Wideband Energy Harvesting System Based on Circularly Polarized Monopole Antenna

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Abstract – This project presents a radio frequency harvesting system designed to cover GSM 1.8 GHz (1.6-2.1GHz), and WLAN 2.5 GHz (2.2 –2 .8 GHz). The system consists of two-part: A wideband circularly polarized monopole antenna with IBW of (1.55-2.47 GHz) and AR-BW of (1.80-2.62 GHz) and a rectifier circuit to convert the collected RF signal to DC power with a wideband range of frequency starting from 1.5 GHz to 2.7 GHz with minimum output voltage of 0.14 V at input power -10 dBm, and the maximum output voltage of 7.14 V at input power 20dbm, and the maximum efficiency is 67.1%,. the proposed rectenna shows the following measured results: At frequency 1.8 GHz at 0dbm the DC output volage equal 180 mV, at 20dbm the DC output volage equal 1.73V. At frequency 2.1 GHz at 0dbm the DC output volage equal 150 mV, at 20dbm the DC output volage equal 1.6 V. At frequency 2.4 GHz at 0dbm the DC output volage equal 0.13 V, at 20dbm the DC output volage equal 2.1 V.

Keywords — Rectenna, electromagnetic energy harvesting, monopole antenna, circularly polarized antenna, voltage doubler.

I. Introduction

Radio Frequency Energy Harvesting (RFEH) is a technology that has an increasing interest in energy harvesting. The rectenna, which is a combination of a rectifier and an antenna, is a device to harvest wireless energy in the air which enables wireless power delivery to multiple devices from a single energy source. The main components of this technology are the antenna and the rectifying circuitry that converts the RF signal into DC power. The devices which are using Radio Frequency (RF) power may be integrated into Wireless Sensor Networks (WSN), Radio Frequency Identification (RFID), biomedical implants, Internet of Things (IoT), Unmanned Aerial Vehicles (UAVs), smart meters, telemetry systems and may even be used to charge mobile phones. Aside from autonomous systems such as WSNs and RFID, the multi-billion portable electronics market from sensors to smart phones– would be an attractive application for RF energy harvesting if the power requirements are met and investigating the potential for ambient RFEH in this project.

In [1] the proposed A cross-dipole antenna with wide bandwidth to receive signals at range (1.7-2.5 GHz) with parallel feed lines is convenient to connect with a low-pass filter. While, the proposed rectifier circuit work with wide bandwidth at range (1.7-2.5 GHz). The design achieves a maximum efficiency 57% at 1.7 GHz and a maximum DC output voltage equal 1.4 V at input power equal 20 dBm. In [2] The proposed Slot antenna with wide bandwidth to receive signals at range 2.15-2.9 GHz. The rectifier is composed of a voltage doubler rectifying circuit and a matching network. The system achieved a maximum output voltage of rectenna system is 1.5 V at the input power of 20 dBm. In [3] The proposed Fractal planar hexagon-shaped monopole antenna array was used to cover a wide range of frequency from 0.91 GHz to 2.55 GHz. The Rectifier circuit upper branch is designed to matched around 2.1 and 2.4 GHz, while the lower branch is designed to get the circuit matched around 0.9 and 1.8 GHz. The series-mounted Schottky diode HSMS285C from Avago is used for the rectifier circuit. The output DC voltage is 1.47 V at input power 20 dBm. In [4] The antenna operates well at several frequencies including at 2.3GHz (WiMax), 2.4 GHz (WLAN), 2.6 GHz (LTE/4G) and also 5.2 GHz (WLAN) is fed by a coplanar waveguide (CPW) line where the central conductor is separated from a pair of ground planes. The CPW offers several advantages including the ability to work in lower frequencies and ease of fabrication. fabricated on a double-sided FR-4 printed circuit board using an etching technique. The rectifier circuit is suitable for the energy harvesting system that been conducted at frequency range of 2 GHz to 4 GHz. The maximum DC voltage that has been achieved from the rectenna is 1.023 V at 20 dBm.

