A Broadband High Efficiency Rectifier for Ambient RF Energy Harvesting

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***Abstract*—Ambient energy harvesting is a key technology to the success of wireless sensor networks. Among various energy sources available in daily environment, electromagnetic RF energy is a good source due to the wide signal coverage from various wireless communication systems. Harvesting a wide frequency band RF signals is useful to boost the total energy level. In this paper, a broadband high efficiency RF rectifier with a shunted Schottky diode is presented. The source pull simulation is used to find the optimal source impedance over the wide frequency range while maintaining good conversion efficiency. A 3^{rd} transmission line low-pass matching network is designed to realize the optimal source impedance. The measurement results agree well with the simulation results. The highest measured efficiency is 81% and a frequency band 0.78-1.43 GHz with efficiency exceeding 50% is achieved for an input power level of 25 mW.**

***Index Terms*—Energy harvesting, rectifiers, conversion efficiency, low-pass matching network.**

I. INTRODUCTION

Autonomous wireless sensor networks have become more and more mature with the advancement in the areas of ultralow power MCUs and wireless communication transceivers and efficient energy harvesting techniques. The deployed wireless sensor nodes should be ideally self-powered, or without a frequent maintenance of changing batteries, which is both time consuming and labor costly. All the required energy can be collected from various ambient energy sources, such as solar, thermal, vibration , electromagnetics and etc [1]. Given the nature of these energy sources, each or a combination of several energy sources may be useful for certain physical environment or application. Solar may be prevailed for outdoor applications other than indoors, while vibration is available for many industrial machines. Nowadays our living environment is filled with many electromagnetic energy sources as wireless communication is integrated with almost every aspect of our lifes. Examples are digital TV (DTV), radio broadcast stations, cellular mobile base stations, and WiFi routers. These RF energies are available without the limit of day and night shift, weather condition, physical location and human mobility. When the wireless communication is not disturbed, these RF energies can be harnessed or recycled to power on wireless sensor nodes. Such kind of ambient RF energy harvester usually consists of an RF rectenna, a DC/DC converter and a suitable energy storage device. A number of research work and demonstration have been published recently. In [2] ambient Digital TV 550 MHz signals are harvested with the highest efficiency of 18.2%. In [3] an 82% efficiency rectenna is achieved for wireless power transfer at 5.8 GHz, which shares the same working principle as the RF energy harvester. Later this group expanded the working frequency to both 2.45 GHz and 5.8 GHz using a novel dual band rectenna, with a coplanar stripline low-pass filter, exceeds 80% at both frequencies [4]. Several techniques are explored to enhance the RF-DC conversion efficiency in rectifiers, which is crucial to the achievable output power from the energy harvester. Harmonic termination techniques, which are widely used in RF power amplifiers, are applied in rectifier design to improve rectenna efficiency, such as 2.45 GHz class-C rectifier with 72.8% efficiency [5] and 900 MHz class-F rectifier with 80.4% efficiency [6]. Though good efficiency is achieved in these works, the operating frequency does not cover the broad spectrum of the available RF energy sources. Given the relative low energy level of RF signals available in the space compared with solar, thermal and vibration, a broadband rectifier is of great interest to harvest more energy to compete with other energy harvesting technologies. In [7] microwave energies in the range of 2-18 GHz is harvested with the help of a wideband antenna array, while the efficiency does not exceed 20%. In this work a broadband and high efficiency rectifier is proposed using the similar principle reported in [8] which demonstrates a broadband and high efficiency continuous inverse Class-F and continuous Class-F PA with 60%-84% drain efficiency from 1.3 to 3.3 GHz. The source pull simulation of the rectifier gives the range of proper source impedance to guarantee both wide operating frequency band and optimal high efficiency. A low pass filter is then implemented to achieve such source impedances. Both simulation and measurement results prove the feasibility of the proposed idea.

II. BROADBAND RECTIFIER DESIGN

The proposed rectifier adopts a conventional circuit topology that consists of a low-pass filter, a shunted Schottky diode, a DC pass filter and a resistive load. The RF-DC conversion efficiency is defined and determined as the ratio of the output DC power to the RF input power in equation (1).

$$\eta = \frac{P_{DC}}{P_{RF}} \tag{1}$$

A source pull simulation is setup in ADS to get the impedance contours for conversion efficiency, as shown in Fig.1. In this setup the Schottky diode is HSMS8202 from Avago Technology, a 480 nH RF inductor from Murata is used

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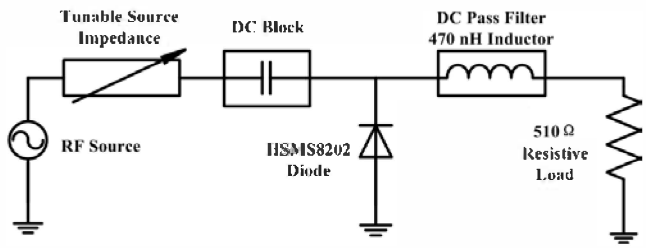

Fig. 1. Schematic of source pull simulation.

