Multi-Bandwidth CPW-Fed Open End Square Loop Monopole Antenna for Energy Harvesting

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***Abstract*—Compact CPW-fed open end square loop monopole antenna is presented. The antenna can harvest ambient power at different radio frequencies of 1.8, 1.9, 2.4 and 5.2 GHz. The multi-band coplanar waveguide antenna (MCPW) is designed and fabricated on a very thin and low-profile substrate. The proposed antenna is used to measure the ambient spectrum in two different places. One of them is indoor and the other is outdoor, in order to see the effect of the place on the proposed energy harvesting system. A multi-band rectifier circuit is designed and integrated with the proposed antenna. The maximum simulation efficiency is 60.98% at 1.9 GHz and -1 dBm input power. The maximum measured efficiency is 60.57% at 2.5 GHz and -1 dBm RF received power. Also, the proposed rectenna has 53.1% measured efficiency at 2.5 GHz and RF received power of -5 dBm.**

***Keywords*—Bandwidth, Coplanar waveguide antenna, Energy Harvesting, RF (radio frequency), Matching circuit.**

I. INTRODUCTION

The basic requirement for sustaining our life is the energy, because it exists in each and every one of our activities. The energy is required in household applications, industrial applications, transportation, electric power generation, and agriculture. In the near future it will be hard to satisfy our requirements of the energy, because increasing energy demand puts restrictions on the current available energy sources. As a result of that, searching for new sources specially the renewable energy sources are a recent trend. The renewable energy is the energy which can be extracted from the natural sources and is not exhausted, such as the sunlight, wind, flowing water. The conversion of this wasted energy into a useful electricity is known as the energy harvesting [1]. Ambient energy sources are widely used as a clean energy source. The ambient energy is one of the environment friendly energy sources. It can be used for the production of electric energy. Ambient energy sources use different energy harvesting methods [2], such as mechanical, optic, thermal energy extraction, and wireless energy harvesting [3-5].

Wireless energy harvesting has proven to be one of the most promising solutions because of its simplicity, ease of implementation, and availability. The ability to harvest RF energy from ambient or dedicated sources enables the wireless charging of low power devices. The wireless energy harvesting system consists of three main subsystems. The first one is the receiving antenna, which is used to capture ambient radio frequency energy which will be converted to DC power. The second subsystem is the matching network between the antenna and the rectifier. The third subsystem is the rectification circuitry, which converts the input RF power into DC output power. An output DC filter (post rectification filter) is used to provide a DC to the load by separating the high-frequency components from the DC signal [6]. When the antenna is integrated with the rectifier, the system is called rectenna [7].

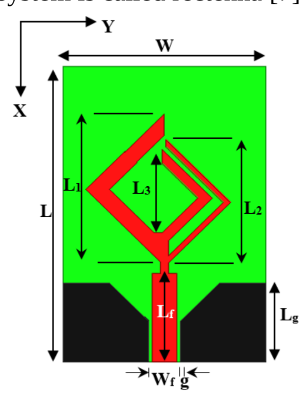

Fig. 1. The geometry of the proposed antenna.

In recent years the wireless technology became the main subject for the rapid enormous changes in frequency allocation, policies and procedures of operations, and techniques to enhance the wireless system performance. Many of wired systems are converted into wireless, for example wired LAN is converted into a wireless. As a result of that an increased demand for multiple antennas covering different wireless communication bands on the same platform increased extremely. This makes the antenna more important day by day, specially the multi-bandwidth antenna. As a result of that a multiband and broadband fractal patch antenna is presented in [8]. Four different planar multi-band antennas are designed, modeled, fabricated, and measured in [9]. A meandered planar inverted-F antenna introduced in [10] for

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LTE/GSM/UMTS multi band operation. In [11], reconfigurable and multiband antenna is introduced for wireless and radar applications. Printed inverted F-antenna (PIFA) is a type of compact antenna. The design of compact multiband and environmental isolation for mobile phones is presented in [12] using planar inverted-F antenna (PIFA).

