ELECTRICAL ENERGY HARVESTING USING SOLAR RADIATIONS

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ABSTRACT

ELECTRICAL ENERGY HARVESTING USING SOLAR ANTENNAS

Sun is the greatest source of almost all kind of energies. The amount of energy transmitted by sun to planet earth in one day is capable of meeting the current energy needs of the entire world for next 27 years [1]. This entire energy transmitted is in various forms and different efforts have been undertaken in the world so far to tap this tremendous sun’s energy. Approximately 90% of material experts are tapping the particle nature of Sunlight using solar cells. Every day passes with a technological breakthrough in some efficient material discovery/invention for making more and more efficient solar panels. Despite of all these efforts, commercial efficiency of solar cell is maximum 40%.While material engineers and researchers claim solar cells approach of harvesting the suns energy to be the best, electrical engineers and experts shall not stop exploring their domain, because an innovational solution of utilizing the sun’s energy in far more efficient and economical manner is proposed.

Harvesting the suns energy using particle nature (solar cell) limits the efficiency of energy converted to very low level as compared to wave nature (solar antenna) of solar radiations if received on solar antennas and then converted into commercial electricity.

Among the entire solar spectrum, Infra-Red (IR) heat radiations have been selected to generate electricity and render cooling effect. IR is the second most energy abundant portion of solar spectrum and is present both at day and night [2].

DECLARATION

This thesis is our own work, and no part of it has been submitted for a degree at this, or at any other university or level.

CERTIFICATE

Certified that the contents and form of project report entitled **“Electrical Energy Harvesting Using Solar Radiations”** submitted by 1) Ali Anjum, 2) Jawad Khalid, 3) Sidrah Javed and 4) Mehreen Rehman have been found satisfactory for the requirement of the degree.

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DEDICATION

In the name of Allah, the Most Merciful, the Most Beneficent

To our parents, without whose unflinching support and unstinting cooperation, a work of this magnitude would not have been possible. May Allah Almighty bless them with long lives and always provide us their loving and sincere guidance.

ACKNOWLEDGEMENTS

This project would not have been possible without the guidance and the help of several individuals who in one way or another contributed and extended their valuable assistance in the preparation and completion of this project.

First and foremost, the utmost gratitude goes to Dr. Naveed Iqbal whose steadfast support of this project was greatly needed. He allowed the room to work in best possible way. Asst. Prof Zeeshan Zahid has been the ideal co-supervisor. His sage advice, insightful criticisms, and patient encouragement aided the completion of the project and the writing of this thesis in innumerable ways.

The valuable contributions of Mr. Fahad and Mr. Shahid CMND COMSATS for accommodating our queries and Prof. Arshad Saleem Bhatti of Physics department COMSATS need to be acknowledged, who not only gave of his time generously and imparted enormous detail, but also followed up with further advice or sources of information.

The Engineering students and colleagues assisted in one way or another in our daily work and staff in the Electrical Engineering Departments, NUST need to be thanked for the use of facilities in the labs.

Last but not the least, we wish to express our love and gratitude to our families for their understanding and unconditional support and for helping to put us through college and the one above all of us, the omnipresent God, for answering our prayers for giving us the strength thank you so much Dear Allah.

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ABBREVIATIONS

SUNEHRI	Sun Energy Harvesting Research Initiative
AC	Alternate Current
DC	Direct Current
AC	Air Conditioner
EM	Electro Magnetic
IR	Infra-Red
UV	Ultra violet
THz	Tera Hertz
RF	Radio Frequency
UHF	Ultra high frequency
MoM	Metal oxide Metal
SM	Surface Mount
IFL	Inter Feed Length
UWB	Ultra Wide Band
NEC	Nantenna Electromagnetic Collector
PVC	Photovoltaic Cell
PTFE	Poly Tetra Flory Ethylene
VNA	Vector Network Analyzer
SEM	Scanning Electron Microscope
HFSS	High frequency Structure Simulator

Chapter 1

Introduction

1.1. Overview

This chapter introduces and gives basic information about the project. The chapter covers problem statement, our approach, both academic and application based objectives, project scope and the organization of report. Different phases of the project have been also discussed.

1.2. Project Problem Statement

Solution of the Pakistan's greatest problem of energy deficit is intended. The industrial development and population increase has created an enormous increase in the global demand for energy. Growing in parallel is the rapidly rising cost of electricity in Pakistan. Tormented by a persistent energy crisis and hostage to the increasing electricity costs, Pakistan's only viable solution to all problems is alternate energy sources.

1.3. Project Objectives

The basic academic objective of this project is the acquisition and best practical utilization of existing EM and antenna modeling software's. Main aim is to carry out research activity in order to propose an alternate energy resource led by electrical engineers. The aim is to resolve the energy crisis and reduce country's dependency on oil by producing efficient, cost effective and portable EM solution systems.

The objective of the project is to design **Cooling system:** which can cool down buildings without electricity consumption if fabricated on large scale. **Electricity Production** (future work): Eliminating Energy crisis of Pakistan by producing electricity from electromagnetic energy. **Eliminating electricity short fall**: Cooling systems would be able to replace AC's which consume a lot of electricity causing major electricity short fall. **Providing green solution**: It is an environment friendly cooling solution with no waste products and can eliminate global warming caused by AC's.

1.4. Project Scope

In the energy starved era misery increases due to usage of electrical and electronic home appliances, which provides comfort while putting heavy burden on the utility budget.

After detailed research and available nanotechnologies, Infrared has been considered to be most suitable to create cooling effect and to generate electricity. Project focus is to capture abundant Infra-red (IR) radiations which are the sole cause of heat in environment. Initially while capturing IR radiations, it can effectively cool down surroundings, buildings and homes and later (future work) these captured radiations can be converted into electricity by rectification methods, for commercial use.

The abundant IR radiations are available in atmosphere with high energy in them, mostly originating from the sun and few reradiated from earth and manmade objects. Fabrication of tiny solar radiation collectors by stamping specific patterns of conducting metal onto substrates by using Nano fabrication is intended. Energy stored in the radiations is absorbed by these collectors and these collectors can be described as very small solar antennas as depicted in figure 1.1.

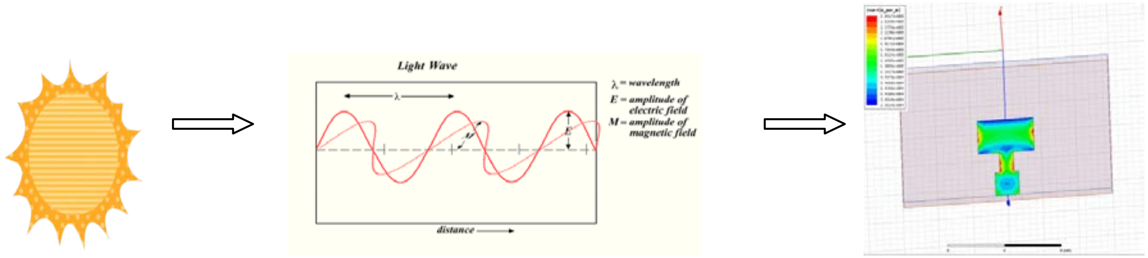


Figure 1.1 Infrared (IR) Heat Radiations Emitting from Sun in the form of EM Radiation and being Received on Solar Antenna

The project will be implemented in two main phases i.e. Software Phase and Hardware Phase. The Software phase includes the analytical calculations, software simulations and validations of simple solar antenna, series solar antenna array, corporate solar antenna array, solar power combiner and a unified solar antenna array which would be capable of receiving IR efficiently and combining the entire received power onto 50 Ohms matched transmission line.

The Hardware phase includes the procurement of materials required for solar antennas and setting up calibrated photolithography process in Clean room which is shown in figure 1.2. It also includes formation of multi-layer physical model which sets the base for patterning of antennas. It remains one of the greatest challenge before actual photolithography takes place.

Figure 1.2 Calibration of Photolithography machine in clean room

1.5. Organization of Thesis

The report about the project covers all the necessary information required to understand the proposed solar energy harvesting system using solar antennas. It also emphasizes on why there was a need to develop it and how it is achieved.

The first chapter contains basic information about the project. The chapter covers problem statement, our approach, both academic and application based objectives, project scope and the organization of report. The second chapter gives the detail study involved in materials selection keeping in view i.e. Antenna theory, Nano Physics and availability of materials.

The third chapter deals with the software simulations based on theoretical calculations for solar antenna and series solar antenna arrays. It also includes the new researched resonant behaviors of patch antennas as a function of its length and width. Moreover, step by step improvement of results has also been shown to increase the understanding of the extent of research work done in developing software solar antenna array model.

The fourth chapter includes the simulation models of novel power combiners operating efficiently in entire IR spectrum. The understanding of this chapter remains vital as the entire received IR energy on solar antennas in previous chapter is subject to the performance of power combiner's efficiency. The fifth chapter contains the software simulations of corporate solar antenna array which is made by integrating series solar antenna arrays with solar power combiners. This chapter sets the visual understanding of entire proposed solar antenna system which not only receives IR but also combines the entire IR received power onto single port.

The sixth chapter includes the hardware implementation of above developed simulated models. It includes the fabrication work done at Center of Micro and Nano Devices (CMND), COMSATS, Islamabad. This chapter organizes itself in chronological sequence so that clear understanding of Nano physics might be developed practically. The seventh chapter deals with the qualitative testing and validation of fabricated solar energy harvesting system. It provides the proof of concept and sets the comparison of research work done in MCS with respect to the entire world. Eighth chapter provides the scope for future work and the capabilities of harvesting the suns energy through solar antennas.

Chapter 2

Material selection

2.1. Overview

Any planar antenna is made up of at least two materials, the conductor and the dielectric resonant material. Before setting up any theoretical or simulation model, first step is to select the materials required to be used in fabrication of solar antenna. Constraints from fabrication and theoretical point of view were required to be matched. This chapter provides the properties of the selected materials and the reasons as to why these materials were selected.

2.2. Selection of Conducting Material

Copper, Silver and Gold were the candidates for conducting material being used in antenna pattering and ground layer. Electrical and thermal conductivity along with thermal expansion were the major requirements from these conductors. Copper is being used as conducting layer in microwave patch antennas but using it in the THz frequency range causes multiple problems such as air corrosion (due to very small features) and thermal expansion with respect to Gold. Silver also got dropped because of its availability and greater thermal expansion than gold. Table 2.1 shows the comparison between above named conductors.

Table 2.1 Comparison between Conductors

S/No	**Material**	**Thermal conductivity (W/m.k)**	**Thermal expansion Linear/volumetric (μm/m/k)**	**Remarks**
1.	Gold	318	14/42	Selected due to minimum thermal expansion
2.	Copper	401	17/51	
3.	Silver	429	18/52	

There are few other advantages which stamped our selection of gold i.e. it suffers minimum corrosion in air or upon physical contact. Maximum purity of gold can be achieved. Gold targets for thin film deposition are easily available. It is preferred by CMND fabrication experts. Hence gold is selected to be used as conducting layer in solar antennas.

2.3. Selection of Dielectric Resonant Material

While working in THz frequency ranges, dielectric layers become critical in limiting the feature sizes of corresponding antennas. Lower the dielectric constant, minimum feature size of antenna structure gets improved. Lower dielectric constant is also favored in antennas because it controls fringing fields hence radiations are improved. Similarly lower dielectric constant consequently gives larger bandwidth of the antenna, hence efficiency can be improved. Conversely speaking if we use high dielectric constant then it will result in large impedance mismatches which will add towards losses and efficiency will decrease.

Smallest feature size is also a function of dielectric resonant layer height ‘h’. As we increase ‘h’, antenna minimum feature size gets improved. Hence major critical parameters are dielectric constant and loss tangent along with thermal expansion. Loss tangent depicts dielectric losses of the dielectric resonance layer at a particular frequency, that how far this layer allows to pass E-field from it before dying down to 33% of peak magnitude of E-field.

Thermal expansion coefficient should also be minimum so that size of antennas remains intact even when high temperature is applied during photolithographic process. Minimum dielectric constant, loss tangent and thermal expansion is required. Moreover, constraints in fabrication process put by CMND fabrication team were also required to be addressed. Following comparison table was developed before finalizing any material.

Table 2.2 Comparison between Dielectric Materials

S/No	**Material**	**Thermal conductivity (W/m.k)**	**Thermal expansion (µm/m/k)**	**Permittivity**	**Loss tangent**	**Remarks**
1.	SiN	15	3/9	7		Permittivity between 6-8
2.	SiO_2	10	0.5/1.5	3.5		Permittivity 3.9. It varies widely
3.	PTFE	0.22	-125	2.2	0.0009	Selected

Table 2.2 shows comparison between dielectric materials. Three materials are compared because these are most widely used materials in nano fabrication process and are easily available in various sizes. Their characteristics are compared for final selection of dielectric resonance layer.

Poly Tetra Flora Ethylene (PTFE) commonly known as Teflon is finalized to be used as dielectric resonant layer in solar antenna because it has minimum values of thermal expansion, permittivity (dielectric constant) and loss tangent. Its thermal conductivity is also minimum which serves the purpose of cooling device as it does not let heat (Infrared radiations) to pass through it considerably.

