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Article

A Dual-Band Rectifier for RF Energy Harvesting

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Abstract. Our cities are surrounded by a large number of radio frequency (RF) signals broadcasted by various wireless systems. In order to enhance the efficiency of energy usage in addition to the purpose of communication, ambient RF energy harvesting systems are designed to harvest and recycle wireless energy for many applications such as battery chargers, sensor devices and portable devices. The main element of the ambient RF energy harvesting system is a rectenna which is the combination of an antenna and a rectifying circuit. Even though the ambient RF energy is widely broadcasted by many systems, the energy is extremely low. Therefore, high performance antenna and rectifying circuits have to be designed for supporting small incident power; also the number of frequency channels of the rectenna can enhance the performance and support different harvesting locations. This paper proposes a dual-band rectifier for RF energy harvesting which is designed to operate at 2.1 GHz and 2.45 GHz. The first channel can provide the maximum efficiency of 24% with 1.9 V of the output voltage at 10 dBm of input power. On the other hand, a maximum efficiency of 18% and 1.7 V of the output voltage can be achieved by the second channel at 10 dBm of input power.

Keywords: RF energy harvesting, rectenna, rectifier, voltage doubler, Schottky diode.

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1. Introduction

Recently, energy harvesting at radio frequency (RF) has been a fast growing topic. Since the first wireless energy transmission was proposed and demonstrated in the 1890's by Nikola Tesla using the electromagnetic wave propagation technique of Hienrich Hertz [1, 2], the topic is developed and applied to many applications such as microwave-powered helicopter prototype, solar power satellite system (SPSS), microwave power transmission in space and radio-frequency identification (RFID) [3-8]. The RF energy harvesting is developed by the wireless energy transmission technique for harvesting and recycling the ambient RF energy which is widely broadcasted by many wireless systems such as mobile communication systems, Wi-Fi base stations, wireless routers, wireless sensor networks and wireless portable devices. In order to extend the battery life and avoid using battery, the RF energy harvesting has been applied to be a rechargeable circuit and a small power supply for portable devices and tiny devices such as mobile phones, tablet, sensor devices and biomedical implants [3, 9]. Although a lot of wireless systems broadcast into the environment, the power density of ambient RF energy is very low which makes it challenging to design a rectenna for harvesting a sufficient amount of energy.

A rectifier and an antenna are combined to form a rectenna which was initially designed by Brown for converting the microwave power to be direct current (DC) power [3, 10]. Therefore, the main element of an RF energy harvesting system is the rectenna that detects the ambient RF energy by the antenna and converts the received energy to be the DC power by the rectifier circuit, as shown in Fig. 1.

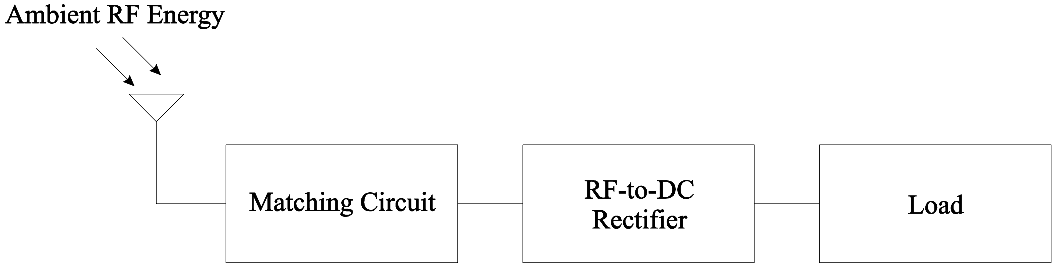

Fig. 1. Block diagram of an ambient RF energy harvesting system.

To achieve the high RF-to-DC power conversion efficiency for RF energy harvesting, high gain and wideband antennas must be designed to increase the power density and harvest as much as possible the ambient RF energy. On the other hand, the rectifier circuit has to be implemented to provide a high efficiency in RF-to-DC power conversion and support multiband for obtaining high DC power from various frequencies.

