LAB REPORT

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Embedded Electronics IE1206

Module 1

1. DC MEASUREMENTS

1.1 Resistive network with Arduino

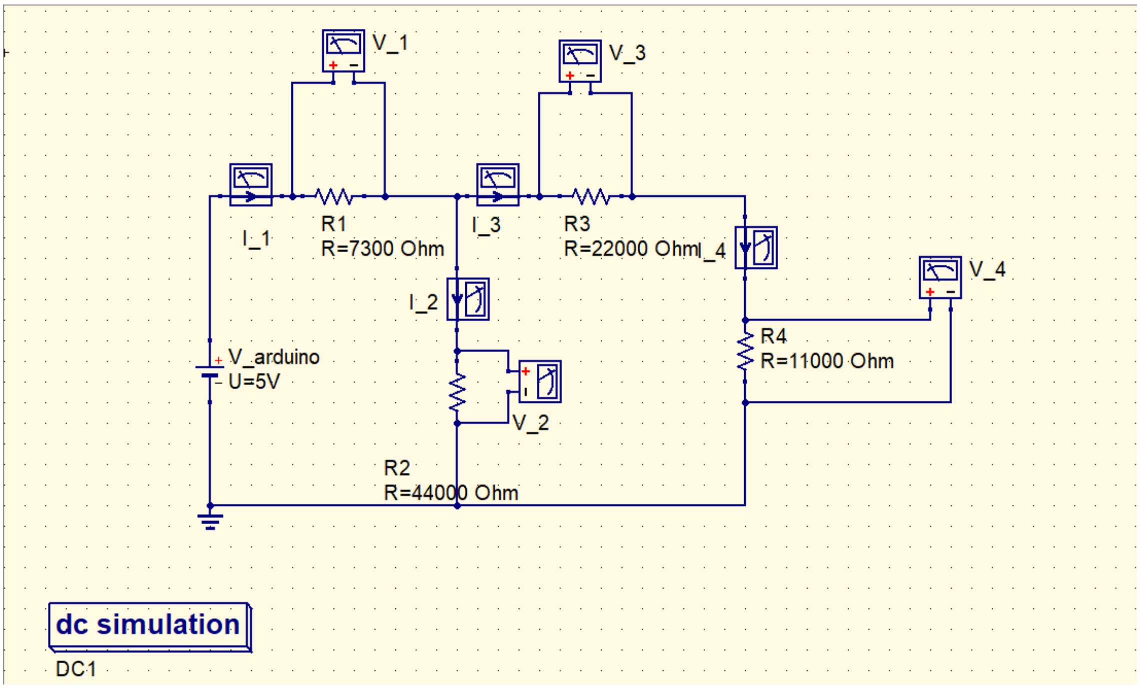

Figure 1: Circuit to be built on Arduino

– Observation:

Comp	Meas (kΩ)	Meas U (V)	Meas I (mA)	Calc (kΩ) R = U/I	Calc (mW) P = UI	Calc (mW) P = U^2/R	Calc (mW) P = I^2/R
R1	7.3	1.4	0.191	7.329	0.267	0.267	0.267
R2	44	3.6	0.0819	43.956	0.294	0.294	0.295
R3	22	2.4	0.109	22.018	0.262	0.261	0.261
R4	11	1.2	0.109	11.009	0.130	0.130	0.130

Table 1: Observation from simulation on QUCS

Comp	Meas (kΩ)	Meas U (V)	Meas I (mA)	Calc (kΩ) R = U/I	Calc (mW) P = UI	Calc (mW) P = Uˆ2/R	Calc (mW) P = Iˆ2/R
R1	7.29	1.398	0.191	7.31	0.267	0.267	0.267
R2	44.02	3.61	0.0818	44.132	0.295	0.294	0.295
R3	21.99	2.41	0.108	22.31	0.260	0.260	0.261
R4	11.1	1.2	0.109	11.009	0.130	0.130	0.130

Table 2: Observation from circuit on breadboard

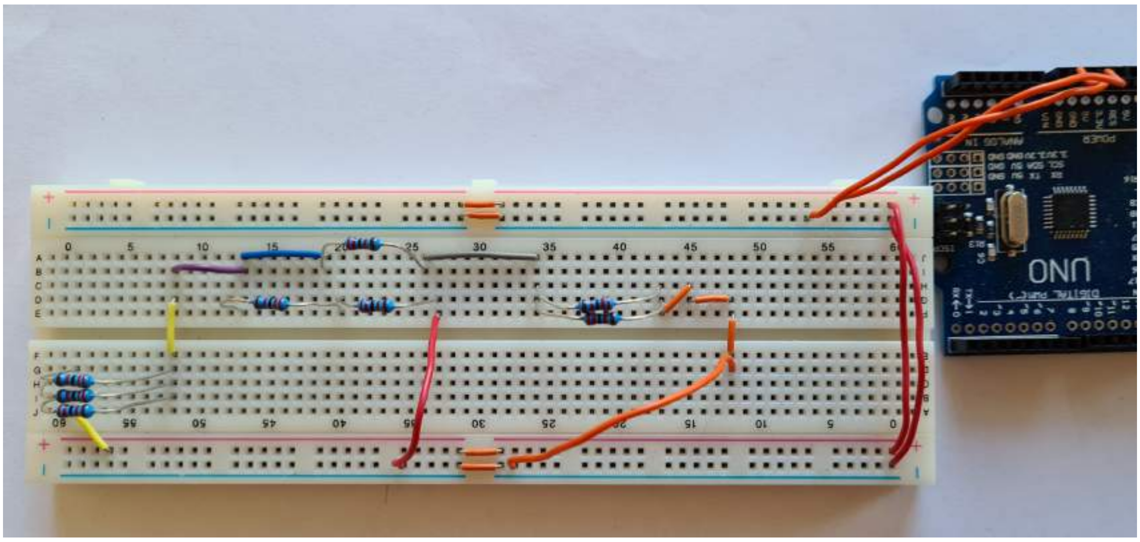

Figure 2: Connections on breadboard

1. The values simulated and measured using multi-meter on the breadboard are same in all the cases with slight round up error in few cases.
2. The resistance calculated from measured voltage and current agree with each other.
3. (a) KVL in loop U-R1-R2

$$V - V_2 - V_3 = 0$$
$$V - I_1R_1 - I_2R_2 = 0$$
$$5 - 0.000191 \times 7300 - 0.0000819 \times 44000 = 0$$
$$5 \approx 4.9979$$

Thus it is valid.

(b) KVL in loop R2,R3,R4

$$-V_2 - V_3 - V_4 = 0$$
$$-I_2R_2 - I_3R_3 - I_4R_4 = 0$$
$$-(-0.0000819) \cdot 44000 - 0.000109 \cdot 22018 - 0.000109 \cdot 11009 = 0$$
$$3.6036 \approx 3.5989$$

Thus it is valid.

4. KCL in R1,R2, and R3

$$I_1 = I_2 + I_3$$
$$0.000191 = 0.0000819 + 0.000109$$
$$0.000191 \approx 0.0001909$$

Thus KCL is also valid.

5. The power delivered by the arduino can be measured by having a resistor attached on the breadboard and calculating the current through it. The current, I found can be used in

$$P = I \cdot V$$

Through measurement, we found current to be 0.2mA. By using the above formula we get power delivered as 1mW. This value is approximately equal to the sum of power consumed by all resistors in the circuit. Therefore, we can say that the power is balanced.

1.2 Thevenin equivalent for Arduino 5 V and 3.3 V outputs

– Observation:

1. Four 100 Ω resistors in parallel would give an equivalent resistance of

$$R_{eq} = 25\Omega$$

2. If 5V is applied to this resistance, the power per resistor would be

$$P = \frac{V^2}{R}$$

$$P = \frac{25}{100}$$

$$P = \frac{1}{4}W$$

3. Measurements using Multi-meter
   (a) U (5V unloaded) = 5.06V
   (b) U (5V loaded) = 4.77V
   (c) U (3V unloaded) = 3.29V
   (d) U (3V loaded) = 3.26V
   (e) I (5V) = 0.2A
   (f) I (3V) = 0.13A
4. 5V
   (a) R_i using Voltage division method

$$\frac{U(5V unloaded)}{U(5V loaded)} = \frac{R}{R + R_i}$$

$$\frac{5.06}{4.77} = \frac{25}{25 + R_i}$$

$$R_i = 1.43$$

   (b) R_i using the current measured

$$R_i = \frac{5.06 - 4.77}{0.2}$$

$$R_i = 1.45$$

5. 3.3V

(a) R_i using Voltage division method

$$\frac{U(3.3V unloaded)}{U(3.3V loaded)} = \frac{R}{R + R_i}$$

$$\frac{3.29}{3.26} = \frac{25}{25 + R_i}$$

$$R_i = 0.23$$

(b) R_i using the current measured

$$R_i = \frac{3.29 - 3.26}{0.13}$$

$$R_i = 0.23$$

6. The internal resistance of 3.3V is low compared to that of 5V because the voltage of 3.3V comes from the voltage regulator which makes it very stable and thus has low internal resistance while the 5V voltage comes from the USB connector so the internal resistance varies based on the connection of the USB.

1.3 Resistance of MOSFETs on output pins

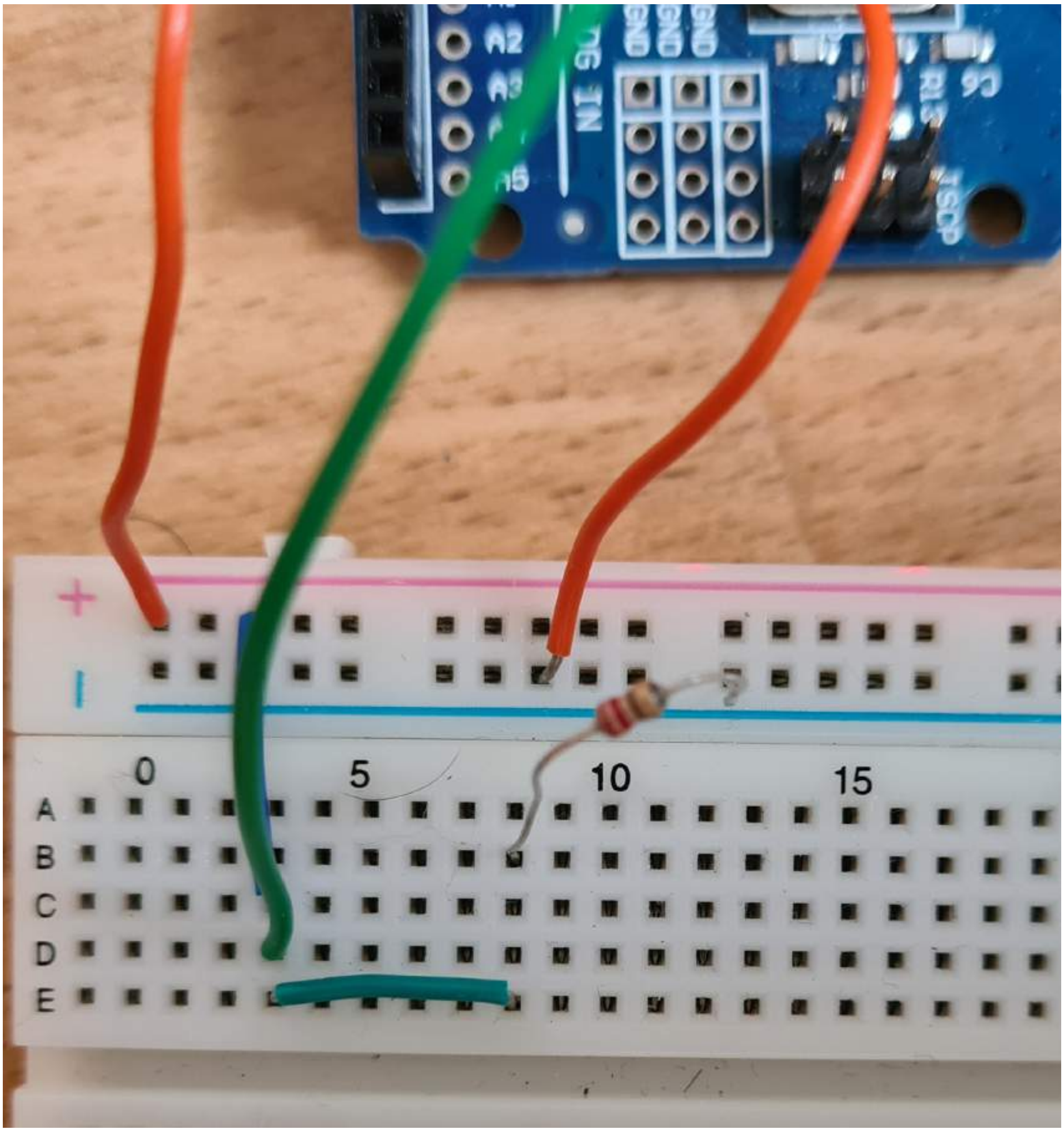

Figure 3: Simulation on QUCS

– PMOSFET

For measuring resistance of PMOSFET, we use pin 11 from arduino as our PMOSFET and find voltage and current to determine resistance. We use a load resistor of 220 Ω for this.
Measured Current = 21.5mA
Measured Voltage = 0.5V
Calculated Resistance = 2.3 Ω