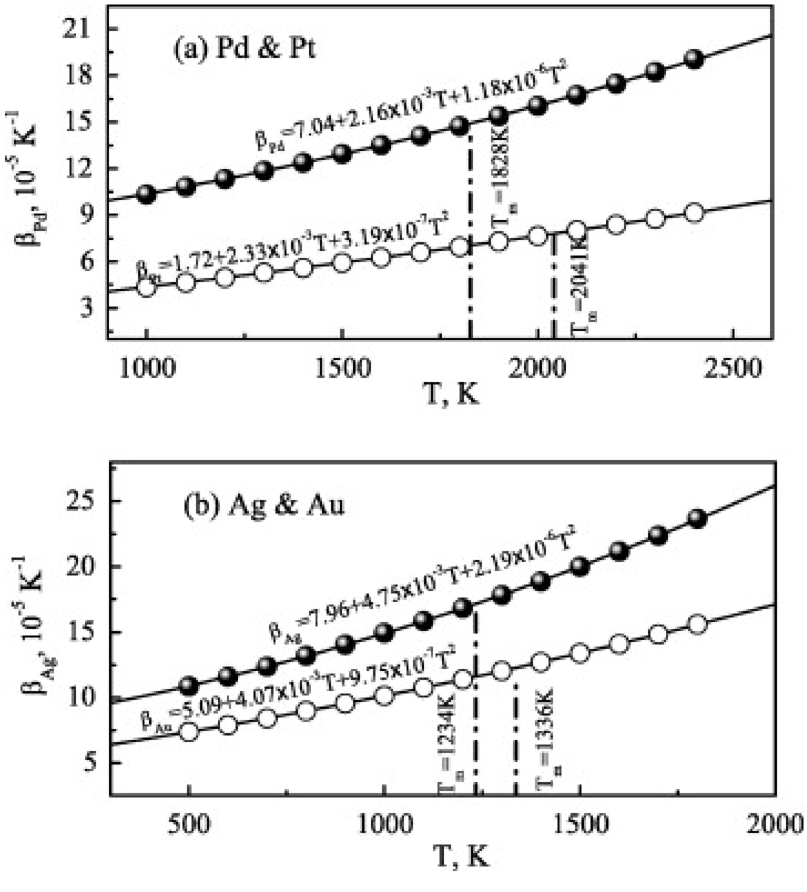


Figure 2.1 Thermal Expansion Coefficients of Lead, Platinum, Silver and Gold

Figure 2.1 represents thermal expansion coefficient curves Vs rise in temperature. It can be clearly seen that β_{Au} is less than β_{Ag} at any given temperature.

Chapter 3

Software Simulation of Solar Antennas

(Single and Serial Array)

3.1. Overview

This chapter includes the step by step details and theoretical calculations leading towards the simulation of solar antenna models. This chapter discusses software design and model of Ultra Wide Band (UWB) IR antenna, its simulation and results like reflection coefficient curve, gain plots at different frequencies representing radiation pattern and 3D plot of radiation efficiency.

3.2. HFSS Simulation Model for Single Solar Antenna

The structure of the single element patch antenna is shown in figure 3.1, the reflection coefficient curve is shown in figure 3.2 which depicts achieved bandwidth of (20-100) THz.

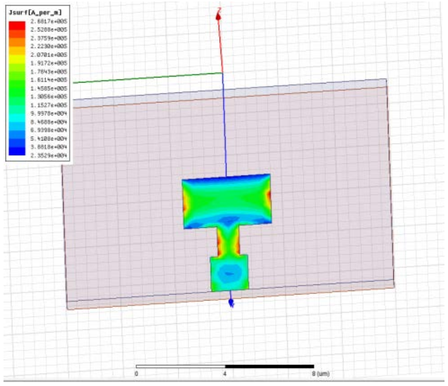


Figure 3.1 HFSS Model of Single Element

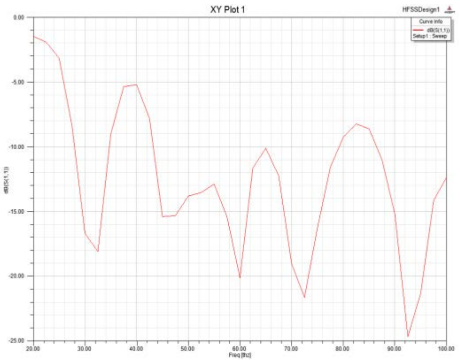


Figure 3.2 Reflection Coefficient Curve

The gain plot in figure 3.3 shows a gain of 6 dB at 30THz achieved by single element of patch antenna. Figure 3.3.1 and 3.3.2 represent 3D gain plots at 72THz and 90THz respectively.

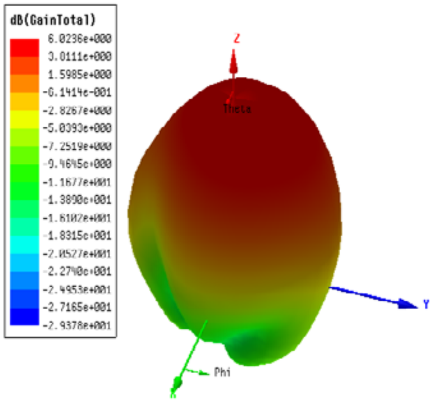


Figure 3.3 Gain in dB

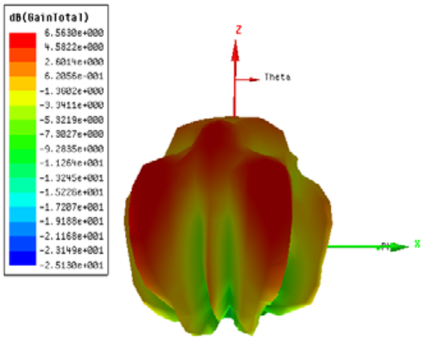


Figure 3.3.1 Gain at 72 THz

The plot for the radiation efficiency is shown in figure 3.4 indicating radiation efficiency of 60%.

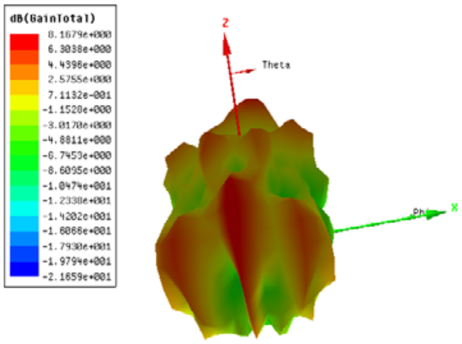


Figure 3.3.2 Gain at 90 THz

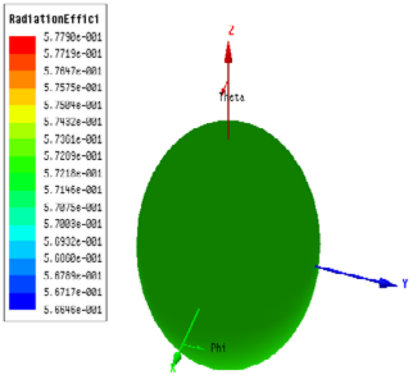


Figure 3.4 Radiation Efficiency

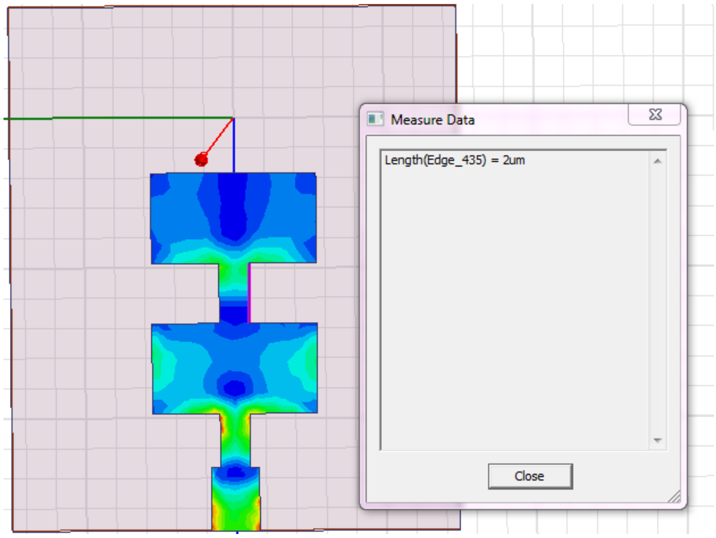
In connection to figure 3.1, extensive optimizations were performed in order to improve the dimension of smallest feature size of solar antenna. For this, length and width of patch antenna was optimized. Observations and conclusions based on these optimizations are tabulated in table 3.1.

Table 3.1 Observations based on optimizations

S/no	**Observation**	**Simulated Experiment Performed**	**Geometry simulated**	**Remarks**
1.	A large leverage in the “width” is available while simulating/fabricating the single element rectangular patch antenna.	Single element at 30Thz resonates fine and shows improvement in gain as we increase its width. Gain(width=4um)=5.5dB Gain(width=5.5um)=6.0dB	Single rectangular patch	Increase in width may improve the gain and prove helpful in improving the dimensions/sizes of patterns as well in Thz frequencies applications.
2.	Observation 1 is invalid while making arrays of antenna	Results of gain and S11 deteriorates as the geometry violates the theory	2 element series array	Increase in width and length of patch beyond theory of Balanis may work good for single element patches only

3.3. HFSS Simulation Model for Solar Series Antenna Array

The optimization of micro strip line (Inter Feed Length) connecting two series patches in figure 3.5 is the first step to move forward in making solar antenna arrays. This length was optimized to give the best results. Best results were only achieved while keeping the distance between two series patches as the half of the wave length at which the antenna is required to resonate. A lot of better results in simulation come across before finalizing this Inter Feed Length (IFL) but focus shall not detour from basic theory of Balanis.



Length(Edge_435) = 2um

Figure 3.5 Two Element Series Array with IFL=2um

The gain improvement with IFL=2um and while increasing number of antenna elements in series is tabulated in table 3.2.

Table 3.2 Number of Antenna Elements with their corresponding Gains

S/no	**Elements**	**Gain**	**Antenna efficiency**	**Remarks**
1.	1 element	5.50dB	58%	
2.	2 elements	5.95dB	56%	
3.	3 elements	7.7dB	54%	
4.	4 elements	8.74dB	51%	All patches are not radiating in phase
5.	5 elements	9.20dB	49%	
6.	6 elements	9.70dB	47%	
7.	7 elements	9.95dB	45%	
8.	8 elements	10.2dB	43%	
9.	9 elements	10.3dB	40%	

The HFSS model of 9 element solar series antenna array is shown in figure 3.6.

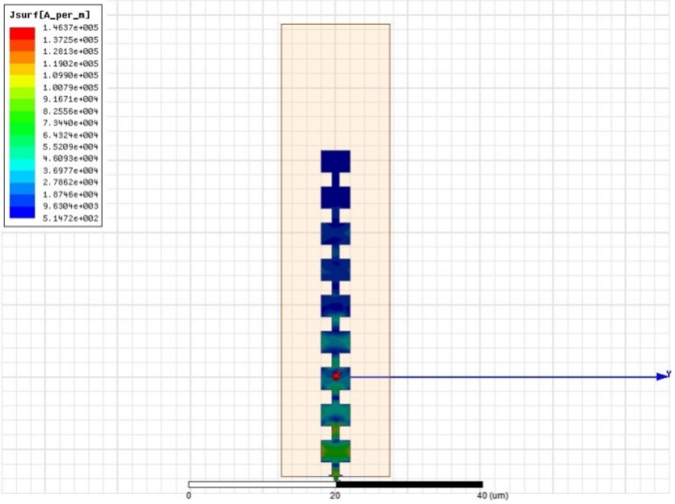
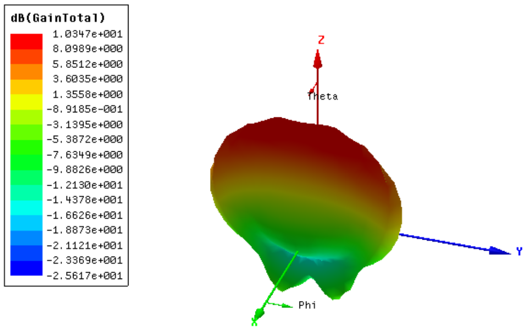


Figure 3.6 Nine-Element Solar Antenna Array

Gain plots at frequencies 30 and 75 THz are shown in figure 3.7.1 and 3.7.2 respectively.



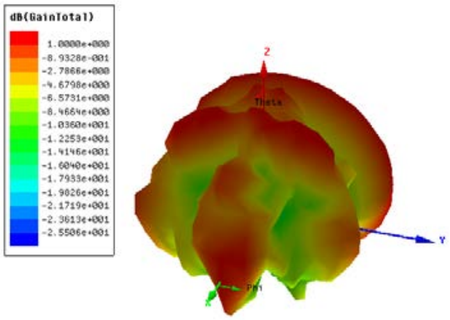


Figure 3.7.1 Gain at 30 THz

Figure 3.7.2 Gain at 75 THz

Increment in gain is seen while adding antenna elements in series which validates the theoretical concepts. Moreover, while extending series elements beyond nine elements in figure 3.6 resist the further improvement in gain, this is because of the fact that strength of source (wave port in HFSS) is limited and magnitude of current flowing through antenna elements in series tends to decrease as we increase the number of antenna elements. Conversely speaking, figure 3.6 antenna model is intended for reception of IR radiations and not transmission, hence every single antenna element is contributing same amount of electrical energy towards 50 Ohms matched port. This is because of the fact that the energy flux present in atmosphere is equal for every independent antenna element as shown in figure 3.8.