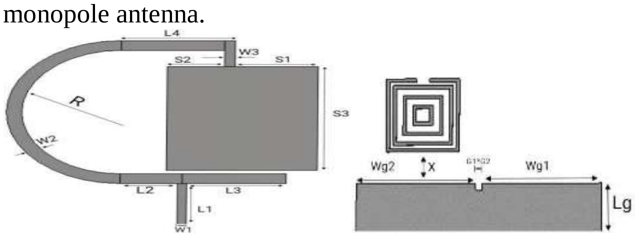
II. Antenna Design

Nowadays circular polarization is very important in the antenna design industry, it eliminates the importance of antenna orientation in the plane perpendicular to the propagation direction. It gives much more flexibility to the angle between transmitting & receiving antennas. For circular polarization to be generated in microstrip antenna two modes equal in magnitude and 90° out of phase are required Microstrip antenna on its own doesn't generate circular polarization. The circular polarization allows wave reception with minimum polarization loss regardless of the transmitter and the receiver antennas orientations and reduces the multipath reflections effect which gives a freedom mobility of transmitter and receiver devices.

A CP antenna presented in [5] was designed to cover the frequency band from the largest RF contributors, ranging from 1.73 to 2.61 GHz in GSM1800, UMTS, WiMAX and ISM bands. Hence, a simple single feed electromagnetic (EM) coupled circularly polarized antenna with high gain is presented. The wideband CP is achieved by implementing EM coupled feed with a defected ground plane structure.

Experimental results showed the antenna achieved an axial ratio bandwidth of 25% with respect to 2.08 GHz center frequency. [6] A special feeding technique of an off-centered microstrip feedline slot-coupled circularly polarized (CP) cylindrical dielectric resonator antenna (DRA) for 2.4-GHz industry, science and medicine (ISM) band applications Good CP characteristics can be achieved using two coupling points with a quarter-wavelength path difference and 90° phase shift, resulting in a series feeding circuitry. The 10-dB impedance bandwidth and the 3-dB axial ratio of the proposed antenna are 141 and 85 MHz, respectively. In [7] a circular polarized microstrip-fed patch antenna with improved bandwidth and harmonic suppression, to enhance the impedance bandwidth and harmonic suppression. The bandwidth of proposed CP antenna around 1260MHz (1.69-2.95GHz) is 18 times higher than traditional CP antenna. CP antenna has axial ratio (AR) bandwidth of 550 MHz i.e. 22.91% covering the frequency range of (2.21GHz - 2.76GHz). In [8] the microstrip antenna can be used for RFID application especially for tag antenna. The existed RFID tag antenna usually use dipole model to get the maximum performance. However, the dipole antenna which has linear polarization performance has disadvantages on alignment that makes data detection on RFID cannot be accurate. The antenna covers 2.4 GHz of its frequency range of 2 up to 3.3 GHz which S-parameter level below -9.54 dB and the direction of the transmitted power omnidirectionally and has circular polarization at frequency range of 2.39 until 2.46 GHz which has axial ratio below 3dB.

The proposed antenna is a wideband circularly polarized monopole antenna.



(a) (b)

Fig. 1 The design of the proposed monopole antenna(a) top view, and (b) bottom view.

The proposed antenna achieves BW of (1.55- 2.49 GHZ) and AR-BW of (1.80-2.62 GHZ) Figure 1 shows the proposed wideband circularly polarized monopole antenna is printed over the two-sides of Rogers 4003C substrate with relative permittivity of 3.38, 0.81 mm thickness and loss tangent of 0.0027 with a total area of 57 x 60 mm2.

