RF Energy Harvesting Circuit Design Using Broadband Wilkinson Power Combiner for Low Power Electronics

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Abstract

RF energy harvesting is a new area of interest as a research topic during last decade. This paper presents the development of RF energy harvester circuits using a broadband Wilkinson power combiner technique. A modified broadband Wilkinson power combiner is introduced and studied. Authors have proposed a modified voltage multiplier circuit which is the combination of conventional voltage multiplier circuits like Greinacher and Villard voltage multipliers. Author has also proposed and studied a simple MOS based RF energy harvester circuit. The performance of a Schottky diode based RF energy harvester circuit and a MOS based RF energy harvesting circuit have been studied. Author also has carried out Monte Carlo simulation and the simulation results show very small deviation from its nominal output value. Author has developed a prototype of a single stage Greinacher voltage multiplier.

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Key Points: RF Energy Harvesting; Broadband Wilkinson Combiner; MOS Voltage Multiplier; RF Voltage Multiplier Circuits; Broadband Energy harvesting; Monte Carlo Analysis

Abstract

RF energy harvesting is a new area of interest as a research topic during last decade. This paper presents the development of RF energy harvester circuits using a broadband Wilkinson power combiner technique. A modified broadband Wilkinson power combiner is introduced and studied. Authors have proposed a modified voltage multiplier circuit which is the combination of conventional voltage multiplier circuits like Greinacher and Villard voltage multipliers. Author has also proposed and studied a simple MOS based RF energy harvester circuit. The performance of a Schottky diode based RF energy harvester circuit and a MOS based RF energy harvesting circuit have been studied. Author also has carried out Monte Carlo simulation and the simulation results show very small deviation from its nominal output value. Author has developed a prototype of a single stage Greinacher voltage multiplier.

Plain Language Summary

RF energy, vibration energy, solar energy are the common area of energy harvesting technologies. One of the applications of energy harvesting in electronics is the production of enough power which is the essential requirement to recharge the battery or directly supply to the electronics. RF energy harvesting from surrounding environments or dedicated energy sources, low-power wireless devices can be self-sustaining and environment-friendly. These features make RF energy harvesting technique attractive to a wide range of applications. To recharge the battery or power supply is a major problem for the devices at inaccessible. Also energy harvesting is required in the biomedical electronics devices. The unchangeable power delivered by the biomedical devices decreases the patient’s risk of death. An effective hardware design for RF energy harvesting system in the real environment is faced by some practical issues. The goal of this proposed work is to design a RF energy harvesting system for low power electronics applications.

1 Introduction

The Energy harvesting technology is a demanding area of research during this decade due to the problems of facing of energy shortage. Advancements in ultra-low power electronics devices (Shinde et al., 2009) also take a major crucial driving factor for this type of technology. Also energy harvesting technology is taking an important role in the application of biomedical electronics devices (Rajavi et al., 2016). Researchers and scientists have proposed different circuits and methodology for the developments of energy harvesting technology (Singh et al., 2019). Now, using different energy harvesting techniques, the received power is very minimal. The major challenge of this technology is to get sufficient power and the storage of this power, so that it can be applicable in low power devices (Alvarado et al., 2012) at least. This paper presents the focus in the area of RF energy harvesting (Devi et al., 2012), (Divakaran et al., 2018). This work first addresses the comparisons of different diode based multistage voltage multiplier circuits for RF energy harvesting application (Vyas et al., 2019) and then followed by a modified circuit proposed by authors. Later section represents energy harvesting circuit connected with a broadband Wilkinson power combiner (Wentzel et al., 2006) to combine received RF power. Last section represents a complete RF energy harvesting system including a MOS equivalent energy harvesting circuit (Jabbar et al., 2010), (Goncalves et al., 2013) followed by a broadband Wilkinson power combiner and an antenna (Kumar et al., 2015), (Ansarizadeh et al., 2008) as shown in figure 1.

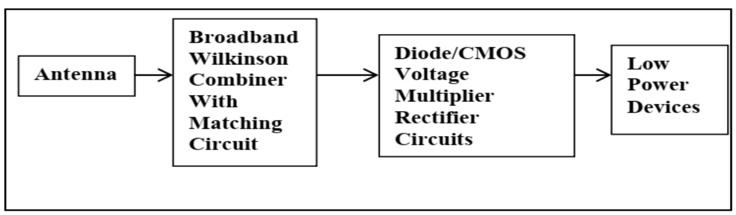


Figure 1. Block Diagram of proposed RF Energy Harvester

2. Components and Methods

Different components are required to design a complete RF energy harvesters and design method is discissed below.

2.1 Different Conventional Voltage mutipliers

In this section authors have discussed three popular voltage multiplier circuits for RF energy harvesting application. These voltage multiplier circuits are Villard voltage multiplier, Dickson voltage multiplier, Greinacher voltage multiplier.

2. 1.1 *Villard Voltage Multiplier*

Villard voltage multiplier is shown in figure 2 (Sari et al., 2019). This circuit consists two diodes and two capacitors for each stage. Operation of these diodes depends on the sign of RF input voltage. If V_{RF} is negative, D1 diode is operating D2 diode is off condition. Again for positive

V_{RF}, D2 is on condition and D1 is off condition. The output voltage for n stage Villard multiplier can be calculated as

$$V_{DC} = \frac{nV_O}{nR_O + R_L} \quad (1)$$

Here, Vo, Ro, R_L are the open circuit voltage, internal resistance of the single stage and load resistance respectively.