This paper presents a multi bandwidth antenna with a good response at 1.8 GHz, 1.9 GHz, 2.4 GHz and 5.2 GHz. The antenna consists of multi arm and each arm is responsible for a specific resonant frequency. A multi band rectifier circuit with high efficiency operating at three frequencies of 1.8, 1.9, and 2.4 GHz is designed for converting the received RF power into DC power. The antenna is fabricated and measured. The ambient RF spectrum is measured using the antenna. Then the antenna is integrated with the rectifier and the rectenna is measured. This paper is organized as follows. Section II presents antenna structure and geometry. The antenna design is given in section III. Section IV introduces the multiband rectifier circuit. The implementation and measured results are given in section V, while conclusion is presented in section VI.

II. Antenna Structure and Geometry

The antenna is designed using thin and flexible substrate of ROGERS (RO3003) with dielectric constant ε_r=3, dielectric loss tangent of 0.04 and thickness 130 µm. The antenna is coplanar waveguide (CPW) fed. The detailed structure of the antenna is shown in Fig. 1. The antenna has area of $L\times W$=60×40 mm^2. Feeding line with width of W_f=5mm and length of L_f=18 mm is used to feed the antenna. The separation gap between the feeding line and the ground plane is g=0.3 mm. The ground plane has length of L_g=16 mm.

III. Antenna Design

A. Design Steps Procedure

The design steps of the CPW antenna is shown in Fig. 2. The first assumed design is indicated in Fig. 2 (a) which consists of a one arm CPW antenna, the arm length is L_1=29 mm that gives one resonant band at 1.8 GHz. Then another arm with length of L_2= 22 mm has been added to give resonance at 1.8 GHz, as shown in Fig. 2 (b). After that a third arm with length L_3=18.5 mm is added between the previous two arms, which drive resonance at 2.4 GHz.

Finally, a modified etched rectangular ground plane with angle $\alpha = 45^o$ is used to improve the impedance matching at the higher bands specially 5.2 GHz. The final design is shown in Fig. 2 (d). Fig. 3 indicates response of the design steps of the multiband proposed antenna which has the following impedance bandwidth (1.58-2.1 GHz), (2.35-2.48 GHz) and (4.6-5.8 GHz) according to -6dB reflection coefficient as a reference.

B. Antenna Current Distribution and Radiation Pattern

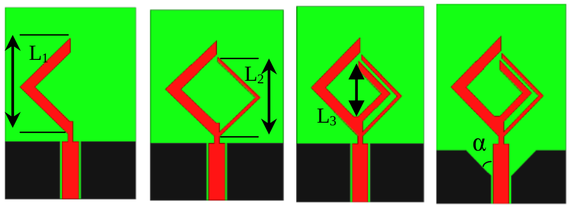
The current distribution on the flexible multi-bandwidth CPW fed antenna at frequencies of 1.8, 1.9, 2.4, and 5.2 GHz is shown in Fig. 4, which indicates that each arm is responsible for a specific resonant frequency. This means that the largest arm gives 1.8 GHz resonant and the smallest arm gives 2.4 GHz resonant, as mentioned before in the design antenna procedure. The current distribution on the antenna at 5.2 GHz indicates that the etched ground plane in a tapered shape improves the antenna matching. The antenna radiation patterns at different frequencies in E-plane and H-plane are shown in Fig. 5. The antenna has a high gain at frequencies 1.8, 1.9, and 5.2 GHz.

IV. Multi Band Rectifier Circuit

A multi-band rectifier circuit is designed in order to rectify the received RF power at three frequencies of 1.8, 1.9, and 2.4 GHz. The schematic diagram of proposed circuit is shown in Fig. 6. The circuit consists of matching circuit and rectifier circuit. The matching circuit composites of short ended stub, 1 PF capacitor and 10 nH inductor. The rectifier circuit is a simple wave rectifier which uses a single Schottky SMS7630 diode, smoothing capacitor and load resistance. The SMS 7630 has a very low turn on voltage [13], which is suitable with the low values of received ambient power. The circuit is fabricated on low cost FR-4 substrate with dielectric constant of 4.5, loss tangent =0.025, and thickness of 0.8 mm. A comparison between simulated and measured reflection coefficient variation with frequency for the multi-band rectifier circuit is shown in Fig. 7 which indicates that the circuit is matched at more than one frequency. The rectifier efficiency can be calculated using the output power from the circuit divided by its corresponding RF input power. Equations (1) and (2) are used to calculate the rectifier efficiency [14]. The simulated rectifier efficiency variation versus different levels of the input RF power at three different frequencies of 1.8, 1.9, and 2.4 GHz is shown in Fig. 8 (a), which indicates that the maximum efficiency for the circuit is achieved at -1 dBm RF input power for the three frequencies. Fig. 8 (b) introduces the effect of the load value on the efficiency of the circuit. It can be seen that the maximum efficiency is achieved at specific load value which is approximately 550 Ohm for the three frequencies:

