

Design of Dual Band Rectifiers for Energy Harvesting Applications

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Abstract—Design, simulation and implementation of dual band radio frequency energy harvesting (RFEH) system operating at 900MHz and 1.8GHz is introduced. In the proposed design, RF-DC conversion system is designed to passively amplify the available voltage for rectification by developing a resonator with high quality factor. Passive amplification and rectification are implemented using a combination of clamper and peak detector circuits. Harmonics presented in the rectified output voltage is eliminated by using an innovative two-section dual band transmission line matching network and filter. Energy harvesting system is designed, simulated and measured. Close agreement has been observed between analytical, simulation and measurement results.

Keywords—Dual band, energy harvesting, matching network, radio frequency, rectanna, rectifier.

I. INTRODUCTION

Wireless sensor networks (WSNs) comprise of a set of active nodes which communicate with each other and a central node. In recent years WSNs have expanded to evolvment of a new area called Internet of Things (IoT) that investigates the connectivity and exchange of data between all physical devices in the network [1]. WSNs have been used in agriculture, healthcare, earth-sensing, industry and myriads of other applications. It is not uncommon to see that the most of the time, sensor nodes are situated in hazardous locations with limited accessibility. Hence, these sensors at the nodes are typically powered by battery. Since, battery is limited form of energy source, they require periodic recharge or replacement which brings along the added cost of maintenance and replacement [2]. Disposal of battery is also a cumbersome task which is hazardous to the environment.

One way to overcome the power problem due to limited battery lifetime is to use a method called energy harvesting. Energy harvesting also known as power harvesting, or energy scavenging is the process of extracting energy from external sources using solar power, thermal energy, wind energy, salinity gradients, and kinetic energy which all can be referred as ambient energy. Energy harvester once extracts the energy in the ambient it then converts that energy to DC, rectifies the signal and powers wireless autonomous devices that might be part of larger networks [3-4]. Radio Frequency (RF) energy harvester systems have antenna, and impedance matching networks to interface the rectifier system as illustrated in Fig. 1. This system can energize any type of network that has low power requirement such as wireless sensor networks.

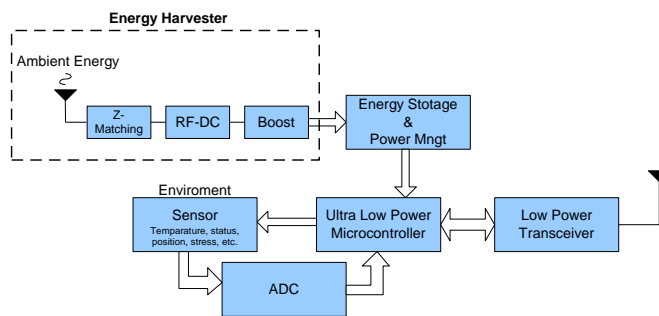


Fig. 1. Block diagram of RFEH.

In this paper, design, simulation and implementation of dual band radio frequency energy harvesting system operating at 900MHz and 1.8GHz is introduced. The proposed energy harvester has integrated impedance matching network, filter and cascaded three stage rectifier which is based on voltage doubler circuit to convert RF-DC. The system is simulated with Agilent Design System (ADS) and implemented. It has been confirmed that the analytical, simulation and measurement results are all in agreement.

II. DESIGN OF RECTIFIER CIRCUIT

Clampers or DC resonators hold the peak of a waveform at the desired DC level. In other words, it clamps the waveform either in positive or negative direction using diode with a capacitively coupled signal as shown in Fig. 2. The output voltage of the clamper circuit can be expressed as:

$$V_{\text{clamp}} = 2V_p - V_{\text{th}} \tag{1}$$

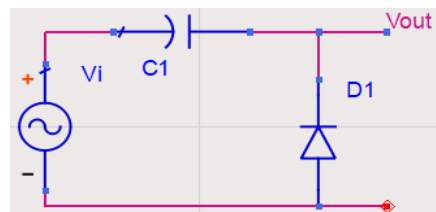


Fig. 2. Voltage clamper circuit.

Since the energy is considerably low in the ambient, we need to take into account the effect of diode threshold voltage, V_{th} . The diode should be capable of fast switching with a very low threshold voltage which is required for conduction.

To produce a steady voltage from the rectifier we incorporate peak detector with clamper circuit. A peak detector is a series connection of a diode and a capacitor outputting a DC voltage equal to the peak value of the applied sinusoidal signal. The peak detector circuit with voltage waveforms is illustrated in Fig. 3.

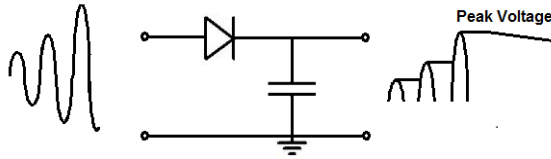


Fig. 3. Peak detector circuit.