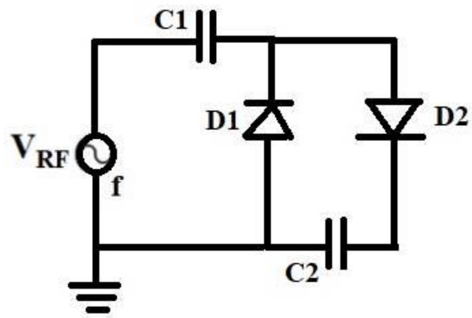


Figure 2. Single Stage Villard Voltage Multiplier circuit

2. 1.2 Dickson Voltage Multiplier

Dickson voltage multiplier is shown in figure 3 (Sari et al., 2019). The circuit consists capacitors in parallel configuration in each stage. This configuration reduces the impedance of circuit and makes better matching. The output voltage of n stage Dickson multiplier is given as (Sari et al., 2019).

$$V_{DC} = n.V_m \quad (2)$$

Where, n, V_m, are the number of stages, peak amplitude of input voltage respectively.

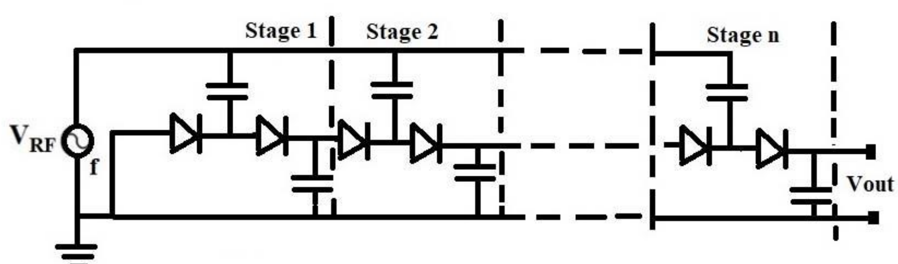


Figure 3. Dickson Voltage Multiplier Circuit

2. 1.3 Greinacher voltage multiplier

Greinacher voltage multiplier is given in figure 4. The circuit consists 4 diodes and 4 capacitors respectively as shown in figure 4. It is also called double voltage rectifier (Samakkhee et al., 2017). The output voltage of Greinacher voltage multiplier is given as

$$V_{DC} = 2nV_m \tag{3}$$

Here, n is the number of stage of Greinacher voltage multiplier and V_m is the peak RF input voltage.

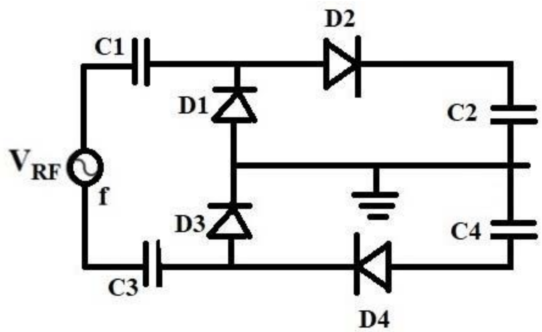


Figure 4. Greinacher voltage multiplier circuit

2. 2 Broadband Wilkinson Power combiner circuit

In this work authors have proposed a multistage broadband Wilkinson power combiner circuit (Wentzel et al., 2006), (Salimi, 2017) to connect with energy harvesting circuit. This broadband Wilkinson power combiner is capable to receive RF power from a wide range of signal frequency. In this work authors have proposed a modified broadband Wilkinson Power combiner circuit which is capable to receive power in the frequency range of 100 MHz-2.45 GHz. Here, a two way (N=2) broadband Wilkinson power combiner is designed. Here, Wilkinson power combiner is not considered for N>2 value. In the design of N=3 way (N>2) Wilkinson power combiner circuit, more crossover is required, therefore difficulties will arise during fabrication in planar form (Pozar, 2007). The transmission lines are designed with λ/4 length. In this design a variable capacitor should be placed at the output for proper impedance matching. An improved design of two stage broadband Wilkinson power combiner is considered here for this energy harvesting application as shown in figure 5 and a PS-Spice model of broadband Wilkinson power combiner, connected with a voltage multiplier circuit is shown in figure 6 (Wentzel et al., 2006).

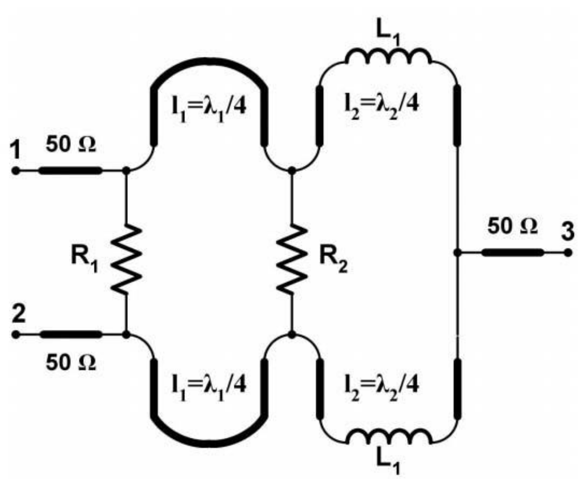


Figure 5. Broadband Wilkinson Power Combiner proposed by Wentzel et. al.