In this paper, a dual-band rectifier is proposed to support the RF energy harvesting at 2.1 GHz and 2.45 GHz that are UMTS-2100 and Wi-Fi operating frequencies, respectively. In order to harvest at both frequencies, the input matching of the rectifier is designed to provide the high conversion efficiency at both frequencies; also a high sensitivity Schottky diode is selected to be a small signal detector for the rectifier circuit, as shown in section 2. The simulation and experimental results are compared and discussed in section 3. Finally, the summary of the proposed design is concluded in section 4.

2. Dual-Band Rectifier Circuit Design

The rectifier circuit is designed by Greinacher voltage doubler topology that is a good candidate for ambient RF detection. Furthermore, the Schottky diode was selected to support the fast switching of the high frequency of the incident signal. To determine the optimum input impedance and design an input impedance matching of the rectifier circuit, the Advance Design System (ADS) was chosen to be the simulator for this design.

2.1. Diode Specifications

To achieve the high efficiency in RF-to-DC conversion, the fast switching-time diode is a promising device to detect the ambient RF energy [11]; and the diode proposed in this design is Schottky diode HSMS-285C of Avago Technology. The diode has been developed for low cost and small signal applications ($P_{in} < -20$ dBm), and it has two detector diodes inside which are connected in series. Therefore, the device is suitable for use as a voltage doubler circuit. The diode is a zero bias Schottky diode that can provide low forward voltage (V_f) from 125 mV to 250 mV, 3.8 V of break-down voltage (V_b), 25 Ohms of series resistance (R_s), and 0.18 pF of zero bias junction capacitance (C_{j0}). From the prominent properties of the diode, it is suited in the proposed circuit.

2.2. Schematic of Rectifier Circuit

The rectifier consists of three parts which are input matching, voltage doubler circuit and load resistance R_L, as shown in Fig. 2.

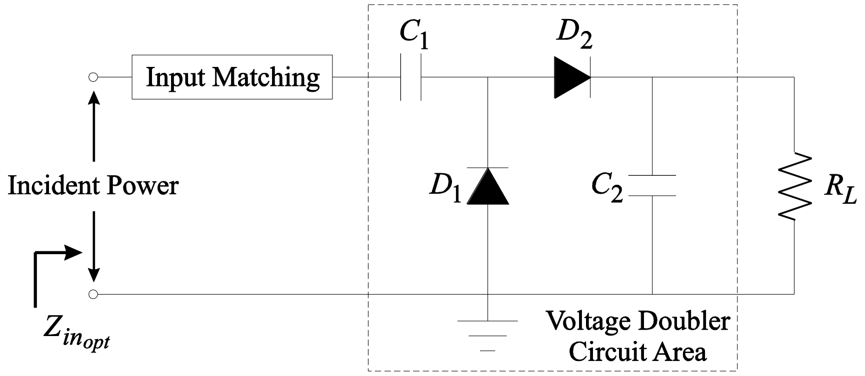

Fig. 2. Schematic diagram of the RF-to-DC rectifier circuit with voltage doubler circuit.

The full-wave peak-to-peak voltage of the incident RF signal (V_{in}) is rectified by the voltage doubler circuit that consists of a voltage clamp (D_1 and C_1) and a peak rectifier (D_2 and C_2) [12]. On the negative half-cycle of the incident signal (V_{in^-}), the current flow through D_1 and it was stored by C_1 while D_2 is cutoff. The voltage across D_1 is nearby its threshold voltage (V_{th1}), thus the stored voltage of C_1 (V_{C_1}) can be determined by Eq. (1):

$$V_{C_1} = V_{in^-} - V_{th1} \tag{1}$$

On the positive half-cycle of the incident signal (V_{in^+}), D_1 is cutoff while D_2 is turned on by the twice incident signal that is combined by the stored voltage of C_1 and the positive half-cycle. Therefore, the output voltage (V_{out}) of the circuit can be calculated by Eq. (2):

$$V_{out} = 2V_{in} - V_{th1} - V_{th2} \tag{2}$$

In order to match the voltage doubler circuit with the standard antenna port of 50 Ohms, the source-pull technique is used to determine the optimum input impedance ($\underline{Z}_{inopt}$) for converting the optimum performance for the circuit [13]. The source-pull technique can be applied to determine the optimum point by sweeping input impedance. The performance of the circuit can be determine by the efficiency of the RF-to-DC power conversion (η) relative between the incident RF signal (P_{in}) at the input port and the DC output power (P_o), as in Eq. (3). The DC output power (P_o) can be calculated by the multiplication of DC output voltage (V_o) and DC load current (I_o).