The voltage output of the peak detector circuit is given as:

$$V_{\text{pkDetect}} = V_{\text{clamp}} - V_{\text{th}}. \quad (2)$$

The clamping and peak detector circuits can now be integrated to form single stage of the radio frequency energy harvesting (RFEH) system as shown in Fig. 4. The single stage RFEH can be cascaded to increase the amount of output voltage. In the proposed system, three stage RFEH is used to accomplish RF-DC conversion.

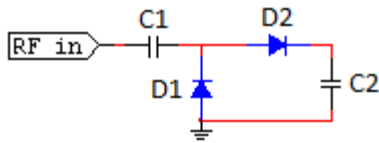


Fig. 4. Single stage of RFEH.

III. DUAL BAND TRANSMISSION LINE MATCHING

To ensure maximum power is transferred from the antenna to rectifier we need to provide a matching network as shown in Fig. 5. Primary challenge of designing matching network for the proposed circuit lies in the fact that load impedance of an antenna varies with frequency due to the presence of capacitance. Another challenge is the complexity of matching circuit required to work at two different frequencies simultaneously.

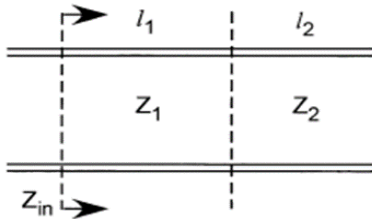


Fig. 5. Two-section dual-band transformer.

Two-section transformer which can match impedance with frequency dependent load is proposed in [5]. A practical dual-band two-section 1/3-wavelength transformer [6] that works at the fundamental frequency and its second harmonic is designed for the proposed system. Such a novel transformer is of a high interest because of the requirements for a low profile, and more efficient RF low-noise down converter, and desecration of frequency recycle in commercial and military operations.

The dual band matching network is designed as follows. Let's assume, load impedance connected to energy harvesting

antenna to be Z_1 and Z_2 , at the two frequencies, f_1 and f_2 , respectively. f_1 and f_2 are set to be 900MHz and 1.8GHz, respectively.

The input impedance Z_{in} of the two-section transmission line shown in Fig. 5 is:

$$Z_{\text{in}} = Z_1 \frac{z'_L + jZ_1 \tan(\beta l_1)}{Z_1 + jz'_L \tan(\beta l_1)}, \quad (3)$$

$$Z'_L = Z_2 \frac{R_1 + jZ_2 \tan(\beta l_2)}{Z_2 + jR_1 \tan(\beta l_2)}, \quad (4)$$

where β is the wave number. For proper impedance matching, input impedance should be equal to characteristic impedance Z_0 at the two intended frequencies f_1 and f_2 . Relating Z_{in} to Z_0 and solving for Z'_L in (3) we get,

$$\frac{Z_0 - jZ_1 \tan(\beta l_1)}{Z_1 - jZ_0 \tan(\beta l_1)}, \quad (5)$$

$$Z'_L = Z_1 \frac{Z_0 - jZ_1 \tan(\beta l_1)}{Z_1 - jZ_0 \tan(\beta l_1)}.$$

From (4) and (5), we can write:

$$(Z_1^2 - Z_2 Z_0) \tan(\beta l_1) \tan(\beta l_2) = Z_2 Z_0 (R_1 - Z_0), \quad (6)$$

$$n \quad (7)$$

which leads to:

$$\tan(\beta l_1) \tan(\beta l_2) = \alpha \frac{Z_2 Z_0 (R_1 - Z_0)}{(R_1 Z_1^2 - Z_2^2 Z_0)}, \quad (8)$$

$$\frac{\tan(\beta l_1)}{\tan(\beta l_2)} = \gamma \frac{Z_1 (Z_2^2 - Z_L Z_0)}{Z_2 (R_1 Z_0 - Z_1^2)}. \quad (9)$$

From (8) and (9), we obtain:

$$(\tan(\beta l_1))^2 = \alpha \gamma, \quad (10)$$

$$(\tan(\beta l_2))^2 = \frac{\alpha}{\gamma}. \quad (11)$$

When $f_1 = f_1$, is substituted into (10)-(11), the following equations are found:

$$(\tan(\beta_1 l_1))^2 = \alpha \gamma, \quad (12)$$

$$(\tan(\beta_2 l_1))^2 = \alpha \gamma, \quad (13)$$

$$(\tan(\beta_1 l_2))^2 = \frac{\alpha}{\gamma}, \quad (14)$$

$$(\tan(\beta_2 l_2))^2 = \frac{\alpha}{\gamma}. \quad (15)$$

The solutions of (12)-(13) give:

