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Architecture of an efficient dual band 1.8/2.5 GHz rectenna for RF energy harvesting

Jahariah Sampe*1, Noor Hidayah Mohd Yunus2, Jumril Yunas3, Alipah Pawi4
1,2,3Institute of Microengineering and Nanoelectronics, Universiti Kebangsaan Malaysia (IMEN-UKM),
43600 Bangi, Selangor, Malaysia
4Communication Technology Section, Universiti Kuala Lumpur, British Malaysian Institute (UniKL-BMI),
Batu 8, Sungai Pusu St., 53100 Gombak, Selangor, Malaysia
e-mail: jahariah@ukm.edu.my1, noorhidayahm@unikl.edu.my2, jumrilyunas@ukm.edu.my3,
alipah@unikl.edu.my4

Abstract

This paper presents a highly efficient rectenna of RF energy harvesting systems operating at 1.8 GHz and 2.5 GHz bands for battery-less sensor application. The antenna is design by CST-MWS. The Schottky diode used for rectifying circuit is HSMS 286B in which designed by Agilent ADS. The key finding of the paper is that the simulated DC output voltage of the rectenna is 1.35 V for low input power of -25 dBm at a high resistance load of 1M Ω. Correspondingly, the RF-DC conversion efficiency of the rectification process is 59.51% and 45.75% at 1.8 GHz and 2.5 GHz, which are high efficiency and much better compared to literature respectively. The rectenna is capable to produce 1.8 V from an input power of -20 dBm. Thus, the proposed RF energy harvesting system offers a promising solution designed for efficient functionality at a low power level of RF energy in the dual band.

Keywords: *microstrip patch antenna, rectenna, rectifying circuit, RF energy harvester, RT/Duroid 5880*

1. Introduction

Autonomous powered sensor devices using alternate harmless sources and continuous supply of energy has attracted raising attention research and development (R&D) in industry and academia. Recently, batteries supply finite power to conventional devices. Batteries store chemical energy and convert directly into electrical energy when required. Chemical batteries released may be poisonous and harmful to human life and the environment if leakage occurs, either through accident or spontaneously. For this issue, many researchers recommend to develop new long-lasting sources and reformative power to meet the desired energy of these devices. One of the most attractive solution for battery-free and automated powering the nodes and devices is by ambient energy harvesting technique [1, 2].

Comparing among ambient energy for harvesting such vibration, thermal, solar and other kinds of energy source, radio frequency (RF) energy harvesting is a practical alternative as the RF energy is present at any time and everywhere [3-6]. The ambient RF energy and the dedicated RF energy are resource factors of the harvesting of RF. RF energy harvesting is the technique that implemented to convert RF energy into electricity in the form of direct current (DC) power. However, RF energy is omnipresent in a low power density at a few µW [7].

RF energy harvesting is demand for high conversion efficiency and high sensitivity of rectenna with average low input power. Most of the literature applies the RF energy harvesting system operating at the far-field directive powering with low input power setup as shown in Figure 1. The rectifier is the key component in RF energy harvesting, which converts the RF energy from the receiving antenna into DC power. Thus, the RF-DC conversion efficiency parameter is obtain by evaluating the rectifier circuit performance. Capturing the lower input power by the receiving antenna leads to lower conversion efficiency parameter [8]. A pertinent antenna is greatly required since an antenna can affect the amount of incoming RF energy captured to the matching circuit and cascaded rectifier in the harvesting system.

To attain a high-energy conversion efficiency, various frequency bands of rectifiers have been investigated for instance, single band [9, 10], multi band [11-13] and broadband [14]

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designs. Generally, single band rectifiers easily attain a high efficiency. However, in single band approach, the RF energy captured is low and the output voltage is insufficient for powering battery-less sensor devices. Broadband rectifiers are the candidates to attain more output voltage; however, the trade-off might decrease the peak efficiency. In line for the limitations explained, multi band rectifiers are a good alternative candidate approach. However, designing the rectifier is challenging due to nonlinear characteristics of the multi band operations [15], but the nonlinear characteristics lead the input impedance varies at the frequencies function that matched between the energy source level and the impedance load.

