization of the proposed solar antenna.
5. Polycrystalline Silicon Solar Cell as Reflector for Dipole Antenna

Figure 5.7. (a) Exploded layout of the proposed printed dipole solar antenna and (b) detailed geometry of the dipole and integrated balun. The design parameters are $d_{sus} = 1.52 \, \text{mm}$, $l_d = 47 \, \text{mm}$, $w_d = 5 \, \text{mm}$, $g = 3 \, \text{mm}$, $w_t = 3 \, \text{mm}$, $w_s = 10 \, \text{mm}$, $s_x = 2.5 \, \text{mm}$ and $s_d = 24 \, \text{mm}$.
The solar cell in this real structure is acting both as reflector for the dipole and RF ground for the microstrip feed and balun, so again the two possible orientations of the silver lattice were considered anyway to see if this will make a difference in the solar antenna performance. A picture of the prototypes can be seen in Figure 5.8.

### 5.2.2. Impedance Characteristic and Gain Results

The simulated and measured $S_{11}$ of the printed dipole antenna of Figure 5.1, for both parallel (para-Ag) and perpendicular (perp-Ag) orientation of the poly-Si solar cell, as well as for an homogeneous copper (Cu) reflector, are shown in Figure 5.9. A comparison of resonant frequency, impedance bandwidth and gain is summarized in Table 5.2. It can be seen there is a reasonable agreement in the frequency of resonance for both the dipole with copper reflector and the structures with solar reflector around the 2.34 GHz frequency. The peak gain at boresight exceeds 8 dBi for the three models considered. A small decrease in gain was found for the integrated solar structures when compared with the reference antenna with copper reflector. This deviation and the observed discrepancy in impedance bandwidths are attributed to the non-ideal balun performance, especially when shorted to the Ag-lattice of the solar cell.

<table>
<thead>
<tr>
<th>Integrated Configuration</th>
<th>Frequency (GHz)</th>
<th>$-10$ dB Bandwidth (%)</th>
<th>Peak Gain ${\theta = 90^\circ}$ (dBi)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Simulated</td>
<td>Measured</td>
<td>Simulated</td>
</tr>
<tr>
<td>Cu</td>
<td>2.347</td>
<td>2.346</td>
<td>13.4</td>
</tr>
<tr>
<td>Para-Ag</td>
<td>2.339</td>
<td>2.323</td>
<td>15.8</td>
</tr>
<tr>
<td>Perp-Ag</td>
<td>2.348</td>
<td>2.346</td>
<td>13.1</td>
</tr>
</tbody>
</table>

**Table 5.2.** Summary of simulated and measured parameters for microstrip dipole antenna with copper reflector and both parallel and perpendicular orientation of poly-Si solar cell.
5. Polycrystalline Silicon Solar Cell as Reflector for Dipole Antenna

Figure 5.8. (a) Perspective view of the solar dipole antenna for parallel orientation of the Ag-lattice and (b) front view of the solar dipole antenna for perpendicular orientation of the Ag-lattice.
5. Polycrystalline Silicon Solar Cell as Reflector for Dipole Antenna

Figure 5.9. Simulated and measured S_{11} for the dipole with poly-Si solar cell as ground plane. Comparison of copper reflector with two possible orientations of the Ag-lattice.
Figure 5.10. Measured radiation patterns for the dipole antenna with poly-Si solar cell as reflector. Co-polar and cross-polar components for both E-plane and H-plane.
5. Polycrystalline Silicon Solar Cell as Reflector for Dipole Antenna

5.2.3. Radiation Properties

The E- and H-plane radiation patterns for the dipole antenna with reflector for both Ag-lattice orientations of the solar cell and the arrangement with copper reflector are shown in Figure 5.10. Some distortion was found for the case of the printed microstrip dipole with integrated balun and the solar cell as reflector for both parallel and perpendicular orientation of the Ag-lattice.

5.3. Conclusion

The use of a poly-Si solar cell as reflector for a half-wave dipole antenna was investigated in this chapter. The simulation of the dipole antenna ideally fed with a discrete port was undertaken to establish a reference performance of such structure and to analyse the behaviour of the different conductive layers of the solar cell. These simulation results show a performance independent of the orientation of the poly-Si solar cell with respect to the dipole, and very close to that of an ideal copper reflector.

The dipole antenna with poly-Si solar cell as reflector was then prototyped. This involved the design of a microstrip feed system with integrated balun for the dipole. The measured results suggest that the fabrication of a high gain and large bandwidth solar dipole antenna is feasible, while only shading a 3.7% of the solar cell area. The three fabricated solar antennas for both orientations of the Ag-lattice and a model with copper reflector showed a similar resonant frequency and a peak gain exceeding the 8 dBi. This suggests that performance is independent of the orientation of the silver lattice as seen from the previous simulation work with an ideal dipole, although a small reduction in peak gain was found in the measurement when compared with the copper prototype. This is attributed to the non-ideal performance of the balun when shorted to the Ag-lattice. To avoid drilling a hole in the brittle solar cell, the design of the balun became quite
5. Polycrystalline Silicon Solar Cell as Reflector for Dipole Antenna

complex, resulting in an imperfect operation that created some distortion in the measured impedance bandwidth and radiation pattern.
6. Transparent Antenna on Amorphous Silicon Thin Film Module

Electrically conductive materials used for microwave antennas are typically metals which are opaque to visible light. Fortunately, materials that are both optically transparent and electrically conductive have been developed by coating clear polyester sheets with nano layers of metal oxides [175-178] or carbon nanotubes [178-180].

