IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE)
e-ISSN: 2278-1676,p-ISSN: 2320-3331, Volume 13, Issue 4 Ver. II (Jul. – Aug. 2018), PP 37-45
www.iosrjournals.org

Wireless Energy Harvesting Using RF-Dc Module

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Abstract: *This project presents an optimization of the Voltage doubler circuit in an energy conversion module for Radio Frequency (RF) energy harvesting system at both 900 MHz and 900Hz band. The function of the energy conversion module is to convert the radio frequency(RF) signals into direct-current (DC) voltage at the given frequency band to power the low power devices. The design is based on the Villard Voltage Doubler Circuit. A seven stage Schottky diode voltage doubler circuit is designed, modelled and simulated in this project. Multisim 11.0 and MATLAB R2012b have been used for the modelling and the simulation work. For an input of RF signal of 900MHz, the circuit can produce 3.67V across a 100 kΩ load and for 900Hz input RF signal, the circuit can produce around 7.7 V across a 100kΩ load. This voltage can be used to power low power devices and sensors in networks in place of batteries.*
Keywords: *RF-DC, Energy Conversion, Schottky Diode, Villard Voltage Doubler,Capacitor Manipulation*

Date of Submission: 23-07-2018 Date of acceptance: 07-08-2018

I. Introduction

Wireless energy harvesting using RF energy as its source is an uprising research interest for the past decade. RF energy harvesting is a process by which energy is derived from external sources by scavenging DC power from propagating RF radiation generated by nearby electronic component, i.e. cell phones, communication towers, antennas etc.The rapid development of sensors network with requirement of reliable power supply places severe stringent on battery technology, which still is in slow process of catching up with the electronic devices; particularly in the nanometer (nm) technology where batteries are no match for such miniaturization. The advantage of such system is to eliminate the need for a battery.The ability of RF power harvesting device to replace the batteries and provide a unique and independent energy source to save on the operation and maintenance cost has made it a favourite alternative source of energy,and has brought much attention and care for development.

The concept needs an efficient antenna along with a circuit capable of converting RF signals to DC voltage. The efficiency of an antenna mainly depends on its impedance and the impedance of the energy converting circuit. If the two impedances aren't matched, then it will be unable to receive all the available power from the free space at the desired frequency band. Matching of the impedances means that the impedance of the antenna is the complex conjugate of the impedance of the RF-DC converter e RF-DC converter circuit.

Bandwidth of the working antenna can be chosen accordingly such as in RF energy harvesting, radio signals with frequency range from 300GHz to as low as 3kHz are used as a medium to carry energy in a form of electromagnetic radiation. Although it has been observed that being compatible with the RF-DC converter circuit component, it is wise to use MHz range bandwidth. The RF-DC converter module designed in this thesis is based on a voltage doubler circuit which can be able to output a DC voltage typically larger than a simple AC-DC converter circuit i.e. diode rectifier circuit. [1] The module presented in this can function as an AC to DC converter that not only rectifies the input AC signal but also elevates the DC voltage level depending on the working principle of Villard voltage doubler circuit. RF energy transfer and harvesting is one of the wireless energy transfer techniques. The other techniques are inductive coupling and magnetic resonance coupling. Inductive coupling is based on magnetic coupling that delivers electrical energy between two coils tuned to resonate at the same frequency. The electric power is carried through the magnetic field between two coils. Magnetic resonance coupling utilizes evanescent-wave coupling to generate and transfer electrical energy between two resonators. The resonator is formed by adding a capacitance on an induction coil. Both of the above two techniques are near-field wireless transmission featured with high power density and conversion efficiency. The power transmission efficiency depends on the coupling coefficient, which depends on the distance between two coils/resonators. The power strength is attenuated according to the cube of the reciprocal of the distance.

