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# Effect of Parallel Capacitor in Matching Network of RF Energy Harvesting Circuit

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**ABSTRACT-**This paper is an outcome of a wide research on RF energy harvesting techniques presented so far along with the development and implementation of the new idea of using a matching network with and without including parallel capacitance. While working with variable signal power in RF energy harvesting there is always a problem with nonlinear behavior of rectifying diode in harvesting circuit, to overcome the same a variety of matching networks are proposed in this manuscript with the variable RF power along with the variable load. Simulation results shows that output has been achieved upto 1.8Volts with maximum power conversion efficiency up to 79% at -10 dBm input power. Experimental results represented DC output of 1.62 volts at a frequency of 900 MHz with -10 dBm input power. Optimization technique is used to select parameters value which maximizes output voltage and efficiency. Variation of load resistance and input power plays a major role in output voltage and conversion efficiency. Comparison of the same is also presented in this particular research paper.

***Keywords:*** RF Energy, Impedance Matching, L matching network, Rectifier.

## 1. INTRODUCTION

Recently, RF energy harvesting has become a topic of interest for various researchers and industrialist. As invention of low power devices is on high, everyday a new device is being introduced in the market. Along with that a new way of charging or a new specification of power backup is also being introduced. But so far, none of the low power device manufacturing company has introduced a device which doesn't require charging or a battery which doesn't discharge frequently. RF energy harvesting can be a life saver for such manufactures. Ambient source of energy is lying unused. In this technique this ambient energy is converted into an electrical signal or into a usable form. This process removes the need of charging or battery replacement.

Due to environmental condition like free space path loss, temperature changes, humidity and sometimes low received power signal may results into lower output voltage and low efficiency, but fair enough to keep the battery charged all the time.

Due to variation in received input power their might be mismatch in the impedance of the circuit that lead to disturbance in the output power, this problem may also occur due to nonlinear behavior of the diode. For such cases or to maintain the circuit behavior the input and output of the rectifier circuit need to be optimized for specific power input and specific load resistance.

Huge amount of ambient RF energy is transmitted by numbers of cell tower in the environment whose power level varies with distance from the tower [9]. This energy is received by RF signal receiver works as transducer that converts the available RF energy into electrical signal. Then circuit has matching network which provide a lossless connection between transducer and rectifier. Matching network circuits are used for matching the impedances of antenna with the impedance of rectifier.

Matching network plays a vital role in the RF energy harvesting circuit. The proper and efficient use of the matching network can significantly control the sensitivity of the rectifier circuit and may help to gain the output voltage and efficiency in spite of the weather conditions which may result to frequent variation in the received power.

This paper comprises the study of the input impedance of the rectifying diode and the designing of the matching network L-type matching network, single inductor in series then a circuit with parallel capacitor and series inductor. Variation of different matching networks leads to the improvement in the output voltage. Section II describes system architecture, circuit design is explained in section III, results are discussed in section IV and conclusion is given section V.

## 2. SYSTEM ARCHITECTURE

The proposed harvesting circuit is operated on 900MHz frequency band shown in Fig.1 below. Electrical signal or into a usable form. This process removes the need of charging or battery replacement.

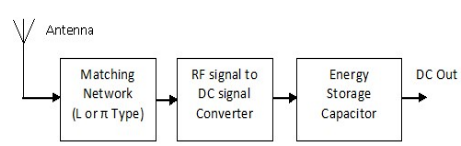


**Fig.1**: Single stage harvester circuit

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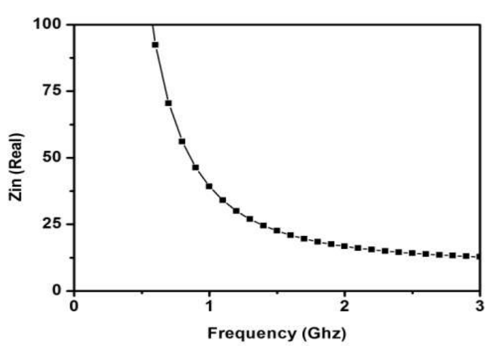
Figure 1 shows fundamental block diagram of microwave frequency energy harvesting system. It consists of a receiving antenna, matching network, RF to DC signal convertor and storage capacitor. Antenna receives ambient electromagnetic RF signals and converts it into electrical signal [5, 6] by using electromagnetic induction. Receiver Antenna may be broadband [12] to cover large frequency band. By using properly designed matching networking maximum of induced electrical AC signal transferred to RF to DC convertor which produces output voltage used to charge storage capacitor, which provides DC output voltage for charging up wireless devices.

