Journal of ELECTRONIC MATERIALS, Vol. 45, No. 8, 2016
DOI: 10.1007/s11664-016-4441-5

Design and Implementation of RF Energy Harvesting System for Low-Power Electronic Devices

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Radio frequency (RF) energy harvester systems are a good alternative for energizing of low-power electronics devices. In this work, an RF energy harvester is presented to obtain energy from Global System for Mobile Communications (GSM) 900 MHz signals. The energy harvester, consisting of a two-stage Dickson voltage multiplier circuit and L-type impedance matching circuits, was designed, simulated, fabricated and tested experimentally in terms of its performance. Simulation and experimental works were carried out for various input power levels, load resistances and input frequencies. Both simulation and experimental works have been carried out for this frequency band. An efficiency of 45% is obtained from the system at 0 dBm input power level using the impedance matching circuit. This corresponds to the power of 450 μW and this value is sufficient for many low-power devices. The most important parameters affecting the efficiency of the RF energy harvester are the input power level, frequency band, impedance matching and voltage multiplier circuits, load resistance and the selection of diodes. RF energy harvester designs should be optimized in terms of these parameters.

Key words: RF energy harvester, efficiency, impedance matching, voltage multiplier

INTRODUCTION

The energy requirements of low-power devices are supplied by chemical batteries. But the life of batteries is finite and it is mostly difficult or impossible to change or recharge the batteries of the devices. This is a big problem in terms of labor, time and costs when the low-power devices are located at a difficult access environment.[1–4] Moreover, the chemical batteries contain heavy metals, which can pollute the environment.[5] The energy harvester systems overcome the problem of battery replacement and eliminate the system dependency on external power supply, which make the system self-powered.[6] There are many types of energy harvesting systems such as photovoltaic, wind, thermoelectric, vibration and radio frequency (RF).[7–12]

(Received December 23, 2015; accepted February 27, 2016; published online March 14, 2016)

RF energy harvesting systems have emerged in recent years as alternative or supplementary energy sources to batteries. These systems capture ambient RF signals in the environment. The number and level of the RF signals are continuously increasing because of wireless systems such as wireless sensor networks (WSNs), mobile base stations, wireless field (WiFi) systems, TV and radio base stations, wireless routers and the other wireless systems. Therefore, RF energy harvesting systems are becoming more popular and efficient. In addition, these systems are much less affected by weather conditions compared with other energy harvesting systems.[13,14] However, they have some disadvantages such as low power density and being much more sensitive. For example, while the power density of vibration energy harvesters is 100 μW/cm^2, this ratio decreases to 10 μw/cm^2 or less in RF energy harvesters.[15]

A number of studies have been carried out to investigate the feasibility of RF energy harvesting for both close and remote areas to the RF source.[16–18] Some battery-free devices are powered by ambient RF energy from WiFi, Global System for Mobile Communications (GSM) and digital television (DTV) bands as well as ambient mobile electronic devices.[17–20] Gunathilaka et al.[21] have managed to run a calculator using GSM signals. Mikeka et al.[22] has reached an efficiency of 18.2% for −20 dBm input power level in the DTV band. Alneyadi et al.[23] have designed an RF energy harvester which operates at WiFi frequency bands to power sensor nodes in industrial or residential environments. The harvester includes multiple microstrip patch antennas, a power combiner, a Greinacher rectifier circuit, and a super-capacitor to store the harvested energy. Arrawatia et al.[24] designed an RF energy harvester which can generate electrical energy from a 900-MHz cell tower. They used different numbers of stages for voltage multipliers and generated approximately 41 μW power at 0 dBm input power. In locations where the signal level is weak and the obtained power is low, some researchers have designed broadband RF energy harvesters that can generate power from signals with different frequencies.[25–27] But these designs are too sensitive and the circuit sizes are larger.

The generated power from an RF source is related to its incident power level, signal frequency, antenna and the efficiency of the circuit. In such systems, the obtained power can be calculated by the Friis equation as shown in Eq. 1.

$$P_r = P_t G_r G_t [\lambda/(4\pi R)]^2 \quad (1)$$

where P_r is the obtained power, P_t is the transmitted power, G_t is the gain of the source antenna, G_r is the gain of the receiver antenna, λ is the wavelength of the transmitted signal, and R is the distance between the source and receiver.

