Rectenna structure analysis for ambient RF Energy Harvesting

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ABSTRACT

The paper proposes an efficient structure of RF Energy Harvesting (RFEH) system that can improve efficiency of the system. The paper analysis and indicate relationships between characteristics of the RFEH system such as: center frequency, bandwidth, Q factor, passive gain, and number of rectifier stages. After that, paper proposes design steps to design the RFEH system in which high enough Q and wide bandwidth are guaranteed. The RFEH system is designed and tested to proved the effectiveness of the proposed method. Mesurement results show that a sensitivity of 1V output DC voltage reaches at -20 dBm input power of 950 MHz signal. The power conversion efficiency (PCE) of the system is 57% at -10 dBm input level. The system can generate 3.58 μW *output power when input power of the LTE signal is -19.4 dBm.*

Keywords: RF energy harvesting; Rectenna; Q factor; Passive gain; Bandwidth.

1. INTRODUCTION

The explosion of science and technology has allowed the construction of Wireless Sensor Networks (WSN) and the realization of Internet of Things (IoT) systems. These systems allow the use of a large number of sensors to collect data. However, one of the problems for sensor systems is the power supply to the sensors. Traditional powering methods by batteries have gradually become obsolete because of the difficulty in replacing batteries when they run out of capacity for a large number of sensors. In addition, the use of an enormous amount of batteries for multi-sensor systems also has a huge impact on the environment. Therefore, currently, scientists are looking towards solutions using alternative energy sources to power devices. In particular, an effective solution is to harvest available energy such as wind energy, solar energy, and thermal energy,... to convert these types of energy into electricity to supply equipment [1-3].

The RF Energy Harvesting (RFEH) system collects RF signals in the environment and converts them into a DC signal for storage or direct supply to the equipment. Research on RFEH is gaining a lot of interest from scientists due to the ubiquitous nature of RF signals. In addition, along with RF harvesting, the system can use the information as well as the energy of the received RF signal itself, this is the basis for the foundation of Simultaneous Wireless Information and Power Transfer (SWIPT) [4]. RF signals in the environment have many types such as mobile phone signals, WiFi signals, television signals,... In the environment, the level of these signals is very low. Several studies have shown that the level of ambient RF signal is in the range of a few $\mu W/cm^2$ [5, 6]. At this power level, the efficiency of RFEH systems is low because the RF signal level is not large enough to open the active elements used to convert RF energy into DC. To improve the performance of the system, a number of solutions are proposed: using new types of rectifying elements [7], proposing a new circuit structure [8], proposing the use of an energy harvesting system that scavenges some different types of signals [9],...

The structure of the RFEH system with a high Q factor has been proposed to improve the efficiency of the circuit [10, 11]. In this method, the RFEH system is built to achieve a high Q-factor to increase the passive gain of the circuit, thereby increasing the input voltage of the rectifier circuit and improving the DC output. This system has been proven to improve system sensitivity and performance. However, the performance of the RFEH system built with a very high Q factor drops drastically when harvesting the energy of the actual signal in the environment. Therefore, a high-Q RFEH system is not suitable for energy harvesting of the actual RF signal in the environment.

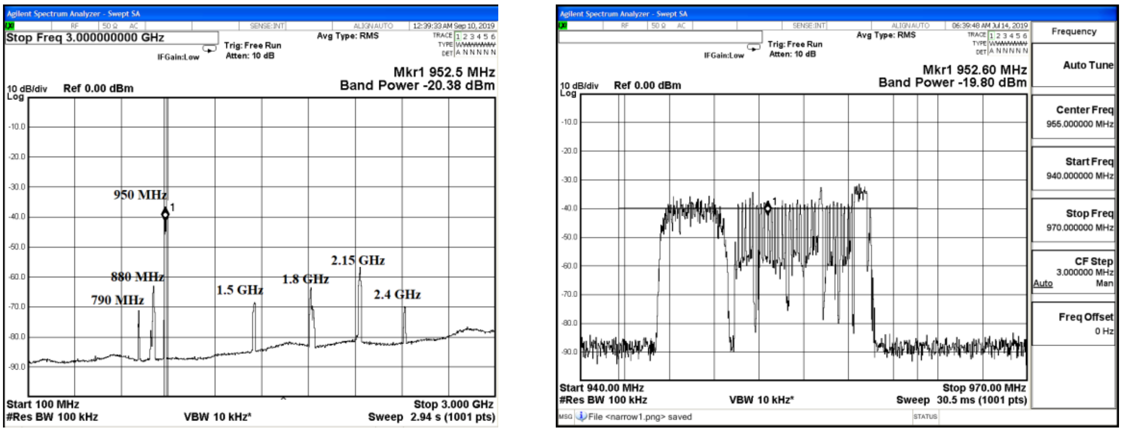
The paper is based on an analysis of the characteristics of the actual RF signal in the environment to determine the relationship to the design parameters of the RFEH harvesting system. In the previous work of the authors, the authors proposed the design of an energy harvesting system with a suitable quality factor to be able to improve the performance of the system when receiving RF signals in the environment [12]. In this paper, the author performs additional analysis related to the design parameters of the system such as bandwidth, quality factor, and number of rectifying circuit stages. From there, the theoretical basis for proposing effective structural design steps of the ambient RFEH system is completed.

