IET Microwaves, Antennas & Propagation

Research Article

# An efficient small size electromagnetic energy harvesting sensor for low-DC-power applications

ISSN 1751-8725
Received on 18th April 2016
Revised 25th August 2016
Accepted on 30th September 2016
E-First on 9th February 2017
doi: 10.1049/iet-map.2016.0304
www.ietdl.org

*Fayçal Meddour*[1] ✉, *Zohir Dibi*[1]
*[1]Department of Electronic, University of Batna, Batna 05000, Algeria*
✉ *E-mail: faycal.meddour@yahoo.fr*

**Abstract:** An efficient small size electromagnetic energy harvesting sensor for low-DC-power applications is proposed. The sensor consists of two main parts: a dual polarisation square patch antenna used to collect the RF energy at a central frequency of 2.45 GHz, and two voltage doublers rectifier circuit for the RF-to-DC conversion. The overall size of the design is 50 × 50 × 6.2 mm$^3$. Firstly, the antenna is designed using high-frequency structure simulator software; followed by the design of the rectifier circuit in advanced design system. After simulations, a sensor prototype is fabricated using F4B as the antenna substrate. Measurements show that the sensor achieves a comparatively high maximum measured efficiency of 41% for a power level of −10 dBm. The sensor has a simple structure, it is compact sized, light weight, and presents a high RF-to-DC conversion efficiency for low-RF-power levels which can be used to charge different low-DC-power devices.

## 1 Introduction

RF energy is spread everywhere around us. Nowadays, researchers tend to find an efficient way to harvest this energy and convert it to DC power to charge low-DC-power devices. This RF energy can be broadcasted over different frequency bands such as the Industrial, Scientific, and Medical (ISM) band with the central frequency of 2.45 GHz as demonstrated in this work. This ISM frequency band is widely used in existing wireless telephones, bluetooth devices, and wireless local area networks. The important RF power spread through these features and its easy availability in our environment, including for instance, homes and working places, make it possible to be harvested and converted to DC power.

One of the techniques to harvest electromagnetic (EM) energy and convert it to DC power is based on the use of a rectenna as a sensor. A rectenna is mainly composed of an antenna and a rectifying circuit. The antenna collects the RF energy spread from an ambient or specific source; while the rectifying circuit converts it to a DC power to charge a dedicated load. Schottky diodes are commonly used to design the rectifying circuit because they have the lowest voltage drop and the highest speed, so have the lowest power loss due to conduction and switching [1, 2].

Several rectennas have been presented [3–23]. Most of them have the RF-to-DC efficiency improvement as a constraint in their design. In [3], a novel dual-frequency circularly polarised rectenna at 2.45 and 5.8 GHz is introduced. The antenna realises a considerable output DC voltage; however, it occupies a large space of 89 × 78 × 1.52 mm$^3$. In [4], a rectenna design and optimisation using reciprocity theory and harmonic balance analysis for EM energy harvesting is presented. The rectenna has a maximum simulated efficiency of 38.2% at 1.5 µW/cm$^2$ (−10 dBm). However, in our work, a maximum simulated value of 55% and a comparatively high measured maximum efficiency of 41% for the same power level are obtained. In [5], a dual circularly polarised 2.45-GHz rectenna for wireless power transmission is investigated. The overall size occupied by this antenna is two times larger than the size of our design. An ISM band rectenna using a ring loaded monopole is described in [6]. The volume occupied by this antenna is quite large (about 60 × 77.8 × 18.2 mm$^3$) and its measured maximum gain is only 2 dBi. The antenna presented in [7] has a comparatively high measured gain at the central frequency 2.45 GHz. However, it uses a large reflecting metal plane of 93 × 135 mm$^2$ and 22 mm away from the back side of the antenna.

Our work targets realising a rectenna with improved performances including increasing the maximum efficiency; while keeping an acceptable antenna gain, compact size, and reduced lumped components for the matching network, as well as the RF filter between the antenna and the rectifier circuit. The reduced size of the design may be very important when designing a large rectenna array.

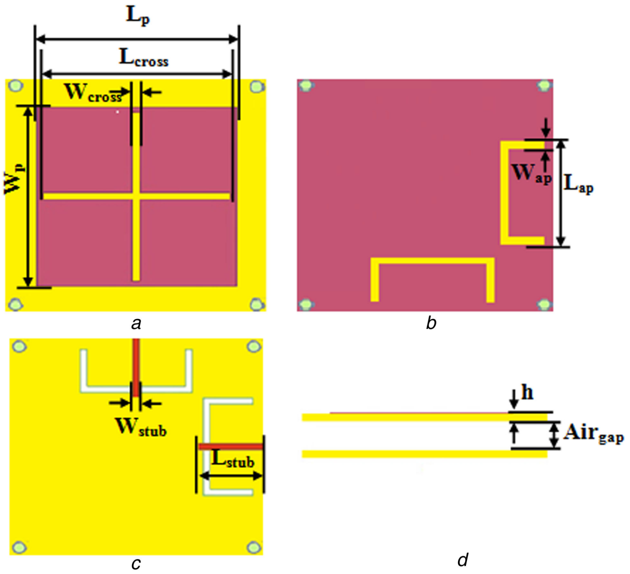
This paper is structured as follows: First, the basic principles of the antenna design using high-frequency structure simulator (HFSS) software are outlined. Then, the design of the two voltage doublers rectifier circuit using advanced design system (ADS) software is presented. A matching network circuit is also introduced to match the antenna with the rectifier circuit. After simulation of all our sensor components, a prototype is fabricated to validate the proposed approach. A good simulated to measured agreement is obtained making our sensor suitable for some low-DC-power application.