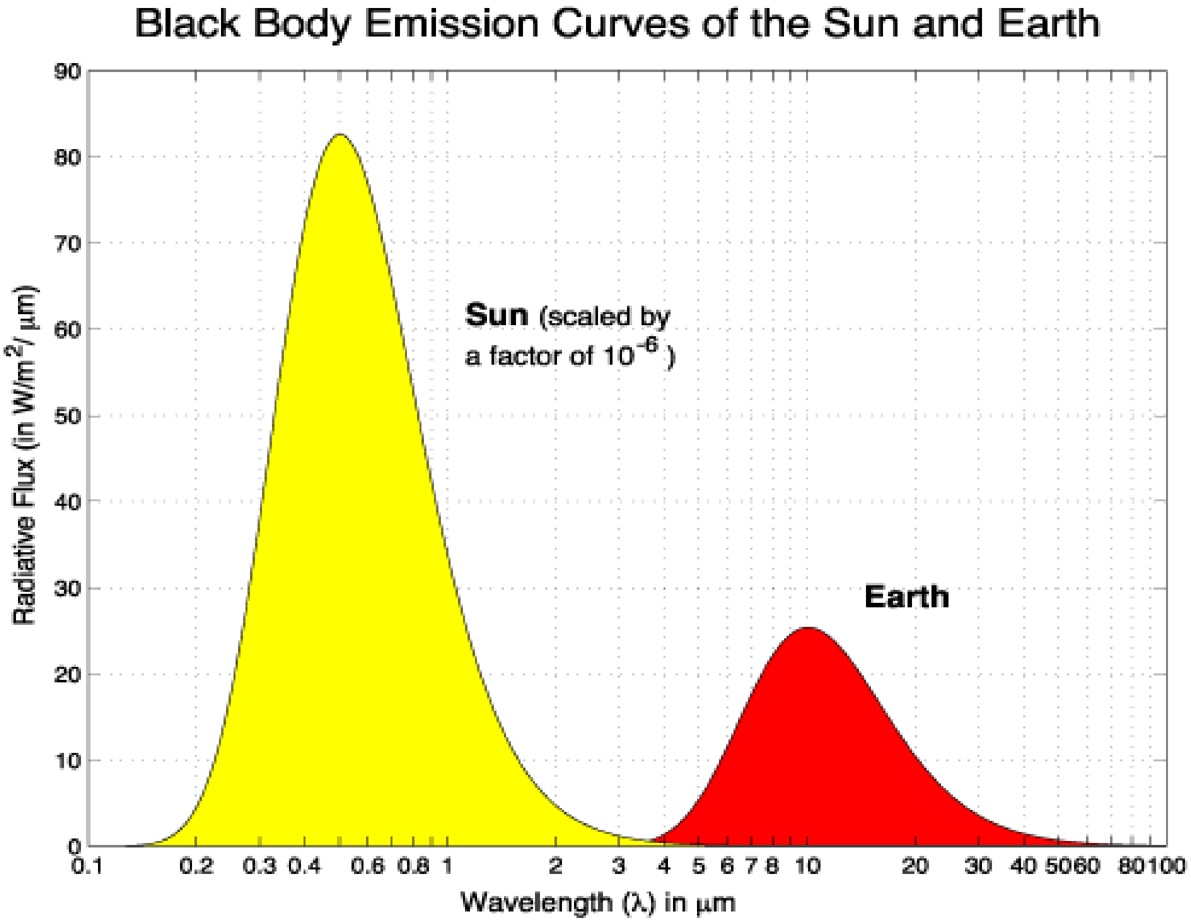


Figure 3.8 Energy Flux of up to 25 Watts is present at IR Frequency of 30 THz

Chapter 4

Software Simulation of Solar Electrical Power Combiner

4.1 Overview

The chapter includes the software simulations and results of solar electrical power combiner which serves as corporate feeding structure and power combiner at a time. This part of simulation is very vital as to the power received on solar antennas simulated in previous chapter is subject to the combining efficiency of power combiners. Efficient IR receiving antennas will be of very little use if the power received upon them is not efficiently combined.

4.2. HFSS Simulation Model for Solar Electrical Power Combiner

Electrical power combiner is characterized by its reflection, coupling and isolation coefficients. In order to grow the combiner network complex and to accommodate more series arrays, spacing between two parallel ports is increased yet maintaining acceptable results.

4.2.1 First Combiner with spacing of 5µm

First stage power combiner model is shown in figure 4.1 and acceptable results of reflection and coupling are achieved from 20 to 50 THz shown in figure 4.2 and 4.3 respectively.

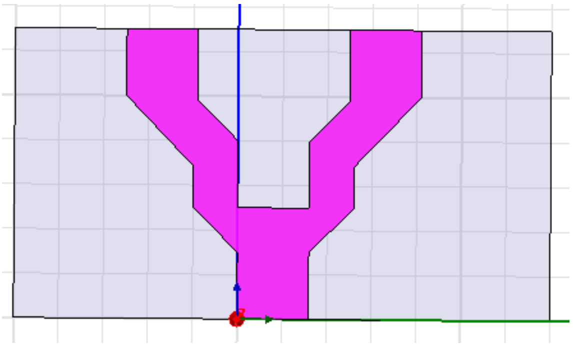


Figure 4.1 HFSS Model of First Stage Power Combiner

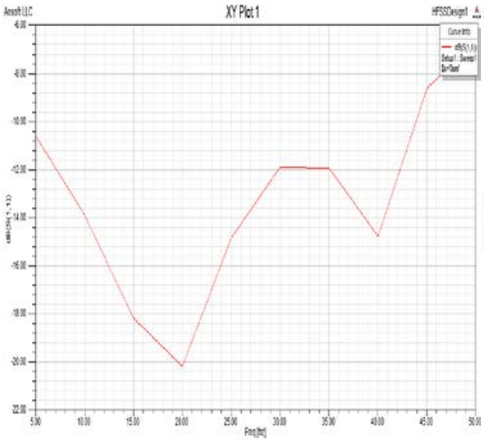


Figure 4.1.2Reflection achieved from

20 to 50 THz

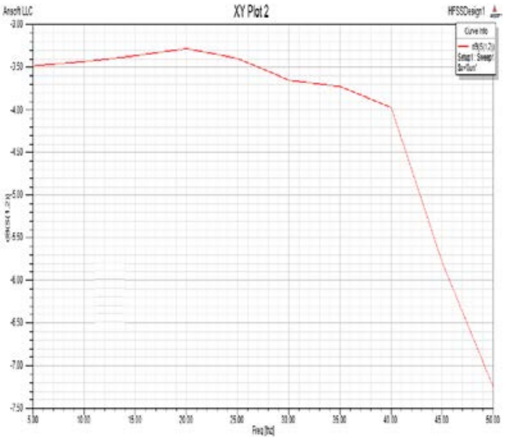


Figure 4.1.3 Coupling achieved from

20 to 50 THz

4.2.2 Second Combiner with spacing of 10 μm

Second stage power combiner model is shown in figure 4.4 and acceptable results of reflection and coupling are achieved from 20 to 50 THz shown in figure 4.5 and 4.6 respectively.

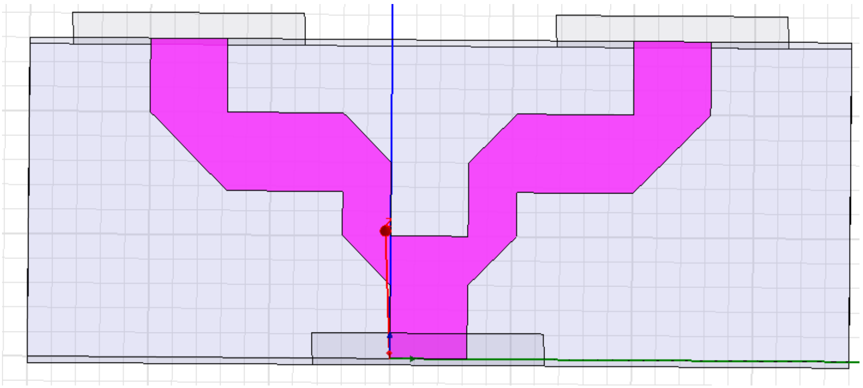


Figure 4.2 HFSS Model of Second Stage Power Combiner

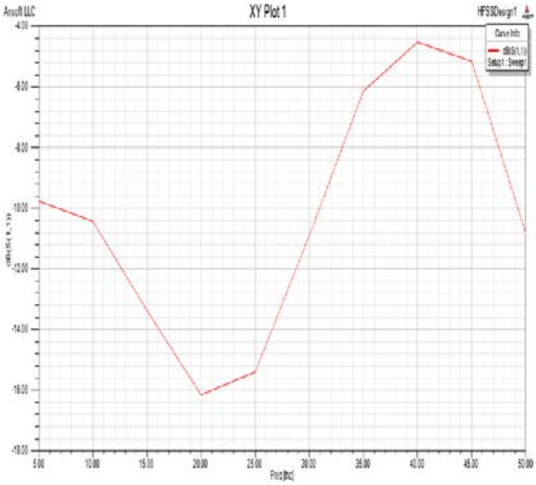


Figure 4.2.1 Reflection achieved from
20 to 50 THz

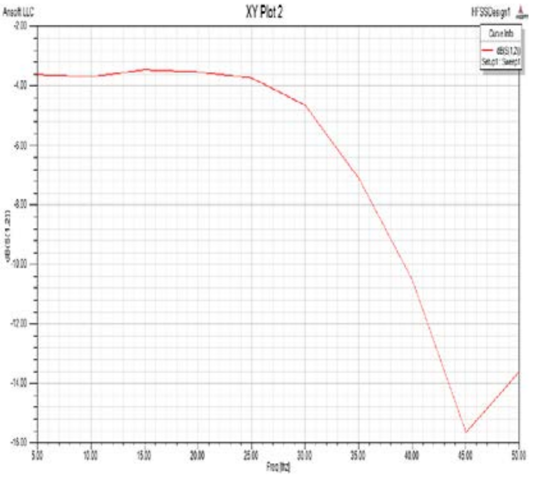


Figure 4.2.2 Coupling achieved from
20 to 50 THz

4.2.3 Third Combiner with spacing of 20 µm

Third stage power combiner model is shown in figure 4.7 and acceptable results of reflection and coupling are achieved from 20 to 50 THz shown in figure 4.8 and 4.9 respectively.

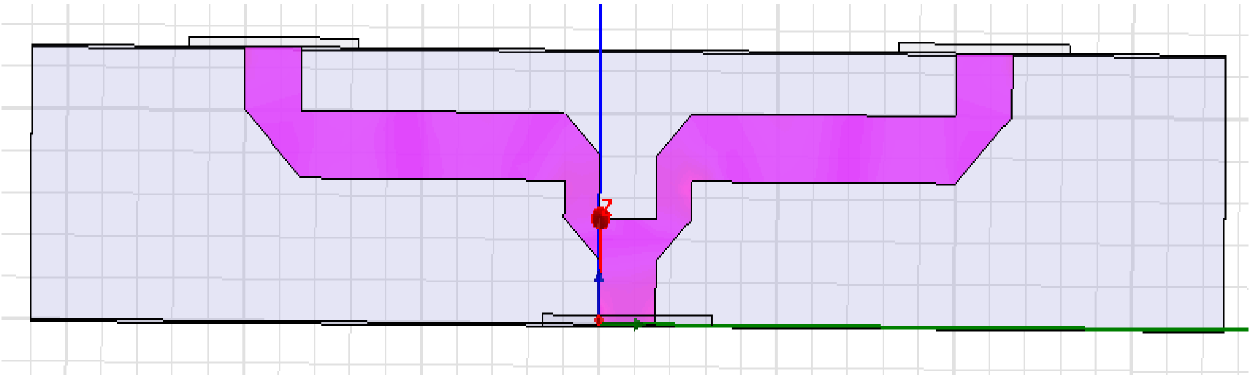


Figure 4.3 HFSS Model of Third Stage Power Combiner

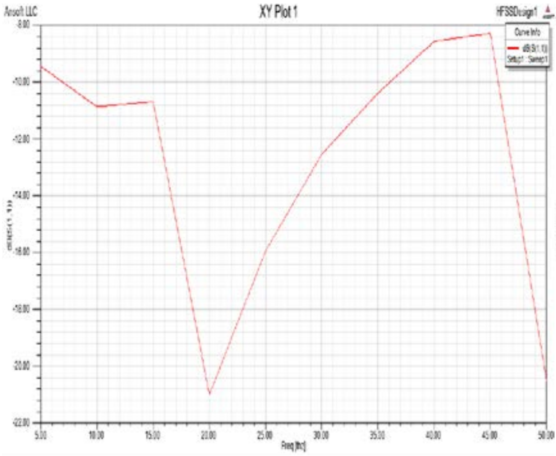


Figure 4.3.1 Reflection achieved from

20 to 50 THz

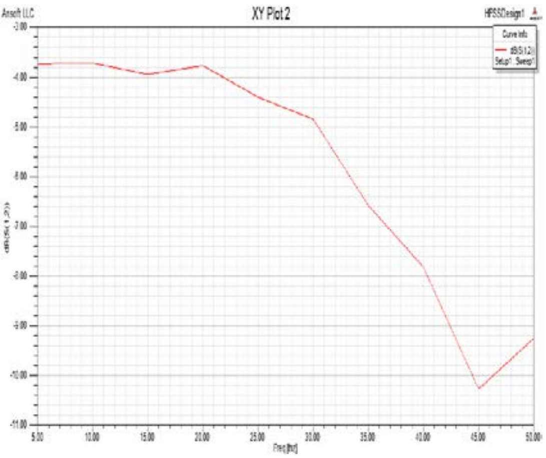


Figure 4.3.2 Coupling achieved from

20 to 50 THz

4.2.4 Fourth Combiner with spacing of 40 µm

Fourth stage power combiner model is shown in figure 4.10 and acceptable result of reflection coefficient curve is shown in figure 4.4.1 and coupling is achieved from 20 to 50 THz as shown in figure 4.4.2.