The next parts of the paper are organized as follows: Section 2 performs a system architecture analysis to determine a system design method, Section 3 presents the design of a 950 MHz LTE RFEH system according to the method proposed in Section 2, Section 4 presents the measured results of the system, Section 5 concludes the research content.

2. THEORY ANALYSIS

2.1. Ambient RF characteristics and RF energy harvesting system

A spectrum of RF signals in the environment is measured and shown in Fig.1. It can be seen from Fig.1(a) that there are many types of signals available in the environment such as 780 MHz, 880 MHz, 950 MHZ, 1.5 GHz, 1.8 GHz, 2.15 GHz, 2.4 GHz signals. The RFEH system harvests one of these signals and converts it to a DC signal. Besides, the system can harvest energy from multiple bands to increase the total received energy. The article analyzes the design parameters of the energy harvesting system, so in this paper, we present a structure of the RFEH system to harvest an RF signal at a single band. The signal at 950 MHz has the highest energy level at the selected measurement point and it is a suitable signal for scavenging.



(a) (b)

Figure 1. *Measurement results of RF spectrum in the environment: (a) Spectrum of RF signals at mesurement point, (b) Magnified spectrum of the 950 MHz signal.*

The magnified spectrum of the signal at 950 MHz is analyzed as shown in Fig. 1(b). Accordingly, it can be seen that the spectrum of the signal has the form of an OFDM modulated signal, corresponding to this band, this is a downband LTE signal. From the spectrum analysis of the signal, the 950 MHz signal occupies 15 MHz bandwidth. In this paper, the influence of the actual RF signal bandwidth on the RFEH system design process is analyzed.

The simple structure of the RFEH system is shown in Fig. 2. Accordingly, the RFEH system collects RF signals in the environment through an antenna, with the use of a matching circuit, the received RF signal is transmitted to a rectifier circuit without being reflected back. In the rectifier circuit, the RF signal is converted into a DC signal. Depending on the requirements of the applications, the system can use the DC-DC converter circuit to convert the output voltage level to suit the input voltage level of the applications. Besides, the energy of the DC signal after harvesting can be used to supply directly to the application or stored in the storage block.

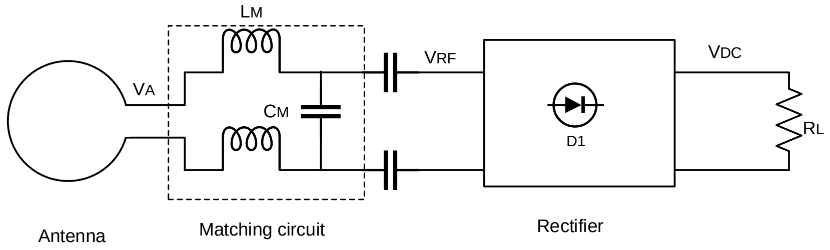


Figure 2. *Structure of a simple RFEH system.*

The rectifier circuit uses active elements (diodes, MOSFETs,...) to convert the energy of the RF signal into DC. As mentioned above, the level of RF signal available in the environment is very low and in many cases, this level is less than the threshold voltage of the active element used for rectifying. Therefore, the efficiency of the detector circuit is very low, causing the overall efficiency of the RFEH system to decrease.