A number of transparent antennas have been studied which show promising characteristics, but gain data was not reported [181-184]. More recent work reports significantly lower gain for transparent antennas compared to their copper counterparts; a transparent PIFA fabricated on a sheet of resistivity 20Ω/sq yielded approximately 10 dB lower gain at 2.4 GHz [185], and planar monopole UWB antenna on AgHT-4 reported 5 dB lower gain due to the inherent low conductivity of the transparent film [186].

This chapter presents a novel approach to solar antennas by mounting an optically transparent square microstrip patch made of AgHT-4 film on the surface of a glass cover of an a-Si thin film solar module. This post-manufacture technique considerably simplifies the integration process by placing the radiator on the glass of commercially available solar modules. Furthermore, the transparent patch is fed using an electromagnetic coupling technique in a two layer arrangement of glass-Perspex which provides improved gain when compared to reported transparent antennas.

The nature of the a-Si thin film solar module and the transparent con-
6. Transparent Antenna on Amorphous Silicon Thin Film Module

![Cross-sectional view of a-Si thin film on glass substrate](image)

Figure 6.1. Cross-sectional view of a-Si thin film on glass substrate

The conductive film used in the manufacturing of the proposed solar antenna is described in the first and second section. The antenna design is illustrated in the third section, and antenna gain, impedance properties and radiation characteristics are evaluated and compared with a copper patch counterpart in the fourth and fifth section. Finally, the sixth section discusses the power output.

### 6.1. A-Si Thin Film on Glass Substrate

A-Si thin film is deposited on glass substrate in a multilayered structure alternating the deposition of the front transparent conductive oxide (TCO) contact, the a-Si, and a back metal contact with the pattern mode by narrow laser scribes to create a series connection of thin-strip shaped solar cells [163, 167, 168] as seen in Figure 6.1.

The first layer of the thin film a-Si solar cell on glass is a TCO, typically ITO (indium tin oxide) or ZnO (zinc oxide), which will form the front electrode. The thickness of this layer is of a few hundred nanometres (from 50 nm up to 700 nm) [187, 188].

Then, the a-Si is deposited on a “p-i-n” structure, having usually an ultra-thin (about 0.008 μm) p-type top layer, a thicker (0.5 to 1 μm) intrinsic middle layer, and a very thin (0.02 μm) n-type bottom layer. The top layer is made so thin and relatively transparent that most light passes through it, to generate free electrons in the intrinsic layer. The p- and n-layers
produced by doping the amorphous silicon create an electric field across the entire intrinsic region, thus inducing electron movement in the i-layer [163, 168, 189, 190]. The back metal electrode, usually aluminium (Al), generally comprises a 200 µm thick layer [188, 190].

The a-Si solar panel used for the antennas presented in this chapter is a Solarex plate [191] of dimension 85 mm × 55 mm, comprising a series of 8 cells, providing a nominal output of 6.4 V and 54 mA (345.6 mW). The a-Si thin film solar cells are deposited on a 2.3 mm thick borosilicate glass with $\varepsilon_r = 6.4$ and a $\tan\delta = 0.02$ for the frequencies of interest.

### 6.2. AgHT-4 Transparent Conductive Film

The AgHT-4 optically transparent conductive film [176] used for the transparent radiator presented in this chapter comprises a 170µm thick clear polyester film with $\varepsilon_r = 2.8$ and $\tan\delta = 0.005$ [192], coated with a thin layer of titanium oxide and aluminium of less than 750 Ångström.

Optically transparent conductive films are required to meet a compromise between high transmission in the visible region (75% or more) and relatively “high” conductivity (less than 10 $\Omega$/sq of sheet resistance) [175]. The AgHT-4 film from CPFilms meets these requirements with a minimum visible light transmission (VLT) of 75% and $4.5 \pm 1 \Omega$/sq of sheet resistance.

### 6.3. Antenna Design

The proposed structure, designed for the 3.5 GHz frequency band, consists of amorphous silicon (a-Si) thin film solar cells, glass, Perspex and transparent AgHT-4 film layers as shown in Figure 6.2(a). The transparent 19 mm square AgHT-4 microstrip patch is centred on top of a clear Perspex substrate of thickness 3 mm. The Perspex electrical properties are $\varepsilon_r = 2.6$, $\tan\delta = 0.015$ and has an overall visible light transmission of 92%. The trans-
6. Transparent Antenna on Amorphous Silicon Thin Film Module

Figure 6.2. (a) Layout and (b) photo of the proposed transparent antenna with dimensions $w = 55$ mm, $l = 85$ mm, $l_p = 19$ mm, $w_{tx} = 1.8$ mm, $d_{per} = 3$ mm and $d_{sol} = 2.3$ mm.

Parent radiator is fed by an electromagnetically-coupled copper microstrip line, with a width of 1.8 mm for 50 $\Omega$ line impedance, placed directly beneath the Perspex substrate and attached to the glass substrate of the solar panel. The thin film a-Si solar cells are deposited on the back of the glass substrate. They are in the order of 3$\mu$m thick, and comprise a layered structure involving a transparent conductive oxide (TCO) front electrode, p-n silicon junctions, and an aluminium rear electrode as characterized in Section 1.1. A 50 $\Omega$ SMA port is connected to the copper transmission line and grounded to the metallic rear electrode of the solar panel, so the solar cells serve as ground plane for the microstrip antenna as well as providing its DC generation function. A photograph of the solar antenna is shown in Figure 6.2(b). The transparent radiator is substituted by copper of the same size for comparison purposes.
6. Transparent Antenna on Amorphous Silicon Thin Film Module

6.4. Impedance Characteristic and Gain Results

Figure 6.3 shows the measured and simulated $S_{11}$ and gain for the proposed transparent patch antenna, while Figure 6.4 shows the values for its copper counterpart. The measured return loss was found to be greater than 6 dB in the frequency range 3.390 – 3.850 GHz (460 MHz) for the transparent patch and 3.372 – 3.845 GHz (473 MHz) for the case of copper patch. This corresponds to a fractional impedance bandwidth (6 dB) of 12.7% and 13.1% for transparent and the copper patch, respectively. The measured gain for the transparent patch on the solar substrate was better than 2.5 dBi over the frequency range of 3.4 – 3.8 GHz with a peak value of 3.96 dBi. The values for the copper patch were better than 3.4 dBi across the band (with a peak of 5.81 dBi). Thus the difference in peak gain is 1.85 dB.