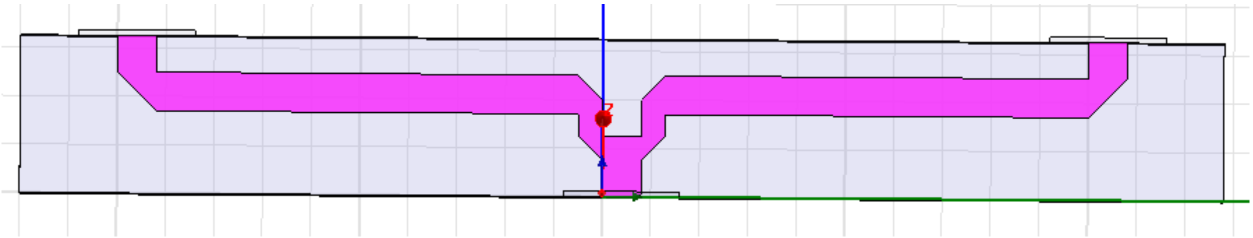
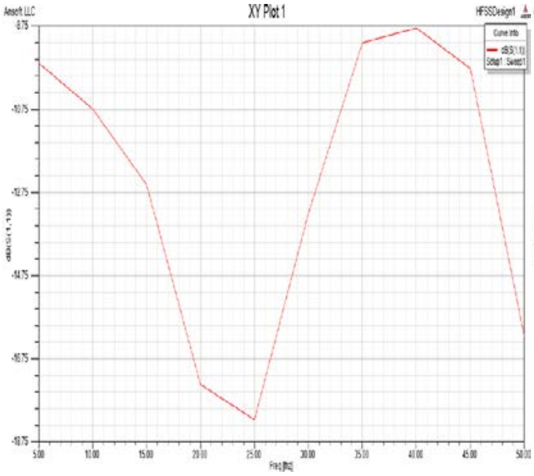


Figure 4.4 HFSS Model of Fourth Stage Power Combiner



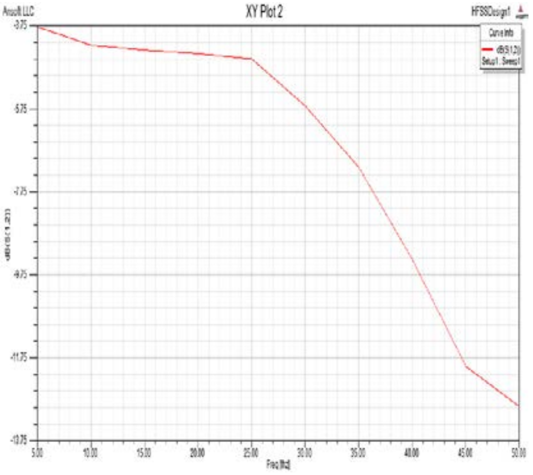


Figure 4.4.1 Reflection achieved from

20 to 50 THz

Figure 4.4.2 Coupling achieved from

20 to 50 THz

4.3 Entire Feed Network

The simulated stages of combiners shown in figures 4.1, 4.2, 4.3 and 4.4 are combined to form a complex corporate feed Network as shown in figure 4.5.

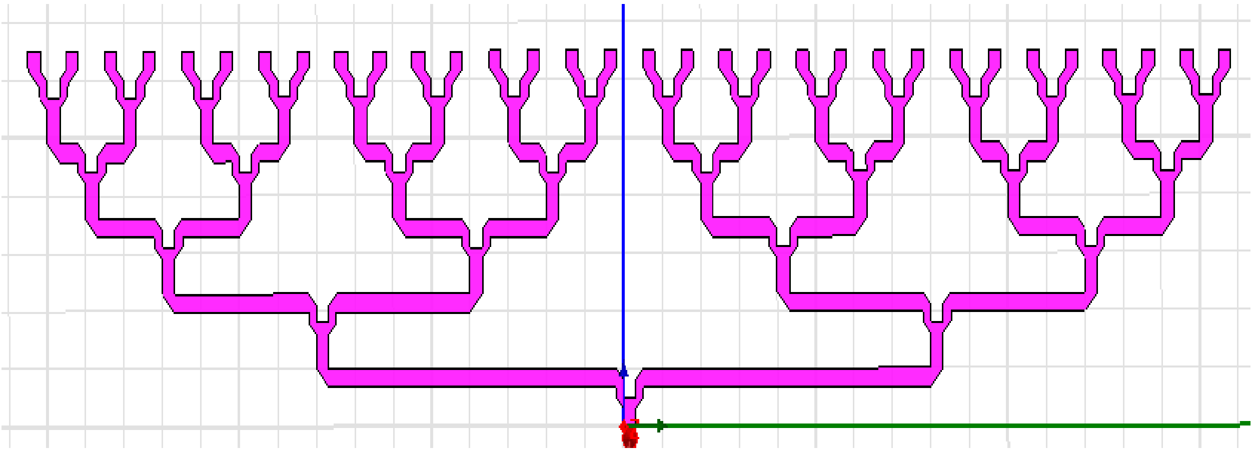


Figure 4.5 Feed Network

The entire feed network shown in figure above is capable of combining the electrical energy of frequency 20THz to 50 THz which allows further use of the combine electrical energy. Frequency range of 20 to 50 THz covers almost 75% of IR spectrum which includes far, mid and near infrared radiations.

4.4. Software Simulation of Solar Corporate Antenna Array

The later part of this chapter provides the final simulated desired structure of solar corporate antenna array which is resulted after the integration of the simulated models in chapter 3 and 4. It provides the **Solar Energy Harvesting** structure which is not only capable of receiving IR efficiently in almost entire IR (near, mid and far) band but also combining the entire power received onto single 50 Ohms matched port.

4.5. Basic 18 Element Solar Corporate Antenna Array

Nine element series arrays of figure 3.6 are integrated with 1st stage power combiner of figure 4.1 to formulate 18 elements corporate antenna array which is shown in figure 4.6.

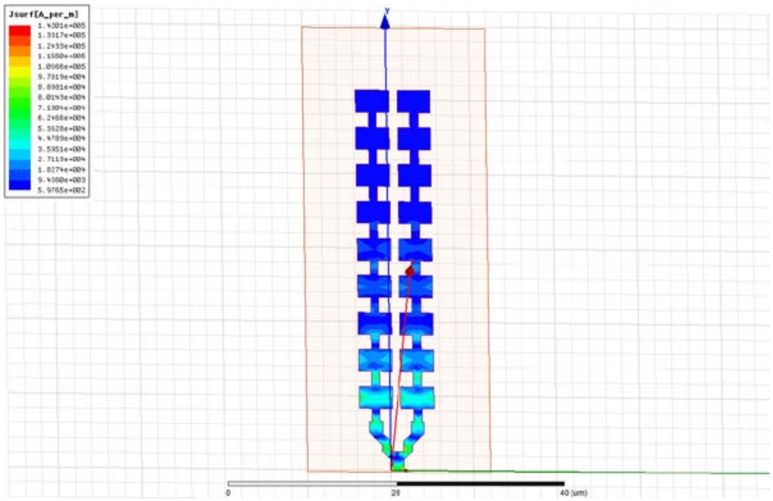


Figure 4.6 18 Elements Corporate Antenna Array

The gain of 18 elements corporate antenna array at frequency of 30 THz is shown in figure 4.7 which is almost 10dBs.

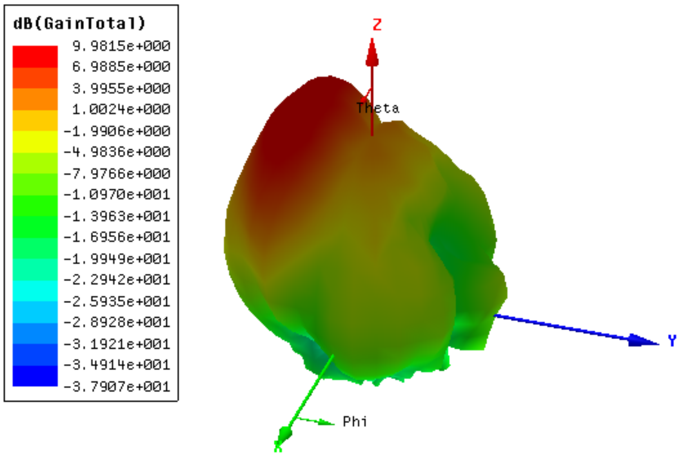


Figure 4.7 Gain of 18 Elements Corporate Antenna Array at Frequency of 30 THz

The difference in gains of figure 3.7.1 and figure 4.7 is not much because of the limited strength of source (wave port in HFSS).

4.6. Solar Antenna Array Structure

Solar antenna array is formed by combining corporate structures of figure 4.6 on multiple stages of power combiners shown in figures 4.1, 4.2, 4.3, 4.4, 4.5. This array looks as in figure 4.8.

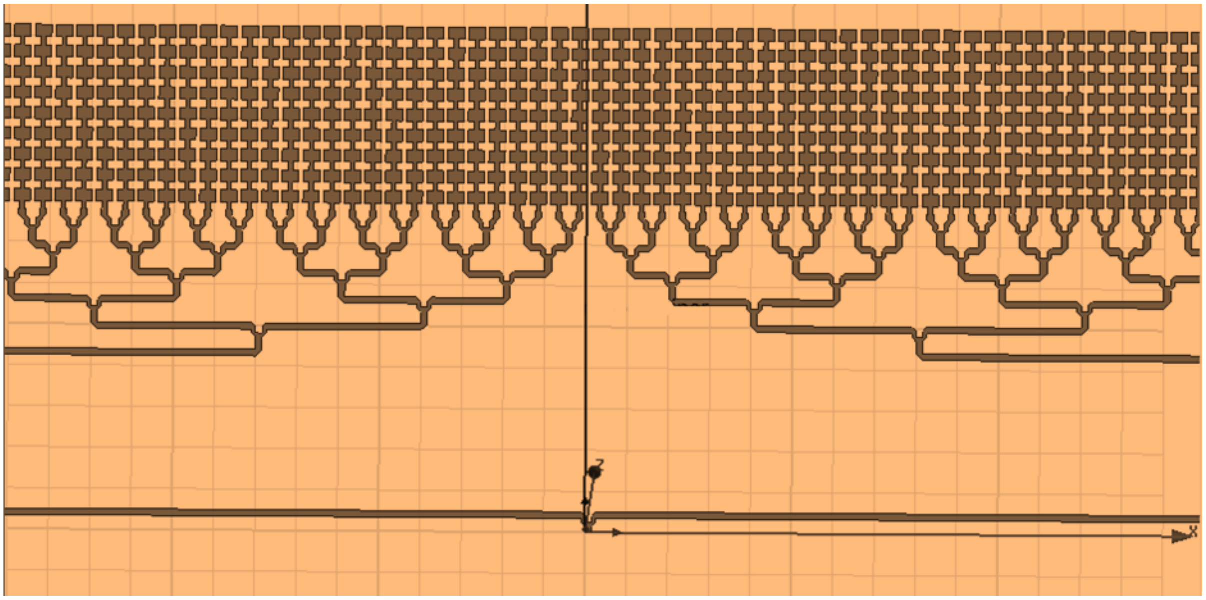


Figure 4.8 Solar Antenna Array Structure

4.7. Three Dimensional Model of Solar Antenna

Before moving on to fabrication phase of project it is now important to understand the desired simulated 3D antenna model which will set the basis for the progress in the fabrication phase. Solar antenna 3D model is shown in figure 4.9. From top to bottom it consists of layers whose consistence is shown in chronological order.

Layer1: Initially layer1 is a simple gold layer with 0.2um thickness which after patterning takes the form of patch and behaves as antenna top surface (dark brown).