The transmitted power level is very important for these systems. The signal level decreases rapidly with distance, and therefore the converter circuit should be designed very carefully and efficiently. Another factor affecting the efficiency is the antennas. High-gain antennas should be selected for high efficiency, while wideband antennas may be preferred if they have higher gain. Thus, it is possible to obtain energy even at low efficiency from different frequencies apart from the target frequency. For this, a special antenna design can be made or commercially available antennas can be used such as Loop-, Yagi-uda-, and Straight-type.[28] However, in general, commercial multiband antennas enlarge the circuit size.

Figure 1 shows a block diagram of a base RF energy harvester system. In general, an RF energy harvesting system consists of a matching network, a voltage multiplier and a load and/or storage unit. However, these systems can sometimes include other components such as converters and transformers. A matching network is essential to increase the obtained power, because the source and receiver impedances should be equaled to obtain maximum power from the systems. RF systems provide low power and voltage, and in addition RF signals are alternating. To reduce the losses due to the diodes and to rectify the RF signals, voltage multipliers are used. The storage unit is optional because the generated power can only supply the load directly.

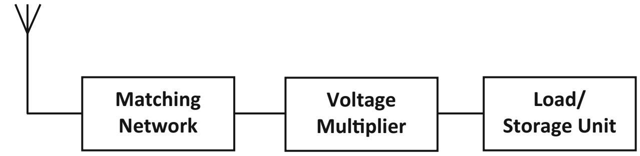

Fig. 1. Block diagram of a base RF energy harvesting system.

The goal of this work is to design a proper RF energy harvester system and provide power to the devices with low power consumption. This paper is organized as follows: the RF energy harvesting system architecture is explained in the "RF to DC Conversion System" section, simulations and experimental studies are presented in the "Simulations and Experimental Results" section, and finally some conclusions and future work are given in the "Conclusions" section.

RF TO DC CONVERSION SYSTEM

In general, a RF to direct current (DC) conversion system consists of two modules, one of them a voltage multiplier circuit and the other an impedance matching network. In this work, Dickson voltage doubler topology was used as the RF to DC converter due to the simplicity of analysis. The HSMS-2852 Schottky diode was selected to support the fast switching at the high frequency. To get maximum efficiency from the system, an impedance matching circuit was added to the system. The simulations were carried out by an Agilent Advanced Design System (ADS). Figure 2 shows the proposed RF energy harvester.

In RF to DC converter systems, to obtain a smoother DC voltage, an extra filter can be added to the output of the voltage multiplier. However, this filter will increase both the size and the cost of the circuit.

The Voltage Multiplier and RF Schottky Diode Modeling

RF signals are alternating and have a too low amplitude. The voltage multiplier circuits increase the voltage and rectify the alternating voltage to direct voltage. There are various voltage multiplier types such as Dickson, Villard and Greinacher circuits. The Dickson voltage multiplier is used to realize the RF to DC power conversion. This voltage multiplier consists of two diodes and two capacitors for each stage. In this work, a two-stage voltage

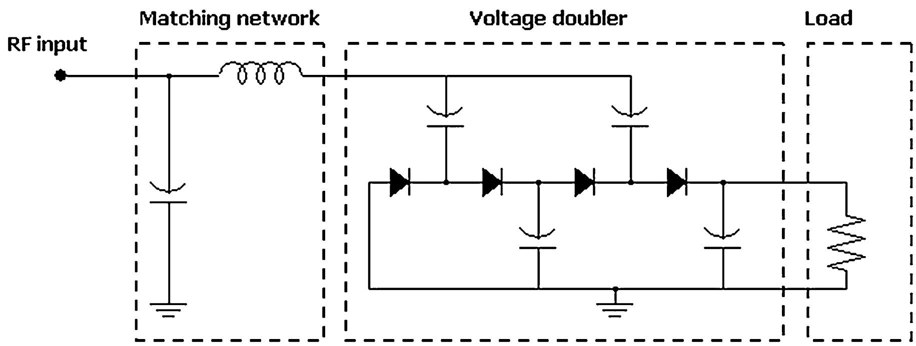

Fig. 2. The proposed RF energy harvester design.