It is worth mentioning that, for the transparent antenna, the electro-magnetically-coupled copper line was replaced by a transparent film feedline and a peak measured gain of $-0.8$ dBi was obtained. An early attempt to employ the Solarex panel directly as a single-layer substrate (without Per-
6. Transparent Antenna on Amorphous Silicon Thin Film Module

Figure 6.4. Simulated and measured $S_{11}$ and gain for a-Si thin film antenna with copper patch.

spex and using copper microstrip feed) for the transparent patch resulted in a peak gain of $-2.5$ dBi, thus the combination of the Perspex and the proximity coupling are key in improving gain.

6.5. Radiation Properties

The measured E- and H-plane radiation patterns for the transparent solar antenna proposed in this chapter are compared in Figure 6.5 with those measured for the same solar arrangement but with a copper patch on top. The radiation pattern of the transparent antenna is clearly similar to that of the copper counterpart, and good symmetry was achieved. The measured cross-polar rejection is better than $-15$ dB for both planes.

6.6. Power Output

The output power of the solar antenna panel was measured while illuminated with 1,000 W/m$^2$ with a solar Griven INSE 1200 MSR metal halide
6. Transparent Antenna on Amorphous Silicon Thin Film Module

Figure 6.5. Measured radiation pattern for both copper and transparent antenna on a-Si thin film glass module. Co-polar and cross-polar components are for both E-plane and H-plane.

lamp to compare solar efficiencies of the transparent and copper configurations. If the output power of the solar panel by itself without the integration of the antenna arrangement is of 345.6 mW, the following reduction was found for each step or the integration: copper transmission line 0.56%, clear Perspex 6.2%, copper patch 6.5% and transparent patch 1.7%. Therefore, the use of the transparent film improves the solar efficiency by 4.8% when compared with the use of a copper patch.

6.7. Conclusion

A novel solar antenna with integrated transparent radiator was modelled, fabricated and tested for use in the 3.5 GHz band. The two-layer arrangement of amorphous silicon on a glass solar module and Perspex was used for integration with an electromagnetically-coupled transparent patch an-
tenna. The measured gain was better than 2.5 dBi across 3.4 – 3.8 GHz with a peak value of 3.96 dBi, which is 1.85 dB less than for a copper patch on the same Perspex/glass substrate. The integration enables a reduced footprint structure. The use of transparent film improves the solar efficiency by almost 5%.
7. PHOTOVOLTAIC DIPOLE ANTENNA WITH SOLAR CONCENTRATOR

A different approach of solar antenna design is presented whereby a solar concentrator is used as a reflector for a novel photovoltaic dipole antenna. Four identical Emitter-Wrap-Through (EWT) rear contact solar cells are connected in series forming a folded dipole and used simultaneously for power generation and as the antenna radiating element. A compact decoupling circuit integrated in the dipole feed gap is used to separate the RF and DC current. The EWT folded dipole is located in the focal line of a parabolic solar concentrator to increase the illuminated flux on the photovoltaic (PV) surface, thus reducing the amount of PV material required, and simultaneously acting as an antenna reflector. Full wave electromagnetic simulation with supportive experimental work validates this design.

The internal structure of an EWT back contacted solar cell is described in the first section. Its impedance at the microwave frequencies is measured and compared with a metal brass strip of the same size. The novel solar antenna structure with photovoltaic dipole and parabolic reflector is presented in the second section. The impedance antenna characteristics, gain values, and radiation properties are discussed in subsequent sections followed by power generation performance.
7. Use of EWT Rear Contact Solar Cell

Conventional crystalline and amorphous silicon solar cells used so far in solar antenna approaches have contact metallization on both front and rear sides to extract current as seen in Chapter 3. In the emitter-wrap-through (EWT) rear contact solar cells used for this design, the front surface is devoid of any metallization so that the complete cell surface is available for light absorption [123]. Even though the emitter is located near the front, both negative and positive polarity contacts are placed on the rear surface with the negative contact connected to the front through emitter wrapped holes as depicted in Figure 7.1.

Thus there is no fully covered metallization on any side in this type of cell, just an interdigitated structure with alternating positive and negative polarity metal fingers. The exact dimensions of this interdigitated structure is unknown due to the encapsulation, so the RF impedance has to be determined for the microwave frequencies of interest and compared with an homogeneous metal structure of the same size to validate the suitability of the solar cell to be integrated as part of a dipole antenna. For antenna ap-
7. Photovoltaic Dipole Antenna with Solar Concentrator

Applications the EWT solar cell must be as low loss as possible at microwave frequencies. Therefore the transmission coefficient of a single cell was measured over a 50 $\Omega$ transmission line and compared with a brass strip of the same dimension ($L = 40\text{ mm}$, $W = 3\text{ mm}$). The most robust setup was chosen after simulation analysis with CST Microwave Studio [102–104] to minimize the effect of sensitivity in the mechanical fabrication, and it is pictured in Figure 7.2.

