RADIO FREQUENCY ENERGY HARVESTING

By

MOHD FAROUK BIN MOHD SAAD

FINAL PROJECT REPORT

Submitted to the Electrical & Electronics Engineering Programme
In Partial Fulfillment of the Requirements
For the Degree
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(Electrical & Electronics Engineering)

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
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Approved:

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December 2010

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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Mohd Farouk Bin Mohd Saad

ABSTRACT

The non-renewable energy reservoir had been decreased as the time past. The energy demand has been increase as the country develops through times which need more and more energy. Renewable Energy is the only potential energy source that could replace the running out hydrocarbon based energy. The objective of this project is to study and make research on Radio Frequency Energy Harvesting. This project aims to come out with a system that able to exert some energy from radio waves that able to use by other electronics equipments. This device consists of three main parts to works which are, Radio Frequency Transducer, Power Management circuit, and the Energy Storage Device. The Radio Frequency Transducer is the main part that used to extract the electromagnetic energy from the Radio Frequency around us, while the Power Management circuit which consist of charge pump circuits, will convert the extracted energy and transform into electrical energy The electrical energy that derived from the circuit then will be stored in the Energy Storage Device for future usage. This project, the study will only study on specific frequencies of FM radio frequency which start from 88MHz until 108 MHz of the radio frequency band. Research conducted by referring to the same technology that applied by the RFID. The research conducted through literature research on the three main parts, which are the antenna, the transceiver part and the storage part.

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CHAPTER 1
INTRODUCTION

1.1 Background of Study

Energy is one of the physical quantities that used to describe the amount of work that can be performed by a force. In the daily life, lots of energy are used which in different form, depending on its applications. Different forms of energy can be found everyday that used to help human such as, potential, thermal, gravitational, electrical, electromagnetic, and others.

Energy cannot be created but it could transform from one to another form. For an example, a simple application of energy transform is conversation over the hand phone. During the conversation, there were lots of energy transformation happened by the help of electronic devices. From sound, the energy than is transform into electrical energy before being transform into electromagnetic energy that then be transferred to the recipient. Another important energy transformation process is electrical energy transformation from raw material such as, petroleum product, and coal.

The energy could be classified into two categories which are nonrenewable energy, and renewable energy. Non-renewable energy is a natural based energy that cannot be produced or regenerated and to sustain the consumption rate. This type of energy source is normally found in a big and fixed amount in a form of, coal, petroleum and natural gas. The main problem faced by this type of energy is, the energy produced are consumed much faster than nature can recreate it. This will result of running out of this type of energy.

Renewable energy is energy that generated from the available natural resources such as wind, tides, and sunlight. This renewable energy quickly replaces itself and is usually available in a never-ending supply. With the help of special collectors, the energy able to extracted and stored to be used. Energy harvesting is a new technology that used to derived energy from external source. With the help of science, this new technology is being developed, to exerted energy from different source such as thermoelectric which came from heat source, piezoelectric that converts mechanical strain into electrical and others and Radio Frequency energy harvesting.

Transmission of energy through wireless medium has been proved as early of 1891 by an electrical and mechanical engineer, Nikola Tesla. Tesla has demonstrated the transmission of electrical energy without wires and this type of electrical conduction is named after his, The Tesla effect. This is a big step for energy conduction which resulting the idea of wireless energy transfer.

In our daily life, the Radio Frequency energy harvesting has been implementing by the usage of RFID tag. This RFID tag function based on the electromagnetic wave, where the card reader supply electromagnetic energy, and the RFID tag then will exert some of the energy and return back as communication signal. With this technology, in future we may have a device that always rechargeable that no need for us to charge the electronic appliances.

1.2 Problem Statement

The main problem that first needs to encounter is, how the Radio Frequency could be extracted from air so that we can manipulated to electrical energy. As for the wind energy, we may have a blade to convert the mechanical energy into electrical. For this electromagnetic energy to be exerted, we need to have an antenna that able to exert the electromagnetic energy around us.

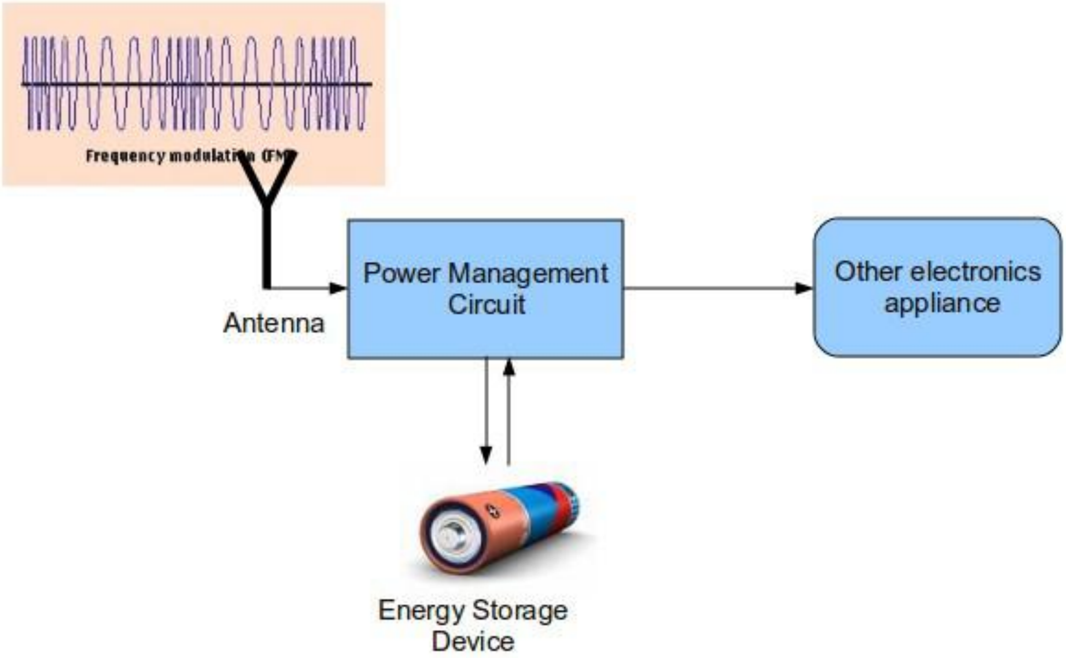

Figure 1 : Main part of radio frequency energy harvesting system

For the antenna, there are lots of specifications that need to consider improving its efficiency such as, the shape, the impedance, and the conductivity coefficient. This parameters need to consider so that the energy can be captured from the electromagnetic waves, and been delivered to the circuit effectively.

Secondly, the Power Management circuit is designed based on the charge pump circuits. The charge pump circuit will be designed and simulated so that able to delivered then energy effectively. Since the circuit is build based on electronic based, the circuit should be able to operate at less power than the captured amount of power. With this, then only we could capture and stored the energy.

Other than that, another important factor is how strength is the electromagnetic energy is there around us to be exerted. Certain area may have stronger electromagnetic energy compared to other area. For an example, on hills, the strength of the electromagnetic energy is not good enough compared to the urban area. This may affect the amount of energy that the device could exert from it.

1.3 Objective

The main objective of this project is to study and make research on radio frequency energy harvesting. This project targets is to come out with a system that able to exerted energy from the radio waves and able to use for other electronics purpose. The system should be able to exert the Radio Frequency effectively and stored into the storage device which may be a battery or super capacitor.

CHAPTER 2
LITERATURE REVIEW

2.1 Radio Frequency

Radio frequency is a term that refers to the resultant of an alternating current pass through an antenna; it will propagate an electromagnetic field. This electromagnetic then will be travel through the air or space. These electromagnetic operates in specific radiation spectrum which from 9kHz to thousands of gigahertz. The length of the wavelength is inverse of the wave frequency. As the frequency is increased beyond that of the radio frequency spectrum, electromagnetic energy takes the form of infrared, visible, ultraviolet, X rays, and gamma rays.

Many types of wireless devices make use of radio frequency field such as hand phone, radio and television broadcast stations. This radio frequency also been applied to medicine field where generally for minimally invasive surgeries by using Radio frequency ablation. Amount of energy transfer between 2 (transmitter and receiver), could be represented by Friis Transmission Formula as shown in Equation 1.

$$\frac{Pr}{Pt} = GtGr\left(\frac{\lambda}{4\pi r}\right)^2 \qquad (1)$$

Pr= Power received
Gt= Transmitter antenna gain
Pt= Power transmitted
Gr= Receiver antenna gain
r= Distance between the two antenna

The source of radio frequency generally can be categorized into 3 general categories which are, intentional sources, anticipated ambient sources, and unknown ambient sources. The intentional sources could be controlled its availability, and amount of power to be delivered by the source. Normally it is design and engineered for specific application such as RFID reader, and WIFI router. The anticipated ambient source relies on the concentration of number of transmitters. Depending on transmit power, multiple phones in close proximity can provide several mill watts of power. Unknown ambient sources are sources of radio frequency energy of which there is no control and no knowledge that provide a continual source of power. For example, mobile radio that been use by police and military.

2.2 Energy Harvesting

Energy harvesting is the process by which energy readily available from the environment is captured and converted into usable electrical energy. This term frequently refers to small autonomous devices, or micro energy harvesting. The source of energy that have potential to be harvest such as:

- Mechanical Energy – from sources such as vibration, mechanical stress and strain
- Thermal Energy – waste energy from furnaces, heaters, and friction sources
- Light Energy – captured from sunlight or room light via photo sensors, photo diodes, or solar panels
- Electromagnetic Energy – from inductors, coils, transformers and radio frequencies
- Natural Energy – from the environment such as wind, water flow, ocean currents, and solar
- Human Body – a combination of mechanical and thermal energy naturally generated from bio-organisms or through actions such as walking and sitting
- Other Energy – from chemical and biological sources

Radio frequency energy harvesting generally captured the radio waves, and convert it into DC source. This process could be approached by receiving the Radio Frequency through the antenna, convert the wave into DC source and conditioning the output power of the harvester. The amount of power that could be produce by the harvester circuit depends on several factors such as, the source power, distance from the source, the antenna gain, and the conversion circuit efficiency.

2.3 Antenna

An antenna is a device that made of one or more conductors that used to transmit or receive electromagnetic waves. Antenna works as a converter which converts current into waves and vice versa. Antenna is a crucial part in radio, television, walkie talkie, wireless Internet hand phones, radar and even spacecraft. The antenna's job is very simple, it converts electrical signals flowing down a conductor into radio waves or it converts radio waves into electrical signals flowing down in a conductor. Most antennas work equally well in both directions.

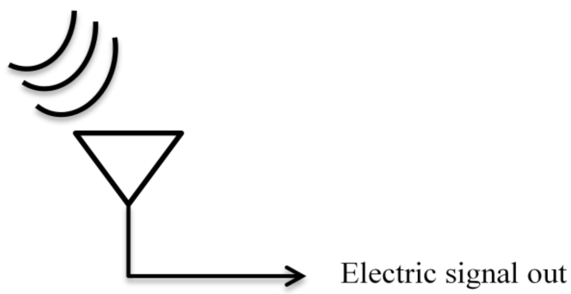

Figure 2 : Block diagram of an antenna

Antenna can be classified into two main characteristics, active and passive. Passive antennas are consisting of hunk of metal configured in a very specific way. The active antenna has a power supply attached somewhere. Basically, active antennas are nothing more than passive antennas with amplifiers inside it.

2.4 Charge Pump Circuit

As the technology moving forwards, the electronics circuit requires power-supply voltages of less than 2V to enable low power operation and increased the battery life. The low power technology has become a primary target for the most electronic devices to increase the performance of the devices itself.

However, most of the sub-system of the devices such as audio, image sensor circuits and LCD display, require internal voltages higher than the system supply voltage. To accommodate that, this internal high voltage supply needs to be generated in the system by using the small voltage supply. The charge pump turns out as one of the solution to produce higher voltage from a smaller voltage source.

The history of producing higher voltage from a lower voltage source has existed since the discovery of electricity. The invention of Michael Faraday, the British physicist and chemist in 1831 which is the “induction ring” has begin the first step of generating higher voltage from an available lower voltage using transformers.

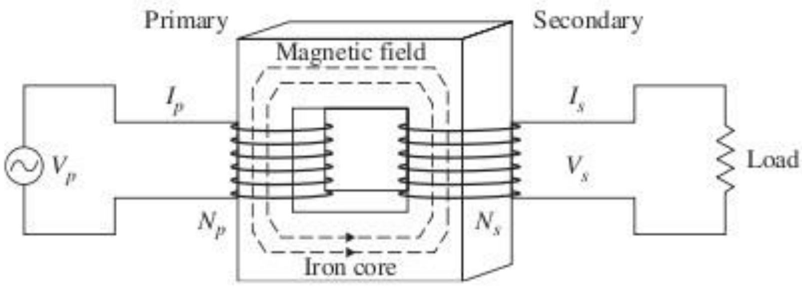

Figure 3 : Simple transformers

The need of producing even higher voltages was accentuated by the requirement from physicist using particle accelerators, to create high energy particles for studying subatomic physics. During this time, Cockcroft and Walton invented a method of producing extremely high voltage using a unique connection of discrete diodes and capacitors.

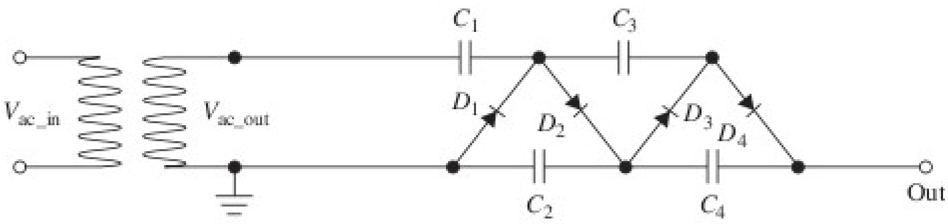

Figure 4 : Cockcroft-Walton charge pump circuit design

The Cockcroft and Walton technique then was adopted by John F. Dickson for implementation on a modern integrated circuit. It operates in a similar manner as the Cockcroft-Walton multiplier circuit only that the nodes of the diode chain are coupled to the inputs with the capacitors in parallel, instead of in series as shown in Figure 4.

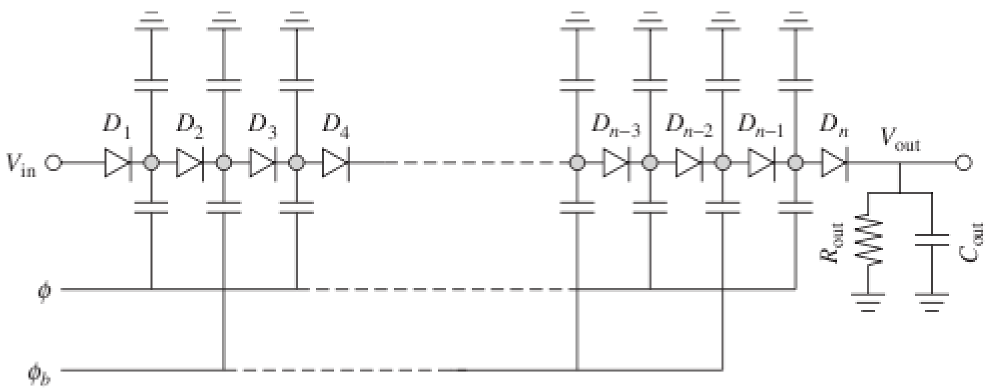

Figure 5 : Dickson charge pump circuit design

With this circuit design created, the charge pump circuits eliminate the need for DC/DC boost converters, and expensive low profile inductors. To add, the circuits give solutions to meet the size limitation of hand held devices and cell phones [2]. Signal electromagnetic field will induces current inside the conductor of the antenna and create a corresponding voltage at the antenna terminal. Antenna performance are rely on lots of things such as the conductivity of the conductor, length, the bandwidth that it going to receive or transmit, the impedance of the antenna to suit the circuit for better power delivery.

CHAPTER 3

METHODOLOGY

3.1 Projects Identification

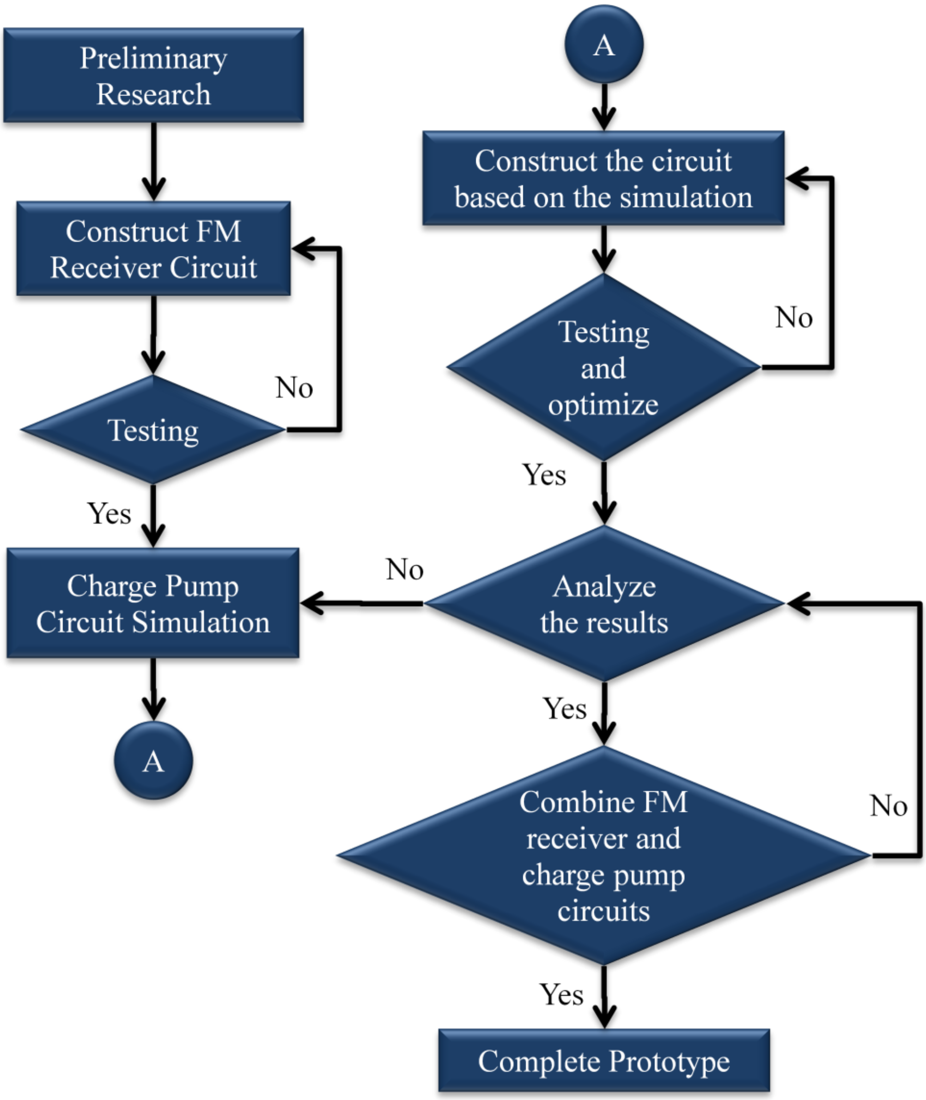

Figure 6 : Flowchart Project Activities

3.2 Project Activities

3.2.1 Research Methodology

The radio frequency energy harvesting involves new kind of technology. The early stage of the project, it involve lots of literature research regarding this technology. Literature research was done through books from Information Resource Center, Universiti Teknologi PETRONAS and from internets. The literature research were done focusing more on certain topics such as current progress of this technology by other researches, similar applied technology such as RFID, FM receiver, and others.