2.2. Analysis of design parameters

As mentioned above, in the low-level input power of the RF signal, the overall system efficiency is low because the rectifier circuit is operating in the cut-off region. The co-design method was proposed to improve the system performance [10, 11]. In this system, the rectifier circuit has a high Q factor and the antenna is designed to fully match with the rectifier circuit. The RFEH system now consists of only an antenna and rectifier circuit, and therefore, the system is also known as Rectenna. The equivalent diagram of Rectenna designed by the co-design method is shown in Fig. 3.

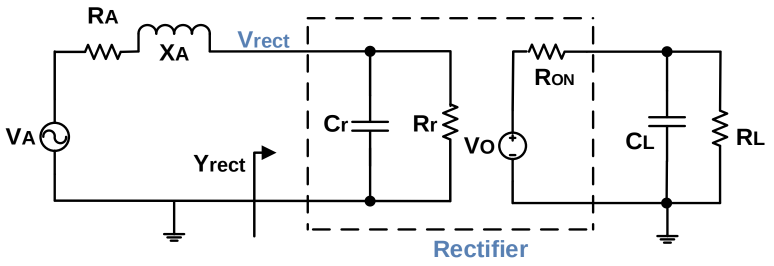


Figure 3. *Equivalent ciruit of a co-design Rectenna.*

The system parameters are now calculated as follows:

The antenna impedance is:

$$Z_A = R_A + jX_A \tag{1}$$

Equivalent conduction of the rectifier circuit:

$$Y_{rect} = \frac{1}{Z_{rect}} = \frac{1}{R_{rect} + jX_{rect}} = G_{rect} + jB_{rect} = \frac{1}{R_r} + j\omega C_r \tag{2}$$

Where, $Y_{rect}, Z_{rect}, R_{rect}, X_{rect}, G_{rect}, B_{rect}$ are admitance, impedance, resistance, reactance, conductance, and susceptance of the rectifier circuit.

The Q factor of the rectifier circuit is:

$$Q_{rect} = \frac{X_{rect}}{R_{rect}} = \frac{B_{rect}}{G_{rect}} = \omega R_r C_r \tag{3}$$

The Q factor of the Rectenna is:

$$\frac{1}{Q_{total}} = \frac{1}{Q_{antenna}} + \frac{1}{Q_{rect}} \tag{4}$$

where, $Q_{total}, Q_{antenna}$ are the Q factors of the Rectenna and antenna, respectively.

In the co-design Rectenna, we have these following conditions:

$$Q_{antenna} = Q_{rect} \tag{5}$$

$$X_A = -X_{rect} \tag{6}$$

$$Q_{total} = \frac{Q_{antenna}}{2} = \frac{Q_{rect}}{2} \tag{7}$$

Input voltage of the rectifier is:

$$V_{rect} = Q_{total}\sqrt{8P_A R_A} = \frac{Q_{rect}}{2}\sqrt{8P_A R_A} \tag{8}$$

where, P_A is the power of the RF signal in the Rectenna antenna.

Assume that V_{Drop} is a drop voltage of the rectifying detector. The output voltage of the rectifier is:

$$V_{out} = V_{rect} - V_{Drop} \tag{9}$$

Output power of the Rectenna is:

$$P_{out} = \frac{V_{out}{}^2}{R_L} = \frac{\left(V_{rect} - V_{Drop}\right)^2}{R_L} \tag{10}$$

The equations (8) and (10) indicate that with the same power level of the signal on the antenna, the higher Q the higher V_{rect} will get. As a result, the higher output voltage and output power can reach.

On the other hand, the Q factor of a typical circuit relates to power, energy, center frequency, and bandwidth by the following expression [13]:

$$Q = \omega_c\left(\frac{E_S}{P_D}\right) = \frac{f_c}{\Delta f} \tag{11}$$

where, $E_S, P_D, f_c, \Delta f$ are the energy in the circuit, the average power dissipated in the circuit, the center frequency of the circuit, and the bandwidth of the circuit, respectively.

The equation (11) indicates that the Q factor is inversely proportional to the bandwidth of the circuit. Therefore, in a co-design Rectenna, the Q factor is limited and depended on the center frequency and bandwidth of the harvested RF signal.