Layer2: The dielectric resonant layer of 0.5um thick PTFE (Blue**). Layer3**: The ground layer of gold (Orange). **Layer4**: (Optional) Epoxy is used as base to ease the fabrication process of antenna (grey). Layer1 (without pattern), layer2 and layer 3 are collectively known as substrate.

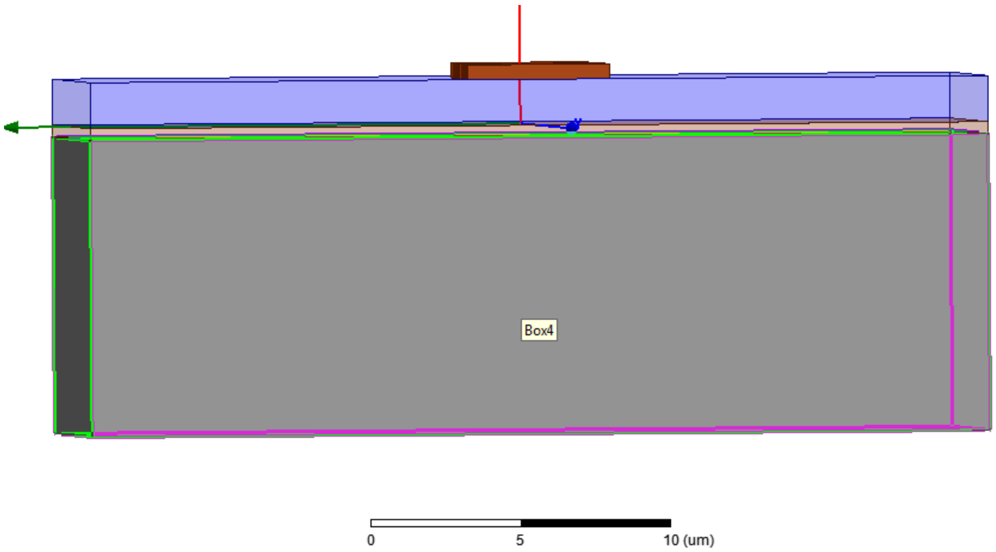


Figure 4.9 3D Model for Solar Antenna

It is important to mention that materials being used in this antenna model are the same which are selected in chapter 2 (Material Selection). Moreover in the current 3D model top layer consists of a single rectangular patch antenna of figure 3.1. The same layer will look much more complex if series and corporate antenna array structures are seen in 3D model. This complexity in top antenna layer leads to the need of some sophisticated tool which can transfer the desired antenna patterns on substrate.

Chapter 5

Hardware Fabrication of Simulated Solar Antenna Models at CMND

5.1. Overview

This chapter discusses how the pursuit for fabrication of multi-layer small structures is done. It starts from the simulated HFSS 3D model and chronologically terminates at the fabricated design. It covers almost all the steps involved in micro/ Nano fabrication of micro antenna in particular and any micro device in general. This chapter covers both software and hardware requirements involved in micro fabrication process.

5.2. Mask development in Ankara, Turkey.

The top layer (layer1) in figure 4.9 requires some sophisticated tool which can transfer the desired antenna patterns on substrate. Mask is one of the technical words used in Nano world for such tool. It is analogous to a stencil which is used to draw shapes/alphabets/numbers over a piece of paper in a precise and sophisticated manner. Mask can be understood as a very small scale stencil which is used to draw/ transfer micro/Nano patterns onto any substrate.

Layer1 of solar antenna 3D model has a minimum feature size of 1um; hence we need the mask with the same preciseness and delicacy. Fabrication of mask is done by Mask writers which are of various kinds. Most of them work on laser or electron beam writing. Mask writer to our access is a laser mask writer which takes input file in “.gds” format. HFSSv.13 being an up to date software of Ansoft exports “.hfss “format to “.gds” format which resolves one of the major problems. This is done by exporting top layer antenna model with limited vertices of 200 from hfss to gds format. The gds format design was sent to Ankara via CMND COMSATS Islamabad and payment for the fabrication of mask was done by CMND. Replica of original mask is seen through optical microscope and it is shown in figure 5.1.

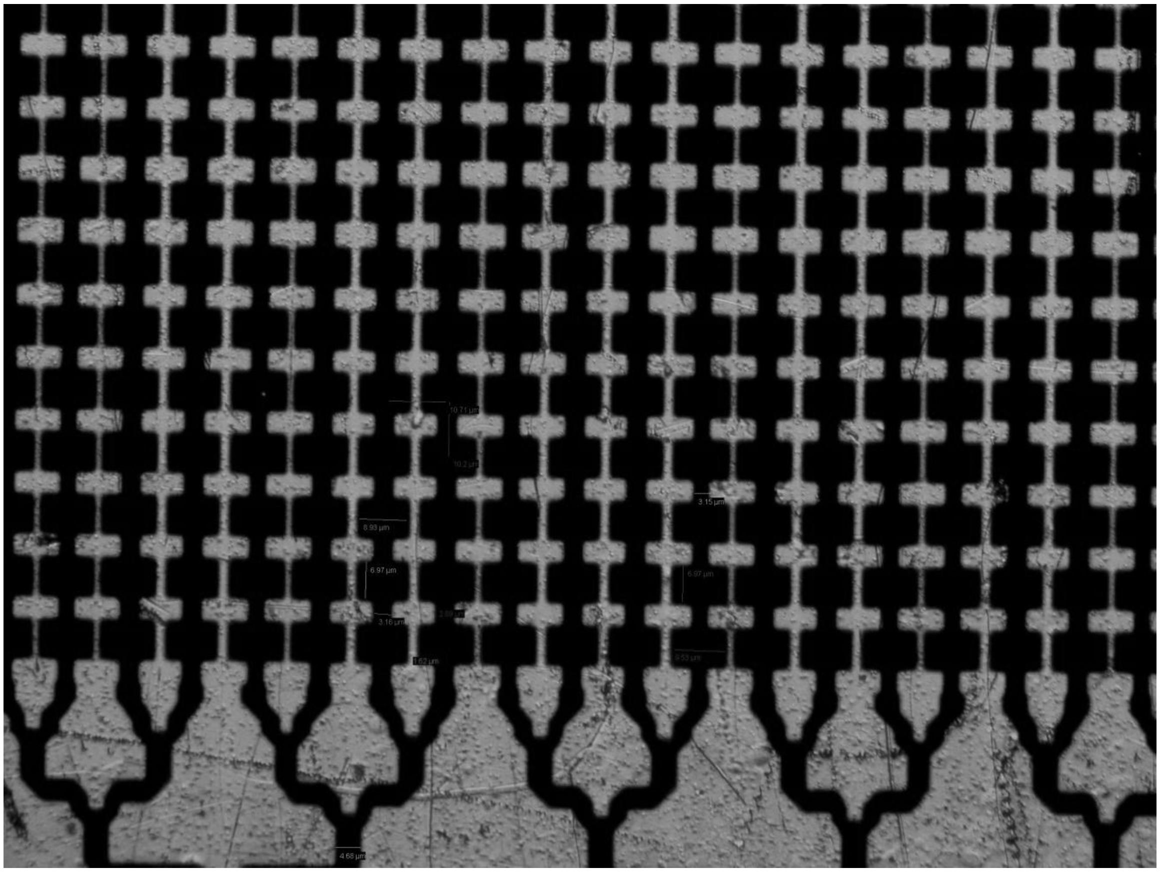


Figure 5.1 The replica of original Mask

5.3. Formation of Substrate

Substrate consists of the several layers as shown in figure 4.9. **Layer1**: Top layer is a simple gold layer with 0.2um thickness. **Layer2**: Middle dielectric resonant layer of 0.5um thick PTFE. **Layer3**: Bottom ground layer is of gold/ copper with minimum thickness. **Layer4**: (Optional) Epoxy is used as base to ease the fabrication process of antenna (grey).

Mask patterns seen in figure 5.1 are required to be transferred on the top layer of substrate. There are a number of techniques in which formation of substrate could be done. While trying out multiple techniques like sputtering our final approach was to build the substrate over 300um epoxy base. This process is completed in following chronology:-

First single clad, 300um thick wafers of Epoxy are purchased from Smart PCB's, Airport road, Rawalpindi. Single clad means that only one side of epoxy wafers are coated with copper whose thickness is set as 7um. Secondly, purchased epoxy clad wafers are cut in a size (2 square inches) which provides ease in fabrication process. This is important because of the fact that clean room equipment has a maximum capability to hold and process three inches of substrate (length/width).

Thirdly these clad wafers are sealed and sent to PTFE suppliers and Spray Coaters in Sialkot. A detailed requirement of the thickness of PTFE and top gold layer were sent and ensured. It took a couple of weeks' time to receive the substrate formulated onto Epoxy clad wafers. SEM measurements were done to ensure the desired thickness of dielectric (PTFE) and top layer of gold. These measurements were done by SEM engineer M.Shams at SCME, NUST.

5.4. Deposition of Photo Resist Film on Top Layer

At this stage of fabrication process the substrate and mask are ready to interact in clean room at CMND for transferring mask patterns onto substrate. First step to do this is deposition of photo resist over the top layer of substrate. Photo resists are of two types i.e. Positive and Negative. Positive photo resist is selected and deposition is done by spin coating machine which sets the thickness of photo resist automatically. Figure 5.2 shows spin coating machine operating in clean room at CMND.

Figure 5.2 Spin Coating Machine Ready for Operation

The substrate is covered by photo resist through spin coating. A viscous photo resist solution is dispersed onto substrate, and substrate is spun rapidly to produce a uniform thick layer. The spin coater runs at 1200 to 4800 rpm for 30 to 60 seconds, and produces desired thickness of layer (usually between 0.5 and 2.5 um). This process results in a uniform thin layer, usually with uniformity of 5 to 10 Nano meters. After the deposition of photo resist onto substrate, sample is now ready for photo lithography.

5.5. Photolithography

Photolithography is also known as "optical or UV lithography". It is a micro fabrication process to selectively remove parts of a thin film/bulk of a substrate. It uses light to transfer a specific pattern from a mask to a light-sensitive chemical called "photo resist", or commonly "resist," on the substrate.

CMND COMSTAS is one of the 5 labs in Pakistan which holds CLEAN ROOM and has the capability of transferring patterns of up to 0.5um through photolithography using sophisticated mask aligner shown in figure 5.3.

Figure 5.3 Photolithographic Mask Aligner at CMND

Transferring patterns from the mask onto photo resist is done by mask aligner expert M.Fahad Bhopal who is the key user of the equipment. Mask is set in vacuum chamber and hard contact is made with the “resist covered substrate”. This contact is made for four exposure cycles of approximately 120 seconds each. This exposure time and cycles are set according to the corresponding feature sizes which are required to be transferred from mask to photo resist. The process is shown in figure 5.4.

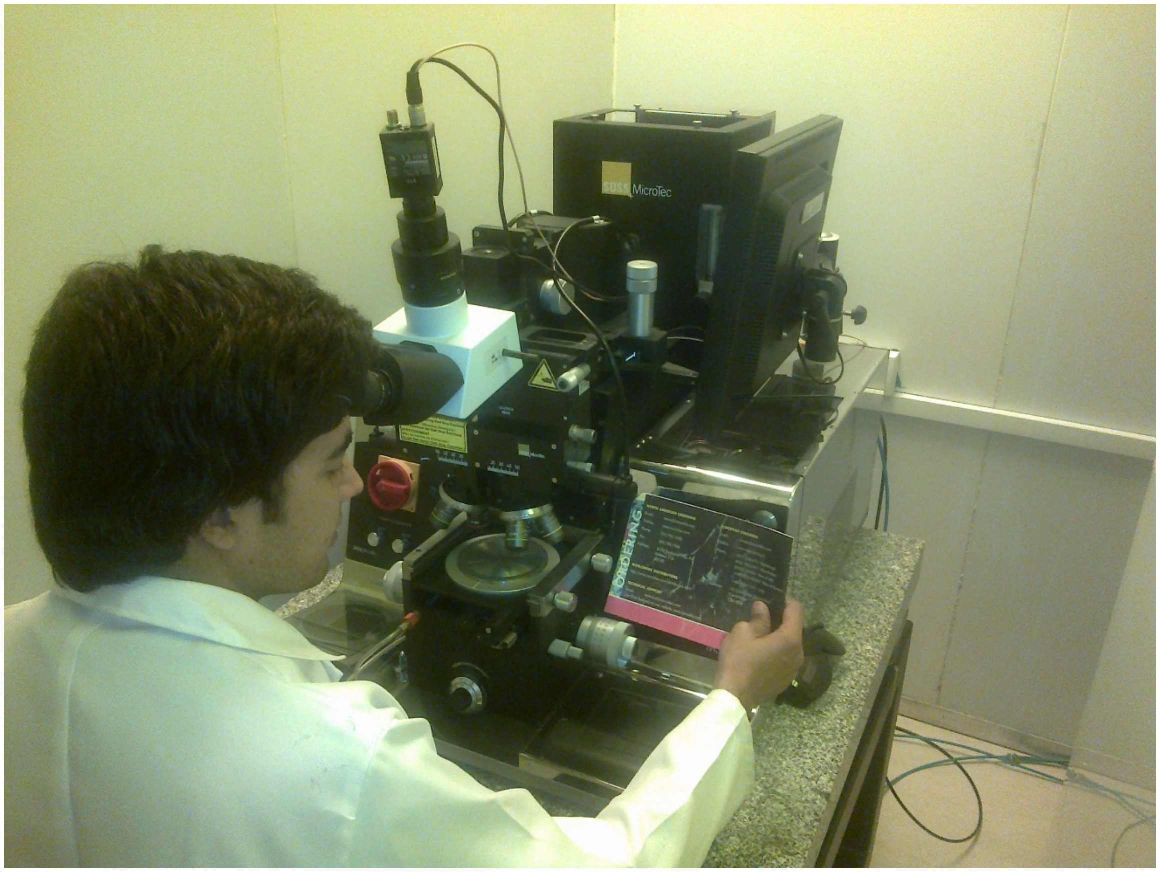


Figure 5.4 Photolithography in Progress

Till now, solar antenna patterns from mask have been transferred onto photo resist coated substrate. To develop better understanding of how photolithography transferred the patterns and how the substrate top surface looks now, optical microscope taken image is shown in figure 5.5.