$$\boldsymbol{\eta} = \frac{p_{out(DC)}}{p_{input\,(RF)}}\,, \tag{1}$$

$$\boldsymbol{\eta} = \frac{V_{o(DC)}^2}{p_{input\,(RF)\times R_L}}\,. \tag{2}$$



(a) (b) (c) (d)

Fig. 2. Design steps of the antenna.

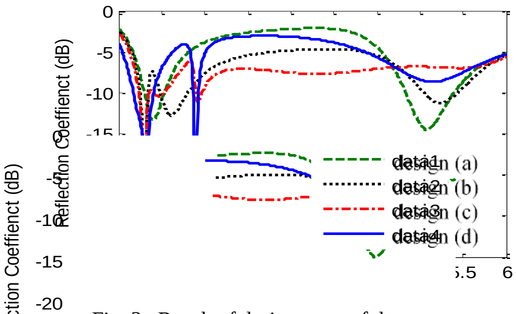
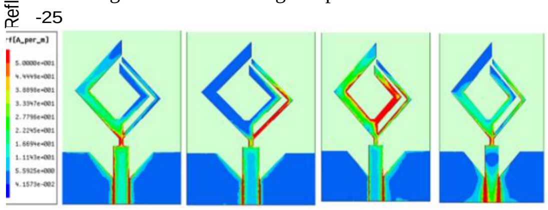
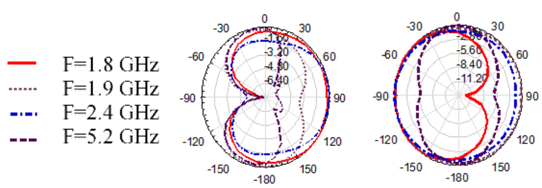


Fig. 3. Result of design steps of the antenna.



(a) (b) (c) (d)

Fig. 4. The current distribution at 1.8GHz, 1.9GHz, 2.4GHz, and 5.2GHz.



(a) E-plane (b) H-plane

Fig. 5. The radiation pattern of the antenna in E-plane, and H-plane at different frequencies 1.8, 1.9, 2.4, and 5.2 GHz.

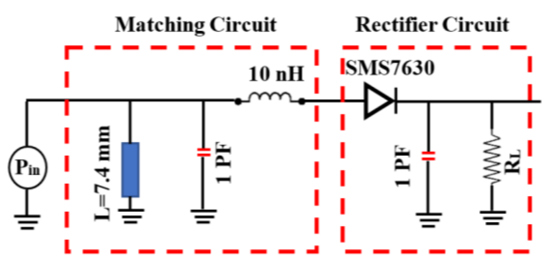


Fig. 6. Schematic diagram of multi-band rectifier circuit.

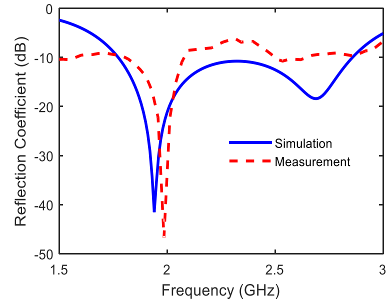
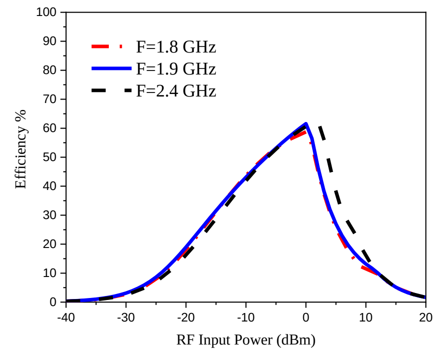
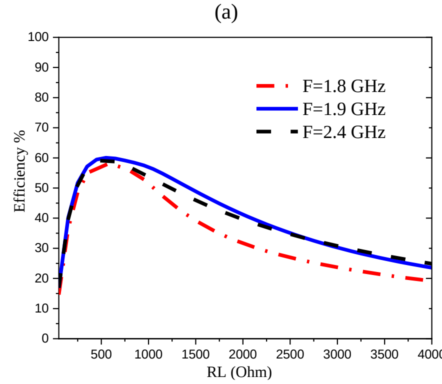


Fig. 7. Simulation and measured reflection coefficient variation versus frequency for the rectifier circuit.