multiplier called the voltage doubler is preferred for its ease of analysis and smaller circuit design. Figure 3 shows that the system efficiency depends on the number of stages in the Dickson voltage multiplier. This figure was obtained using ADS software for voltage multipliers at different stages from 1 to 12. During the simulations, an input signal with constant frequency was applied to the systems which have different stage voltage multipliers. The increase number of stages does not cause a significant change in the efficiency. However, this increase can lead to a bulky and expensive circuit.

The determination of the diodes has crucial importance in the design of RF energy harvester circuits. The diodes must have a fast switching speed, low forward voltage drop and low junction capacitance in order to operate efficiently even at low input power levels. Therefore, HSMS-2852 Schottky diodes were used because their forward voltage drop is 0.15 V and capacitance is 0.3 pF.[29] These diode are very efficient especially at low input power levels such as −20 dBm. The impedance of a diode depends on the resistive and capacitive impedance provided by the junction of the diode and its connected load.[30] Moreover, HSMS-2852 Schottky diode packages include two series diodes. Only two diode packages and four capacitors are used for the voltage doubler in this work. Therefore, the system is not bulky. The equivalent linear circuit model of a bare Schottky diode is shown in Fig. 4.

The equivalent impedance in Fig. 4 can be expressed as follows:

$$Z_D = R_s + \frac{R_j}{1 + j\omega R_j C_j} \tag{2}$$

where Z_D is total impedance of the diode, and C_j and R_j are the junction capacitance and the junction resistance, respectively. The packaging inductance and capacitance should also be taken into account for complete diode modeling. R_j is given by,[29]

$$R_j = \frac{8.33 \times 10^{-5} \times N \times T}{I_b + I_s} \tag{3}$$

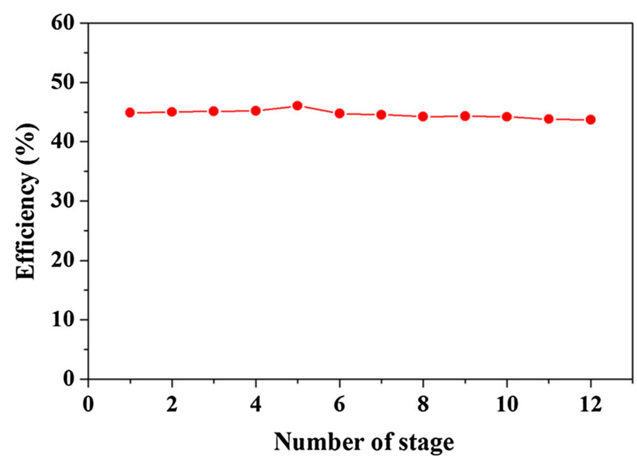

Fig. 3. The system efficiency versus number of stages of the voltage multiplier.

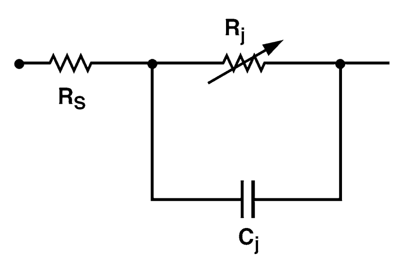

Fig. 4. Equivalent linear circuit model of the Schottky diode.

where I_b is the bias current in μA, I_s the saturation current in μA, T the temperature, K, and N the ideality factor.

The temperature and saturation current are two important parameters for determining diode impedance, and they show variable features. Therefore, the diode impedance is nonlinear. For instance, the temperature of diodes increases when the input power is higher, so that the impedance varies and the efficiency decreases.