The transmission coefficient $S_{21}$ was measured for both the solar cell and the brass strip. The results, presented in Figure 7.3, show that the behaviour of the solar cell and the brass strip is nearly identical. We can conclude that the EWT back contact solar cell, despite having both positive and negative DC polarity contacts in the same surface, acts like a metallic plate from an RF point of view over 1 – 3.5 GHz band. Furthermore good agreement is found when compared with the response of the simulated structure for a perfect electric conductor (PEC) strip. Accordingly, it is envisaged that the EWT solar cell properties are appropriate to act as conductive elements in a folded dipole.

7.2. Antenna and Solar Concentrator Design

The proposed folded dipole consists of four identical 40 mm x 3 mm rear contact solar cells interconnected in series as shown in Figure 7.4. The dimensions of the folded dipole arms are 85 mm and 82 mm with a feed gap of $g = 5\text{ mm}$. The spacing between the arms is $s = 4\text{ mm}$, and the connection gap in the folded arm is $s_c = 2\text{ mm}$.

A split-coaxial balun is implemented by introducing two identical slots of dimension $l_s = 45\text{ mm}$ and $w_s = 1.5\text{ mm}$ on opposite sides of the outer conductor of the semi-rigid Flexiform 402 NM 50 $\Omega$ coaxial line, as seen in Figure 7.5(a). A 4:1 impedance transformation is achieved with this balun by adjusting the length of the slot [97].
Figure 7.2. Experimental setup to analyze the S-parameter response of EWT back contacted solar cell, with dimensions $l_{ewt} = 40$ mm, $w_{ewt} = 3$ mm, and $s = 5$ mm.
Figure 7.3. Comparison of the measured transmission coefficient $S_{21}$ for EWT solar cell and brass strip, as well as for simulated PEC strip. The size for the three of them is $40 \text{ mm} \times 3 \text{ mm}$. 
Figure 7.4. Detailed view of the EWT solar folded dipole: (a) layout with dimensions $L_{ewt} = 40 \text{ mm}$, $W_{ewt} = 3 \text{ mm}$, $s_c = 2 \text{ mm}$, $g = 5 \text{ mm}$, $s = 3 \text{ mm}$, and (b) photo image.
7. Photovoltaic Dipole Antenna with Solar Concentrator

Figure 7.5. Detailed view of RF-DC decoupling network and balun: (a) layout with component values for the filter $L = 68 \text{nH}$, $C = 100 \text{pF}$, and balun slot dimensions $l_s = 45 \text{mm}$, and $w_s = 1.5 \text{mm}$; (b) photo image.

Since the solar cells in the presented structure are working simultaneously as power sources and microwave radiating elements, a DC/RF decoupling circuit is necessary, which is integrated into the feed gap of the folded dipole solar antenna. A standard arrangement of 100 pF chip capacitors and 68 nH chip inductors are used to isolate the DC and RF as shown along with the split-coaxial balun in Figure 7.5.

The 300 $\Omega$ input impedance of the folded dipole is reduced to 200 $\Omega$ by the introduction of the parabolic solar concentrator as seen in Figure 7.6. The folded solar dipole antenna is then positioned along the focal line of the parabolic concentrator, with the active side of the cells facing the reflector. The DC connection and feedline pass through a 9 mm radius hole to the back of the reflector. The design was optimized using a full wave electromagnetic simulator, CST Microwave Studio [102–104]. For a parabolic curve $z = 0.005 \times x^2$, the vertical distance between the antenna and reflector for a 200 $\Omega$ dipole input impedance was found to be $s_d = 55 \text{mm}$. The reflector has dimensions $l_r > 85 \text{mm}$ and $s_p > 55 \text{mm}$ to maximize its
light concentration characteristics. The actual dimensions of the parabolic trough were chosen to be \( l_t = 205 \text{ mm} \) and \( s_p = 75 \text{ mm} \) to ensure a minimum gain of 10 dBi over the entire band. 3M Vikuiti™ Enhanced Specular Reflector (ESR) Film was used as the conducting reflector surface. The advantage of selecting a folded dipole over an ordinary dipole is the fact that the series connection of solar cells provides additive total DC voltages, as well as its broader bandwidth and convenient matching.

### 7.3. Impedance Characteristic and Gain Results

The simulated and measured \( S_{11} \) of the proposed antenna is shown in Figure 7.7 with good agreement. The measured return loss was found to be greater than 10 dB in the frequency range from 1.35 GHz to 1.68 GHz, which corresponds to a fractional impedance bandwidth of 21%. The measured gain at the centre frequency was found to be 11.1 dB with little variation across the band.

### 7.4. Radiation Properties

The measured and simulated E- and H-plane normalized radiation patterns for centre frequency are shown in Figure 7.8. The front-to-back ratio for the E and H plane was better than 27 dB and 30 dB respectively. The cross-polar rejection is better than 20 dB for both planes.

### 7.5. Power Output

Single junction silicon solar cells provide approximately 0.5 V–0.6 V, independently of the cell size. The dipole comprising 4 cells in series, realized a voltage of 2.2 V. The DC current through all the cells connected in series is however the same, equal to the lowest current of the configuration,
Folded dipole aligned with focal line

Figure 7.6. (a) General view of the proposed solar folded dipole antenna with parabolic reflector and dimensions $l_t = 205\, \text{mm}$, $s_p = 75\, \text{mm}$, $l_p = 260\, \text{mm}$, and $s_d = 55\, \text{mm}$; (b) photo image.
Figure 7.7. Simulated and measured $S_{11}$ for the EWT solar folded dipole with parabolic reflector.