3.2.2 FM Receiver Circuit Construction

To know actual amount of the radio frequency that able to exert from the atmosphere, a FM receiver circuit was build to measure the actual power. The circuit was fabricated follow below shown schematic (Figure 7). For this circuit, the electronics components that used are:

- TDA 7000 (FM Radio Circuit)
- Capacitors, Variable Resistors, Diodes
- Breadboard

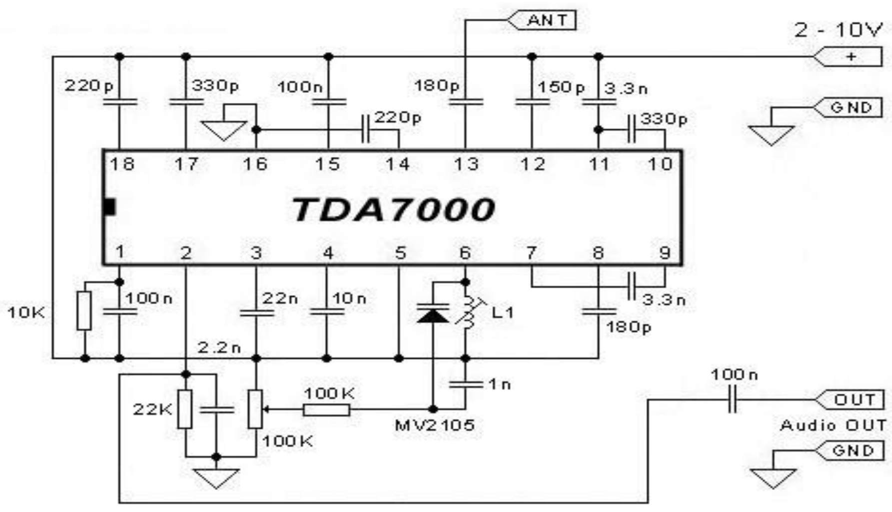

Figure 7 : TDA 7000 FM receiver schematic

Figure 8 : TDA 7000 IC

3.2.3 *FM Receiver Circuit Testing and Improvement*

The FM receiver which fabricated was tested using oscilloscope that available in the EE lab. The objective is to identify the output voltage that harvest from the Radio Frequency energy. The data collected then used to design the amplifier for the signal captured from the FM receiver circuit. This data is use to design the charge pump circuit which will act as amplifier to amplify the voltage. The circuit is improved by replacing the antenna with a monopole antenna that increase the RF amount captured.

3.2.4 *Charge Pump Simulation*

For the project, simulations were done for better understanding of the charge pump circuits which function to act like transformers which increase the voltage output. The simulations were done using simulation software, Multisim. The main objectives of the simulations are to understand the basic operations of charge pump circuits and how the voltage output change as the number of stages increase. The increments of the output voltage could be calculated as defined in Equation 2. Simulation was done to find out what is the lowest input for the charge pump circuit able to works. The charge pump circuit simulated using different values of inputs.

$$\mathbf{V_{dd} = 2N\,(V_{pk}-V_{on})} \qquad (2)$$

3.2.5 Charge Pump Circuit Construction and Testing

Charge pump actual circuit were constructed on veroboard. Different types of diodes were used during the constructions which are 1N4148 and OA90 diodes. Different stages were constructed and tested to see the output. During the testing, the input is being fed by signal generator and the output is monitored using digital oscilloscope available in EE Lab. Two testing were done on all the charge pump circuits which are:

- Fix frequency input, varies input voltage
- Varies Frequency input, fix input voltage

3.3 Tools and Equipments

The software involved during the simulations was:

- NI Multisim Analog Device Edition Version 10.0.1

The hardware involved during the fabrication of FM receiver circuit was:

- Breadboard
- Basic electronics components such as, resistors, capacitors, single core wires etc.
- Signal generator
- Digital Oscilloscope
- FM receiver IC, TD 7000
- Diodes, OA90, DN4148
- Monopole antenna

CHAPTER 4
RESULT AND DISCUSSION

4.1 FM Receiver Circuits Construction and Testing

Based on the schematic shown in Figure 7, the FM receiver circuit is constructed. Initially, the circuit was constructed on breadboard and then transferred onto veroboard. A monopole type of antenna is used for the FM receiver circuit. For the prototype, the FM receiver tested and the output is measured using oscilloscope that available in EE lab.

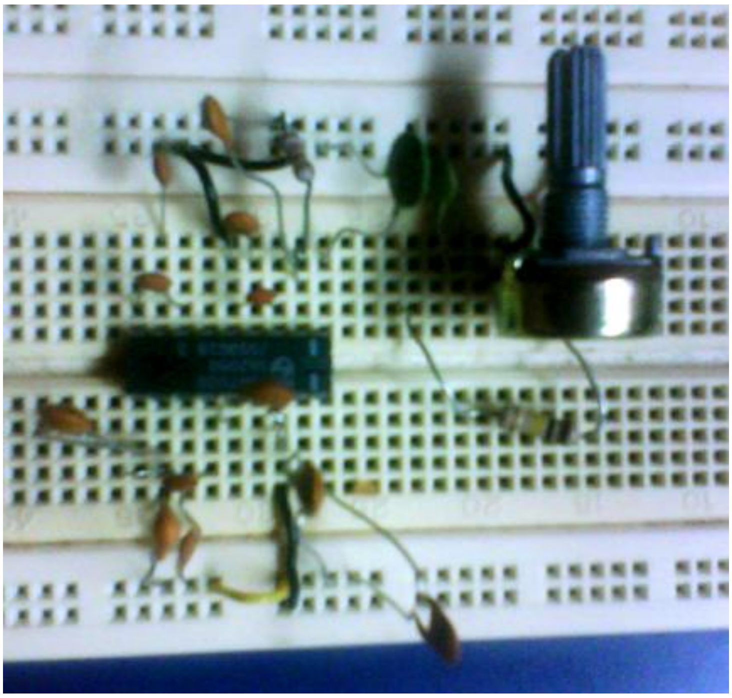

Figure 9 : FM Receiver circuit on breadboard

Figure 10 : FM Receiver Circuit on veroboard

Output of the receiver which captured from the radio waves was measured. The output that captured by the oscilloscope are shown in below Figure 11. The results of the measuring is summarized and shown in Table 1.

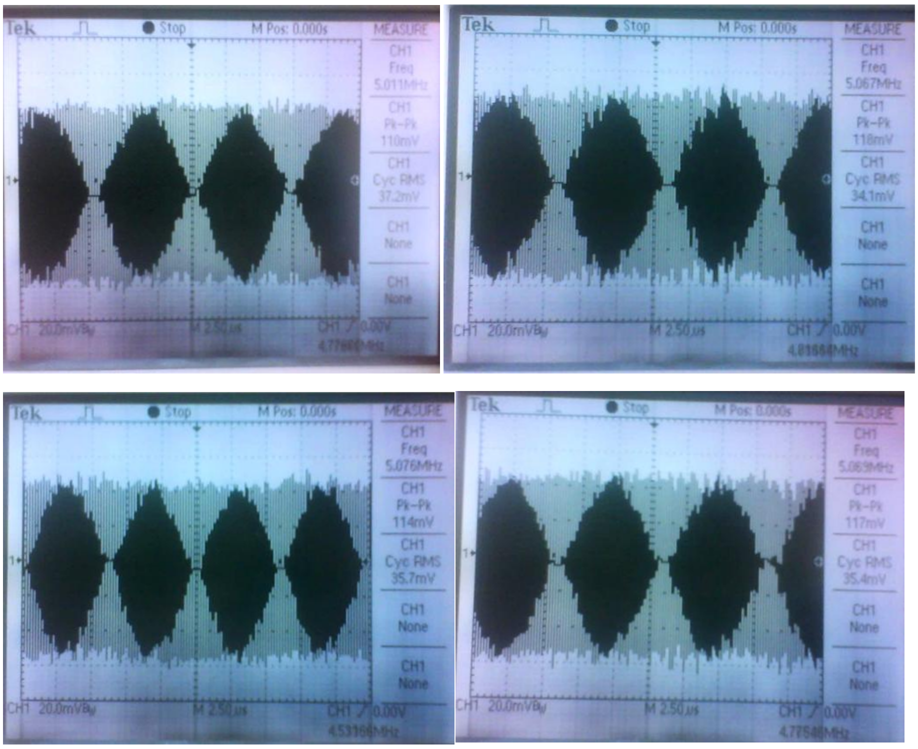

Figure 11 : Output of FM receiver captured by oscilloscope

Table 1 : Measured output from FM receiver circuits

Testing	RF input, $V_{pk\text{-}pk}$ (mV)	RF input, V_{rms} (mV)
1	114.00	35.70
2	110.00	37.20
3	118.00	34.10
4	117.00	35.40
Average	114.75	35.60

4.2 Charge Pump Circuit Simulation

Multisim software is used for the simulation parts. Charge pump circuit is constructed and simulated. Three types of simulations were done which focused on three different criteria which are,

- The effect of stages in the charge pumps circuit to the output.
- The effect of varies input voltage to the output.
- The effect of varies frequency of input signal at fix voltage to the output.

In the simulation, the source used for the charge pump circuits is sinusoidal voltage source and the output is monitored using oscilloscope.

4.2.1 The effect of stages in the charge pumps circuit to the output.

The objective of this simulation is to give better understanding on the effect of varies number of stages in the charge pumps circuits to its outputs. Different stages of charge pump circuits are constructed in the software, Multisim. For the simulation, the source of the simulation source is represented by a sinusoidal voltage source that set at fixed frequency 1 MHz and 1 V_{pk}. The output of the charge pump is measured by oscilloscope and DC voltmeter. The result of the simulation is shown in below figures (Figures 12-16). From the figure, in the oscilloscope, the Channel A represents the output value while the Channel B represents the input of the charge pump circuits.

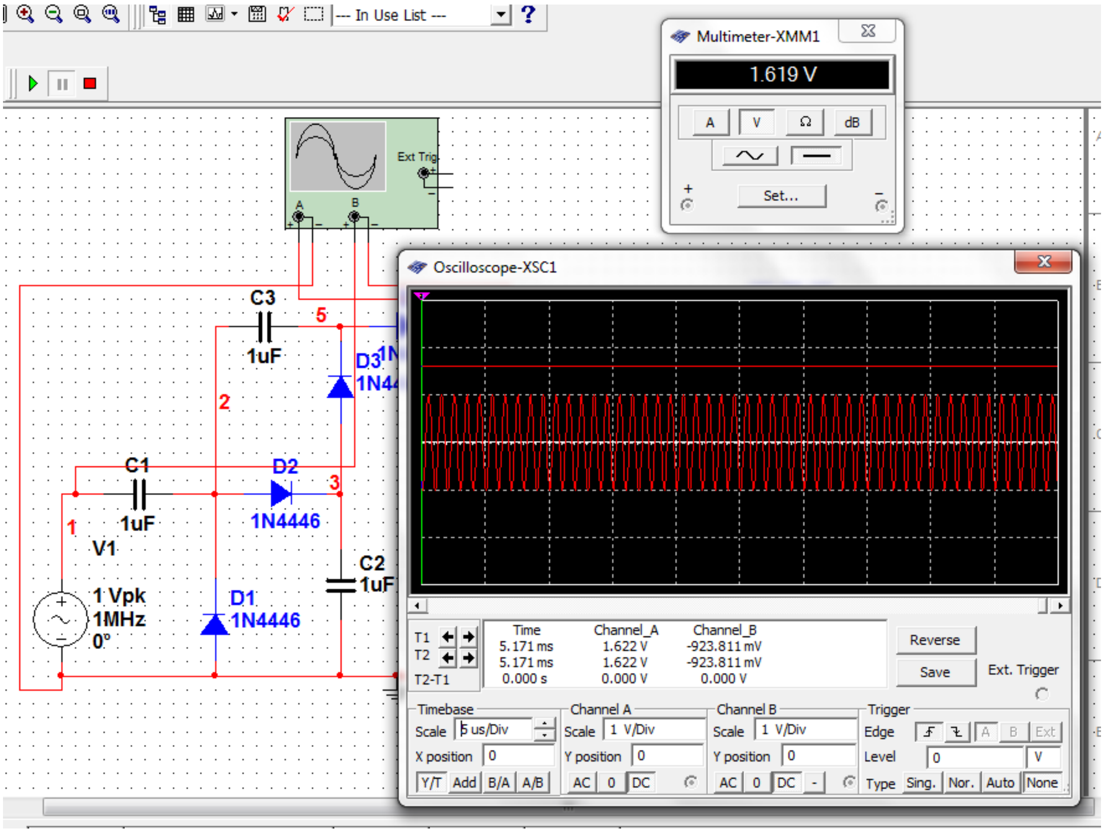

Figure 12　: Simulation result for 2 stages charge pump circuits

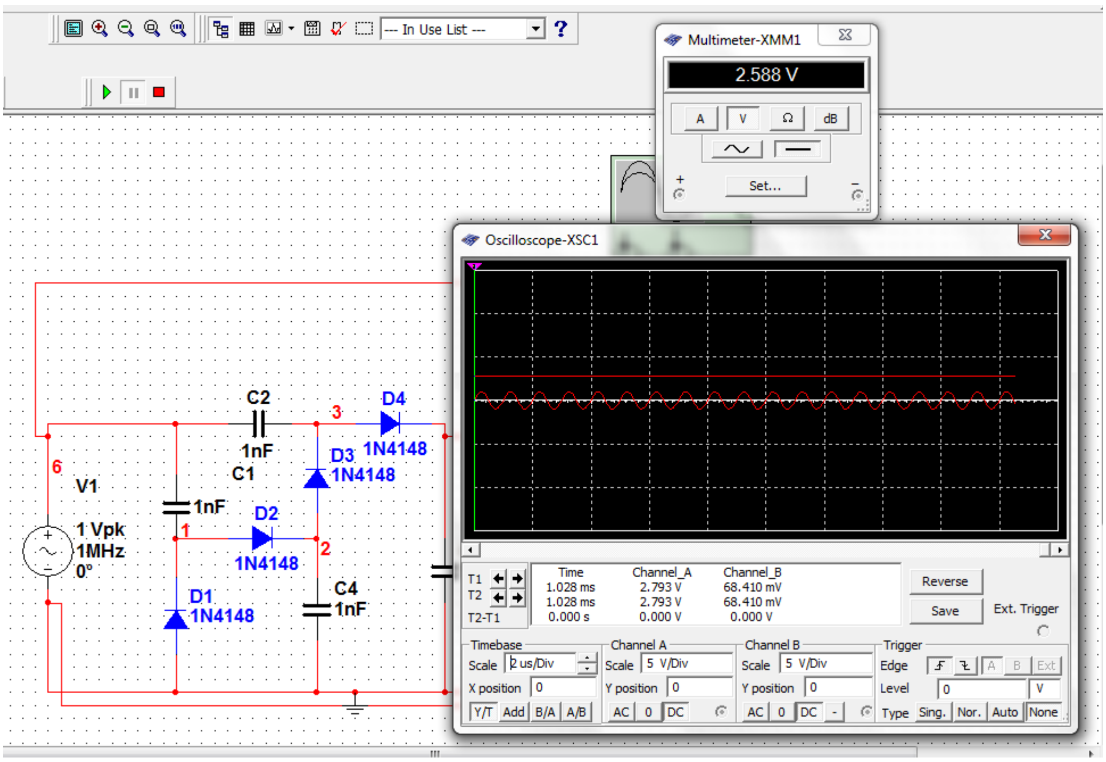

Figure 13　: Simulation result for 3 stages charge pump circuits

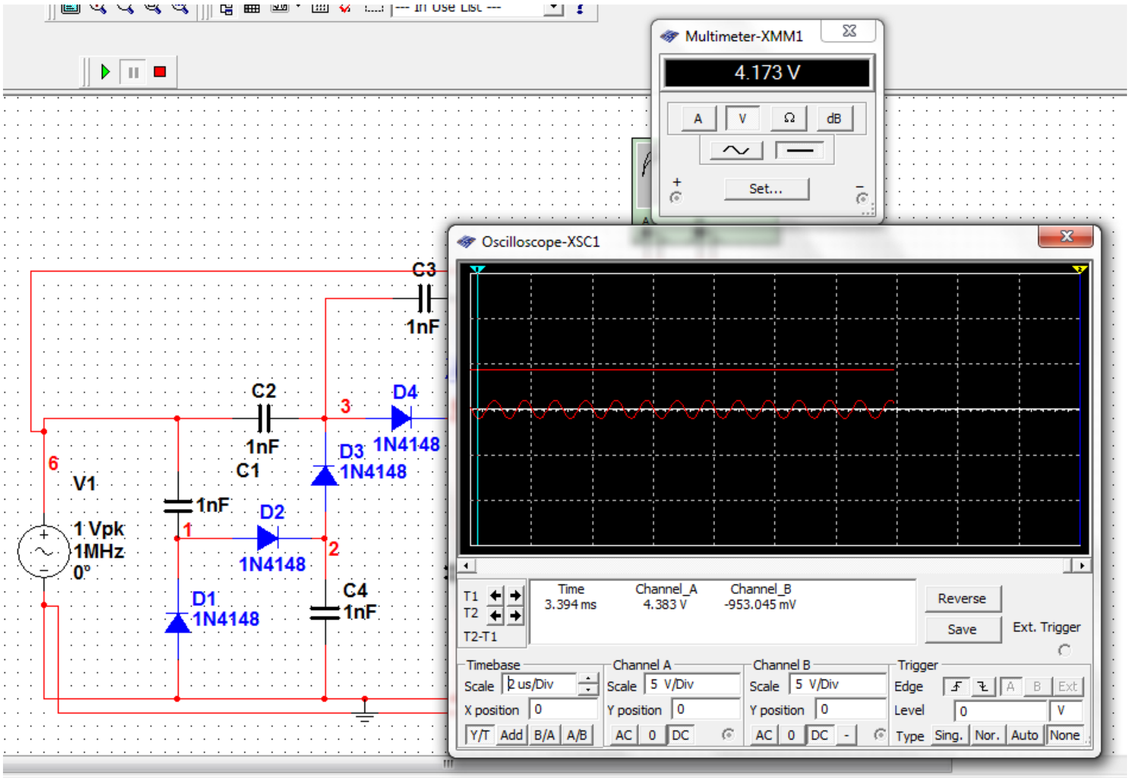

Figure 14 : Simulation result for 5 stages charge pump circuits

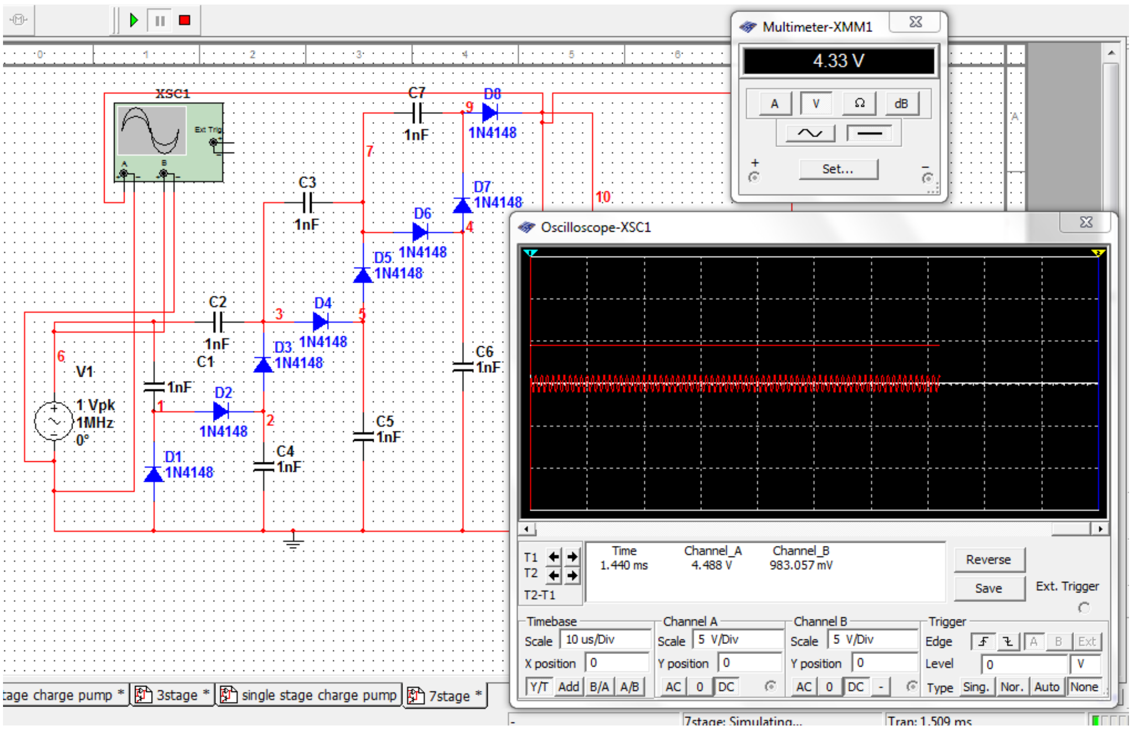

Figure 15 : Simulation result for 7 stages charge pump circuits

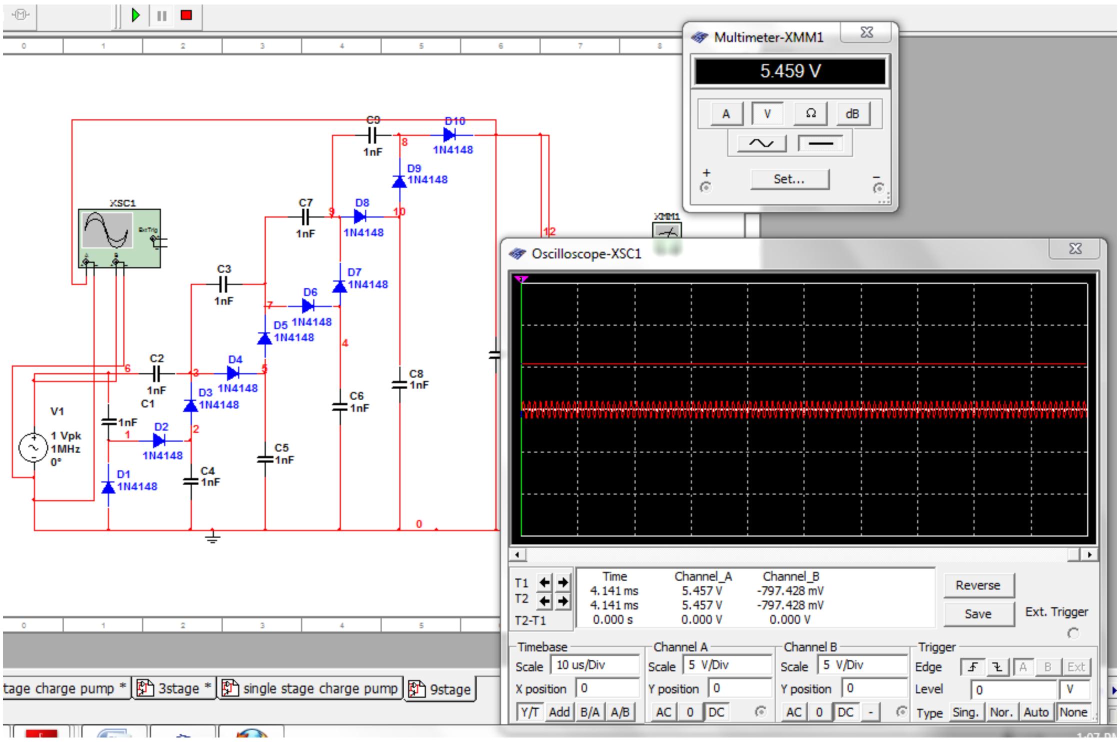

Figure 16 : Simulation result for 9 stages charge pump circuits

The result of the simulation is summarized into Table 2. Vrms is reading taken from the multimeter application in the Multisim and the Vmax is the max reading by the oscilloscope. Its conclude that , the more the stages of the charge pump circuits, the higher the voltage outputs at a fixed voltage input.