Variation of the input impedance of diode with input signal frequency for rectification purpose is simulated. HSMS-2852 Schottky diode has been selected for designed circuit because Schottky diode has very low forward voltage drop and high switching speed [7][11] and all simulation work is performed in ADS software. Fig.2 shows the real and imaginary values of input impedance of diode as a function of input frequency. As it can be observed through the imaginary values of $Z_{in}$ that diode accounts negative reactance throughout the working frequency. Therefore, it can be represented as a series or parallel combination of resistance and capacitor. Since, the input power source or antenna has an internal impedance of 50Ω and the diode may be represented as a parallel combination of R and C hence a resonating circuit can be formed.

## 3. CIRCUIT DESIGN

Along with the maximum power transfer capability, matching network also enhance the incoming signals for later stages [10]. Thus, to overcome the conversion efficiency problem, a challenging issue in designing of RF energy harvester is an appropriate selection of circuit components.



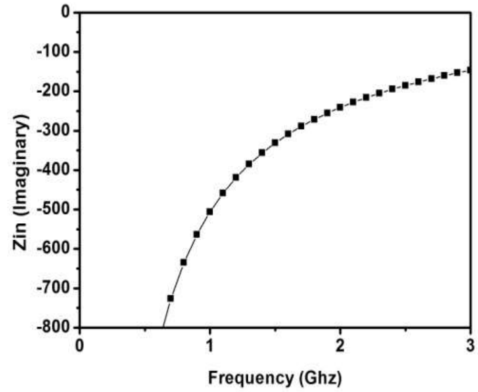




**Fig. 2:** Real and Imaginary values of input impedance of Schottky diode

The output DC voltage and conversion efficiency of RF energy harvester badly affected due to diode's nonlinear behavior and value of matching network's element. Hence efficient design of matching network is essential to get optimum performance. For L matching network consisting of series inductor and shunt capacitor, the element value may be determined by using design equations [13]:

$$B_L = \pm\sqrt{R_L(Z_o - R_L)} - X_L \quad (1)$$

$$B_C = \pm\frac{\sqrt{(Z_o - R_L)/R_L}}{Z_o} \quad (2)$$

Using above equations parameters of L-type matching network were calculated. Calculated values of inductor and capacitor of matching network are, $L_{match}$= 100 nH and $C_{match}$= 1 pF.

Following figure shows the harvester circuit with L-type matching network.

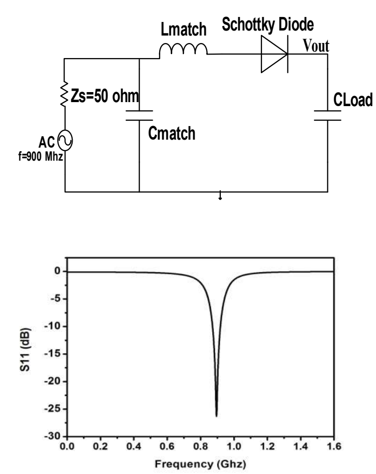



**Fig. 3:** Harvester circuit with L-matching network and its simulated S-parameter

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S-parameter result shows the lowest return loss at nearly 0.9GHz frequency which proved perfect matching condition.

Output voltage of circuit shown in fig. 3 with L-matching network is represented in figure 4. It shows 0.716 volt output voltage at -10 dBm and 0.294 volt at -20 dBm input signal level at 0.9GHz.