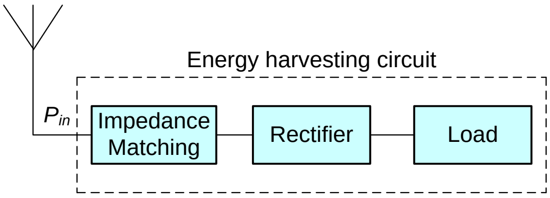


Figure 1. Conventional rectenna structures

In literature, a few studies reported for multi band rectifier with low input power development. The literature applies the input power to energy harvesting circuit at equal or larger than -10 dBm (≥ -10 dBm) in which leads to larger conversion efficiency parameter as achieved in the study by [16, 17]. Recent studies by [18-21] emphasis on the antenna performance that able to capture larger input power with a high antenna gain parameter. However, nonlinear characteristics of multiband rectifier required careful design to tackle inherently different cases with low input power presence to the energy harvesting circuit.

Thus, from the challenge, this paper proposes a highly efficient energy harvesting circuit achievable over -30 dBm to 0 dBm (1µW to 1mW) input power at 1.8 GHz and 2.5 GHz dual band operations. The harvesting circuit designed based on 50 Ω matching line at the dual band operation. The dual band rectifier configuration consists of diodes, capacitors and a resistor as the resistance load, which will be presented in section 2. Performance results attained are discuss and presented in section 3. Finally, concluding remarks of the dual band RF energy harvesting is presented in section 4.

2. Research Method

Here, the RF energy harvester employs an exceptional antenna known as a rectifying antenna or rectenna. Rectenna applies to the system, which, comprises an antenna with transmission line-based matching network and the use of typical discrete diodes (Schottky type) fabricated on a printed circuit board (PCB). The sub-blocks of the proposed RF energy harvesting system are presented as follows.

2.1. Dual Band Patch Antenna

The proposed antenna design is simulated and optimized by Computer Simulation Technology-Microwave Studio (CST-MWS) software. Simulation is conducted based on a 50 Ω port impedance of a transmission line feed. The radiator patch is fabricated on standard RT/Duroid 5880 substrate with important specifications of dielectric constant ε_r = 2.20, dissipation factor tan δ = 0.0009, substrate thickness = 1.57 mm and copper thickness = 17.5 µm. The fabricated antenna is evaluated by a Vector Network Analyzer (VNA). The patch antenna is designed with horizontal and vertical rectangle slot as well as a shorting pin to realize on dual band operations and to optimize the antenna size, respectively. The layout of the proposed antenna is shown in Figure 2. The rectangle slots are designed as U pattern. While, the shorting pin is analyzed by the transmission line model which is located at the feed point, (x_0, y_0) = (0, -1.665). The (l x w) patch antenna size of 39.2x40.1 mm^2 is good enough to be integrated with the energy harvesting circuit on the PCB process.

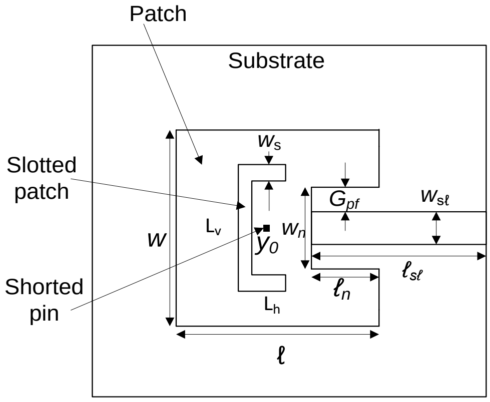


Figure 2. Proposed antenna layout

2.2. Impedance Matching Circuit

A matching circuit is placed between the antenna and rectifier sub-blocks which need to be 50 Ω matched to ensure the dual band operation can be generated and achieve maximum power transfer to the circuit. Although various matching circuits are introduced, conjugate matching method is widely used in energy harvesting systems. Here, L-section matching circuit is used. L-section consists of inductor and capacitor (LC) components that are designed to conjugately match the antenna impedance with the rectifier. It is possible to boost the voltage of the input voltage received from the antenna by the conjugate matching method. This method gives advantage in an energy harvesting system where the received voltage possibly insufficient to turn on the diodes or transistors in the rectifying circuit without voltage boosting.

Despite the advantage in energy harvester, it is challenging owing to the non-linearity characteristic of the rectifier that constructed using diodes or diode-connected transistors. Accordingly, the power transfer amount also exhibits a dependence on the received input power, frequency and resistance load of the energy harvester. However, with the used of tuning parameter for precise pull in Agilent ADS, the optimal component`s value can be easily obtained.