Figure 7.8. Measured and simulated radiation pattern for the EWT solar dipole with parabolic reflector. Co-polar and cross-polar components for both E-plane and H-plane.
7. Photovoltaic Dipole Antenna with Solar Concentrator

and proportional to the irradiation and the size of the solar cell elements [193]. The behaviour of the solar dipole as a power source was investigated for solar irradiation values of 500 W/m$^2$, 750 W/m$^2$ and 1,000 W/m$^2$ measured at the aperture of the reflector, by illumination with a Griven INSE 1200 MSR metal halide lamp continuous solar simulator. The solar cells do not face the light directly but through reflections from the parabolic reflector. Higher current values were measured for the dipole placed at the concentrator focal line, when compared with a dipole alone facing the light directly as shown in Figure 7.9. As for solar concentrating characteristics, the four cell solar dipole supplies 73.7 mW ($I = 33.2$ mA, $V = 2.2$ V) at an insolation of 1,000 W/m$^2$ for the reflector with 3M Vikuiti™ ESR film, and 66.6 mW ($I = 30.3$ mA, $V = 2.2$ V) without the reflector. The concentrator accounts for an improvement of almost 10%.

Figure 7.9. Comparison or measured direct current extracted from the folded dipole with reflector and for the dipole alone directly exposed insolation.
7.6. Conclusion

A novel folded dipole made up of Emitter-Wrap-Though (EWT) rear contact solar cells with a parabolic reflector is proposed in this chapter. The full integration of solar cells and antenna in one device where the PV cells act as RF radiating element is demonstrated. Furthermore, the parabolic reflector works simultaneously as an antenna reflector enhancing the gain and as solar concentrator increasing the solar array output. The measured fractional impedance bandwidth and gain were 21% and 11.5 dBi respectively. The antenna/solar arrangement provide a power output of 73.7 mW for an irradiance of 1,000 W/m², which corresponds to almost a 10% increase in power output when compared with the dipole without concentrator, facing the light directly.
8. Influence of Solar Heating on Poly-Si Solar MPA

Antennas incorporated into building façades will experience diurnal temperature variations. It is necessary to determine antenna properties as substrate materials undergo thermal expansion with temperature. The dielectric constant can be sensitive to temperature and thus shift the frequency of operation.

The aim of this section is to characterise the change in performance of microstrip patch antennas (MPA) with polycrystalline silicon (poly-Si) solar cell as ground plane when subjected to temperature changes due to solar radiation. The study compares experimental device performance for microstrip patch antennas printed on three commercial laminates with different thermal coefficients of the dielectric constant, for both the solar prototypes and conventional antennas with copper ground plane.

The characterization of the prototypes is presented in Section 2. Section 3 explains the measurement procedure and set-up used to undertake the measurements. The results of the variation with prolonged irradiation for both $S_{11}$ and temperature in the fabricated antennas are presented in Sections 4 and 5 respectively.

8.1. Characterization of Manufactured Prototypes

The feasibility of using poly-Si solar cells as the ground plane for inset-fed microstrip square patch antennas has been examined on a single 156 mm ×
156 mm cell as described in Chapter 4 under ambient room temperature and illumination condition (293 K, 40 W/m²). Experimental results suggested the viability of using a poly-Si ground for a microstrip patch antenna (MPA) when compared with a conventional square patch antenna with copper ground plane.

In this chapter, the sensitivity of the photovoltaic (PV) antenna resonant frequency to change of temperature induced by solar radiation was measured and compared with the behaviour of the conventional patch antenna on the same laminate and under the same solar radiation conditions. Three laminates with different thermal coefficient of dielectric constant ($TCK'$) were considered: FR4 (LPKF Laser and Electronics AG [194]), RF45 (Taconic Advance Dielectric Division [195]), RO4003 (Rogers Corporation [196]). MPAs were fabricated on double-sided copper-clad laminates, with 35µm electrodeposited copper on a dielectric resin substrate. A 34 mm × 34 mm square-shaped patch and a microstrip feed line was etched on one side of the laminates using a LPKF ProtoMat C60 circuit plotter and milling robot. Table 8.1 characterizes the three laminates involved in terms of the composition of the substrates, their dielectric constant ($\varepsilon_r$), loss tangent ($\tan \delta = 0.015$), thermal coefficient of the dielectric constant ($TCK'$), height of the substrate ($d_{sus}$) and the thickness of the copper layer ($d_{cu}$).

A microstrip patch antenna’s resonant frequency depends not only on its physical dimensions but also on the electrical properties of the dielectric material. The $TCK'$ is a measure of how the dielectric constant is affected by changes in temperature. Its unit is K$^{-1}$, positive when $\varepsilon_r$ increases with temperature. Laminates with an absolute value of $TCK' < 60 \times 10^6$ K$^{-1}$ are considered to be stable with temperature.

The photovoltaic (PV) antennas were fabricated by removing the rearside copper cladding of the corresponding laminate and attaching the solar cell to act as ground plane as shown in Figure 8.1. Figure 8.2 shows the conventional microstrip patch antenna built for comparison. If Figure 8.1(a) and Figure 8.2(a) are compared, it can be observed that the spare substrate
8. Influence of Solar Heating on Poly-Si Solar MPA

Figure 2. Antenna with poly-Si solar cell as groundplane: (a) front view and (b) back view. F and B denote the position of the thermal probes for the front and back of the structure respectively.

Table 8.1. Description of FR4, RF45 and RO4003 in terms of the substrate composition, dielectric constant ($\varepsilon_r$), loss tangent (tan$\delta$), thermal coefficient of the dielectric constant ($TCK'$), height of the substrate ($d_{sus}$) and the thickness of the copper layer ($d_{cu}$).

