EFFECT OF MATCHING NETWORK ON AMBIENT RF ENERGY HARVESTING CIRCUIT FOR WIRELESS SENSOR NETWORKS

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Abstract

Limited battery life of wireless devices is encouraging companies and research groups to develop new technologies which operate these devices for an enhanced period of time. Transfer of Radio Frequency (RF) energy and its harvesting techniques have become an attractive and very promising alternatives for powering the wireless sensor networks and devices. In wireless sensor networks, low power consumption is a major challenge. From the point of view of system cost and lifetime, energy dissipation in wireless sensor networks has become an emerging and active research field For mobile and mini electronics or sensor devices, the best possible solution is to capture and store the energy from ambient energy sources, are the type of renewable energy. It holds a promising future for generating a required amount of electrical energy for operating wireless communicating electronics devices. In this paper we have reviewed the various Radio Frequency (RF) energy harvester circuits which utilized different rectifier and voltage boosting circuit. Simulation results represents that by using matching network of high-Q, output voltage of harvesting circuit increases and it becomes more sensitive with respect to input signal frequency and value of elements used.

Keywords: Radio frequency energy harvesting, matching network, RF to DC power conversion, diode's non linear behavior.

I. INTRODUCTION

In last decades the size and amount of power supply has been drastically reduced for many devices which require very less amount of power to recharge the battery. Wireless sensor networks (WSN) used in environment, agriculture and structures application demands continuous availability of power sources with long lifetime. With growing development of wireless communication, plenty amount of RF energy broadcasted through millions of public services signal sources like cell phone tower, handheld radios, Wi-Fi networks and television (T.V.) or radio broadcast stations. Hence it is very useful to collect this energy and may provide to different wireless devices such as wearable medical sensors, headsets, microcontrollers, cell phones and so on, which may increase their battery life or even may avoid the requirement of battery through this technique [1]. Since huge amount of ambient RF energy is available, spread over several frequency bands according to their application areas. Hence it is possible to receive them in combined form and converted into equivalent electrical energy by employing appropriate circuit.

Electromagnetic RF signals are omnipresent these days and they carry a tiny amount of energy employed for communication and other purposes like cellular mobile signals, TV transmitter, WiFi and DTH signals. Therefore, energy harvesting from these resources cannot be exploited for power hungry applications, and it is restricted only to small ultralow power applications. Specifically, a wireless sensor network (WSN) may include a large number of individual sensor nodes that may be difficult to access due to being implanted within a wall, a ceiling, or in a hostile environment, where frequent human access is very difficult and replacement of their batteries become impractical. Therefore, powering these tiny sensor nodes remotely through RF energy harvesting may extend their existing battery life or even they can work satisfactorily without these batteries. This concept may also be extended for other purposes such as Internet of Things (IoT) etc. An IoT system having three essential elements sensors, connectivity and processor. The major objective of energy harvesting systems is to ensure uninterrupted (or on demand basis) supply of energy for the life time of these systems, which works on its own without any human intervention. The increasing use of wireless devices like wireless computing devices, cell phones and remote sensor networks resulted in an increased demand for self powered systems. Hence there is a need of development of system which extracts energy more efficiently from the ambient and converts it into electrical energy, used to charge-up a battery operated system.

Several research groups have selected to recycle ambient energy such as in Micro-electromechanical Systems (MEMS) [18]. The charging of mobile devices is much convenient and easy for the user, like for mobile phones. But for other equipments, like wireless sensor nodes which are located in inaccessible places, the charging of the batteries present a major challenge. This becomes major issue when the number of devices is large and are distributed in a wide area or located in difficult to access environments. The development on RF energy harvesting techniques provides reasonable solution of overcoming these problems. For charging of battery it is required that received RF signal is converted in to DC power through rectification. The process of rectification of microwave signals to DC power has been proposed and researched in the case of high-power signal. It has been proposed for helicopter powering [18], solar power satellite [11], the SHARP System [29]. The DC power depends on the available RF power, the choice of antenna and frequency band.

Ambient RF energy is freely available from RF transmitters which are not intended for transfer of RF energy. The transmitted RF power varies from 1Megawatt for TV transmitter, approx. 10 watt for cellular mobile system and 0.1 watt for mobile devices and WiFi systems. The RF energy available from the wireless sources is much higher up to 30W for 10GHz frequency [19], but only a small amount can be propagated in the real environment. The remaining is dissipated as heat or absorbed by other materials. Maximum theoretical power available for RF energy harvesting is 7.0 μW for 2.4 GHz and 1.0 μW for 900 MHz band, for a free space distance of 40 m [19]. A great motivation behind the energy harvesting research and development is ultra-low-power applications.

