Progress In Electromagnetics Research Letters, Vol. 90, 29–36, 2020

A High Gain Dual Band Rectenna for RF Energy Harvesting Applications

Mohammed C. Derbal* and Mourad Nedil

Abstract—In this article, a high gain dual band rectenna is proposed for energy harvesting applications. A dual band antenna is designed and optimized to operate at 3.5 GHz and 5.8 GHz frequency bands. The antenna is based on a multilayer substrate structure excited by aperture-coupling feed. In order to achieve a maximum gain of the antenna in both bands, a rectangular cell optimized by genetic algorithms is etched on the radiating element (patch). This antenna was simulated and fabricated, and the results show a good agreement in both bands (3.5 and 5.8 GHz) with a high gain of 10.2 dBi and 8.92 dBi for the first and second bands, respectively. A dual-band rectifier is also designed and studied to harvest the radio frequency energy absorbed by the antenna to DC energy at these frequency bands (3.5 GHz and 5.8 GHz). This rectifier shows a good performance in terms of conversion efficiency which achieves 44% in the first band and 29% in the second band. As a result, an output voltage of 656.88 mV for a low input power of 0 dBm is observed when the rectifier operates at both bands.

1. INTRODUCTION

Nowadays, there is tremendous growth in using wireless devices in daily activities, such as domestic, medical, or military applications [1]. In fact, most of these devices are powered using a battery which requires low input power. However, the conventional battery has a limited lifetime, and in most cases, their maintenance or replacements will be difficult or complicated [2]. Therefore, several research works have been conducted to find an alternative way to power these devices. Lately, RF energy harvesting has emerged as one of the most effective methods to power different sensors by exploiting the available RF ambient energy using rectennas. Generally, a rectenna (Rectifying Antenna) is a combination of a receiving antenna and a rectifying circuit. Nevertheless, the main drawback of energy harvesting is the low RF power density which leads to low RF to DC conversion efficiency [3]. In order to maximize the absorbed RF ambient energy delivered to the rectifying circuit, a high gain antenna is needed.

Recently, various rectenna designs have been proposed in the literature for RF energy harvesting [4–8]. In [4], a compact rectenna for high efficient WiFi energy harvesting was presented. Fractal geometry was used in the design of the receiving antenna for miniaturization, with a gain of 3.25 dBi and RF to DC conversion efficiency of 52% (input power of 0 dBm) at 2.45 GHz. A differential microstrip antenna with a high gain was also introduced in [5]. The antenna was designed to operate at the GSM900 band (890–960 MHz) with a gain of 8.5 dBi. Moreover, a compact antenna with a high gain of 10.1 dBi at 5.8 GHz is also proposed in [6].

On the other hand, multiband antennas are also proposed to increase the harvested energy when multiple RF sources are available [7–10]. In [7], a dual-band circular patch antenna was introduced to cover the frequency bands of 1.95 GHz, and 2.45 GHz with a gain of 8.3 and 7.8 dBi, respectively. A compact slot-loaded dual-band folded dipole rectenna operating at 915 MHz and 2.45 GHz was developed which provides a gain of 1.87 and 4.18 dBi at 915 MHz and 2.45 GHz, respectively [8]. The dual-band

Received 26 December 2019, Accepted 8 February 2020, Scheduled 19 February 2020
* Corresponding author: Mohammed Cherif Derbal (mohammedcherif.derbal@uqat.ca).
The authors are with the School of Engineering, University of Quebec (UQAT), Val d'Or, Quebec, Canada.

rectifier showed an efficiency of 37% and 30% at 915 MHz and 2.45 GHz for 9 dBm input power. In [9], a concentric square patches rectenna operates at the WiFi frequency bands of 2.4 and 5.5 GHz with a gain of 7.52 dBi and 7.26 dBi, respectively. In [10], a compact, optimized tree-like receiving antenna was introduced to operate at 2.45 GHz WiFi and 3.5 GHz WiMAX bands with a gain of 2.16 dBi and 1.92 dBi, respectively.