<table>
<thead>
<tr>
<th>Laminate</th>
<th>Substrate</th>
<th>$\varepsilon_r$</th>
<th>tan$\delta$ (Npm$^{-1}$)</th>
<th>$TCK'$ (K$^{-1}$)</th>
<th>$d_{sus}$ (mm)</th>
<th>$d_{cu}$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR4</td>
<td>Epoxy-glass resin</td>
<td>4.2</td>
<td>0.0200</td>
<td>+600 $10^{-6}$</td>
<td>1.52</td>
<td>0.035</td>
</tr>
<tr>
<td>RF45</td>
<td>Ceramic woven glass</td>
<td>4.5</td>
<td>0.0013</td>
<td>-135 $10^{-6}$</td>
<td>1.57</td>
<td>0.035</td>
</tr>
<tr>
<td>RO4003</td>
<td>Ceramic filled PTFE</td>
<td>4.3</td>
<td>0.0037</td>
<td>+017 $10^{-6}$</td>
<td>1.52</td>
<td>0.035</td>
</tr>
</tbody>
</table>
Figure 8.2. Conventional microstrip patch antenna with copper ground plane: (a) front view and (b) back view. F and B denote the position of the thermal probes for the front and back of the structure respectively.
around the radiating patch was eliminated to reduce shade over the cell. An additional dielectric layer of FR4 material is placed beneath the solar ground plane to provide mechanical support due to the brittle nature of the solar cell (see Figure 8.1(b)). In the analysis of the performance of the PV antennas with temperature variation due to solar radiation only the parallel orientation of the front Ag-lattice was considered, because it provides the best gain performance. A cross-sectional view of both photovoltaic antenna and conventional structure is shown in Figure 8.3.

8.2. Measurement Procedure

The measurement on each of the proposed AUT (Antenna under Test) took place in a closed chamber with no forced ventilation (estimated convection coefficient \( h_c = 5.25 \text{ W m}^{-2} \text{K}^{-1} \)) and an ambient temperature of 293 K.

A Griven INSE 1200 MSR metal halide lamp with variable light intensity was used as solar simulator. Incident insolation was sensed at the centre of the illuminated area (“test zone”) using a Kipp & Zonen CM11 pyranometer [197] as shown in Figure 8.4. A DL2e Delta-T Data Logger [198] acts as an interface between the pyranometer and the PC logging continuously the values read by the pyranometer at given intervals, and transferring this insolation readings to the computer. A PC equiped with the corresponding software to the DL2e is used to initialize and control the data logger, as well as to store the transferred raw data into a tabular format for further processing. The distance between the test zone and the aperture of the lamp was kept constant to 1.5 m due to the dimensions of the supporting table. The focus of the lamp was adjusted until the pyranometer reported an insolation of 1,000 W/m². The position of the test zone and the focus of the lamp would stay the same for the rest of the measurements.

The pyranometer was then removed and substituted by the antenna under test (AUT) connected to a ZVB24 Rohde & Schwarz vector network anal-
Figure 8.3. Cross-sectional view of the antenna structure for both (a) standard microstrip patch antenna with copper ground plane and (b) microstrip patch antenna with poly-Si solar cell as ground plane.
Figure 8.4. Lighting set-up.
yser [83], which was used to measure the $S_{11}$, which is recorded at various time intervals during a 30 minute insolation period, as shown in Figure 8.5. The measurements for each antenna under test took place on a different day, to allow the chamber to cool down between the operation of the lamp.

The temperatures reached by the antennas during the continuous 30 min irradiation were also measured for the front of the patch and the back of the AUT with T-type Copper-Constantin thermocouples [199], at the points F and B shown in Figure 8.1, Figure 8.2 and Figure 8.6. This measurements were done for each antenna under test on a different day as the $S_{11}$ measurements, as the attachment of the metallic thermocouples would impair the $S_{11}$ response.

### 8.3. $S_{11}$ **Variation with Prolonged Solar Insolation**

Figure 8.7 shows the variation of the antenna operational bandwidth in form of $S_{11}$ parameter for both copper and photovoltaic based antennas. Results are presented for the patch on FR4, RF45 and RO4003 dielectric substrates.

A summary of the measured results are listed in Table 8.2 where $f_0$ GHz denotes the original resonant frequency of the evaluated device just before illumination (time = 0 min in Figure 8.8). The reduction in resonant frequency seen when replacing the copper ground plane by the poly-Si ground plane is caused by an increase in effective dielectric constant for the patch as seen in Chapter 4. Although there is a shift in the resonant frequency with change in illumination as observed from Figure 8.5 and Table 8.2, the bandwidth remained stable.

The gain values presented in Table 8.2 were measured through the standard RF antenna measurement procedures in an anechoic chamber. A slight drop in gain and increase in bandwidth was observed when the solar cell replaced the copper ground plane. This can be attributed to the
Figure 8.5. Set-up for $S_{11}$ measurement under 30 min continue insolation.
Figure 8.6. Set-up for temperature measurement under 30 min continue insolation.
Figure 8.7. Variation of measured antenna $S_{11}$ parameter for prolonged irradiation with 1,000 W/m$^2$, for both copper and solar based MPAs. Results presented for the laminates FR4, RF45 and RO4003.
increase losses of this inhomogeneous ground plane (hybrid combination of silver front contacts, silicon and aluminium layer).

The maximum deviation of the resonant frequency with temperature during 30 minutes of 1,000 W/m² continuous irradiation is also displayed in Table 8.2. This difference is presented both as an absolute value in MHz and also as a percentage of the original $f_0$. In a laminate with a positive $TCK'$, the substrate’s εᵣ will increase with temperature and the resonant frequency decreases.

The variations observed in the $S_{11}$ for both copper and PV based antennas are dependent on the thermal stability of the dielectric substrate used, and reversible when the solar simulator was switched off. The microstrip patch antenna fabricated on the RO4003 laminate ($TCK' = +617 \times 10^6 K^{-1}$) shows no change in its operational bandwidth with illumination (temperature) for both copper and PV ground planes. The change observed with illumination for the RF45 prototypes ($TCK' = -135 \times 10^6 K^{-1}$) was 2 MHz for the copper prototype and 4 MHz for the PV antenna. The highest deviations were observed with the FR4 prototypes ($TCK' = +600 \times 10^6 K^{-1}$); up to 12 MHz for the ideal antenna, and a maximum of 13 MHz for the PV antenna.