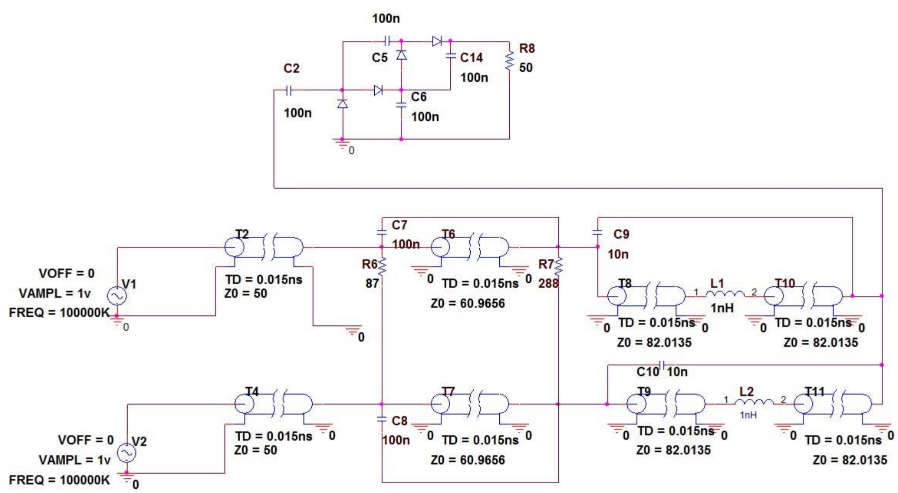


Figure 6. A Wilkinson power combiner connected broadband RF energy harvesting circuit

2.3 Antenna and Impedance matching:

Multiband antennas are required here to capture RF signals properly. Different small size antennas (Makhdoomi, 2018) such as patch, printed, spiral antennas can be used for this purpose but also other high gain, quad band antennas are available in market. The 50 **Ω** feeding line impedance is very popular and widely used for antenna. A proper impedance matching is one of the crucial part to deliver maximum power to a load. The performance of impedance matching network can be significantly improved using the inductor along with capacitor at integrated circuit level design but it is difficult to construct low value inductor at the higher frequencies. However, a tunable capacitor can be used to achieve proper impedance matching in antenna matching circuit and is possible to tune the antenna at its resonant frequency. The frequency of operation can be obtained using following formula given in equation 4.

$$f = \frac{1}{2\pi\sqrt{L_{antenna}.C_{tune}}} \qquad (4)$$

Where, (C_{tune}), ($L_{antenna}$), f are tuning capacitance, inductance of antenna and the frequency of operation respectively. But it also should be taken in consideration that the diode capacitances at reverse bias also have contribution to resonant frequency of matching network and the diode capacitance depends on the reverse voltage and received input RF voltage. Multiple antennas are used independently to capture RF energy. A proper impedance matched transmission line is used to design power combiner circuits and this circuit is engaged to combine the total power captured by independent antenna. This circuit is suitable for broadband application. In this design an quarter wave matching RG-174 or RG-58 transmission line having a propagation velocity 66% of light is considered. However this is an effective technique for RF power combining. Most popular frequency allocations for Wireless Power Transfer (WPT) are 900 MHz and 2.4 GHz ISM (Alneyadi et al., 2014) , (Thierry et al., 2014) bands but also comparatively low frequency radio, TV signals can take crucial role as energy sources, since the attenuation of the RF waves is inversely proportional to the frequency.

3 Simulated and Experimental Results

A simple experimental and simulated work has been carried out by author. The experimental set up is arranged to capture RF signal from Kolkata FM broadcasting station which is 10 Km away from the place of experimental arrangement as shown in figure 7. RF power is received at different frequency using a single dipole antenna. A level meter is used to measure RF power captured by dipole antenna. This level meter has the capability to measure RF power upto 800 MHz frequency. RF power captured by receiving dipole antenna is in table 1.

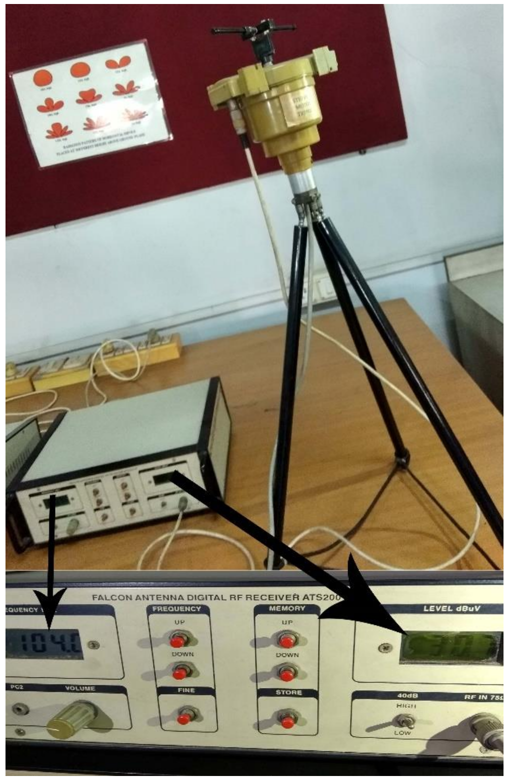


Figure 7. Experimental arrangement for capturing RF signal from Kolkata FM

Table 1. Experimental Input Voltage captured from RF energy sources in FM range

SL. NO.	Frequency (MHz)	Input Voltage (dBμV)
1	94	18.8
2	98	28.1
3	104	30.7
4	106	19.6