In the same area, the concept of antenna arrays is also proposed to achieve a high gain of the receiving antennas. In [11] a 3×2 antenna array has been used to achieve a gain of 10.3 dBi at 950 MHz. A broadband planar Log-Periodic Dipole Array antenna has been developed using triangular-shaped dipole antennas [12]. It covers all the cellular bands from 570 to 2750 MHz with a gain of 7.2 dBi over the entire bandwidth. However, using antenna array makes the size of the receiving antenna too large, which is not suitable for nowadays applications that require compactness, besides, to the coupling problem between the array elements.

In this paper, a dual band antenna has been designed and optimized to operate at 3.5 GHz and 5.8 GHz frequency bands. To achieve a maximum gain of this antenna, a rectangular unit cell optimized by genetic algorithms has been etched on the patch radiating element. Thus, the increase of the harvested energy can be optimized as the receiving antenna collects energy from two bands with the highest gain. A dual-band rectifier has also been designed to harvest the radio frequency energy absorbed by the antenna.

2. ANTENNA DESIGN

Figure 1 shows the layout of the proposed multilayer antenna. This antenna is designed to operate at the frequency bands of 3.5 GHz and 5.8 GHz. The first layer (feed substrate) is an RT/Duroid 5880 substrate with a dielectric constant $\varepsilon = 2.2$ and thickness 0.787 mm. The feed line is on the bottom side and the ground plane with a coupling aperture on the other side. This layer is followed by a foam of 4 mm of thickness, with a low dielectric constant $\varepsilon = 1.07$. On the top of the foam, a thin layer of RT/Duroid substrate, with dielectric constant equal to 2.2 and 0.127 mm of thickness, is used to support the radiating microstrip patch which has a width of 75 mm and length of 35 mm with an etched rectangular unit cell. The dimensions of the proposed antenna are illustrated in Fig. 2 (unit: millimeter).

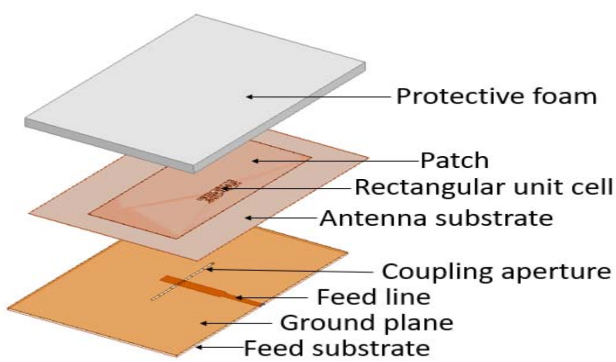


Figure 1. Layout of the proposed antenna.

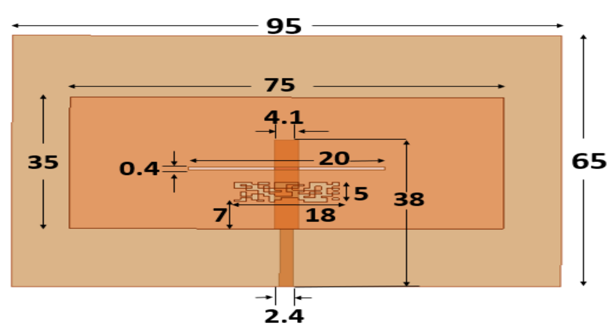


Figure 2. Top view of the of propped antenna.

To achieve the dual-band response, the rectangular unit cell shown in Fig. 3 is etched on the patch. The proposed antenna is then optimized using multi-objective genetic algorithms (GA). The GA was developed to optimize the rectangular unit cell to allow the antenna operating at 3.5 GHz and 5.8 GHz while providing a maximum realized gain at both bands. The optimization procedure is detailed in [13].

The GA divides the rectangular cell into 18×10 pixels, which provides $Q = 180$ (Q is the total number of pixels), and each pixel has a dimension of 1×0.5 mm. The presence and absence of the pixels can be represented by binary digits $xq\{0; 1\}$, $q = 1, 2, ..., Q$, which are grouped into vector $x = \{x1; x2; ...; x_Q\}$ to describe the configuration of the pixels in the unit cell.