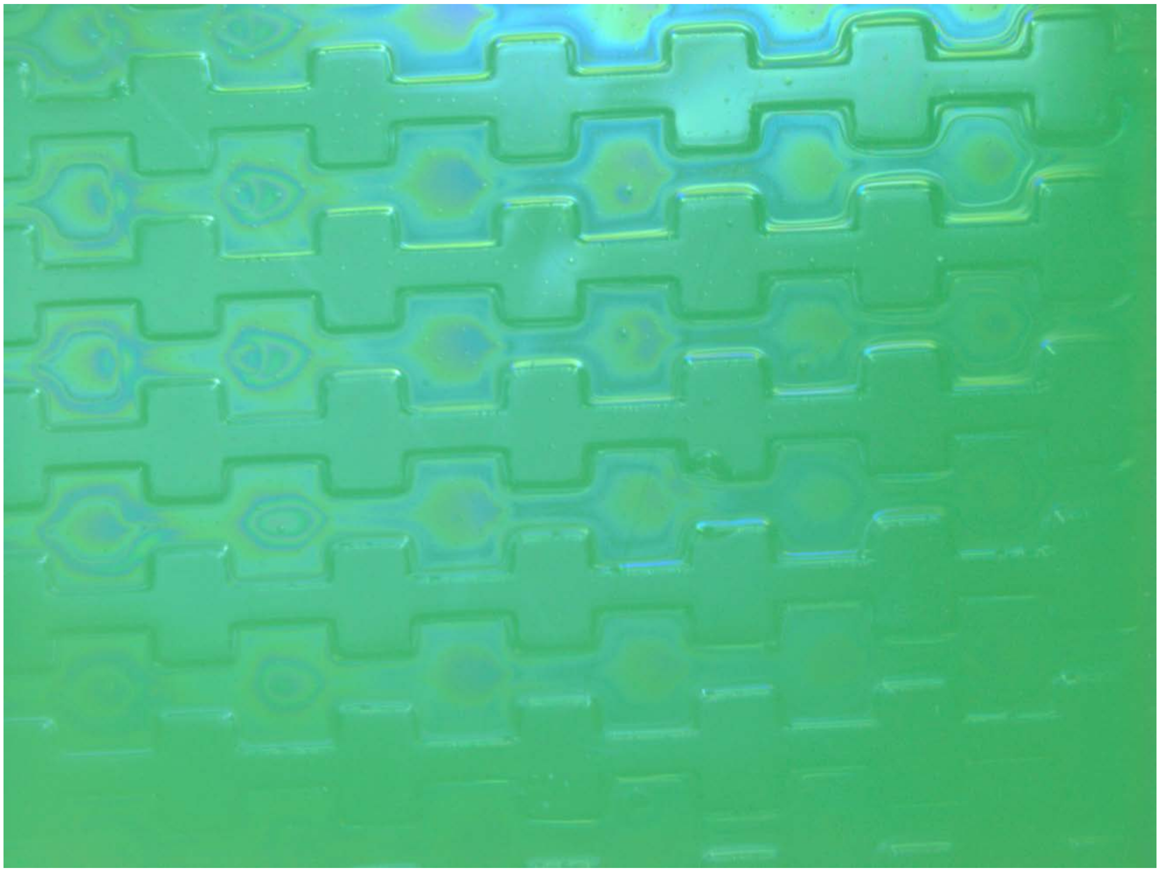


Figure 5.5 Substrate after Photolithography

Close image of same structure is shown in figure 5.6. It gives visual understanding of individual solar antenna elements after developing in chemical. At this stage of fabrication process, photo resist is still wet to some extent. Hence before developing the substrate, firstly, substrate is subjected to 200-300 degrees Celsius temperature so that photo resist is 99.99% dried up and secondly it is dipped in developer for some time so the antenna patterns transferred on photo resist are visible. Figure 5.6 contains invisible patterned photo resist over rectangular series patches.

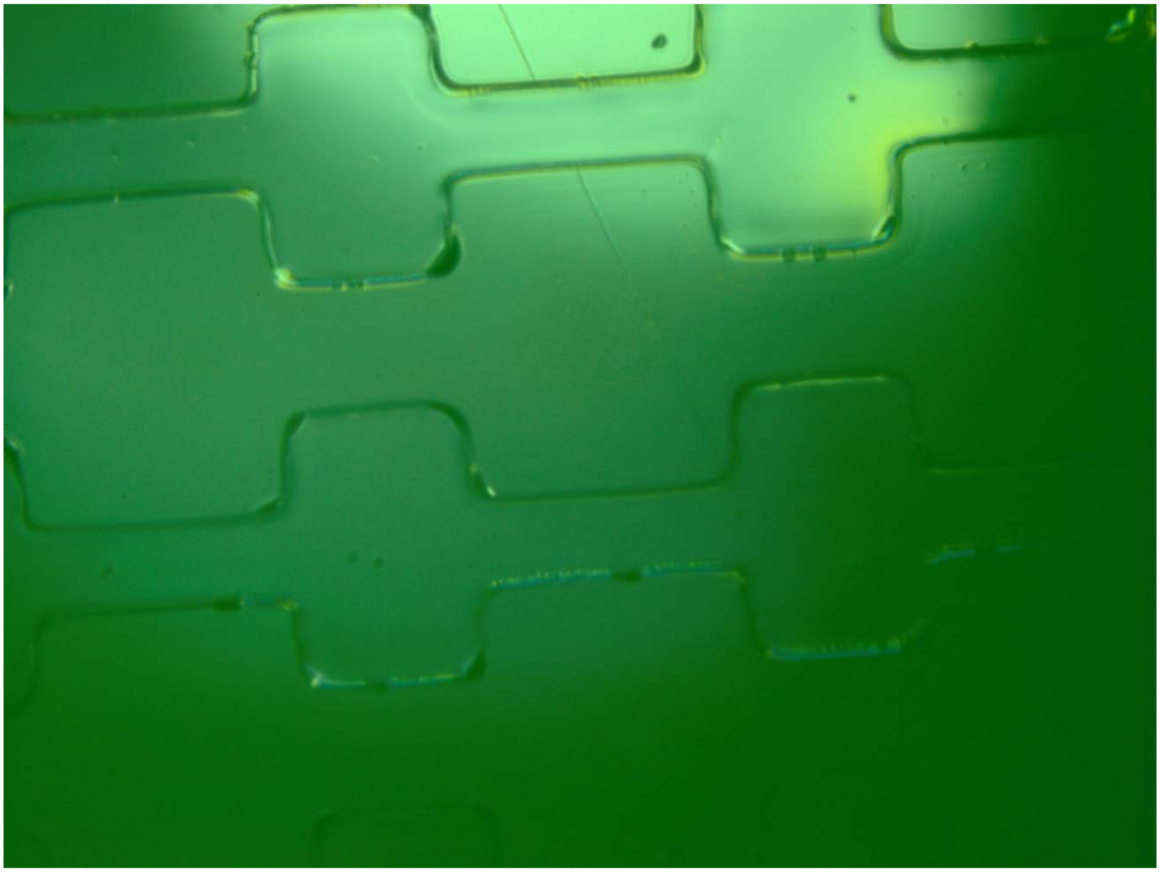


Figure 5.6 Patterned Substrate ready for Plasma Etching

The patterned substrate in figure 5.6 is now ready for plasma etching so that the undesired conducting gold is removed from substrate top layer and original solar antenna can be realized. This figure is showing series 2x2 array in which 2, 2 elements are in series to each other and then parallel to each other. Pattern is not so much clear as edges of each patch antenna are not sharp but rounded, it can be visualized in figure 5.6. It is because of the fact that machine calibration at such small dimension is very difficult. It is the best pattern that we have achieved so far.

5.6. Plasma Etching of Conductor

Substrate at this stage is exposed to plasma etching for 48 Hours. Plasma etching is a process in which those parts of conductor are etched out which are not covered by photo resist. This process is the last step before we claim to make the Novel Solar Antenna practical model in the world and Pakistan’s First Solar Antenna. Plasma etching machine is also a part of clean room equipment and is shown in figure 5.7.

Figure 5.7 Plasma Etching Machine

5.7. Optical Microscopic Images of Pakistan’s First Solar Antenna

Images of the final design taken from optical microscope are as follows Single Rectangular Patch Solar Antenna is shown in figure 5.8. 2 x 1 Series Rectangular Patch Solar Antenna Array is shown in figure 5.9. 4 x 1 Series Rectangular Patch Solar

Antenna Array is shown in figure 5.10. 9 x 1 Series Rectangular Patch Solar Antenna Array is shown in figure 5.11. 9 x 2 Series Rectangular Patch Solar Antenna Array is shown in figure 5.12. 1st stage Power Combiner is shown in figure 5.13. Multi Stage Power Combiner is shown in figure 5.14. n x m Corporate Solar Antenna Array is shown in figure 5.15.

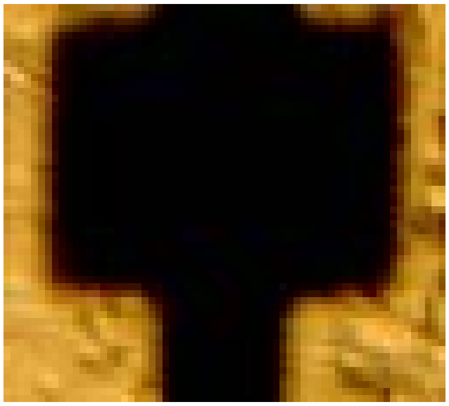


Figure 5.8

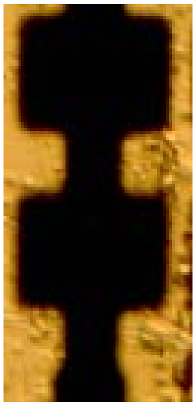


Figure 5.9

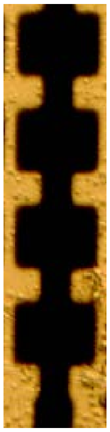


Figure 5.10

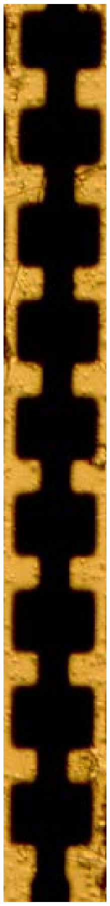


Figure 5.11

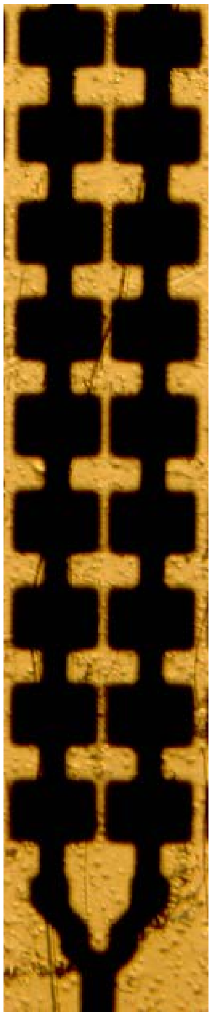


Figure 5.12

Figures 5.8 till 5.12 illustrate the sequential enhancement of solar antennas, so that more and more power could be received upon them. It’s important to envisage that a unit meter square of such solar antenna array can absorb up to 20 Watts of electrical energy from ambient IR EM radiations.

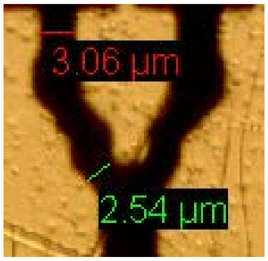


Figure 5.13

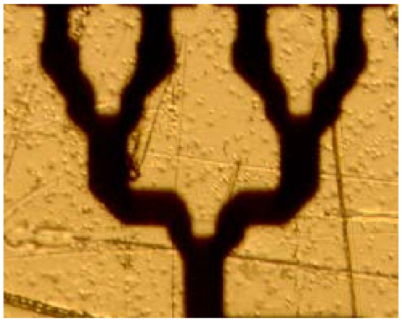


Figure 5.14.1

Figure 5.13, 5.14,1, 5.14.2 gives the visual understanding of fabricated power combiners, their dimensions and feed structure which were simulated as mentioned in chapter 4.