$$\eta(\%) = \frac{P_o}{P_{in}} \times 100 \tag{3}$$

$$P_o = V_o \times I_o \tag{4}$$

2.3. Design Methodology

The design methodology can be summarized as follows:

- Connect the HSMS-285C with the DC-filter capacitors and the assumed load resistance R_L in the form of voltage doubler circuit, as shown in Fig. 2.
- Determine the optimum input impedance of the voltage doubler circuit for the two operating frequencies by the source-pull technique. From the simulation result, the input impedance is $\underline{Z}_{inopt} = 60.077 - j116.184$.
- Create the input matching for the voltage doubler circuit that is matched to $\underline{Z}_{inopt}$ and 50 Ohms of input port at the desired frequencies.

3. Simulation and Experimental Results

The proposed circuit was designed and simulated in ADS to predict its performance before fabrication. The simulated schematic diagram is shown in Fig. 3 that consists of 50 Ohms of input termination, multi-stub matching, the voltage doubler circuit, DC-filter capacitor and the load resistance termination.

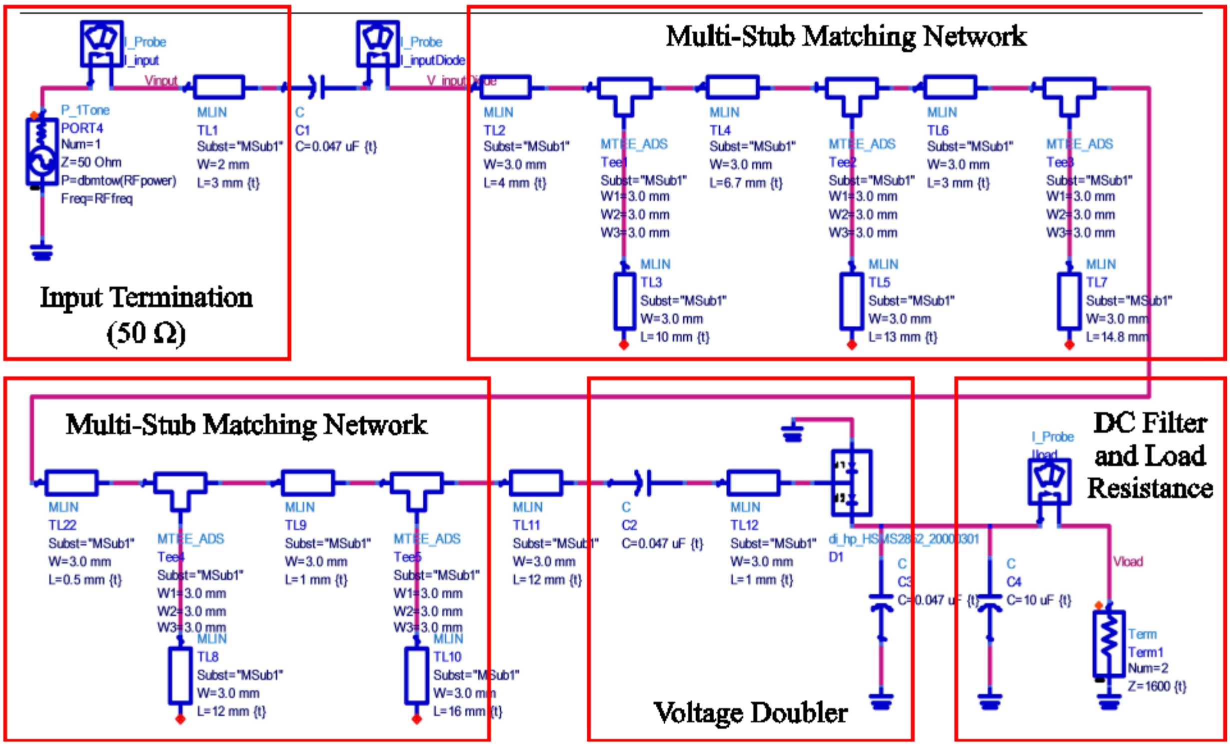

Fig. 3. ADS simulation schematic of the dual-band rectifier circuit.