The remainder of this paper is organized as follows. Section II illustrates circuit design of RF energy harvester. Section III explains the methods and techniques developed for implementing RF energy harvesting circuit. Section IV describes the effect of matching network on output voltage of harvesting circuit. Conclusion is given in Section V.

II. CIRCUIT DESIGN

Energy harvesting process is a method of conversion of the abundant available atmospheric energy into useful electrical energy. There are different forms of energy available in the atmosphere, as light and heat, solar, wind and vibration energy. Energy harvesting from RF signal is different from other sources and has following characteristics:

- Inexhaustible nature and abundant availability in the atmosphere.
- Energy scavenging process is not harmful and do not pollute the atmosphere.
- Constant RF energy available from distant RF sources can be easily controlled.
- The output energy available from harvester is predictable and stable for long time in a fixed RF energy harvesting network.
- Since the intensity of RF energy harvesting depends upon the distance between RF sources and harvesting device, the wireless sensor nodes at different location may have different amount of harvested RF energy.
- RF energy harvesting circuit provides non removable power source in

biomedically implanted devices such as pacemaker, stimulator and drug deliverer, which reduces the patient's risk of death.

- Work in perpetually dark and hazardous locations and eliminates the need of charging mats or charging stations for wireless devices.

This section introduces hardware devices of RF energy harvesting circuit. Here the main object is to provide the understanding of communication aspects of the energy harvesting network. Basic block diagram of RF energy harvesting circuit is shown in fig. 1. It contains

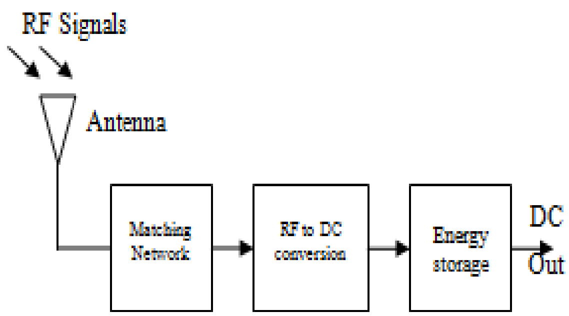

Fig. 1 Block diagram of RF energy harvesting circuit [21]

A. Antenna

Antenna receives RF energy of different frequency band from ambient [8][14][15][21] and converts it in to equivalent electrical signal through electromagnetic induction. It may be single band [27][29], dual bands [30] and triple bands [31] – [33]. A broadband antenna [13] receives RF power over wide frequency band with maximum 20% efficiency.

B. Matching Network

To deliver maximum received power from antenna to rectifier stage, it is necessary that antenna impedance must be matched to input impedance of diode used in rectifier stage, called impedance matching. It reduces transmission loss. For this purpose matching network [2],[9] is connected between antenna and rectifier stage which consist of inductive and capacitive element or LC network in 'L', 'T' or 'π' shape, according to which these are called 'L', 'T' or 'π' matching network.

C. RF to DC converter or Rectifier

To charge the battery of wireless devices or sensors, RF electrical signal supplied from matching network have to convert in DC power through rectifier circuit. Since signal strength depends upon distance between transmitter and receiver, power of RF sources, size / gain of receiving antenna and transmission frequency as given by Friis transmission equation [6], this arises a problem of low conversion efficiency, gives low output DC voltage. Hence to boost up the DC voltage we may use voltage multiplier circuit [4]. The Schottky barrier diode [28] is most commonly used device for this purpose due to lower built in voltage capable of providing high conversion efficiency at lower input power level.

D. Energy storage

To ensure smooth power delivery from RF to DC power converter stage to the load, the energy storage device is connected at output, which works as a reserve for durations when external energy is unavailable or insufficient.