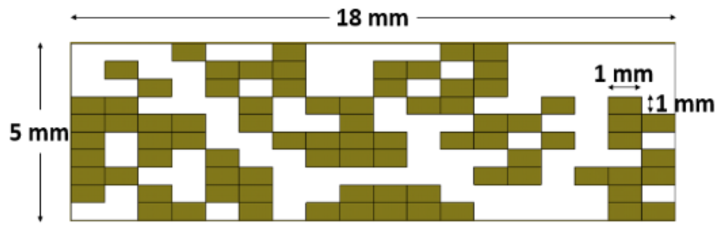


Figure 3. The optimized rectangular cell.

From 2^Q different configurations of x, the GA will determine the x corresponding to the best solution of the following multi-optimization problem.

$$\begin{cases} \min\limits_{x} S_{11}\left(x, f_1\right), S_{11}\left(x, f_2\right) \\ \max\limits_{x} G(x, f_1), G(x, f_2) \end{cases} \tag{1}$$

where $S_{11}(x, f_k)$ is the reflection coefficient of the antenna, $G(x, f_k)$ the realized gain, and $f_1 = 3.5\,\text{GHz}$, $f_2 = 5.8\,\text{GHz}$.

In order to solve problem 1, the GA is lunched using CST Microwave Studio. After a few hours of optimization, the best solution is achieved, and the optimal structure is illustrated in Fig. 3.

To validate the proposed design, a prototype of the proposed antenna has been fabricated. The comparison between the measured and simulated reflection coefficient results of the proposed antenna is shown in Fig. 4. It can be seen that the measurement results agree well with the simulation ones. Thus, the proposed antenna operates at the frequencies 3.5 GHz and 5.8 GHz with a good matching performance in both bands.

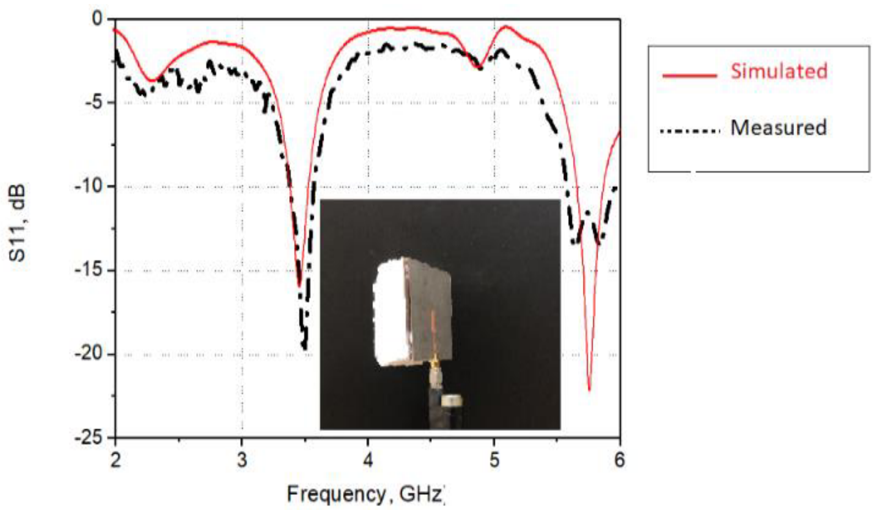
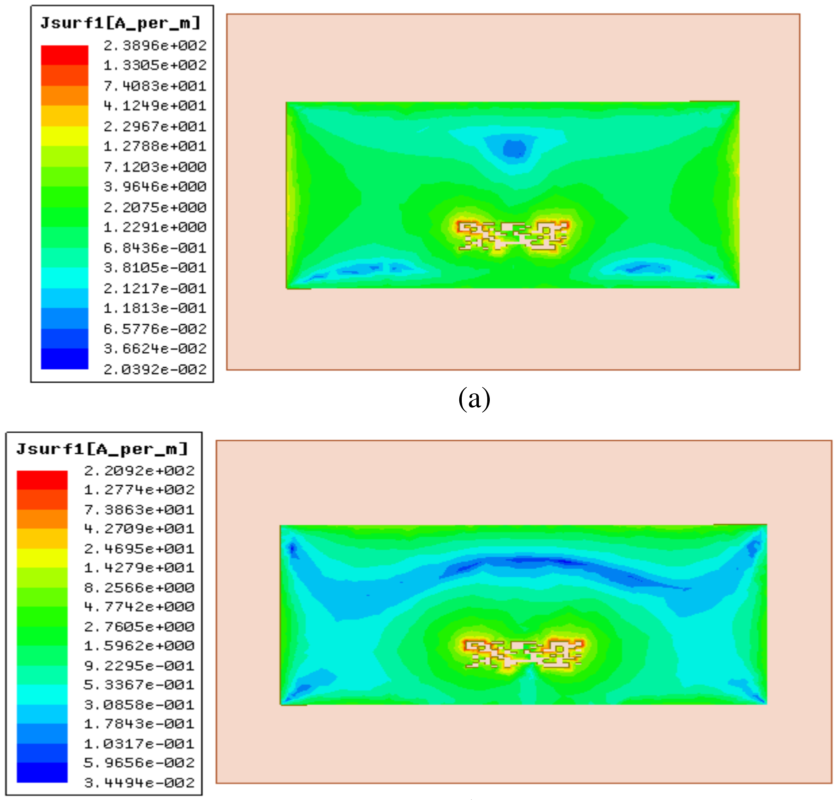