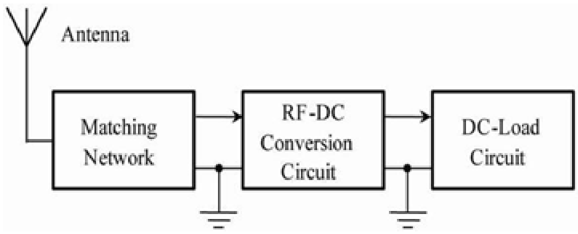

Figure 1: Schematic Diagram of a RF Energy Harvesting system

II. Voltage Multiplier

The Voltage Multiplier is a special type of diode rectifier circuit which can potentially produce an output voltage many times greater than of the applied input voltage. Voltage multipliers are similar in many ways to rectifiers in that they convert AC-to-DC voltages for use in many electrical and electronic circuit applications such as in microwave ovens, strong electric field coils for cathode-ray tubes, electrostatic and high voltage test equipment etc. where it is necessary to have a very high DC voltage generated from a relatively low AC supply. Generally, the DC output voltage of a rectifier circuit is limited by the peak value of its sinusoidal input voltage. But by using combinations of rectifier diodes and capacitors together we can effectively multiply this input peak voltage to give a DC output equal to some odd or even multiple of the peak voltage value of the AC input voltage.

The design used in this module is derived from the function of peak detector or a half wave peak rectifier. The Villard voltage multiplier circuit was chosen in the circuit design of this paper because it produces two times of the input signal voltage towards ground at a single output and can be cascaded to form a voltage multiplier with an arbitrary output voltage and its design simplicity.

2.1 Diode Modeling

The voltage multiplier circuit in this design uses zero bias Schottky diode HSMS-2850 from Agilent. The attractive feature of these Schottky diodes are low substrate losses and very fast switching but leads to a fabrication overhead. This diode has been modelled for the energy harvesting circuit which comes in a one-diode configuration.

This diode has been used in Multisim circuit implementation in order to achievethe simulation results. Themodeling is done by transforming the diode into an equivalent circuit using passive components which are described by the SPICE parameters in

Table 1.

The structure of a Schottky diode is shown in and its equivalent circuit is shown in **Figure 2**. HSMS-2850 is a fast recoverySchottky Diode which provides a low forward voltage, low substrate leakage and uses the non-symmetric properties of a diode that allows unidirectional flow of current under ideal condition.

Parameters	**Units**	**HSMS-2850**
Bv	V	3.8
C**j0**	pF	0.18
EG	Ev	0.69
IBV	A	3e-4
Is	A	3e-6
N	No Unit	1.06
Rs	Ω	25
PB(VJ)	V	0.35

PT(XTI)	No Unit	2
M	No Unit	0.5

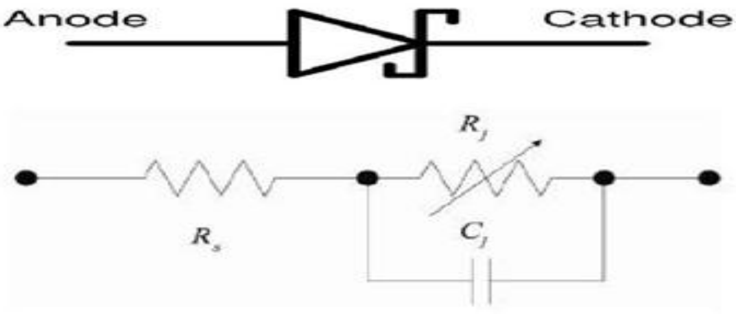

Figure 2: Equivalent Circuit of HSMS 2850

The diodes are fixed and are not subject of optimization or tuning. This is described using the following derivations. By neglecting the effect of diode substrate, an equivalent linear model that can be used for the diode as shown in **Figure 2.**

The diodes are fixed and are not subjects of optimization. By neglecting the effect of diode substrate, an equivalent linear model that can be used for diode.

Rs is the parasitic series resistance of the diode, the sum of the bond wire and the lead frame resistance, the resistance of the bulk layer of silicon, etc. Rf energy coupled into Rs is lost as heat-it does not contribute to the rectified output of the diode. Cj is the parasitic junction capacitance of the diode, controlled by the thickness of the epitaxial layer and the diameter of the Schottky contact. Rj is the junction resistance of the diode, a function of the total current flowing through it.

2.2 Single Stage Voltage Multiplier

Represents a single stage voltage multiplier circuit. The circuit is also called as a voltage doubler because in theory, the voltage that is arrived on the output is approximately twice that at the input.