TABLE I

DIMENSIONS OF THE PROPOSED MONOPOLE ANTENNA

W1	L1	W2	L2	L3	L4	R	W3	S1
1.8	13	3	19.1	11.1	22	19	2	16
S3	LG	WG1	WG2	X	G1	G2	S2	
32	8.5	18	18	4.75	1	1	11	

The proposed antenna consists of C-shaped with a rectangle shape monopole fed with a linear line used to match the radiator with the 50-ohm port and on the other side of the substrate a partial ground modified by a rectangular slit and rectangular stub with one split ring resonator and two square ring resonators are printed. The dimensions of the antenna are optimized using CST optimization techniques and listed in table.1all dimensions in mm. In order to explain the procedure of the antenna design, four antennas (Ant. 1-4) are illustrated in figure.2 while figure.3 shows the reflection coefficient and axial ratio simulation results of the four antennas (Ant.1-4) in figure.4. As shown in figure.2 (a), the C-shaped conventional monopole produces its fundamental resonance at 1.54GHz and the initial length of the monopole is quarter wavelength at its resonance frequency. By using the rectangular stub, a new resonance has been added at 1.58GHz which expands the IBW from 1.58GHz to 2.38GHz, while adding the rectangular stub and four -square resonators with initial length of the outer resonator edge equal to quarter wavelength at its resonance frequency in step 3 can excite extra resonance at 1.57GHz which can improves the impedance matching at higher band. For the simulated axial ratio shown in figure.4 the C-shaped radiator in step 1 can provide the perturbation of current distributions in x and y directions due to its curved structure Thus, CP operation can be realized by splitting the fundamental resonant mode into two near-degenerate modes along the orthogonal arms of the C-shaped monopole. Moreover, the main function of the rectangular slit added on the ground in step 2 is to break the surface current distributions balanced on the unmodified ground in step1, so that a single CP mode is excited at 1.95GHz.The resonators considered offset-coupled with the C- shaped monopole, while the rectangular stub can be used to couple with the open-loop and the C- shaped monopole, so that by adjusting the dimensions and positions of the square resonators and the rectangular stub embedded on the ground plane in step 3, a CP mode can be excited at 1.80GHz by properly proximity coupling of the C-shaped monopole and the resonators which improves the AR at the higher band. The combination of step 2 and step 3makes the proposed design (step4) which achieves IBW of (1.55-2.47 GHz) and AR-BW of (1.80-2.62 GHz).

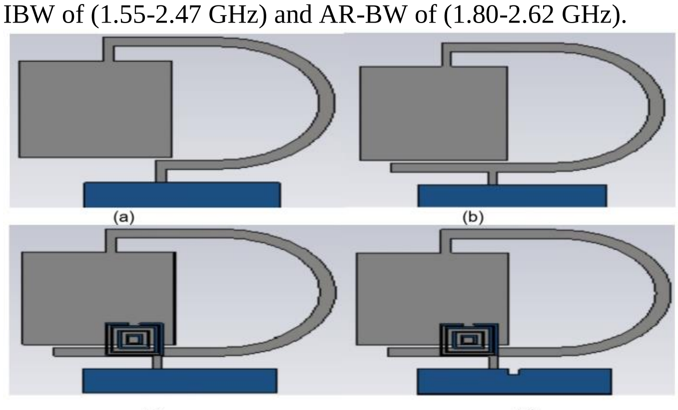


Fig .2 The design procedure of the proposed antenna (a) step 1, (b) step 2, (c) step3 and (d) step 4.

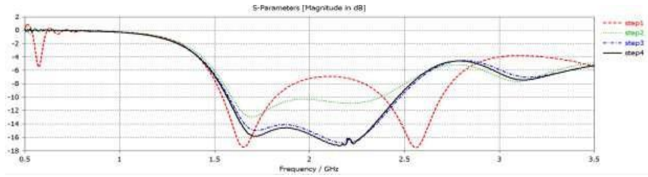


Fig. 3 The simulated results for Ant. 1-4 return loss

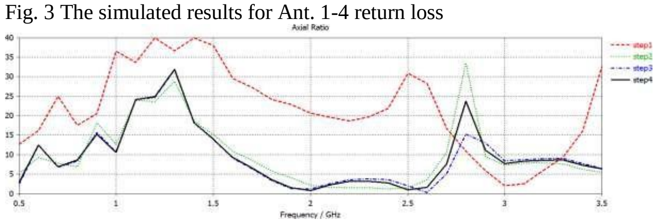


Fig. 4 The simulated results for Ant. 1-4 axial ratio

For further explanations of the operation of the CP mechanism, Figure.5 shows the simulated surface current distribution at 2.1GHZ for the phases of 0˚, 90˚, 180˚and 270˚. In this figure, the black arrow represents the direction of the predominant surface current which rotates counterclockwise. Hence, right-hand CP (RHCP) waves in the broadside direction (+Z axis) can be excited.