Table 2 : Simulation results of all stages

Number of Stages	V_{in} (V_{pk})	V_{rms} (V)	V_{max}(V)
2	1	1.656	1.659
3	1	2.588	2.793
5	1	4.173	4.383
7	1	4.330	4.488
9	1	5.459	5.457

4.2.2 The effect of varies input voltage to the output.

The objective of this simulation is to give better understanding on the effect of varies input voltage for the charge pumps circuits to its outputs. For this simulation, the 7 stage charge pump circuits input voltage varies from 100mV until 1.0V. The output then will be monitored again using multimeter and oscilloscope that available in the Multisim Software. The result of the simulation is shown in below figures (Figures 17-26). From the figure, again, as previous simulation, for the oscilloscope, the Channel A represents the output value while the Channel B represents the input of the charge pump circuits.

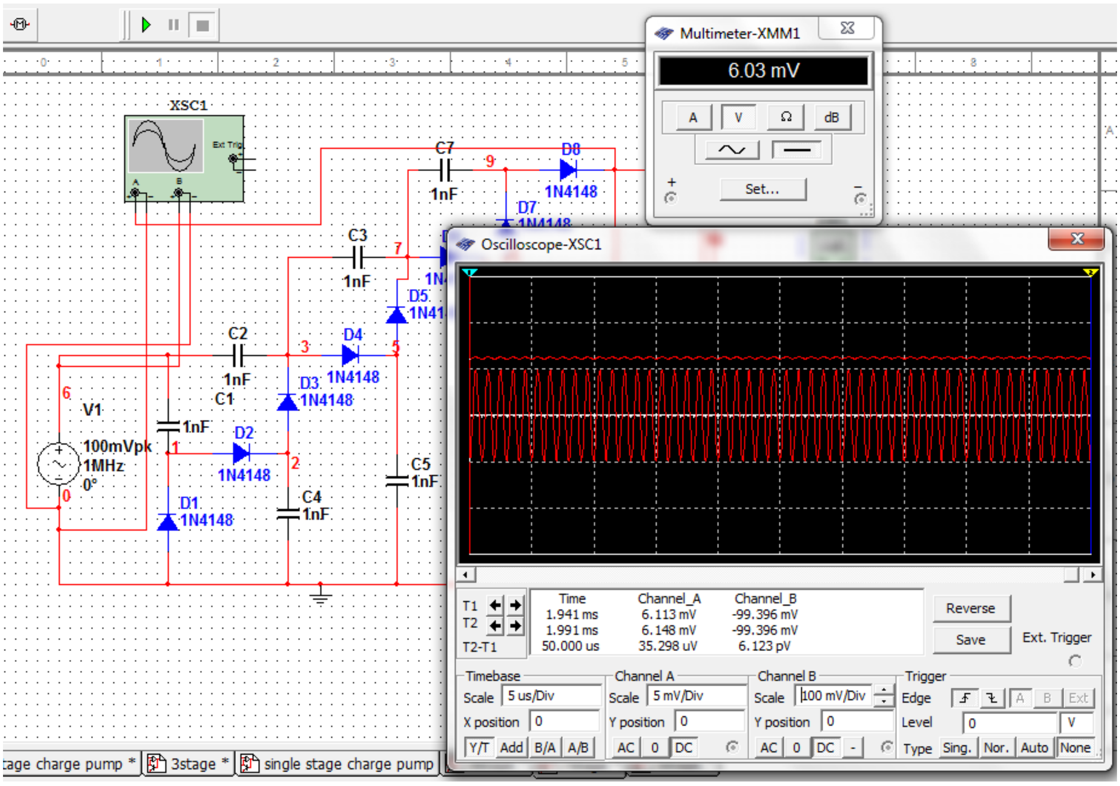

Figure 17 : Simulation result for Vin 100mV

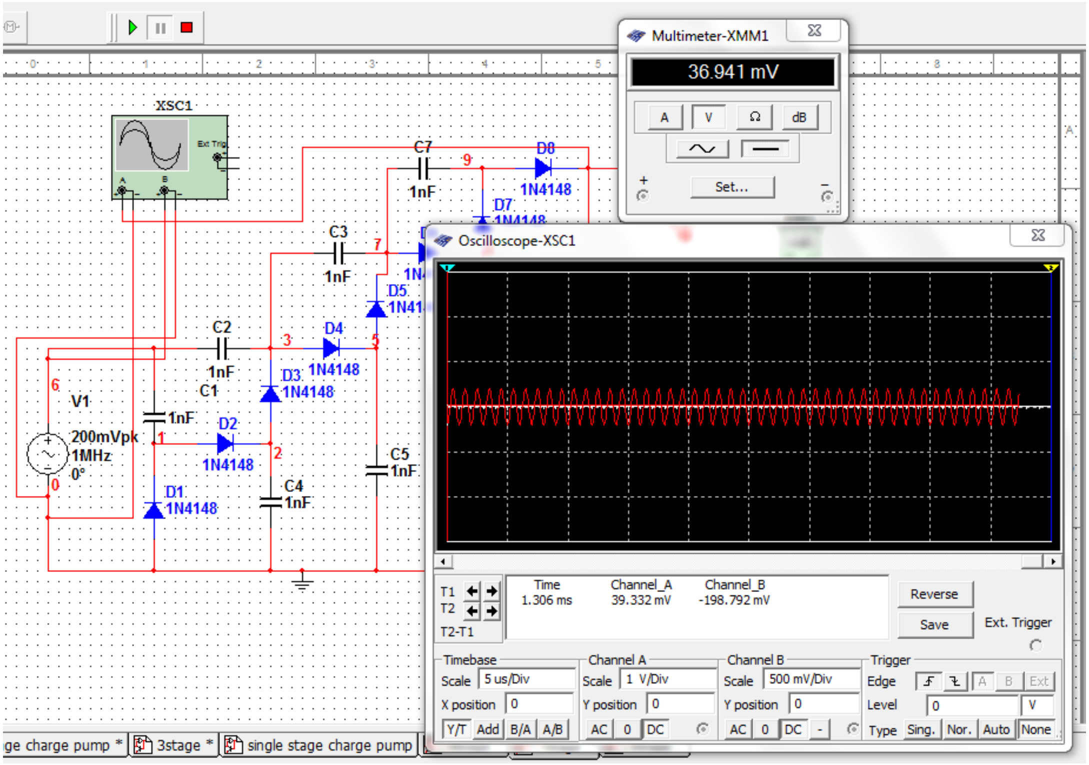

Figure 18 : Simulation result for Vin 200mV

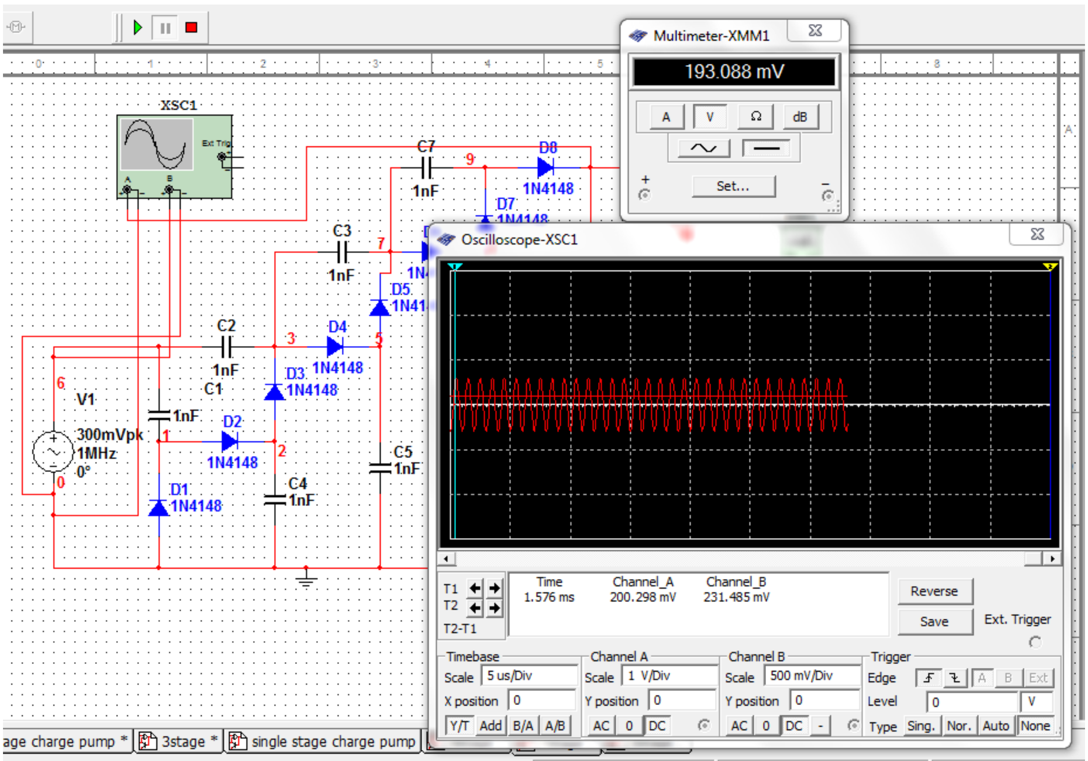

Figure 19 : Simulation result for Vin 300mV

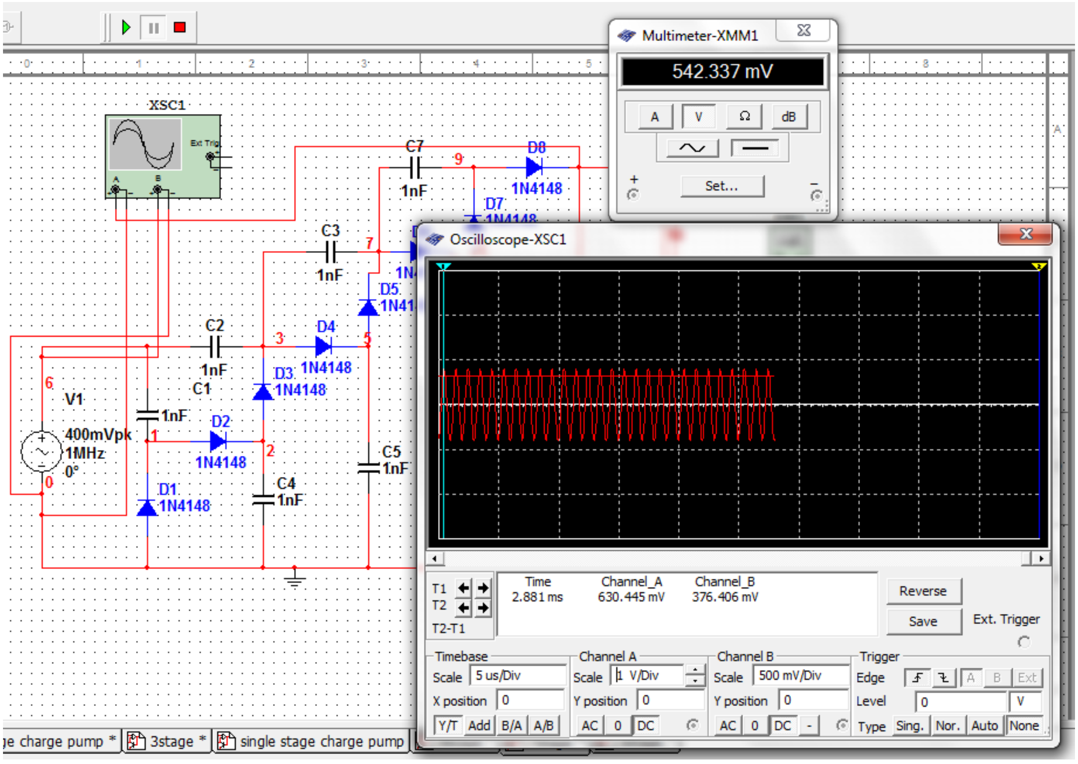

Figure 20　: Simulation result for Vin 400mV

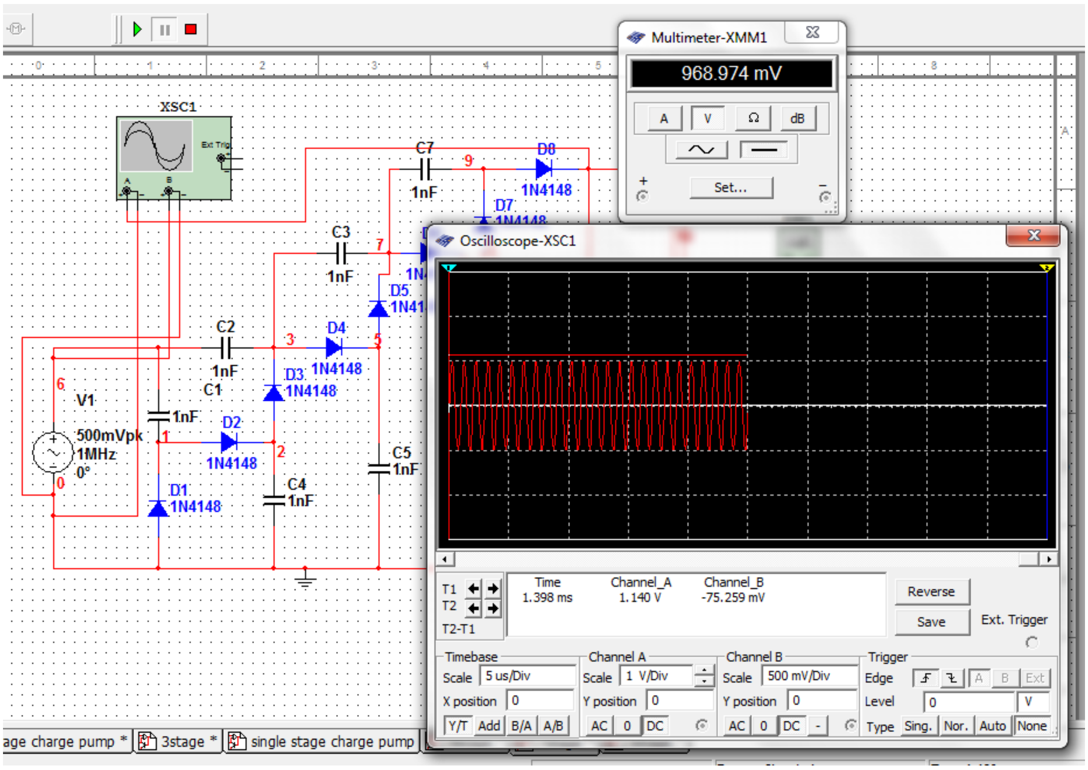

Figure 21　: Simulation result for Vin 500mV

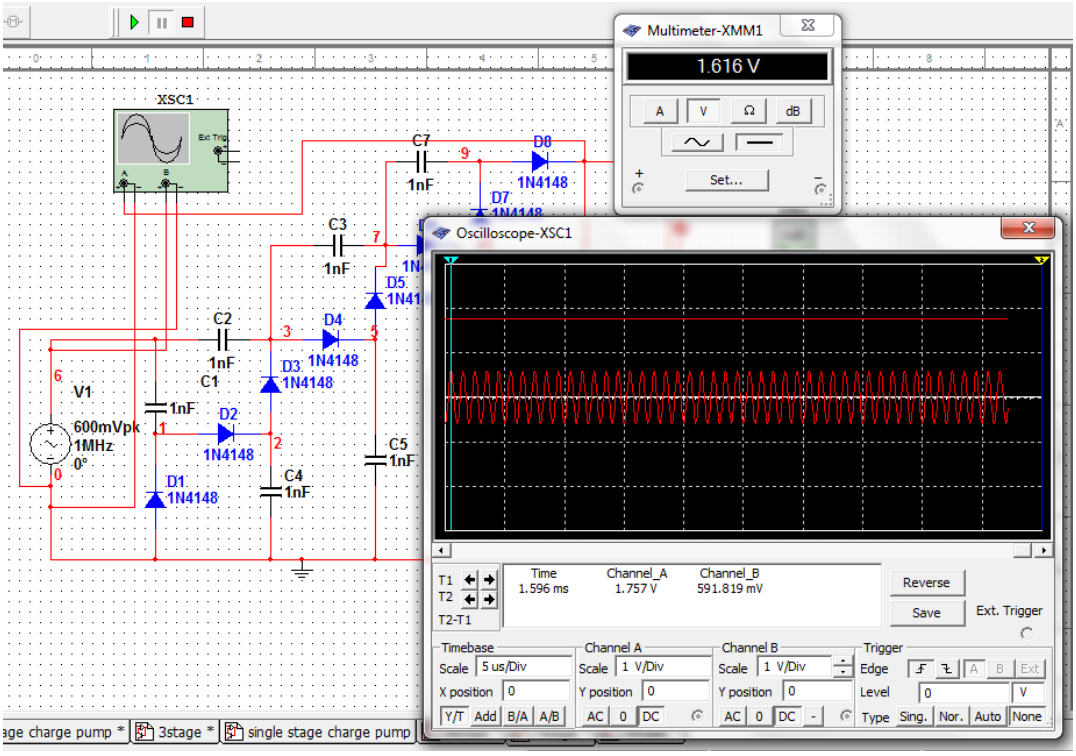

Figure 22 : Simulation result for Vin 600mV

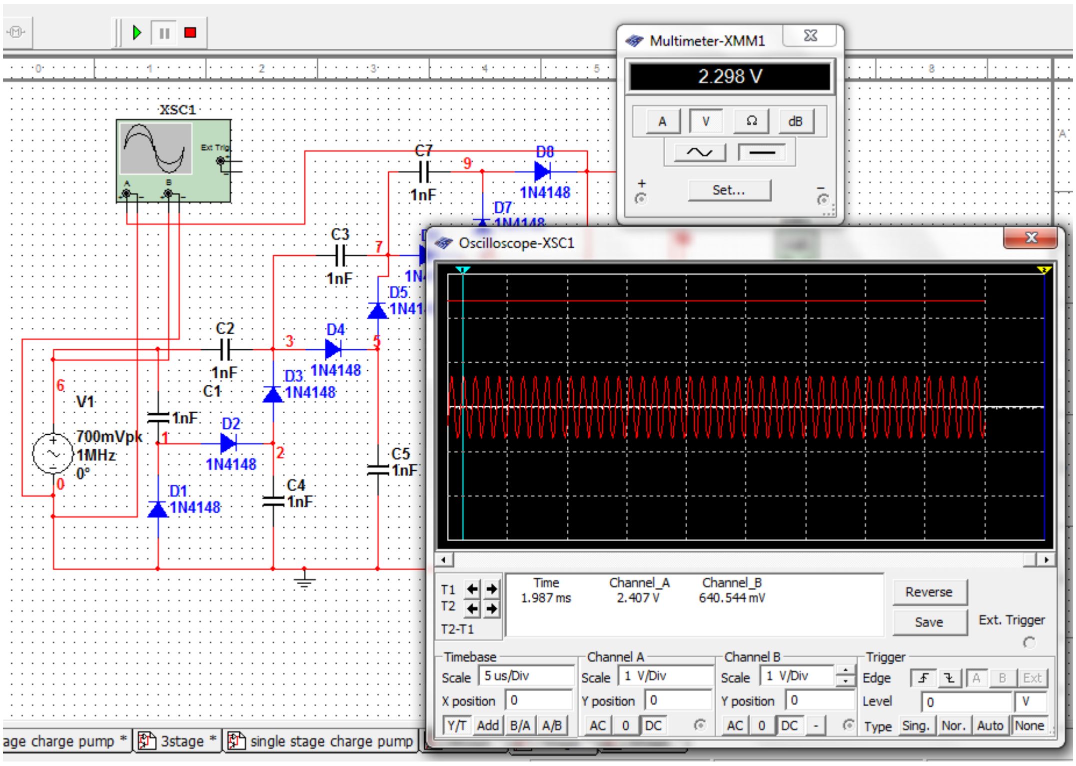

Figure 23 : Simulation result for Vin 700mV

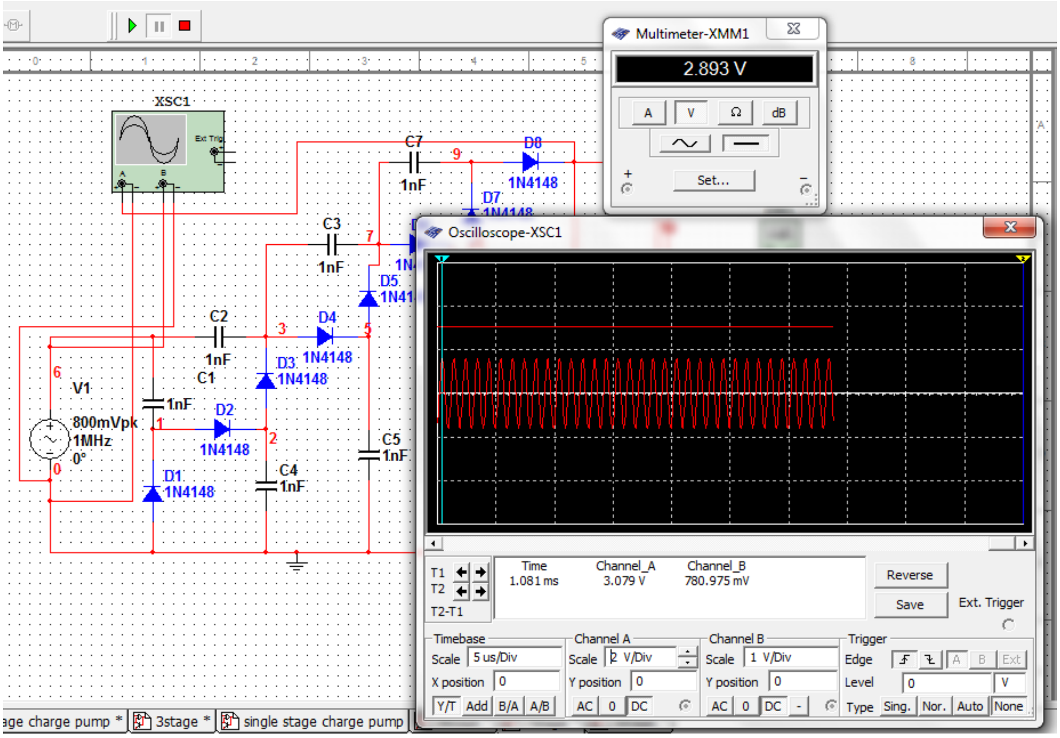

Figure 24 : Simulation result for Vin 800mV

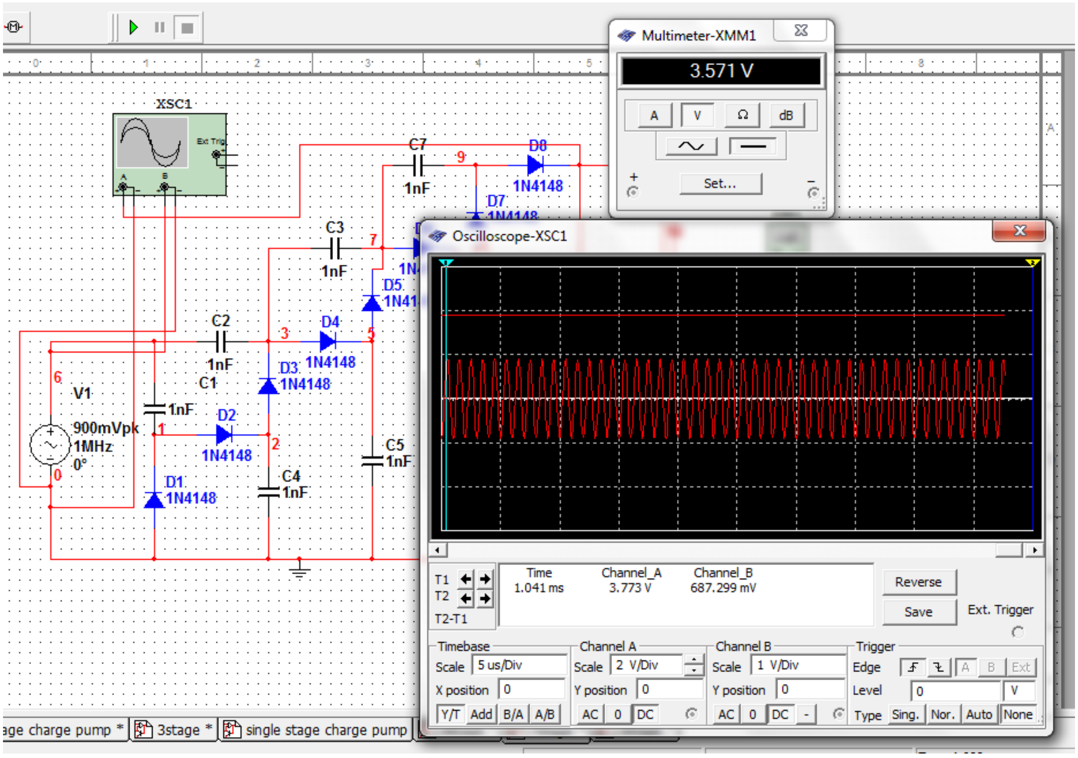

Figure 25 : Simulation result for Vin 900mV

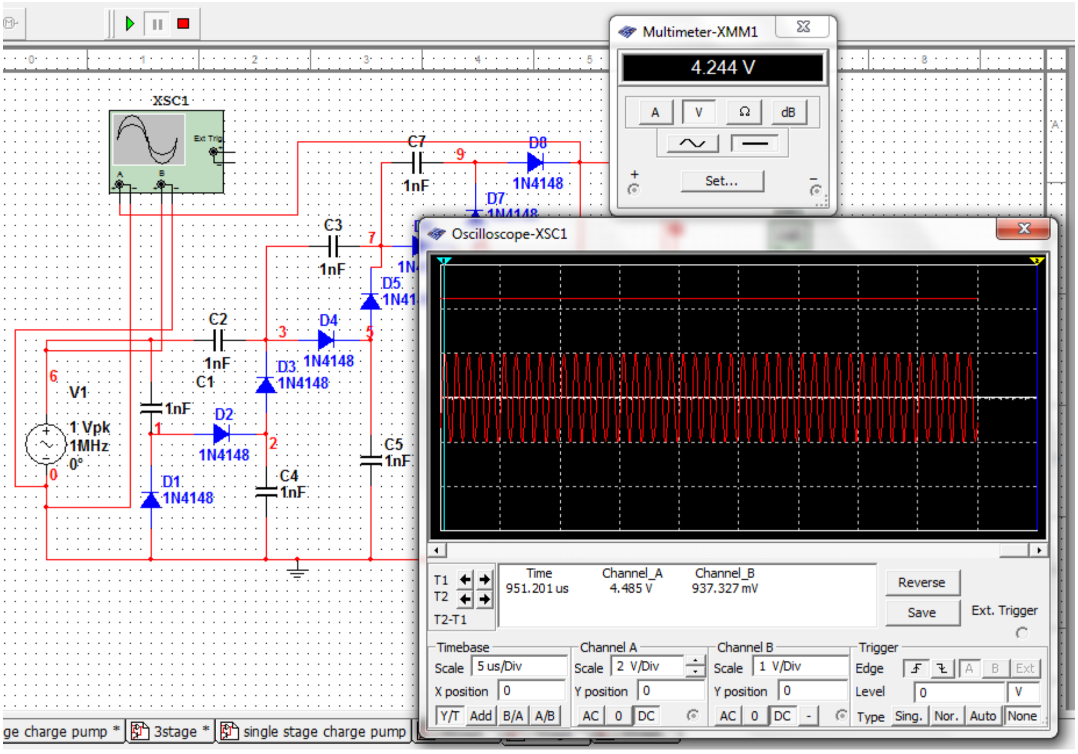

Figure 26 : Simulation result for Vin 1V

The result of the simulation is summarized into Table 3. Vrms is reading taken from the multimeter application in the Multisim and the Vmax is the max reading by the oscilloscope.

Table 3 : Simulation results of different voltage input value

V_{in} (mV)	V_{rms} (V)	V_{max}(V)
100	0.006	0.006
200	0.036	0.039
300	0.193	0.200
400	0.542	0.630
500	0.968	1.140
600	1.616	1.757
700	2.298	2.407
800	2.803	3.079
900	3.571	3.773
1000	4.244	4.485

4.2.3 The effect of varies frequency of input signal at fix voltage to the output.

The objective of this simulation is to give better understanding on the effect of varies frequency of input signal for the charge pumps circuits to its outputs. For this simulation, the 7 stage charge pump circuits again is used for simulation, and the frequency of the input source will be varies from 100 kHz until 3 MHz. The frequency range is chosen since the available signal generator in the EE lab only able to generate up to 3MHz frequency signals. The output then will be monitored again using multimeter and oscilloscope that available in the Multisim Software. The results of the simulation are shown in below figures (Figures 27-33). From the figure, again, as previous simulation, for the oscilloscope, the Channel A represents the output value while the Channel B represents the input of the charge pump circuits.