## 2 Antenna design

This section details the antenna design. The software used for the simulation is HFSS based on finite elements method. The antenna that will be used to harvest the RF energy is a square patch antenna, with a cross shape etched on its surface for size reduction. A planar form is selected to reduce the occupied space and to realise a compact design. Patch antenna is a good candidate which leads to a reduced volume size and a high antenna gain. The coupled aperture RF feeding technique is adopted in this design. The structure of the antenna is shown in Fig. 1.

It presents two layers separated by an air gap. The top layer is dedicated to the square patch radiator. However, the bottom layer contains two sides: on one side is the ground plane where two "*U*" aperture shapes are etched, and the other side includes the feed lines. The substrate used for our design is F4B with a dielectric permittivity, $\varepsilon_r$, of 2.55, a loss tangent of 0.002, and a thickness $h$ of 0.764 mm. The dimensions of the radiator patch $W_p$ and $L_p$ are obtained using patch antenna equations for an operating frequency of 2.45 GHz [24].

$$W_p = \frac{C}{2f}\sqrt{\frac{2}{\varepsilon_r + 1}} \tag{1}$$



a b

c d

**Fig. 1** *Antenna structure*
***(a)*** Layer 1: Radiator with the etched cross shape (top view), ***(b)*** Layer 2: The U-aperture etched on the ground plane (Side 1: top view), ***(c)*** Layer 2: Feed/aperture (Side 2: bottom view), ***(d)*** the antenna (Side view)

where $C$ is the light velocity, $\varepsilon_r$ is the relative permittivity of the substrate, and $f$ is the operating resonant frequency.

$$\varepsilon_{\text{reff}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{W}\right]^{-1/2} \tag{2}$$

where $\varepsilon_{\text{reff}}$ is the effective permittivity, $h$ is the substrate thickness, and $W$ is the width of the microstrip line.

$$\frac{\Delta L}{h} = 0.412\frac{\varepsilon_{\text{reff}} + 0.3}{\varepsilon_{\text{reff}} - 0.258}\frac{((W/h) + 0.264)}{((W/h) + 0.8)} \tag{3}$$

$\Delta L$: The extension of the patch length.

$$L_p = \frac{C}{2f\sqrt{\varepsilon_{\text{reff}}}} - 2\Delta L \tag{4}$$

The optimisation goals tend to realise an antenna with a compact structure and a reduced radiating antenna surface. Several antenna parameters are carefully adjusted in order to obtain a high gain, and high antenna efficiency. The cross shape etched on the radiating patch antenna aims at reducing its length, $L_p$. For an ordinary patch antenna with the same substrate characteristics, the length $L_p$ is 38.9 mm. However in our design, after optimisation, the value obtained for $L_p$ is 33.8 mm, indicating a 13.1% size reduction. For practical engineering considerations, coupled with the demand to integrate several components on the same platform (integration technology), antenna size reduction still is an important design consideration. The values of the parameters are presented in Table 1.

**Table 1** Antenna parameters for a resonant frequency of 2.45 GHz

| Parameter | Value (mm) |
|---|---|
| radiator length ($L_p = W_p$) | 33.8 |
| cross shape length ($L_{\text{cross}}$) | 31.8 |
| cross shape width ($W_{\text{cross}}$) | 1.27 |
| aperture length ($L_{\text{ap}}$) | 19.2 |
| aperture width ($W_{\text{ap}}$) | 1.2 |
| stub length ($L_{\text{stub}}$) | 12 |
| stub width ($W_{\text{stub}}$) | 1.2 |
| the air gap ($\text{Air}_{\text{gap}}$) | 4.6 |
| thickness of the substrate ($h$) | 0.764 |

The simulated antenna results are presented in this section:

- The antenna input impedance, $Z_{\text{in}}$ is $(48.7 + j0.2)\Omega$;
- The obtained total gain is 6.44 dBi;
- The antenna bandwidth is 95 MHz, and it covers the ISM frequency band.

The antenna reflection coefficient ($S_{11}$) for different radiator sizes and the simulated antenna radiation pattern are shown in Fig. 2.

A good impedance matching is obtained for the operating frequency 2.45 GHz. The simulated peak gain at this frequency is 6.44 dBi with a peak efficiency of 72%.

It is worth noting that all the parameters included in the antenna simulation are carefully adjusted to obtain the desired results. The next step after designing the antenna is to design the rectifier circuit which includes the matching network.

## 3 Rectifier circuit design

The purpose of the rectifier circuit is to convert the harvested RF energy into a DC power. Our design is based on a double voltage rectifier which doubles the output voltage while keeping an acceptable efficiency.