– NMOSFET

For measuring resistance of NMOSFET, we use pin 10 from arduino as our NMOSFET and find voltage and current to determine resistance. We use a load resistor of 220 Ω for this.
Measured Current = 23.3mA
Measured Voltage = 4.87V

Calculated Resistance = 20.9 Ω

1.4 LED Circuits

– Circuit 1

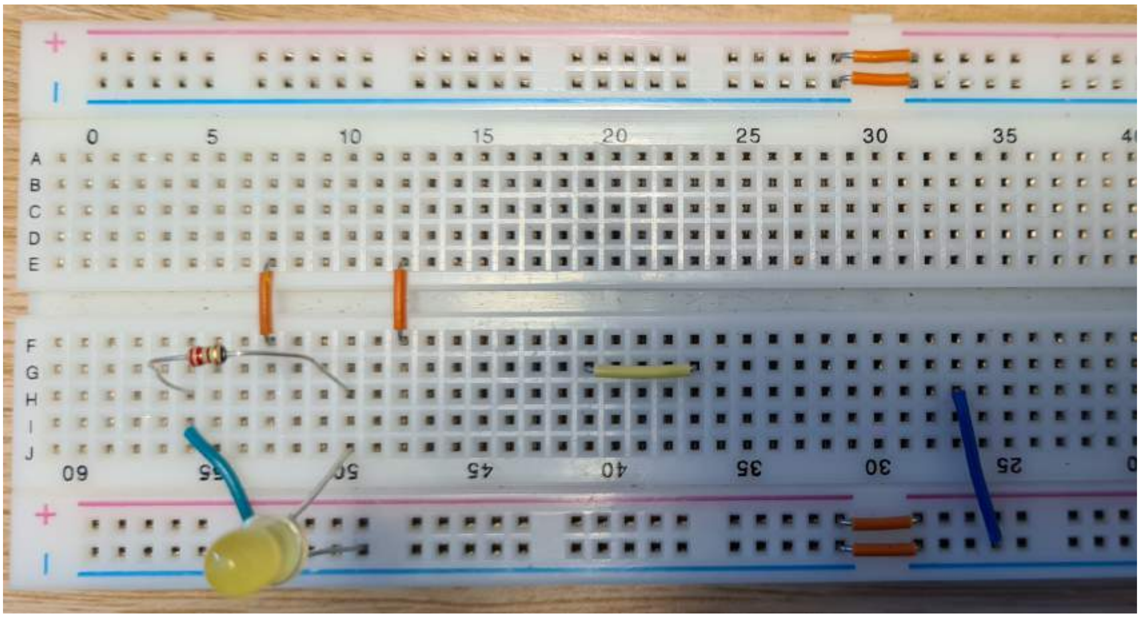

Figure 4: Breadboard with connections

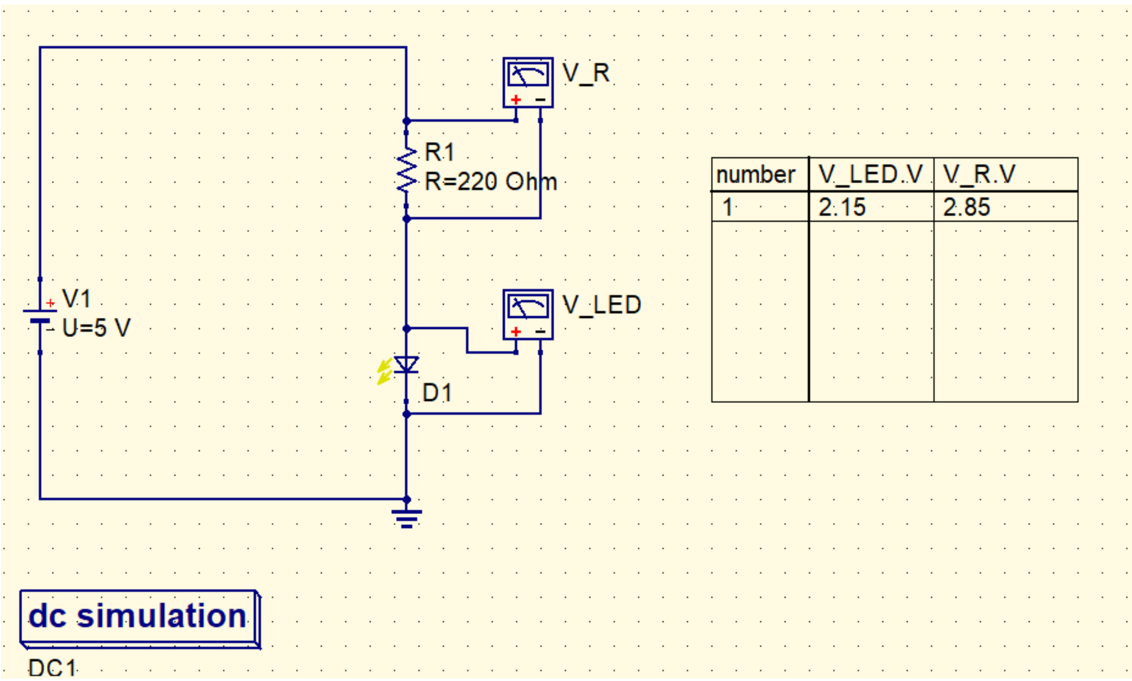

Figure 5: Simulation on QUCS

– Circuit 2

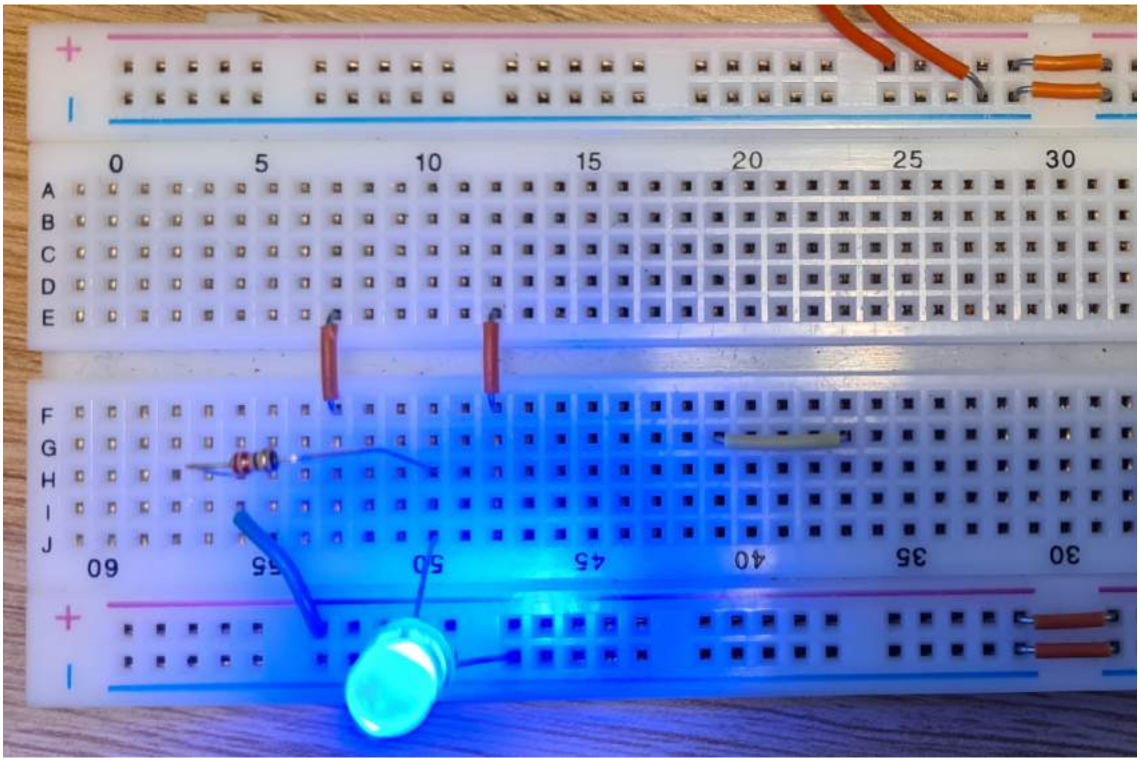

Figure 6: Breadboard with connections

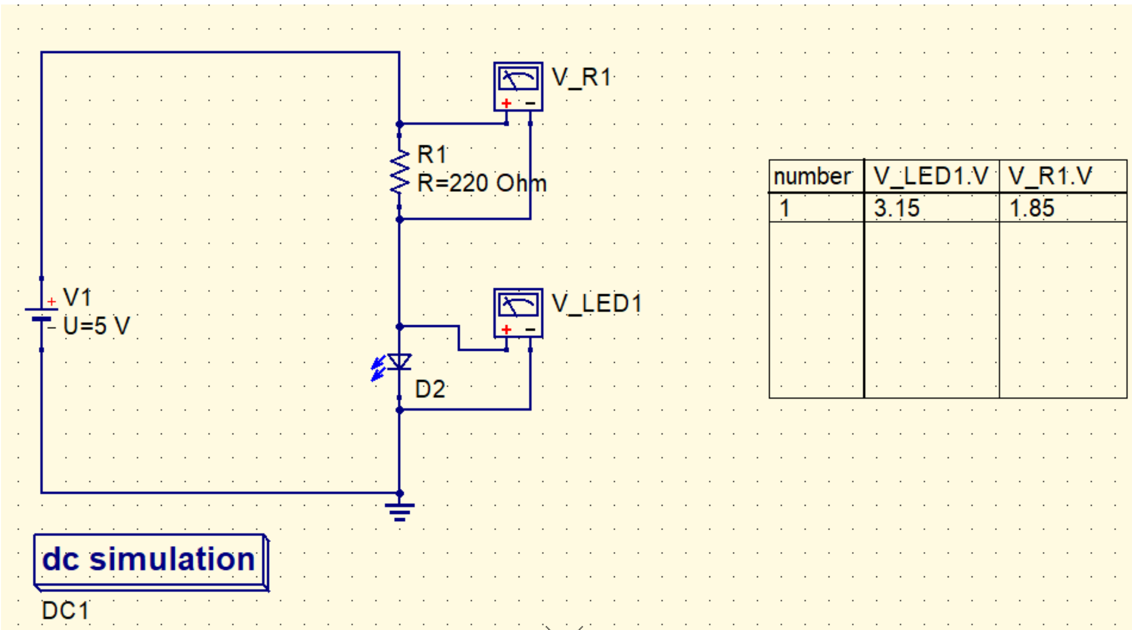

Figure 7: Simulation on QUCS

– Circuit 3

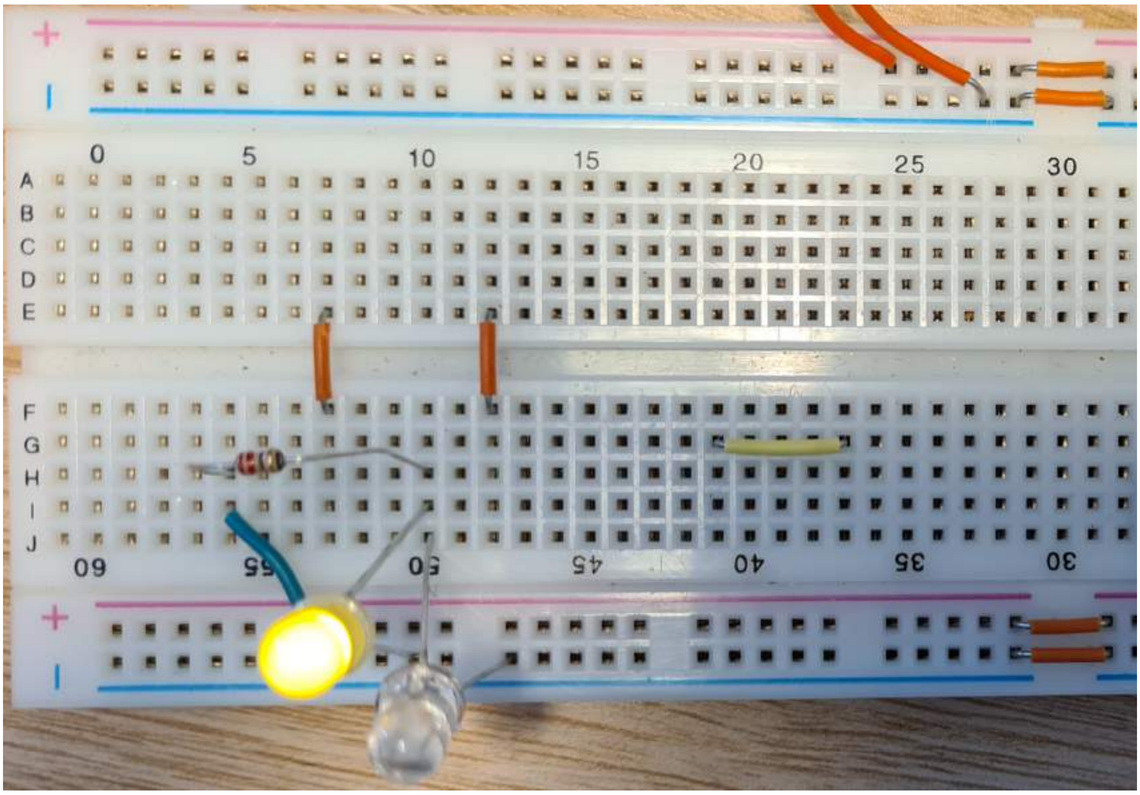

Figure 8: Breadboard with connections

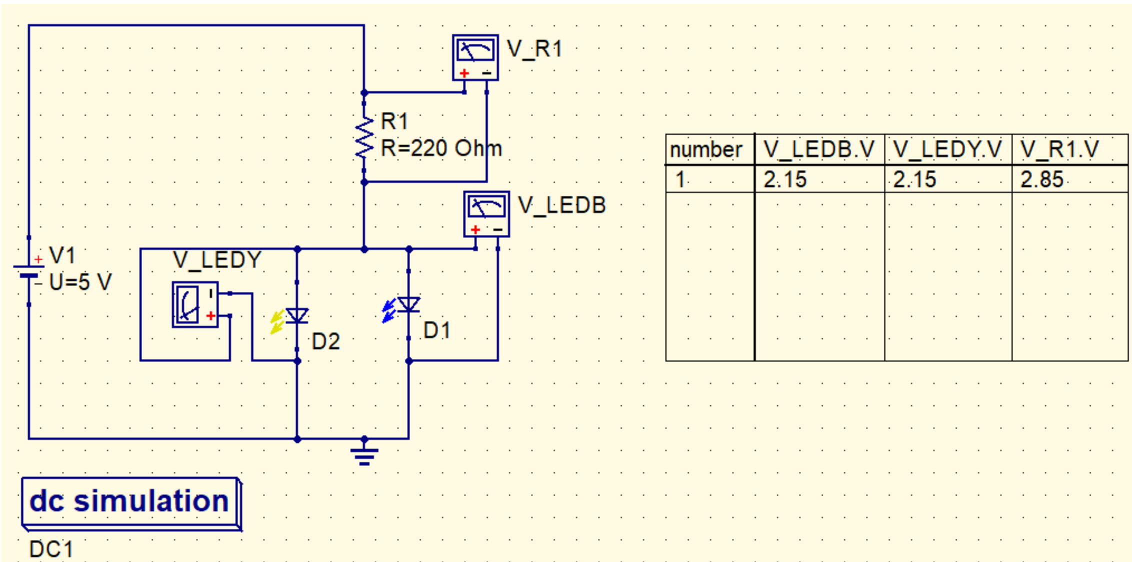

Figure 9: Simulation on QUCS

– Circuit 4

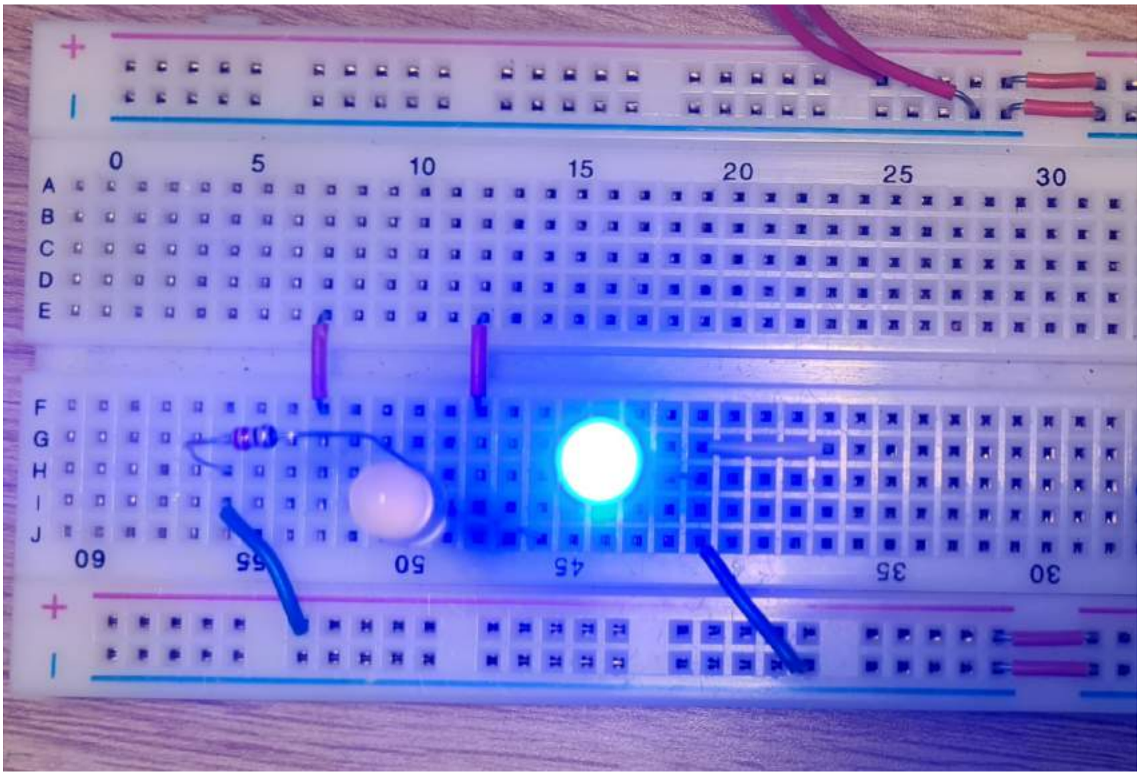

