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Flexible Rectenna for Energy Harvesting System

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Abstract: This paper presents a flexible rectenna for RF energy harvesting application. The textile wideband antenna is designed using CST software. The Fleece and Shieldit fabrics are used as substrate and conductive material, respectively. The antenna is fabricated and its measurement performances are described in terms of reflection coefficient and the radiation pattern is measured. Then, the rectifier circuit is designed and simulated using ADS software and the integration between antenna and rectifier (rectenna) is achieved using the same software. The flexible rectenna is experimentally verified at different distances from the RF source. The highest measured DC output voltage is 35 mV at a distance of 0.5 m. The system harvests DC output voltage successfully even though it only produces a small value. This system can be improved more and used for obtaining continuous energy for future wearable applications.

Keywords: Textile antenna, rectenna, RF energy harvesting.

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1. INTRODUCTION

With the rapid development of integrated electronics towards high frequencies, low power consumptions, and low power supply, wireless power transfer is a promising research topic that is used to meet these requirements. Wireless power transmission is essential in remote and isolated places. The need for such a system is increased rapidly over the years [1]. Energy harvesting can be defined as the process by which energy from different sources is captured and stored. In urban areas, there are many RF energy sources such as broadcast televisions, mobile phone signals, and wireless networks [2]. Therefore, part of the energy can be collected and converted into usable DC voltage, where this collected energy depends on the efficiency of the harvesting devices. William C. Brown firstly introduced the rectenna in 1964, which is used to receive and convert RF energy into DC output [3]. It composes of rectifying circuit and antenna. The antenna could be any type such as microstrip antenna, a dipole antenna, Yagi Uda antenna, or parabolic antenna. However, a circularly polarized antenna is the best since the alignment can be any position [4]. Microstrip antenna is the most widely used for energy harvesting due to its advantages such as compact structure, lightweight, and simplicity of fabrication [5,6]. The conversion of RF energy to DC output is performed by rectifying circuit. The elements of the rectifying circuit could be a Schottky diode (SMS7630-79, HSMS-2820, and SMS7630), Bridge rectifier, or NMOS bridge in addition to storage capacitor and load resistor [7]. The efficiency of the rectifying circuit is determined by the amount of input power intensity and the optimum load [8]. The characteristic of the diode is important in determining the performance of the whole rectifier.

In this work, the textile material has been chosen for the flexible material of the rectenna. The functionalities of the clothes are enhanced through a combination of textile and electronics devices. The wearable textile material is used as a substrate that is designed to be part of the clothing. The textile antenna is simulated and experimentally verified. Then, the rectenna is designed and its performance is investigated. The proposed rectenna successfully harvested the DC output voltage of 35mV at 2.45 GHz. The proposed flexible rectenna can be used as an alternative to the heavy portable power source with compact size and lightweight configuration advantages. The design of the flexible wideband antenna is discussed in section II. Section III introduces the rectifier circuit design while the measurements process of the rectenna is presented in section IV. The results are discussed in section V. Section VI concludes the work.

2. FLEXIBLE WIDEBAND ANTENNA DESIGN

An antenna is an essential part of designing rectenna systems. Without proper design of the antenna, the system will fail to operate and no signal will be radiated or be received. Various types of antennas can be designed for different applications. The planar antenna is the best candidate for wideband application- since the structure is simple, small, and it is easy to control the operating frequency simply by modifying the patch shape of the antenna. There are specific methods used to design wideband antennas. In this work, the textile material used is Fleece fabric for the substrate of the antenna and Shieldit fabric is used as a conductive material. The antenna patch can be easily printed on the Shieldit using Silhouette printer and ironing it on the Fleece fabric. Normally, the antenna bandwidth for microstrip antenna is narrow, which can be increased by methods such as partial ground [9]. To design a wideband antenna, the initial reference size is obtained by calculating the centre frequency using (1) through (4) based on the concept of microstrip antenna [10]. The patch dimension, L, can be calculated using the formula:

$$L = \frac{c}{2f\sqrt{\varepsilon_{reff}}} - 2\Delta L \qquad (1)$$

where

$$\Delta L = 0.412h\frac{(\varepsilon_{reff}+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon_{reff}-0.258)\left(\frac{W}{h}+0.8\right)} \qquad (2)$$

and

$$\varepsilon_{reff} = \left(\frac{\varepsilon_r+1}{2}\right) + \left[\left(\frac{\varepsilon_r-1}{2}\right)\left[1+12\frac{h}{W}\right]^{-0.5}\right] \qquad (3)$$