In fact, the Rectenna will be designed with a multistage rectifier structure in order to improve the output voltage and output power of the system. In addition, the rectifier circuit designed on CMOS technology normally can achieve a high Q-factor. As a result, in the co-design method, the rectifier circuits are designed on the CMOS technology. In order to consider the parasitic parameters of the rectifier, the equivalent circuit of the n-stage rectifier is shown in Fig. 5.

In Fig.4, the off-chip parasitic components include L_B, C_{PAD1}. L_B is parasitic inductance of the bonding wire between the CMOS chip and PCB board. The bonding wire is normally made of gold so the value of L_B is 1 nH/mm. C_{PAD1} is the parasitic capacitance of PAD on PCB. The parasitic component on the CMOS chip is mainly caused by the parasitic capacitor C_{PAD2} of the input/output on-chip PAD. The actual measured result of C_{PAD2} on 65 nm SOTB CMOS technology with ESD protection circuitry is a few pF [12]. Therefore, the influence of the parasitic parameters of the circuit is mainly due to the influence of the capacitor C_{PAD2}.

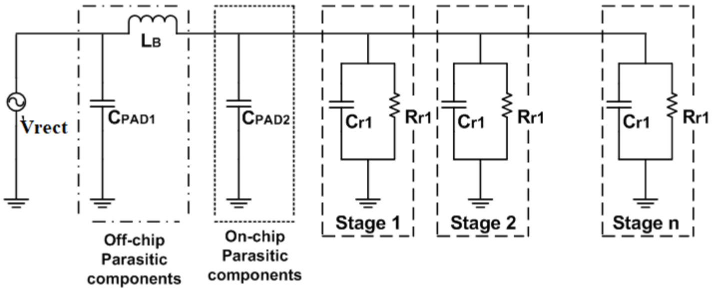


Figure 4. *Equivalent circuit of the n-stage rectifier.*

In case of n-stage rectifier circuit, a relationship between number of stage (n) and the Q factor is indicated below:

The equivalent addmitance of n-stage rectifier is:

$$Y_{n-rect} = \frac{n}{R_{r1}} + j\omega\left(C_{PAD2} + nC_{r1}\right) \tag{12}$$

The Q factor of n-satge rectifier is:

$$Q_{n-rect} = \frac{\omega\left(C_{PAD2} + nC_{r1}\right)}{\frac{n}{R_{r1}}} = \omega R_{r1}\left(\frac{C_{PAD2}}{n} + C_{r1}\right) \tag{13}$$

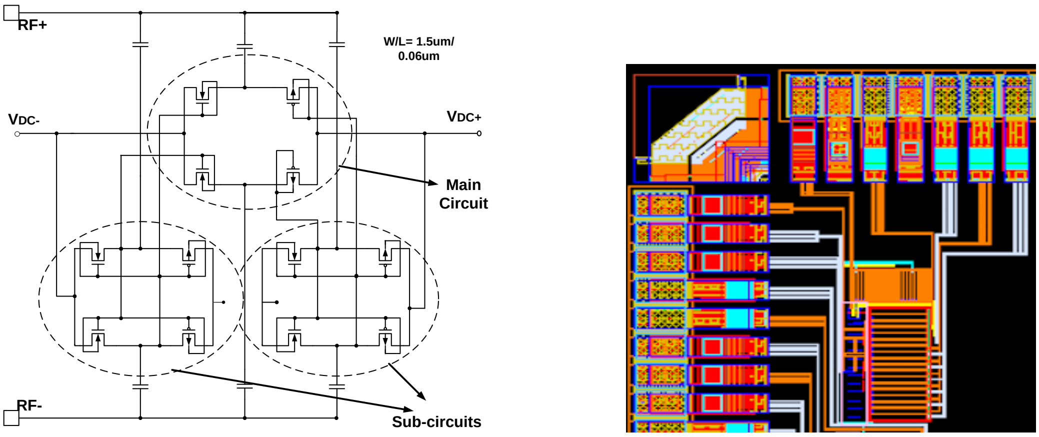
The equation (13) shows that the Q factor is inversely proportional to the number of stages of the rectifier. Therefore, in system design, the selection of the number of rectifier stages is limited by the Q factor of the rectifier circuit to ensure that Q satisfies equations (11) and (13).