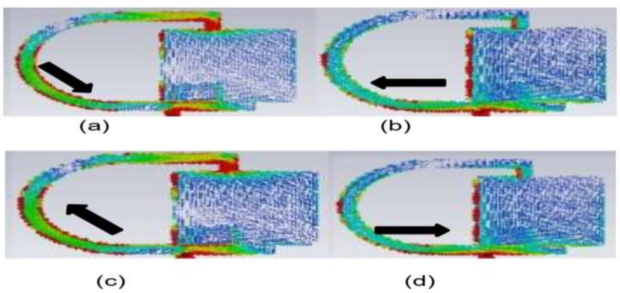


Fig. 5 Simulated surface current distributions of the proposed antenna at 2.1GHz at four different phases (a) 0°, (b) 90°, (c) 180°, (d) 270°.

The simulated realized gain over the entire operation band of the proposed CP monopole antenna is shown in figure.6 the antenna archives maximum realized gain of 4.27dBi with 3.61dBi average value. The simulated antenna simulated E-plane and H-plane radiation patterns at 2.1 GHz shown in figure 7 wherein the antenna has quasi-bidirectional radiation patterns in XZ and YZ planes.

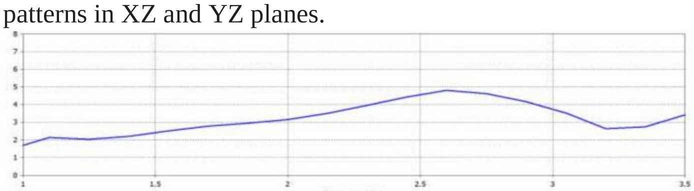


Fig. 6 The simulated realized gain of the proposed circularly polarized monopole antenna

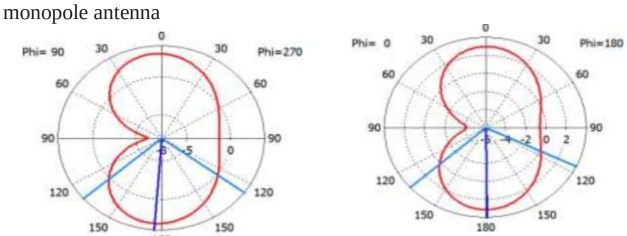
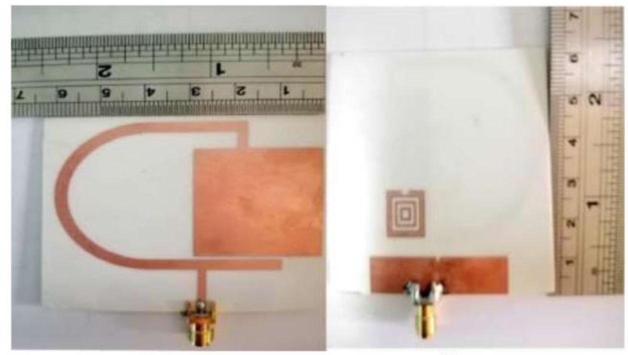


Fig .7 The simulated E-plane and H-plane radiation patterns at 2.1 GHz

The antenna has been fabricated using the photolithographic technique. Figure.8 shows a photograph of the fabricated antenna which is printed over the two-sides of Rogers 4003C substrate with relative permittivity of 3.38, 0.81 mm thickness and loss tangent of 0.0027 with a total area of 57 x 60 mm2. The input reflection coefficient has been measured using a ROHDE&SCHWARZ ZVA 67 vector network analyzer. The simulation and measurement results are illustrated in Figures.9.



(a) **(b)**

Fig.8 Photograph of fabricated antenna. (a) front view, and (b) back view

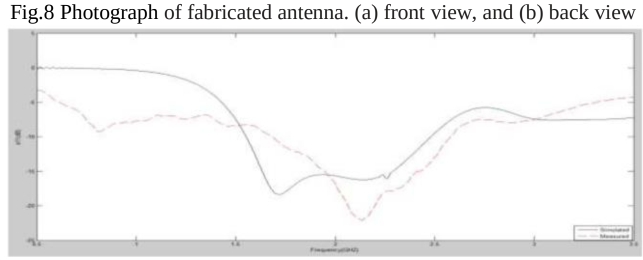


Fig .9 The simulated and measured reflection coefficient of the antenna

TABLE II

COMPARISON OF PROPOSED WIDEBAND ANTENNA WITH ANOTHER SAME ANTENNAS

Reference	Dielectric constant	Size (mm x mm)	Sensing band -10dB IBW GHZ	Sensing band 3 dB AR-BW GHZ
[5]	4.6	66x66	1.8-2.6	1.9-2.4
[6]	4.4	60x60	2.36-2.51	2.4-2.48
[7]	4.4	56x56	1.68-2.95	2.21-2.76
[8]	4.4	30x40	2-3.3	2.39-2.45
This work	3.38	57x60	1.55-2.49	1.8-2.62

III. RECTIFIER PERFORMANCE ANALYSIS

Rectifier circuit is the second part of our Energy harvesting system; it is the responsible part for receiving power which comes from antenna, and transforming power to DC Volt.