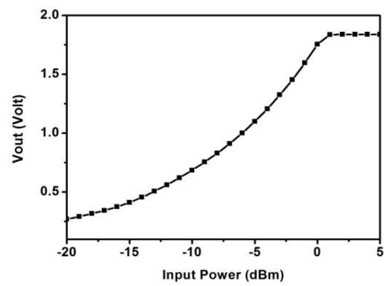


**Fig.4:** Output voltage with respect to the applied input power

It can be observed from fig. 2 that HSMS-2852 Schottky diode exhibit negative reactance for given input frequency which may be considered as series or parallel RC combination. So a resonating voltage boosting network may be designed by inserting inductor between antenna and rectifier. The required inductor value may be determined by considering the resonance frequency (i.e. $L=1/\omega^2C$) of the circuit. Where, C is the capacitance value corresponds to reactive impedance part of diode and ω be corresponds to frequency with which matching network has to be designed. Single inductor RF energy harvesting circuit is designed and simulated. Results show 0.825 volt DC output at -10 dBm and 0.302 volt at -20 dBm input power working with 0.9 GHz frequency.

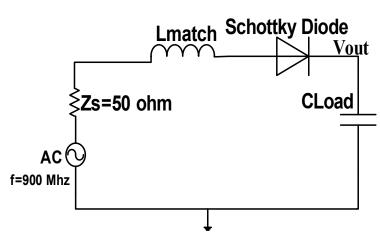


**Fig. 5:** Harvester circuit with single inductor matching network

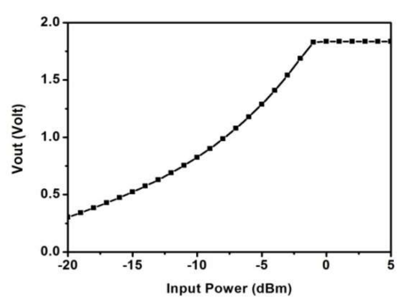


**Fig.6:** Output voltage with respect to the applied input power

It has been observed that the harvesting circuit with single inductor as matching network exhibits almost same but somewhat improved performance as compared to RF energy harvester circuit with L-matching network for 0.9GHz.

Now it has to be figure out whether the inclusion of shunt capacitor makes any difference in the input impedance of the rectifier circuit, for such case simulation of input impedance of harvester circuit with and without parallel capacitor was carried out.

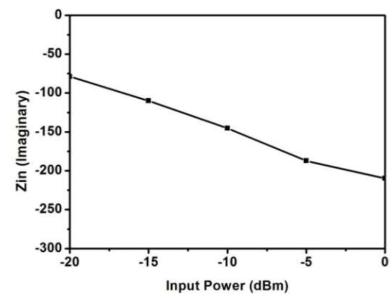


**Fig.7**: Input impedance without parallel capacitor

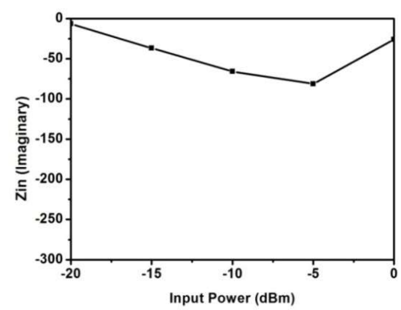


**Fig.8:** Input impedance with parallel capacitor

After observing the variation in the input impedance it has been found that if received power will vary by any of the weather conditions or signal unavailability, impedance definitely will be going to change and circuit becomes more mismatched at high input power. If reactive part of input impedance becomes zero or approximately zero, then circuit shows highly matched condition. The variation of input impedance with parallel capacitor represents this matched behavior. Hence to maintain the sensitivity of the system a parallel capacitor need to be introduced in the system for vulnerability of the harvester circuit. By analyzing the behavior of different types of matching network, it has been observed that selection of matching network strongly affects the harvesting circuit performance. In this section realization of the matching network through resonance behavior of circuit was done and found that matching network offers improved output voltage than the conventional one. To produce maximum output voltage for each power simultaneously, reactance part of the impedance should be minimized. To achieve improved output, a technique may be

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called reactance compensation technique comprises of parallel capacitor and series inductor becomes a perfect solution. It improves matching quality of RF energy harvesting circuit. This technique was implemented and the circuit is shown in fig. below which shows the combination of series inductor and parallel capacitor.