According to the above analysis, in the RFEH system design, it is necessary to first determine the center frequency and the bandwidth of the actual RF signal to be received. Following that, the Q factor is determined by the equation (11). Next, we select a suitable rectifier circuit structure to ensure that the required high Q-factor can be achieved. From there, we can determine the number of rectifier stages to ensure the relationship with the Q factor according to the equation (13). Finally, we design the antenna and complete the total system design.

3. RFEH SYSTEM DESIGN

The RFEH system is designed and evaluated to test the performance of the proposed design method. This system is built to harvest the 950 MHz band signal. This signal has been measured and analyzed in Fig. 1. The center frequency of the signal is 952 MHz, the bandwidth is 20 MHz. The limiting Q factor of the circuit according to the equation (11) is calculated as Q_{gh} = 47.

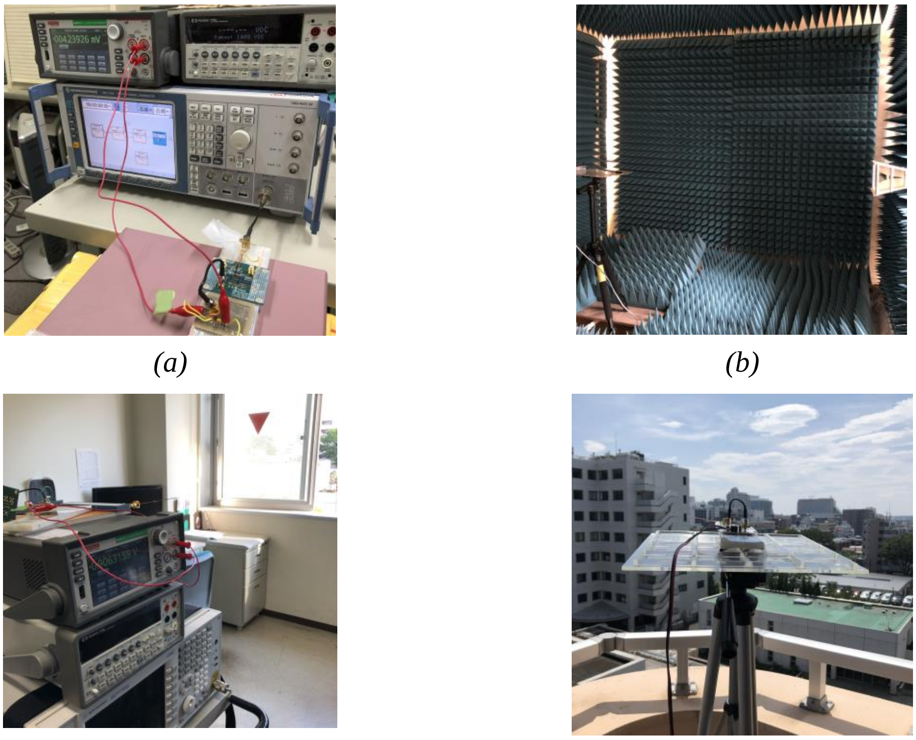
The rectifier is a differential-drive rectifier circuit which is shown in Fig. 5. ***This topology is proven the effectiveness in [12] by combining a main differential-drive rectifier circuit and two sub-circuits. The sub-circuit is utilized to supply an open-DC voltage to the gates of MOSFETs in the main circuit. The size of the MOSFETs is 60 nm in length, and 1.5 μm width***. The structure of the MOSFETs used in the rectifier circuit is DTMOS configuration to improve the efficiency of the circuit. In this configuration, the Body of the MOSFET is connected to the Gate, so that the voltage to control the Body is the voltage taken from the Gate. Thanks to the DTMOS structure, the drain current of the MOSFET will be larger in the region where the voltage difference between the Gate-Source terminal (V_{GS}) is small. With the selected rectifier structure, the Q factor of the circuit is $Q_{3-stage} = 43 < Q_{gh}$. Therefore, the number of rectifier stages is 3 stages. Fig. 5(b) shows the layout of the rectifier circuit on 65 nm SOTB (Silicon on Thin Box) CMOS technology. The RF input chip pins are used pins with ESD protection circuit to protect the input from electrostatic discharge.



