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CMOS Based Dual Band Radio Frequency Rectifier for Energy Harvester

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RF energy harvesting, cross-coupled rectifier, Cadence EDA, power conversion efficiency

Abstract

This paper proposed a dual-band rectifier for RF energy harvesting based on the CMOS architecture which is designed to operate at 900 MHz and 2.4 GHz using Cadence EDA tools with 45 nm CMOS technology. The multi-band cross-coupled rectifier designed with 5 stages at 900 MHz and 5 stages at 2.4 GHz. The load resistance of 100 KΩ is connected at 900 MHz rectifier and 2.4 GHz rectifier to measure the output voltage above 1 V and verify the functionally of multi-stage cross-coupled rectifier circuit. The greatest efficiency that the 900 MHz rectifier can achieve is 35% when the output voltage is 4.64 V and the input power is 10 dBm. On the other hand, the 2.4 GHz rectifier can attain a maximum efficiency of 36% and 4.7 V of the output voltage at 10 dBm of input power. Last but not least, the cross-coupled rectifier circuit is designed with a layout size of 53.24 nm2. In summary, it is possible to construct the suggested CMOS dual band rectifier circuit in a low voltage application.

1. Introduction

It is not a novel idea to power electrical gadgets with renewable energy sources. Energy harvesting, also known as energy scavenging, is the technique of obtaining energy from the surrounding environment in order to produce electricity (Chalasani et al., 2008; Sudevalayam et al., 2011). This energy can be obtained from a variety of environmental sources, including radiant energy (Mateu et al., 2007; Böttner, 2004), mechanical energy (Tan et al., 2006; Yu et al., 2011), and thermal energy (Böttner, 2004). Energy is extracted from a system's surroundings and transformed into useable electric power through a process called energy harvesting, sometimes referred to as power harvesting or energy scavenging. Electronics can function without a traditional power supply thanks to energy harvesting, which also removes the need for frequent battery replacements and wire runs. Typically, an energy harvesting system consists of circuitry for managing electricity, charging energy storage cells, and offering regulation and protection (Ibrahim et al., 2022).

Reducing radio frequency (RF) energy from the environment and using it in low-voltage electronic devices is the main goal of harvesting RF energy. To detect radio frequency energy emitted by the radio environment, one needs either narrow-band antennas or antenna-like patches with ultra-wide band characteristics. However, the utilization of the latter depends on the frequency bands that are going to be detected. As a result, the output voltage is low and useless, which presents a challenge for real-world use. Since dual band RF harvesting may capture wireless signals at various frequencies depending on the source's availability, it is therefore viewed as a potentially beneficial alternative. In theory, this leads to an increase in the system's harvesting capacity and level of flexibility.

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2. Research Methods

Fig.1 shows overall flowchart of the work.

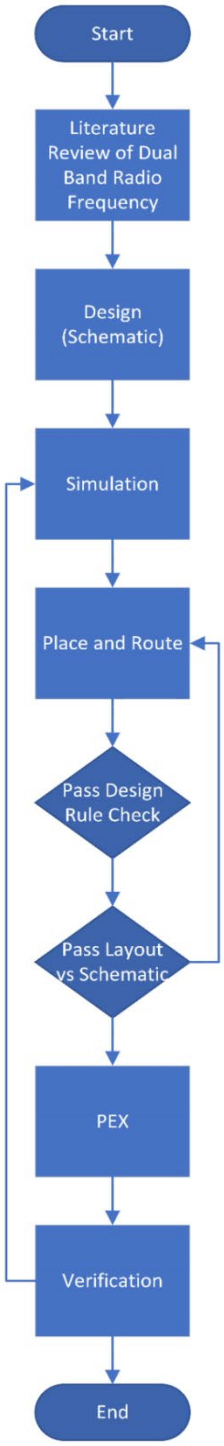

Fig. 1 *Whole flowchart of the work*

2.1 Device Structure

The three fundamental parts of a traditional RF energy harvester are the antenna, impedance matching network, and RF rectifier. Consider the antenna as a voltage source with an internal resistance of 50 Ω. The RF signal can be amplified by an impedance matching network, and the RF rectifier can be thought of as a variable resistance in parallel with a capacitor. The purpose of an RF rectifier is to convert an impedance matching network-boosted signal to DC voltage and charge a sizable on-chip capacitor. The most important thing is to design an RF rectifier with high conversion efficiency because the RF signal is low in amplitude and high in frequency. From this CMOS dual band rectifier circuit, the band of 2.4 GHz where have five stages in circuit connected to л-type matching network and the band of 900 MHz where have five stages in circuit connected to L-type matching network. The both of band will be connected to the capacitor load and resistor load where the value are 70 pF and 100 kΩ, respectively. Fig. 2 shows the equivalent circuit of the RF energy harvester.