The prototype was fabricated on a low cost FR-4 substrate with a dielectric constant (ε_r) of 4.3 and thickness (H) of 1.6 mm. The dimension of the circuit is 70 × 35 mm². The multi-stub was designed to be input matching of the voltage doubler circuit that consists of HSMS-285C and DC-filter capacitors, as shown in Fig. 4.

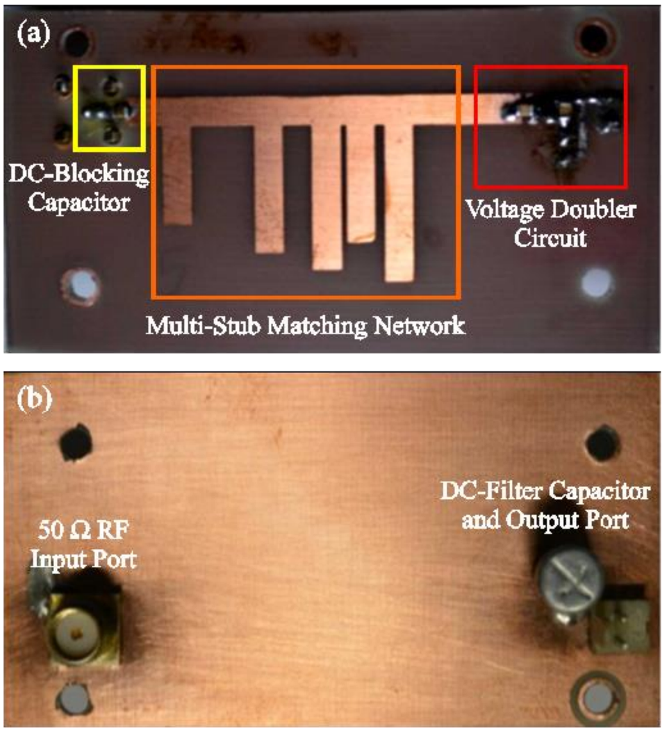

Fig. 4. Prototype of the dual-band rectifier circuit: (a) top view, (b) bottom view.

The performance testing system of the dual-band rectifier circuit was shown in Fig. 5. The main equipment of the system consists of the signal generator, digital multimeters and RF cables. The proposed prototype was fabricated with other designs, thus the circuit under test in Fig. 5 is bigger than the prototype. However, the circuits are not related to each other.