Since the input resistance of harvesting circuit is higher than the radiation resistance of the antenna, thus downward impedance transformer circuit is applied to the antenna. It transforms a high parallel resistance into a low series resistance at the input. The downward impedance transformer circuit is shown in Figure 3. For the L-section matching circuit, the impedance is calculated as (1)-(3) [22].

$$Z_{eq} = R_p // \frac{1}{j\omega C} \tag{1}$$

$$Z_{in} = j\omega L + Z_{eq} = j\omega L + \frac{R_p}{1 + jR_p\omega C} \tag{2}$$

$$Z_{in} = \frac{R_p + (\omega L + {R_p}^2\omega^3 LC^2 - {R_p}^2\omega C)j}{1 + {R_p}^2\omega^2 C^2} \tag{3}$$

Thus, in complex conjugates, the real and imaginary part of the input impedance given by (4), (5). The input reactance must be canceled yields (6), (7). The antenna radiation resistance should be equal to the input resistance as in impedance-matched condition. In (4) is given for the series input resistance value as (6) when cancelling the input reactance, while inductance value as (7) is obtained by equating (5) to zero [22].

$$R_{in} = \frac{R_p}{1 + {R_p}^2\omega^2 C^2} \tag{4}$$

$$X_{in} = \frac{\omega L + {R_p}^2\omega^3 LC^2 - {R_p}^2\omega C}{1 + {R_p}^2\omega^2 C^2} \tag{5}$$

$$R_s = \frac{R_p}{1+{R_p}^2\omega^2C^2} \tag{6}$$

$$L = \frac{{R_p}^2C}{1+{R_p}^2\omega^2C^2} \tag{7}$$

when ${R_p}^2\omega^2C^2 >> 1$, these formulas simplify to the L-section matching circuit and the resonance.

$$R_s = \frac{L}{R_pC} \tag{8}$$

$$L = \frac{1}{\omega^2C} \tag{9}$$

Other than considering the impedance matching model, it might become necessary to use of low voltage threshold (V_{TH}) diode in rectifier circuit, thus high voltage can be generated.

2.3. Rectifier Topology

The rectifier is important for RF-DC conversion between the conversion of alternating current (AC) waveform from the antenna input and DC waveform of the input voltage to the desired circuit or load. The maximum far-field RF-DC conversion of the rectifier is influenced by the input signal amplitude in the first stage order. However, the rectifier is tuned operate for low input power level ranging from -30 to 0 dBm using the matched antenna as input at the dual bands. In order to optimize the rectifier, it is designed by Keysight Advanced Design System (ADS) software.

Voltage doubler is the best selection of RF-DC rectification owing to the simplicity topology that able to produce twice of the output signal amplitude of the corresponding input signal and to attain high efficiency. A single stage of the voltage doubler is shown in Figure 4. The output voltage of a voltage doubler is given as $V_{out} = 2V_{in} – 2V_{th}$, where V_{in} and V_{th} are the input voltage and the threshold voltage of the diodes, respectively.

Here, a fast switching of Schottky diodes are the component used in the rectifying circuit for RF-DC conversion. HSMS 286B is chosen owing to the DC bias at above 1.5 GHz and low breakdown voltage [23]. The RF-DC conversion efficiency η of the rectifying circuit is given as,

$$\eta(\%) = \frac{P_{out}}{P_{in}} x \;\; 100\% = \frac{{V_{out}}^2}{P_{in} x \;\; R_{load}} x \;\; 100\% \tag{10}$$

where, V_{out}, P_{in} and R_{load} is the DC output voltage, the input or received power to the rectifier and the resistance load, respectively.

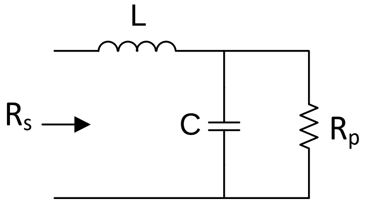


Figure 3. Downward impedance transformer

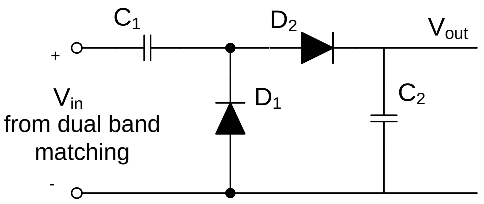


Figure 4. Voltage doubler

3. Results, Discussions and Analysis

The antenna is passive structure that converts RF energy to electricity and vice versa. Here, the antenna as in [24] is focused on the antenna, which is based on receiving the RF energy then it is converted to electrical form. The power losses possibly happen in the transmission line in which characterized as S-parameter S_{11} of the antenna. The S-parameter S_{11} of the proposed antenna is shown in Figure 5.