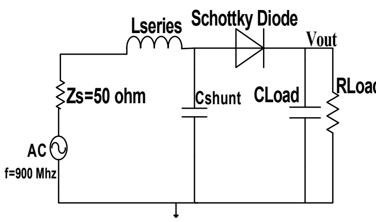


**Fig. 9:** Harvester circuit using parallel capacitor

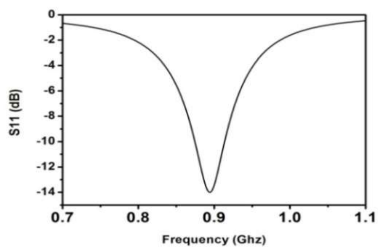


**Fig. 10**: S-parameter of Harvester circuit with parallel capacitor

## 4. RESULTS

Variation of output DC voltage with input power for different values of parallel capacitor is simulated.

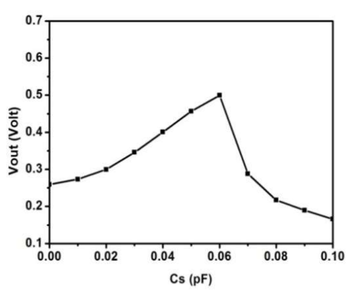


**Fig.11:** Output voltage with varying Parallel capacitor at input power of -20dBm

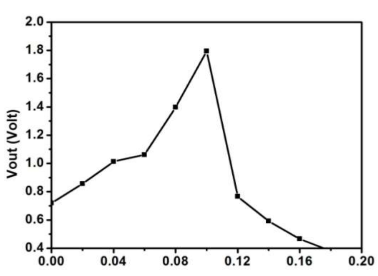


**Fig. 12:** Output voltage with varying Parallel capacitor at input power of -10dBm

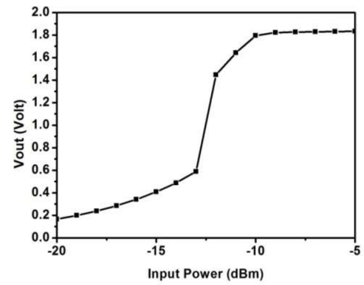


**Fig.13:** Simulated output voltage with Parallel capacitor of 0.1 pF along with varying input power

It has been achieved that circuit provides peak output with $C_{shunt}$ = 0.06 pF for -20 dBm input and with $C_{shunt}$ = 0.1 pF for -10 dBm input power. Proposed circuit produces 1.8 volt DC output for $P_{in}$ = -10 dBm at 100 kΩ load for 900 MHz frequency. As can be seen that by increasing the capacitor value circuit becomes more resonating and thus ensuring the maximum power transfer to rectifier circuit. Here the reason behind this improved performance with parallel capacitor is that the combination of inductor and capacitor act as a passive amplifier between antenna and rectifier.

After output voltage calculation following graphs represents the power conversion efficiency of the rectifier by varying the input power and output load. Maximum achieved power conversion efficiency (PCE) is 79% for -10 dBm and 84.78% for -5 dBm input power. Thus PCE increases with increasing input power.

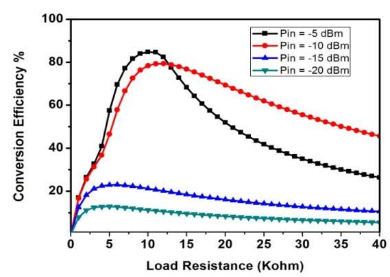


**Fig. 14:** Circuit Power Conversion efficiency with different input power for varying Load $R_L$

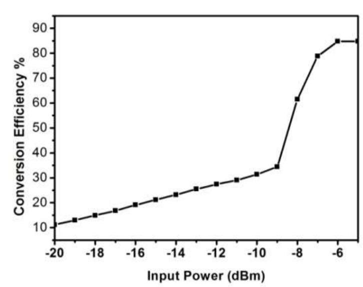


**Fig. 15:** Circuit Power Conversion efficiency with varying input power

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A resonant rectifier using parallel capacitor with SMD technique was fabricated on a 1.6mm thick glass epoxy substrate having dielectric constant of 4.6. The fabricated resonant rectifier is shown in fig. below.

