A COMPARATIVE STUDY:
VOLTAGE MULTIPLIERS FOR RF ENERGY HARVESTING SYSTEM

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ABSTRACT. Voltage multipliers are widely used for energy harvesting processes to convert the received AC signal to DC signal, also enhanced the low level received signal. In this study, Villard, Dickson and Greinacher type voltage multipliers are analyzed without impedance matching and substrate materials to decide the effective voltage multiplier type depending on the inputs of the harvester. So, load resistance, input power and input frequencies' effects are analyzed and compared with each other. Agilent Advanced Design System (ADS) is used for simulations. HSMS 2852 Schottky diode and capacitors are used for these voltage multipliers. Results show that, determining load resistance is important for evaluating high efficiency, e.g. efficiency differences are reached 33% between 2kΩ and 20 kΩ for Dickson voltage multiplier at 100 MHz input frequency. Furthermore, the best efficiency is obtained by Greinacher voltage multiplier for low input frequencies which is lower than 1 GHz but there are no significant differences are observed for high frequencies. This study shows that load resistance, input frequency and input power are important parameters for voltage multiplier selection and Greinacher voltage multiplier is the best choice to obtain high efficiency for low frequency application of RF harvesting.

1. INTRODUCTION

There has been a significant increase in the number of low power consuming devices with the development of technology. These devices are widely used especially for measurement, data recording, transfer, and so on, and they are generally supplied with chemical batteries. Energy harvesting from sources such as solar, thermal, microwave or Radio Frequency (RF) gives an opportunity to supply energy for low power devices instead of using short-lived and replacement required batteries. RF energy harvesting is one of the most promising type of energy harvesting because

RF signal is easily and continually accessible. RF frequency bands covers frequencies from 10 kHz to 30 GHz which vary from very-low frequency (VLF) to super-high frequency (SHF) [1], [2]. Cellular base stations, RFID, Wi-Fi access points, television and radio broadcast stations can be used as a source for RF energy harvesting system. The amount of power which can be obtained from RF sources is very low. Therefore, it is very important that the obtained power must be converted to usable with the least loss. Some auxiliary circuits are used for this process.

RF energy harvesting system is shown in Figure 1 which consists of antenna, matching circuit, voltage multiplier circuit for AC to DC conversion and DC load circuit. Antenna is used for capturing RF signal from ambient air and designed for the frequency to be used. Single-band and multi-band antennas and their efficiencies were investigated in [3]–[7]. Matched circuit is used for compensating the impedance of antenna and the load, thus maximum power can be transferred [8], [9]. Voltage multiplier circuit, consisting of diodes and capacitors, is the indispensable part of energy harvesting because at this stage captured signal is enhanced and converted to DC voltage with minimum losses [10]–[19]. Actually, Voltage Multiplier (VM) devices are diode rectifier circuit, convert AC to DC, which can produce an output voltage greater than of the input voltage.
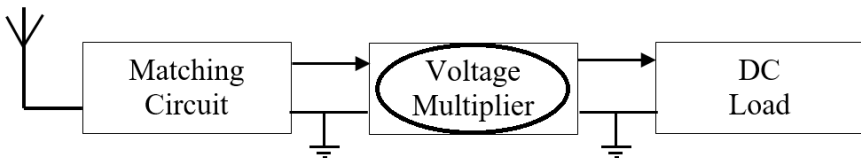
Figure 1. Basic RF energy harvesting structure

Different type and n-stage voltage multiplier circuits were investigated in literature. Villard voltage doubler were used for three band (2.1 GHz, 2.4 – 2.8 GHz, 3.3 – 3.8 GHz) in [7], results showed that maximum efficiency was obtained at the lower frequency band. Seven stage Villard voltage multiplier circuit was analyzed for 900 MHz in [20] and voltage level of 5.0 V was achieved in the measurement. Different stage Villard and Dickson voltage multiplier circuits were compared in [10] for frequency at 915 MHz and input power ranges between -20 dBm up to 20 dBm and approximately 100% improvement over other existing designs in the power range of 20 to 7 dBm was achieved. In [8], six stage Cockcroft –Walton (CWVM) voltage multiplier was used for 88 – 108 MHz frequency range to analyze load resistance and capacitance effect. In [21] Dickson and Villard type voltage multipliers were

compared depending on their efficiency for 868 MHz, results were showed that Dickson gave high efficiency and increasing number of stage provided high output power.