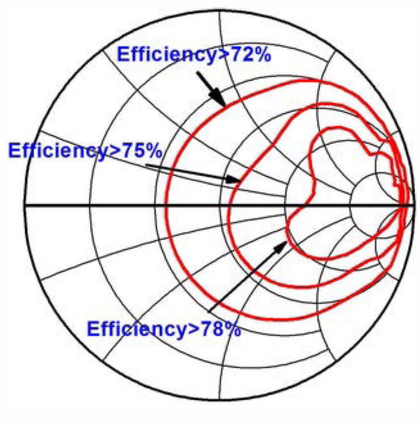

Fig. 2. Efficiency contours for 0.8 GHz based on source pull simulation

as the DC pass filter, the load is a 510 Ω resistor, and the input power level is fixed at 25 mW.

Since harmonic tuning is helpful to improve efficiency performance [6], higher order harmonic impedances are set according to class F operation, in which an ideal open impedance is applied to odd harmonics and a short impedance to even harmonics. Fig. 2 shows the source pull simulation results of this rectifier working at 0.8 GHz. When the source impedance is located inside the smallest contour, the conversion efficiency can be better than 78%. As the source impedance deviates from this region, the efficiency drops gradually. Then a source impedance can be chosen from this plot for the required efficiency value, and a simple impedance matching network (LC network or single stub network) can be applied to transform this source impedance to 50 Ω. Since the impedance matching network has a narrow band response, the efficiency will not maintain a good value as the operating frequency differs from 0.8 GHz.

To understand how this rectifier performs under various frequencies, the input signal frequency is swept from 0.8 GHz to 1.4 GHz with all the other setting unchanged in the source pull simulation. A target of no less than 75% efficiency is set to plot the resultant efficiency contours on Smith chart, shown in Fig.3. It is clear that the efficiency contour moves as the frequency changes, however there exists an overlapped area where the efficiency is kept above 75%. This gives one an impedance map to choose in order to achieve broadband rectifiers with high efficiency at the same time. For simplicity

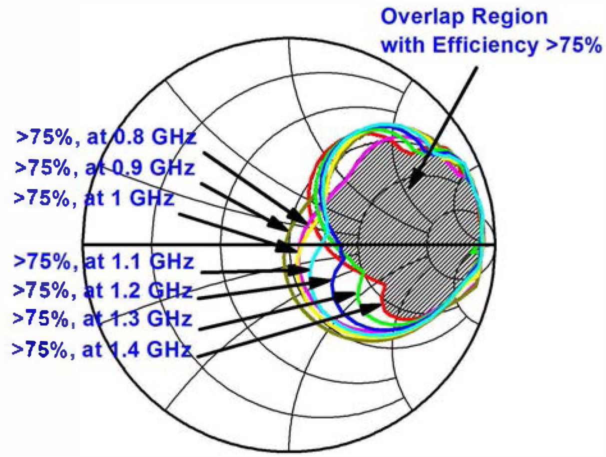

Fig. 3. Source impedance region with efficiency greater than 75% from 0.8 GHz to 1.4 GHz.

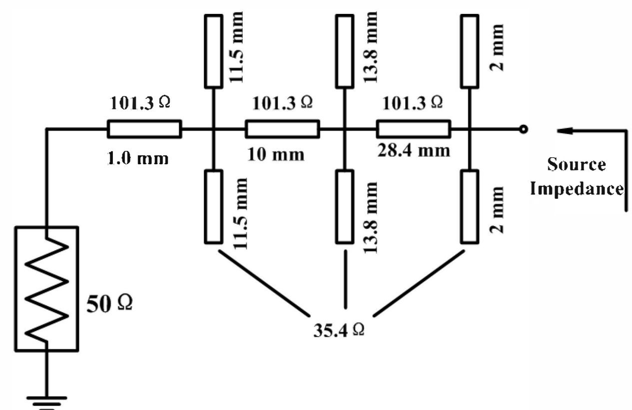

Fig. 4. Third order transmission line low-pass matching network.

a source resistance of 150 Ω is chosen for the design.

Then the low-pass matching network is used to transform this selected source impedance to 50 Ohm at the fundamental frequency in the range of 0.8-1.4 GHz. A 3^{rd} order Chebyshev low-pass filter prototype with 0.1 dB ripple is used to synthesis the low-pass matching network, giving a real to real impedance transformation ratio of 3:1 [9]. Optimization of each inductor and capacitor is carried out to achieve the low pass filter response and the required higher order harmonics impedances for class F operation as well. Finally the optimized lumped elements are designed with distributed transmission lines, where series inductors are realized by high impedance microstrip lines and shunt capacitors by low impedance open-end shunted microstrip lines [10]. Detailed dimensions of the low pass filter are shown in Fig.4.