Figure 10: Breadboard with connections

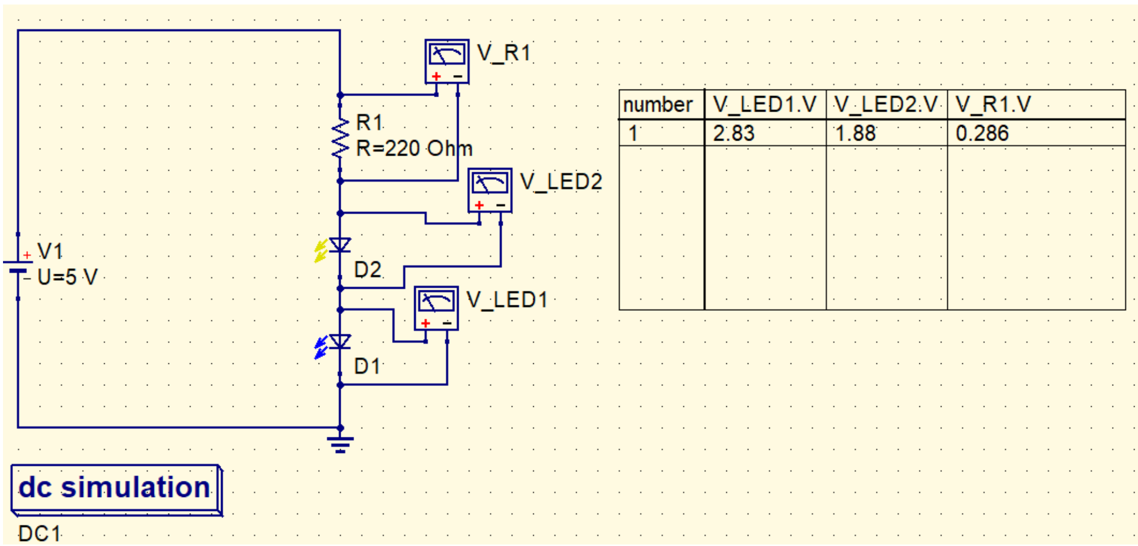

Figure 11: Simulation on QUCS

– Observations

	Blue LED (V)	Yellow LED (V)	Through The Resistor (V)
Circuit 1	N/A	2.08	2.92
Circuit 2	3.1	N/A	1.9
Circuit 3	2.1	2.1	2.9
Circuit 4	2.79	1.85	0.3

Table 3: Measure Voltage on Breadboard

	Blue LED (I)	Yellow LED (I)
Circuit 1	N/A	0.00945
Circuit 2	0.014	N/A
Circuit 3	0.0095	0.0095
Circuit 4	0.0126	0.0084

Table 4: Calculated Current

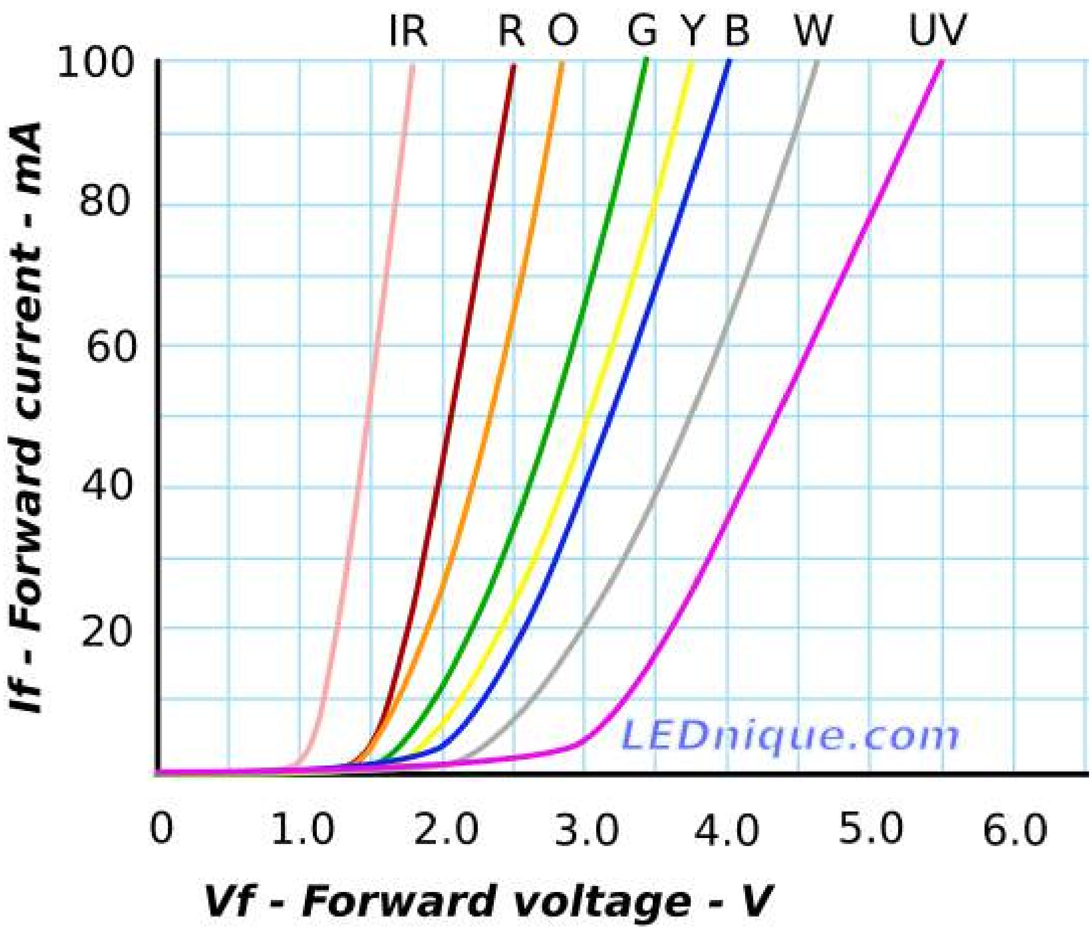

Figure 12: Forward Voltage of different LEDs (Source: Google Images)

As we can see the graph, the forward voltage of white LED is much more than any other LED. Due to this, the LED with low forward voltage will take all current and light up. This causes the yellow LED to light up and not white LED when connected in parallel.