3. 1. *Performance of Single stage multiplier and prototype of Greinacher Voltage Multiplier circuit*

The output voltage has been carried out from the single stage of different voltage multiplier circuits as shown in figure 8. Results show that higher output voltage is generated by Greinacher voltage multiplier comparing other voltage multiplier circuits. A prototype of a single stage Greinacher voltage multiplier is made by authors as shown in figure 9. An experimental study is also conducted to carry out the output voltage of a single stage Greinacher voltage multiplier as shown in figure 10. In this experimental work, two 1N4148- varactor diodes, two 224J, 220kpf and two Keltron 100μf valued capacitors and a simple wire antenna are used to function the prototype as shown in figure 8.

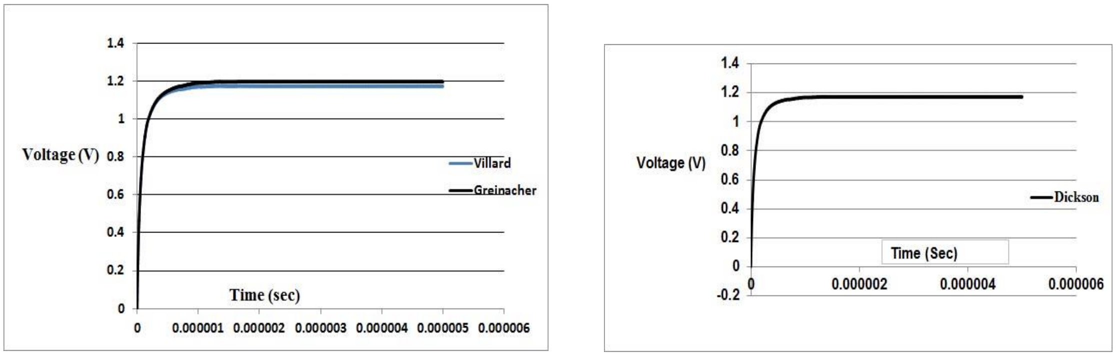


Figure 8. Comparisons of output voltage for different Voltage multiplier circuits

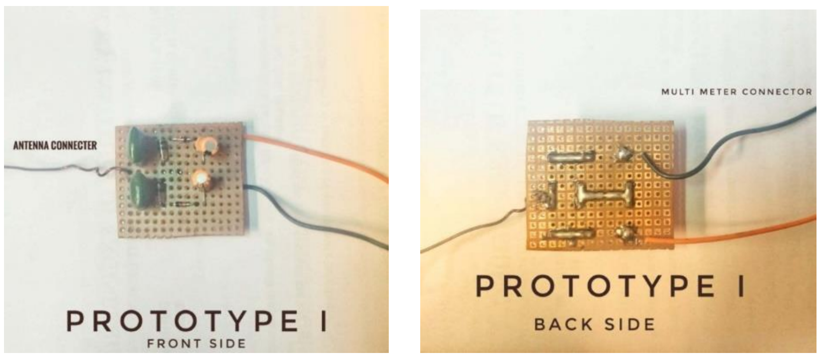


Figure 9. Prototype of a single stage Greinacher voltage multiplier circuit

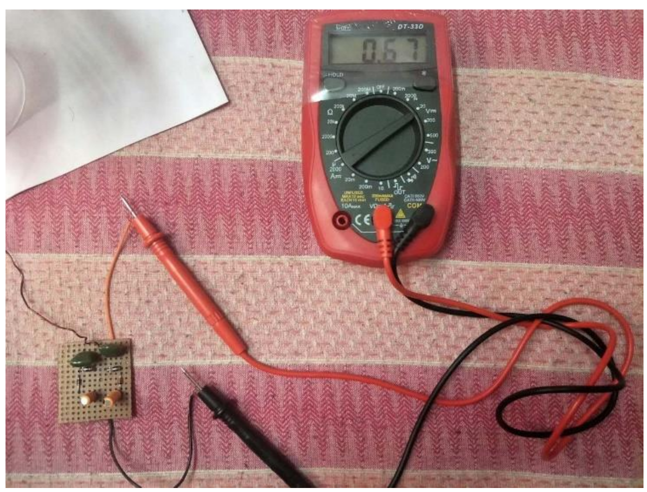


Figure 10. Experimental output voltage of a single stage Greinacher voltage multiplier circuit

Now, It is complex to design Greinacher voltage multiplier circuit for multistage. Authors have proposed a simple circuit which is a combination of Greinacher and Villard Voltage multiplier circuit. Here, first stage of the proposed circuit is Greinacher voltage multiplier circuit and next stages are followed by Villard voltage multiplier circuits (Greinacher- Villard Voltage multiplier) as shown in figure 11. The simulation work has been carried out using Cadence ORCAD 10.5 PSPICE simulator.