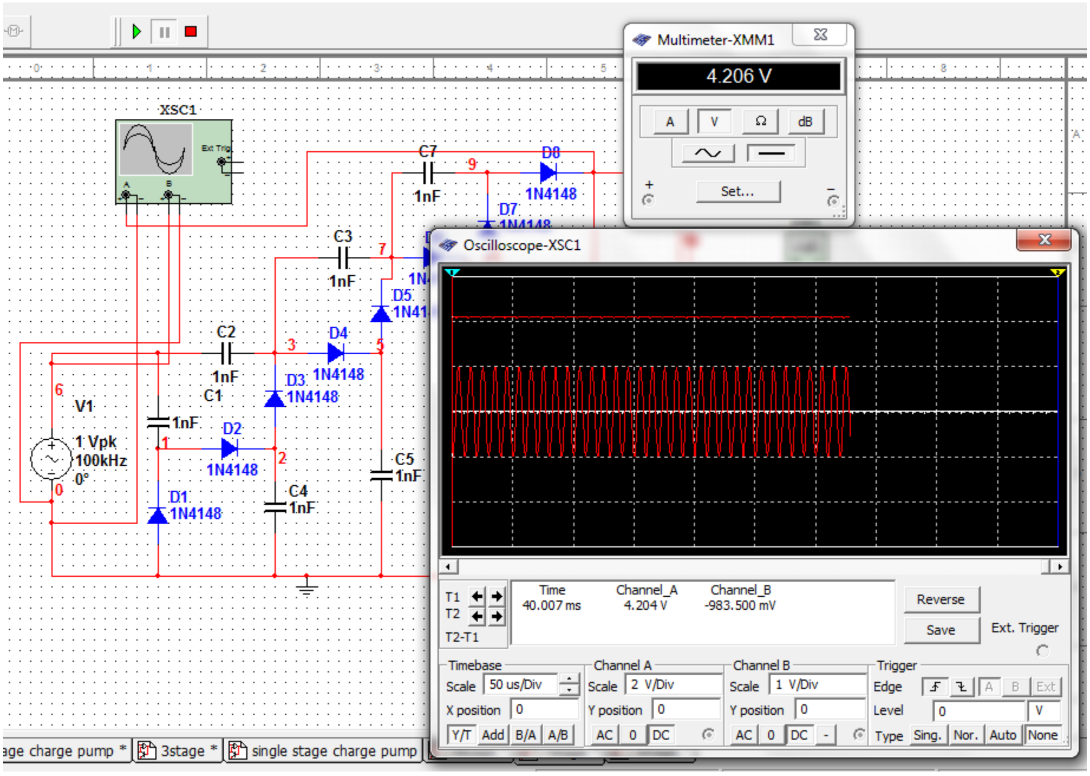

Figure 27 : Simulation result for frequency input 100 kHz

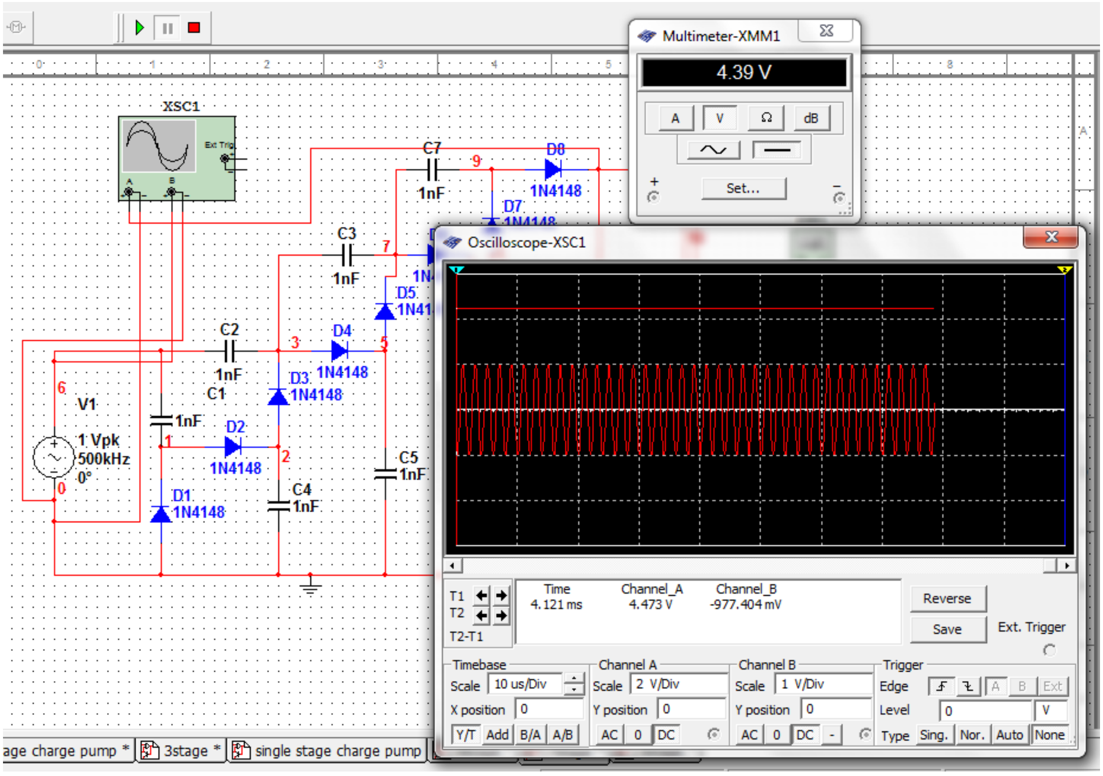

Figure 28 : Simulation result for frequency input 500 kHz

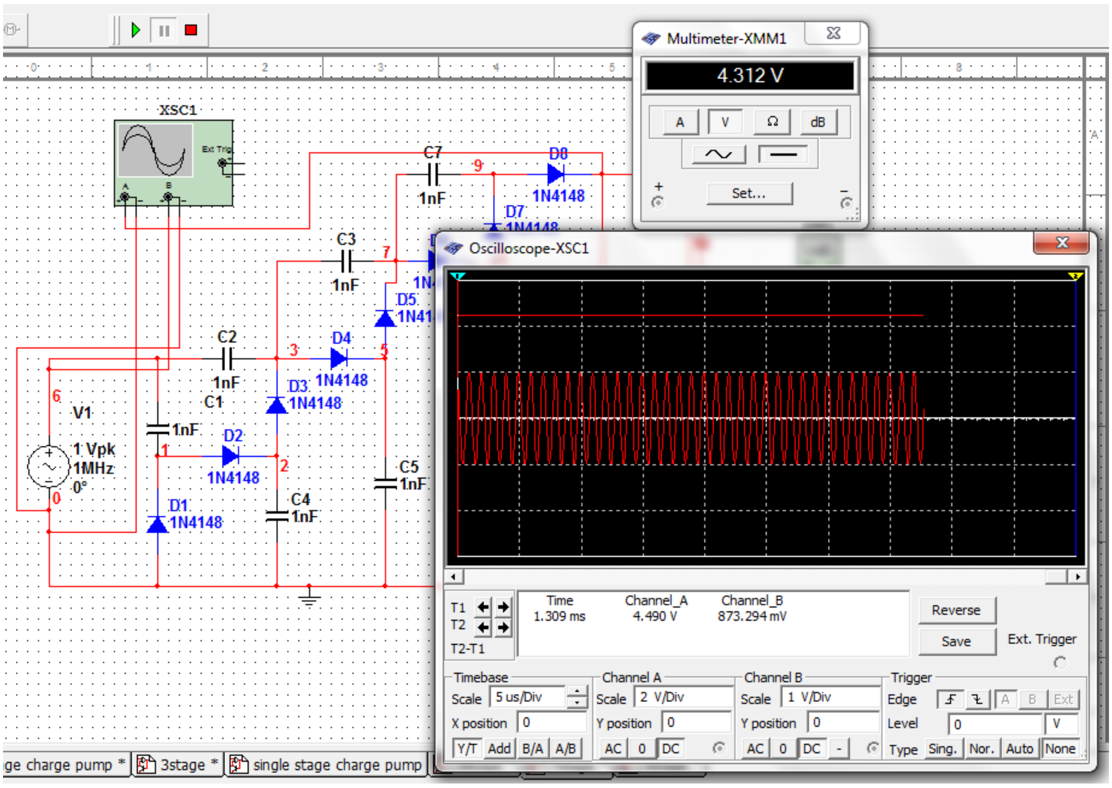

Figure 29 : Simulation result for frequency input 1 MHz

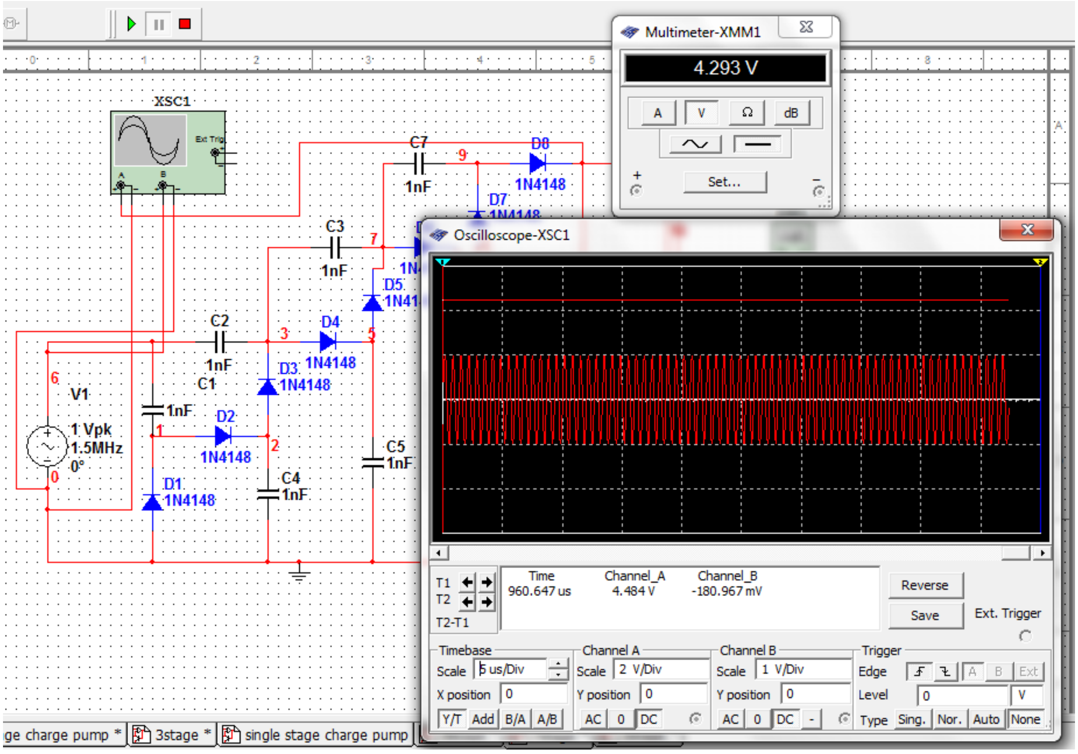

Figure 30 : Simulation result for frequency input 1.5 MHz

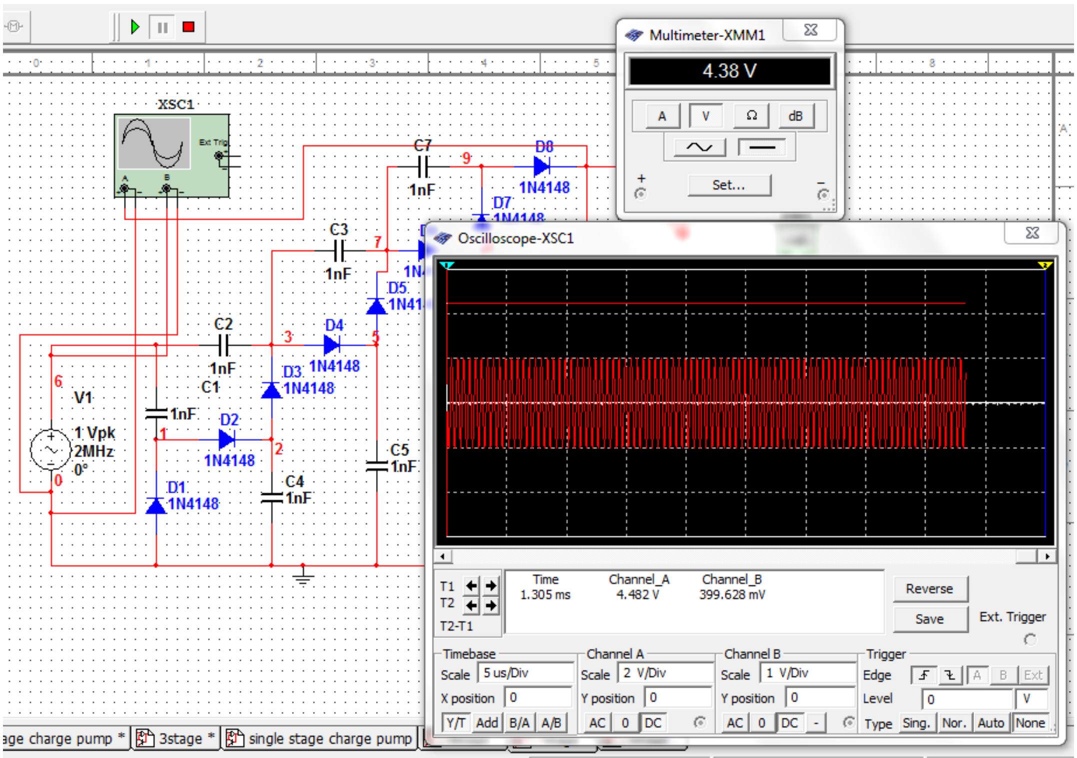

Figure 31 : Simulation result for frequency input 2 MHz

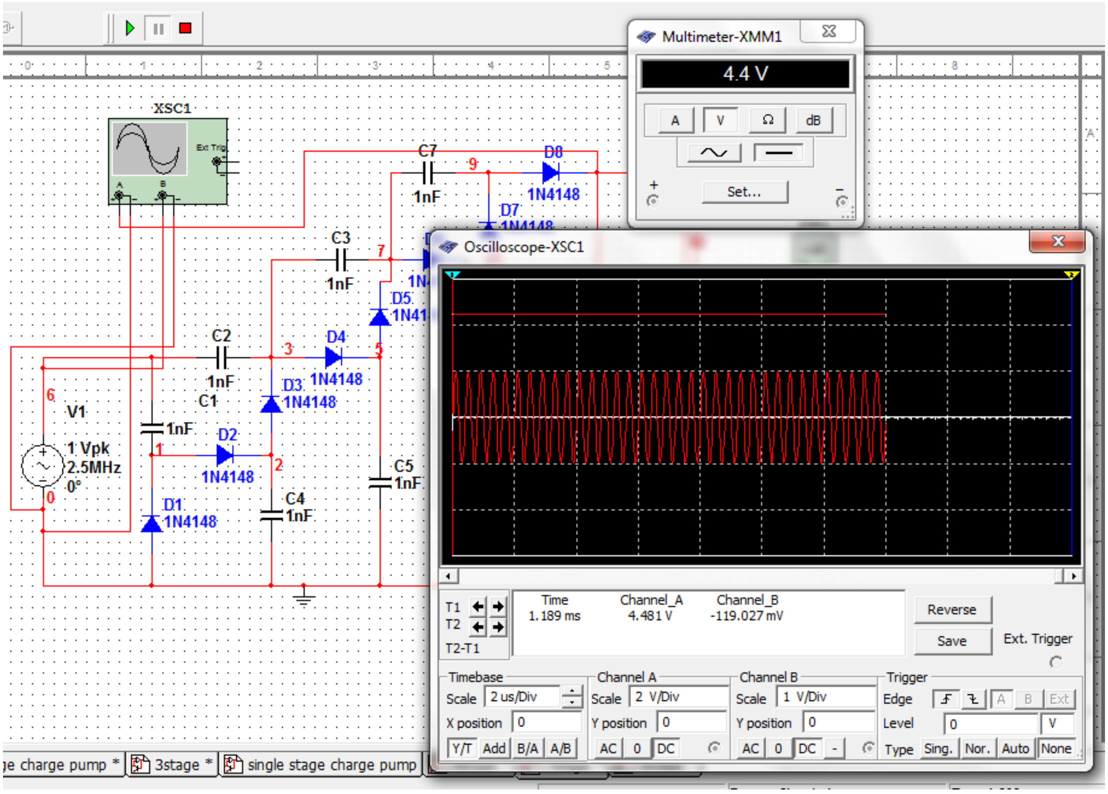

Figure 32 : Simulation result for frequency input 2.5 MHz

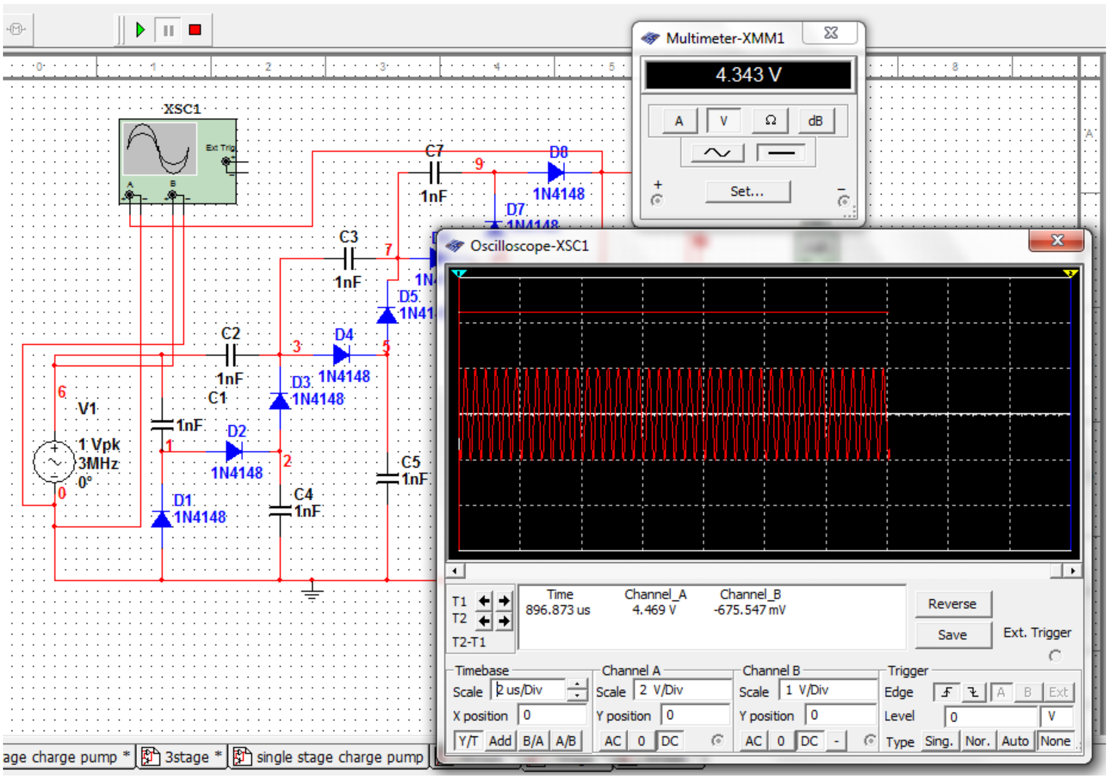

Figure 33 : Simulation result for frequency input 3 MHz

The results of the simulation are summarized into Table 4. V_{rms} is reading taken from the multimeter application in the Multisim and the V_{max} is the max reading by the oscilloscope.

Table 4 : Simulation results for varies frequency of input signal

Frequency Input Voltage (MHz)	V_{rms} (V)	V_{max}(V)
0.1	4.206	4.204
0.5	4.390	4.473
1.0	4.312	4.490
1.5	4.293	4.484
2.0	4.380	4.482
2.5	4.400	4.481
3.0	4.343	4.469

4.3 Charge Pump Circuit Construction and Testing

The charge pump circuit is construct using two types of diodes which are DN4148 diodes (Silicon Epitaxial Planar Diode), and OA90 diodes (Germanium Diode). The circuit is constructed directly on the veroboard as shown in Figure 34, and the signal generator is used as the source and the output is measured and monitored using digital oscilloscope available in EE Lab as shown in Figure 35.

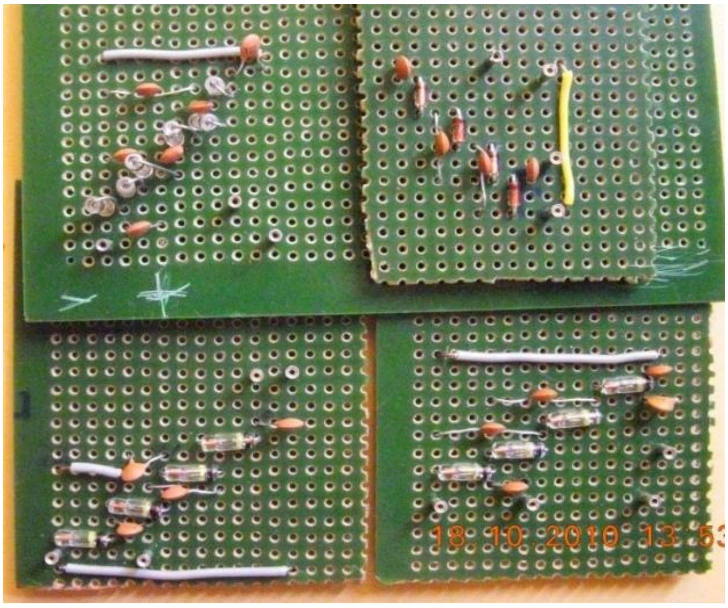

Figure 34 : Constructed charge pump circuit.

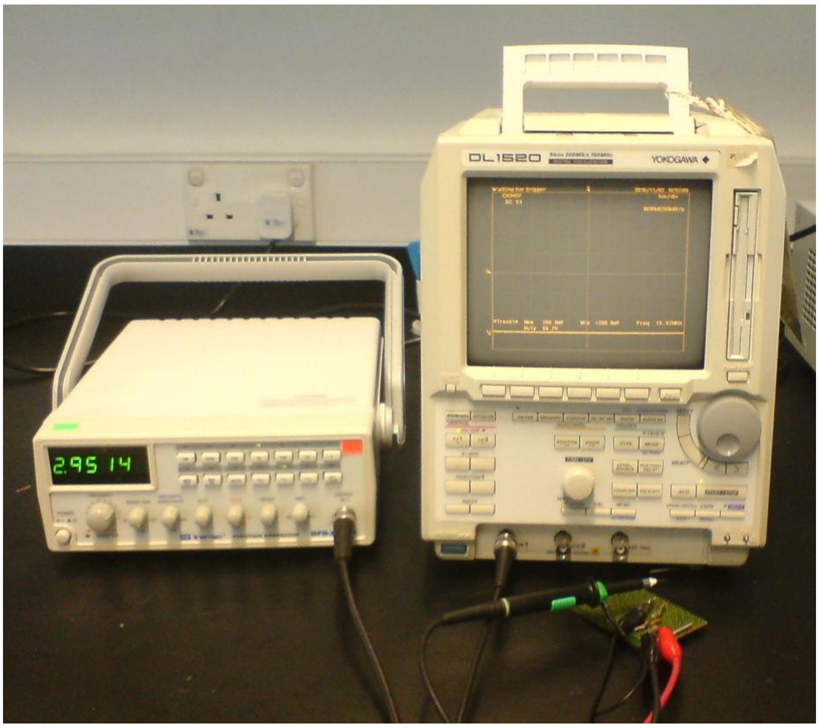

Figure 35 : Charge pump circuit during testing

4.3.1 Constructed charge pump using DN4148

Initially the circuit is design according to the simulation result of circuit using, DN4148 diodes and 1uF capacitor and 3 stages of charge pump circuit. The signal generator was set to 1 $V_{pk-pk,}$ and the frequency is varies throughout the testing which are from 0.5 MHz until 3 MHz where 3MHz is the highest frequency able to generate from the signal generator. The results of the testing are shown in figures below (Figure 36-42). Trace 1 is the output voltage from the charge pump circuit while the Trace 2 is the input of the charge pump circuits. For the waveform, the waveform for each traces are corresponding to its ground which could be seen at left of the wave form.