Module 2

2. TIME-DEPENDENT MEASUREMENTS

2.1 Time dependent behavior of RL circuits

– R = 1000 Ω

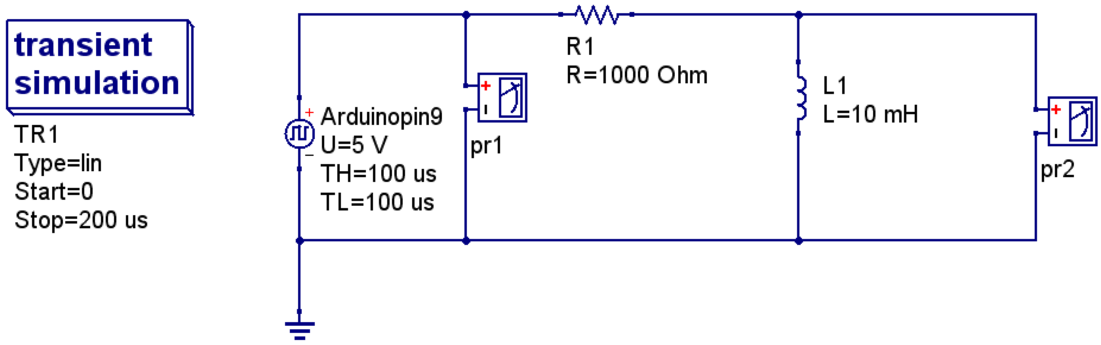

Figure 13: QUCS Simulation

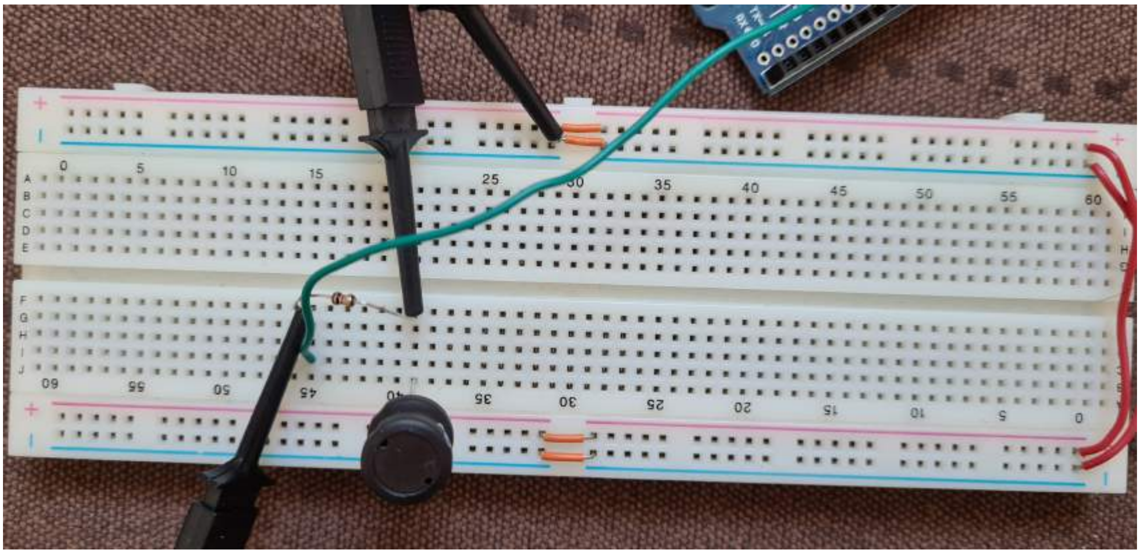

Figure 14: Connection on Breadboard

– **R = 470** Ω

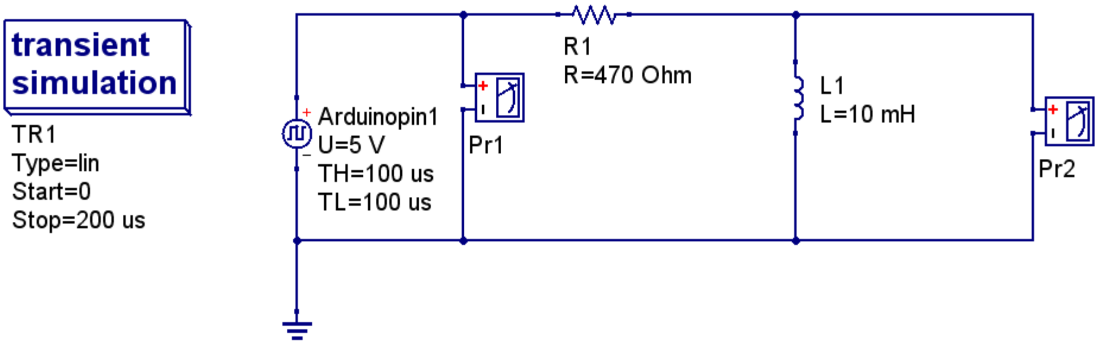

Figure 15: QUCS Simulation

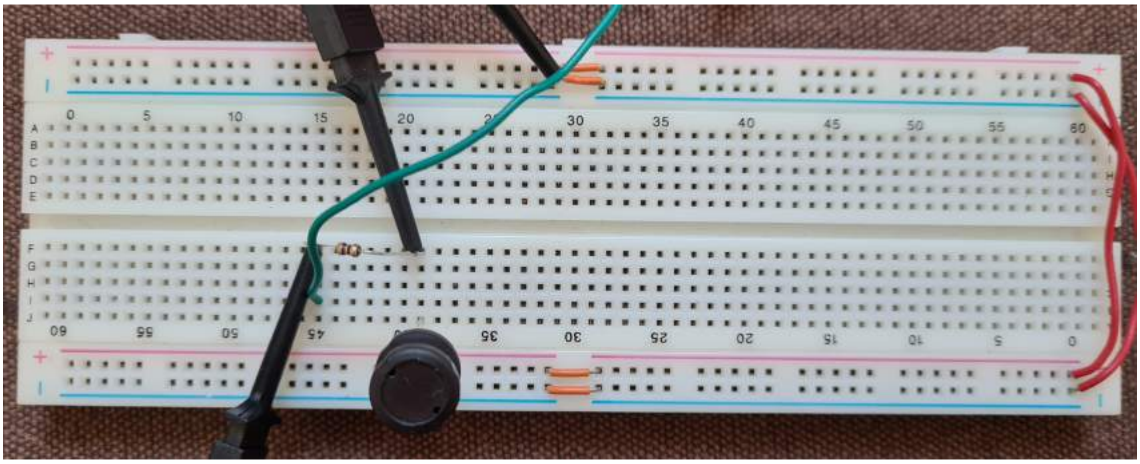

Figure 16: Connection on Breadboard

– R = 2200 Ω

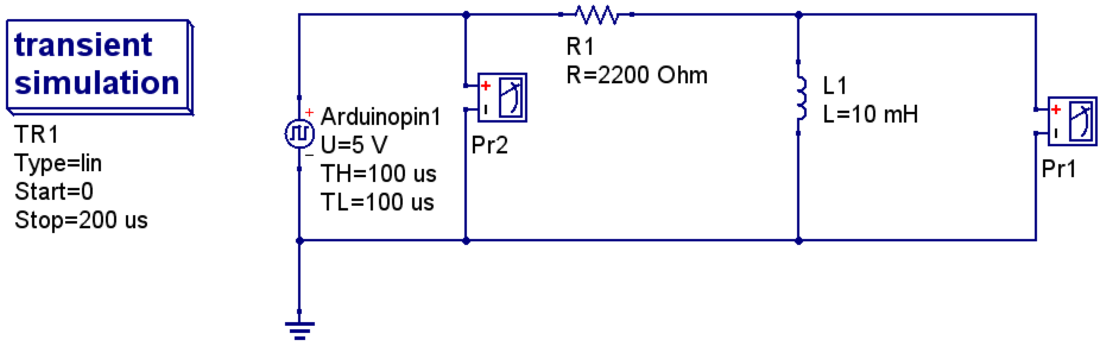

Figure 17: QUCS Simulation

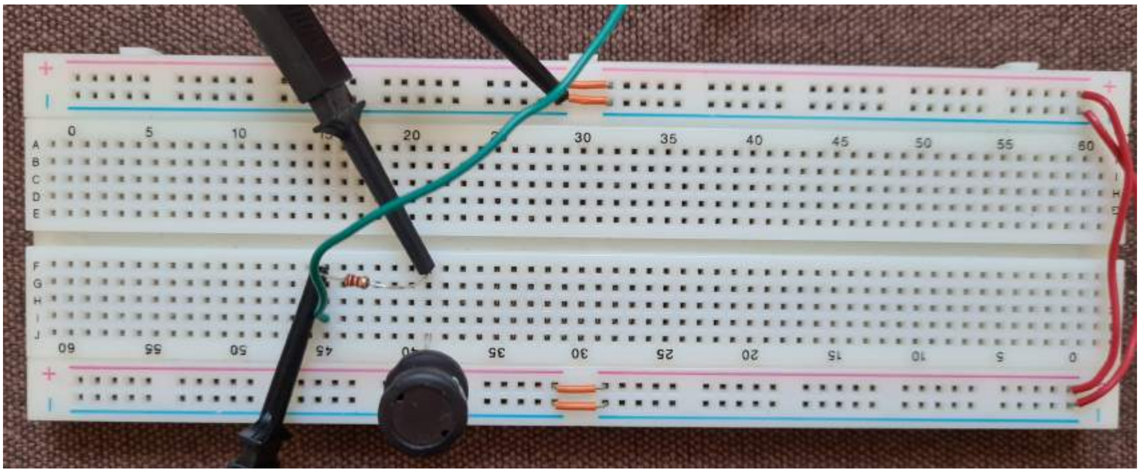

Figure 18: Connection on Breadboard

– Observed Curves

—- R = 1000 Ω

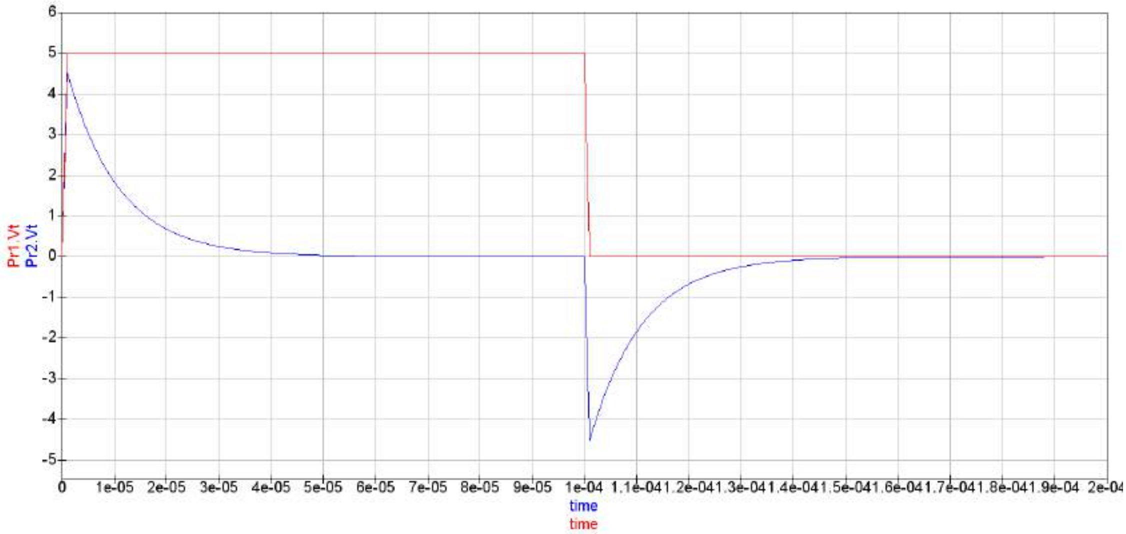

Figure 19: QUCS Curve

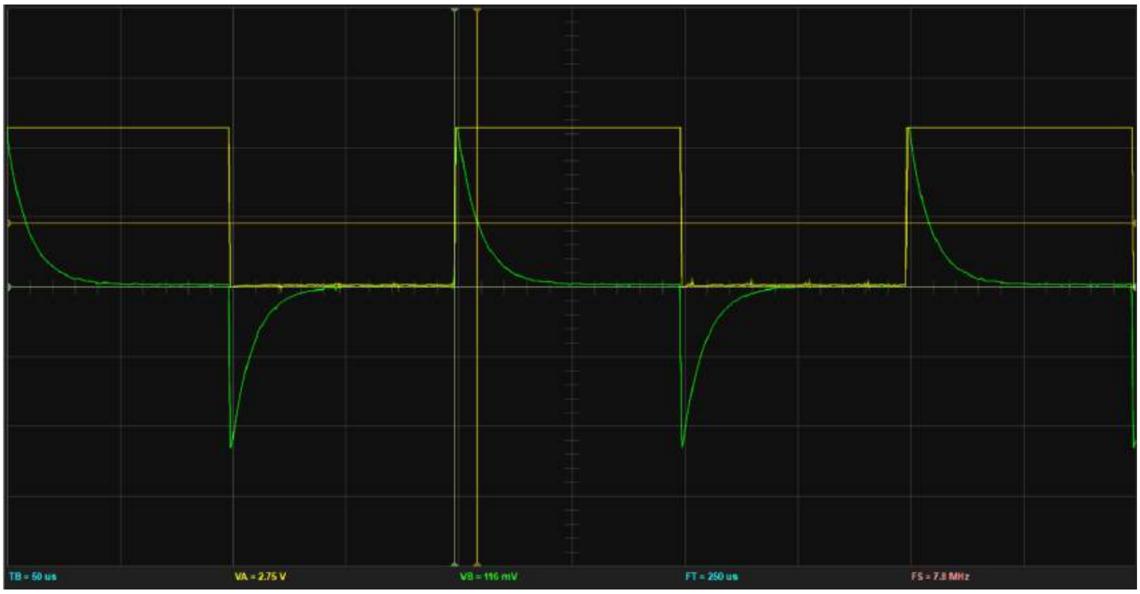

Figure 20: Bitscope Curve

—- R = 470 Ω

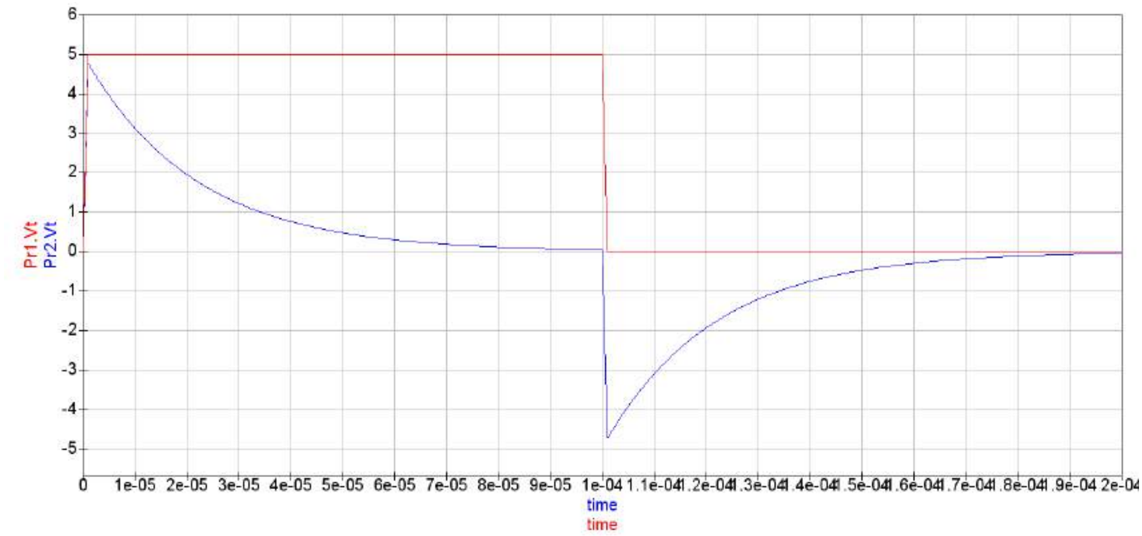