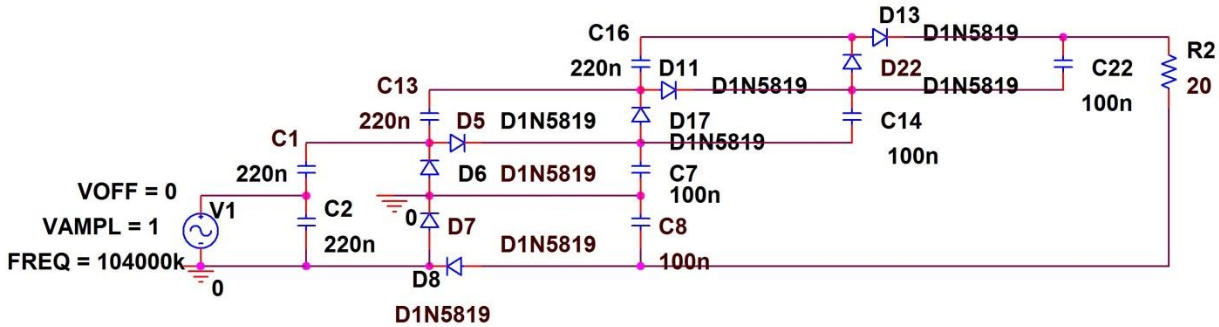


Figure 11. Multistage Greinacher- Villard Voltage multiplier circuit proposed by authors

Now, the output voltage for multistage voltage multipliers are also obtained. The output voltages are obtained for multistage Villard voltage multiplier, Dickson voltage multiplier and the voltage multiplier circuit proposed by authors as shown in figure 12. The results show that the circuit proposed by authors, provides higher output level comparing with other conventional voltage multiplier circuits for energy harvesting application.

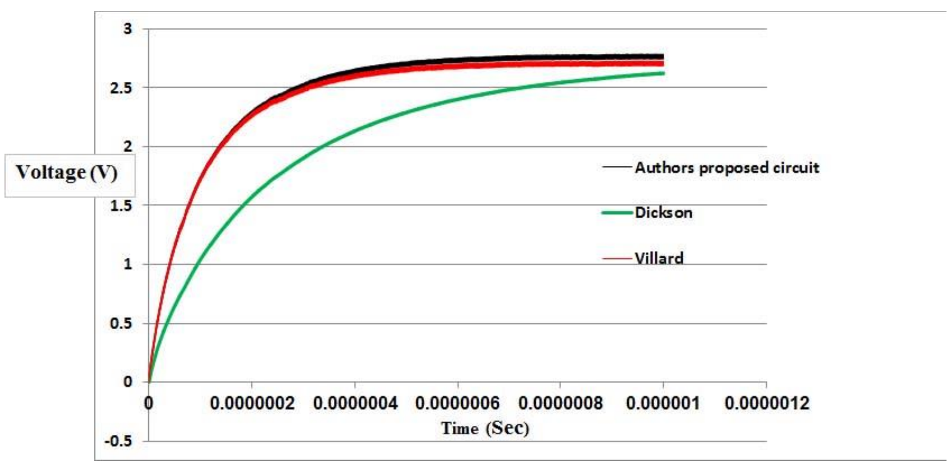


Figure 12. Comparisons of output voltages of different Voltage multiplier circuit

The output voltages at different stages are shown in the figure 13 for the multistage circuit proposed by authors for 1 V input voltage at 2.45 GHz RF signal frequency.

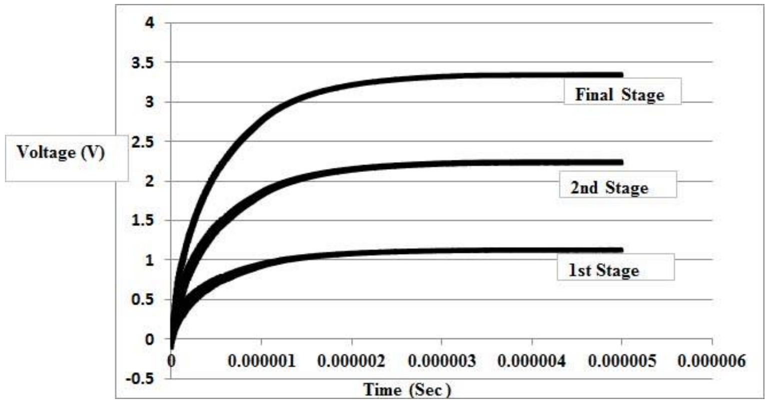


Figure 13. Output voltages of multistage Greinacher- Villard multiplier (Author's proposed)

A Monte Carlo simulation has been carried out for final stage output voltage of 3 stage Greinacher- Villard Voltage multiplier circuit at 1 V input voltage for 20 samples for 10% tolerance values of circuit components as shown in figure 14. Result shows that output voltage varies in the range 3.32V to 3.40V. A worst case of Monte Carlo simulation also has carried out for output power generation across a 20 Ohm load resistor at output. Results show good proximity with nominal or actual value as shown in figure 14. It is observed from the result that worst case simulation value is 95.602% of nominal or actual value.