III. METHODS

Energy harvesting circuits have been demonstrated for more than 50 years, but only a few have been able to harvest energy from freely available ambient (i.e., non-dedicated) RF sources. Several RF energy harvesters are implemented using various technologies such as CMOS, SMS and HSMS schottky diode. The authors in [10] proposed a resonant voltage boosting network followed by a two stage voltage doubler rectifier for RF energy harvesting. Since at low input RF levels, the peak voltage of the RF signal is much smaller than the diode threshold voltage, a resonant tank based voltage boosting network designed for a given frequency to maximize the boosted voltage amplitude. The authors in [5] proposes RF power harvesting through inductive coupling, which has proved efficient over a distance of up to 25 mm between coils, with the primary coil driven with an RF amplifier to create an electromagnetic field, and the secondary coil on the implanted device used to induce a current and hence a voltage depending on the coupling factor and the current through the primary coil. The study in [22] investigates the theoretical issues in the design of power harvesting systems in terms of the trade-off between matching network gain and bandwidth. C-MOS rectifier is designed for RFID application by using 0.5 μm and 0.18μm MOSFET based rectifier structure with 4 transistor cell operating around 950 MHz. The work in [3] represents power harvester circuit for an RF identification transponder fabricated in a 0.18 µm CMOS (Complementary Metal Oxide Semiconductor) process operates at the UHF band of 920 MHz. The circuit employed an impedance transformation circuit to boost the input RF signal with optimum values for the circuit parameters. The authors in [23] design a RF-DC power conversion system in a 0.25 µm CMOS technology using floating gate transistors as rectifying diodes to efficiently convert far-field RF energy to DC voltages in low power sensor network with the 36-stage rectifier.

The work in [26] presents UHF 900-MHz RFID transponder front end implemented in a 0.35-μm CMOS technology, having zero-threshold MOS transistors which are particularly helpful for increasing the conversion efficiency of RF–DC rectifier in transponders. Instead of conventional Schottky diodes, diode-connected MOS transistors with zero threshold are used as a power supply generator in the on-chip RF–DC voltage rectifier to improve the compatibility with standard CMOS technology. The authors in [7] designed a compact dual polarized rectenna operating at 2.45 GHz consists of a square aperture coupled patch antenna with a cross shaped slot. The received signal from each slot output is rectified by using two stages, two voltage doubler circuits. The first stage is formed by a series capacitor and a shunt Skyworks SMS7630 Schottky diode. The second stage uses a series SMS7630 diode and a shunt capacitor.

A new design for an energy harvesting device by using schottky diode HSMS – 2852 and one stage voltage doubler is presented in [17]. The authors in [12] present a 2.4 GHz RF energy harvester integrated into a low-power transceiver (TRx) operating at the same frequency. To keep performance degradation of the TRx low, an RF switch is used which decouples the harvester from the TRx and enable the harvester to operate without a DC power supply. The circuit is implemented in a 130 nm CMOS process, requires a minimum input RF power of -10 dBm.

A dual-band rectenna which can harvest ambient RF power of GSM-1800 and UMTS-2100 bands efficiently, based on a broadband Yagi antenna array with bandwidth from 1.8 to 2.2 GHz is designed in [8]. It used dual band matching network with a Schottky diode HSMS-2852 (Vth = 150 mV, Cj = 0.18 pF, Rs = 25 Ω) is inserted between the matching circuit and the DC-pass filter to convert the RF power into DC power. The DC-pass filter is realized by a simple stepped impedance microstrip line low pass filer, followed by a resistive load to extract the DC power. The authors in [16] report a highly sensitive energy harvester using CMOS rectifier in 90 nm technology. They reported 1 volt output at minimum - 27 dBm input power.

TABLE I
Performance Comparison of various Circuit Techniques

S. No.	Reference	Technology Used	Maximum Conversion Efficiency with RF input power	Frequency
1	[22]	0.18 µm CMOS	37% with -17.7 dBm	950 MHz
2	[3]	0.18 µm CMOS	N. A.	920 MHz
3	[23]	0.25 µm CMOS	30% with -8 dBm	906 MHz
4	[26]	0.35 µm CMOS	15.76% with 12.7 dBm	900 MHz
5	[7]	SMS-7630	42.1% with -10 dBm	2450 MHz
6	[17]	HSMS-2852	10% with -10 dBm	915 MHz
7	[12]	130 nm CMOS	22.7% with -3 dBm	2400 MHz
8	[28]	HSMS-286B	55% with -30dBm	13.56 MHz
9	[16]	90 nm CMOS	40% with -17 dBm	868 MHz

A carbon nano tube (CNFET) based voltage multiplier or rectifier circuit for RF (radio frequency) energy harvesting applications is presented in [25]. The passive multi-stage RF to DC voltage booster circuit uses AC input signal of 60 mV to produce a DC output voltage of 389 mV, which is sufficient to drive circuits &

systems in subthreshold region for ultralow power applications. Table I shows the various method used and their performance. Mostly designs are based on CMOS technology which requires minimum RF input power but maximum RF to DC conversion efficiency is lower as compared to HSMS technology.