Figure 21: QUCS Curve

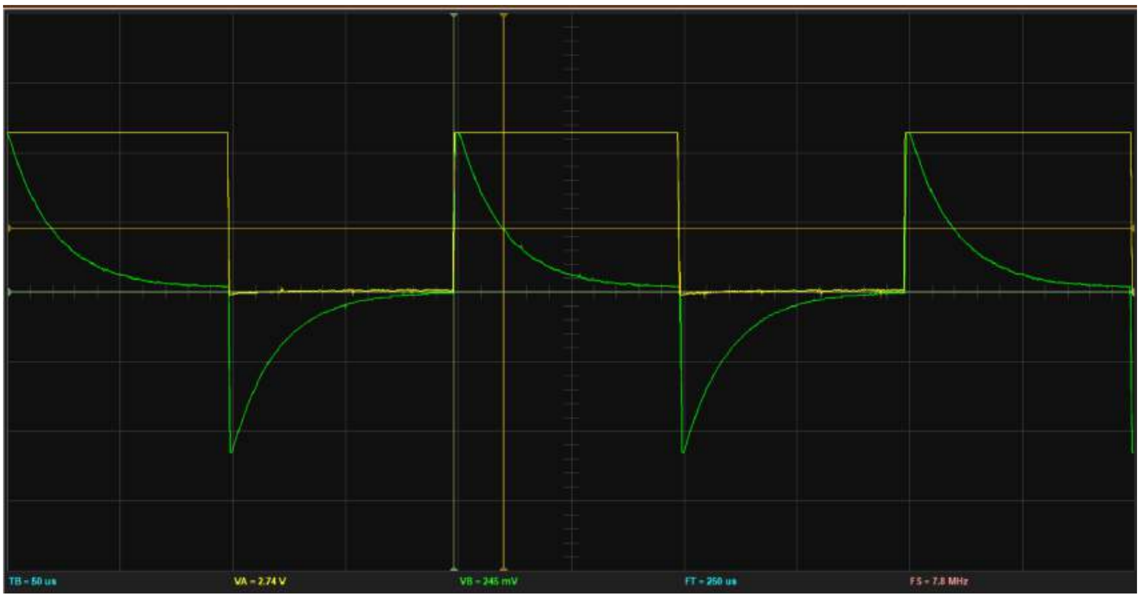

Figure 22: Bitscope Curve

—- R = 2200 Ω

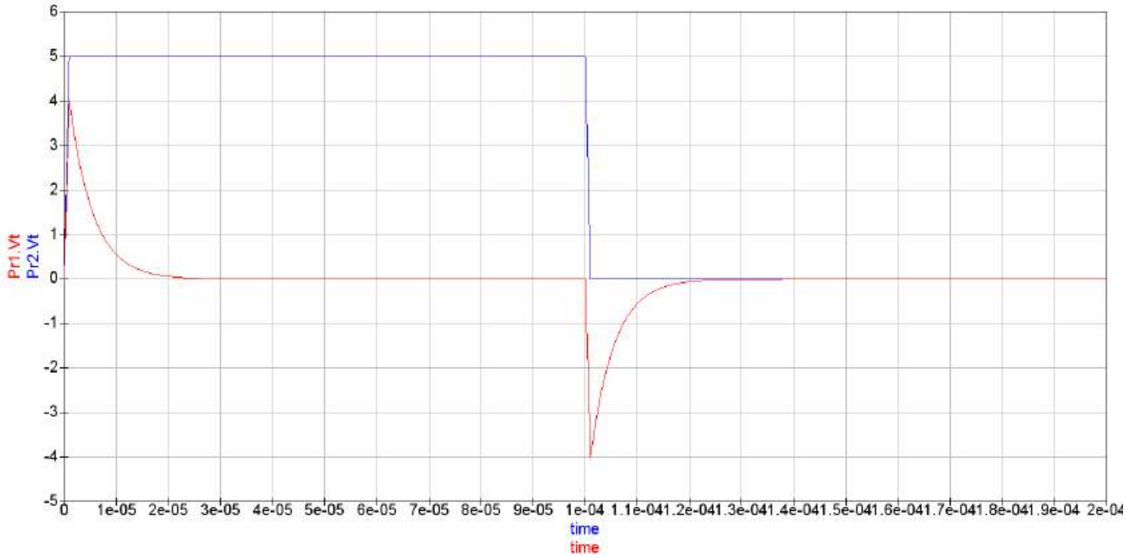

Figure 23: QUCS Curve

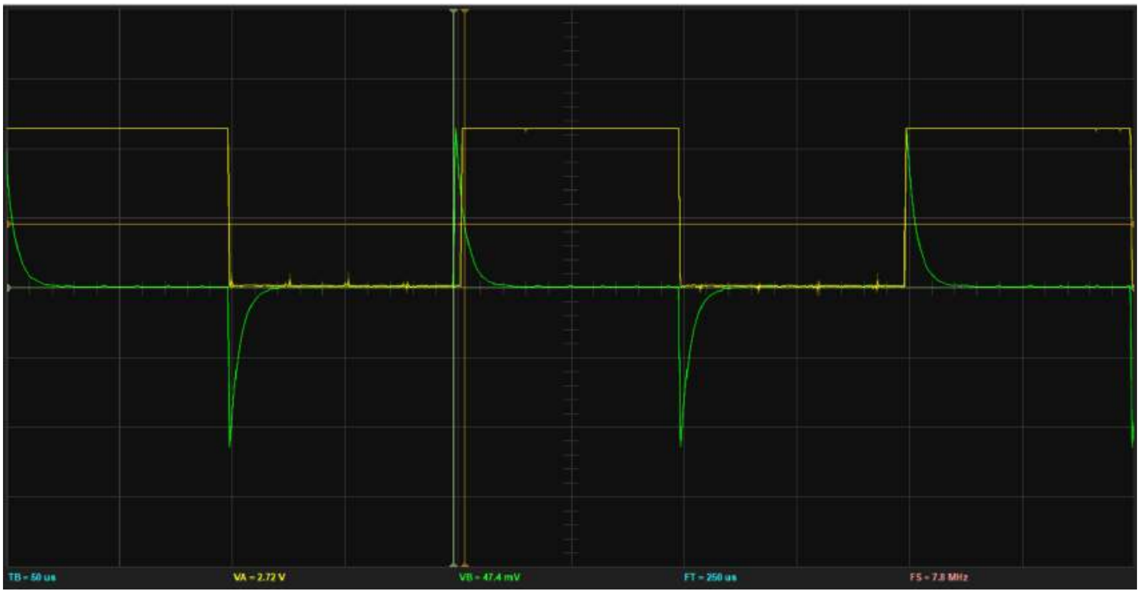

Figure 24: Bitscope Curve

– **Time Constant**

Resistance	Calculated Time Constant (L/R)	Measured Time Constant (BitScope)
470 Ω	$21.2 \cdot 10^{-6}$	$22 \cdot 10^{-6}$
1000 Ω	$10 \cdot 10^{-6}$	$10 \cdot 10^{-6}$
2200 Ω	$4.54 \cdot 10^{-6}$	$5 \cdot 10^{-6}$

We take point 1.84V on each curve that we get on QUCS and compare the point on Bitscope curve we notice that they lie very close to each other.The reason we take 1.84V in each case as our V is 5V in all cases and after one time constant we are at 63.2% of the initial value which is 3.16V and are left with 1.84V left to be discharged.