Table 8.2. Comparative antenna parameter values and maximum deviation with temperature for an insolation of 1,000 W/m² for the laminates FR4, RF45 and RO4003.

<table>
<thead>
<tr>
<th>Laminate</th>
<th>Antenna Type</th>
<th>$f_o$ (GHz)</th>
<th>BW (MHz)</th>
<th>Gain (dBi)</th>
<th>Change in $f_o$ (MHz)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR4</td>
<td>copper</td>
<td>2.27</td>
<td>59</td>
<td>2.5</td>
<td>2.60</td>
<td>-12</td>
</tr>
<tr>
<td></td>
<td>PV</td>
<td>2.19</td>
<td>90</td>
<td>4.0</td>
<td>1.23</td>
<td>-13</td>
</tr>
<tr>
<td>RF45</td>
<td>copper</td>
<td>2.28</td>
<td>26</td>
<td>1.1</td>
<td>5.24</td>
<td>+2</td>
</tr>
<tr>
<td></td>
<td>PV</td>
<td>2.21</td>
<td>34</td>
<td>1.5</td>
<td>4.82</td>
<td>+4</td>
</tr>
<tr>
<td>RO4003</td>
<td>copper</td>
<td>2.53</td>
<td>30</td>
<td>1.2</td>
<td>5.96</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>PV</td>
<td>2.43</td>
<td>49</td>
<td>2.0</td>
<td>4.95</td>
<td>0</td>
</tr>
</tbody>
</table>
8.4. Temperature Variation with Prolonged Insolation

The temperatures reached by the antennas during the continuous 30 minutes exposure to 1,000 W/m² insolation was measured for the front of the patch and the back of the devices with T-type Copper-Constantin thermocouples, at the points F and B shown in Figure 8.1 and Figure 8.2. Measured results were compared with simulations using FLUENT (ANSYS FLUENT Flow Modelling Software [200]) for the material properties presented in Table 8.3. Figure 8.8 shows the FR4 based antenna’s temperature variation during 30 minutes exposure to 1,000 W/m² insolation. Good agreement between measurement and simulation was achieved in general. However, only reasonable agreement was achieved for the rear side of the PV antenna, due to the presence of small air gaps present in the bonding of the solar cell to the mechanical rear support.

The measured temperature at the front of the radiating patch in the copper antenna as shown in Figure 8.8(a), reaches 327.6 K, whereas the patch in the PV antenna in Figure 8.8(b) reaches 330.8 K due to the presence of the solar cell. The difference between the front and back temperatures is

<table>
<thead>
<tr>
<th>Material</th>
<th>ρ_m (kg m⁻³)</th>
<th>C_m (J kg⁻¹ K⁻¹)</th>
<th>k_m (W m⁻¹ K⁻¹)</th>
<th>α_m</th>
<th>d_m (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>8939^c</td>
<td>393^c</td>
<td>360^c</td>
<td>0.5^d</td>
<td>0.035</td>
</tr>
<tr>
<td>FR4</td>
<td>1900^c</td>
<td>840^c</td>
<td>0.23^c</td>
<td>0.65^d</td>
<td>1.600</td>
</tr>
<tr>
<td>PV</td>
<td>2330^a</td>
<td>712^a</td>
<td>148^a</td>
<td>0.7^b</td>
<td>0.259</td>
</tr>
</tbody>
</table>

^a Source: [201]  ^b Source: [202]  ^c Source: [203]  ^d Empirical estimation
Temperature variation for the FR4 based prototypes for prolonged insolation with 1,000 W/m², for (a) copper antenna and (b) poly-Si solar antenna.

**Figure 8.8.** Temperature variation for the FR4 based prototypes for prolonged insolation with 1,000 W/m², for (a) copper antenna and (b) poly-Si solar antenna.
larger for the PV antenna due to the extra layer of FR4 support shown in Figure 8.1(b). The measured difference is 2.4 K for the copper antenna and 6.2 K for the PV antenna. Figure 8.8 also shows the simulated temperature trend at the FR4-PV boundary for the PV antenna. A temperature of 329.0 K was achieved at this internal boundary after the 30 minutes of 1,000 W/m$^2$ insolation.

8.5. Conclusion

In this chapter the influence of solar heating on microstrip patch antenna (MPA) with poly-Si solar cell as ground plane is investigated. The performance of the proposed structure for an incident radiation of 1,000 W/m$^2$ is presented. A comparative study on three commercial laminates (RO4003, FR45 and FR4) with different thermal coefficients of the dielectric constant was undertaken.

The radiating patch in the PV antenna was found to reach slightly higher temperatures due to the presence of the solar cell compared to a conventional microstrip patch antenna with copper ground plane. However, the PV antenna resonant frequency shows similar sensitivity to temperature variation to the corresponding copper prototypes. This shows that the performance of a microstrip patch under temperature stress is mainly dependent on the thermal stability of the dielectric substrate and so the PV ground plane in the proposed structure does not significantly degrade the antenna performance compared to a conventional antenna.

In order to avoid changes in the operational frequency and consequential performance degradation, temperature stable laminates ($|TCK'| < 60| \times 10^6$ K$^{-1}$) should be employed in solar antennas for façade applications.
9. Conclusions and Future Work

This chapter combines general conclusions of the thesis as well as some identified topics of relevant future work.