In [9] a 1.8–2.6 GHz wideband rectifier is designed for radio frequency (RF), using this method, three RF bands, i.e. GSM1800, UMTS and WLAN, are covered. The theoretical analysis is confirmed by simulations and measurements. From measurements results, the prototype has output voltage of 0.5V, and RF-to-DC conversion efficiency is 42% at 0dbm from 1.8 to 2.6 GHz. In [10] A compact broadband rectifier for microwave energy harvesting has been proposed. This approach utilized a novel three-stage transmission lines-based impedance matching technique to achieve a broadband rectifier with excellent RF to DC conversion efficiency. The fabricated broadband rectifier achieved a conversion efficiency of more than 50% at a 5 dBm input power, there design has the smallest overall dimension 24×36 mm2 at Rogers 4350B material of 1.52mm thickness with a relative permittivity of 3.48, The result of output voltage is 3.1V and conversion efficiency is 58% at 10 dBm. In [11] presented the design and the realization of an antenna and a rectifier circuit for RF and microwave energy harvester. Our study is focused on the analysis of the suitable rectifier circuit for capturing the set RF power, from wireless and mobile communication networks, operational in the frequency band (0.890 - 4) GHz, they have obtained just 1V output DC with efficiency 54.5% at 0dbm. To improve this result, they have to replace the passive electronic elements by elements under microstrip technologies. In [12] circuit can collect signals efficiently over broad bandwidth spanning from 0.87 to 2 GHz which includes UHF ISM 900 MHz, GSM 900 and 1800 MHz, wireless communication, PCS, and ISM 2.4 GHz. In order to obtain sufficiently large rectifier bandwidth, a matching circuit based on high-pass type L-section for lower band impedance matching and inductive L-section for higher band impedance matching is proposed. The rectifier circuit is constructed using voltage doubler configuration with Schottky diode SMS7630-005LF. The rectifier circuit is fabricated on 0.8-mm low-cost commercial FR-4 substrate with $\varepsilon r = 4.4$ and $\tan\delta = 0.02$, The rectifier has a measured conversion efficiency exceeding 40% from 870 MHz to 2.5 GHz at 0 dBm input power and a load terminal of 2 k and a dc output voltage equal to 1 V.

The proposed rectifier has input impedance must be 50 ohms to maintain the maximum power. It consists of three main parts: a broadband-matching network, a single stage Schottky diode, and a dc pass filter. The rectifier topology is the voltage doubler. It contents two diodes; each one of them is rectifying different half of the cycle. This topology could be considered as a combination of series and shunt diode rectifiers, it is the part responsible for transforming power to DC volt. for low power coming from antenna Schottky diodes can achieve the highest rectifier efficiency, but the output voltage is not high. To increase the output voltage, we select the single-stage voltage double configuration (25). Two single diodes of Schottky diodes (SMS7630-079LF) are suitable for low-power RF EH, the output DC voltage will be twice the incident voltage. The capacitor adopts the Murata GRM18 series, where C1 = C2 = C3 = 100 PF. Matching circuit is designed to match between the output impedance of antenna and input impedance of voltage doubler. The standard output impedance of antenna is 50 ohms, so we calculate the Input impedance of voltage doubler circuit and put it in smith chart.

By using Roger material 4003C with dielectric constant $\mathcal{E}r = 3.38$, thickness h= 0.81mm, and loss tangent 0.0027, The optimized size of the entire circuit is W1=2.1, W2=3.5, W3=0.3, W4=4.4, L1=17.8, L2=1, L3=13.4, and L4=18 all dimensions in (mm), ADS used to simulate the circuit, and the results that we get from the schematic design are different from the results of circuit after fabrication so we used layout, shape of circuit in schematic is shown in Figure.10.