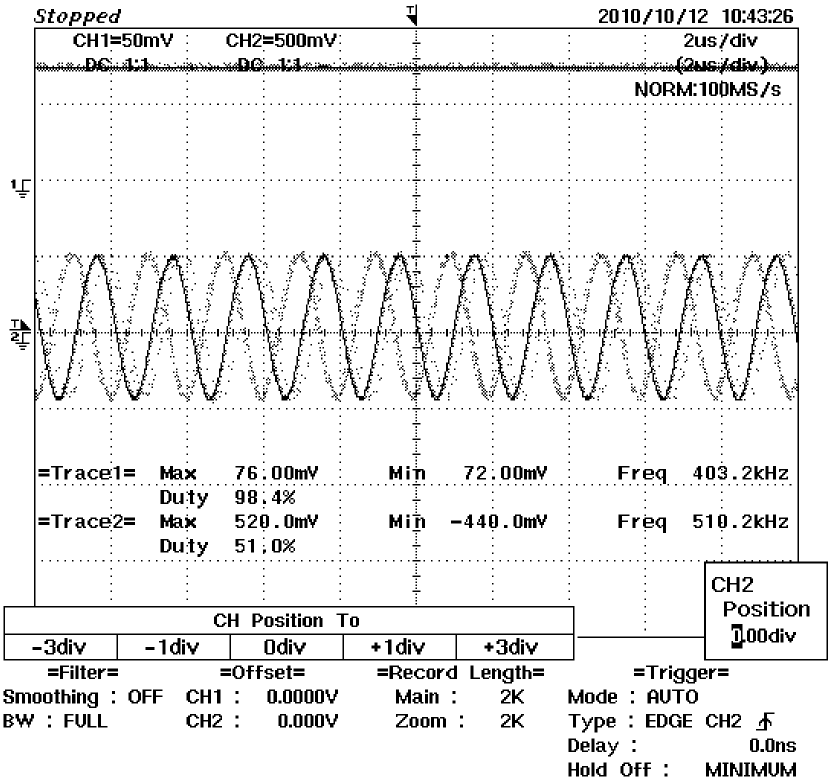

Figure 36 : DN4148 charge pump testing using frequency 0.5 MHz

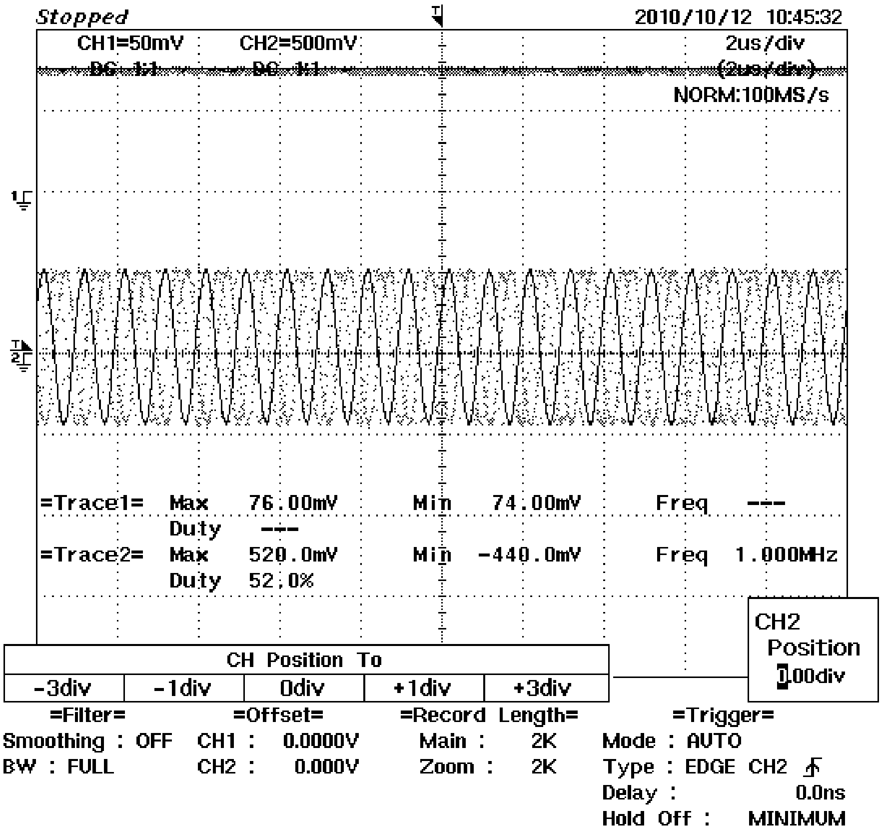

Figure 37 : DN4148 charge pump testing using frequency 1.0 MHz

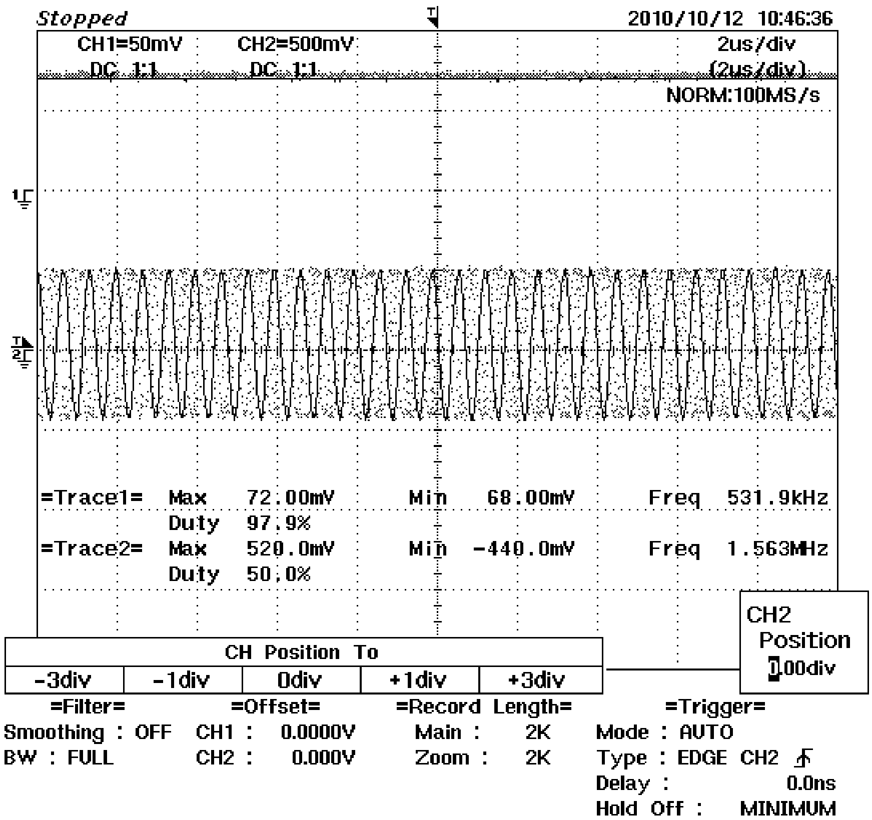

Figure 38 : DN4148 charge pump testing using frequency 1.5 MHz

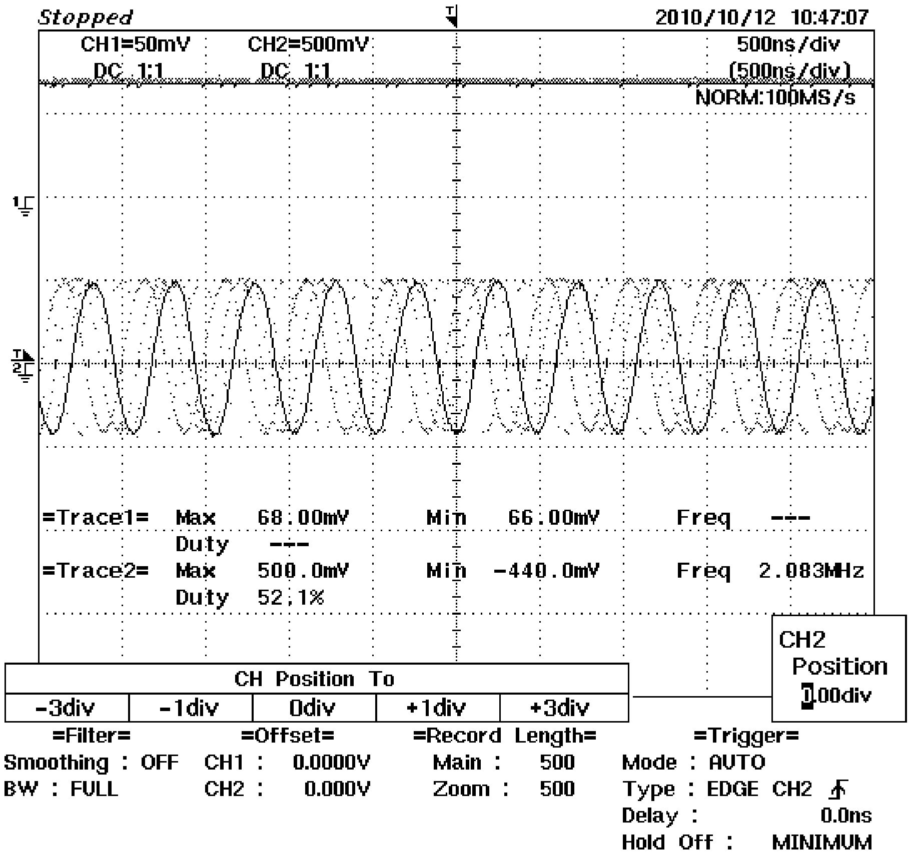

Figure 39 : DN4148 charge pump testing using frequency 2.0 MHz

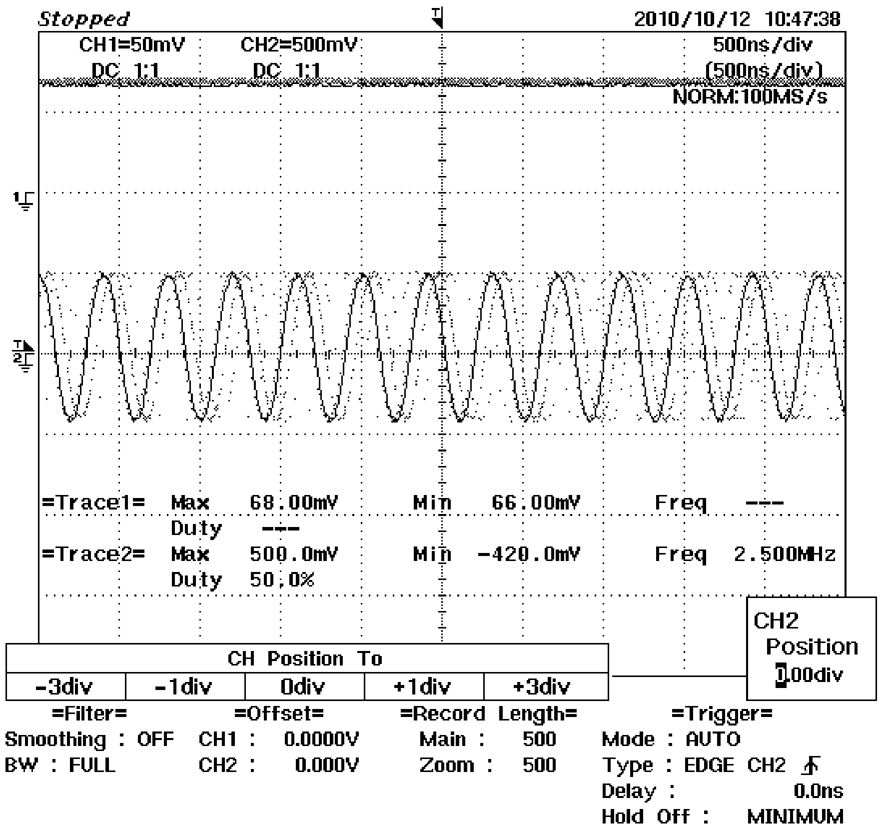

Figure 40 : DN4148 charge pump testing using frequency 2.5 MHz

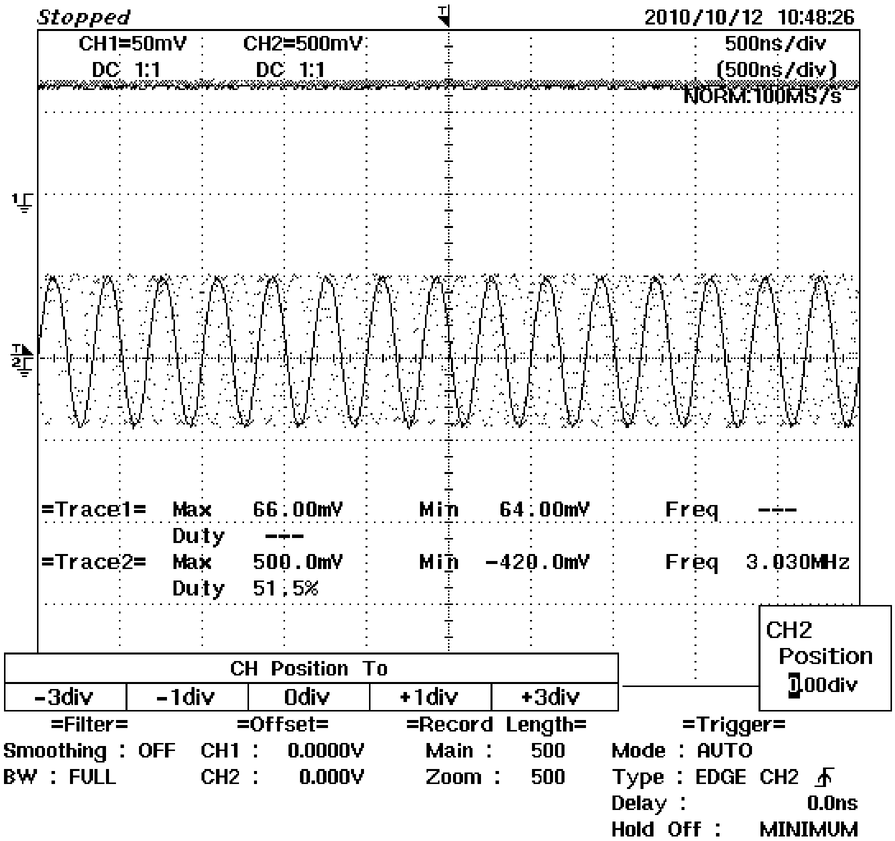

Figure 41 : DN4148 charge pump testing using frequency 3.0 MHz

All the results shown in figures above are summarized in Table 5. From the results, it shows that the charge pump circuits fails to works as simulation shows. This occurs due to the threshold voltage of DN4148 measured using digital multimeter actually is 592mV. Therefore the circuit fails to work.

Table 5 : DN4148 charge pump circuit results

Frequency (MHz)	Output Voltage (mV)	
	Max	Min
0.5	76.0	72.0
1.0	76.0	74.0
1.5	72.0	68.0
2.0	68.0	66.0
2.5	68.0	66.0
3.0	66.0	64.0

4.3.2 Constructed charge pump using OA90

Since the DN4148 charge pump circuits is not working due to its high threshold voltage, the DN4148 is replaced by OA90 diodes which germanium diode that has lower threshold voltage. The threshold voltage of OA90 measured is 320mV. The same circuit is constructed but the DN4148 is replaced by OA90 diodes as shown in Figure 42.

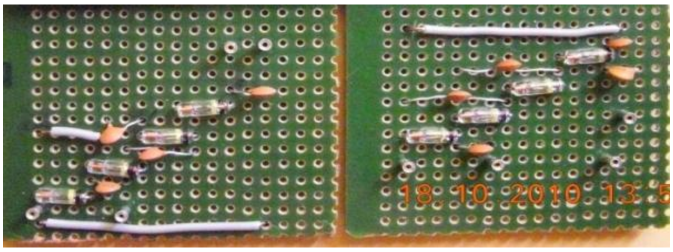

Figure 42 : OA90 charge pump circuits

The constructed charge pump then are tested again same procedure as previous testing using signal generator as source and the digital oscilloscope to monitor the output. Since the first test shows that the charge pump circuits works, the charge pump then tested again by varying the voltage input from 0.6 V until 4.4V. The results are shown in figures below (Figure 43-50). Again, Trace 1 shows the output and Trace 2 shows the input of the charge pump circuit.