The circuit consists of two sections; each comprises a diode and a capacitor for rectification. The RF input signal is rectified in the positive half of the input cycle, followed by the negative half of the input cycle. But, the voltage stored on the input capacitor during one half cycle is transferred to the output capacitor during the next half cycle of the input signal. Thus, the voltage on output capacitor is roughly two times the peak voltage of the RF source minus the turn-on voltage of the diode.

The most interesting feature of this circuit is that when these stages are connected in series. This method behaves akin to the principle of stacking batteries in series to get more voltage at the output.
The output of the first stage is not exactly pure DC voltage and it is basically an AC signal with a DC offset voltage. This is equivalent to a DC signal superimposed by

Figure 3: Linear Circuit Model Of ripple content. Due to this distinctive
feature, succeeding stages in the circuit can get more voltage than the preceding stages. If a second stage is added on top of the first multiplier circuit, the only waveform that the second stage receives is the noise of the first stage. This noise is then doubled and added to the DC voltage of the first stage. Therefore, the more stages that are added, theoretically, more voltage will come from the system regardless of the input. Each in-dependent stage with its dedicated voltage doubler circuit can be seen as a single battery with open circuit output voltage V0, internal resistance R0 with load resistance RL and the output voltage Vout.

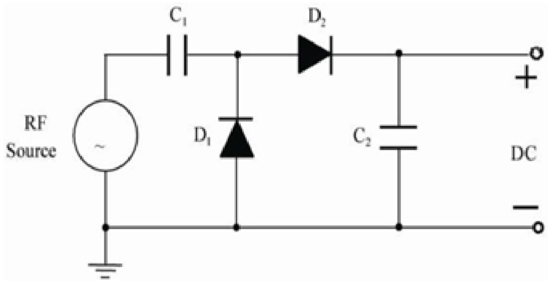

Figure 3: Single Stage Voltage

Multiplier Circuit

The capacitors are charged to the peak value of the input RF signal and discharge to the series resistance (Rs) of the diode. Thus, the output voltage across the capacitor of the first stage is approximately twice that of the input signal. As the signal swings from one stage to other, there is an additive resistance in the discharge path of the diode and increase of capacitance due to the stage capacitors.

2.3 Seven Stage Voltage Multiplier

The Seven Stage voltage multiplier circuit design implemented in this paper is shown in **Figure 4**. Starting on the left side, there is a RF signal source for the circuit followed by the first stage of the voltage multiplier circuit. Each stage is stacked onto the previous stage as shown in the Figure 4 Stacking was done from left to right for simplicity instead of conventional stacking from bottom to top.

The circuit uses eight zero bias Schottky surface-mount Agilent HSMS-285X series, HSMS-2850 diodes. The special features of this diode is that, it provides a low forward voltage, low substrate leakage and uses the non- symmetric properties of a diode that allows unidirectional flow of current under ideal conditions. The diodes are fixed and are not subject of optimization or tuning. This type of multiplier produces a DC voltage which depends on the incident RF voltage. Input to the circuit is a predefined RF source. The voltage conversion can be effective only if the input voltage is higher than the Schottky forward voltage.

The other components associated with the circuit are the stage capacitors. The chosen capacitors for this circuit are of through-hole type, which make it easier to modify for optimization. The circuit design in this paper uses a capacitor across the load to store and provide DC levelling of the output voltage and its value affects the speed of the transient response. Without a capacitor across the load, the output is not a good DC signal, but more of an offset AC signal.

In addition to the above, an equivalent load resistor is connected at the final output node. The output voltage across the load decreases during the negative half cycle of the AC input signal. The voltage decreases is inversely proportional to the product of resistance and capacitance across the load. Without the load resistor on the circuit, the voltage would be hold indefinitely on the capacitor and look like a DC signal, assuming ideal components. In the design, the individual components of the stages need not to be rated to withstand the entire output voltage. Each component only needs to be concerned with the relative voltage differences directly across its own terminals and of the components immediately adjacent to it. In this type of circuitry, the circuit does not change the output volt- age but increases the possible output current by a factor of two. The number of stages in the system is directly proportional to the amount of voltage obtained and has the greatest effect on the output voltage as.