Figure 4. Simulated and measured reflection coefficient of the proposed dual band antenna.

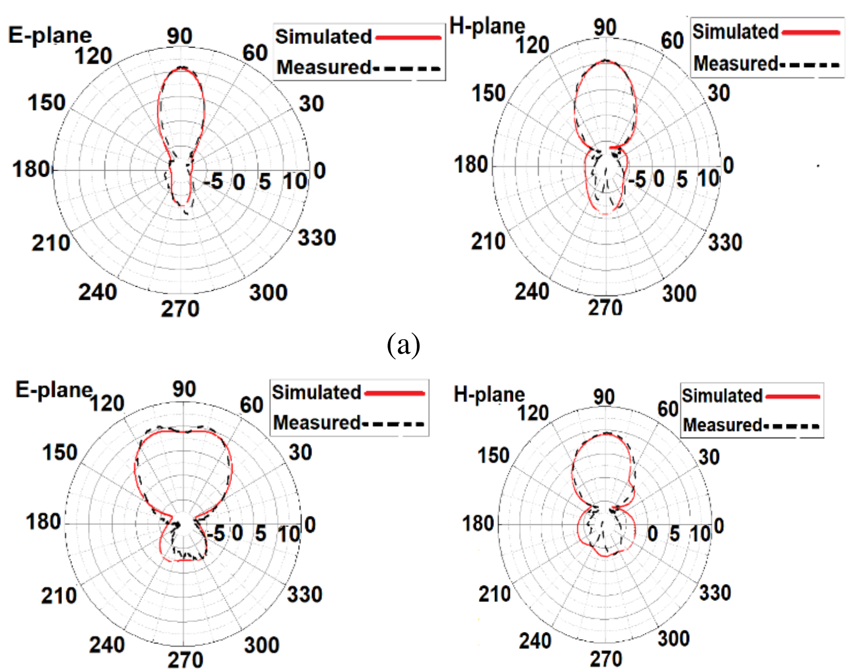
Surface current distributions of the proposed antenna at both bands are illustrated in Fig. 5. It can be noticed that most of the current is concentrated in the rectangular unit cell at both frequencies, especially at frequency 5.8 GHz.

To examine the radiation performance of the fabricated prototype, radiation patterns for the proposed antenna at these two resonance frequencies are measured using a hybrid near-far field system from ANTCOM. For measurements, the antenna under test is set inside an anechoic chamber. Fig. 6 shows the simulated and measured radiation patterns of the proposed antenna in the E plane and H plane. A directional radiation pattern in both planes is obtained, with a maximum realized gain of 10.2 dBi and 8.94 dBi at frequencies 3.5 GHz and 5.8 GHz, respectively.