9.1. Conclusions

There is an increased interest in combining antennas with solar panels for both satellite and terrestrial applications where antennas and solar cells compete for the same scarce surface and the integration can yield significant savings, improving the economic viability of renewable energy. A number of novel designs for the integration of antenna and photovoltaic (PV) technology have been developed and are described in this thesis. The solar cells and modules used in this work for the integration with antennas are all commercially available. The proposed solar antennas were designed and optimized with the 3D Finite Integral Equation based electromagnetic simulation software CST Microwave Studio, and then manufactured and measured within the facilities of the DIT Antennas & High Frequency Research Centre.

The first proposed integration solution used a polycrystalline silicon solar cell as ground plane for a 2.19 GHz square microstrip patch antenna (MPA). This structure was low profile, low cost, avoided the perforation of the brittle solar cell and the need for RF-DC decoupling. The employed microstrip technique favors the possible integration with versatile patch shapes if the application requires it so.

The solar cell acts an inhomogeneous ground plane for the patch antenna
due to the different conductivities of its layered structure and the higher permittivity of the silicon. Its microwave performance was evaluated for different orientations of the front silver lattice electrode. The general performance of this solar antenna was found similar to that of a conventional antenna with a copper ground plane but for a slight decrease in gain and increase in bandwidth, evidence for increased losses due to the Si properties. While both silver lattice orientations mitigate the energy loss in the silicon, the perpendicular orientation provided the poorest isolation. The main drawback of this configuration is clearly the large shading obstruction of the light due to the microstrip patch and feed arrangement, which covered 13.2% of the solar cell area.

To reduce this shading, a solar antenna comprising a half-wave dipole was then developed for the same type of solar cell as reflector. The shadow of the radiating element was reduced dramatically with this arrangement to 3.7% of the solar cell area. Furthermore, for this structure, the two different orientations of the front silver lattice result in the same performance with larger bandwidth and high gain exceeding the 8 dBi was achieved. This construction technique is however not appropriate when a low-profile is required.

To further reduce the solar cell shading, without compromising the antenna’s low profile of the integration solution, the radiation performance of the AgHT-4, a material that is both optically transparent and electrically conductive, was evaluated. The proposed structure consisted of a multilayer proximity-coupled feed configuration with an amorphous silicon thin film module deposited on glass, as ground plane and lower substrate. The feed transmission line directly placed on the glass of the solar module couples to a square transparent patch located on top of a clear Perspex substrate. A solar antenna with 3.9 dBi of gain was achieved for use in the 3.5 GHz band. This represents a considerable improve in gain when compared with previous reported transparent antennas.

A unique and different approach for the integration of photovoltaics and
antennas was investigated with the development of a photovoltaic dipole made of emitter-wrap-through (EWT) rear contacted solar cells for use with a solar concentrator. Four EWT solar cells were connected in series as folded dipole and used both for power generation and as the radiating element. A metallic parabolic structure acts as solar concentrator for the photovoltaic cells increasing the illuminated flux on the PV surface, thus reducing the amount of PV material required, and simultaneously as reflector for the dipole. The resulting solar antenna achieved a 10% increase in current due to solar concentration, and provided a 21% bandwidth in the 1.5 GHz band, with a maximum gain of 11.1 dBi.

Solar antennas aim to operate in outdoor environments where they will experience diurnal temperature variation. Substrate materials undergoing thermal expansion with temperature may lead to shifts in the operational radiofrequency of the antenna. The influence of solar heating on the operational frequency of an MPA with polycrystalline silicon solar cell as ground plane was investigated. The results suggest that laminates with an absolute value of the thermal coefficient of the dielectric constant lower than $60 \times 10^{-6} \text{K}^{-1}$ should be employed in this type of integration to avoid performance degradation.

The developed technologies are a promising solution for the unification of building façade transceivers as part of an integrated autonomous system, as well as for base stations in remote areas, or standalone applications such as sensor networks.

### 9.2. Future Work

In addition to the integrated solar antenna structures achieved in this thesis, some areas of possible future study have been identified and are outlined here.

Further investigation of the performance impact of temperature variation
due to solar radiation could be carried out for the variety of solar antennas proposed. Both indoor and outdoor measurements would provide a dataset of broader range of design configurations and material selections that would be employed for the fabrication of a full-scale demonstrator. This include a proprietary battery and base station electronics connected to the solar antenna. Completion of outdoor trials would include radio wave propagation assessment in the vicinity of the solar transceiver module and solar energy conversion efficiency.

Possible future research efforts could also be focused on the study of bifacial solar cell’s transparency at radio frequencies. Some preliminary work was done on this novel idea during this PhD period, showing great potential [204]. As seen in Section 3.5, bifacial solar cells are sensitive to light in both sides by the lack of the rear side metallization. This is relevant for radio frequency (RF) and microwave applications, because the surface can be transparent for certain electromagnetic frequencies and polarizations, following the principle of operation of a wire grid polariser [148, 205, 206]. Such a device can prevent or allow transmission of incident field components of an electromagnetic wave depending on the polarization and relationship of the wave period to the periodicity or pitch of the grid. The aforementioned wire-grid polariser effect can therefore also be used to control the transmission of certain frequencies by controlling the pitch of the structure. Similar to the wire-grid polariser, fine finger parallel metallic lattice electrodes are placed in one or both sides of a bifacial cell, according to a certain pitch. This can therefore be controlled to be used as a frequency selective surface allowing the transmission of certain frequencies and polarizations. A possible application for this technology is the use of bifacial cells in front of the radiating element like a frequency selective radome for example, protecting and powering the antenna system, at the same time that the frequency selective behavior may help to reduce the constraints on the transceiver’s filter.
BIBLIOGRAPHY


APPENDIX A.

LIST OF PUBLICATIONS

Journal Publications


Appendix A. List of Publications

International Conference Publications


Appendix A. List of Publications

National Colloquia