(a)



(b)

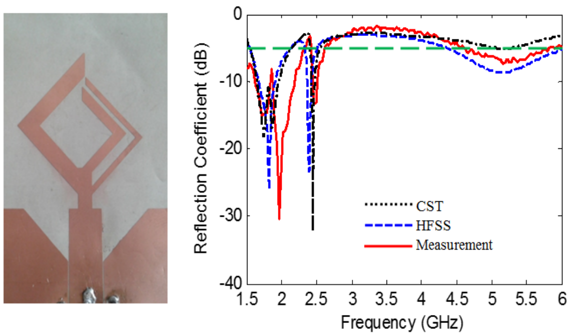
Fig. 8. Efficiency variation at frequencies of 1.8, 1.9, 2.4 GHz versus different values of: (a) RF input power and (b) load resistance.

V. IMPLEMENTATION AND MEASURED RESULTS

A. Antenna Fabrication and Spectrum Measurememt

The antenna is fabricated and tested. The fabricated antenna photo is shown in Fig. 9 (a). A comparison between the simulated and measured result for the antenna reflection coefficient variation versus frequency is indicated in Fig. 9 (b), which indicates a good agreement between CST [15], HFSS [16], and measured results.

A survey on the RF spectrum was done in order to understand the conditions of the harvesting system in Egypt RF spectrum. This survey is performed in two places one of them is outdoor measurements in the street and the other is indoor in our Electronics Research Institute (ERI) buildings. The proposed antenna is used to measure the ambient RF spectrum at frequency band of 1.5 to 3 GHz. The Agilent Technology N9918A is used to measure the spectrum. Figure 10 shows a comparison between both indoor and outdoor spectrum measurement. It can be seen that the maximum peak for the indoor received power is at 2.4 GHz which is the Wi-Fi band and that is because in the Electronics Research Institute there are many hotspots which provide RF waves at 2.4 GHz band. According to the outdoor measurement, the value of the power at GSM 1800 band is the highest value comparing to other bands, which means that there was a GSM 1800 base station tower near to us during the outdoor measurements. Also, it is noticed that the value of the ambient RF power at Wi-Fi band is very low at the street comparing to the indoor measurements in the ERI. This is because the street in Egypt does not contain hot spots so that there is no Wi-Fi 2.4 GHz transmitted power outdoor and the Wi-Fi hotspots which is indoor are transmitting a power within 10-100 meter. As a result of that it is too hard to sense the Wi-Fi hotspots powers in the streets in Cairo.



(a) (b)

Fig. 9. (a) Photo of fabricated antenna, and (b) Comparison between simulated and measured results.

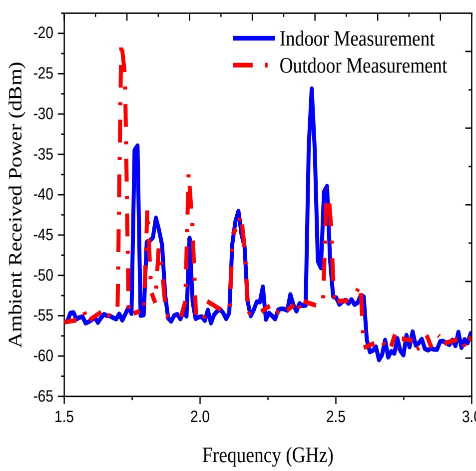
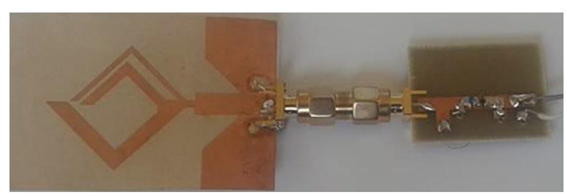