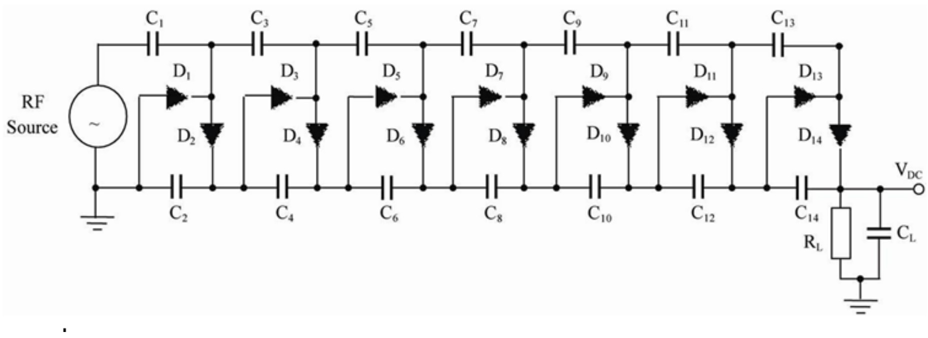

Figure 4: Seven Stage Voltage Multiplier Circuit Diagram

III. Simulation

Multisim software was chosen for modelling and simulation which is a circuit simulation tool by National Instruments. The simulation and practical implementation were carried out with fixed RF at 945 MHz ± 100 MHz, which are close to the down link centre radio frequency (947.5 MHz) of the GSM-900 transmitter. The simulations were carried out from 4 stages doubler circuit to 9 stages doubler circuit. On the basis of the statistical data output, it has been observed that optimum output is achieved for 7 stage voltage multiplier circuit. The simulations were also carried out using same stage capacitance value (3.3nF) and then with a varied capacitance value for all stages from 4 stages through 9 stages.

The capacitance value was varied in such a way that, from one stage to the next, it was halved. For example, if the first stage was 3.3nF, the second stage was 1.65nF, third stage was 825 pF, fourth stage was 415 pF and so on. But keeping in view of testing, the capacitance values were chosen to have a close match with the standard available values in the market. [1]

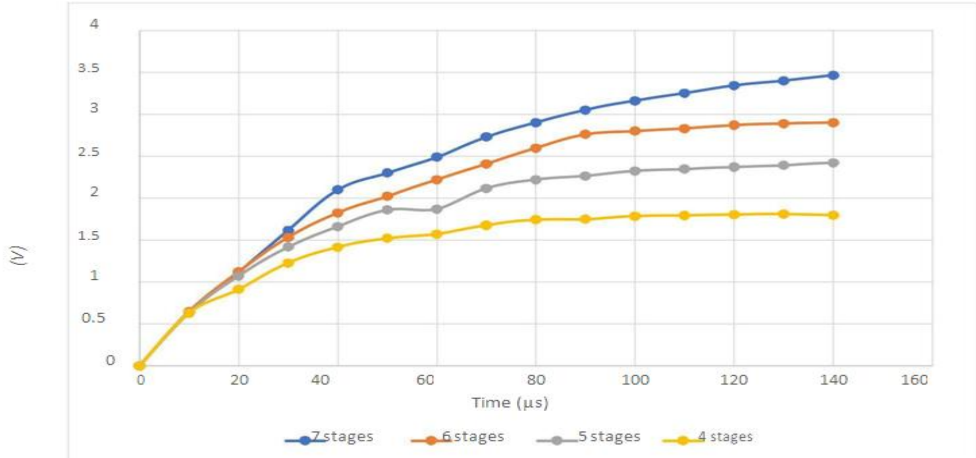

Figure 5: DC output voltage verses rise time of voltage doubler circuit through 4 to 7 stages with half stage capacitance

The above graphical representation Figure 6 shows that optimum DC output voltage is obtained for 7 stages voltage doubler circuit while in case of 4 to 6 stages, it is not up to the mark and for 8 and 9 stages the output value degrades after achieving the optimum point

IV. Result & Analysis

The simulation of the circuit has been examined in two different RF ranges, one is in 900 Hz range and another one is 900 MHz range. Different results have been achieved which is discussed below.