The simulated S-parameter by CST-MWS are -11.95 dB and -14.16 dB, while the measured S-parameter obtained by a VNA is -14.32 dB and -12.1 dB at 1.8 GHz and 2.48 GHz, respectively. The shifting resonant frequency of 20 MHz in the measured result is perhaps owing to the inaccuracy factor of the rectangular slots of the radiator patch. However, the frequency shifted of the antenna does not affect the antenna gain parameter in which obtained at the desired dual band as shown in Figure 6.

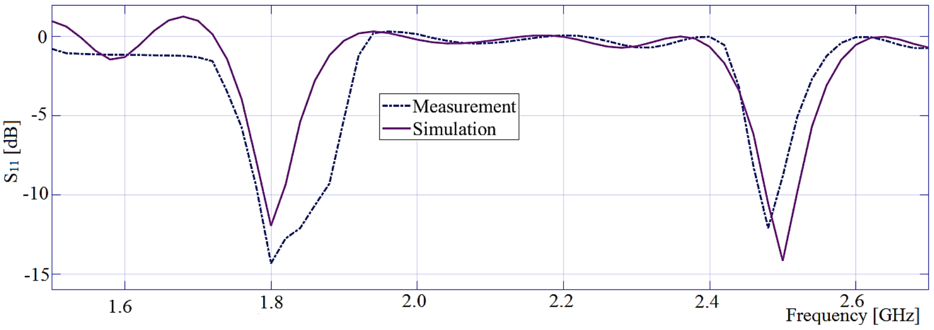


Figure 5. Measured and simulated of S-parameter

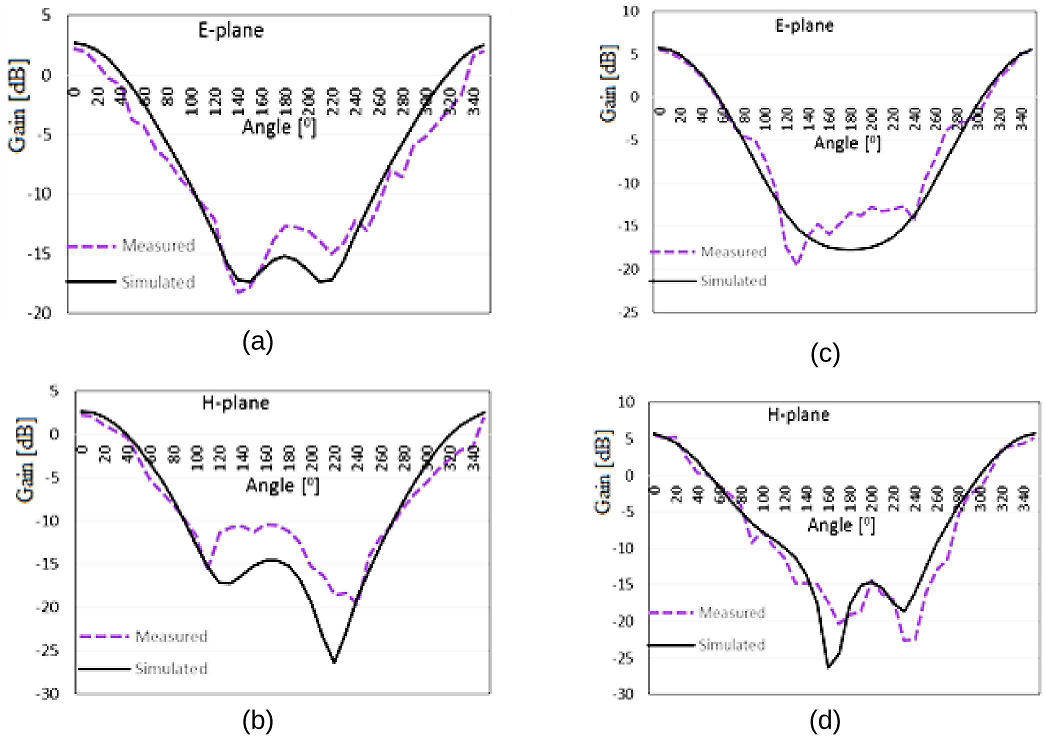
The measured and simulated radiation patterns of E-plane (y-z plane) and H-plane (x-z plane) are optimized at the dual band. A slight difference between the measured and simulated antenna gain is owing to the tolerance of the pieces substrate dimension. The measured peak gain results are 2.29 dB and 5.51 dB besides the simulated results are 2.73 dB and 5.74 dB at 1.8 GHz and 2.5 GHz, respectively at 0^0 or 360^0 angular. Accordingly, it results in a good top radiation pattern from the radiator patch of the antenna for both E-plane and H-plane. It shows that the signals received are lying under acceptable parameter in which a high antenna gain obtained is more than 5 dB at 2.5 GHz band. Accordingly, it is beneficial for rectifying circuit. However, this paper presents the rectification of the RF input signals that is evaluated ranged from -30 dBm to 0 dBm.