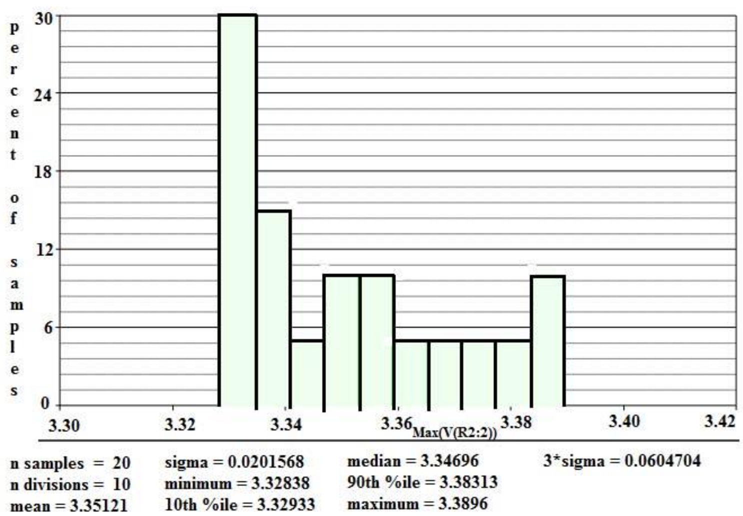


Figure 14. Monte Carlo Simulation of final stage output voltage of Greinacher- Villard multiplier)

Authors have proposed to insert a broadband Wilkinson power combiner circuit between antenna and voltage multiplier circuit to improve the performance of energy harvesting circuit as shown in figure 16. A Schottky diode based energy harvesting circuit is shown in the figure 15. Authors have used a modified two stage broadband Wilkinson power combiner circuit. This circuit provides highest possible bandwidth and lowest insertion loss at the same time (Wentzel et al., 2006). Bandwidth can be improved using two stage power combiner comparing with a single stage power combiner circuit. In this proposed circuit additional inductors and capacitors are inserted as shown in figure. These additional inductors in the in the second stage of the circuit provide a shorter physical length of the transmission lines and improve the insertion loss and matching performance at higher frequencies. Additional capacitors are also used in both stages of the circuit that provide low transmission loss and low ripple over the entire bandwidth. This is an improved two stage broadband Wilkinson power combiner design comparing with the classic two stage power combiner. In this proposed design same dividing ratio (k=1:1) (Devi et al., 2012) is considered for simplicity. Authors have used the calculated parameters value for two stage power combiner design by (Salimi, 2017). Authors have optimized the resistance value for T8 and T9 section. Capacitance and Inductance values are also optimized by authors for the application of this proposed energy harvesting circuit.

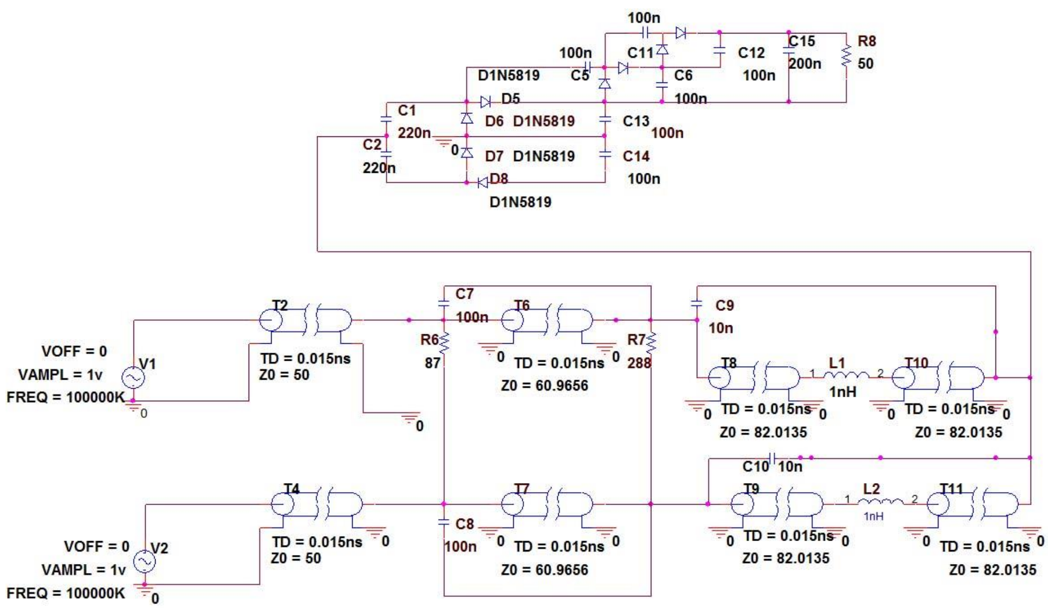


Figure 15. Broadband Wilkinson power combiner connected Greinacher-Villard multiplier circuit

Now, the output voltage of the prosed broadband Wilkinson power combiner connected multiplier circuit also has been carried out at three different frequency 104 MHz (FM), 1800 MHz (GSM) and 2.45 GHz (Wi-Fi) as shown in figure 16. It is observed that output voltage level of this circuit is decreasing with increasing frequency.

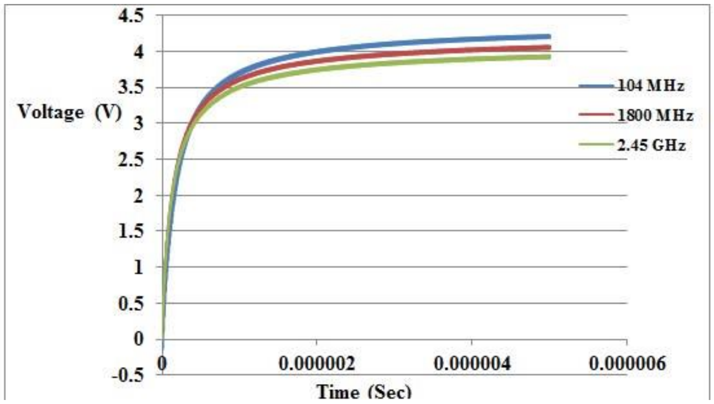


Figure 16. Variation of output voltage of Greinacher- Villard multiplier at different frequency

Output voltages at different stages for a Wilkinson power combiner connected Greinacher-Villard multiplier have been carried out as shown in figure 17.