(a) (b)

Figure 5. *The differential-drive rectifier circuit in CMOS technology: (a) Schematic of the designed rectifier; (b) Layout of rectifier in 65 nm SOTB CMOS technology.*

4. MEASUREMENT RESULTS AND DISCUSSION



(a) (b)

(c) (d)

Figure 6. *Measurement conditions: (a) In a laboratory with the SG, (b) In the chamber room, (c) Indoor condition with ambient signal, (d). Outdoor condition with ambient signal.*

The designed Rectenna system is measured under different conditions as shown in Fig. 6. Fig. 6a presents the measured condition in the laboratory. Accordingly, the standard signal generator (SG) generates the RF signal into the RF-DC board, the output detection results will be displayed on a digital multimeter. Fig. 6b shows the measurement condition in the Chamber. The Rectenna system is placed in an anechoic chamber room to ensure that only RF signals generated by the SG are received.

The measurements shown in Figs. 6c and 6d are measurements with actual signals in the environment. The spectrum of the signals in the indoor condition in Fig. 6c is shown in Fig. 1. Accordingly, the 950 MHz signal is the signal with the highest energy level at the measurement point. In Fig. 6c, the Rectenna system is placed in the center of the room to harvest the RF signal available in this place. Fig. 6d presents the measurement condition in the outdoor environment when the RFEH system is positioned towards the mobile base station.

The measurement results of the design RF-DC board with the signal from the standard SG in the laboratory are shown in Fig. 7. It can be seen from the Fig. 7 that the designed circuit can achieve 1V output sensitivity at the input level of -13 dBm. At -10 dBm input power, the output voltage of the harvester circuit reaches approximately 1.4V. Fig. 7b presents the power and efficiency (PCE) measurement results of the designed RF-DC board. The board achieves 58% efficiency when the input signal level is -7 dBm. The efficiency of the circuit is over 50% when the input signal level is greater than -10 dBm.

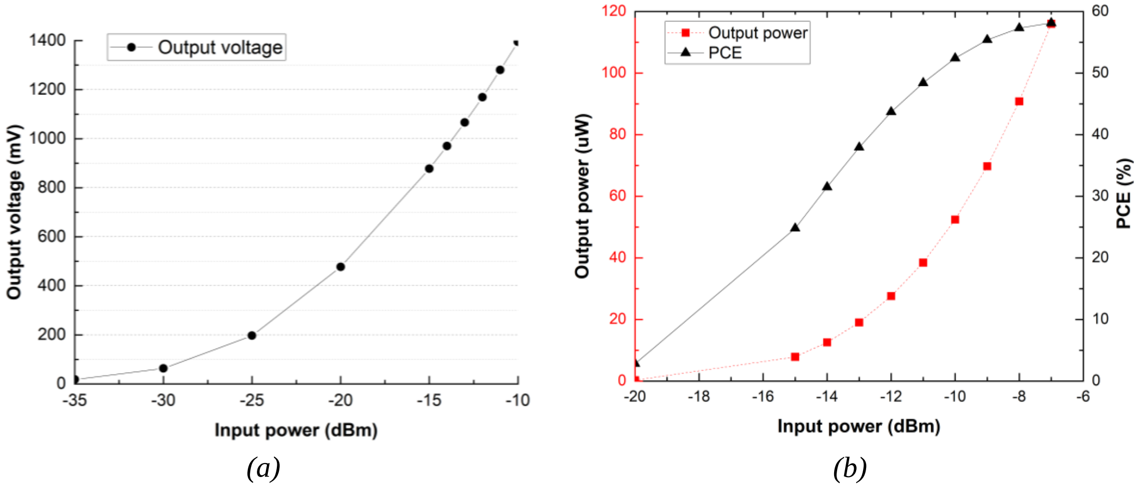
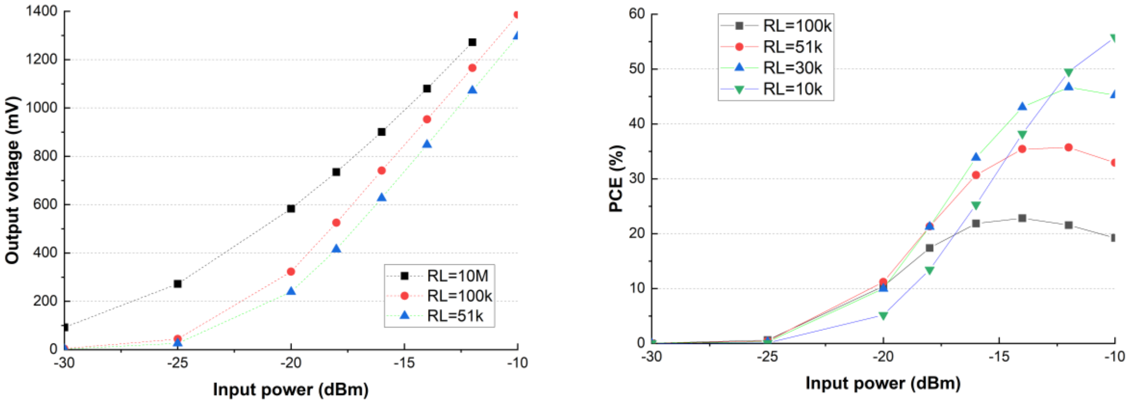