The source impedance of the final low-pass matching network is shown in Fig. 5. Though it is slightly different than the design value of 150 Ω, the in-band (0.8 GHz to 1.4 GHz) impedance is still in the designed overlap region as shown in Fig. 5. The 2^{nd} and 3^{rd} harmonic impedances are not ideal open and short for the typical class F requirement, and they

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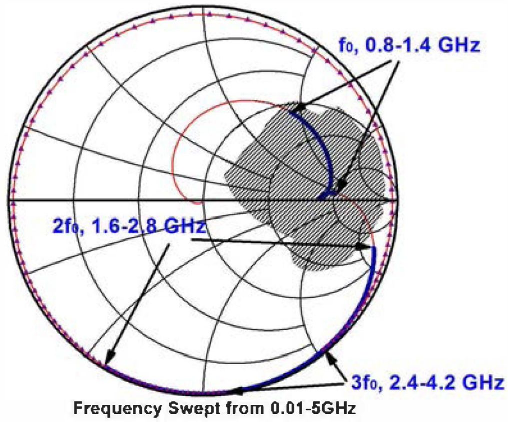

Fig. 5. Source impedance of low-pass matching network.

can be further optimized.

III. RECTIFIER IMPLEMENTATION AND MEASUREMENT

The broadband rectifier is fabricated on a 0.813 mm thick Rogers 4003C printed circuit board as shown in Fig. 6. The rectifier is measured with an input signal ranging from 0.7 GHz to 1.5GHz with a step of 10 MHz, with a constant power of 25 mW from a signal generator. The voltage on the resistive load is measured by a voltmeter and the efficiency is calculated according to (1). The measured result agrees with the full wave EM simulation result as shown in Fig. 7. The highest measured efficiency is 81% at 1.04 GHz. An efficiency above 60% is achieved in the bands of 0.83-1.18 GHz and 1.23-1.39 GHz. When the accepted efficiency is relieved to above 50%, a much wider operating frequency range is realized from 0.78 GHz to 1.43 GHz. The discrepancy of the measurement results to the designed goal (above 75% from 0.8 to 1.4 GHz) is due to several reasons, such as non-ideal 2^{nd} and 3^{rd} impedance by the low pass network, and loss from the practical PCB and components.

IV. CONCLUSIONS

A broadband high efficiency rectifier is designed with the help of source pull simulation. The required wideband source impedance is realized through a careful design of a low pass impedance network. The fabricated rectifier shows an overall efficiency higher than 50% in the frequency range of 0.8-1.4 GHz. The highest efficiency is 81% at 1.04 GHz. The demo rectifier is suitable for harvesting ambient RF energies in a wide frequency range, thus the total harvested energy is greatly increased.

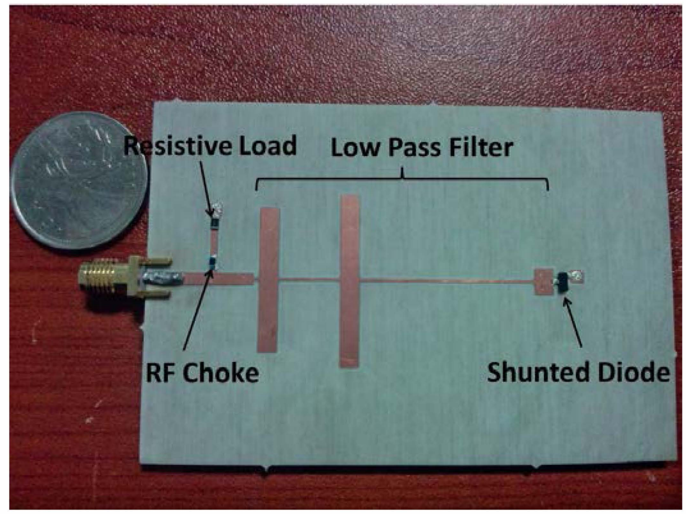

Fig. 6. Photo graph of fabricated rectifier.

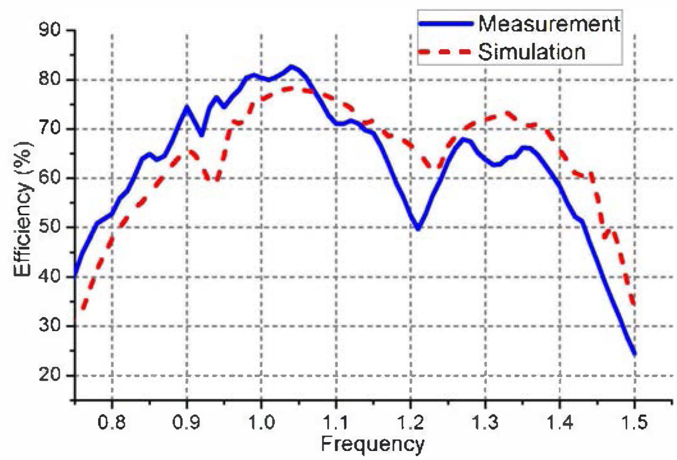

Fig. 7. Comparison of measured and simulated rectifier efficiency.

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