Matching Network

The maximum power transfer theorem states that the maximum power is transferred to the load when

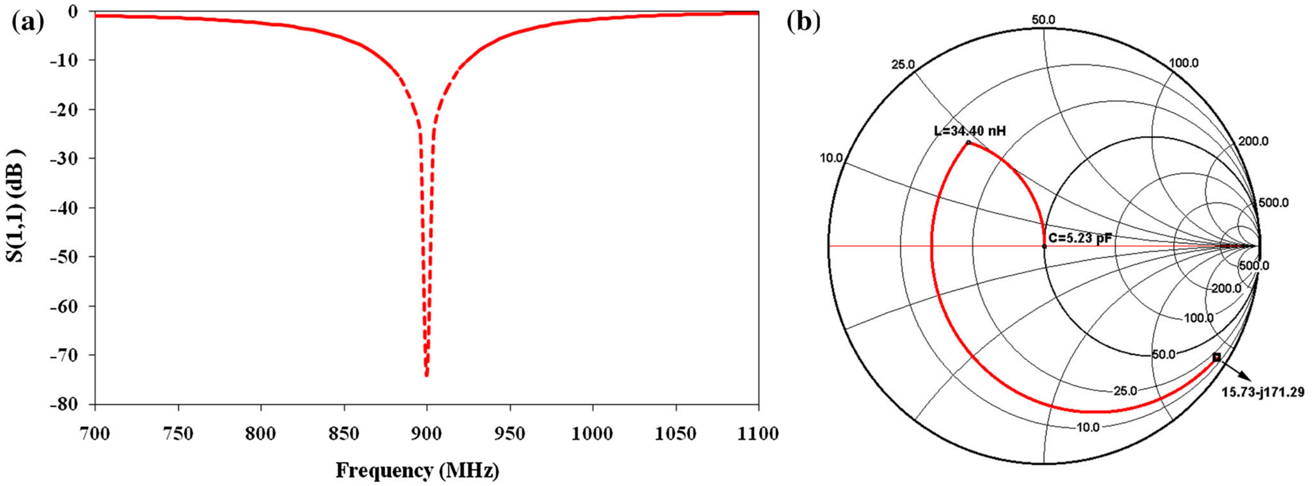

Fig. 5. (a) S(1,1) diagram and (b) Smith chart of the system.

the source impedance is equal to the load impedance. Real and imaginary parts should be equaled with each other for source and load in the systems including resistive and reactive impedances. One of the features that should be in the RF energy harvesting circuits is the maximum power transfer. The circuit impedance varies with the input power level and frequency because the nonlinear behavior of the diodes depends on the saturation and radiation resistance. Therefore, the proper impedance matching circuit can be used by estimating the approximate operating frequency and input power levels.

Even a little change in the impedance matching parameters can substantially affect the frequency at which the system efficiency is maximised. In this work, the L-type impedance matching circuit consists of a series inductor with a shunt capacitor. The RF signal generator with 50 Ω resistive impedance was used for this work, and hence the impedance of the RF energy harvester circuit was 50 Ω.

The impedance matching circuit should be employed to provide maximum power transfer, especially in low power level. In general, RF to DC conversion systems are able to work at low input RF power levels, because the RF signals are too low in the environment. Therefore, it is required to use impedance matching circuits to get more power from the system.

There are several types of impedance matching processes. In this study, an L-type impedance matching circuit was selected because of its simplicity, while this circuit is also sufficient for the impedance matching process for this design. The components of the circuit were determined by the software. Figure 5a and b shows the S(1,1) diagram and the Smith chart of the design obtained from the ADS software, respectively. This configuration consists of just an inductor and a capacitor. Therefore, the impedance matching network causes only a small increase in the circuit size. As in this study, RF energy harvester circuits with one frequency band can be used for this matching type. The impedance matching components were obtained from simulations and previous theoretical work[31] considering resonant frequency. Resonant frequency was determined to be equal to 900 MHz which is the input frequency of the system.