– **With Different combination of Inductor**

—- **L in Series**

For Inductor in Series, the Equivalent inductance is given by

$$L_{eq} = L_1 + L_2 ...$$

Thus L_{eq} in our case will be $20mH$

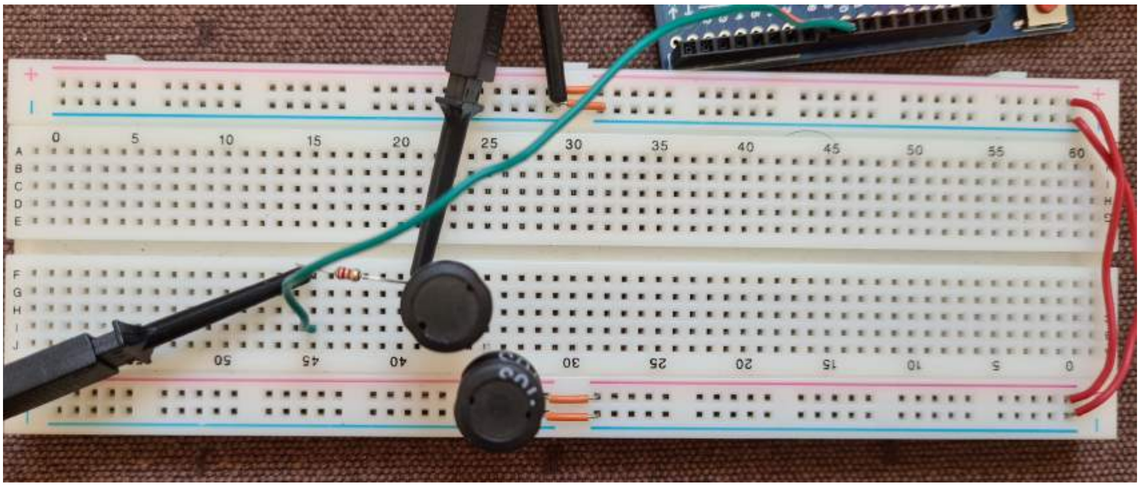

Figure 25: Connections

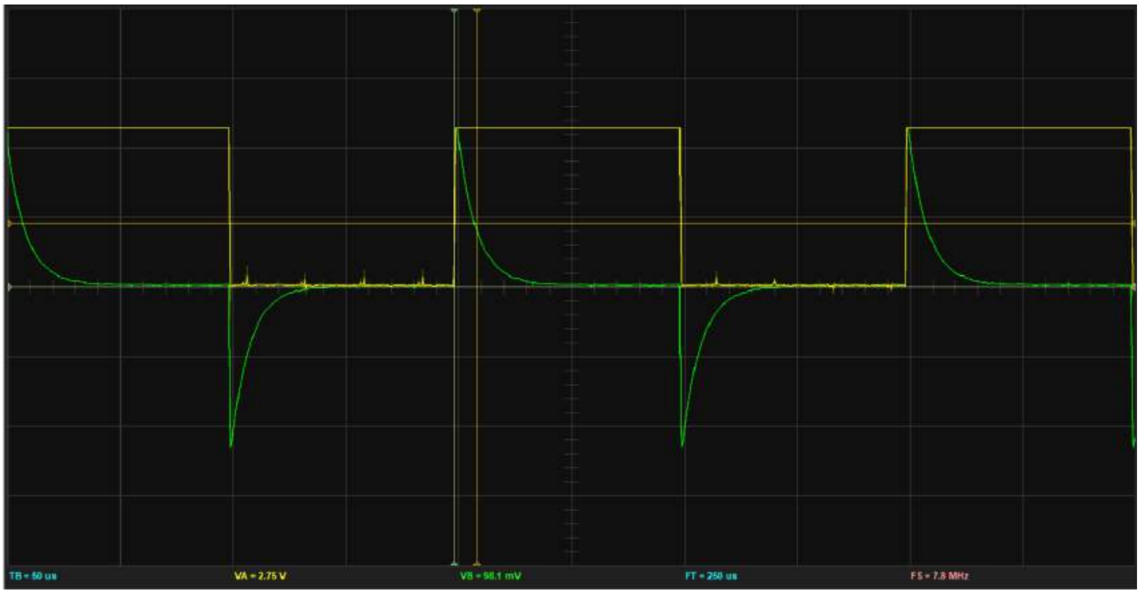

Figure 26: Bitscope Curve

Calculated Time Constant$= 4us$
Observed Time Constant$= 5us$

—- L in Parallel

For Inductor in Parallel, the Equivalent inductance is given by

$$L_{eq} = \frac{1}{\frac{1}{L_1} + \frac{1}{L_2}}$$

Thus L_{eq} in our case will be $5mH$

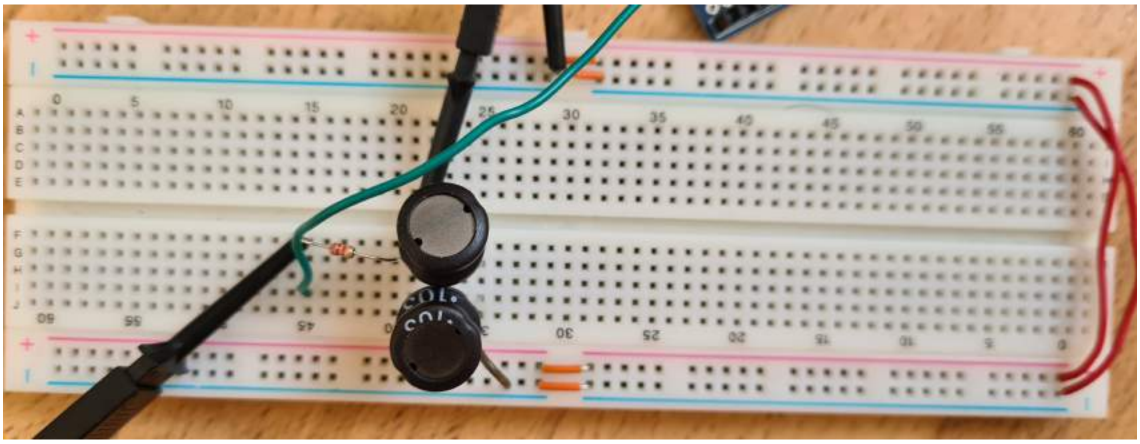

Figure 27: Connections

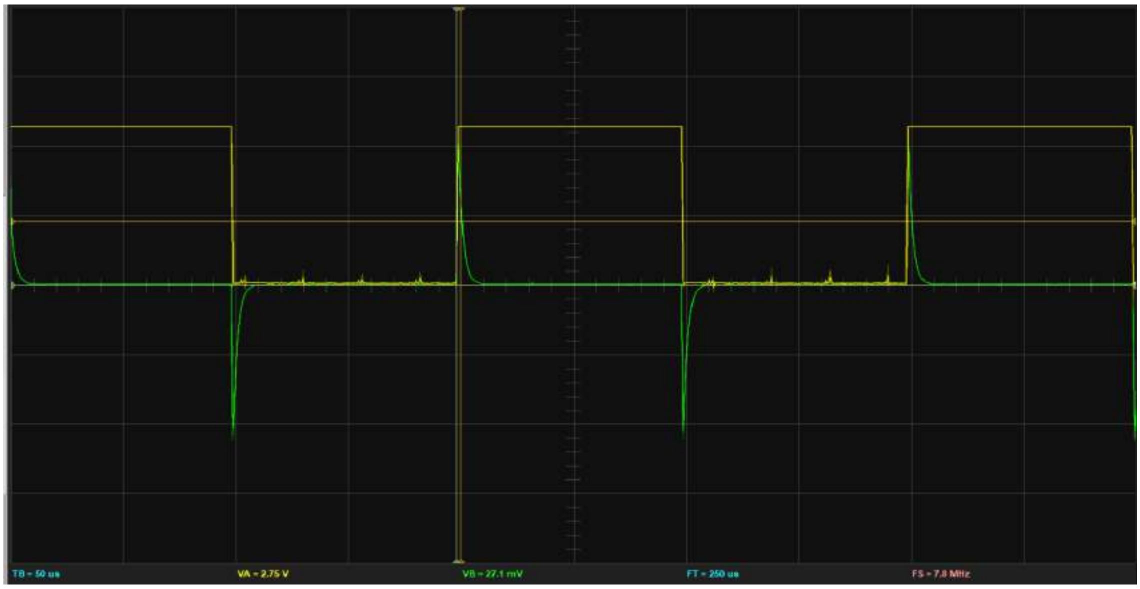

Figure 28: Bitscope Curve

Calculated Time Constant$= 2us$ **Observed Time Constant**$= 2us$
We can manipulate the time constant by changing the values of Inductor and Resistance. If we increase the Inductance the Time constant Increases and if we increase the Resistance Time Constant reduces.

