

## List of Figures

Figure 1. 1 satellite solar power station (SSPS) [1] .....	2
Figure 1. 2 A 10 GW SSPS baseload plant model [29].....	5
Figure 1. 3 1979 SSPS Reference System Concept (GEO) [7] .....	7
Figure 1. 4 Sun Tower based SSPS model from NASA's 1995-1997 Fresh Look Study [29].....	8
Figure 1. 5 (a) Integrated with the symmetrical concentrator. (b) Unmanned Space Experiment Free Flyer (USEF) proposed a tethered model of SSPS. (c) Thin film solar based model [1].....	9
Figure 1. 6 view of the first rectenna made by Raytheon Co. (1963) [28] .....	11
Figure 1. 7 some early rectennas [28].....	12
Figure 1. 8 (a) Half- wave rectifier (b) Single Shunt Rectenna (c) Single stage voltage multiplier (d) Villard charge pump (e) Dickson charge pump (f) Modified Cockcroft-Walton charge pump [10] .....	14
Figure 2. 1 Satellite solar power station [5] .....	20
Figure 2. 2 Electrical energy available from the terrestrial photovoltaic and SSPS [2].	22
Figure 2. 3 Directive beam propagation [10].....	28

Figure 2. 4 A properly designed phase antenna array with amplitude tapering is utilized for Gaussian beamforming [65] .....	29
Figure 2. 5 Gaussian beam propagation [65] .....	30
Figure 2. 6 Microwave power transmission in space [48] .....	32
Figure 2. 7 A pilot control Microwave power transmission [17].....	33
Figure 2. 8 Microwave power transmission impacts and assessment on space [1] .....	34
Figure 2. 9 Cost variation with antenna size .....	39
Figure 2. 10 LCOE for different GW power at 2.45 GHz .....	40
Figure 2. 11 LCOE for different GW power at 5.8 GHz .....	41
Figure 3. 1 Rectenna block diagram [72] .....	44
Figure 3. 2 RF-DC conversion Efficiency of rectifying diode with different input power .....	45
Figure 3. 3 Equivalent circuit model of a rectenna system .....	46
Figure 3. 4 Antenna matched to rectifier using conjugate impedance matching [76] ....	48
Figure 3. 5 Commercially available, packaged Schottky diodes (SOT- 23), and their equivalent circuit model [80] .....	52

Figure 3. 6 Real and imaginary parts of the input impedance of the Schottky diode HSMS-286X versus frequency for a maximum available power level of 0 dBm calculated using the analytical model and harmonic balance (HB) simulations.  $R_a = 50 \Omega$  ..... 54

Figure 3. 7 Real and imaginary parts of the input impedance of the Schottky diode HSMS-286X versus frequency for a maximum available power level of 5 dBm calculated using the analytical model and harmonic balance (HB) simulations.  $R_a = 50 \Omega$  ..... 54

Figure 3. 8 Design layout a CP 2.45 GHz rectenna with CMRC ..... 56

Figure 3. 9 CP 2.45 GHz rectenna with CMRC and Zoomed view of CMRC ..... 57

Figure 3. 10 Antenna with CMRC measured return loss ..... 58

Figure 3. 11 CP antenna measured axial ratio and gain ..... 58

Figure 3. 12 Measured return loss and insertion loss of CMRC ..... 59

Figure 3. 13 Rectifier's input impedance (a) complex (b) real and imaginary value variation with input power (dBm), here zim3 is input impedance of the rectifier and pin is RF input power ..... 60

Figure 3. 14 Smith chart utility in ADS ..... 61

Figure 3. 15 The simulated and measured efficiency of CP rectenna with CMRC ..... 62

Figure 4. 1 Geometry of proposed circular polarization antenna with harmonics suppression, the parameters (values in mm) are,  $W_s = 60$ ,  $L_s = 80$ ,  $R = 16.3$ ,  $R_s = 11.7$ ,  $T_p = 4.1$ ,  $S_w = 4$ ,  $S_g = 4.5$ ,  $W_1 = 0.7$ ,  $W_2 = 3.02$  ..... 67

Figure 4. 2 Surface current orientation at (a) 0. (b) 90. (c) 180. (d) 270 degrees, here degree means time progress in one period. ....	68
Figure 4. 3 Simulated and measured return loss .....	70
Figure 4. 4 Surface current densities of the proposed antenna's resonance at (a) Fundamental (2.45 GHz). (b) Second order (4.75 GHz). (c) Third order (6.75 GHz)....	71
Figure 4. 5 Simulation of proposed antenna with varying Tp (values in mm) .....	72
Figure 4. 6 Simulation of proposed antenna with varying Rs (values in mm).....	73
Figure 4. 7 Simulation of proposed antenna with varying Sg (values in mm).....	74
Figure 4. 8 Simulated and measured radiation pattern of the proposed antenna (a) E- plane (b) H- plane .....	75
Figure 4. 9 Simulated and measured axial ratio .....	75
Figure 4. 10 Single source antenna connected to a rectifier circuit .....	76
Figure 4. 11 Circuit diagram of a Single driven rectifier .....	77
Figure 4. 12 Circuit schematics of the proposed single-driven rectifier, the parameters are, L1= L2= 2.5 mm, L3= 8.2 mm, L4= 8.2 mm, L5= 3 mm, L6= 7.1 mm, L7= 9.7 mm, L8= 7.4 mm and W1=W2=W3=W4= 1.12 mm,W5= 2.4 mm, W6= 5.1 mm, W7= 3.8 mm, W8 = 3.5 mm, C1= 1 pF, C2= 4 pF, C3= 4 pF, RL= 1200 ohm .....	78