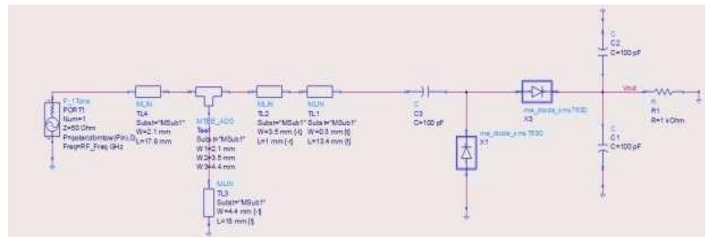


Fig. 10 Schematic diagram

The rectifier becomes a wide band rectifier circuit started from 1.4 GHz to 2.6 GHz as shown in Figure.11 and at 1.8 GHz the matched impedance was 40.35 Ohms with minimum voltage of 0.175V and maximum voltage of 8.46V, and the maximum efficiency is 71.5%.

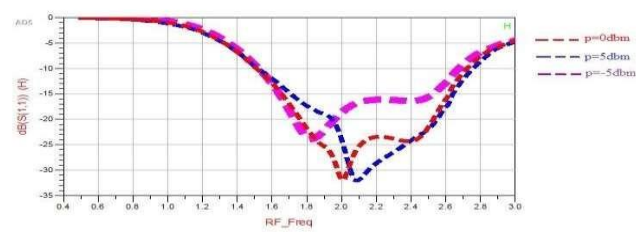


Fig 11 Result of s11 of schematic circuit at different input power

To make the rectifying circuit more compact, the microstrip line is bent, the fabricated circuit shown in Figure.12.

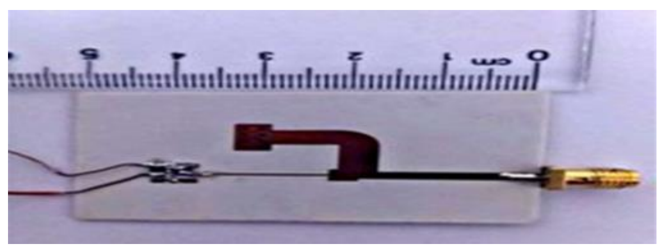
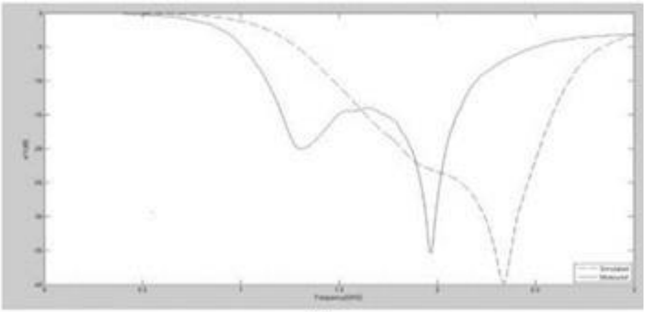
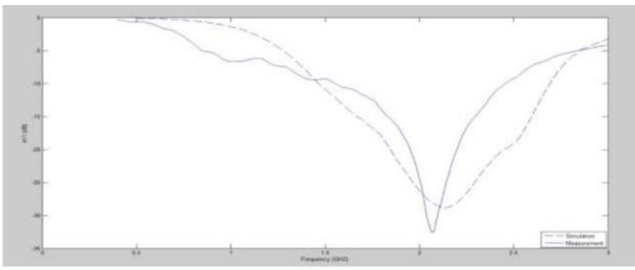


Fig.12 Photograph of fabricated rectifier

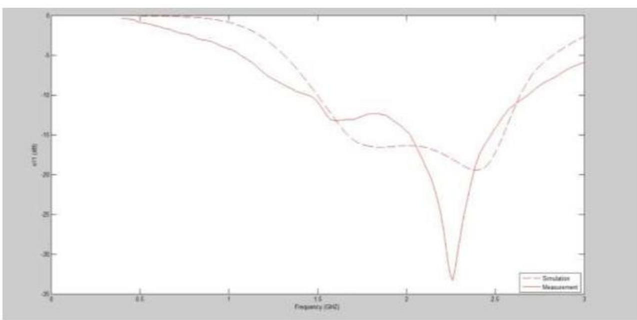
The measured results are slightly frequency shifted due to manufacturing tolerances and inaccurate diode modeling. The input reflection coefficient has been measured using a ROHDE&SCHWARZ ZVA 67 vector network analyzer simulation and measurement results are illustrated with different input power in Figures.13.