The value of W is not critical but can be calculated with:

$$W = \frac{c}{2f\sqrt{\frac{\varepsilon_r+1}{2}}} \qquad (4)$$

Where ΔL is the fringing field and ε_{reff} is the effective substrate due to the permittivity of the substrate and the permittivity of air. W and L are Patch's width and length, respectively. The h is the thickness of the dielectric. The dielectric constant (ε_r), tangential loss ($tan\ \delta$), and the thickness, h, of the substrate Fleece fabric are 1.3, 0.025, and 0.5 mm respectively. On the other hand, the conductive part fabric thickness and conductivity are 0.17 mm and 196000 S/m, respectively. By using these values, the center frequency of the wideband antenna is at 2.45 GHz. The proposed flexible antenna with its dimension is shown in the power plane of the antenna in Fig.1 (a) where the calculated values are L = 29.14 mm and W = 30.14 mm. However, these values are modified after optimization process. Fig.1 (b) shows the ground plane of the antenna and the fabricated fabric antenna is as shown in Fig.1 (c). The h-slot is proposed at the antenna patch to increase efficiency, in which this increase is due to the reduction of Shieldit loss. The reason for using the half-ground plane is to obtain wide bandwidth and omnidirectional radiation. The fabricated prototype is depicted in Fig.1(c). In this process, the CST design is exported to Silhouette Studio and printed onto the Shieldit fabric. Then, Fleece fabric was cutting according to the size of the layout. Next, the printed antenna on the Shieldit fabric is being ironed on the Fleece fabric.

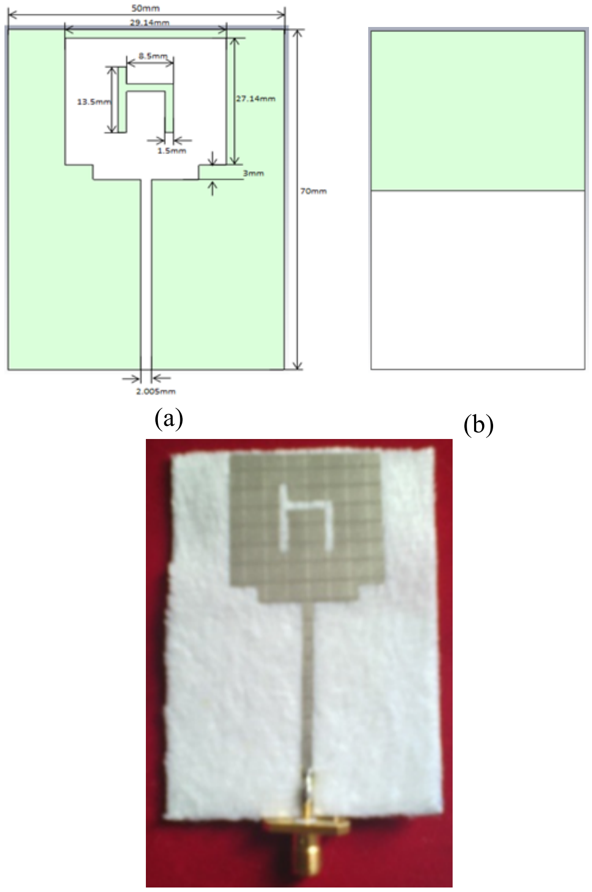


Figure 1. The proposed flexible antenna (a) patch with dimensions (b) ground and (c) Fabric antenna prototype.

3. RECTIFIER CIRCUIT DESIGN

The rectifier circuit is design by using Agilent Advanced Design Software (ADS). The function of the circuit is to convert the RF input energy into a DC output voltage. The circuit consists of HSMS 2860 Schottky diode, capacitors and resistor as a load. A proper matching circuit is needed to ensure that the signal that passes through the antenna to the rectifying circuit produces a maximum power transfer. Then the rectifier is combined with the antenna and the fabric rectenna is proposed. The schematic diagram of conventional rectenna is shown in Fig. 2. Since the component is very small, a proper soldering process needs to be carefully handled. Fig. 3 (a) and Fig. 3 (b) show the rectenna design using ADS and the fabricated fabric rectenna, respectively.