(b)

Figure 5. Surface current distributions of the proposed antenna at both bands, (a) 3.5 GHz, (b) 5.8 GHz.



(b)

Figure 6. Simulated and measured radiation patterns, (a) 3.5 GHz, (b) 5.8 GHz.

A comparison between the proposed antenna and related works on energy harvesting is given in Table 1. It can be noticed that the proposed antenna provides a high gain in both bands, which allows to absorb more RF energy.

Table 1. Comparison of the proposed antenna and related works in literature.

Ref.	Frequency (GHz)	Antenna type	Gain (dBi)
[9]	1.95, 2.45	Stacked disk	8.3, 7.8
[11]	2.4, 5.5	Differential antenna	7.52, 7.26
[14]	2.45, 5	Coupled antenna	8.5, 7.8
[15]	2.45, 5.8	Quasi-PIFA	6.62, 6.25
This work	3.5, 5.8	Coupled antenna	10.2, 8.94

3. RECTIFIER DESIGN

The design of the rectifier is carried out in order to achieve a good compromise between the complexity of the circuit and the performance of the rectifier at low input power.

The schematic of the designed rectifier is shown in Fig. 7. The circuit parameters are optimized to obtain the maximum RF-DC conversion efficiency for an input power level of 0 dBm. The design is carried out using Advanced Design System (ADS). The dimensions of the circuit are illustrated in Fig. 7, where W_{stub} is the width of the line; Stub 1 and Stub 2 are the lengths of the stubs; and $Ln1, Ln2, Ln3, Ln4$ are the lengths of the lines.

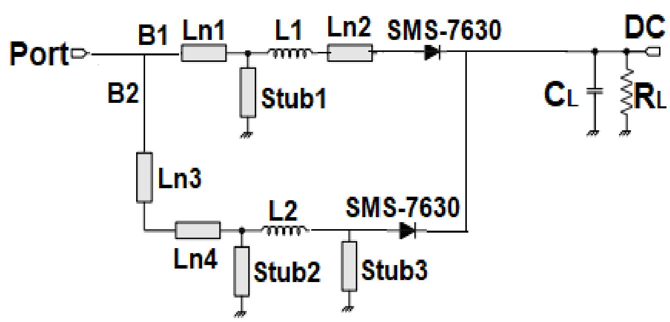


Figure 7. Schematic of the dual band rectifier. ($Ln1 = 6.2$ mm, $Ln2 = 2$ mm, $Ln3 = 3.5$ mm, $Ln4 = 3.5$ mm, Stub 1 = 2.9 mm, Stub 2 = 8.1 mm, Stub 3 = 6.1, $L1 = 5.6$, $L2 = 1.6$ nH, $W_{\text{Stub}} = 2,38$ mm, $R_L = 0.5\,\text{k}\Omega$).

For the purpose of obtaining good RF-DC conversion efficiency of the rectifier in both bands, two diodes are used in parallel, where each diode operates in a specific band according to the approach reported in [1]. Hence, branches, labeled "B1", "B2" in Fig. 6, are designed to operate at 3.5 GHz and 5.8 GHz, respectively. Each RF branch is composed of a bandpass filter, a diode, and a low-pass filter.

In order to match each parallel rectifier to the dedicated frequency bands, two bandpass filters are introduced. Hence, the inductor $L1$ and line $Ln2$ are used to pass the 3.5 GHz band, and the inductor $L2$ and Stub 3 are used as a bandpass filter for the 5.8 GHz band. Finally, all branches are connected to a single RC filter. Stub 1 and Stub 2 are used as a filter to protect the source (The antenna) from the reflected high order harmonics generated by the nonlinear behavior of the diode.