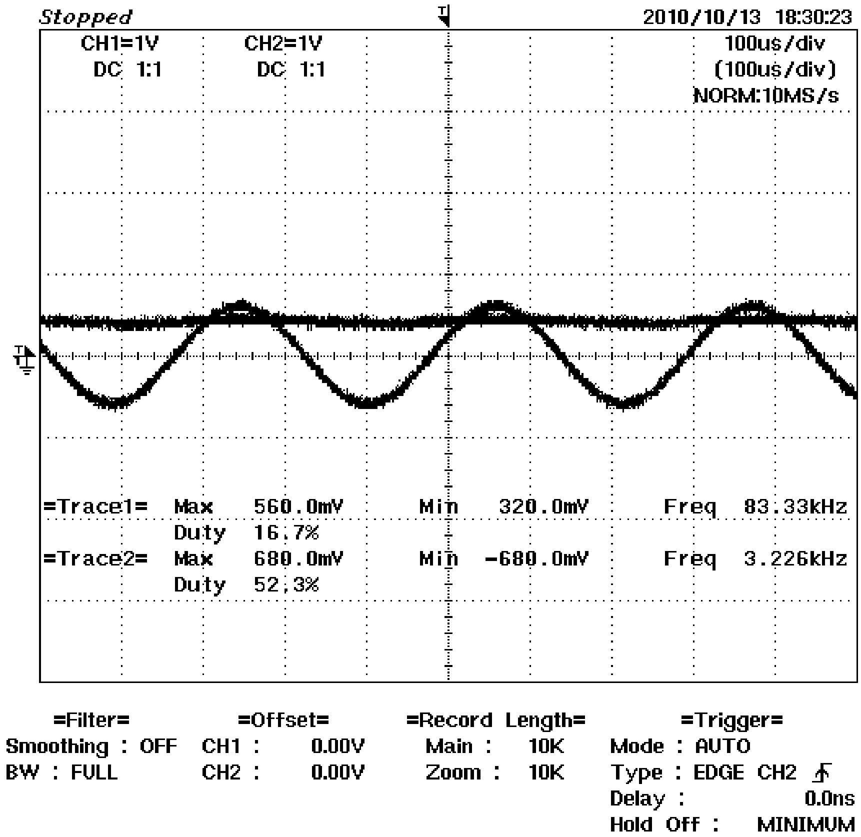

Figure 43　: OA90 charge pumps with $0.68V_{pk\text{-}pk}$ source

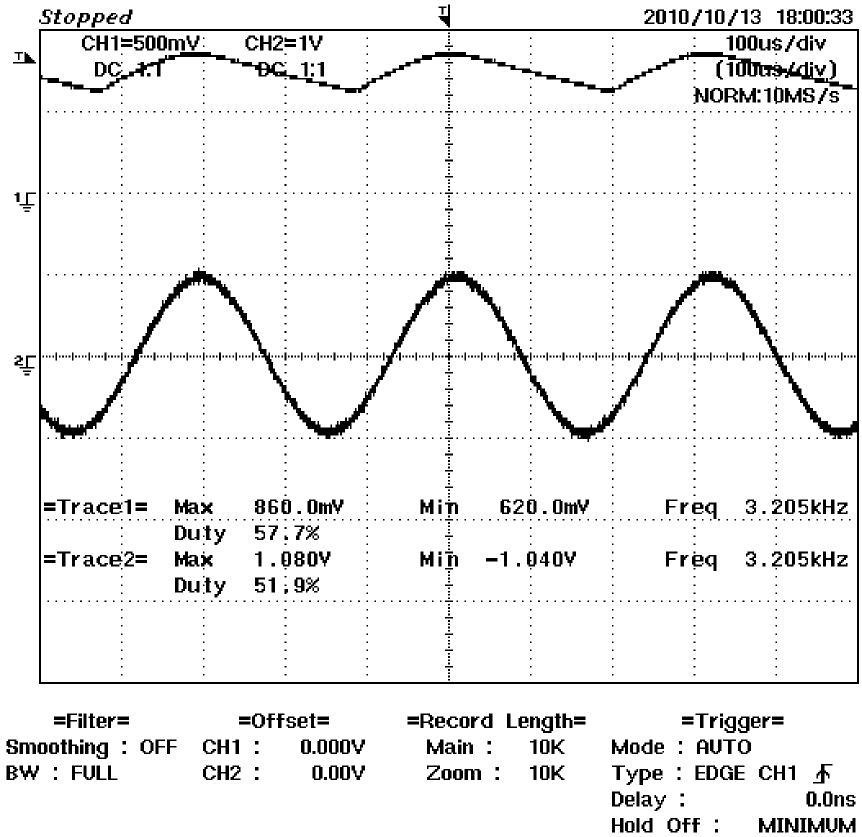

Figure 44　: OA90 charge pumps with $1.080V_{pk\text{-}pk}$ source

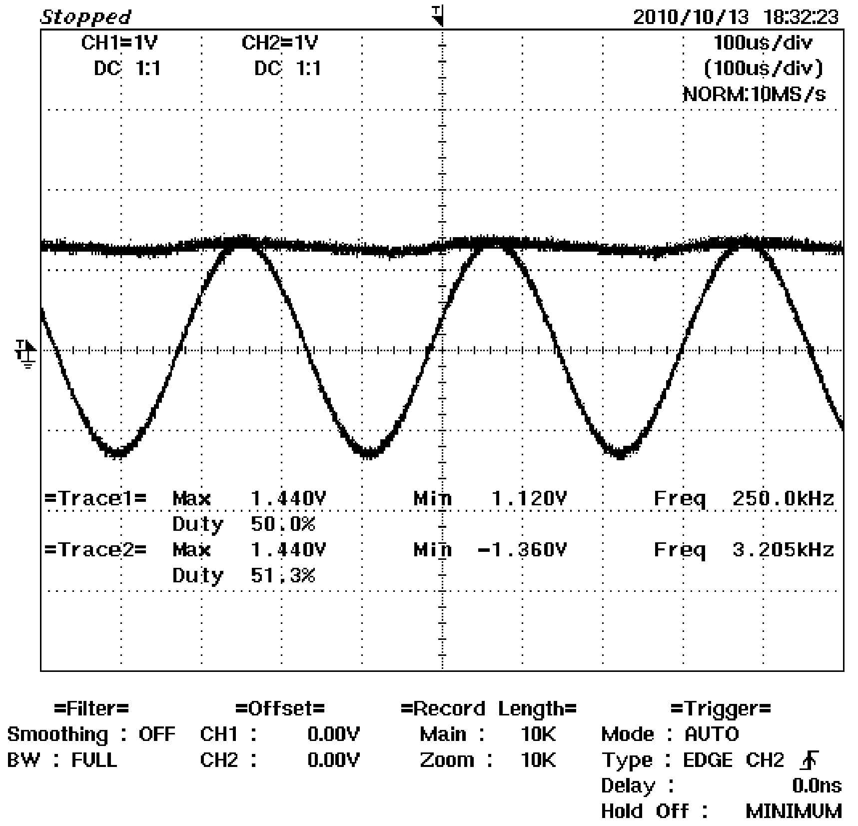

Figure 45 : OA90 charge pumps with 1.44V_{pk-pk} source

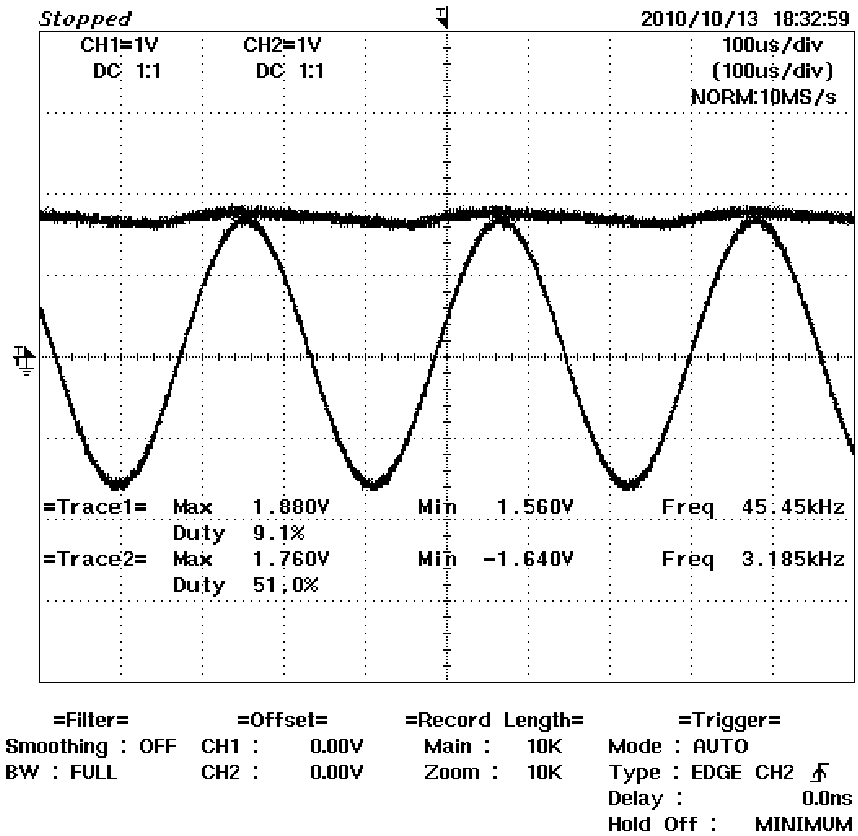

Figure 46 : OA90 charge pumps with 1.76V_{pk-pk} source

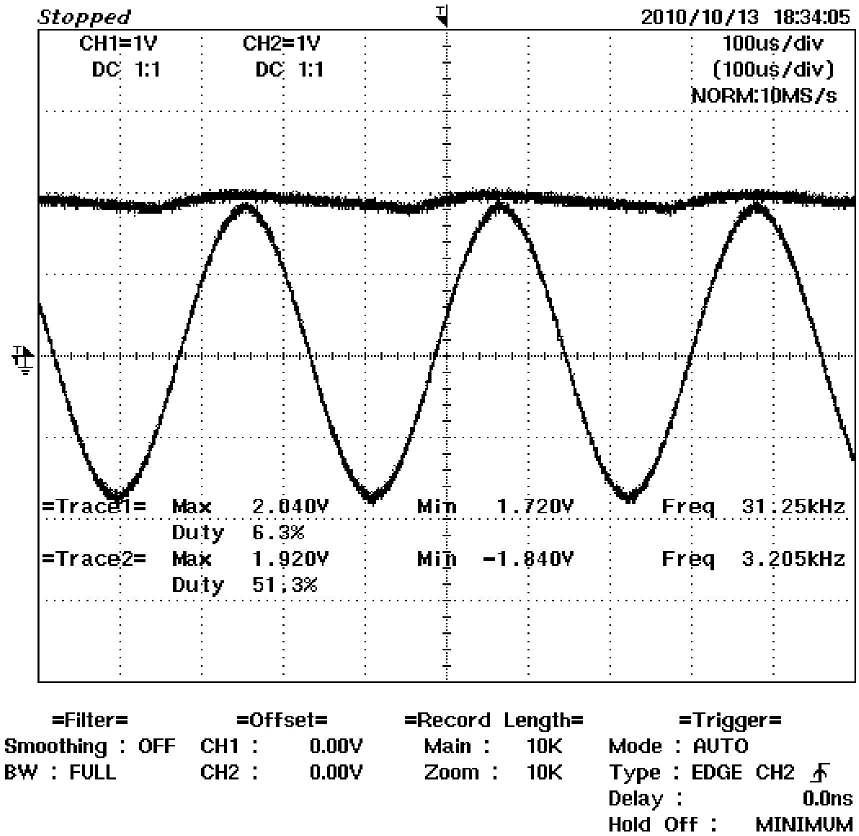

Figure 47 : OA90 charge pumps with 1.92$V_{pk\text{-}pk}$ source

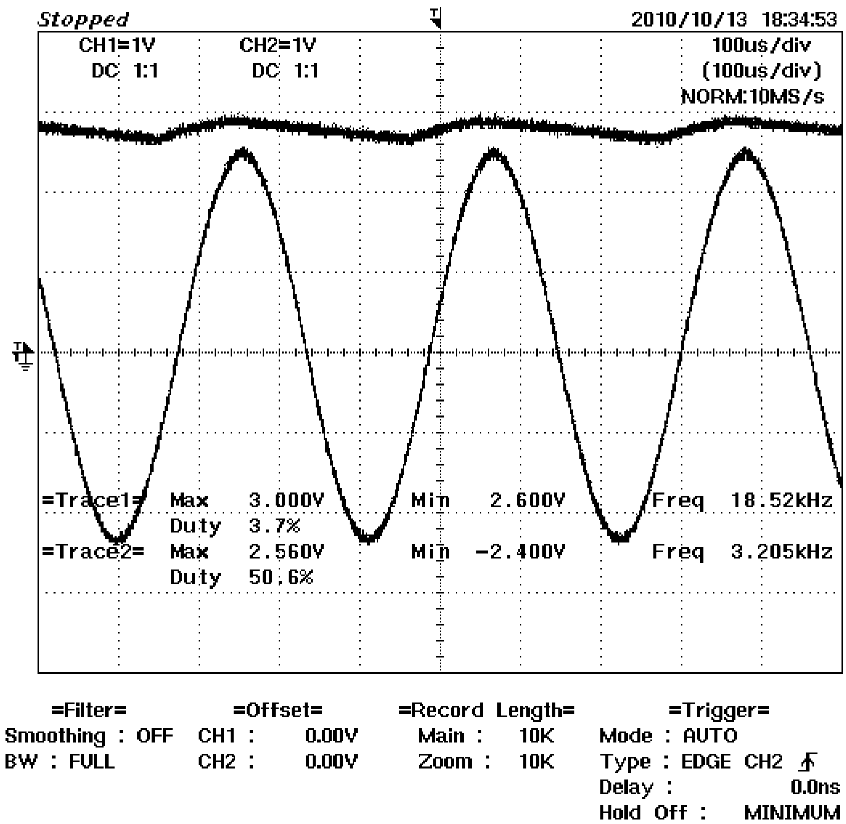

Figure 48 : OA90 charge pumps with 2.56$V_{pk\text{-}pk}$ source

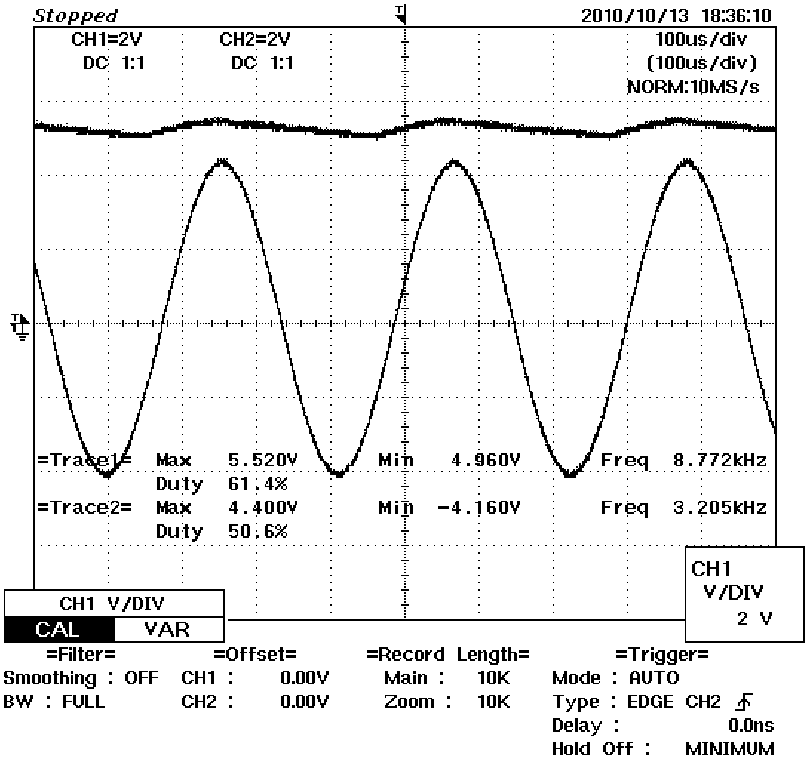

Figure 49 : OA90 charge pumps with 4.44V_{pk-pk} source

The results of the OA90 charge pump circuits are summarized into below Table 6. From the results, it shows that the charge pump circuits works. However, at lower voltage, the charge pump efficiency is not really good compared to higher voltage. Therefore, improvement is by which adding another stage to the circuit.

Table 6 : OA90 charge pump circuits testing results.

Input Voltage (V)	Output Voltage (V)		
	Max	Min	Average
0.680	0.560	0.320	0.440
1.080	0.860	0.620	0.740
1.440	1.440	1.120	1.280
1.760	1.880	1.560	1.720
1.920	2.040	1.720	1.880
2.560	3.000	2.600	2.800
4.440	5.520	4.960	5.240

4.3.3 OA90 charges pump circuit improvement.

The OA90 charges pump circuit then reconstructed again by adding more stages to the circuits. The same components are used for the circuits, OA90 diodes and 1nF capacitors. Two more stages were added to the charge pump circuits. The circuit is constructed as shown below schematic (Figure 50) only the diodes changed instead of DN4148 to OA90.

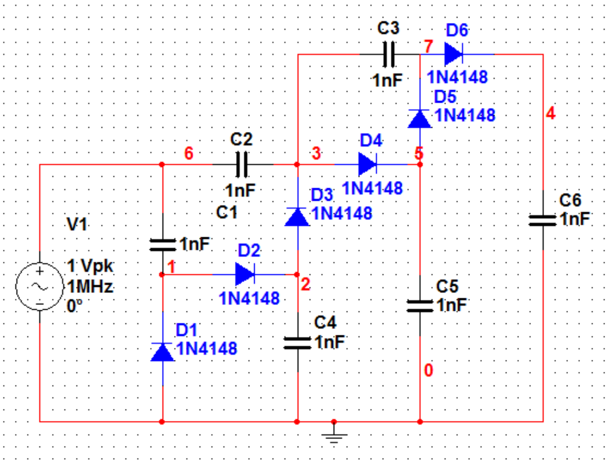

Figure 50 : Schematic diagram for OA90 5 stages charge pump circuit

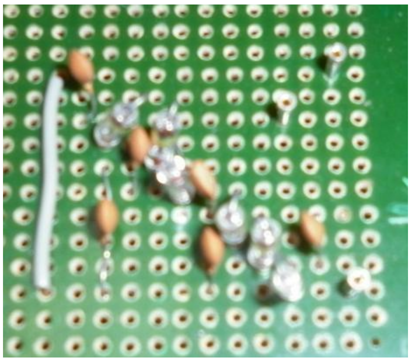

Figure 51 : Actual constructed circuit of OA90

For this charge pump circuits, two testing were done which are the effect of varies voltage input to the outputs, and the effect of varies frequency input signals to the outputs. These testing were done to test the capability of the improved charge pump circuits to cope with the different values of input voltage and frequency of the actual RF signals.

First testing were done to test the effect of varies input voltage to the charge pump circuits outputs. The input voltage is varies from $0.1V_{pk}$ until $1V_{pk}$ represented by Trace 2 and the output is monitored by the Trace 1. The outputs from the oscilloscope is captured and shown in below figure (Figure 52-59).