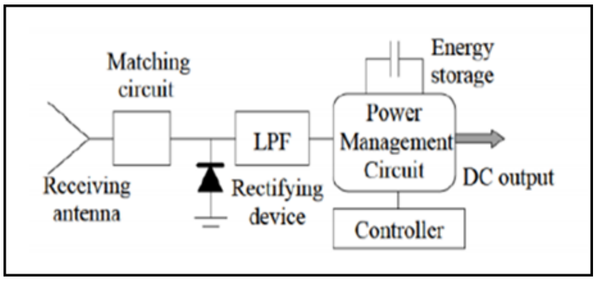
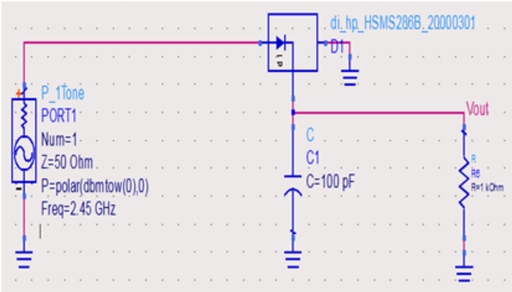
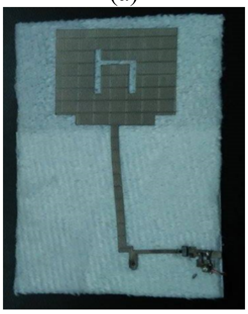


Figure 2. The Schematic diagram of the conventional rectenna.



(a)



(b)

Figure 3. The (a) schematic and (b) the prototype of the rectenna.

4. MEASUREMENTS PROCESS OF THE RECTENNA

This work is aimed to design and simulate the textile antenna that can operate at wideband and analyze the DC output of the rectenna system. Before analyzing the rectenna's DC output, the antenna's performance needs to be tested first to make sure that the antenna can function properly at the proposed operation frequency. The fabricated antenna has been tested using network analyzer to verify its reflection coefficient performance. On the other hand, the radiation patterns of both planes, E-plane and H-plane, also need to be tested. For a rectenna measurement process, the RF power from the signal generator is injected into the reference wideband antenna. The frequency is varied according to the chosen frequencies, which are 2.3 GHz (WiMax), 2.45 GHz (Wifi), and 2.6 GHz (LTE). The fabricated rectenna receives the energy at three different distances: 0.5 m, 1.0 m and 1.5 m. The output DC voltage is measured by using a multimeter. Fig. 4 displays the setup of the rectenna measurement. The measurement of DC output voltage was performed by varying the input power. The signal generator generates the input RF power from range 0dBm to 20dBm.

Figure 4. The setup for the DC voltage measurement of fabric rectenna.

5. RESULT AND DISCUSSION

The simulation part is conducted to determine the characteristics of the designed structures before the fabrication process can take place. In this research, the simulation process has been implemented in two parts; the antenna using CST and the rectenna using ADS. For the antenna simulation, the performance in terms of reflection coefficients and radiation patterns has been investigated. Fig. 5 shows the simulated and measured reflection coefficients of the proposed wideband textile antenna. The antenna is designed to cover the wideband frequency spectrum, which is from 2.0 GHz to 5.0 GHz. Further modification of the patch and ground plane are made to obtain wider bandwidth. From the simulation results, this antenna is operated in the range of 1.8 GHz to 5.0 GHz, referring to the -10 dB bandwidth. As can be seen from Fig. 5, the measured result has been shifted up by about 50 MHz. The difference between the measured and simulated results happened due to the assembly process and the materials' losses.