$$\tan(\beta_1 l_2) = \pm \tan(\beta_1 l_1). \quad (16)$$

And

$$\beta_2 l_1 \mp \beta_1 l_1 = n\pi. \quad (17)$$

Similarly, from (14) and (15), we obtain:

$$\beta_2 l_2 \mp \beta_1 l_2 = m\pi. \quad (18)$$

In (17)-(18), n and m are integers. Assuming $m = n = 1$ and $f_2 \geq f_1$ we get a solution for the above equations as follows:

$$l_2 = l_1, \quad (19a)$$

$$l_2 = \frac{\pi}{\beta_2 + \beta_1}. \quad (19b)$$

When the line lengths are calculated, α and γ can be determined by using (10) and (11) at either f_1 or f_2 . For example, simplifying equation (19), using f_1 we obtain:

$$\alpha = (\tan(\beta_1 l_1))^2, \tag{20}$$

$$\gamma = 1, \tag{21}$$

so,

$$R_l Z_0 = Z_1 Z_2. \tag{22}$$

Equation (22) is valid when $Z_1 + Z_2 \neq 0$. We can also show that:

$$R_l Z_1^2 - Z_2^2 Z_0 = \frac{R_l Z_0 (R_l - Z_0)}{\alpha}. \tag{23}$$

Using (22) and (23), we can now get either Z_1 or Z_2 . Using standard means the solution for Z_1 leads to the real line impedance value:

$$Z_1 = \sqrt{\frac{Z_0}{2\alpha} (R_l - Z_0)} + \sqrt{\left[\frac{Z_0}{2\alpha} (R_l - Z_0)\right]^2 + Z_0^3 R_l}. \tag{24}$$

Z_2 can then be obtained from (22) as:

$$Z_2 = \frac{Z_0 R_l}{Z_1}. \tag{25}$$

Hence, the total length of transmission line in wavelengths can be calculated at the fundamental frequency f_1 using:

$$\frac{l_1 + l_2}{\lambda_1} = \frac{\beta_1 \lambda_1}{\beta_1 + \beta_2},$$

$$L = \frac{\beta_1 \lambda_1}{\beta_1 + \beta_2}. \tag{26}$$

IV. SIMULATION RESULTS

The proposed three stage RFEH is designed and simulated as shown in Fig. 6. Harmonics are presented in the rectified output voltage. The two section matching network discussed in Section III is designed and integrated to eliminate the harmonics. The two section matching network can match impedance at two distinct frequency without causing any deficiency in the circuit. Fig. 7 shows output spectrum without harmonics after the use of two section matching network. Fig. 8 shows the simulated output power in frequency domain where harmonics is present. Without the transmission line we got some ripples at 900 MHz and 1.8 GHz. Voltage peak at 0 Hz is 146 mv.

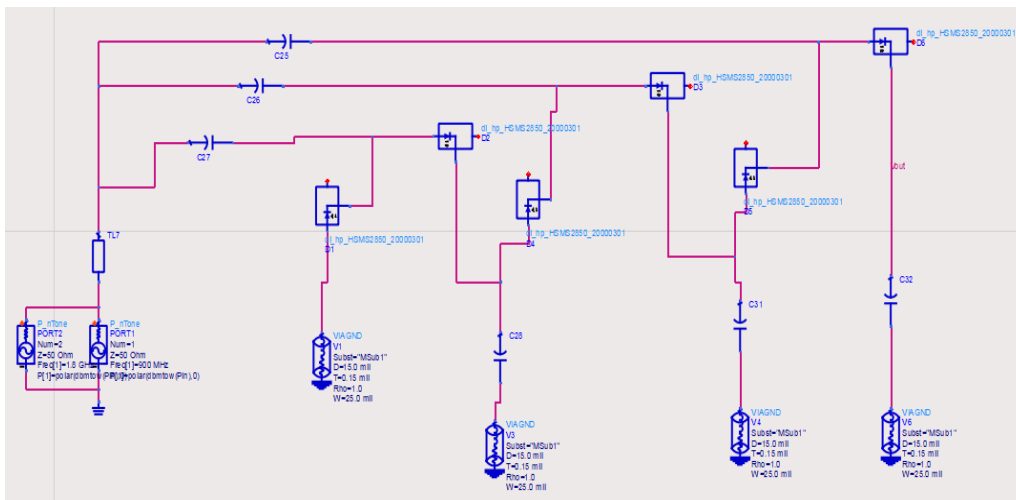


Fig. 6. The complete RFEH system.