2.2 Time dependent behavior of RC circuits

– R = 4700Ω

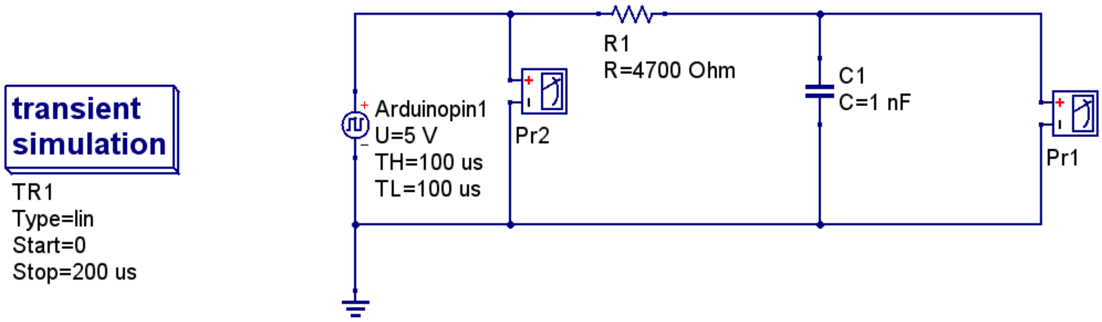

Figure 29: QUCS Simulation

– R = 10000Ω

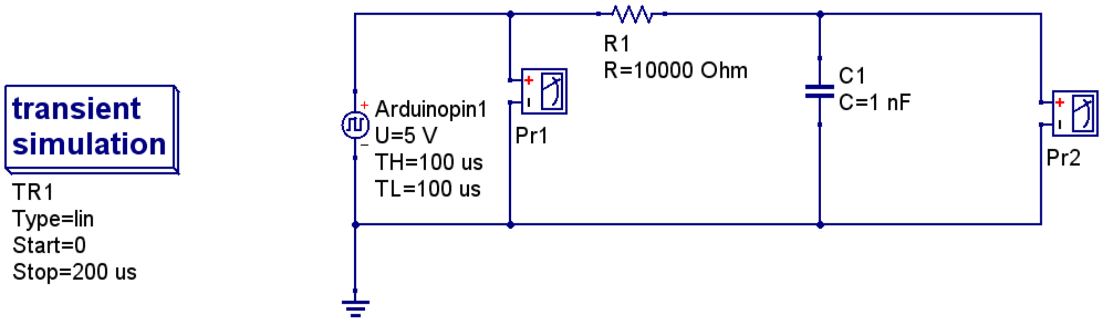

Figure 30: QUCS Simulation

– R = 22000Ω

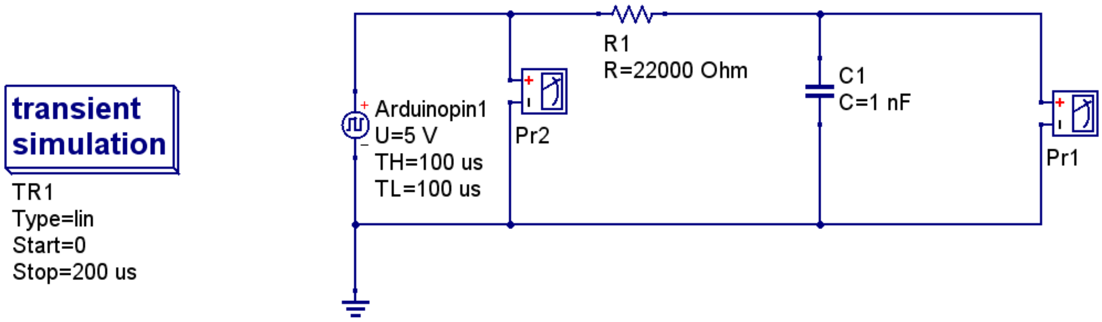

Figure 31: QUCS Simulation

– Observed Curves

—- R = 4700Ω

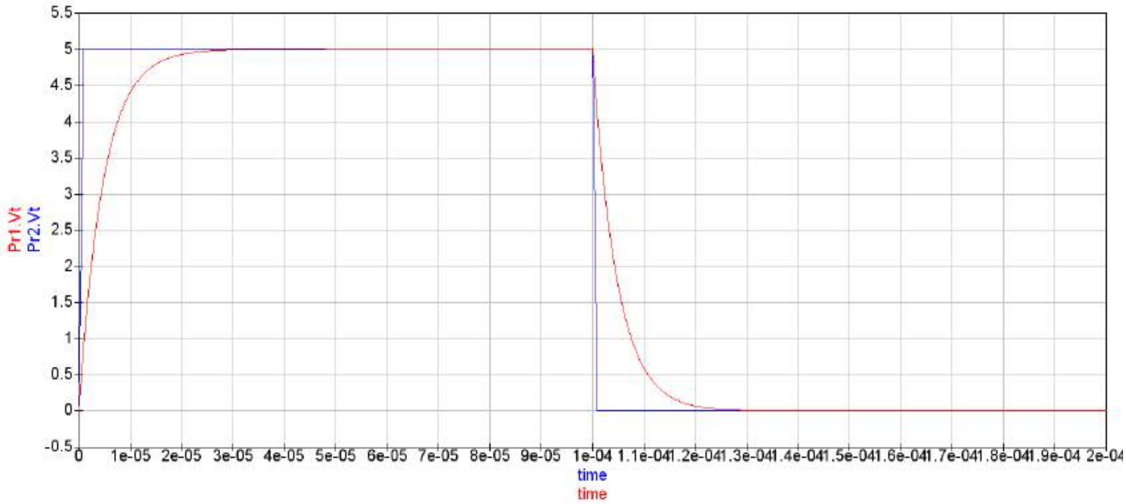

Figure 32: QUCS Simulation

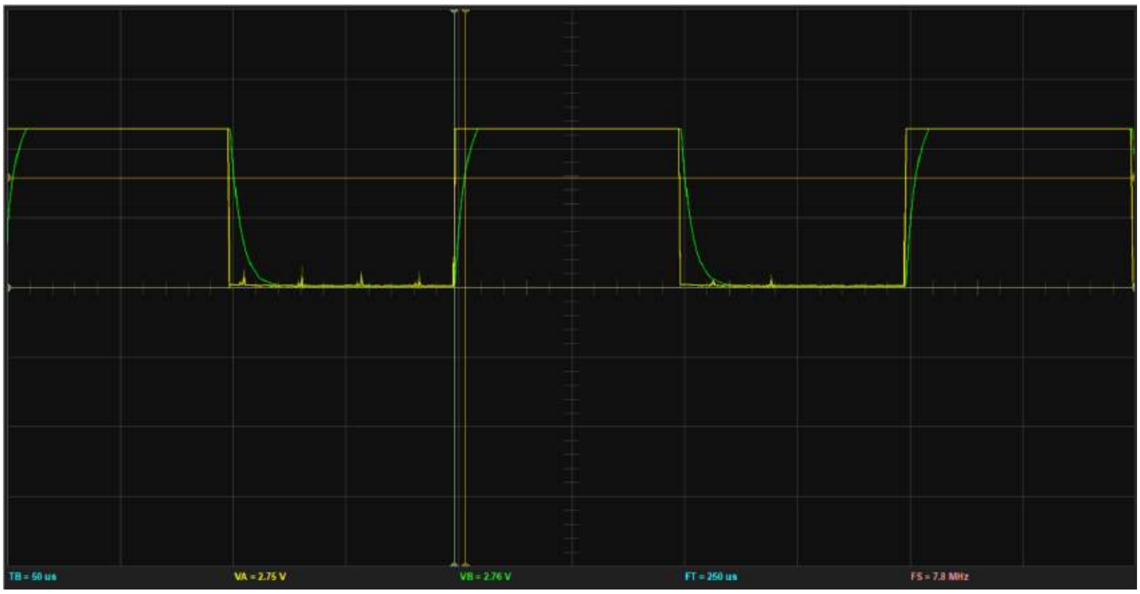

Figure 33: Bitscope

—- R = 10000Ω

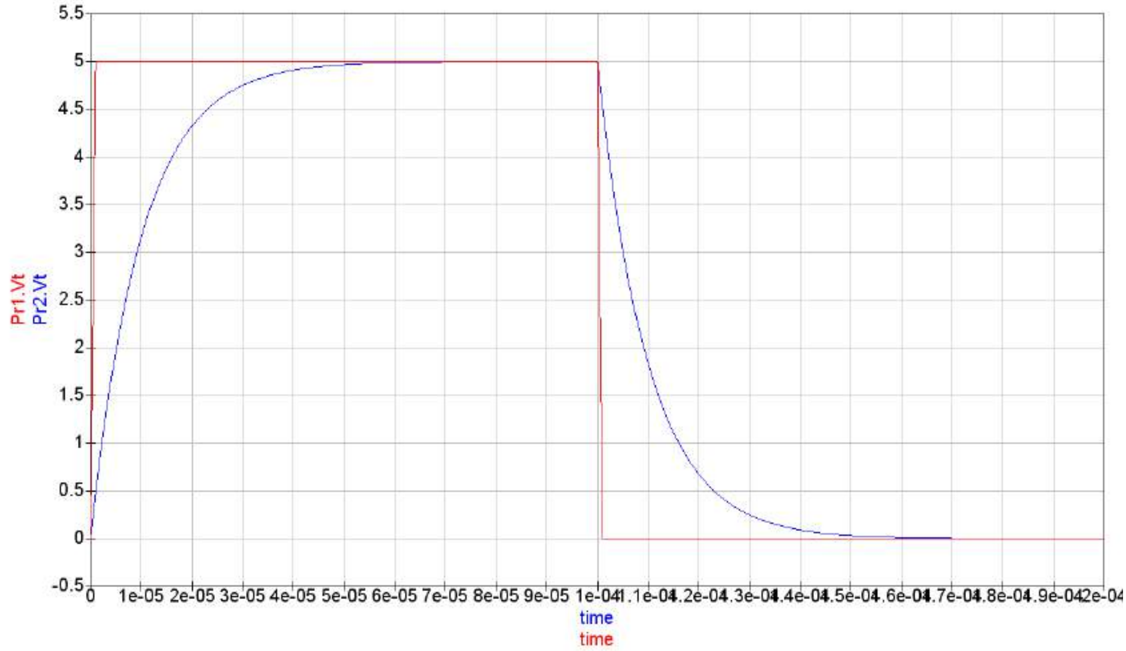

Figure 34: QUCS Simulation

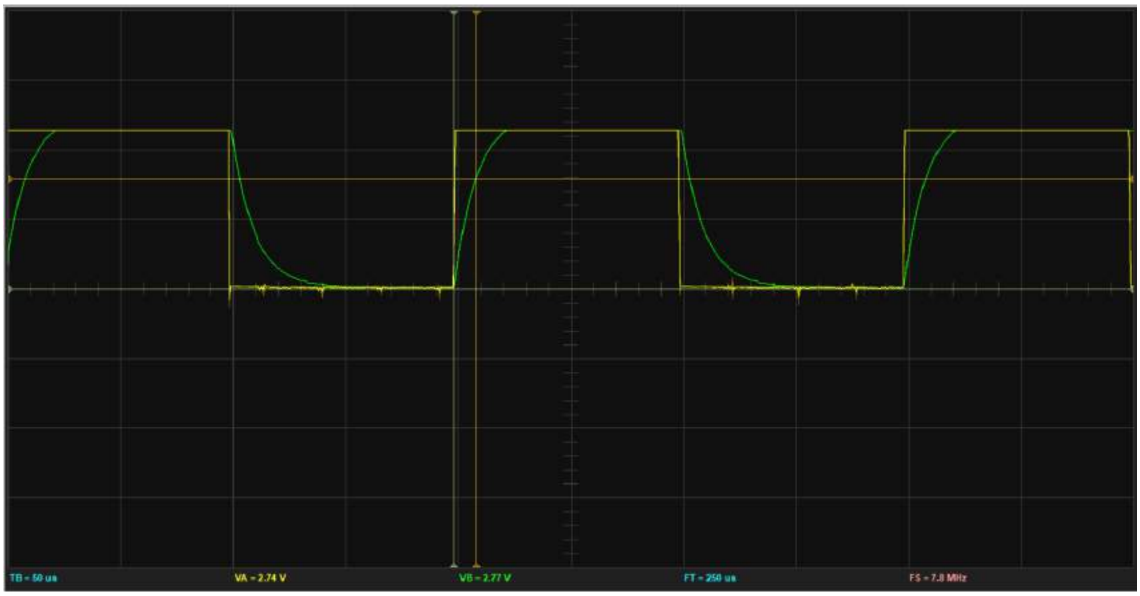

Figure 35: Bitscope

—- R = 22000Ω

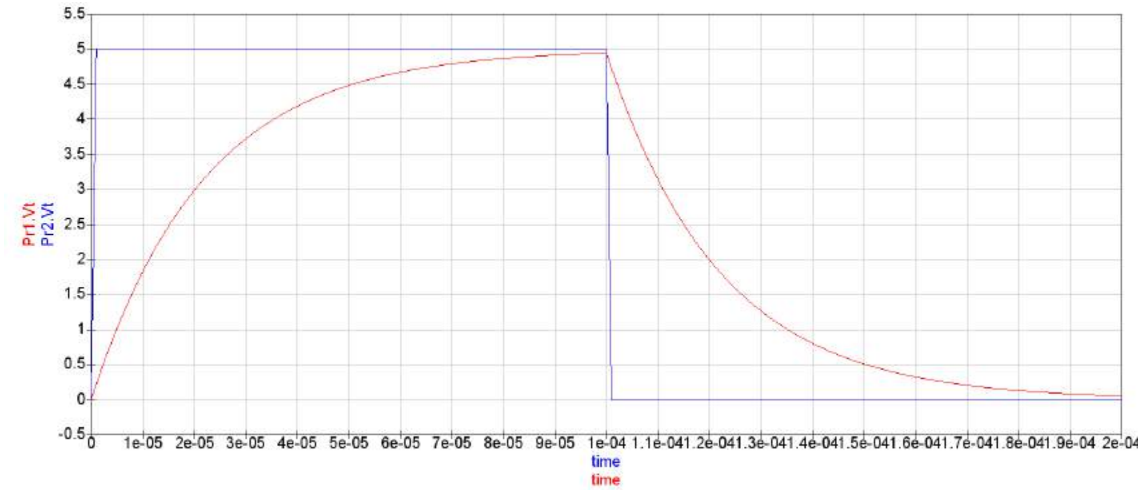

Figure 36: QUCS Simulation

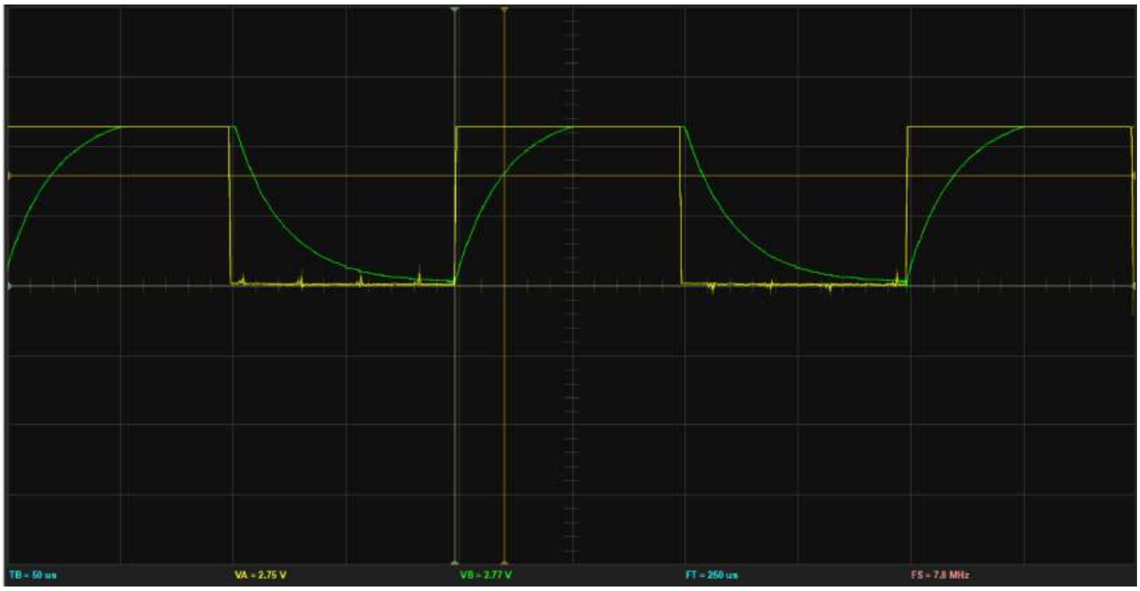

Figure 37: Bitscope

– Time Constant

Resistance	Calculated Time Constant (CR)	Measured Time Constant (BitScope)
4700 Ω	$4.7{\cdot}10^{-6}$	$5{\cdot}10^{-6}$
10000 Ω	$10{\cdot}10^{-6}$	$10{\cdot}10^{-6}$
22000 Ω	$22{\cdot}10^{-6}$	$22{\cdot}10^{-6}$

We take point 3.16V on each curve that we get on QUCS and compare the point on Bitscope curve we notice that they lie very close to each other.The reason we take 3.16V in each case as our V is 5V in all cases and after one time constant the capacitor gets charged at 63.2% of the initial value which is 3.16V.