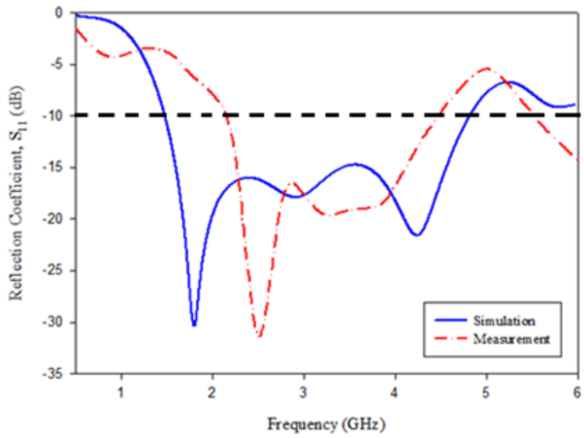
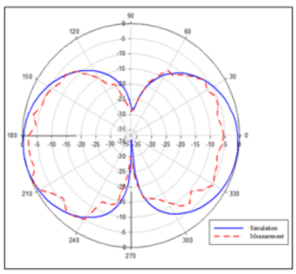
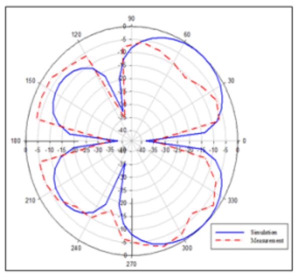


Figure 5. The simulated vs measured reflection coefficient of the antenna.

The radiation pattern of the antenna have been analyzed for three selected frequencies as shown in Fig. 6 through Fig. 8. E and H planes of the antenna performances are measured. For E-plane, the radiation pattern indicates that the antenna acts as omnidirectional, while for H-plane, the antenna radiate like a butterfly shape. The blue solid line represents the simulated result and the red dashed line represents the measured result.

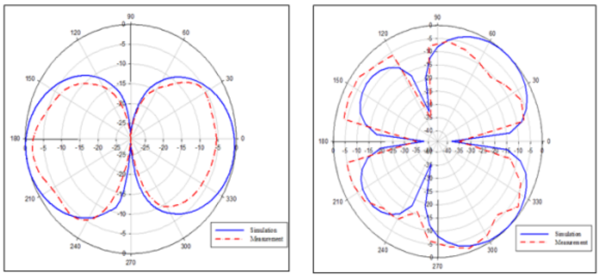


(a)



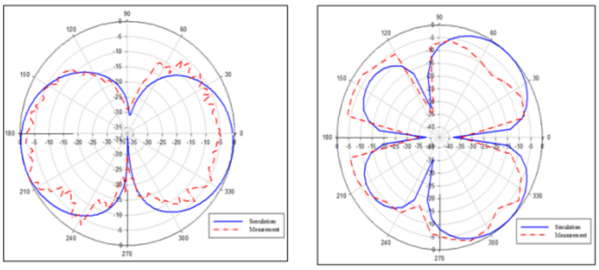
(b)

Figure 6. Radiation patterns of the antenna at 2.3 GHz (a) E-plane and (b) H-plane.



(a) (b)

Figure 7. Radiation patterns of the antenna at 2.45 GHz (a) E-plane and (b) H-plane.



(a) (b)

Figure 8. Radiation patterns of the antenna at 2.6 GHz (a) E-plane and (b) H-plane.

As can be seen, a good correlation is shown between the simulated and measured results. Then, the performance of the rectenna at three selected frequencies is illustrated in Fig. 9. The measured results present quite a huge difference from the simulation results. The maximum measured DC output voltage is around 35mV, which is very small compared to 0.7 V in the simulation. This difference may be due to impedance matching of the antenna - rectifier part and fabrication error. Fundamentally, RF circuit must have good impedance matching to ensure that maximum power transfer can be delivered to the output. Furthermore, the performance of the rectenna is also tested by using different distances between the RF source and rectenna. The performance is investigated at three different distances, which are at 0.5 m, 1.0 m, and 1.5 m. From the measured data, the highest DC output voltage can be obtained at 0.5 m which is 35 mV, as shown in Fig. 10.

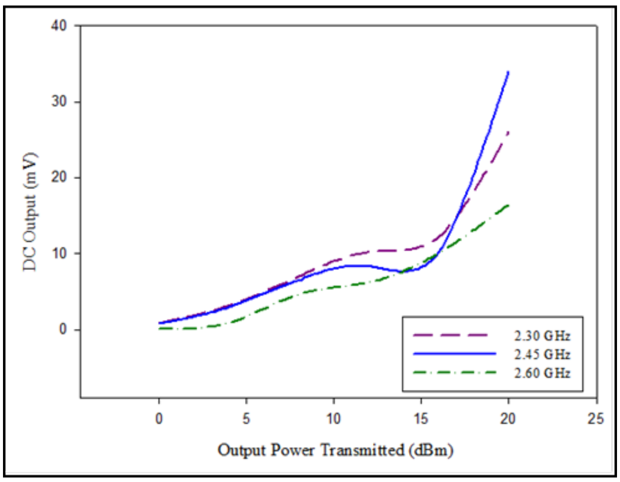


Figure 9. Measured DC output of the rectenna.