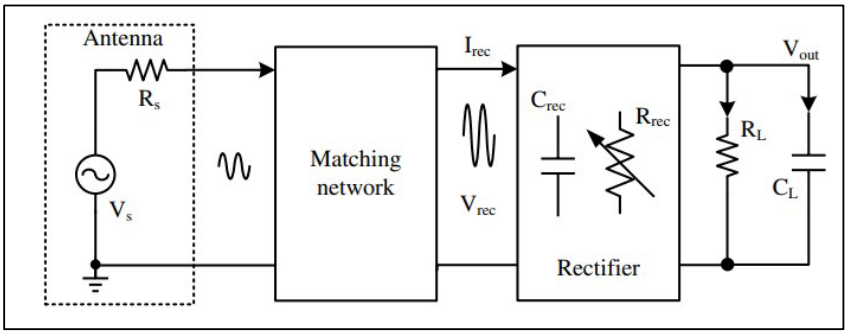

Fig. 2 *The equivalent circuit of the RF energy harvester*

2.2 Parameter for CMOS Dual Band Rectifier

The 2.4 GHz band of this CMOS dual band rectifier circuit has five stages coupled to a л-type matching network, and the 900 MHz band has five stages connected to an L-type matching network as shown in Fig. 3. The resistor load and capacitor load, with values of 70 pF and 100 KΩ, will be linked to both bands as listed in Table 1. Fig. 4 and 5 show the circuit of 5 stages order for 900 MHz and 2.4 GHz RF rectifier, respectively. Whilst, Table 2 and 3 show parameters for 900 MHz and 2.4 GHz RF rectifier, respectively.

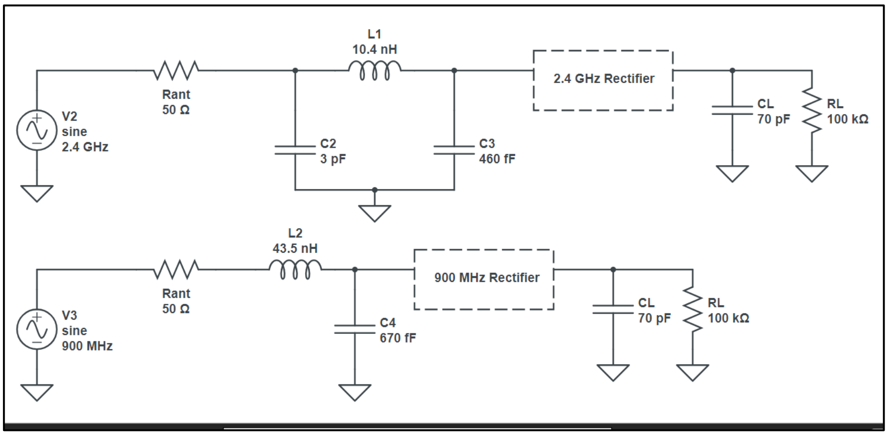

Fig. 3 *Block diagram of CMOS dual band RF rectifier circuit*

Table 1 *Parameter for CMOS dual band rectifier*

Device / Component	Proposed Values
R load	100 KΩ
C load	70 pF
L1	10.4 nH
C2	3 pF
C3	0.46 pF
L2	43.5 nH
C4	0.67 pF
Rant	50 Ω