Figure 7. *Measurement results with SG in the laboratory:*
(a). Output voltage, (b) Output power and PCE.

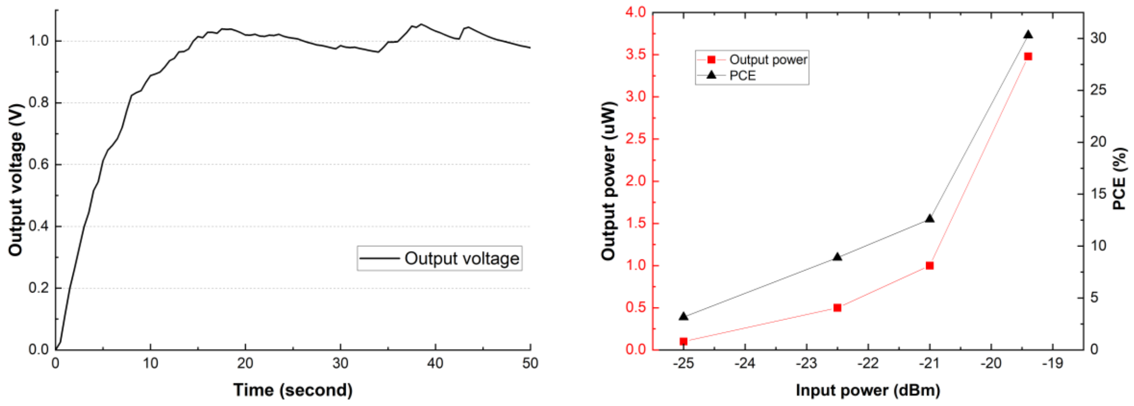
Fig. 8 presents the measurement results of the RFEH system in an anechoic chamber room with different loads. The SG is connected to a horn antenna to transmit RF signal to the designed rectenna. The measurement results show that the energy harvesting system achieves 1V output sensitivity when the input signal level is greater than -13 dBm. This result is in complete agreement with the measurement results by the SG of the RF-DC board shown in Fig. 7. The efficiency of the whole system is over 50% when the input signal is greater than -10 dBm. At -10 dBm of input RF power, the efficiency of the designed RFEH circuit is 57%.

Fig. 9 shows the measurement results of the RFEH system when harvesting the actual 950 MHz LTE signal in the environment in indoor and outdoor conditions. Fig. 9a indicates that the system can charge a 100 uF capacitor to a voltage of approximately 1V at a signal level input of approximately -19 dBm. In addition, the designed system achieves 30% efficiency at -19 dBm input. Besides, at this level, the output power of the circuit is 3.58 μW. These results indicate that the RFEH system can efficiently harvest the energy of the actual RF signal in the environment. Thus, it is necessary to ensure the relationship between the signal bandwidth and the Q factor as shown in the equation (11) to efficiently harvest ambient RF signals.



(a) *(b)*

Figure 8. *Measurement results in the chamber room:*
(a) Measured output voltage, (b) Measured PCE.



(a) *(b)*

Figure 9. *Measurement reults of the designed RFEH system with the LTE 950 MHz signal:*
(a) Measured output voltage, (b) Measured output power and PCE.