This paper is only focused on voltage multiplier circuits for RF energy harvester system, effect of impedance matching and substrates are ignored. The main goal of this paper is to understand the behavior of 2 stage Villard, Dickson and Greinacher voltage multiplier characteristics for different RF input frequencies, input powers and load resistances. The voltage multipliers are compared with each other and advantage and disadvantages are observed. Agilent Advanced Design System (ADS) program is used for these simulations.

2. VOLTAGE MULTIPLIER CIRCUITS

Voltage multiplier circuits are used to convert the randomly changing RF signal to DC signal and enhance it according to the number of n- stage to transfer it to the load. Received power of RF signal is described by Friis transmission equation in (1)

$$P_R = P_T G_T G_R (\frac{c}{4\pi rf})^2 \tag{1}$$

where P_R is the received power in dBm, P_T is the transmitted power in dBm, G_T is the transmit antenna gain, G_R is the receive antenna gain, c is the speed of light, f is the operating frequency, and r is the distance between the transmitter and the receiver antenna. In [7], despite different operating frequencies and transmit powers, almost same received power was obtained at the same distance for three systems. In [2], maximum RF power generated from signal generator is 20 dBm and obtained received power was very low level such as -20 dBm which generates 31.62 mV signal level for typical 50 Ω antenna. So in this study, received power, P_R, is considered fix value and assumed to change between the ranges of -20 to +20 dBm.

Received power produces an DC power at the output of the voltage multiplier. The ratio of the incident power of the RF signal to the DC power at the output of the voltage multiplier is defined as power efficiency which is given in (2)

$$\eta = \frac{P_{out}}{P_R} \tag{2}$$

η is the efficiency, P_{out} is the output power of the circuit and P_R is the received RF power defined in (1).

Especially for low received power level, enhancing stage is necessary to obtain enough power for low power consuming devices so voltage multiplier usage is required for RF energy harvesting. Voltage multipliers, consist of diodes and capacitors, are investigated because of simplicity of application and small size. At the voltage multiplier, diodes act as switches and low forward voltage is required to operate so HSMS- 2852 Schottky diodes are used in this work also these diodes have advantages of low junction capacitance and fast switching speed.

2. 1. Villard Voltage Multiplier

Villard voltage multiplier, sometimes referred to as Cockcroft-Walton voltage multipliers [10], [18], [22], is shown for single and n-stage in Figure 2(a) and (b) respectively[14].
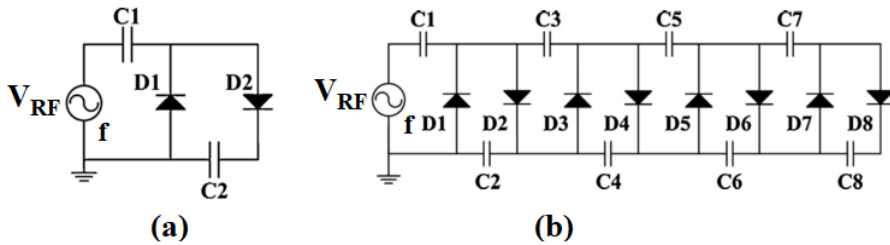
**Figure 2**. Basic circuit of Villard Voltage Multiplier

As shown in Figure 2 (a), the circuit consist of two diodes and two capacitors for each stage. The working principle is depending on the sign of the input voltage, thus emulating diodes behavior: specifically, considering if V_{RF} is negative, D1 is operating and D2 is not functional, while if V_{RF} is positive the two diodes will reverse their configuration [14]. The output of the n-stage VM is given in (3)

$$V_{DC} = \frac{nV_0}{nR_0 + R_L} \tag{3}$$

In (3) V_0 is open circuit output voltage of a single stage and R_0 is internal resistance of the single stage and R_L is load resistance.