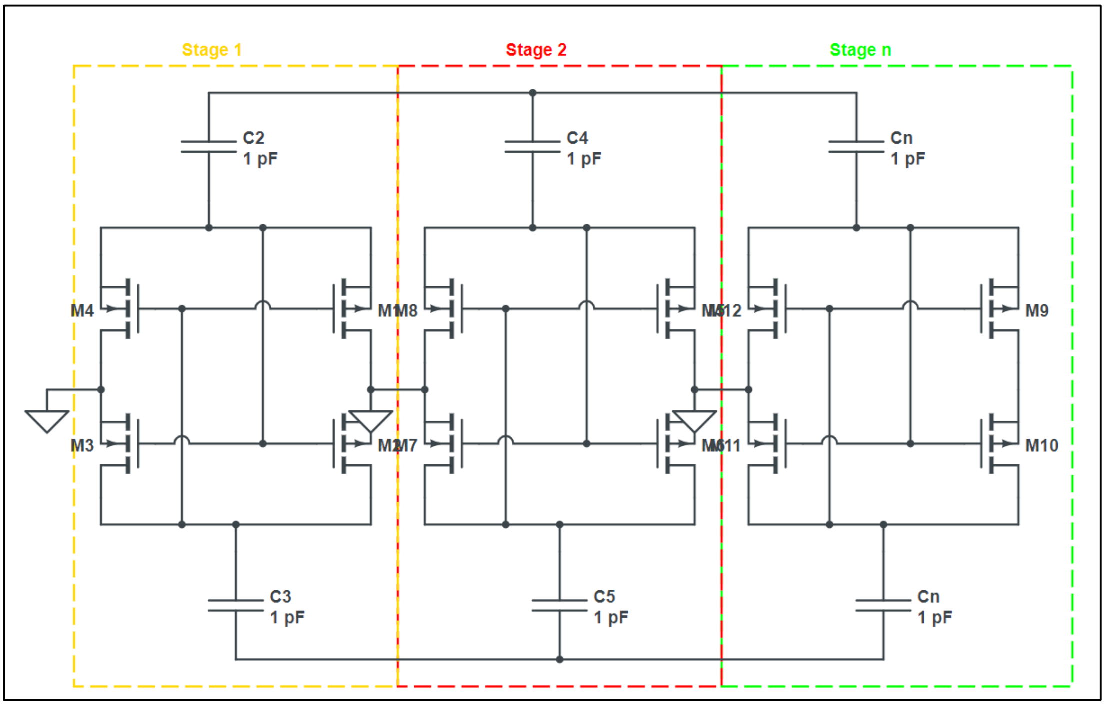

Fig. 4 *5 stages order for 900 MHz RF rectifier*

Table 2 Device parameter for the 5 stages order for 900 MHz RF rectifier

Device/ Component	Values
C2 - C11	1 pF
W/L	120 nm / 45 nm

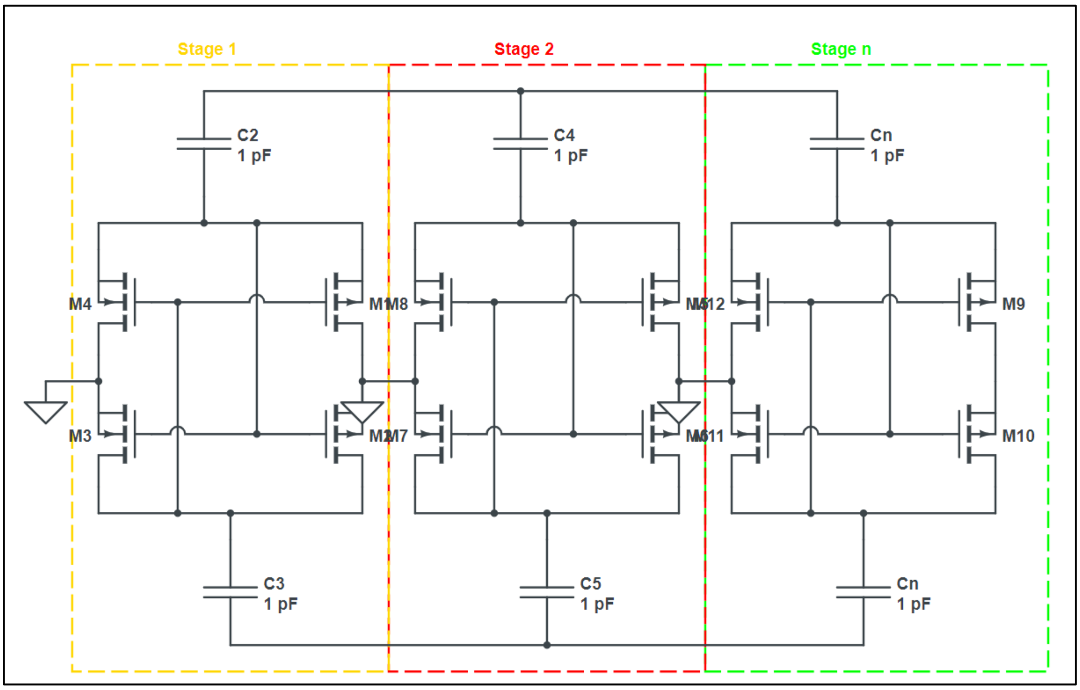

Fig. 5 *5 stages order for 2.4 GHz RF rectifier*

Table 3 Device parameter for the 5 stages order for 2.4 GHz RF rectifier

Device / Component	Values
C2 - C11	1 pF
W/L	120 nm / 45 nm

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3. Result and Discussion

This chapter explain how the dual band rectifier is implemented in Cadence EDA. Dual band rectifier circuit will design in Cadence EDA and run the circuit to get the waveform of the Vin and Vout.

3.1 Simulation Result

Calculation and simulation results are compared to conduct analysis. In this section, the Cadence EDA was used to simulate a cross-coupled rectifier circuit. Fig. 6 shows implementation of rectifier circuit into the testing circuit while Fig. 7 and 8 shows the overall circuit design for 2.4 GHz cross-coupled rectifier structure and overall circuit design for 900 MHz cross-coupled rectifier structure. Using 45nm technology, the simulation is carried out within the Cadence EDA tools environment.