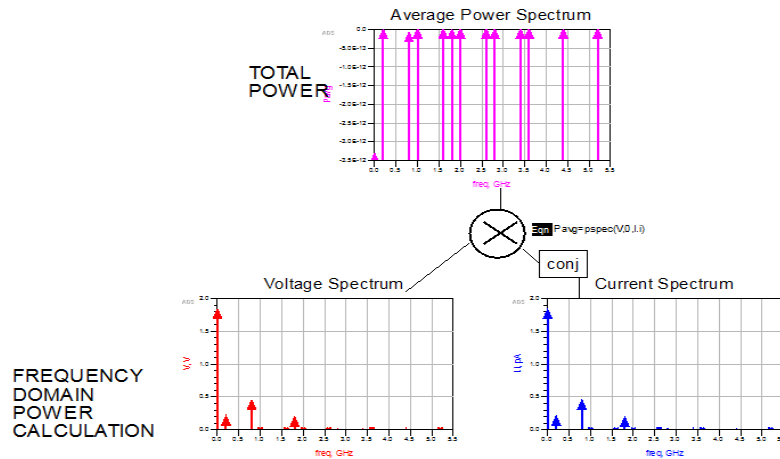


Fig. 7. Frequency Spectrum of Output power.

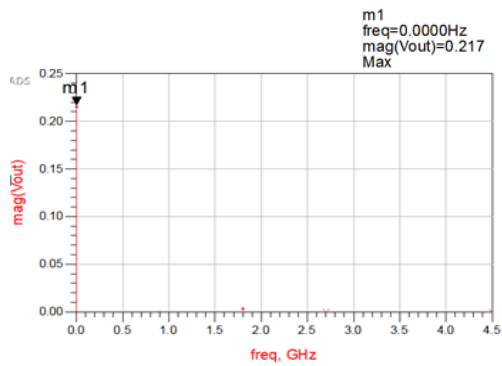


Fig. 8. Voltage spectrum showing elimination of harmonics from output with impedance matching network.

V. MEASUREMENT RESULTS

The prototype of three sections is built and tested. RF-35 material with dielectric constant 3.5 was used to make the prototype. The two critical components used in the design are Schottky diode HSMS 2850 from Broadcom Inc., and 56pf capacitor from Wurth Electronics. The circuit was fabricated in university lab as shown Fig. 9. Figure 9 (a) and 9 (b) shows the top and bottom view of the prototype of the rectifier, respectively

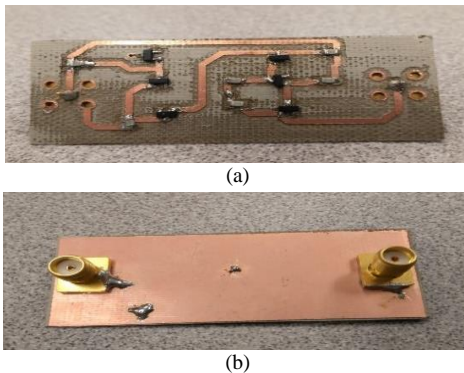


Fig. 9. (a) Top and (b) bottom view of rectifier.

The test set up of the energy harvesting system is illustrated in Fig. 10.

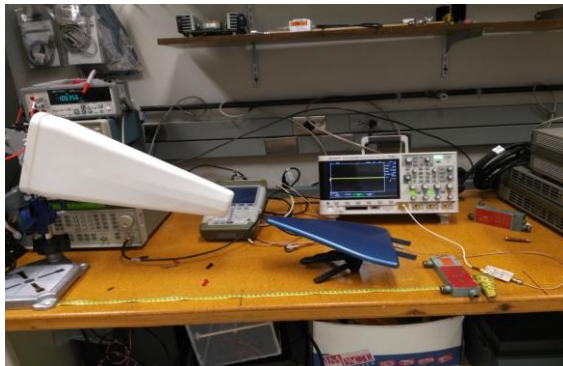
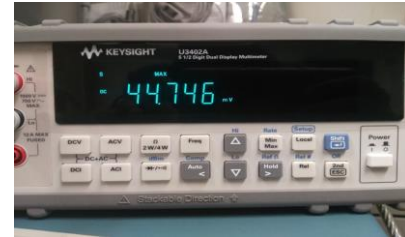


Fig. 10. The test set up for measuring rectifier output.



(a)



(b)

Fig. 11. The DC voltage measurement output at: (a) 900MHz and (b) 1.8 GHz.

The rectifier output at 900 MHz and at 1.8 GHz is measured to be 88.63 mV and 44.74 mV, respectively as shown in Fig. 11.

VI. CONCLUSION

In this paper, design, simulation and implementation of a dual band radio frequency energy harvesting (RFEH) system operating at 900MHz and 1.8GHz is introduced. The proposed harvesting system is designed, simulated and measured. It is shown that RFEH system can passively amplify the available ambient RF energy via three stage voltage doubler circuit. Passive amplification and rectification is implemented using a combination of clamper and peak detector. Harmonics presented in the rectified output voltage is eliminated by using transmission line matching network and filter. Energy harvesting system designed and simulated is then implemented and tested. Close agreement between analytical, simulation and measurement results are obtained.

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