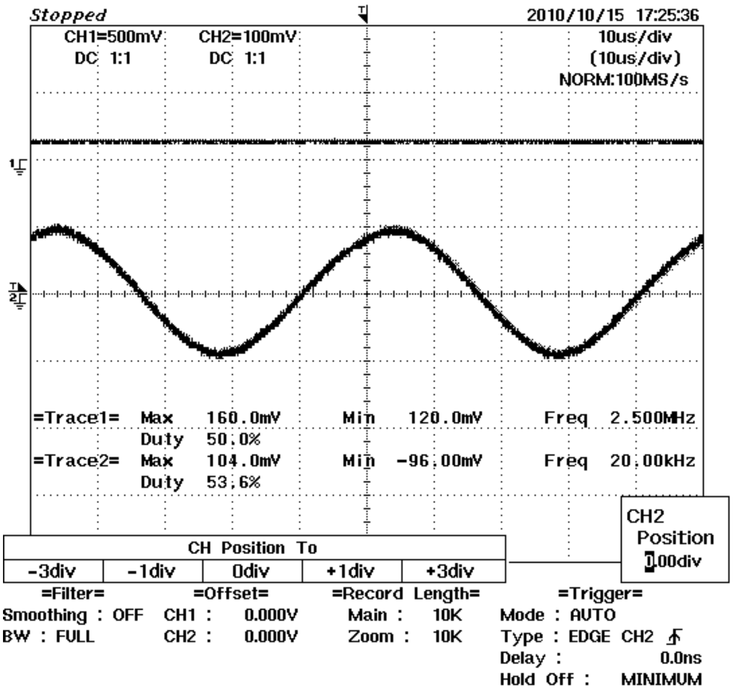

Figure 52 : Output for 5 stages charge pump circuit V_{pk} 100mV

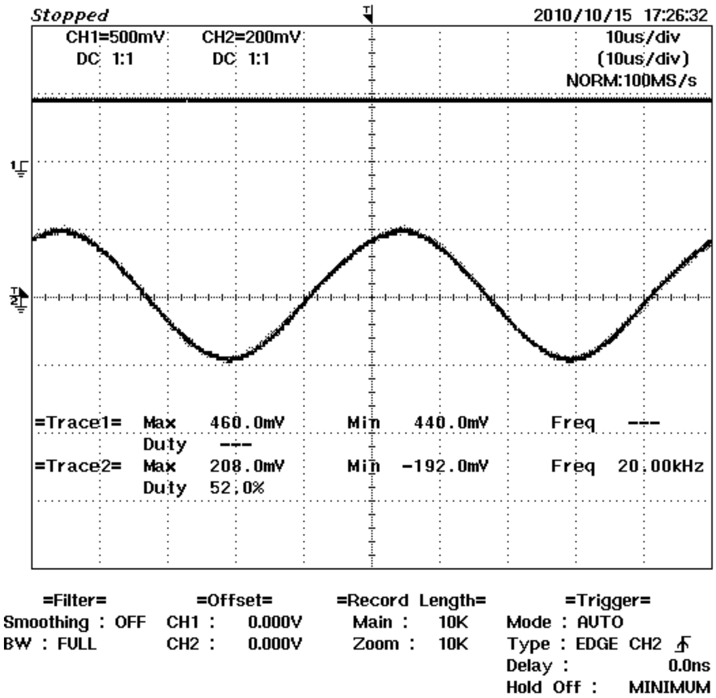

Figure 53 : Output for 5 stages charge pump circuit V_{pk} 200mV

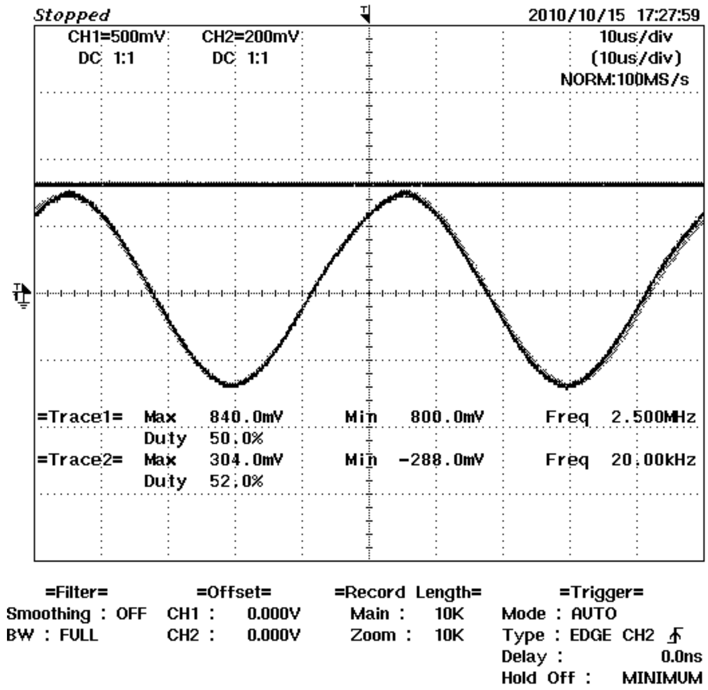

Figure 54 : Output for 5 stages charge pump circuit V_{pk} 300mV

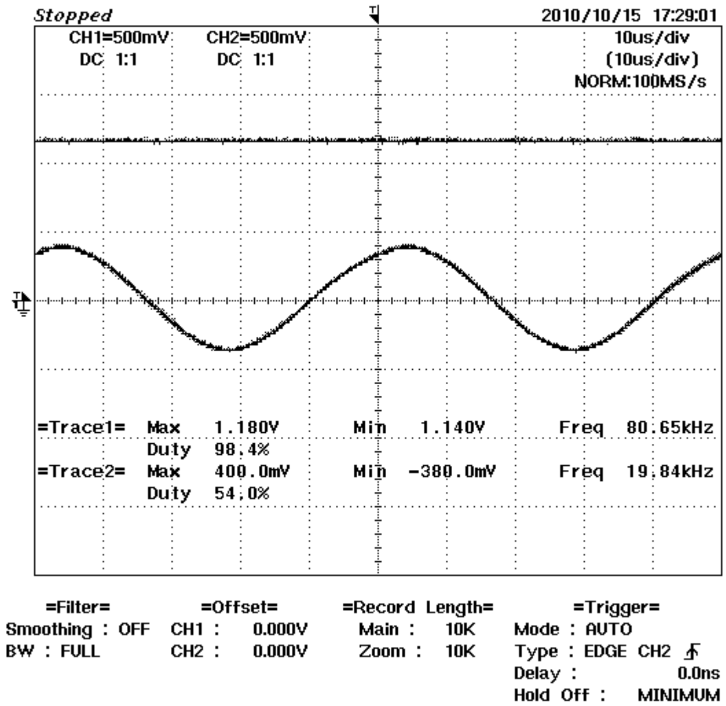

Figure 55 : Output for 5 stages charge pump circuit V_{pk} 400mV

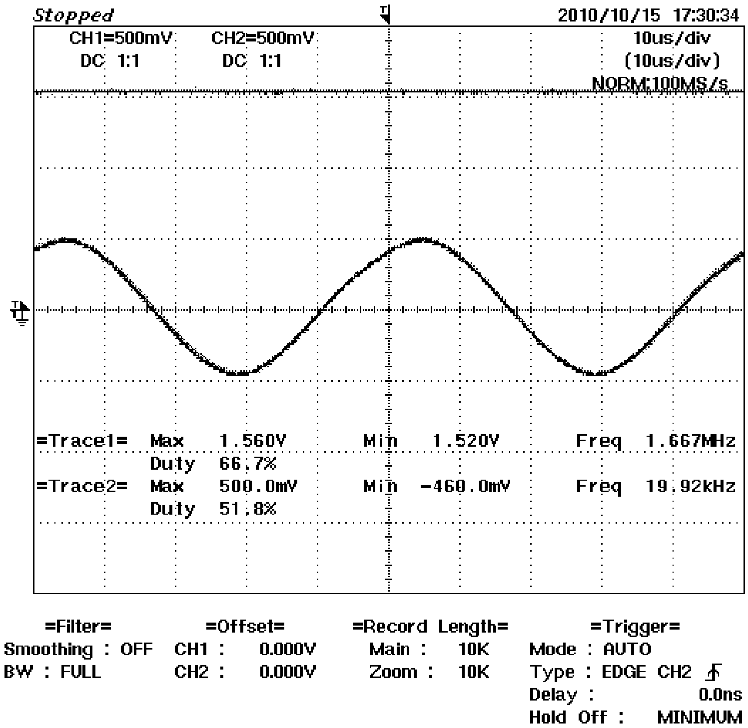

Figure 56 : Output for 5 stages charge pump circuit V_{pk} 500mV

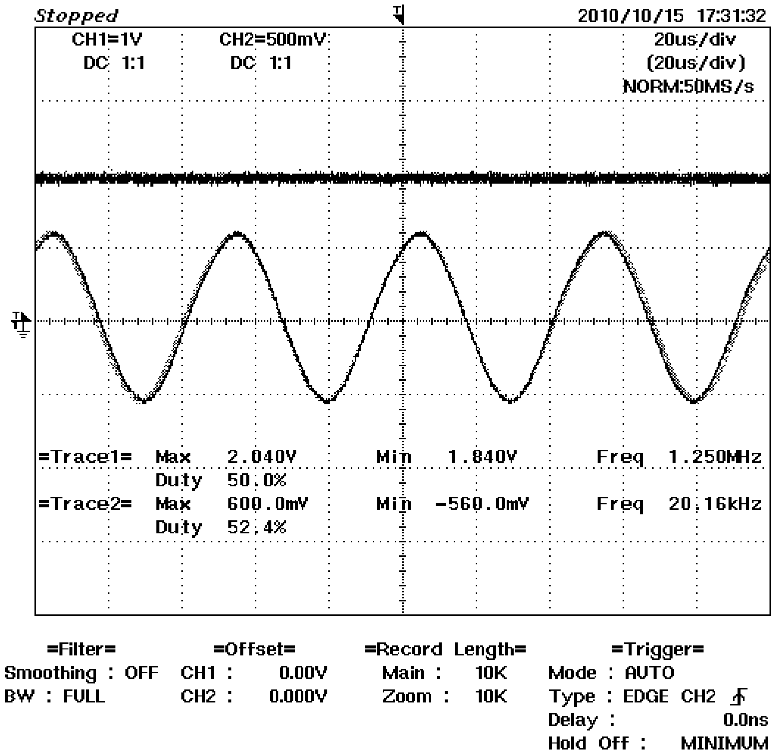

Figure 57 : Output for 5 stages charge pump circuit V_{pk} 600mV

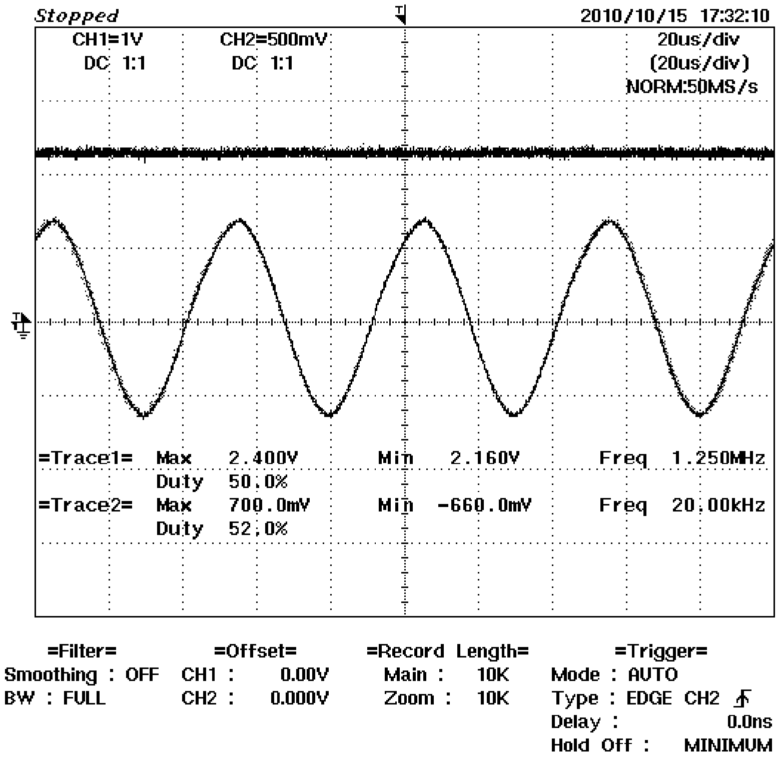

Figure 58 : Output for 5 stages charge pump circuit V_{pk} 700mV

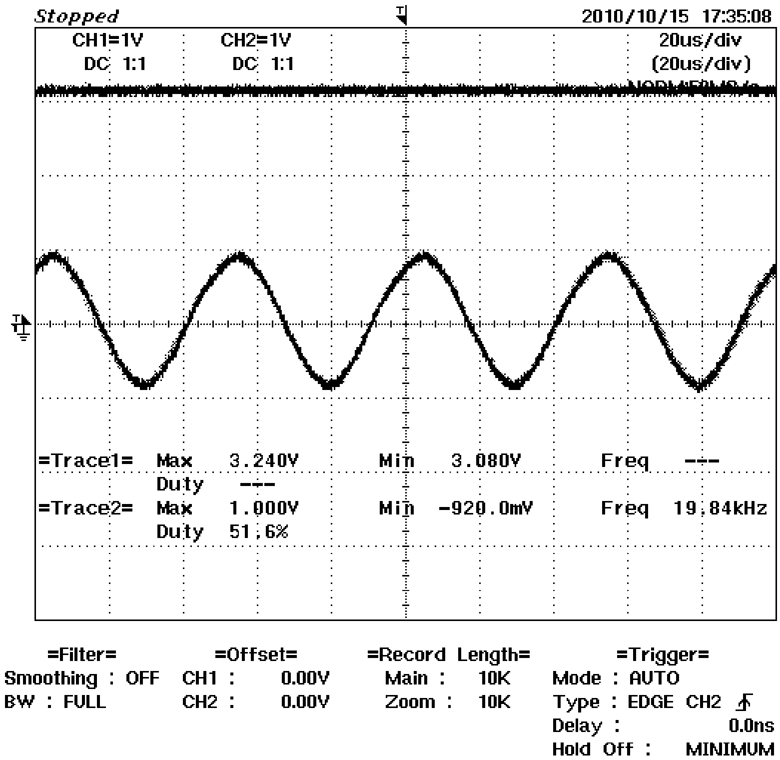

Figure 59 : Output for 5 stages charge pump circuit V_{pk} 1V

The results of the OA90 charge pump circuits are summarized into below Table 7. This circuit is then were proceed for second testing.

Table 7 : Results of 5 stages charge pump circuits with varies input voltage

Input Voltage (V)	Output Voltage (V)		
	Max	Min	Average
0.104	0.160	0.120	0.140
0.200	0.460	0.440	0.450
0.304	0.840	0.800	0.820
0.400	1.180	1.140	1.160
0.500	1.560	1.520	1.540
0.600	2.040	1.840	1.940
0.700	2.400	2.160	2.280
1.000	3.240	3.080	3.160

The second testing were done to see the effect of varies frequency input signals to the outputs of the improved circuits. The frequency of the input voltage is varies from 100 kHz until 3.0 MHz while the input voltage is remains fix throughout the testing. Again, as the previous test for oscilloscope captured results, the Trace 1 is the output signal while Trace 2 is the input voltage. The results are shown in below figures (Figure 60-66).

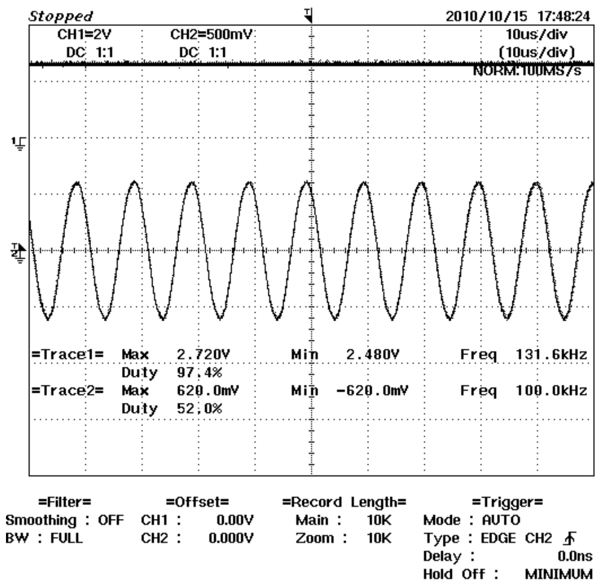

Figure 60 : Output for 5 stages charge pump frequency input 100kHz

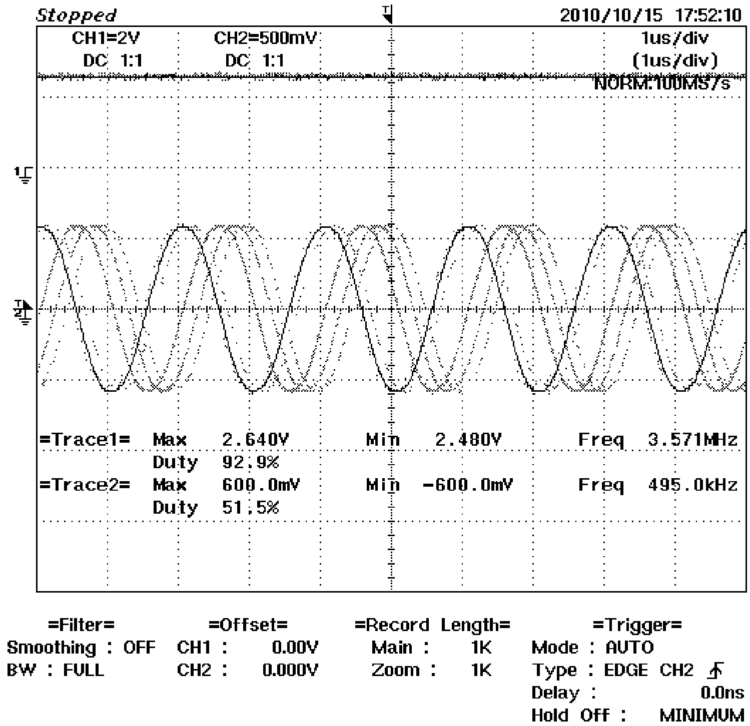

Figure 61 : Output for 5 stages charge pump frequency input 500kHz

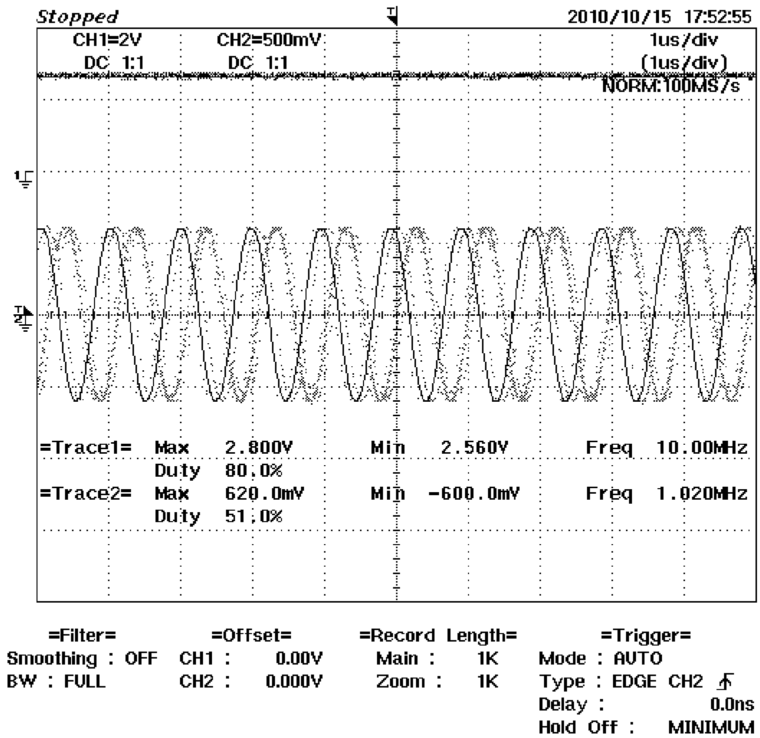

Figure 62 : Output for 5 stages charge pump frequency input 1MHz

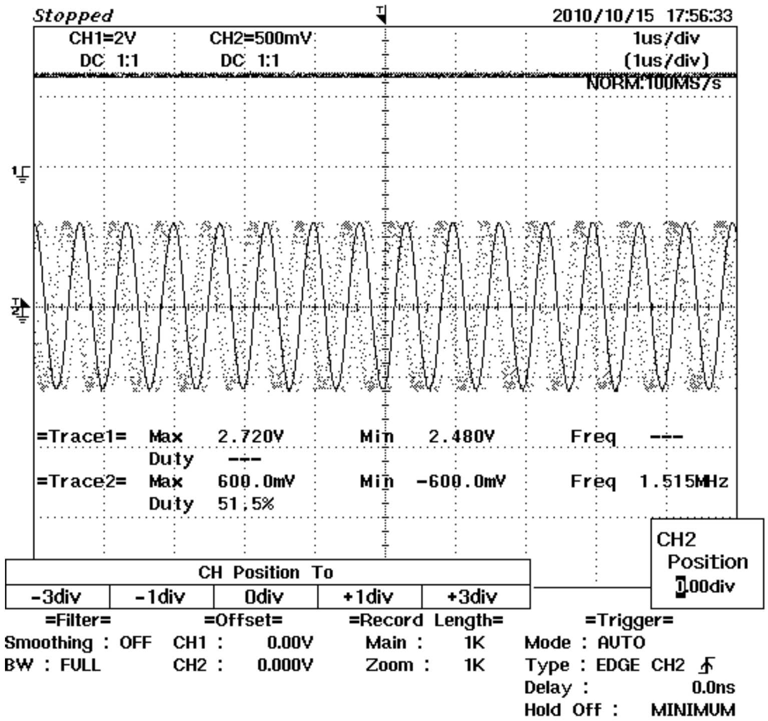

Figure 63 : Output for 5 stages charge pump frequency input 1.5MHz

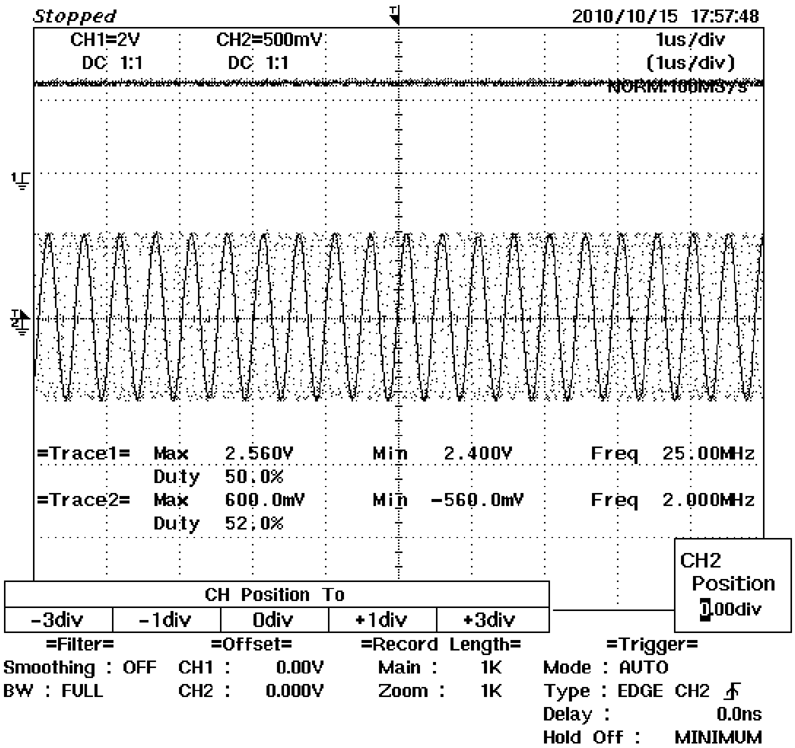

Figure 64 : Output for 5 stages charge pump frequency input 2.0MHz

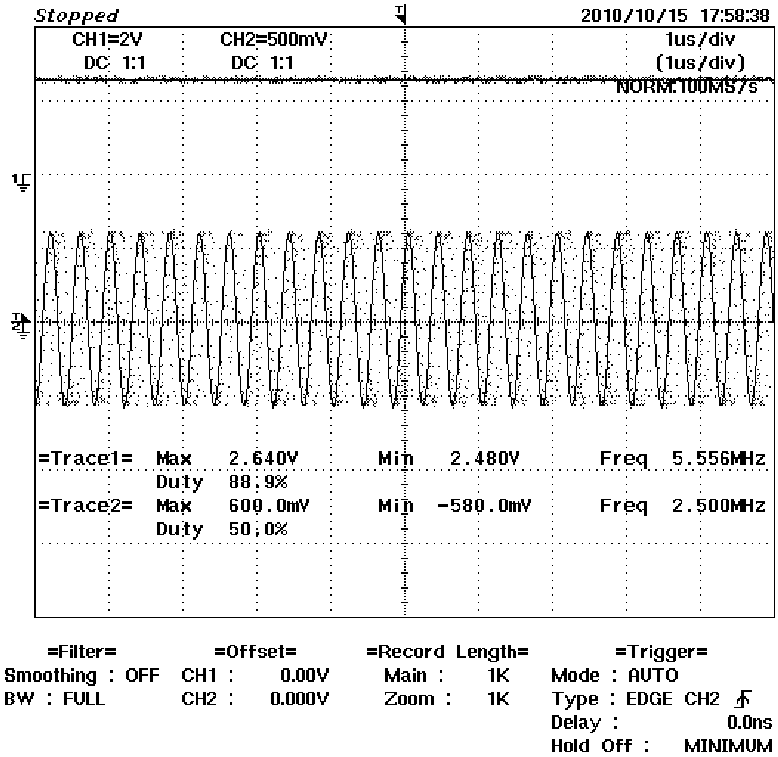

Figure 65 : Output for 5 stages charge pump frequency input 2.5MHz

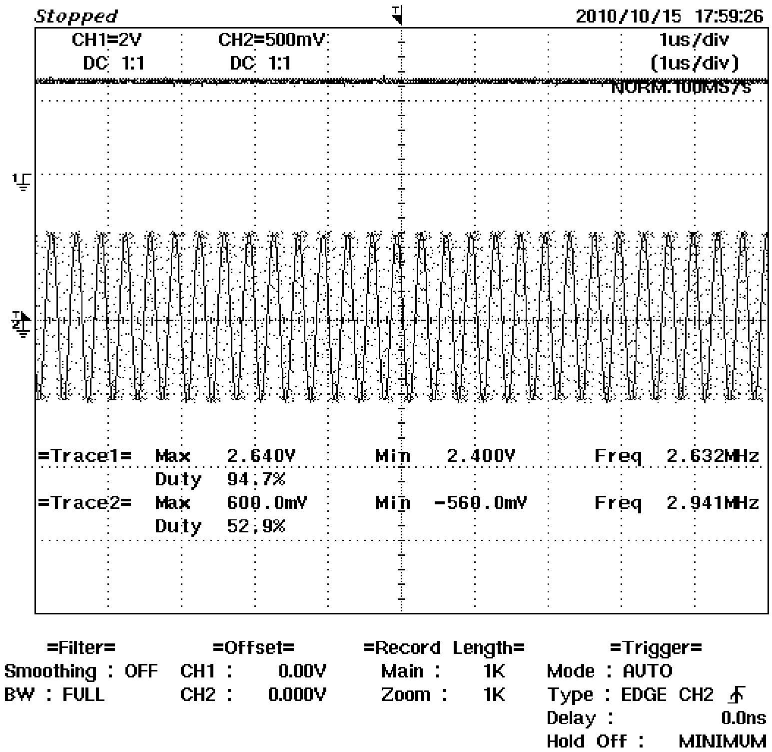

Figure 66 : Output for 5 stages charge pump frequency input 3.0MHz

Table 8 : Results of charge pump circuits with varies frequency input

Input Frequency (MHz)	Output Voltage (V)		
	Max	Min	Average
0.100	2.720	2.480	2.600
0.495	2.640	2.480	2.560
1.020	2.800	2.560	2.980
1.515	2.720	2.480	2.600
2.000	2.560	2.400	2.480
2.500	2.640	2.480	2.560
2.941	2.640	2.400	2.500

The results of the OA90 charge pump circuits are summarized into Table 8. From the results, it shows that the effect of varies frequency thus not effect much on the outputs. It also shows that, the charge pump circuit able to works at varies frequency of input voltage.

CHAPTER 5
CONCLUSION AND RECOMENDATION

5.1 Conclusion

During early stages of this project, the project focused much on literature research related concept such as RFID, charge pump circuits, energy harvesting concept, antenna, and FM receiver. The literature research also focused on the current development of Radio Frequency Energy Harvesting. The literature researches helps to understand better on how the project will be continue and help to have a better understanding of how charge pump circuits really works.