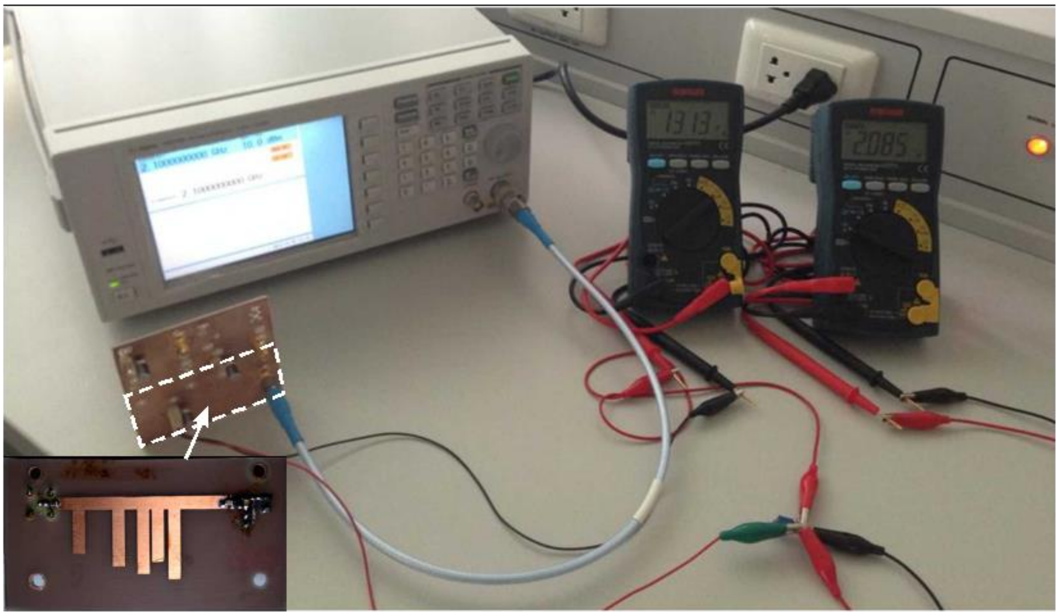

Fig. 5. The dual-band rectifier circuit under test with continuous wave input power at 2.1 GHz.

Figure 6 shows the simulation and measurement results of the input return loss. The simulation and measurement results were plotted by the solid square markers and the solid circle markers, respectively. At 2.1 GHz, the circuit can provide -1 dB in the simulation result and -5.7 dB in measurement. On the other hand, the minimum value of the simulation is -12 dB and -17 dB in the measurement result that can be achieved at 2.45 GHz. Considering in the broadband return loss, the measurement provides the results that is lower than -10 dB from 2.4 GHz to 2.49 GHz.

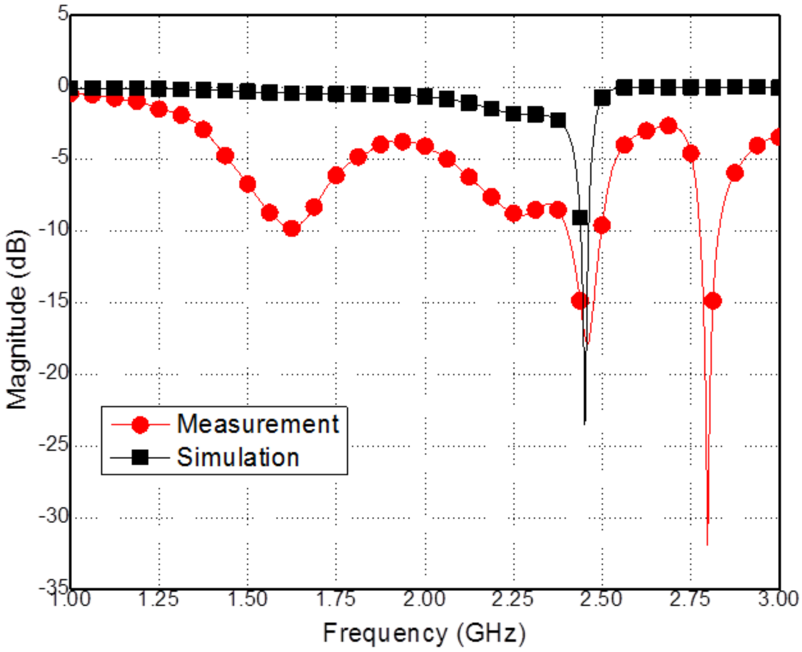

Fig. 6. Simulation and measurement results of input return loss of the rectifier circuit.

Figures 7 and 8 show the performance of the dual-band rectifier circuit at 2.1 GHz and 2.45 GHz, respectively.