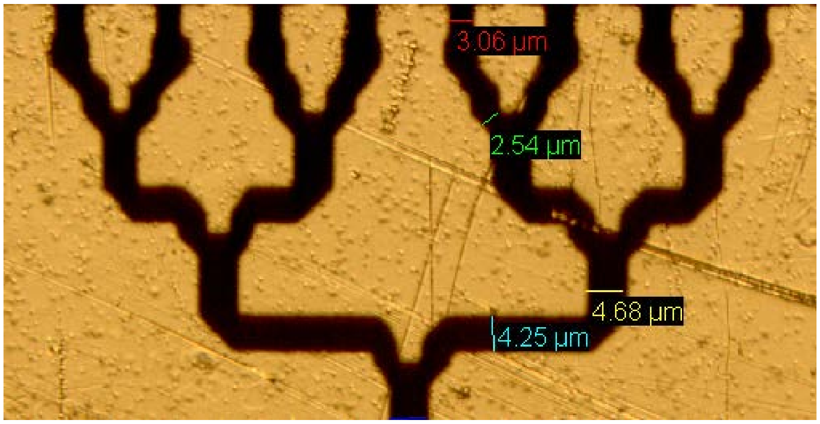


Figure 5.14.2

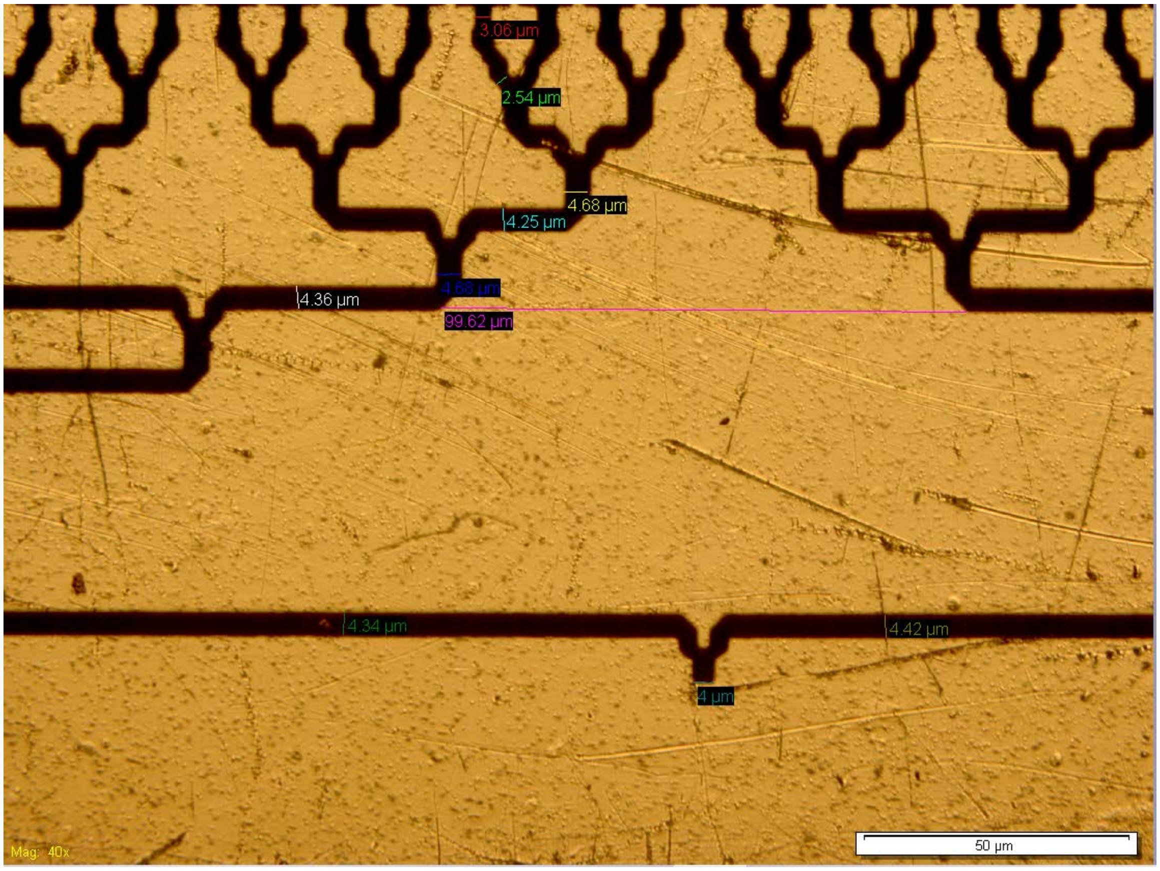


Figure 5.14.3

Figure 5.14.3 also gives the visual understanding of fabricated power combiners and feed structure which were simulated in chapter 4. It also illustrates dimensions of various micro strip lines used in the feeding network [4]. Figure 5.13 may be seen as to visualize the dimensions of minimum feature done at CMND, COMSATS.

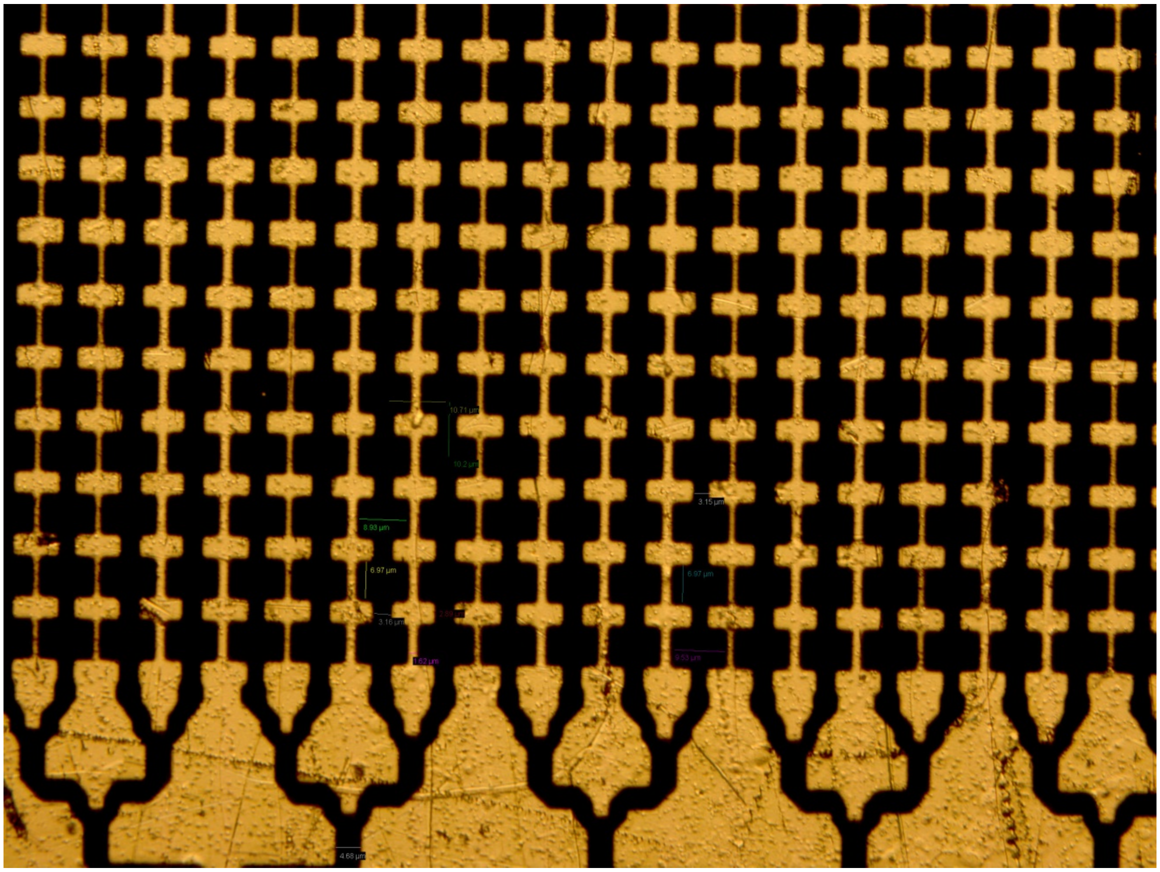


Figure 5.15

Figure 5.15 sets the visual understanding of corporate solar antenna array which is integrated over power combiner of figure 5.14.3. This current integrated structure is capable of receiving ambient and directed EM IR radiations and converting this EM energy to electrical form. Power combiners collect this electrical energy from serial arrays of antennas and combine them onto 50 Ohms matched transmission line. It is important to mention here that the scope of this project is only to receive IR radiations efficiently and by doing so it can be demonstrated that if IR (heat) radiations are received onto antennas, then it can reduce the temperature of surroundings.

Chapter 6

Testing, Analysis and Comparison of Research Work

6.1. Testing

Quantitative and conventional testing is not possible for fabricated solar antenna array because of the unavailability of Vector Network Analyzer (VNA) in THz frequency ranges. IR ellipsiometry is one of another quantitative testing technique which could not be employed because of unavailability of IR wavelength source in CMND and at various Nano labs available in Pakistan.

Different techniques for qualitative testing of IR antennas are also investigated to establish the proof of concept. It is envisaged that as IR antennas are capable of receiving IR (heat) radiations upon them, hence they could be able to isolate a given room covered with IR antenna sheets if heat source is incident upon them. It is implemented by setting up two cubes of equal size on a board and placing thermal sensors in the cubes. Temperature of both the cubes is displayed on 7 segment display above them respectively. The stage for testing is shown in figure 6.1.

Figure 6.1 Testing of solar antenna array: Temperature before Heat Source is applied

In figure 6.1 the left cube (cube1) is covered with IR antenna sheet and right cube (cube2) is covered with substrate only. Temperature of both the cubes is displayed which is almost same when there is no incident heat upon them. Displayed temperature in figure 6.1 is approximately same (cube1= 28 Degrees and cube2= 29 Degrees) which establishes the fact that the thermal sensors are properly calibrated.

After this, spot lights are used to direct heat towards both of the cubes. It is seen that after the incidence of heat upon both the cubes, the temperature of cube2 rises as a function of time. Variation in temperature of both cubes as a function of time after their exposure to heat is tabulated in table 6.1.

Table 6.1 Difference in Temperature as a Function of Time

S.No	**Time after Heat Source is applied (Minutes)**	**Temperature of Cube with IR Antenna (Degree Centigrade)**	**Temperature of Cube without IR Antenna (Degree Centigrade)**	**Remarks (Difference in temperature)**
1.	1	28	30	2
2.	3	28	32	4
3.	5	29	34	5
4.	7	31	36	5
5.	10	32	37-38	6

Table 6.1 shows considerable difference between the temperatures of two cubes which establishes the working of IR antennas on cube1.

6.2. Analysis Based on Testing

Once heat is incident on both cubes, IR antennas can be seen as thermal insulation sheets in one aspect i.e. thermo pore etc. but this IR antenna sheet is far more efficient than thermo pore. As a comparison, it is stated that minimum thickness of thermo pore sheet available is half an inch (12.75mm) and it is capable of reducing the temperature of up to 2-3 degrees whereas IR antenna sheet is capable of reducing the temperature up to 5-6 degrees being 400 um (0.4mm) in thickness. This fact is demonstrated in figure 6.2.

Moreover, it must also be under stood that IR antenna sheets are working on entirely different principle than normal insulation sheets. IR antenna sheets are also more useful than thermal insulation sheets in a sense that they are not only receiving heat radiations and causing reduction of temperature but also collecting the entire energy received upon them onto a single port through extensive and sophisticated power combiners.