Operating Frequency 900 Hz:
When the operating frequency is set to 900 Hz, the following result has been achieved,

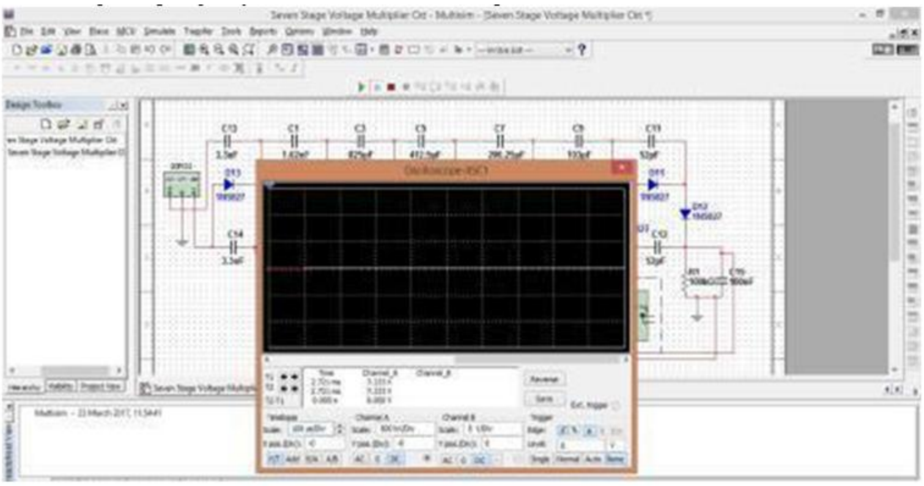

Figure 6: Minimum Time to attain 7 V at 900 Hz

In 2.721ms, amount of output DC voltage achieved is 7.233 V, which is evidently much higher than the maximum output voltage achieved in 900 MHz RF range. The maximum voltage output achieved in simulation is around 7.8 V.

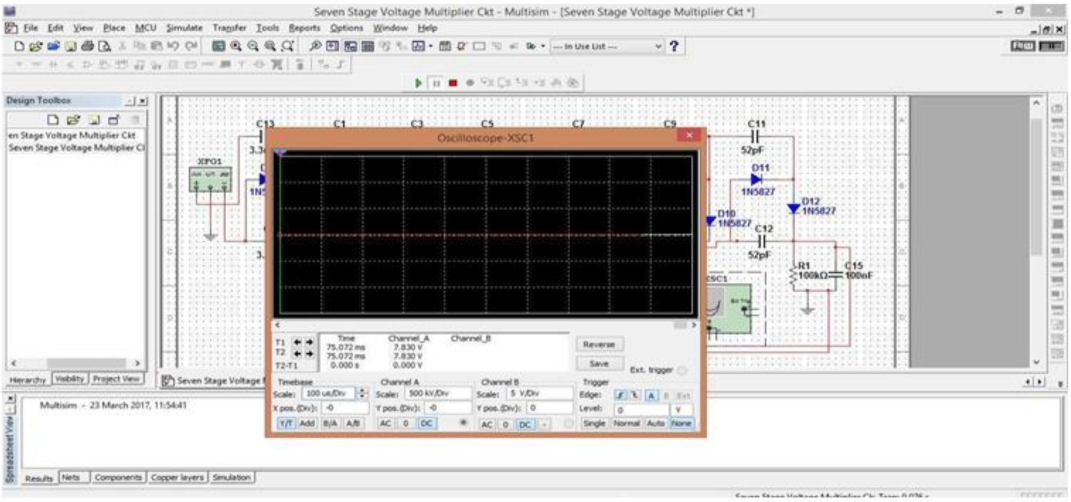

Figure 7: Maximum DC Output Voltage attained at 900 Hz

Operating Frequency 900 MHz:
The simulated results that has been achieved by using Multisim. The DC voltage output of seven stages voltage multiplier circuit is as following,

Time(μs)	Voltage(V)
10	0.637
20	1.118
30	1.614
40	2.1
50	2.3
60	2.494
70	2.732
80	2.9
90	3.052
100	3.161
110	3.252
120	3.343
130	3.4
140	3.465

Table 2: Output voltage at 945 MHz Frequency Band

From Table 2, it is evident that the graphical representation of the Time v/s DC Output Voltage will be a non-linear one. So apparently, it is not possible to calculate the slope or other necessary mathematical components of the curve which is required for the extrapolation.