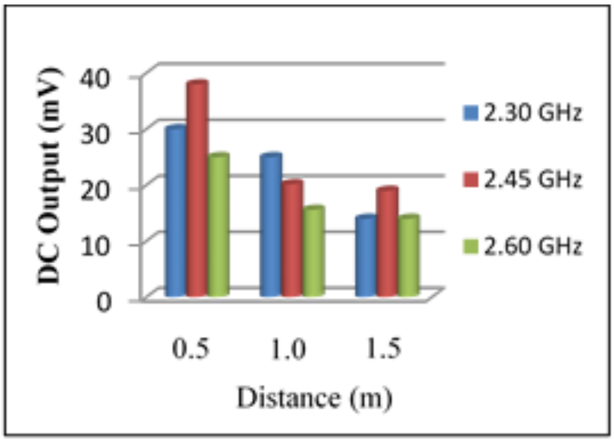


Figure 10. Measured DC output voltage at different distance.

4. CONCLUSION

In conclusion, flexible rectenna was designed and their performance was measured. The textile antenna was simulated using CST software. On the other hand, the rectifier circuit was designed and simulated using ADS software and the integration between antenna and rectifier (rectenna) was done using the same software. After the design specifications has been achieved, the fabrication process was taken place and the textile rectenna performance was measured and analyzed. The flexible rectenna was functioning even though it was only produced a small DC output voltage. The proposed flexible rectenna manage to operate at a wideband frequency and fulfilled the objective of flexible energy harvesting system. This proposed system can be used as a battery to provide continuous energy for future wearable applications.

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REFERENCES

[1] M. Song, P. Belov, and P. Kapitanova, “Wireless power transfer inspired by the modern trends in electromagnetics,” Appl. Phys. Rev., vol. 4, no. 2, p.021102, 2017.

[2] Y. Luo, L. Pu, G. Wang, and Y. Zhao, “RF energy harvesting wireless communications: Rf environment, device hardware and practical issues,” Sensors, vol. 19, no. 13, p.3010, 2019.

[3] E. Donchev, J.S. Pang, P.M. Gammon, A. Centeno, F. Xie, P.K. Petrov, J.D. Breeze, M.P. Ryan, D.J. Riley, and N.M. Alford, “The rectenna device: From theory to practice (a review) ,” MRS Energy & Sustainability, vol. 1, 2014.

[4] M.M. Mansour, and H. Kanaya, “Novel L-Slot matching circuit integrated with circularly polarized rectenna for wireless energy harvesting,” Electronics, 8(6), p.651, 2019.

[5] S. Shrestha, S.K. Noh, and D.Y. Choi, “Comparative study of antenna designs for RF energy harvesting,” Int. J. Antennas Propag, vol. 2013, pp.1-10, 2013.
[6] J.O. Olowoleni, , C.A. Awosope, A.U. Adoghe, O. Obinna, and U. Ebubechukwu Udo, “Design and simulation of a novel 3-point star rectifying antenna for RF energy harvesting at 2.4 GHz,” Cogent Engineering, vol. 8, no. 1, p.1943153, 2021.
[7] S. Ahmed, M.N. Husain, Z. Zakaria, M.S.I.M. Zin, and A. Alhegazi, “Rectenna designs for RF energy harvesting system: a review,” Int. J. Commun. Antenna Propag. (I. Re. CAP), vol. 6, no. 2, 2016.
[8] A.D. Boursianis, M.S. Papadopoulou, S. Koulouridis, P. Rocca, A. Georgiadis, M.M. Tentzeris, and S.K. Goudos, “Triple-Band Single-Layer Rectenna for Outdoor RF Energy Harvesting Applications,” Sensors, vol. 2, no. 10, p.3460, 2021.
[9] S.S. Bhatia, and N. Sharma, “A Compact Wideband Antenna Using Partial Ground Plane with Truncated Corners, L–Shaped Stubs and Inverted T–Shaped Slots,” Progress In Electromagnetics Research M, vol. 97, pp.133-144, 2020.
[10] C.A. Balanis, Antenna theory: analysis and design, John wiley & sons, 2015.