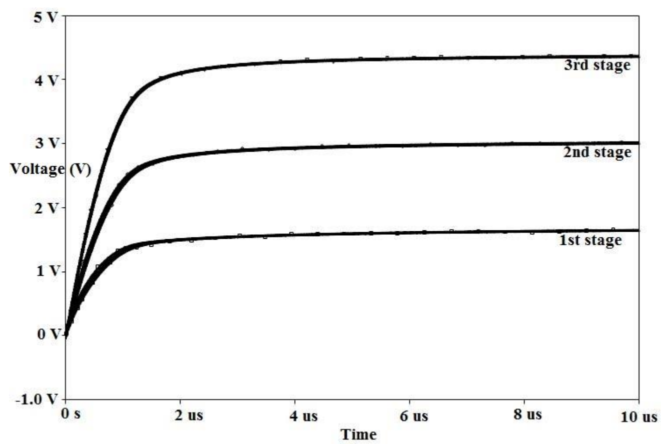


Figure 17. Variation of output voltage of Greinacher- Villard multiplier at different Stages

A worst case of Monte Carlo simulation also has carried out for output power generation across a 50 ohm load resistor at output. Results show good proximity with nominal or actual value as shown in figure 18.

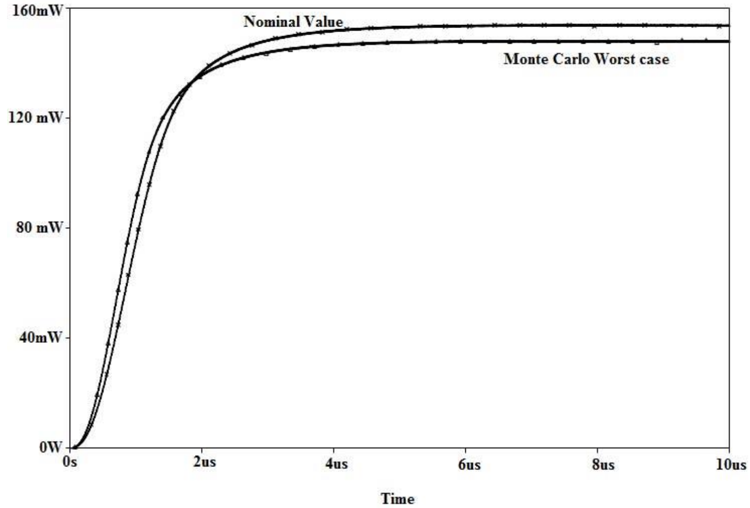


Figure 18. Worst case analysis of output power generation of Greinacher-Villard multiplier

3.2 MOS Transistor based voltage multiplier circuit design and simulated results

A transistor based is required for practical implementation of RF energy harvesting circuit but The Schottky diode can’t be implemented in normal CMOS process (Goncalves et al., 2013). Authors have proposed a MOS based design of Greinacher-Villard voltage multiplier (author’s proposed circuit) as shown in figure 19.

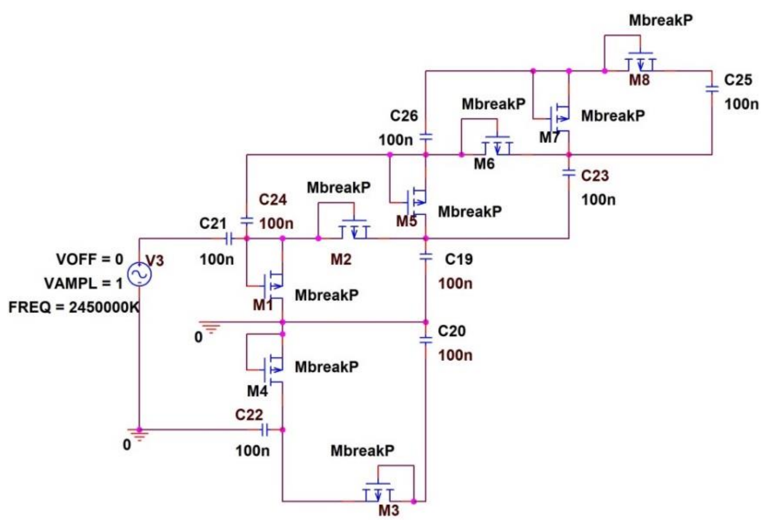


Figure 19. Author’s proposed MOS-based Greinacher-Villard multiplier circuit

The output voltage at different stages of author’s proposed circuit has been carried out as shown in figure 20 for 1 V input voltage and 2.4 mW output power is obtained after 30us as shown in figure 21.