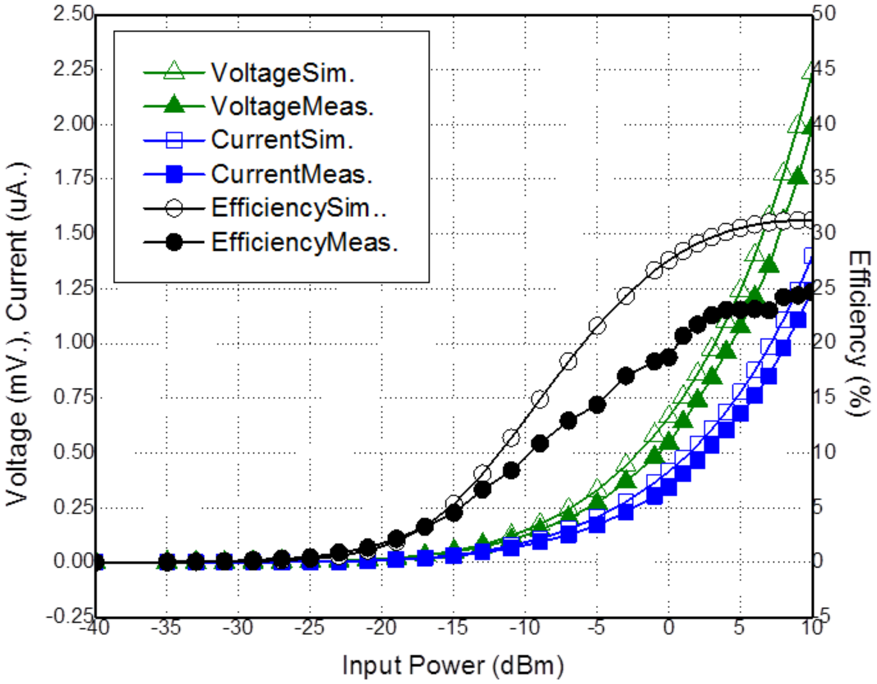

Fig. 7. Simulation and measurement results of DC output voltage, DC load current and efficiency versus continuous wave input power at 2.1 GHz.

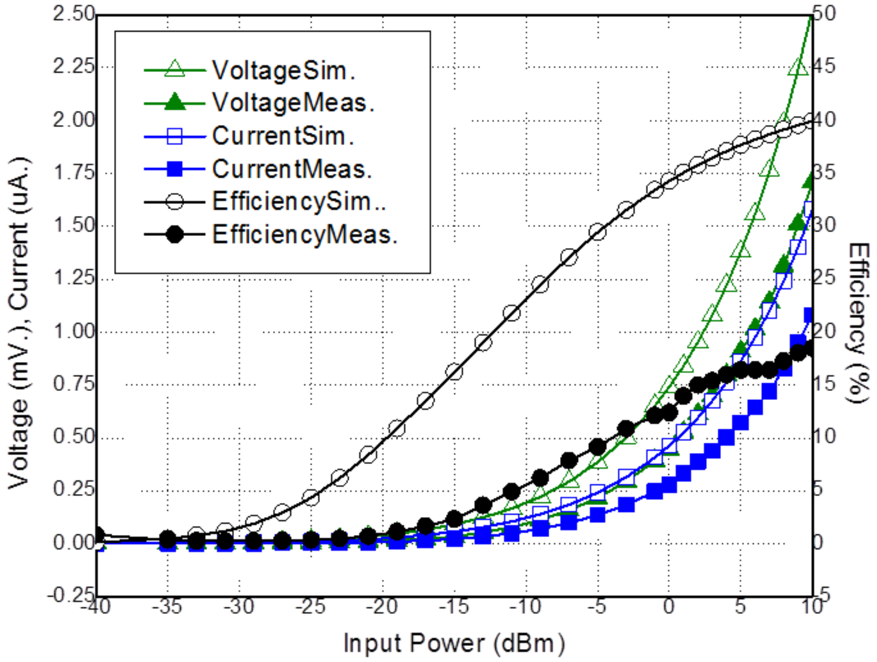

Fig. 8. Simulation and measurement results of DC output voltage, DC load current and efficiency versus continuous wave input power at 2.45 GHz.