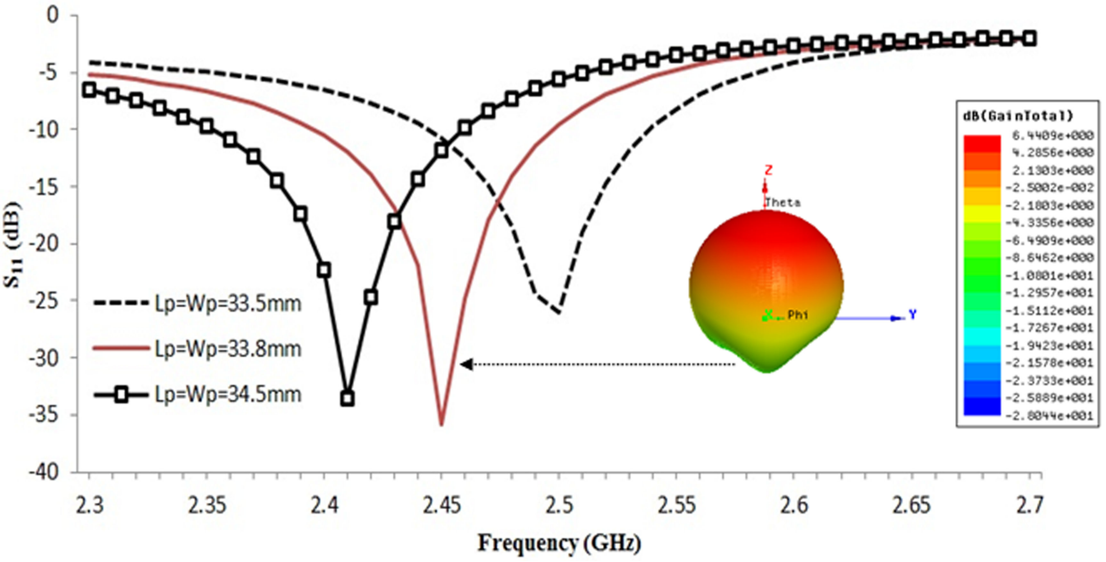


**Fig. 2** *The simulated antenna reflection coefficient ($S_{11}$) for different radiator sizes and the radiation pattern at 2.45 GHz*

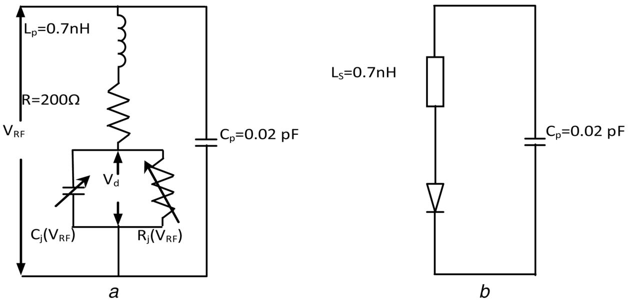


**Fig. 3** *Schottky diode and its equivalent circuit*
***(a)*** Schottky diode SMS7630-79, ***(b)*** Diode equivalent circuit

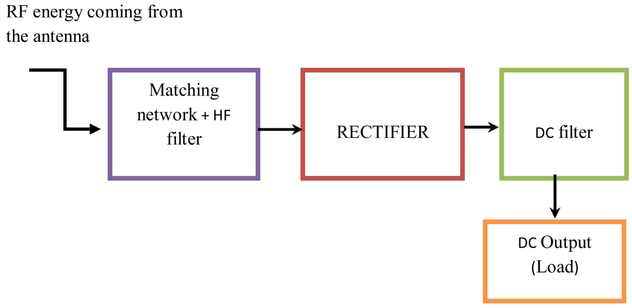


**Fig. 4** *The synoptic schema of the rectifier circuit*

Being the main rectifier component, the choice of the diode is of great importance. Schottky diodes are adopted in this paper. Their characteristics, such as, no delay effect compared with junction diodes, make them widely used [1]. There are several types of Schottky diodes; the one selected for our purpose is SMS7630-79, because of its availability in our laboratory. The diode and its equivalent circuit are presented in Fig. 3. The values of its intrinsic parameters are obtained according to the datasheet of the manufacturer “Skyworks product” [25]. The values $L_S$ and $C_p$ presented in the diode equivalent circuit (Fig. 3*b*) are the parasitic effects of the diode's packaging that should be taken into consideration in all simulations.

Fig. 4 shows the synoptic schema of the rectifier circuit including the matching network which is needed for the impedance matching (antenna with rectifier). The DC low pass filter, used at the output of the rectifier blocks the RF energy while allowing the DC power to pass.

The software used to design the rectifier circuit is ADS. The double voltage rectifier circuit is shown in Fig. 5. Port 1 and port 2 are the two inputs coming from the antenna. $R_1$ is the charge load. To obtain a high efficiency, the rectenna parameters are optimised and adjusted using some features in ADS. Some of the adjustments include slightly and carefully tuning the values of the capacitors $C_1$, $C_2$, and $C_3$ for a dedicated load $R_1$.

The optimised values of the previous parameters realise a good impedance matching which leads to a high-level RF-to-DC conversion. The optimised values are presented in Table 2.

After designing the antenna and the rectifier circuit, a co-simulation is performed. The details of the co-simulation setup are presented in the following section.

## 4 Co-simulation results

The antenna and the rectifier circuit are designed separately in different software; HFSS for the antenna and ADS for the rectifier circuit. To validate the proposed approach, a co-simulation is needed. The issue at hand now is how to implement the antenna parameters into ADS. A single tone source from ADS library solves this problem.

The value of the antenna input impedance obtained in Section 2 is used and considered in this part. Then, the rectifier input impedance is readjusted to satisfy the impedance matching requirement.

Rectification of the received RF signals at each port is achieved using voltage doublers circuit introduced in Section 3. The