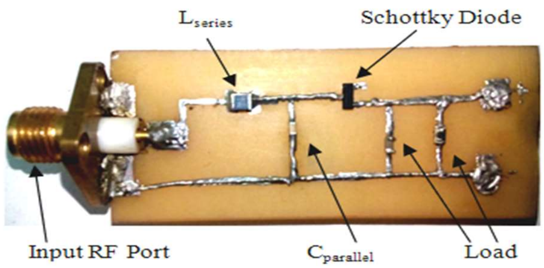


**Fig. 16:** Fabricated design of the proposed harvester circuit

In our experiments, a RIGOL DSG3000 RF signal generator was used which provide the desired RF power at the required frequency and power level.

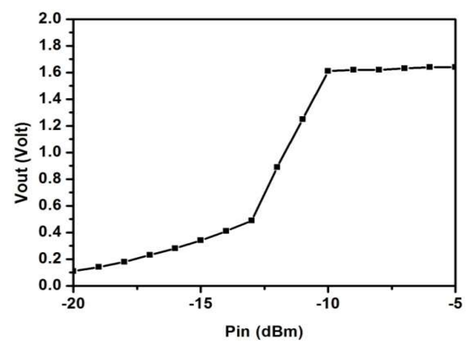


**Fig.17:** Measured output voltage with Parallel capacitor of 0.1 pF along with varying input power

**Table I:** Comparison of circuit performance

| Input Power | Frequency Used | Output Voltage | RF to DC Converter | Technology Used | Reference |
|---|---|---|---|---|---|
| 0 dBm | 900 MHz | 1.8 Volt | Voltage Doubler | HSMS-2852 | [1] |
| -10 dBm | Dual tone of 490 & 860 MHz | 0.8 Volt | Voltage Doubler | HSMS-2820 | [2] |
| -19 dBm | 900 MHz | 1.15 Volt | Five stage Voltage Doubler | 130 nm CMOS | [3] |
| -10 dBm | 945 MHz | 0.62 Volt | Half Wave Rectifier | HSMS-285C | [4] |
| -10 dBm | 915 MHz | 1 Volt | Seven stage Voltage multiplier | HSMS-2852 | [8] |
| -10 dBm | 900 MHz | 1.61 Volt | Half wave Rectifier | HSMS-2852 | This Work |

Measured DC output of fabricated RF energy harvester is presented in fig. 17. Circuit element is optimized for -10 dBm RF input power level. Hence there is rise in output near of -10 dBm $P_{in}$. Table-I depicts the performance comparison of proposed work with the recently published papers, whereas Table-II shows the comparison of the proposed simulated and fabricated harvester circuit results.

**Table II**: Performance Comparison

| Parameter | Simulated | Measured |
|---|---|---|
| Operating Frequency | 900 Mhz | 900 Mhz |
| Input Power | -10 dBm | -10 dBm |
| Output Voltage | 1.8 Volt | 1.61 Volt |
| Conversion Efficiency | 32.4 % | 26 % |

The proposed circuit with concept of parallel capacitor and series inductor not only optimizes the matching network but also offers improved output voltage without increasing the circuit complexity. It provides 1.61 volt DC output with 26% power conversion efficiency for -10 dBm input power at 900 MHz frequency. Fabrication process of the design depicts that it is simple to implement and applicable for each frequency and power level. It confirms that the proposed approach is more reliable in term of its output performance, circuit implementation and the fabrication cost.

## 5. CONCLUSION

In this paper the effect of matching network elements on output voltage is presented as well as the effect of load resistance is also presented. It has been observed that RF energy harvesting circuit possess higher efficiency and higher value of output voltage according to the value of input power and load resistance with optimum value of circuit parameters. The maximum output voltage was achieved 1.8Volts and maximum efficiency was achieved up to 84.78%.

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