SIMULATIONS AND EXPERIMENTAL RESULTS

The simulations were performed by using the ADS software. The responses of the system were observed by changing variables such as load resistance, input frequency and input power level. The experimental works were performed based on the data obtained from the simulations. In the experiments, a Hameg HM8135 RF signal generator was used to provide the input power at the desired frequency and level. It can generate RF signals having 3 GHz frequency and between −120 dBm and 13 dBm power level. The RF signals were observed with the Hameg HMS3000 spectrum analyzer. The energy harvesting circuit was tuned using a R&S ZVL13 vector network analyzer (VNA) by Rohde Schwarz. A NI USB 6351 data acquisition card by National Instruments was used for data transfer of the obtained voltage from the device. The system collected all experimental outputs into LabView software. The experimental setup and dimensions of the RF energy harvester are shown in Fig. 6a and b.

Figure 7 shows that the system efficiency and load voltage depend on the load resistances at 0 dBm input power and 900 MHz frequency. As can be seen from the figure, the efficiency and load voltage of the system are higher when the load resistance is between 10 kΩ and 20 kΩ. Therefore, load resistance is an important parameter in terms

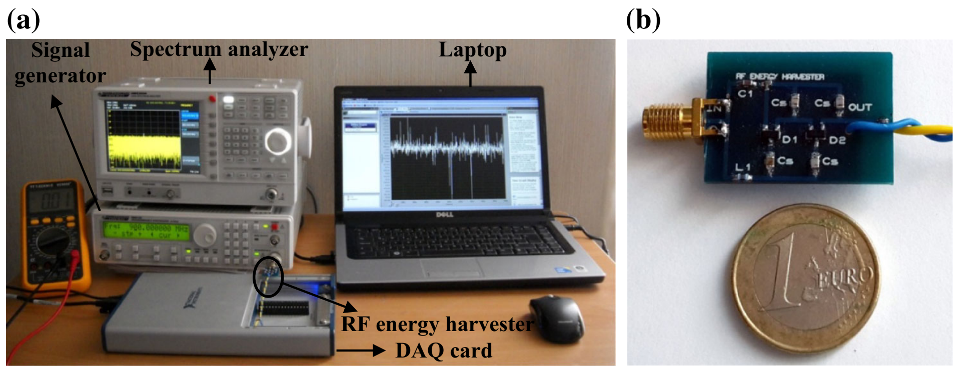

Fig. 6. (a) The experimental setup. (b) RF energy harvester.

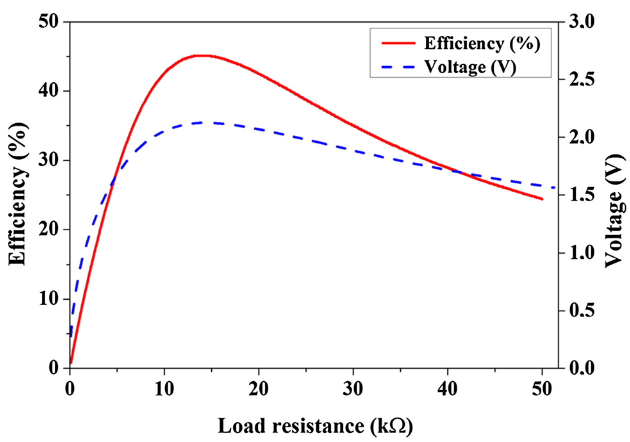

Fig. 7. The system efficiency versus the load resistance.

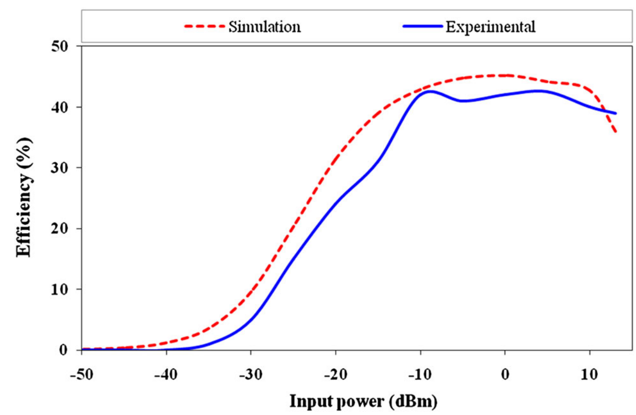

Fig. 8. The system efficiency versus the input power.

of the system efficiency, and the impedance of the circuit to be connected to the system must be known. If there is a mismatch between the loads which gave the maximum efficiency when connected to the system, a second impedance matching circuit should be added before the system load.