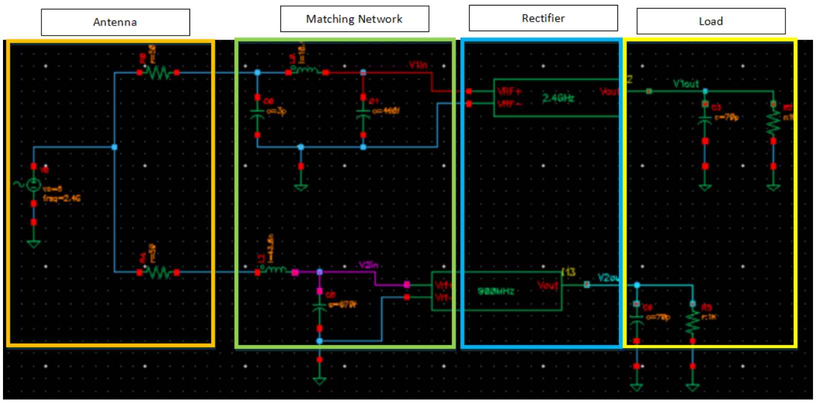

Fig. 6 *Implementation of rectifier circuit into the testing circuit*

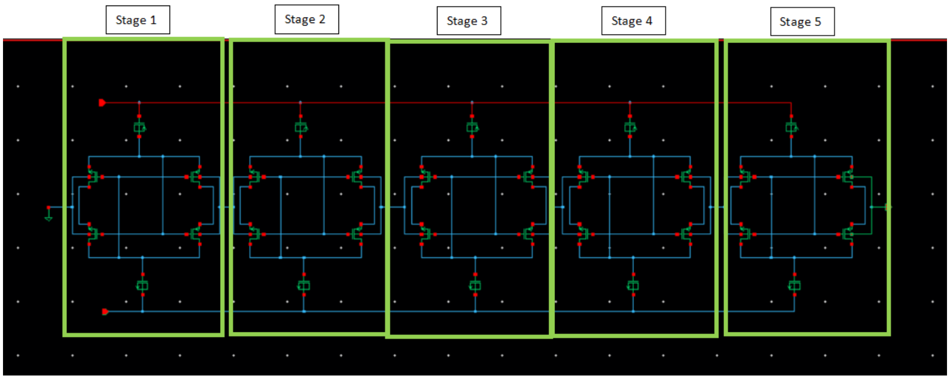

Fig. 7 *Overall circuit design for 2.4 GHz cross-coupled rectifier structure*

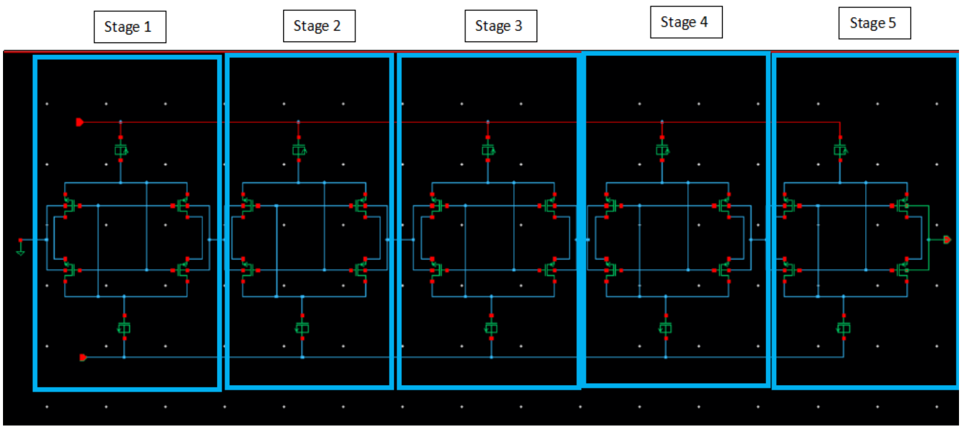

Fig. 8 *Overall circuit design for 900 MHz cross-coupled rectifier structure*

4. Analysis and Discussion

Fig. 9 shows the voltage input and voltage output waveform of the simulated dual band rectifier circuit which measures the voltage against times. From Fig. 8, the V1in is the voltage input for 2.4 GHz rectifier and V1out is the voltage output for 2.4 GHz rectifier. While the the V2in is the voltage input for 900 MHz rectifier and V2out is the voltage output for 900 MHz rectifier.

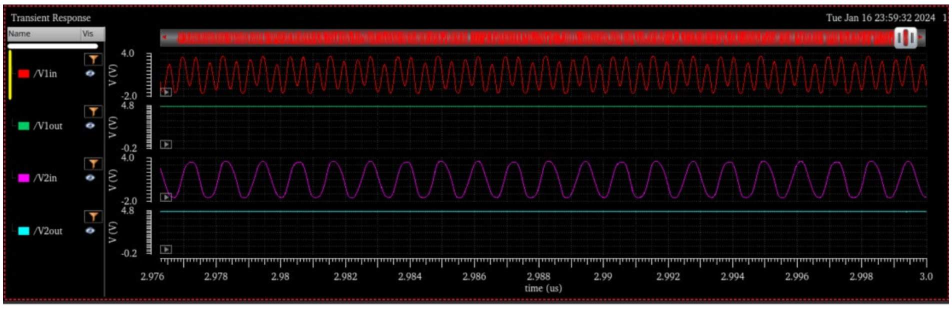

Fig. 9 *Voltage input and voltage output waveform of the simulated dual band rectifier circuit*

From the waveform shown, the peak maximum of voltage input is 3.56 V for the 2.4 GHz and 3.50 V for the 900 MHz while the peak maximum for voltage output is increase 4.70 V for the 2.4 GHz and 4.64 V for the 900 MHz.

4.1 Theories Formula

To find the power conversion efficiency (PCE):

$$\eta = \frac{P_{DC}}{P_{in}} \times 100\% = \frac{\frac{V^2{}_{DC}}{R_L}}{P_{in}} \times 100\% \quad (1)$$

R_L where is the optimum load resistance of the circuit, η is the RF to DC efficiency of the circuit and P_{in} is the input power of the RF signal as shown in Fig. 10 and 11.