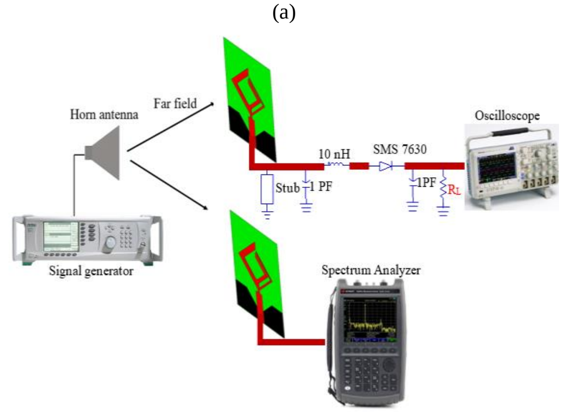
Fig. 10. Ambient RF received indoor and outdoor power by the proposed antenna.

B. System Integration and Measurement

The antenna is integrated with the multi-band rectifier as shown in Fig. 11 (a), then the overall rectenna is measured. The experimental setup for the measurement system is shown in Fig. 11 (b). Anritsu MG3697C RF signal generator is used to feed a wide band horn antenna. Two antennas are used in the measurement setup, the first one is connected with the N9918A analyzer in order to measure the received power by the antenna. The N9918A analyzer in this measurement setup is operated as a spectrum analyzer to detect the received RF power. Simultaneously to this the second antenna is integrated with the matching circuit, voltage doubler and the load resistance R_L. The output of the rectenna system is connected parallel to the Tektronix MD04104C oscilloscope to see the output DC voltage signal. This measurement setup is used each time and the results are recorded at two frequencies of F_1 =1.9 GHz, F_2=2.4, and at different RF received power by the proposed antenna. The measured rectenna efficiency variation versus RF received power using 550 Ohm load resistance is shown in Fig. 12 (a). The maximum efficiency is achieved at -1 dBm RF received power. Figure 12 (b) introduces the efficiency variation versus frequency at different received RF power of 5, -1, 05 dBm. It can be seen that the proposed rectenna has a high and stable efficiency over the frequency band of 1.8 to 2.7 GHz. Which includes GSM 1800, and Wi-Fi 2.4 GHz. The maximum efficiency is 60.57% at 2.5 GHz and RF received power of -1 dBm.

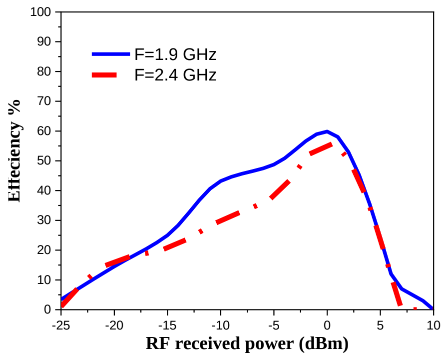


(a)

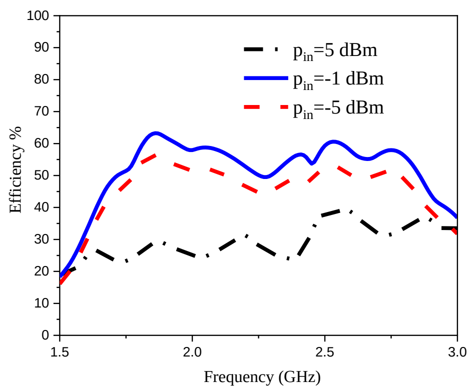


(b)

Fig. 11. (a) Photo of antenna integrated with rectifier circuit, and (b) the measurement system setup.



(a)



(b)

Fig. 12. The measurement efficiency variation versus: (a) RF received power and (b) frequency, R_L=550 Ohm.

VI. CONCLUSION

Multi bandwidth coplanar waveguide fed open end square loop monopole antenna has been designed and optimized using both CST and HFSS electromagnetic packages. The detailed steps of the design were indicated. The antenna was fabricated and measured. There is a good agreement between the simulated and measured results. A wide band rectifier circuit was designed using highly sensitive SMS7630 Schottky diode. The rectifier was fabricated and integrated with the proposed antenna. The rectenna system was measured. The maximum efficiency is achieved at 2.5 GHz, RF received power of -1 dBm, and load resistance of 550 Ohm.

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