IV. EFFECT OF MATCHING NETWORK

The output DC voltage and conversion efficiency of RF energy harvester badly affected due to diode's non linear behavior and value of matching network's element. Hence efficient design of matching network is essential to get optimum performance. The impedance of rectifier circuit varies with input signal frequency and load impedance due to non linear characteristics of rectifier diode, which limits the circuit efficiency. The matching network may effectively solve this problem can be realized either by using lumped element like resistor, inductor and capacitor or by using distributed elements such as microstrip lines. For L-matching network consisting of series inductor and shunt capacitor, the element value may be determined by using design equations [6]:

$$B_L = \pm\sqrt{R_L\,(Z_0 - R_L)} - X_L \qquad (1)$$

$$B_C = \pm\frac{\sqrt{(Z_0 - R_L)\,/\,R_L}}{Z_0} \qquad (2)$$

Where R_L and X_L represents real and imaginary part of the load impedance Z_L. Z_0 is the antenna impedance which is 50 Ω. The rectifier circuit consist of diode HSMS-2852 with impedance value Z_L = (46.25 – J 566.08) Ω at 0.9 GHz. In order to match the antenna impedance with diode, the value of series inductor and shunt capacitor are 102.13 nH and 1 pF respectively calculated from eqn. 1 and 2. With these element values, L-matching network used in energy harvesting circuit is shown in fig. 2(a). Constructed prototype unit fabricated on GML make substrate with dielectric constant value ε_r = 3.7 is shown in fig. 2(c). It uses inductor and capacitor element supplied from Murata electronics to implement the matching network.

Fig. 2(b) represents the simulated and measured output voltage of harvester circuit in the presence and absence of matching network. It can be observe that harvesting circuit gives increased output voltage in the presence of matching network. It gives 0.5 volt output at -10

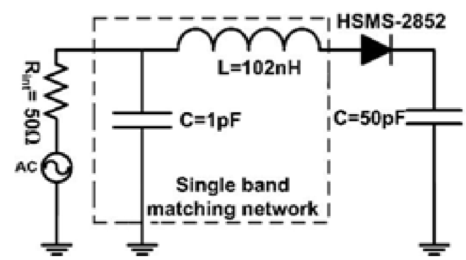

Fig. 2. (a) RF energy harvesting circuit with L-matching network

dBm input signal level with matching network, whereas without matching network it provides only 0.1 volt.

As input signal strength increase, output voltage of harvester circuit also increases. The rate of increase of output voltage is very low up to – 10 dBm input signal, but after it the slope of output voltage curve shows improvement.

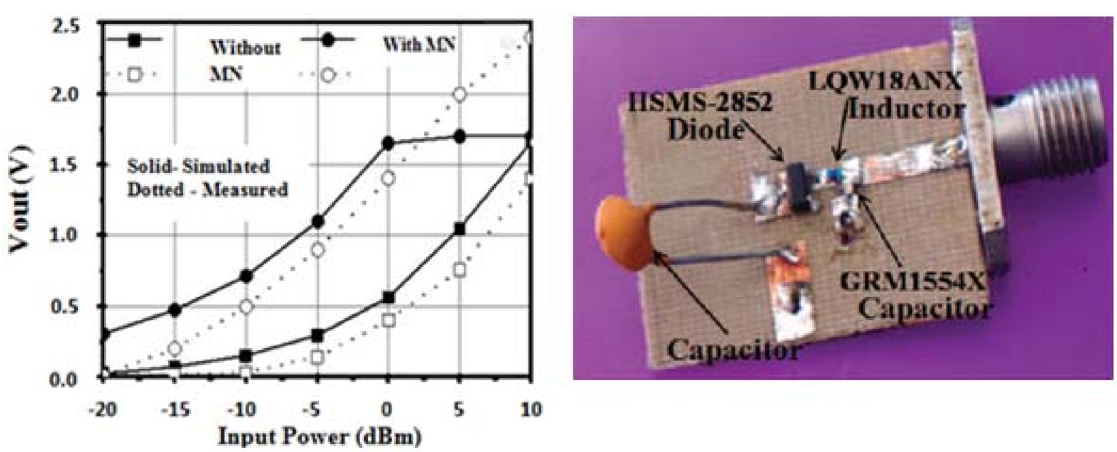

Fig. 2. (b) Simulated and measured output voltage of harvester circuit (c) Constructed harvester unit

V. CONCLUSION

In this paper the effect of diode's non linear characteristics and value of matching network elements on output voltage is presented. It has been observed that RF energy harvesting circuit achieves higher output voltage with High-Q matching network. It provides maximum power transfer from receiving antenna to rectifier circuit so that conversion efficiency of the circuit may increase, because this circuit has to work with very low input RF power level.

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