The Skyworks SMS7630 Schottky diode is chosen for its low turning-off voltage of 150 mv which is suitable for low power applications. The used substrate is Rogers RT/Duroid 5880 (whose dielectric constant is 2.2) with a thickness of 0.787 mm.

A capacitor with a value of 100 pF is employed as a low-pass filter to ensure that only DC current can pass to the load which is equal to 0.5 kΩ. The dimensions of the rectifier are designed and optimized to obtain a good impedance matching and RF to DC conversion efficiency under the constraint of the low input power of 0 dBm. The rectifier is simulated using the Advanced Design System (ADS) with considering the nonlinear SPICE model of the diode, and the S-parameters of the SMD components are provided by the manufacturer. A photograph of the fabricated rectifier is shown in Fig. 8.

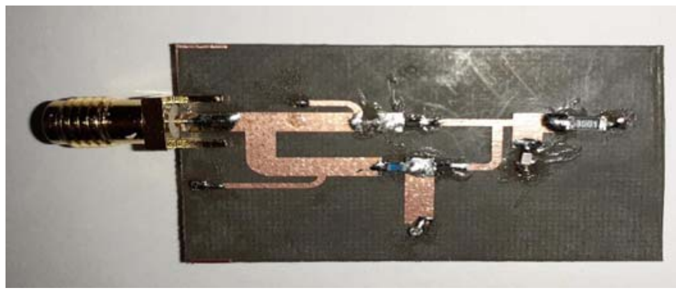


Figure 8. Photograph of the fabricated rectifier.

Figure 9 illustrates the simulated and measured reflection coefficients of the dual-band rectifier at an input power level of 0 dBm. It can be seen that the rectifier works well at the frequencies of 3.5 GHz and 5.8 GHz with a good impedance matching in both bands. Moreover, the measurement results agree with the simulated ones.

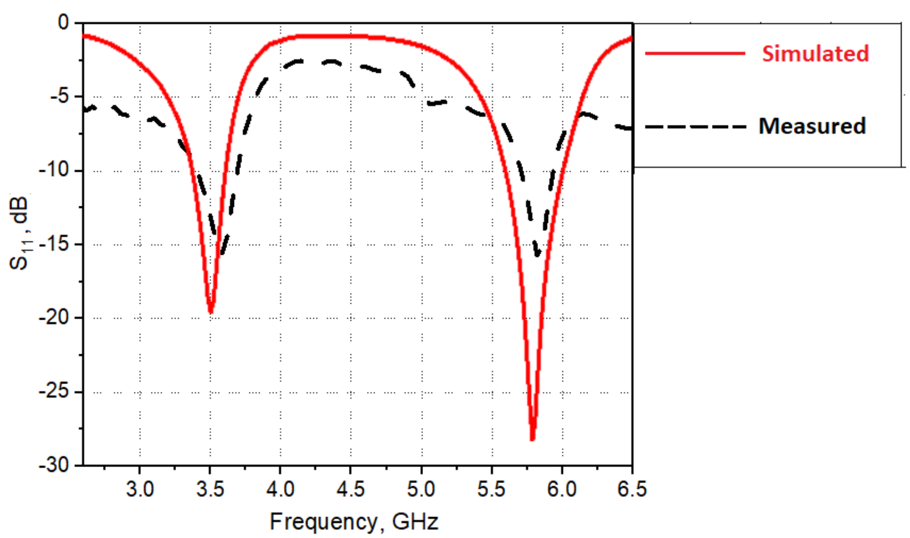


Figure 9. Simulated and measured reflection coefficient of the dual band rectifier at 0 dBm.

The RF-to-DC conversion efficiency of the rectifier versus frequency at the input power of 0 dBm is shown in Fig. 10, which could be measured as

$$\eta_{\mathrm{RF-DC}} = \frac{V_{\mathrm{DC}}^2/R_L}{P_{\mathrm{avs}}} \cdot 100 \tag{2}$$

where R_L is the load resistance, V_{dc}^2/R_L the dc power delivered to the load, and P_{avs} the available RF power at the input of the rectifier. It can be seen that the efficiencies of the rectifier at 0 dBm are 44% and 29% at 3.5 GHz and 5.8 GHz, respectively.