2.2. Dickson Voltage Multiplier

Dickson VM is given in Figure 3, the parallel configuration of capacitors in each stage reduces the circuit impedance, and hence makes the matching task simpler [4], [10], [15] when compared with the Villard VM.
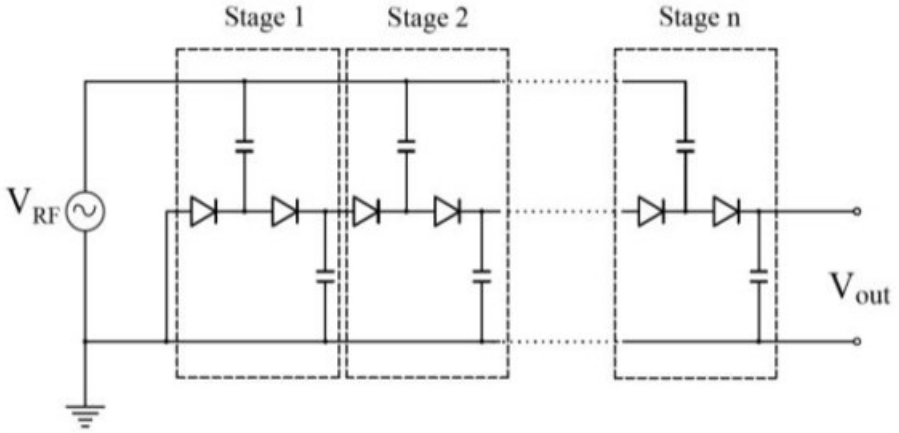
Figure 3. Basic n-stage circuit of Dickson Voltage Multiplier

Output voltage of n stage Dickson voltage multiplier is given in (4) [25].

$$V_{DC} = n(V_m - V_T) \qquad (4)$$

where n is the number of stages, V_m is the peak amplitude of the input voltage and VT is the forward conduction voltage of the diodes.

2.3. Greinacher Voltage Multiplier

Greinacher VM circuit is shown in Figure 4. C1 and D1 shift the input voltage up at node B to be rectified by D2, C3 and D3 shift the voltage down at node C to be rectified by D4 and C4. After reaching balance, the circuit provides a constant output current and voltage to the load [23], [24]. Output voltage of Greinacher voltage multiplier is given in (5) [26]

$$V_{DC} = 2nV_m \qquad (5)$$

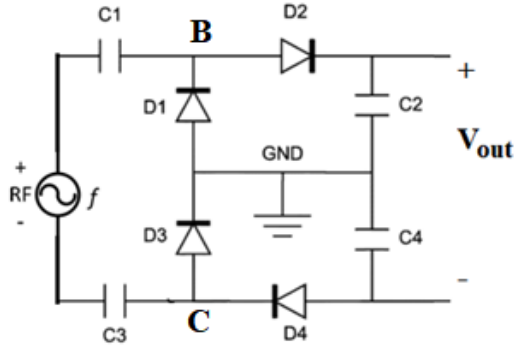where n is the number of stages and V_m is the peak amplitude of the input voltage.

Figure 4. Basic circuit of Greinacher Voltage Multiplier

3. SIMULATION RESULTS

ADS software which is an important software for RF applications is used for Villard, Dickson and Greinacher VM circuits' simulations, ADS application of Villard VM is given in Figure 5. First stage, parameters of voltage multipliers are determined, HSMS 2852 Schottky diodes and 90 pF capacitors are selected for simulations and then load resistor, input frequency and input power effects are analyzed. Smith Chart diagram of the VM multiplier circuits are given in Figure 6.
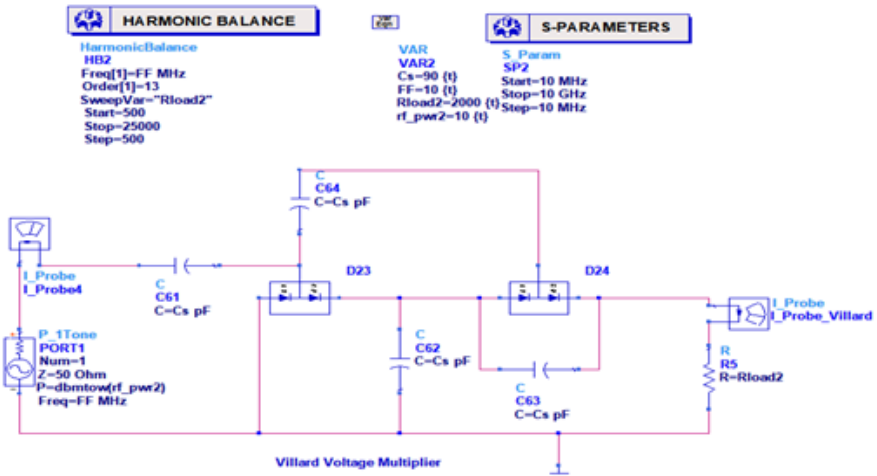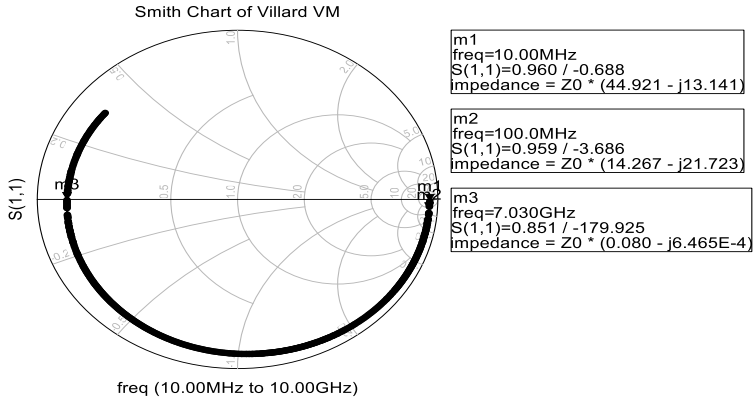