Figure 8 shows the system efficiencies versus the input power level between −50 dBm and 13 dBm at 10 kΩ load resistance and 900 MHz frequency. The frequency was kept constant at 900 MHz and the input power level was swept up from −50 dBm to 13 dBm in both simulations and experimental studies.

There are few differences between the experimental and simulation results in terms of efficiencies. The main reason for this situation is that the system is too sensitive. Although an exact impedance matching process has been achieved, some small impedance changes can occur during the measurements. In this case, the resonance frequency of the system shifts up or down, and therefore the system efficiency decreases. The efficiency is around 25% for −20 dBm input power and it also increases with increasing input power. However, the efficiency decreases for an input power level >5 dBm. The most important reason for this situation is that the diodes were designed for low power levels. The efficiency of the diode increases until the reverse breakdown voltage of the diode. When the reverse voltage on the diode is greater than the breakdown voltage, the efficiency of the diode decreases rapidly and some of the input power is converted to heat in the diode. As can be seen from Fig. 8, this circuit and diodes are appropriate for input power levels lower than 5 dBm. However, since the RF signal level is low in the environment, this power level is in general sufficient. If the input power level decreases below −30 dBm, the efficiency decreases below 10%. In this case, the power that can be obtained at this input power level will be around 0.1 μW. Therefore, the use of the proposed RF energy harvester in the location where the input power is too low is difficult. In such places, two or more systems may be connected to each other or systems that can harvest energy simultaneously at different frequencies may be used.

Figure 9 shows the voltage on the load resistance (10 kΩ) versus input frequency for 0 dBm input power. The input power was fixed to 0 dBm and the frequency was increased from 0 MHz to 1500 MHz in both simulation and experimental studies. The maximum voltage was obtained at around 900 MHz because the impedance matching process was implemented for this frequency level. The 900 MHz frequency was selected because most GSM working

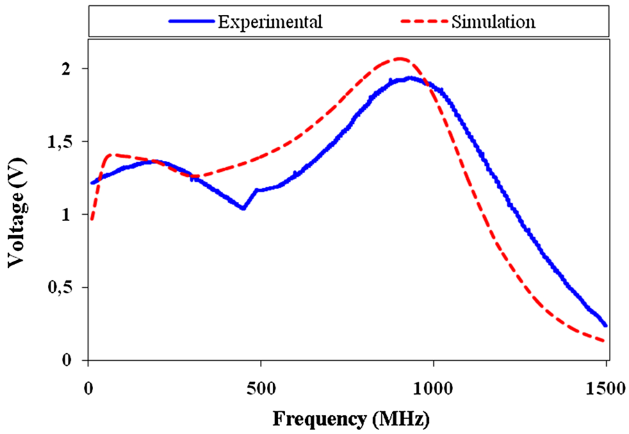

Fig. 9. The load voltage depends on the input frequency (load resistance = 10 kΩ, Input power = 0 dBm).

frequencies are around this frequency band. An efficient working frequency of this energy harvester can be changed easily by varying the component values. However, this circuit works with an acceptable efficiency between 10 MHz and 1200 MHz. This situation causes the circuit to work at low frequencies and it can obtain energy from DTV transmitters.

CONCLUSIONS

RF energy harvester circuits have the potential to energize low-power electronic devices instead of chemical batteries. RF energy harvesters are much less affected by weather conditions compared to other energy harvesting systems. In the RF energy harvester system, the impedance matching and voltage multiplier circuits should be used due to RF signals being weak in the environment. The system has been simulated and the prototype of the system is being manufactured. There is good agreement between the simulation and experimental results. One of the most important parameters that determines the amount of power to be obtained in this system is the input power level. The proposed system can be used at a power level over −30 dBm. The other parameters affecting the system efficiency are the input RF frequency, selection of components, and impedance matching and voltage multiplication processes. The system can operate a device without batteries or it can extend the battery life of the device.

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