So, it is required to find out a generalized equation for the curve which will help to find out DC output voltage value with respect to corresponding time or vice versa.

In this context, Non-linear regression method has been followed to find out a generalized equationThe Circuit first achieves 3.67 V at 350 μs and remains stable in this level after that. So, what is being concluded that after achieving 3.67 V, the output becomes stable and not increasing further.The value of DC output voltage of the seven stages voltage multiplier circuit at 800 μs is observed as 3.67 V as shown below in The Circuit first achieves 3.67 V at 350 μs and remains stable in this level after that. So, what is being concluded that after achieving 3.67 V, the output becomes stable and not increasing further.
The value of DC output voltage of the seven stages voltage multiplier circuit at 800 μs is observed as 3.67 V as shown below in **Figure 9**.

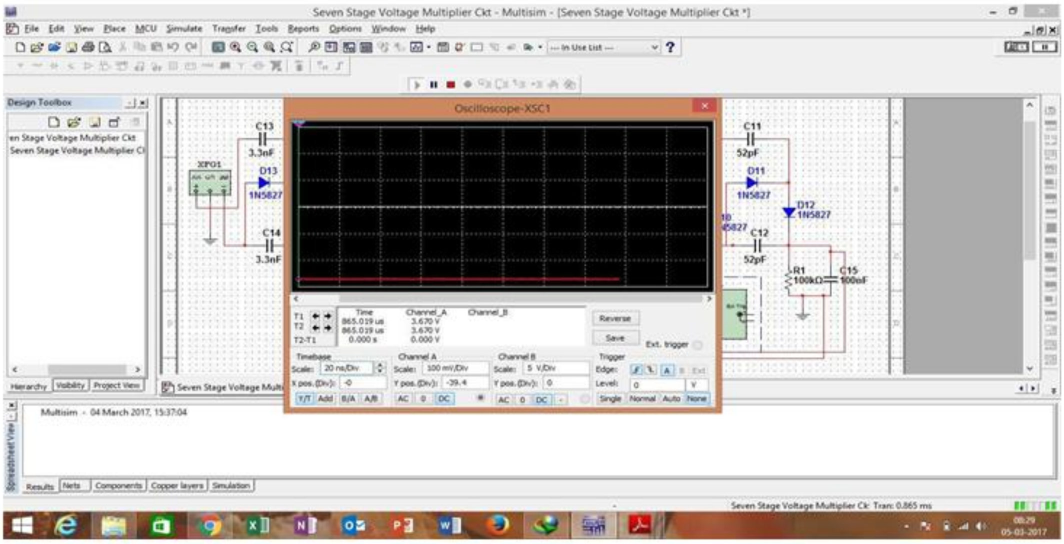

Figure 8: Multisim Representation of DC Output Voltage at 865 μs at 900 MHz

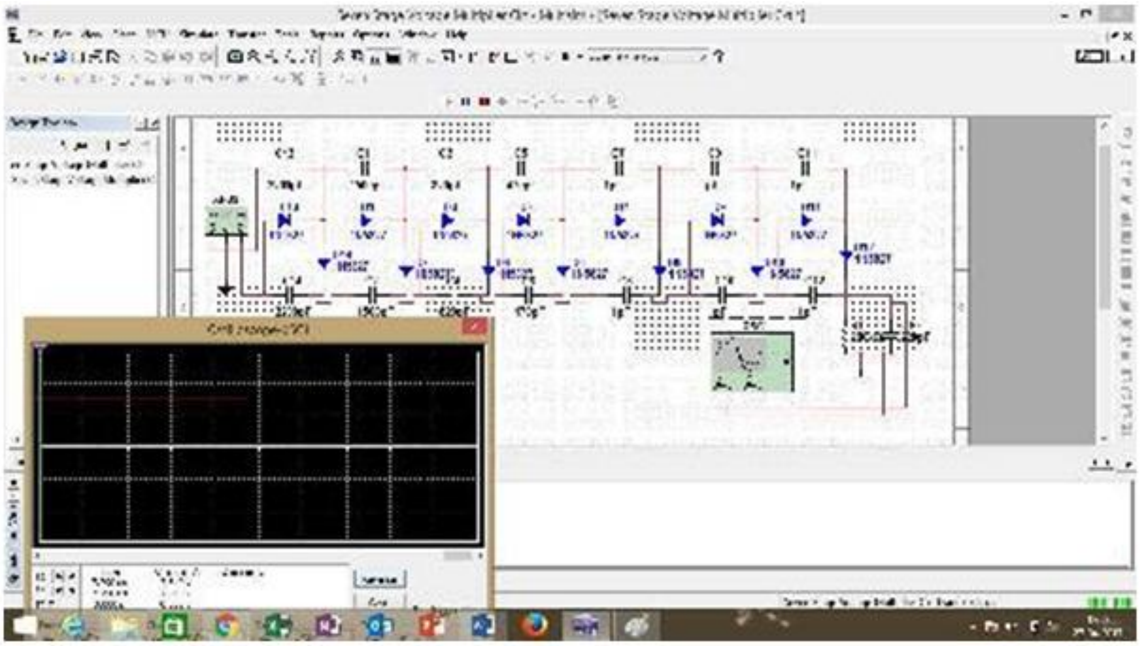

Figure 9: Optimum DC Output Voltage with Manipulated Capacitor Values

Now, analysing the two outputs for operating in different frequency range, that output is less for higher frequency. So, eventually this can be solved if the capacitor values are manipulated accordingly. As the circuit is producing around 7V in Hz range frequency, it will also produce the same in MHz also if the capacitor values are changed. Although the Schottky Diode HSMS 2850 used in this circuit does not work well in Hz range, it is producing better output in simulation as the simulation is totally based on the diode parameters.

As a result, starting from the most left one, capacitor values are manipulated as per values available in market. The following capacitor is half the value of the previous one, this logic is followed till the 4th stage capacitors. After that, it is observed that if the same logic is being followed, output degrades as both the ripple and variation in output increases which is not desirable for any DC output circuit.

It is required to use even lesser values of capacitor for better output. So, the lowest value capacitor available in market i.e. 1 pF is used in all the remaining 3 stages.

Thereafter, the values of both the resistor and capacitor of the filter circuit is also altered accordingly. All the capacitors in the range of 100pF to 500pF is used and optimum output that has been achieved by using a 200kΩ resistor and a 200pF capacitor.

Capacitor value of the filter circuit is manipulated in such a manner that the lowest amount of ripple remains in the output. As the desired output is DC so it is obvious that, lesser the ripple better the output.