Figure 4. 13 (a) direct measurement of differential source fed antennas using rat race coupler to transform two ports into single port (b) Differential source fed rectenna (b) RF voltage applied to the diode in differential source fed condition ..... 79

Figure 4. 14 Differentially operated antenna ..... 81

Figure 4. 15 A differentially driven (a) rectifier schematic with (b) measurement setup ..... 82

Figure 4. 16 Variation of efficiency (%) with different RF input power (dBm), simulated results ..... 82

Figure 4. 17 Variation of Output DC power (Watt) with different RF input power (dBm), simulated results ..... 83

Figure 4. 18 Circuit schematics of the proposed differentially driven rectifier, the parameters are,  $W_1=W_2=W_3=W_4=W_{12}=W_{13}=W_{14}= 1.2 \text{ mm}$ ,  $W_5=W_{15}= 3.4 \text{ mm}$ ,  $W_6=W_9= 1.3 \text{ mm}$ ,  $W_7 = W_{10}= 3 \text{ mm}$ ,  $W_8=W_{11}= 5.5 \text{ mm}$  and  $L_1= 6.5 \text{ mm}$ ,  $L_2= 4.5 \text{ mm}$ ,  $L_3=L_{13}= 9.2 \text{ mm}$ ,  $L_4=L_{14}= 10.2 \text{ mm}$ ,  $L_5=L_{15}= 5.7 \text{ mm}$ ,  $L_6= L_9= 4.9 \text{ mm}$ ,  $L_7=L_{10}= 7.5 \text{ mm}$ ,  $L_8=L_{11}= 4.9 \text{ mm}$ ,  $C_1= 32 \text{ pF}$ ,  $C_2= 91 \text{ pF}$ ,  $C_3= 4 \text{ pF}$ ,  $RL= 1800 \text{ ohm}$  ..... 84

Figure 4. 19 The simulated and measured efficiency of single fed and differentially fed rectenna ..... 86

Figure 5. 1 Detailed geometry of microstrip antenna array (a) single fed antenna array, (b) differentially fed antenna array, the parameters are,  $L_1=L_2=L_3=L_4=L_5=L_6=18.69$ , &  $W_1=W_2=W_3=W_4=W_5=W_6= 2.39$   $L_{1a}= 19.23$ ,  $L_{1B}= 14.65$ ,  $L_{1c}= 110.34$  ..... 91

Figure 5. 2 Surface current densities of the proposed antenna at 5.8 GHz .....	93
Figure 5. 3 Simulated and measured return loss .....	94
Figure 5. 4 Simulated and measured radiation pattern of the single fed antenna array at 5.8 GHz (a) E- plane (b) H- plane .....	95
Figure 5. 5 Simulated and measured radiation pattern of the proposed differentially fed antenna array at 5.8 GHz (a) E- plane (b) H- plane .....	96
Figure 5. 6 Rectenna components .....	96
Figure 5. 7 Rectifier schematic .....	97
Figure 5. 8 Rectifier input impedance's real and imaginary value variation .....	98
Figure 5. 9(a) Circuit schematics of the proposed single-driven rectifier, the parameters are, L1= 2.5, L2= 2.5, L3= 8.2, L4= 8.2, L5= 3, L6= 7.1, L7= 9.7, L8= 7.4 and W1=W2=W3=W4=W5= 1.2, W6= 5, W7= 3.9, W8 = 3.4, C1= 1 pF, C2= 4 pF, C3= 4 pF, RL= 1000 ohm (b) measurement setup.....	99
Figure 5. 10 Variation of Output DC power (Watt) with different RF input power (dBm) .....	100
Figure 5. 11 Variation of efficiency (%) with different RF input power (dBm).....	101
Figure 5. 12 measured efficiency and output power of single fed and the proposed differentially fed rectenna .....	102

Figure 6. 1 Harmonics harvester Rectenna at 2.45 GHz with fundamental rectifier output voltage ( $V_1$ ) and harmonic rectifier output voltage ( $V_{HH}$ ), circuit with individual matching load resistance.....	107
Figure 6. 2 Power versus Resistive load for the fundamental rectifier ( $P_1$ ) and harmonics rectifier ( $P_{HH}$ ) .....	109
Figure 6. 3 Harmonic Harvester Rectenna for Battery Charging .....	110
Figure 6. 4 Fundamental rectifier output and harmonic rectifier output are interfaced through switches integrated with buck-boost converter .....	111
Figure 6. 5 High-frequency period ( $T_{HF}$ ) and low-frequency period ( $T_{LF}$ ), Duration of pulsed operation of switch Q1 is $kT_{LF}$ , and $Q_{HH}$ is $(1-k) T_{LF}$ , inductor current waveform in fixed frequency DCM with on time $t_1$ and off time $t_2$ .....	113
Figure 6. 6 (a) Channel 3- $Q_{HH}$ gate drive voltage, channel 2- Q1 gate drive voltage (b) Fabricated harmonics harvester Rectenna circuit. The numbers in parenthesis are the length and width of transmission lines ( $l, w$ ) in millimeters .....	115
Figure 6. 7 Output DC power versus input RF power .....	115
Figure 6. 8 Harmonic Harvester Rectifier Efficiency versus input RF power .....	117