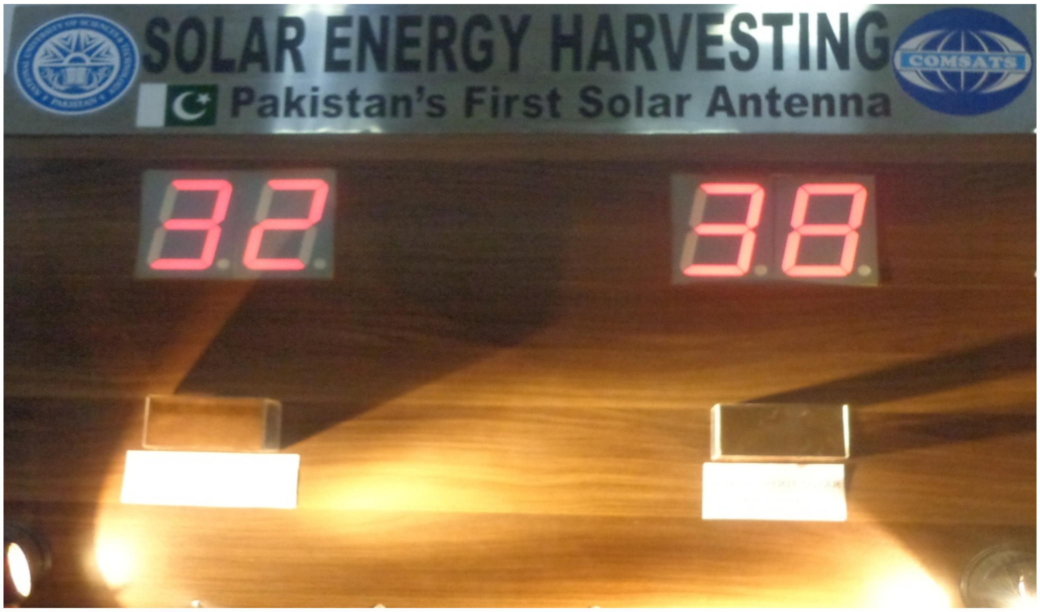


Figure 6.2 Testing of solar antenna array: Temperature after Heat Source is applied

6.3. Comparison with World Wide Research Work

Energy management is the vital issue of every country in the world. Due to the age of this planet earth energy resources like oil and gas are being dried up speedily. USA is one of the main countries who are leading the research in alternate energy resources especially solar energy harvesting. Approach of harvesting the sun's energy through solar radiations using solar antennas was pioneered by Idaho National Laboratories (INL), USA under the supervision of Prof. Steven Novak. The research paper was published on 30th January 2011 by INL, USA. This research paper proved the motivation and pre proof of concept of our proposed final year project. Research work which started at MCS under the supervision and guidance of Dr Naveed Iqbal, Asst Prof Zeeshan Zahid, Dr F.A Bhatti and Lec Safwat Iriza Butt in December 2010 partially terminated in February 2012. Comparison of research work done at INL USA and MCS Pakistan is tabulated in table 6.2.

Table 6.2 Comparison of Research Work

S/No	**Type of antenna**	**Operating frequency Band**	**Power Combiner Band Width**	**Minimum dimension (um)**	**Country of Research work**
1	Rectangular Spiral [1]	30 THz	Not Designed	0.2	USA (figure 7.3)
2	Dipole [2]	30 THz	Not Designed	0.2	USA (figure 7.4)
2	Bowtie [2]	20-40 THz	Not Designed	0.06	USA (figure 7.5)
3	Log periodic toothed [2]	16 – 65 THz	Not Designed	0.2	USA (figure 7.6)
4	Rectangular Patch	20 – 100 THz	20 - 50 THz	1.0	MCS, Pakistan (figure 7.7)

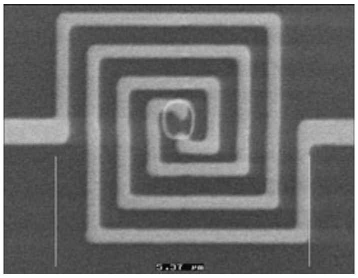


Figure 6.3 Spiral Antenna

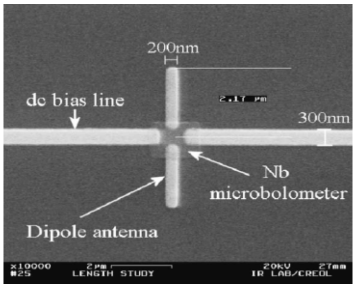


Figure 6.4 Dipole Antenna

Structures of different antennas which can be used for same purpose are shown in figure 6.3 to figure 6.7.

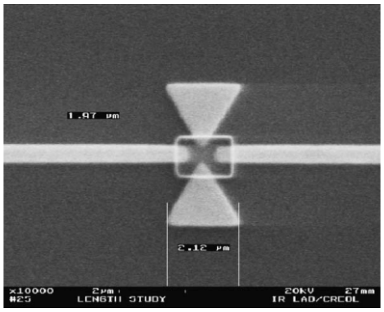


Figure 6.5 Bow Tie Antenna

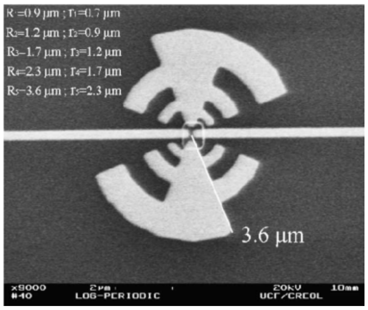


Figure 6.6 Log periodic Antenna

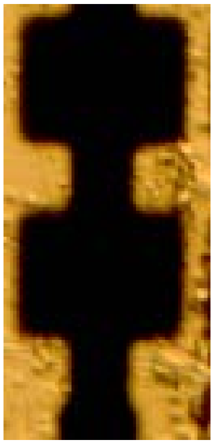


Figure 6.7 Rectangular Patch

Table 6.2 and figures 6.3 through 6.7 summarizes the research work under taken by MCS in comparison to world in general and USA in particular. Our indigenously fabricated solar antenna in figure 6.7 is a better competitor of former solar antennas. It offers better bandwidth and improved minimum dimension of antenna which helps a great extent in micro fabrication process. Getting the resonance up till 100 THz with minimum dimension of 1um is unique achievement in the world so far.

Sun Energy Harvesting Research Initiative (SUNEHRI) at MCS, NUST stands at power with leading worlds UG and PG researchers working in solar antenna. It has honor to be the pioneer in making World’s First Micro Antenna at 30 THz with Minimum Dimension of 1um, Pakistan’s First EM Cooling System, Pakistan’s First Solar Antenna, and Pakistan’s First Research to combine Antenna theory with Nano Physics.

6.4. References of Comparison with World Wide Research Work

This section includes the titles of the research papers from which the comparison in section 6.3 is concluded and also the crux of papers. A bit detail is given to prove the comparison done earlier.

“Solar Nantenna Electromagnetic Collectors *by Dale K. Kotter(Idaho National Laboratory), Steven D. Novack (Idaho National Laboratory), W. Dennis Slafer (MicroContinuum, Inc.)and Patrick Pinhero(University of Missouri)”*

This research paper explores a new efficient approach for producing electricity from the abundant energy of the sun. A Nantenna electromagnetic collector (NEC) has been designed, prototyped, and tested. Proof of concept has been validated. The NEC devices target mid-infrared wavelengths, where conventional photovoltaic (PV) solar cells are inefficient and where there is an abundance of solar energy. Until recent years the nanofabrication methods were not available to fabricate the optical antenna elements. The paper has addressed and overcome both technology barriers.

“Comparison of dipole, bowtie, spiral and log-periodic IR antennas *by F.J. Gonza´lez and G.D. Boreman”*

Antenna-coupled Micro bolometers use planar lithographic antennas to couple infrared radiation into a bolometer with sub-micron dimensions. In this paper four different types of infrared antennas were fabricated on thin grounded-substrates and coupled to micro bolometers. Dipole, bowtie, spiral and log-periodic IR antenna-coupled detectors were measured at 10.6lm and their performance compared. A new method to calculate the radiation efficiency based on the spatial and angular response of infrared antennas is presented and used to evaluate their performance. The calculated radiation efficiency for the dipole, bowtie, spiral and log-periodic IR antennas was 20%, 37%, 25% and 46% respectively. A dipole-length study was performed and shows that the value of the effective permittivity accurately describes the incident wavelength in the substrate at infrared frequencies for antennas on a thin substrate.

Chapter 7

Conclusions and Future Work

7.1. The Rising Future of Solar Antenna Technology

In the full face of developing technology, our solar antenna array will be integrated to a rectifier to make it a solar rectenna (rectifying antenna). In solar rectenna (the future of this project) light is received as EM waves on micro-antennas and converted to DC power using diodes. Semiconductor solar cells have improved over the years but are subject to some fundamental limitations. Long wavelength light is not absorbed, and short wavelength light is only partially used, leading to maximum conversion efficiencies below 30%. Multi-layer cells can improve upon that, but with additional complexity and cost. Semiconductor solar cells also require costly refined materials and transparent conducting layers. In terms of efficiency, solar rectenna is compared to solar cell in table 7.1.

Table 7.1 Comparison between solar rectenna and solar cell

Efficiencies (eff)	**Solar Antenna**	**Solar Cell**	**Remarks**
Energy Flux	25 W/m²/μm²	Depends Upon Incidence Angles/time of day	Flux present is ambient
Energy	Energy Reception	Commercial and	Depending upon

Reception/Conversion	Efficiency= 90%	Laboratory eff= 20 to 40%	nature of material being used in the process
Operating Efficiency	Day and Night	Only in clear sunny day	IR is released from objects, even after the sun is set
Material Requirement	Easily available	Shortage of processed Silicon	
Output Signal	Low frequency AC or DC	DC only	AC can be produced using frequency mixers.
Flexible Working	Does not need direct incidence of solar energy.	Needs direct incidence and tilting of panels towards sun.	As radiation Patterns of antenna can be Omni-directional so it doesn’t require direct incidence.
Cost Efficiency per unit area	$10	$400	Stamp and Repeat process decreases the cost

Solar antenna works on wave nature of light rather than particle nature. Its output current passes through a nanometer-scale UHF diode to get DC and provides usable power. A solar antenna panel would incorporate a large array of millions of these elements deposited onto a substrate. Fabrication costs can be low, with devices processed cheaply in a roll-to-roll process.

The micro antennas' ability to absorb IR radiation makes them promising cooling devices. Since objects give off heat as IR rays, the micro antennas could collect those rays and convert it to electrical form. Such a system could cool down buildings and computers without the external power source required by air-conditioners and fans. But more technological advances are needed before the micro antennas can funnel their energy into usable electricity.

The IR rays create AC in the micro antennas that oscillate trillions of times per second, requiring a component called a rectifier to convert the AC to DC. Today's rectifiers can't handle such high frequencies. We need to design Nano rectifiers that go with our micro antennas. A Nano scale rectifier would need to be about 1,000 times smaller than current commercial devices and will require new manufacturing methods. Another possibility is to develop electrical circuitry that might slow down the current to usable frequencies. If these technical hurdles can be overcome, micro antennas have the potential to be a cheaper and more efficient alternative to solar cells.

Traditional solar cells rely on a chemical reaction that only works for up to 20 percent of the visible light they collect. Scientists have developed more complex solar cells with higher efficiency, but these models are too expensive for widespread use. Micro antennas, on the other hand, can be tweaked to pick up specific wavelengths depending on their shape and size. This flexibility would make it possible to create double-sided micro antenna panels that harvest energy from different parts of the sun’s spectrum. The stamp-and-repeat process in photolithography could also be extended to large-scale roll-to-roll manufacturing techniques that could print the arrays at a rate of several yards per minute.

In principle, the conversion efficiency for rectenna solar cells can be up to 90% but other constraints limit the efficiency to well below this number. The demands placed on the diode are extreme. First, it must operate efficiently at extremely high frequencies—close to a terahertz (10^{12}Hz) for IR light. Second, it must couple electrical power efficiently from the 50 Ohms matched transmission line of power combiner in figure 5.14.3. To do so, the impedance (a measure of the ratio of the voltage magnitude and phase to that of the current in an electronic element) of the diode must match the 50 Ohms impedance of the transmission line.

In future, these micro antenna collectors might charge portable battery packs, coat the roofs of homes and, perhaps, even be integrated into polyester fabric. Double-sided panels could absorb a broad spectrum of energy from the sun during the day, while the other side might be designed to take in the narrow frequency of energy produced from the earth’s radiated heat. At this point, these antennas are good at capturing energy, they’re not very good at converting it but promising research is underway.

In this unique Solar Energy harvesting approach, up to 20 Watts/m^{2}of electricity can be produced. This method can also eliminate the electricity grid, thus making way for energy efficient homes and industry with no waste materials to worry about.

APPENDIX A

MATLAB Code for Micro Strip Patch Antenna

The code takes three inputs to give the corresponding antenna sizes i.e. dielectric resonance layer (substrate) height ‘h’, dielectric constant (permittivity) and desired solution frequency. Formulas are taken from Balanis Book [5]. Code is given as

```
function [ ]= antenna ()
f=input ('plz enter freq for rectangular patch antenna  ');
er= input ('plz enter Er of substrate  ');
h= input ('plz enter height of substrate   ');
formatlong
W= 3*1e8* sqrt(2/(er+1))/(2*f)
Eeff=((er+1)/2)+(((er-1)/2)*((1+12*h/W)^-0.5))
DeltaL=h*(0.412*(Eeff+0.3)*(W/h+0.264))/((Eeff-0.258)*(W/h+0.8));
L=3*1e8/(2*f*sqrt(Eeff))-2*DeltaL
G1= (W*f/(120*3e8))* (1- (1/24*((2*pi*f*h/3e8)^2)))
x=0:1:pi;
func=((sin(pi*f*W.*cos(x)./3e8)./cos(x)).^2).*besselj(0,(2*pi*f*L.*sin(x)./3e8)).*((sin(x)).^3)
G12= sum(func)/(120*pi^2)
Rin=1/(2*(G1+G12))
Yo=(L/pi)*acos(sqrt(50/Rin))
A=(50*sqrt((er+1)/2)/60)+(er-1)*(0.23+0.11/er)/(er+1);
Wo=h*8*exp(A)/(exp(2*A)-2)
```

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