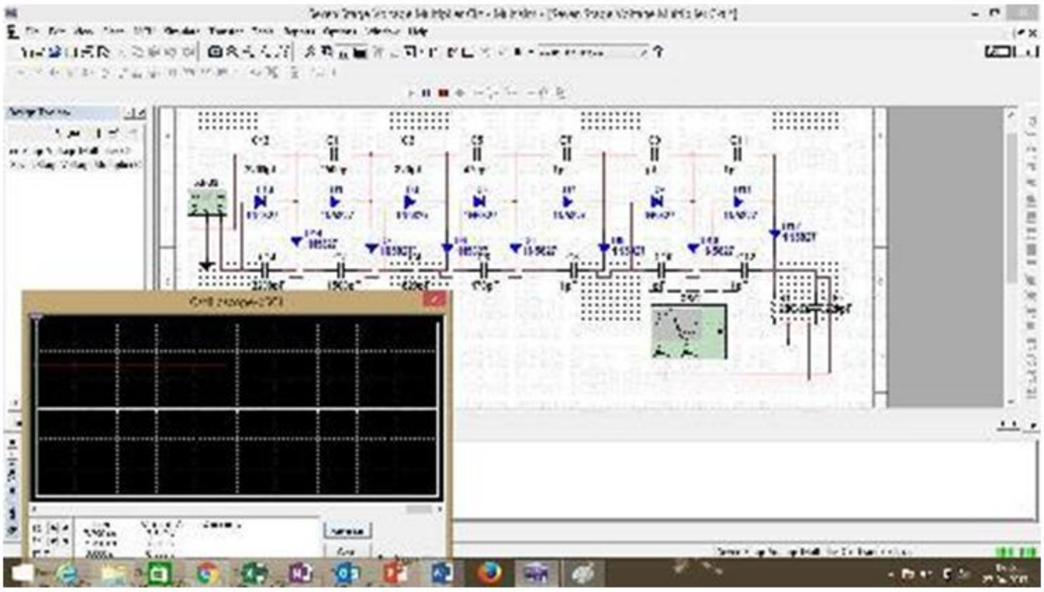

Figure 9: Optimum DC Output Voltage with Manipulated Capacitor Values

Maximum DC output voltage that has been achieved with manipulated capacitor values is around 7.8 V which is sufficient to charge any low power device. This output is achieved in 7.4 µS.

V. Conclusion

From the experimental results, it is found that the proposed voltage multiplier circuit operates in simulation at both the frequency of 900 MHz and 900 Hz. However, it is still under consideration whether the same output result will be achieved in practical implementation of the voltage multiplier circuit same as the simulation result.

Value of the capacitors used in the circuit has been determined in two different ways. First, all the capacitors are chosen of same value and second, the next capacitor is of half the value of the previous capacitor. However, it is observed that better output is achieved in second case.

Although the simulation work has been done in both MHz and Hz RF band, according to [1], [5] and [6] the diode HSMS-2850 that has been used in this circuit, operates in MHz and GHz RF band. But, in the simulation work of this project, the circuit also produced DC output in Hz range. So, the results and analysis that have been showed previously, only considering the simulation results as no practical implementation has been done till now.

In this project, the whole simulation work has been done based on using Duck antenna which has an internal impedance of 50Ω. The reason for choosing an antenna of impedance 50Ω is nothing but the Smith Chart simulation output of impedance. The real part of the impedance at the resonant frequency is 54.3Ω which is close to 50Ω in the desired range of frequency band. The reactive part of the impedance is 0.1, almost negligible and is capacitive. This indicates the best impedance match from the load to the source [4].

It is also possible to design the circuit using patch antenna. A patch antenna is literally a patch of metal or conductor on a flat surface. There may or may not be a ground plane on the other side of the substrate. The directionality, gain, polarization, and impedance are a function of the size and shape, and placement of the feed line.

In that case, a pi matching network is needed to be designed and optimized to provide an impedance matching for the antenna impedance to the complex load impedance. The next phase of the research work is to interface the voltage multiplier circuit through a matching network to the antenna at the input side and a low power device to power from the system at the output side to complete the RF energy harvesting system.

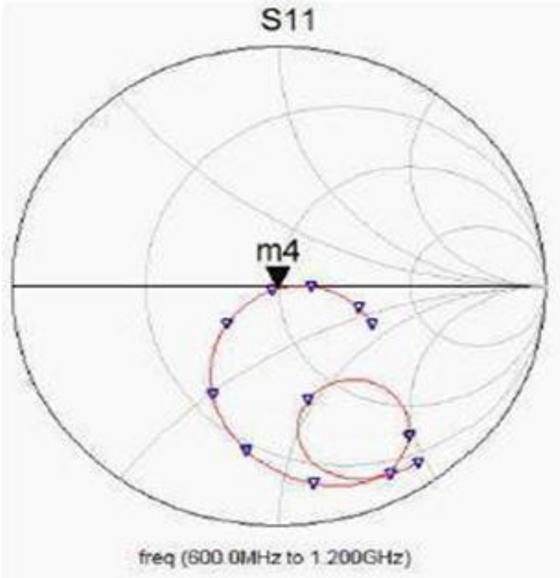

Figure 10: Simulation Result of Impedance on Smith Chart

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Prabrit Bandyopadhyay "Wireless Energy Harvesting Using Rf-Dc Module "IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE) 13.4 (2018): 37-45.