The performance consists of the DC output voltage (V_o), DC load current (I_o) and efficiency (η). The performance was measured by sweeping the input power (P_{in}) from -40 dBm to 10 dBm at 1.6 kOhms of load resistance. The simulation results were plotted by transparent markers and the measurement results were illustrated by solid markers. The DC output voltage V_o, DC load current I_o and efficiency η were presented by triangle, square and circle markers, respectively. Even though the return loss of the 2.1 GHz is higher than -10 dB, the prototype can provide the maximum efficiency of 24%, 1.9 V of output voltage V_o and 1.245 mA of load current I_o at 10 dBm of input power P_{in}. At 2.45 GHz of operating frequency, the maximum efficiency of 18% can be achieved at 10 dBm of input power, also the maximum V_o of 1.7 V and load current I_o of 1.081 mA can be provided by the dual-band rectifier circuit. From all the above results, the difference between the simulation and measurement is generated by many parameters that are the parasitic parameters in the PCB and in the Schottky diode at high frequencies that can create higher parasitic impedance and higher error. This can be seen by that the error of efficiency at 2.1 GHz is lower than the error at the 2.45 GHz. Moreover, the high performance do not come from only the good input matching, but also from the optimum input impedance like the 2.1 GHz can provide performance better than the 2.45 GHz, although at 2.45 GHz the rectifier is matched better than 2.1 GHz. Moreover, the circuit can support GSM-1800 that can convert the mobile to be DC voltage (1.7 V) while the mobile is calling, as shown in Fig. 9.

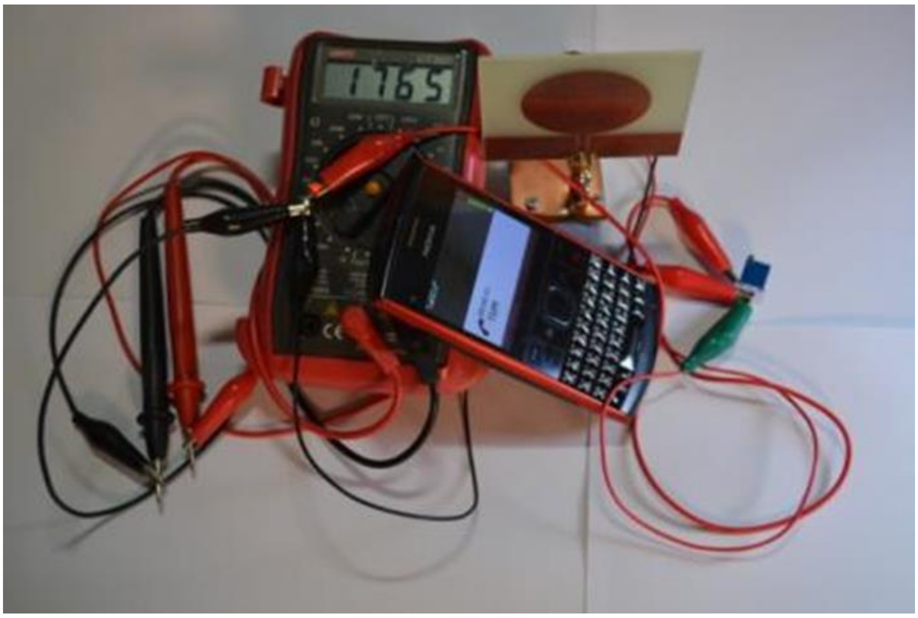

Fig. 9. The dual-band rectifier circuit under test with wideband antenna and GSM-1800 mobile phone.

4. Conclusion

In this paper, a dual-band rectifier for RF energy harvesting was presented. The proposed prototype was designed by voltage doubler topology for converting the RF signal to DC signal. In order to operate at high frequency and small input power application, the Schottky diode HSMS-285C was selected to be the detection elements in the RF-to-DC conversion topology. To achieve the optimum performance for the rectifying circuit, the source-pull technique was proposed to determine the optimum impedance for matching to 50 Ohms of input port by the multi-stub matching that creates the broadband performance for the circuit. The proposed prototype provides the maximum efficiency of 24%, the output voltage of 1.9 V and load current of 1.245 mA at 2.1 GHz with 10 dBm of input power. At 2.45 GHz, the maximum efficiency of 18%, 1.7 V output voltage and 1.081 mA load current can be achieved by 10 dBm input power.

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