Table 1 shows the comparison results between the RFEH system proposed in this paper and the RFEH systems designed by the high Q method in previously proposed papers [10, 11, 14]. It can be seen that, when the circuits collect a sinusoidal signal from a standard signal generator, the high Q system can reach a higher sensitivity than the lower Q system. However, when the circuits harvest real signals in the environment, the proposed system has ensured the signal bandwidth with a Q-factor satisfying the equation (11), resulting in the output power of the circuit has increased larger than in other studies. This proves that the system with the proposed structure can increase efficiency when harvesting the energy of the actual signal in the environment.

Table 1. *Comparison table.*

	This work	***[10]***	***[14]***	***[11]***
Technology	65nm SOTB CMOS	90nm CMOS	GP 65nm CMOS	GP 65nm CMOS
Number of rectifier stages	3-stage	5-stage	6-stage	6-stage
Q factor of the rectifier	43	81	-	120
Sensitivity@ input power	1V@ -20 dBm	1V@-27 dBm	1V@ -30.7 dBm	1V @ -36 dBm
Maximum PCE@ input power (With SG)	**57%@ -10 dBm**	40% @ -17dBm	37% @ -23dBm	-
Center frequency	952 MHz	868 MHz	2.4 GHz	2.4 GHz
Distance@source power	**162m@ - (Base station)**	27m@4.8W	20m@4W	4.5m@0.1W
Output power @ Input power	**3.58 μW @ -19.4 dBm**	0.16μW @-4.6 dBm	-	3.3 nW @ -18.6 dBm

5. CONCLUSIONS

The paper analyzes the characteristics of the real RF signal in the environment to indicate the relationships between the parameters of center frequency, bandwidth, Q factor, and the number of stages of the rectifier circuit in the RFEH system. From the theoretical analysis, the paper designs the Rectenna system to guarantee the proposed conditions. The designed system is measured and tested with the signals from the standard signal generator, and real signals in the environment. The RFEH system is also tested in various measured conditions such as: in the laboratory, in a chamber room, and in indoor and outdoor conditions. The measurement results indicate that the proposed system has effectively harvested the ambient RF signal. The system achieves 1 V sensitivity at -20 dBm RF signal and reaches 57% efficiency at -10 dBm RF input. When harvesting LTE signals in the environment, the proposed system can generate 3.58 µW of DC output power at a level of -19.4 dBm input. The above results have proved the effectiveness of the proposed structure. Besides, the antenna in the designed system is simple wire dipole antenna and has a big size. In the future, the proposed system can be optimized by developing a direct-attached strip antenna together with a rectifier chipboard to reduce the total area of the system and eliminate the use of a matching circuit in the system.

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TÓM TẮT

Nâng cao hiệu suất thu từ môi trường cho hệ thống thu hoạch năng lượng cao tần

Bài báo đề xuất cấu trúc của hệ thống thu hoạch năng lượng (RFEH) giúp nâng cao được hiệu suất thu tín hiệu RF thực tế trong môi trường. Bài báo phân tích và chỉ rõ mối liên hệ giữa các thông số thiết kế hệ thống thu hoạch năng lượng RF trong môi trường như tần số trung tâm, băng thông, hệ số phẩm chất, số tầng mạch tách sóng. Từ đó, bài báo xây dựng các bước thiết kế hệ thống RFEH để đảm bảo có hiệu suất cao nhờ hệ số khuếch đại thụ động đủ lớn mà vẫn đảm bảo băng thông của tín hiệu. Trên cơ sở cấu trúc đề xuất, hệ thống thu tín hiệu LTE 950 MHz được thiết kế để kiểm chứng tính hiệu quả. Kết quả đo đạc chỉ ra hệ thống thiết kế có thể đạt độ nhạy 1V điện áp một chiều đầu ra khi công suất tín hiệu LTE vào là -20 dBm. Hệ thống đạt hiệu suất 57% tại mức công suất vào là -10 dBm và có thể cung cấp 3.58 μW công suất một chiều tại mức công suất vào là -19.4 dBm.

Từ khoá: Thu hoạch năng lượng RF; Hệ số phẩm chất; Băng thông; Hệ số khuếch đại thụ động.