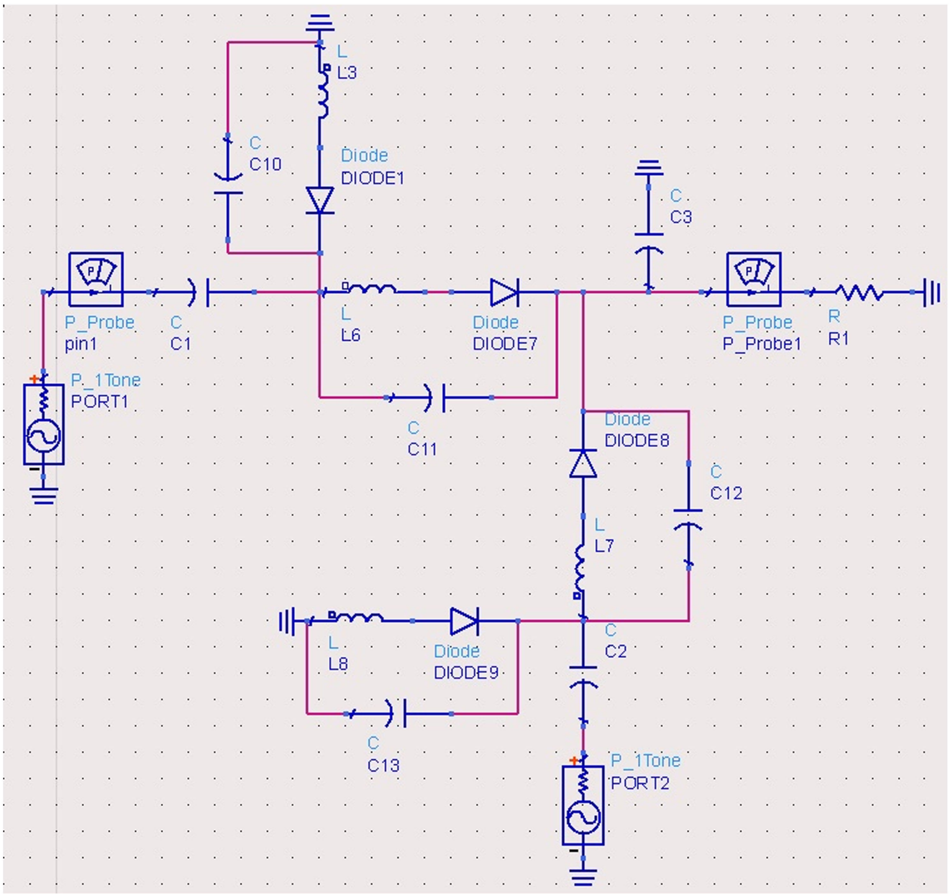
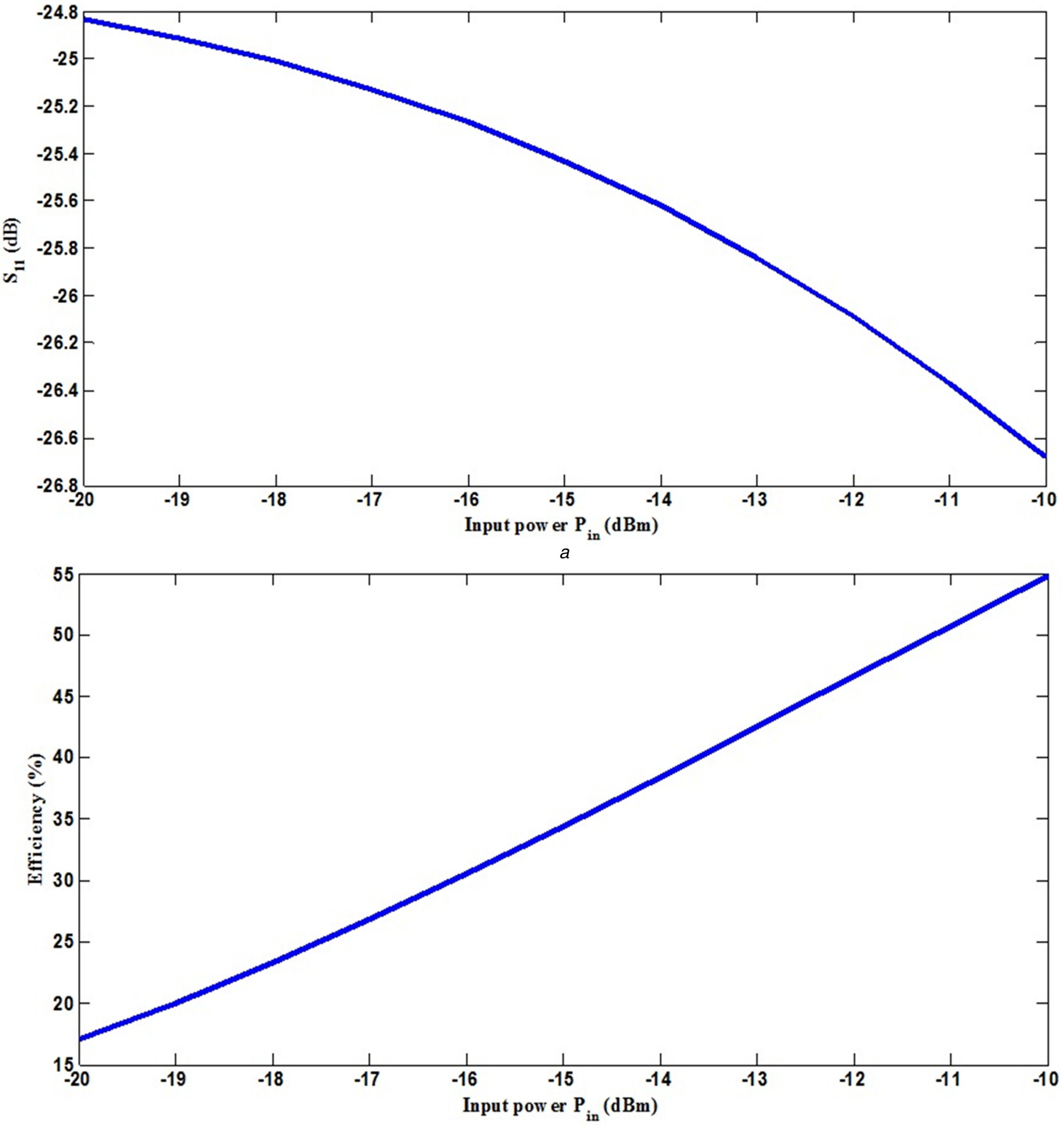