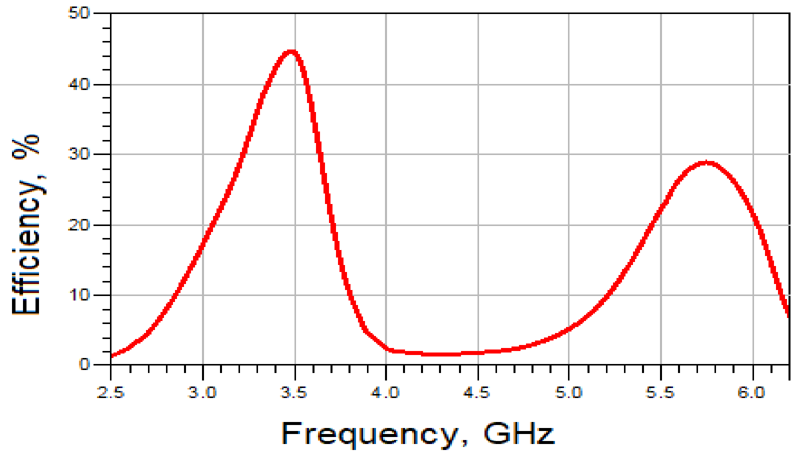


Figure 10. Measured RF-to-DC conversion efficiency of the rectifier versus frequency at input RF power level of 0 dBm.

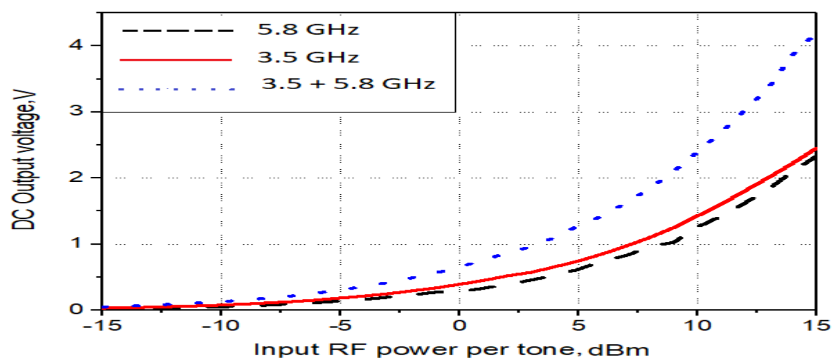


Figure 11. Measured output DC voltage versus an available input power per source for one and two tones.

The measured output DC voltage is recorded as a function of the available input power for one and two tones, and the obtained results are illustrated in Fig. 11. For an input power of 0 dBm, a DC voltage of 458 mV is achieved when the circuit operates only at the frequency 3.5 GHz. Similarly, a voltage of 387 mV can occur if the circuit operates at the frequency 5.8 GHz. On the other hand, an output voltage of 656.88 mV can be obtained when the rectifier operates simultaneously in frequencies 3.5 GHz and 5.8 GHz. Therefore, a good enhancement of the output voltage is observed compared to the voltage obtained at each frequency separately, which shows the benefit of using a multi-band rectifier over a single-band rectifier.

4. CONCLUSION

In this contribution, a novel optimized high gain dual-band rectenna for ambient RF energy harvesting has been presented. The designed rectenna can harvest RF power from WiMAX and WIFI bands. In order to achieve a high gain in both bands, an optimized rectangular unit cell using genetic algorithms is etched on the radiating patch of the rectenna. The results show a directional radiation pattern in both bands with a high gain of 10.2 dBi at frequency 3.5 GHz and 8.94 dBi at frequency 5.8 GHz. Also, the design and performance of a dual-band rectifier operating at the frequency bands of 3.5 GHz and 5.8 GHz are introduced. The results show that the rectifier provides a good DC voltage and efficiency at both bands for a low input RF power level of 0 dBm, which demonstrates the capability of the rectifier to harvest RF power when two RF sources are available. The proposed rectenna design is suitable for wireless sensors networks.