(a)



(b)



(c)

Fig.13 (a) Measured and simulated S11 of the rectifier for power 0 dBm (b) Measured and simulated S11 of the rectifier for power -5 dBm (c) Measured and simulated S11 of the rectifier for power 5 dBm..

After measured the output voltage by using RF signal Generator. The minimum output voltage is 0.14 V at input power -10 dBm, and the maximum output voltage is 7.14 V at input power 20dbm, and the maximum efficiency is 67.1%, Figure.14 shown the measured and simulated output voltage, Figure.15 shown the measured and simulated Efficiency.

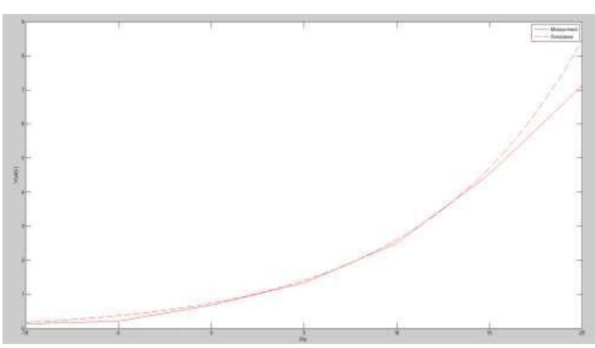


Fig.14 The measured and simulated output voltage

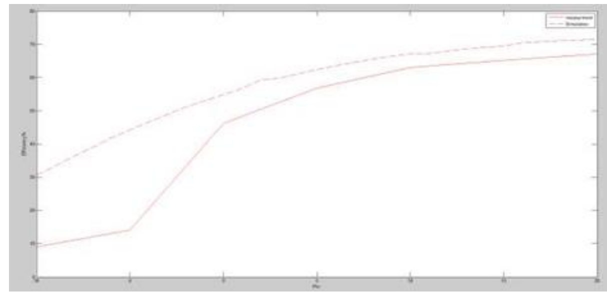


Fig.15 The measured and simulated Efficiency

TABLE III
COMPARISON OF PROPOSED WIDEBAND RECTIFIER WITH ANOTHER SAME RECTIFIERS

Ref	BW(GHz)	Maximum Output Voltage	Maximum Efficiency%
(9)	0.8	0.5	42%at 0dBm
(10)	1.3	3.1	58%at 10dBm
(11)	3.1	1	54.5%at 0dBm
(12)	1.13	1	40% at 0dBm
This work	1.45	7.14	63% at 10dBm

IV. RECTENNA MEASUREMENT RESULTS

This part presents the measurement results of the assembled RF harvesters in the context of wireless power transfer by using RF signal Generator and horn antenna. By connect the Rectifier circuit with monopole antenna far away from horn antenna by 5 cm (the far field of antenna) it shows the results: At frequency 1.8 GHz at 0dbm the DC output volage equal 180 mV, at 20dbm the DC output volage equal 1.73V. At frequency 2.1 GHz at 0dbm the DC output volage equal 150 mV, at 20dbm the DC output volage equal 1.6 V. At frequency 2.4 GHz at 0dbm the DC output volage equal 0.13V, at 20dbm the DC output volage equal 2.1V as shown in Figure.16, and Performance comparison of the proposed reconfigurable rectenna and others shown in table.4.

Fig.16 The process of measured rectenna system with monopole antenna

TABLE IV
PERFORMANCE COMPARISON OF THE PROPOSED RECONFIGURABLE RECTENNA AND OTHERS

Reference	Band width (GHZ)	Antenna type	Type of diode	Maximum output voltage at 20dBm
[1]	1.7-2.5	Dipole antenna	HSMS2852	1.4 V
[2]	2.15-2.9	slot antenna	HSMS2852	1.5 V
[3]	0.9-2.55	monopole antenna array	HSMS285C	1.47 V
[4]	2.2-5.6	Coplaner antenna	HSMS286B	1.023 V
This work	1.55-2.49	monopole antenna	HSMS7630	2.1 V

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