**Fig. 5** *The rectifier circuit*



*b*

**Fig. 6** *The reflection coefficient $S_{11}$.and the rectenna efficiency versus the input power*
***(a)*** The reflection coefficient $S_{11}$, ***(b)*** Rectenna efficiency

doublers circuit consists of a first stage which comprises a series capacitor $C_1 = C_2 = 5$ pF, and a shunt Schottky diode. The second stage consists of a series diode and a shunt capacitor $C_3 = 10$ pF. The antenna ports are matched to the operating frequency 2.45 GHz using a shunt and a series inductor designed as microstrip lines. Thus, another advantage of the proposed approach compared with that one designed in [4] is avoiding the use of lumped components. The outputs of the two voltage doublers are joined together using a common capacitor $C_3$ and a load resistor $R_1$, allowing the circuit to convert the input RF signal to DC power, independent of its polarisation orientation. The antenna matching circuit and the rectifier components are optimised using the Harmonic balance simulator for a low input power of −10 dBm.

**Table 2** Optimized parameters of the rectifier circuit

| Parameter | Value |
|---|---|
| operating frequency | 2.45 GHz |
| capacitors $C_1$, $C_2$ | 5 pF |
| capacitor $C_3$ | 10 pF |
| load $R_1$ | 4.8 KΩ |
| power $P_{in}$ | −20 dBm→−10 dBm |

Simulation results of the reflection coefficient $S_{11}$ and the rectenna efficiency versus the input power are presented in Fig. 6. A good impedance matching and a high simulated maximum efficiency of 55% are obtained along the sweep power range.

After performing the co-simulation, a prototype of our sensor is fabricated and tested to validate the proposed approach. The following section is dedicated to the experimental results.

## 5 Experimental results

Fig. 7 shows the fabricated RF sensor, which consists of two layers joined to each other using four plastic supports.

To validate the performance of our antenna, in addition to the gain and the efficiency demonstrated in Section 2, its reflection coefficient is measured in the laboratory. The test result is shown in Fig. 8. An acceptable value of $S_{11}$ is obtained at the resonant frequency of 2.49 GHz. A deep investigation is carried out to explain the difference between the simulated and the measured $S_{11}$. It is found that the substrate used for the design has a small thickness which makes the fixation of the two layers in horizontal position using just four plastic supports difficult to obtain. A small fluctuation leads to a shift in frequency. In addition to measurement setup and different coaxial connections, the already mentioned factors may account for the shift in frequency. After validating the test for reflection coefficient, a schematic for the test setup is