The simulated of the rectifying circuit is shown in Figure 7. The rectifying circuit consists of input terminal that simulating the RF input coming from the antenna, impedance matching circuit or power matching, five stage voltage doubler and resistance load. In the rectifier circuit, voltage doubler topology is preferred as it rectifies both positive and negative wave of the input signal [25]. In order to increase the amplitude voltage, each of the rectifier stage is connected in cascade.

The stage number of the rectifier brings influence on the DC output voltage produced. Here, five stages of the voltage doubler are the optimal stage number of the circuit design to produce the sufficient voltage for the application. The DC output voltage is proportional to the stage number of the rectifier in the harvesting circuit. However, the DC output voltage decreases as the number of stage increases owing to parasitic effect of the components used in each stage, and becomes negligible as more stages are presented. The effect of the stage number of the rectifier for the harvesting circuit is shown in Figure 8. Parameters sweep by ADS is used for the RF input power of -30 dBm to 20 dBm and varies the stage number from 1 to 5 stages. The plot shows the higher voltage is reached by increasing the stages number. However, when the stage is varied to 7-stage, the DC output voltages are negligible. It is corresponding to increase in power loss that accessible in the low power state.

Simulation of the rectified DC output voltage and the peak RF-DC efficiency achieved for input power in the range of -30 dBm to 0 dBm at 1 MΩ resistance load are depicted in Figure 9 and Figure 10, respectively. From the figure, the maximum RF-DC efficiency for a DC output voltage of 1.38V is 59.51% at 1.8 GHz for -25 dBm or 3.2 µW input power. While at 2.5 GHz, the maximum RF-DC efficiency for a DC output voltage of 0.7V is 49% for -30 dBm or 1 µW input power. The larger the input power, the larger the DC output voltage produced by the rectifying circuit. However, the RF-DC efficiency parameter is not necessarily large or high as it corresponds to the ratio of the output and input power at the resistance load of the rectifying circuit.

The performance of the proposed rectifying circuit is summarized in Table 1 as well as the comparison between the proposed work and some of the other works [9-14] is presented.



(a) (c)

(b) (d)

Figure 6. Measured and simulated of 2D radiation gain, (a) E-plane at 1.8 GHz (b) H-plane at 1.8 GHz (c) E-plane at 2.5 GHz (d) H-plane at 2.5 GHz