Figure 5. Villard VM circuits from ADS software

Smith Chart of Villard VM

m1
freq=10.00MHz
S(1,1)=0.960 / -0.688
impedance = Z0 * (44.921 - j13.141)

m2
freq=100.0MHz
S(1,1)=0.959 / -3.686
impedance = Z0 * (14.267 - j21.723)

m3
freq=7.030GHz
S(1,1)=0.851 / -179.925
impedance = Z0 * (0.080 - j6.465E-4)

freq (10.00MHz to 10.00GHz)

**Figure 6**. Smith Chart diagram for Villard VM circuit

Impedance of VM circuit changes depend on the input frequency, Figure 6, and that means these circuits are required impedance matching to increase the efficiency. But in this study, voltage multiplier circuits are analyzed depending on their output voltage, effect of input power and input frequencies without impedance matching. Figure 7 acquires output voltage levels for 10 dBm input power at 10 MHz and 100 MHz input frequencies.

(a)   (b)
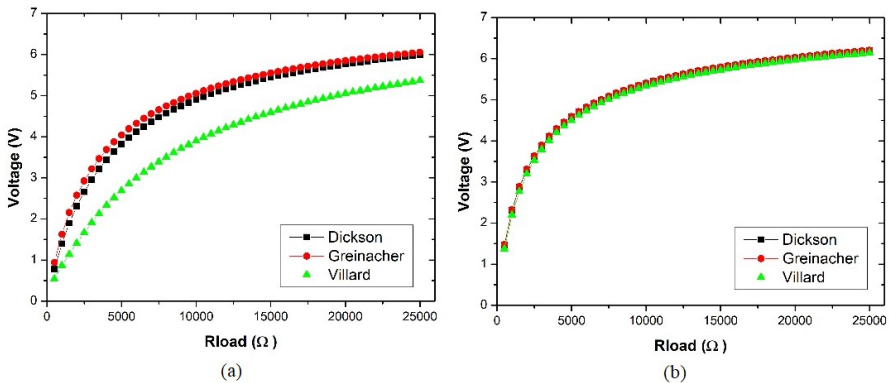
Figure 7. Output voltages versus load resistances for 10 dBm input power (a)10 MHz (b)100 MHz

Greinacher and Dickson voltage multipliers output voltages are close to each other for different input power levels at 10 MHz input power, depicted in Figure 7(a) and higher than Villard type. With the increase of frequency, in this case 100 MHz, all

voltage multipliers achieve the same output voltages, as shown in Figure 7 (b). High voltage levels can be obtained by high input power but input frequencies don't effect the output voltage levels. The voltage level is not enough parameter to compare voltage multipliers with each other so effect of the load resistance to efficiency is examined for 10 dBm input power and input frequencies of 10 MHz and 100 MHz in Figure 8.
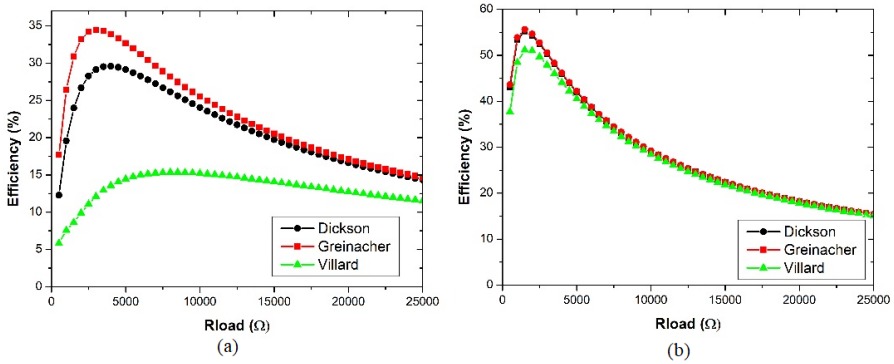