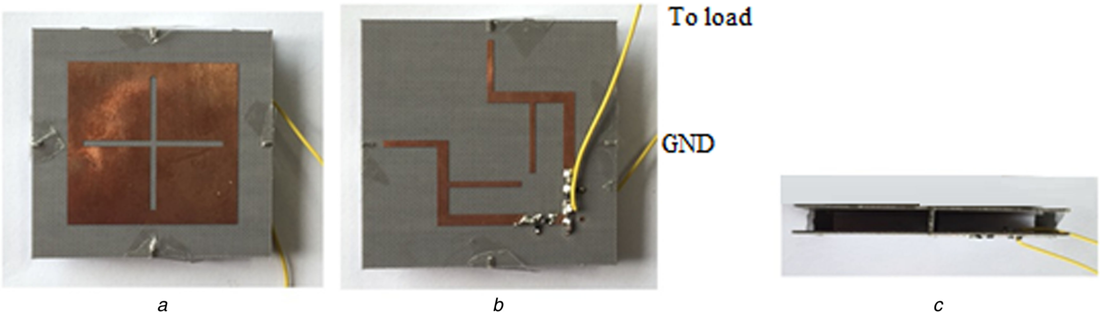


**Fig. 7** *Photograph of the fabricated RF sensor*
***(a)*** Top view, ***(b)*** Bottom view, ***(c)*** Side view

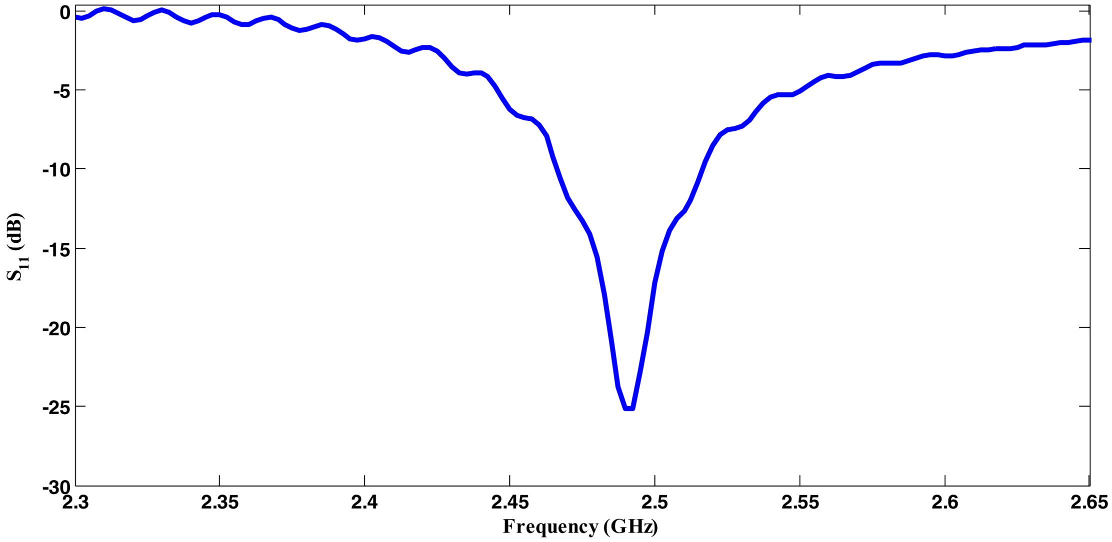


**Fig. 8** *The measured reflection coefficient of the fabricated antenna*

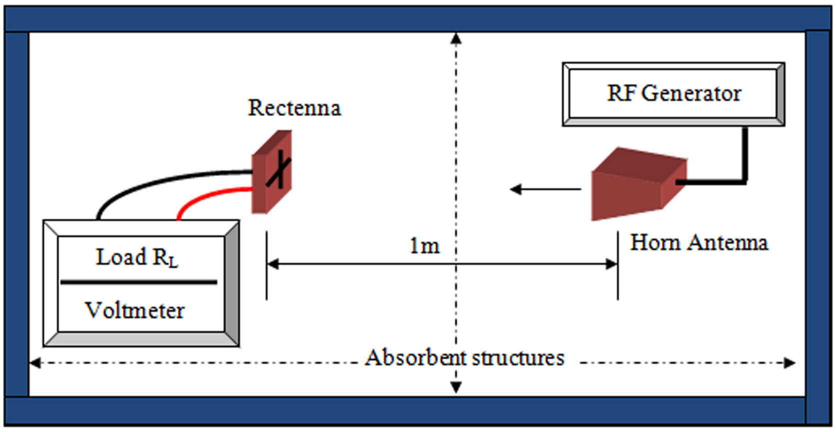


**Fig. 9** *Schematic test setup*

shown in Fig. 9. The experimental RF sensor test setup is set in the laboratory and displayed in Fig. 10.

A horn transmitting antenna with gain of 5.84 dBi is placed at a distance of 1 m from our sensor. A $P_{\text{in}} = -10$ dBm RF transmitted power level is adjusted and set at the surface of our sensor using Friis equation. Then, the collected DC output power ($P_{\text{out}}$) is measured and evaluated. The value −10 dBm of the RF input is available at one antenna port. The rectenna has a symmetric geometry, and the test at each port indicates that the measured efficiency is almost the same. The efficiency is calculated using the following equation:

$$\eta = \frac{P_{\text{DC}}(\text{out})}{P_{\text{RF}}(\text{in})} = \frac{V_{\text{DC}}^2/R_{\text{L}}}{P_{\text{RF}}(\text{in})} \tag{5}$$

where $V_{\text{DC}}$ is the DC output voltage collected for one port and for a dedicated load $R_{\text{L}}$.

We note that the designed sensor has the capability of working in two wave polarisation modes, vertical and horizontal. Measurement results indicate that the maximum efficiency for vertical polarisation is 41% evaluated at 2.49 GHz as shown in Fig. 11*a*.

Measured values of the output DC voltage when the angle between the antenna and the input polarisation wave varies from 0° to 360° are presented and demonstrated in Fig. 11*b*. A maximum value of 214 mV DC voltage is obtained for the angles 0° and 360°, and a minimum value of 171 mV is collected for the angle 315°. We deduce from this result that our RF sensor can convert power from RF to DC regardless the polarisation of the input wave. Compared with a single polarisation rectenna, the proposed design has the advantage of doubling the DC output voltage by using two