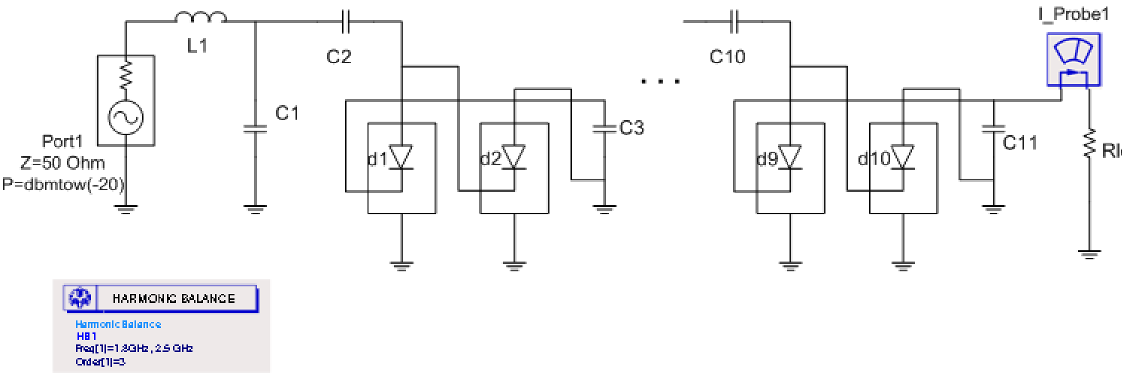


Figure 7. Schematic design of the rectifying circuit

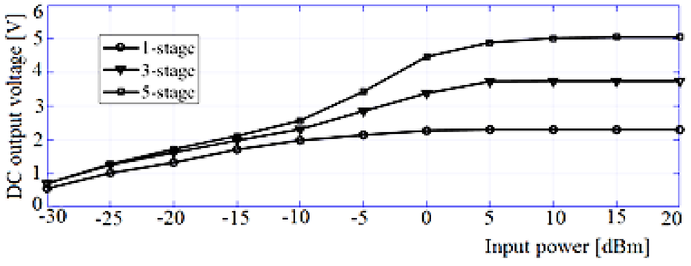


Figure 8. Impact of the stages number of the harvesting circuit

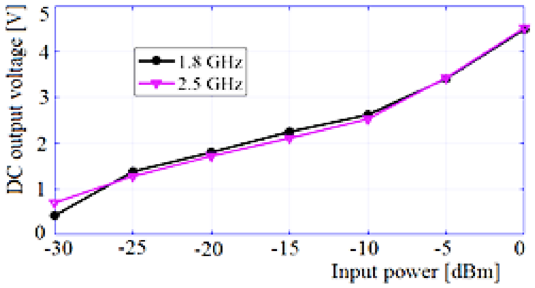


Figure 9. DC output voltage of the rectifying circuit

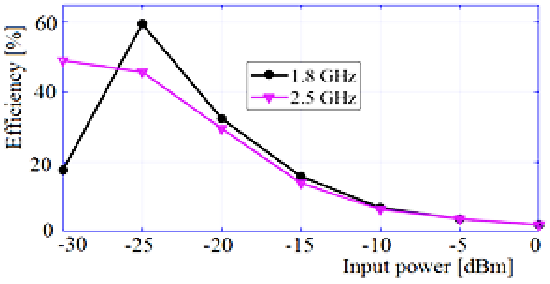


Figure 10. RF-DC efficiency

Table 1. Performance Comparison of the Proposed Rectifier with Other Works

Ref.	Freq. (GHz)	Input power (dBm)	Rectifier component	Efficiency (%)	Output voltage (V)	Resistance load (Ω)
[9]	5.8	-10	pMOS and nMOS	52	2.5	400
[10]	2.45	-12	2 stage CMOS	59.6	1.04	29 k
[11]	1.9 2.45	-20	MOSFET	4.29 26.9	2.09	1 M
[12]	0.8 1.77 2.07	0	HSMS 2850	61.9 71.5 60.5	n/a	2.2 k
[13]	2.45 5.85	-10	SMS 7630	50.7 20.1	n/r	5 – 75 k
[14]	5.05 to 7.45 (at 5.82)	0	HSMS 2860	56	1.5	3.9 k
This work	1.8 2.5	-25	HSMS 286B	59.51 45.75	1.35	1 M

*n/a: not applicable, n/r: not reported

4. Conclusion

This paper proposes a dual band rectifier operate in industrial, scientific, and medical (ISM) radio band, which efficiently convert low input RF energy source into a maximum DC output voltage. Accordingly, a high RF-DC conversion efficiency at the dual band. The HSMS 286B Schottky diodes based for the rectifying circuit are designed by Agilent ADS. A 50 Ω microstrip line based on the microstrip patch antenna is used for the dual band impedance matching. For the antenna, the simulation is carried out by CST-MWS. The performance of the fabricated antenna in terms of its S-parameter, antenna gain, E-plane and H-plane radiation pattern had been experimentally verified. Thus, the proposed RF energy harvesting system presented here is good enough to be applied as an alternative battery-like voltage for powering the battery-less sensor application. Even though the energy harvester is the economical option to acquire the dual band operation from a low power source, the design still can be enhanced further.

Acknowledgement

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