REFERENCES

1. Kuhn, V., C. Lahuec, F. Seguin, and C. Person, "A multi-band stacked RF energy harvester with RF-to-DC efficiency up to 84%," *IEEE Trans. Microwave Theory Techniques*, Vol. 63, No. 5, 1768–1778, 2015.
2. Palazzi, V., et al., "A novel ultra-lightweight multiband rectenna on paper for RF energy harvesting in the next generation LTE bands," *IEEE Trans. Microwave Theory Techniques*, Vol. 66, No. 1, 366–379, 2017.
3. Shen, S., C. Y. Chiu, and R. D. Murch, "A dual-port triple-band L-probe microstrip patch rectenna for ambient RF energy harvesting," *IEEE Antennas and Wireless Propagation Letters*, Vol. 16, 3071–3074, 2017.
4. Shi, Y., J. Jing, Y. Fan, L. Yang, and M. Wang, "Design of a novel compact and efficient rectenna for WiFi energy harvesting," *Progress In Electromagnetics Research C*, Vol. 83, 57–70, 2018.
5. Arrawatia, M., M. S. Baghini, and G. Kumar, "Differential microstrip antenna for RF energy harvesting," *IEEE Trans. Antennas Propag.*, Vol. 63, No. 4, 1581–1588, 2015.
6. Derbal, M. C. and M. Nedil, "A high gain rectenna for energy harvesting applications," *2019 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting*, 1505–1506, Atlanta, GA, USA, 2019.
7. Aboualalaa, M., A. B. Abdel-Rahman, A. Allam, H. Elsadek, and R. K. Pokharel, "Design of a dual-band microstrip antenna with enhanced gain for energy harvesting applications," *IEEE Antennas and Wireless Propagation Letters*, Vol. 16, 1622–1626, 2017.
8. Niotaki, K., S. Kim, S. Jeong, A. Collado, A. Georgiadis, and M. M. Tentzeris, "A compact dual-band rectenna using slot-loaded dual band folded dipole antenna," *IEEE Antennas and Wireless Propagation Letters*, Vol. 12, 1634–1637, 2013.
9. Mattsson, M., C. I. Kolitsidas, and B. L. G. Jonsson, "Dual-band dual-polarized full-wave rectenna based on differential field sampling," *IEEE Antennas and Wireless Propagation Letters*, Vol. 17, No. 6, 956–959, 2018.
10. Wang, M., Y. Fan, L. Yang, Y. Li, J. Feng, and Y. Shi, "Compact dual-band rectenna for RF energy harvest based on a tree-like antenna," *IET Microwaves, Antennas* & *Propagation*, Vol. 13, No. 9, 1350–1357, 2019.
11. Xie, F., G.-M. Yang, and W. Geyi, "Optimal design of an antenna array for energy harvesting," *IEEE Antennas and Wireless Propagation Letters*, Vol. 12, 155–158, 2013.
12. Kumar, H., M. Arrawatia, and G. Kumar, "Broadband planar log-periodic dipole array antenna based RF-energy harvesting system," *IETE Journal of Research*, Vol. 65, No. 1, 39–43, 2019.
13. Derbal, M. C., A. Zeghdoud, and M. Nedil, "A novel dual band antenna design for WiFi applications using genetic algorithms," *IEEE International Symposium on Antennas and Propagation* & *USNC/URSI National Radio Science Meeting*, 1009–1010, Boston, 2018.
14. Mohd Noor, F. S., Z. Zakaria, H. Lago, and M. A. Meor Said, "Dual-band aperture-coupled rectenna for radio frequency energy harvesting," *International Journal of RF and Microwave ComputerAided Engineering*, Vol. 29, No. 1, e21651, 2019.
15. Lu, P., X. S. Yang, J. L. Li, and B. Z. Wang, "A dual-frequency quasipifa rectenna with a robust voltage doubler for 2.45- and 5.8-GHz wireless power transmission," *Microwave and Optical Technology Letters*, Vol. 57, No. 2, 319–322, 2015.