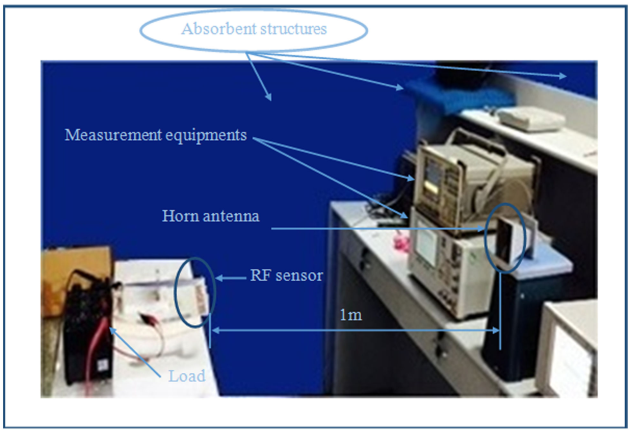


**Fig. 10** *Fabricated RF sensor test setup*

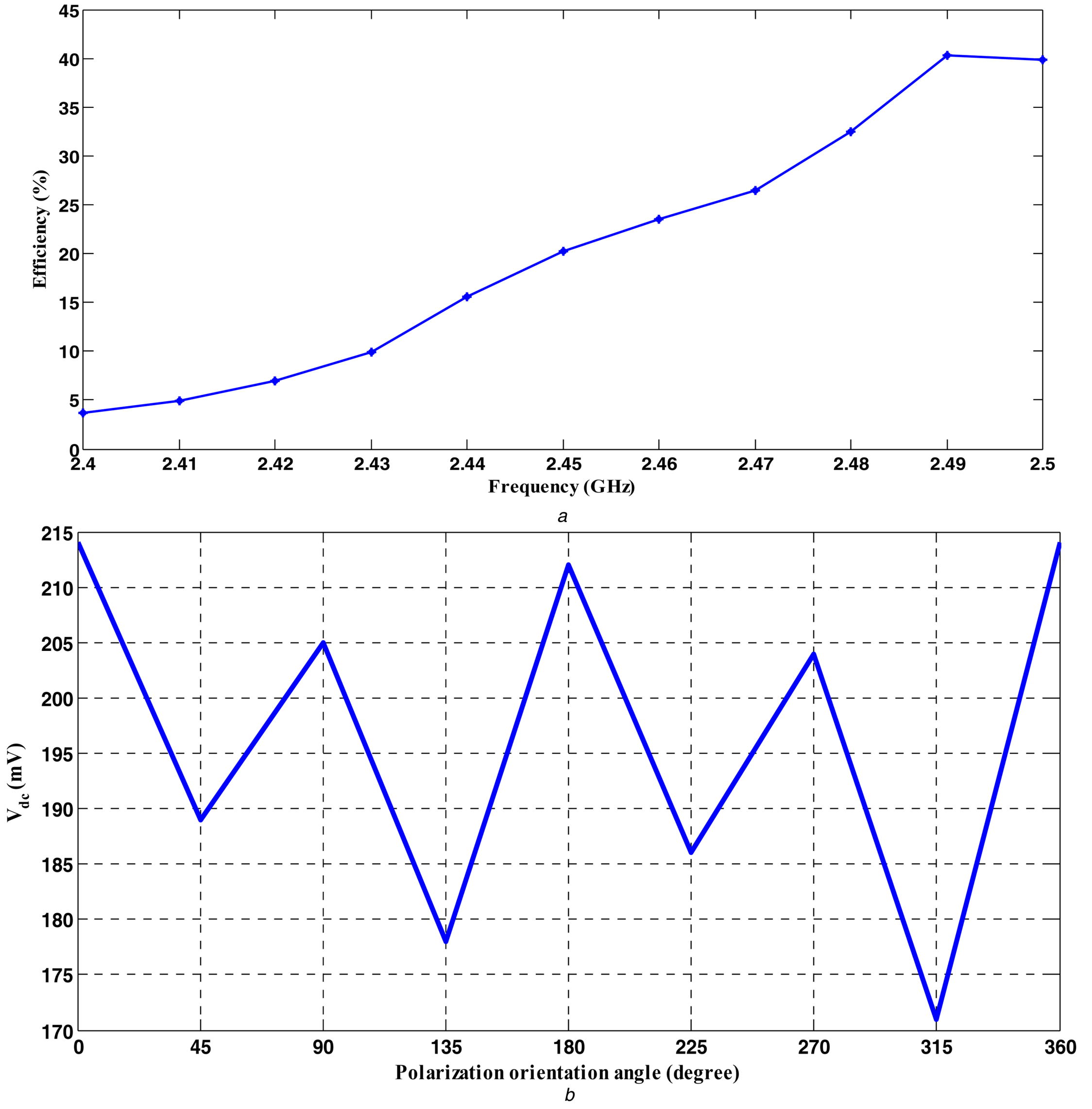
rectifier diodes. In some practical scenarios where the rectenna is mounted on a mobile platform, the polarisation of the received wave changes as the rectenna rotates. Thus, the rectenna is designed to be dual-polarised to collect the RF power regardless the orientation of the received power.

The fabricated RF sensor is tested to validate the proposed approach. Good experimental results are obtained for the 2.49 GHz operating frequency located at the ISM band.

We have compared our work with some references having the same operating frequency band (ISM band with the central frequency 2.45 GHz) and the results are shown in Table 3. The purpose is to validate the features of our design, mainly the compactness and the considerable maximum measured conversion efficiency for low-level RF input powers (−10 dBm). Our rectenna can be further used as an element of a large rectenna array having a reduced size and a high RF-to-DC efficiency conversion.

## 6 Conclusion

In this paper, a novel and compact EM energy harvesting sensor for low-DC-power applications is designed and fabricated. The sensor collects the RF energy using a dual polarisation antenna working at the ISM band with the central frequency of 2.45 GHz. Then, the RF energy is converted into DC power through the rectifier circuit. To validate the proposed approach, the designed prototype is tested in the laboratory. The sensor presents the advantage of having a compact size and acceptable power efficiency ($P_{out}/P_{in}$) compared with previous designs with the same RF input level and operating at the same frequency band. A 41% maximum efficiency value is measured at 2.49 GHz and for an input level of −10 dBm. The sensor displays good performances for low-RF-power levels. Indeed, it can be used to charge small devices working with low-DC-power.



*a*

*b*

**Fig. 11** *Results of Measured efficiency and DC output voltage*

***(a)*** Measured efficiency versus frequency for $P_{in} = -10$ dBm on one antenna port, ***(b)*** DC output voltage variation for different rectenna orientation angles

**Table 3** Comparison between our work and some references

| Reference | Rectenna size, $mm^3$ | RF input power, dBm | Antenna gain, dBi | Antenna polarisation | Maximum efficiency simulated measured, % |
|---|---|---|---|---|---|
| [3] | 89 × 78 × 1.52 | 24 | 4.5 | CP | 62 N.M |
| [4] | 70 × 70 × 7.1 | −10 | 7.7 | dual LP | 38.2 19 |
| [5] | 100 × 110 × 4.7 | 10 | 5.7 | dual CP | N.M 63 |
| [6] | 60 × 77.8 × 18.2 | 15 | 2 | LP | 50 45 |
| [7] | 93 × 135 × 23.5 | 18 | 10 | LP | 74 72.8 |
| our work | 50 × 50 × 6.2 | −10 | 6.44 | dual LP | 55 41 |

## 7 References

[1] Brown, W.C.: 'The history of power transmission by radio waves', *Microwave theory and techniques', IEEE Trans.*, 1984, **32**, (9), pp. 1230–1242