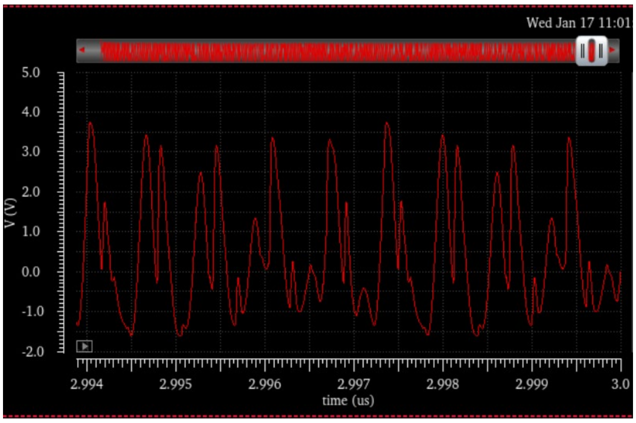

Fig. 10 *Input power waveform of the simulated dual band rectifier circuit*

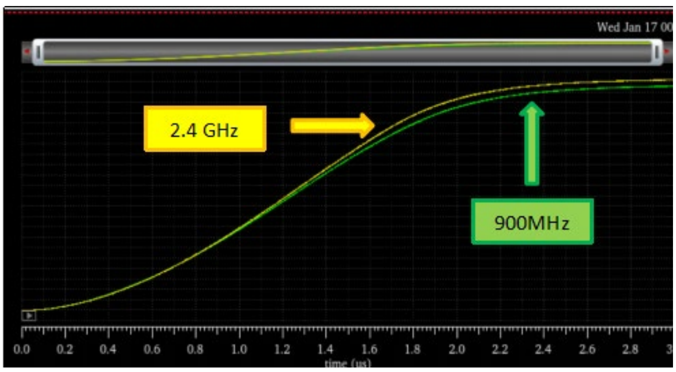

Fig. 11 *Output power waveform of the simulated dual band rectifier circuit*

As shows in the waveform, the input power is 615 µW while the output power is 215.6 µW for 900 MHz and 221.7 µW for 2.4 GHz. The power conversion efficiency (PCE) for 900 MHz and 2.4 GHz can be determined according the formula given:

For 900 MHz,

$$\eta = \frac{V^2{}_{DC}/R_L}{Pin} \times 100\%$$

$$\eta = \frac{(4.64)^2/100000}{615\mu W} \times 100\% = 35\ \%$$

For 2.4 GHz,

$$\eta = \frac{V^2{}_{DC}/R_L}{Pin} \times 100\%$$

$$\eta = \frac{(4.7)^2/100000}{615\mu W} \times 100\% = 36\ \%$$

4.2 Layout Cross-Coupled Rectifier

Fig. 12 and 13 illustrate the layout of the cross-coupled rectifier circuit for 900 MHz and 2.4 GHz. The layout is then needed to undergo the physical verification steps such as DRC, LVS, ERC, and PEX to make sure it is free from any error.

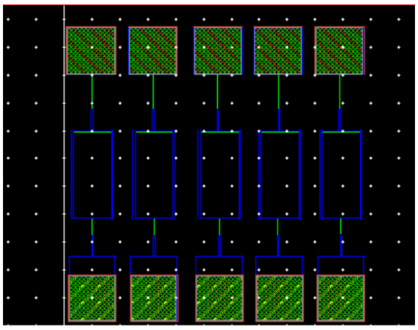

Fig. 12 *Layout of the 900 MHz cross-coupled rectifier circuit*

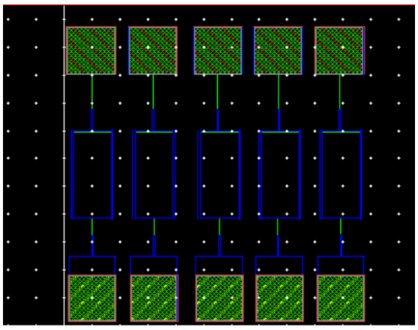

Fig. 13 *Layout of the 2.4 GHz cross-coupled rectifier circuit*

4.3 Discussion

Capturing and converting ambient electromagnetic energy into electrical power is the main objective of a dual-band rectifier energy harvester. The rectifier's efficiency is a critical factor in determining the energy harvester's overall performance. Multiple frequency bands can be used to harvest energy using dual-band rectifiers. Due to its adaptability, the harvester may obtain energy from a variety of sources, including ambient sources with unique frequency characteristics and radio frequency (RF) signals. The energy harvester's versatility expands its possible applications and environments of use.

5. Conclusion

Harvested radio frequency energy shows great promise for directly powering low-power devices, charging batteries, and greatly extending their lifespan. A fully integrated RFEH system with adaptive frequency selection and dual-band capabilities is shown in this study. This is a multi-frequency band RF energy harvesting circuit that can produce an output of 1 V above with high PCE over a broad input power range and frequency range of 900 MHz and 2.4 GHz. Two distinct routes divide the low and high input power in the RF energy harvesting circuit. The 45 nm CMOS technology was used to implement the design. In the range, it presents a PCE of 36% for 2.4 GHz and 35% for 900 MHz.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Muhd Hafizuddin Abd Rahman, Warsuzarina Mat Jubadi;* ***data collection:*** *Muhd Hafizuddin Abd Rahman;* ***analysis and interpretation of results:*** *Muhd Hafizuddin Abd Rahman;* ***draft manuscript preparation:*** *Muhd Hafizuddin Abd Rahman, Warsuzarina Mat Jubadi. All authors reviewed the results and approved the final version of the manuscript.*

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