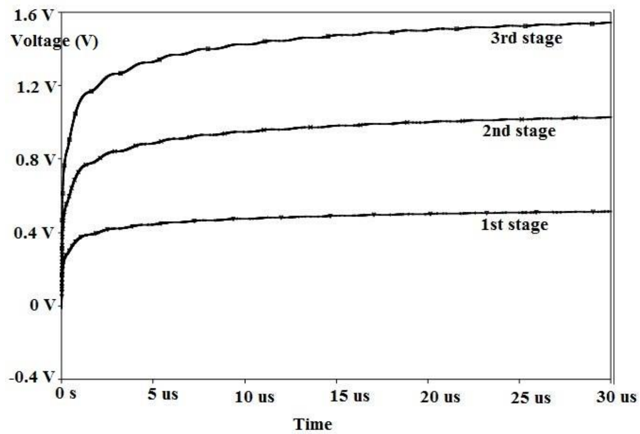


Figure 20. Output voltage of MOS-based Greinacher- Villard multiplier circuit

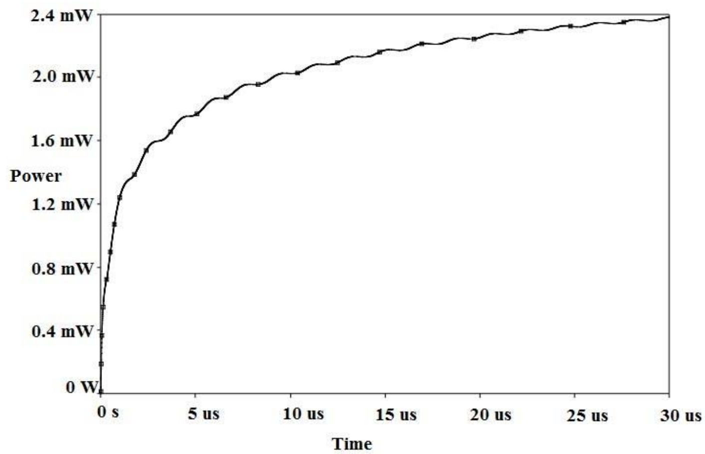
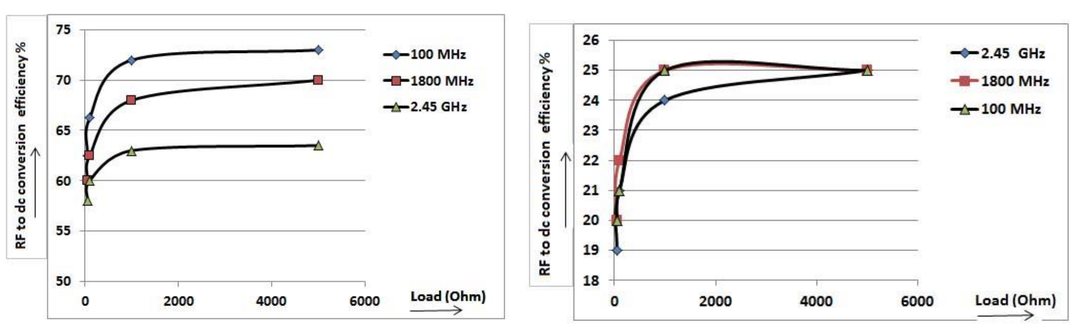


Figure 21. Output power of MOS-based Greinacher- Villard multiplier circuit



(a) (b)

Figure 22. RF to dc conversion efficiecy (a) Doide-based circuit (b) MOS-based circuit

RF to dc conversion efficiency of diode-based and MOS-based circuits has been carried out for three different frequency 2.45 GHz (Wi-Fi), 1800 MHz (GSM) and 100 MHz (FM) by simulation for different load variation as shown in figure 22. It is observed that diode-based circuit shows higher conversion efficiency comparing MOS-based circuit. The large voltage drops between drain-source causes the reduction of conversion efficiency for MOS-based circuit. Authors have compared their data with previous published results in available literature as given in table 2. It is observed that the range of operating frequency increases for author's proposed circuit comparing other energy harvesting circuits. Output voltage is also better for author's proposed circuit comparing other energy harvesting circuits.

Table 2. Comparisons of the performance of different RF energy harvesting circuit

RF energy harvesting circuit	Operating Frequency	Output voltage
Author's proposed diodes based circuits	100 MHz-2.45 GHz	3.95 V
Wilkinson Power Combiner Circuit (Kasar et al.,2018)	540 MHz- 2.7 GHz	1.65 V
Greinacher rectifier using rat-race coupler (Gozel et al., 2018)	125 MHz bandwidth	3.65 V
Ultra-low power Schottky diodes based (Partal et al., 2018)	2.4 GHz	3.39 V

4. Conclusions

The paper presents different diodes and MOS based broadband RF energy harvesting circuits for the future applications. Schottky diodes are suitable for RF energy harvesting application due to it's very low threshold voltage. A simple modified voltage multiplier circuit which is proposed by author, shows better performance comparing with other conventional voltage multiplier circuits for RF energy harvesting application. The proposed circuit includes an antenna followed by a broadband Wilkinson power combiner and a voltage multiplier circuit. This is a new technique which is very suitable for the broadband application of RF energy harvesting. A new simple MOS based circuit also proposed by author shows better performance. The experimental result shows 0.66 V output voltage for a single stage Greinacher voltage multiplier circuit. The maximum efficiency is obtained 73% and 25% for diode based and MOS based circuits, respectively. Worst case Monte Carlo analysis also shows that worst case value of output voltage has very small deviation with the nominal value for the proposed circuit. The results are encouraging to implement these energy harvesting circuits as emerging techniques for broadband operation of RF energy harvesting circuits for the applications of low power electronics, IOT devices and biomedical applications.

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