[2] Pozar, D.M.: 'A reciprocity method of analysis for printed slot and slot-coupled microstrip antennas', *IEEE Trans. Antennas Propag.*., 1986, pp. 1439–1446

[3] Heikkinen, J., Kivikoski, M.: 'A novel dual-frequency circularly polarized rectenna', *IEEE Antennas Wirel. Propag. Lett.*., 2003, **2**, (1), pp. 330–333

[4] Georgiadis, A., Andia, G.V., Collado, A.: 'Rectenna design and optimization using reciprocity theory and harmonic balance analysis for electromagnetic (EM) energy harvesting', *IEEE Antennas Wirel. Propag. Lett.*., 2010, **9**, pp. 444–446

[5] Harouni, Z., Cirio, L., Osman, L., *et al.*: 'A dual circularly polarized 2.45-GHz rectenna for wireless power transmission', *IEEE Antennas Wirel. Propag. Lett.*, 2011, **10**, pp. 306–309

[6] Monti, G., Corchia, L., Tarricone, L.: 'ISM band rectenna using A ring loaded monopole', *Prog. Electromag. Res. C*, 2012, **33**, pp. 1–15

[7] Nie, M.J., Yang, X.X., Tan, G.N., *et al.*: 'A compact 2.45-GHz broadband rectenna using grounded coplanar waveguide', *IEEE Antennas Wirel. Propag. Lett.*, 2015, **14**, pp. 986–989

[8] Tu, W.-H., Hsu, S.-H., Chang, K.: 'Compact 5.8-GHz rectenna using stepped-impedance dipole antenna', *Antennas Wirel. Propag. Lett., IEEE*, 2007, **6**, pp. 282–284

[9] Merabet, B., Costa, F., Takhedmit, H., *et al.*: 'A 2.45-GHz localized elements rectenna'. Microwave, Antenna, Propagation and EMC Technologies for Wireless Communications, 2009 3rd IEEE Int. Symp. on, October 2009, pp. 419–422

[10] Takhedmit, H., Cirio, L., Merabet, B., *et al.*: 'Efficient 2.45 GHz rectenna design including harmonic rejecting rectifier device', *Electron. Lett.*, 2010, **46**, (12), pp. 811–812

[11] Sarker, M.R., Ali, S.H.M., Othman, M.m.: 'Designing a low voltage energy harvesting circuit for rectified storage voltage using vibrating piezoelectric'. Research and Development (SCOReD), IEEE Conf. on, Cyberjaya, 2011, pp. 343–346

[12] Kumar, S.V., Patel, P., Mittal, A., De, A.: 'Design, analysis and fabrication of rectenna for wireless power transmission', Virtual Battery Communications (NCC), 2012, pp. 1–4

[13] Franceschetti, G., Rocca, P., Robol, F., *et al.*: 'Innovative rectenna design for space solar power systems'. Microwave Workshop Series on Innovative Wireless Power Transmission, Technologies, Systems, and Applications (IMWS), Kyoto, 2012, pp. 151–153

[14] Yang, X.-x., Jiang, C., Elsherbeni, A.Z., *et al.*: 'A novel compact printed rectenna for communication systems'. Power and Energy Engineering Conference (APPEEC), 2012, pp. 1–4

[15] Zhang, F., Meng, F.-Y., Lee, J.-C., *et al.*: 'Study of a novel compact rectenna for wireless energy harvesting'. Wireless Symp. (IWS), 2013 IEEE Int., April 2013, pp. 1–4

[16] Moon, J.I., Cho, I.K., Kim, S.M., *et al.*: 'Design of efficient rectenna with vertical ground-walls for RF energy harvesting', *Electron. Lett.*, 2013, **49**, (17), pp. 1050–1052

[17] Del Prete, M., Costanzo, A., Masotti, D., *et al.*: 'An alternative rectenna design approach for wirelessly powered energy autonomous systems'. Microwave Symposium Digest (IMS)', IEEE MTT-S Int., 2013, pp. 1–4

[18] Takacs, A., Aubert, H., Luca, A., *et al.*: 'Rectenna design for *K* band application'. Microwave Conf. (EuMC), 2014, pp. 648–651

[19] Sennouni, M.A., Zbitou, J., Abboud, B., *et al.*: 'Improved circularly polarized rectenna design for microwave power transmission at 2.45 GHz'. Renew. Sustain. Energy Conf. (IRSEC), 2014, pp. 582–586

[20] Tan, G.-N., Yang, X.-X., Tan, C.: 'Design of rectifying circuit for wireless power transmission in Ka band'. Antennas and Propagation Society Int. Symp. (APSURSI), 2014, pp. 639–640

[21] Takhedmit, H., Cirio, L., Costa, F., *et al.*: 'Transparent rectenna and rectenna array for RF energy harvesting at 2.45 GHz'. Antennas and Propagation (EuCAP), 2014 8th European Conf., April 2014, pp. 2970–2972

[22] Jiang, W., Zhang, B., Yan, L., *et al.*: 'A 2.45 GHz rectenna in a near-field wireless power transmission system on hundred-watt level'. Microwave Symp. (IMS), 2014 IEEE MTT-S Int., June 2014, pp. 1–4

[23] Huang, Y.-C., Pan, G.-P., Li, T.-L., *et al.*: 'Design of dual polarized rectenna for wireless power transmission'. Electromagnetic Compatibility (APEMC), 2015 Asia-Pacific Symposium, May 2015, pp. 269–271

[24] Balanis, C.A.: '*Antenna theory analysis and design*' (John Wiley & Sons, INC, 2005), pp. 817–820

[25] 'http://www.mouser.com/ds/2/472/Surface_Mount_Schottky_Diodes_200041W-238274.pdf', accessed 12 December 2015