Figure 8. Efficiency vs load resistance (a) 10 MHz input frequency (b) 100 MHz input frequency

Figure 8 shows that Greinacher type voltage multiplier gives the best efficiency among Villard and Dickson types, efficiency differences are very small for 100 MHz. Also the load resistance is an important parameter for the system efficiency because the highest efficiency is obtained at 3 kΩ for 10 MHz and 2 kΩ for 100 MHz for all types of voltage multipliers. For instance, the efficiency of Greinacher voltage multiplier is 56% for 3 kΩ load resistance, but its efficiency decreases 20% for 20 kΩ load resistance. According to Figure 8, we can say that the selection of voltage multiplier is very important for low frequencies such as 10 MHz, however any voltage multiplier can be selected for high frequencies such as 100 MHz.

Input frequency is another important parameter which can help to determine the voltage multiplier for RF energy harvesting applications. So, after analyzing load resistance effect on the system efficiency for 10 dBm, input frequency effect is compared for fixed 10 dBm input power and 2 kΩ load resistance in the Figure 9.
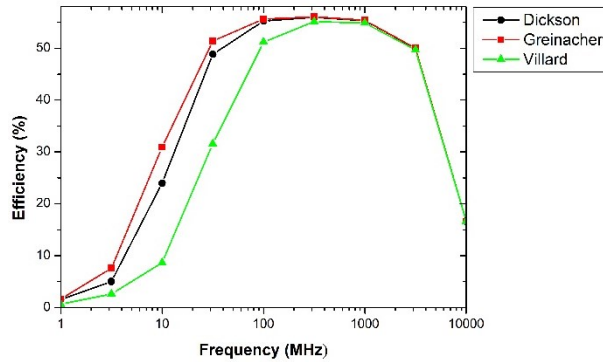
Figure 9. Input frequency effect to the efficiency

As can be seen from Figure 9, significant efficiency differences are observed up to 1 GHz. Such as Greinacher has the best and Villard has the worst efficiencies. But input frequencies higher than 1 GHz all multipliers have same efficiency furthermore, efficiencies of voltage multipliers start to diminish because of the selected diodes. If we will work above this frequency, we must change the diodes. Input power effect is also investigated. Power values of VM's for different input power is given in Figure 10, input power and load resistance are taken fix values 10 MHz and 2 kΩ respectively.
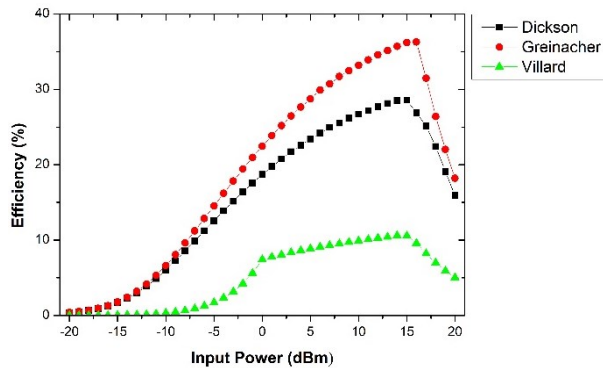
Figure 10. Efficiency vs Input power for 10 MHz input

Among the all voltage multipliers, Villard gives the worst efficiency for all input power levels. Choosing Greinacher voltage multiplier provides higher efficiencies no matter the received signal level.

6. Conclusions

The Greinacher, Villard and Dickson voltage multipliers were compared for RF energy harvester circuits. Among them Greinacher voltage multiplier have the highest efficiency for all input parameters such as input power, input frequency and load resistance. Because the output voltage is obtained from two capacitors and a diode in Villard and Dickson voltage multipliers, however, it is obtained only two capacitors in Greinacher voltage multiplier. There is no extra voltage drop on the diode for output. This is the most important reason for Greinacher voltage multiplier has higher efficiency than the other two circuits. In addition to the selection of voltage multiplier, load resistance, input power and frequency are important parameters for the system efficiency. At the low input frequencies such as 10 MHz, the selection of voltage multiplier has vital importance. However, these selection is not important at the frequencies of 1000 MHz and higher.

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