The project then moves to next activity which construction of the FM receiver circuits. The FM receiver circuit was constructed based on TDA7000 FM receiver IC. Output of the receiver which captured from the radio waves was measured using oscilloscope that available in the EE lab. This data used to design the charge pump circuit which will act as amplifier to amplify the voltage. The circuit is improved by replacing the antenna with a monopole antenna that increase the RF amount captured.

While for the simulation parts, the simulation done on the main circuit of the project which is function to amplify the voltage output of the captured radio wave. Charge pump circuit is constructed and simulated based on three types of simulations. The simulation were done focused on three different criteria which are, the effect of stages in the charge pumps circuit to the output, the effect of varies input voltage to the output, and the effect of varies frequency of input signal at fix voltage to the output.

Based on the gathered information from the simulation parts, the charge pump actual circuits were constructed on veroboard. During the testing, the DN4148 fails to works since it has high threshold voltage, therefore the OA90 diodes were used.OA90 which germanium based diode has lower threshold voltage compared to DN4148. Different stages were constructed and tested to see the output. The testing is done based on two main criteria which are the effect of varies input voltage and varies frequency. Based on these criteria, the charge pump circuit was improved by adding more stages.

5.2 Recommendation

The main problem faced by the author was, the lack of harvested energy from radio waves. The captured radio frequency captured was too small to be manipulated by the harvester circuit, which is the charge pump circuit. For this project, it is recommended to focus more on how to capture more radio wave energy so that able to be manipulated.

This might be done by improving the gain of the antenna, or using a better design antenna instead of the monopole antenna. According to Friss Transmission Formula as shown in Equation 1, the power transmits from transmitter and receiver could be improved through increasing the gain for both antennas. For this project, it is recommended that, the receiver antenna gain should be increase.

Next is to come out with low power consumption of the radio wave transducer which wills helps to harvest more energy from the radio waves. Energy from the captured radio frequency will only able to be stored if, the power consumption of the harvest circuit is lower than the amount of captured energy. This could be done by considering the resistance that cause by the board that connects the components, the components optimum performance range, and the efficiency of overall circuits.

Another way to improve the amount of energy to be harvest by the receiver is, by having multiple receivers which harvest the radio frequency. By having multiple receivers, it could gain more energy and therefore, it could help to solve the problem faced by this project.

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APPENDICES

APPENDIX A

DATA SHEET

TDA7000 FM RECEIVER

APPENDIX B

DATA SHEET

DN4148 DIODE

APPENDIX C

DATA SHEET

OA90 DIODE