– With Different combination of Capacitor

—- C in Series

For Capacitor in Series, the Equivalent Capacitance is given by

$$C_{eq} = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2}}$$

Thus C_{eq} in our case will be $10^{-18}F$

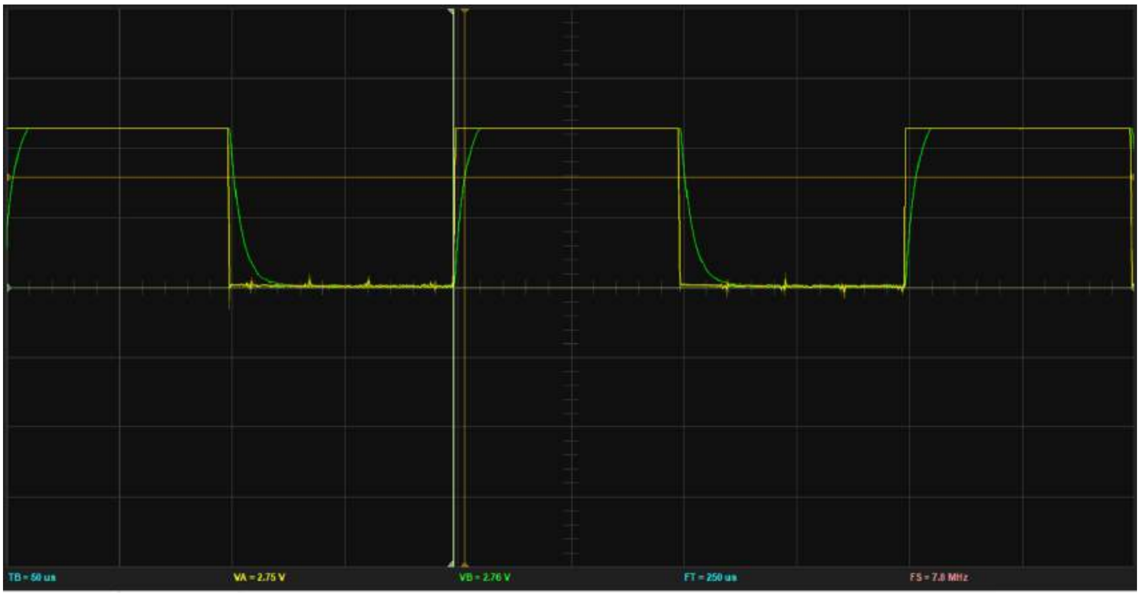

Figure 38: Bitscope

Calculated Time Constant$= 0.0005us$
Observed Time Constant$= 5us$

—- C in Parallel

For Capacitor in Parallel, the Equivalent Capacitance is given by

$$C_{eq} = C_1 + C_2...$$

Thus C_{eq} in our case will be $2nF$

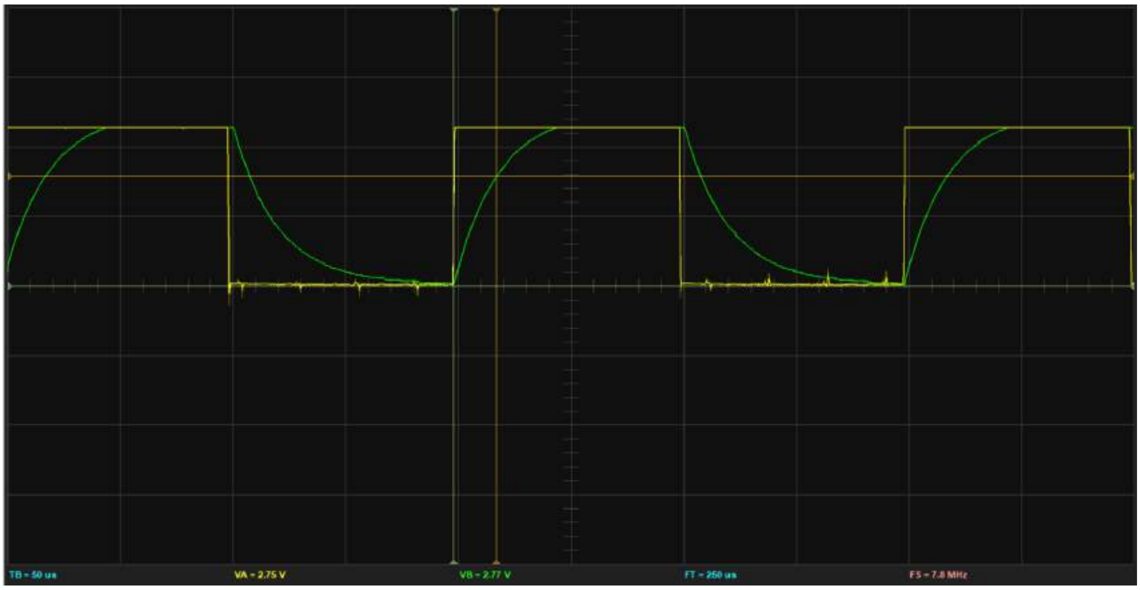

Figure 39: Bitscope

Calculated Time Constant$= 20us$
Observed Time Constant$= 20us$

We see that the time constant of the RC circuit can be increased if either R or C is increased and decreased if either R or C is decreased.

2.3 Negative Voltage Generator

Connection on QUCS

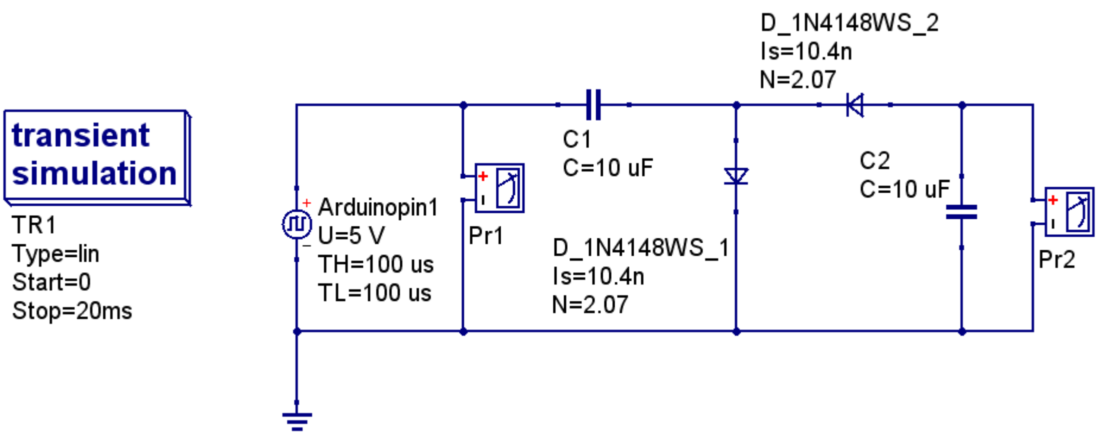

Figure 40: QUCS Simulation

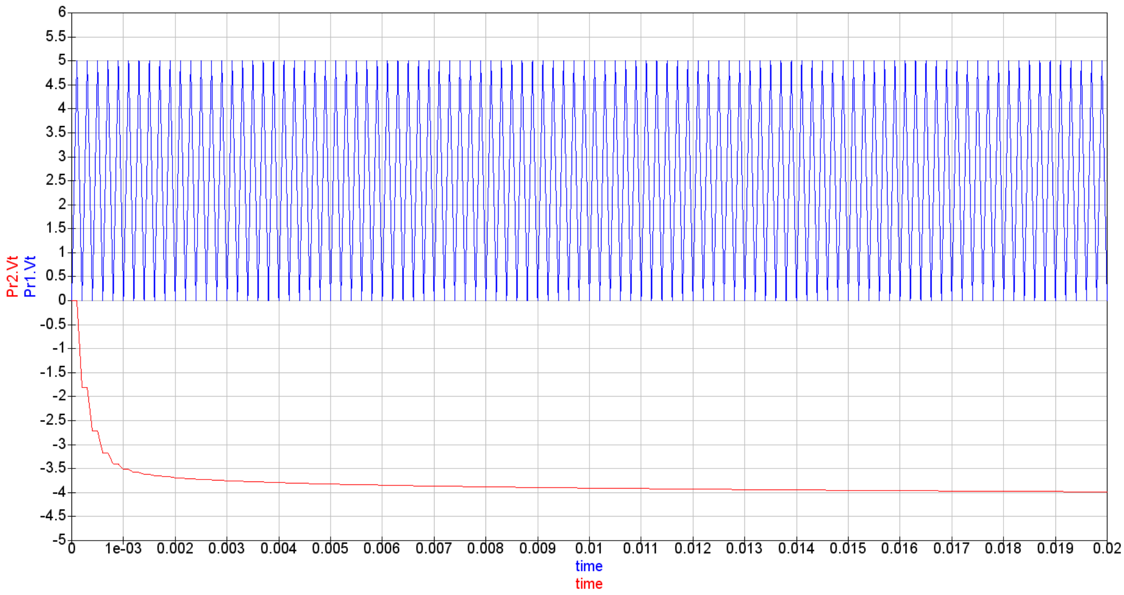

Figure 41: QUCS Simulation

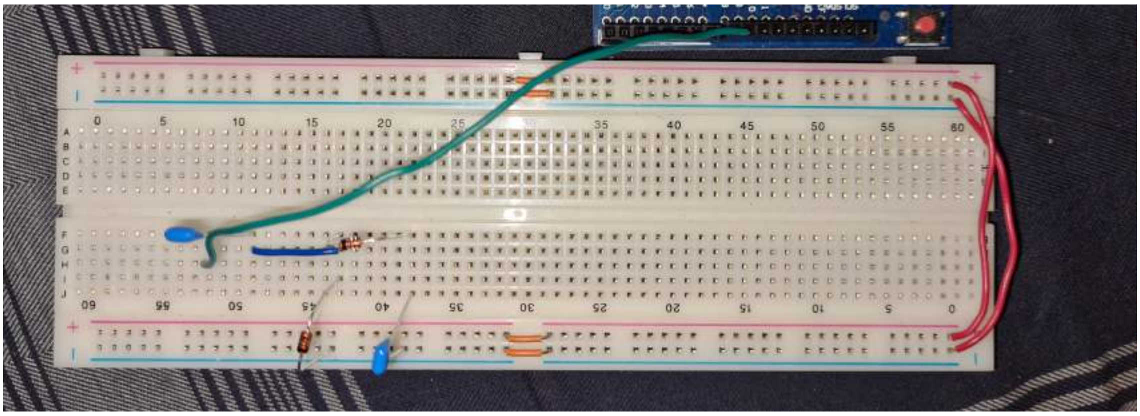

Figure 42: Connection on Breadboard

During the first cycle when the voltage is +5V from the arduino, on the **left side of the capacitor C1 we will have +5V**. A capacitor has a tendency to maintain the same voltage on both the plates so it attempts to make the plate on right side also at +5V. Unfortunately, this attempt is stopped by the diode D1 which has a forward potential of 0.7V. This forward voltage restricts the voltage on the **right plate of C1 to 0.7V.**. Due to this, the potential difference across the plates of C1 becomes 5V-0.7V=4.3V.

Now, when the voltage becomes 0V in the next cycle. The left plate is at 0V and potential difference between the plates is 4.3V so the right plate of C1 reaches -4.3V to maintain the balance. This -4,3V stops the diode D1 from conducting as it's forward voltage is 0.7V. This negative potential stays at D1.

The -4.3V that we get now brings the diode D2 into play. As D2 is connected the other way around. It starts conducting. The voltage at the top plate of C2 will keep decreasing until D2 stops conducting. The diode D2 will stop conducting when voltage drop across it is less than 0.7V. It will stop conducting when the top plate of C2 is at -4.3V-(-0.7V) = -3.6V. That's why the output is not exactly -5V.

– **When replaced C2 with LED and Resistor**

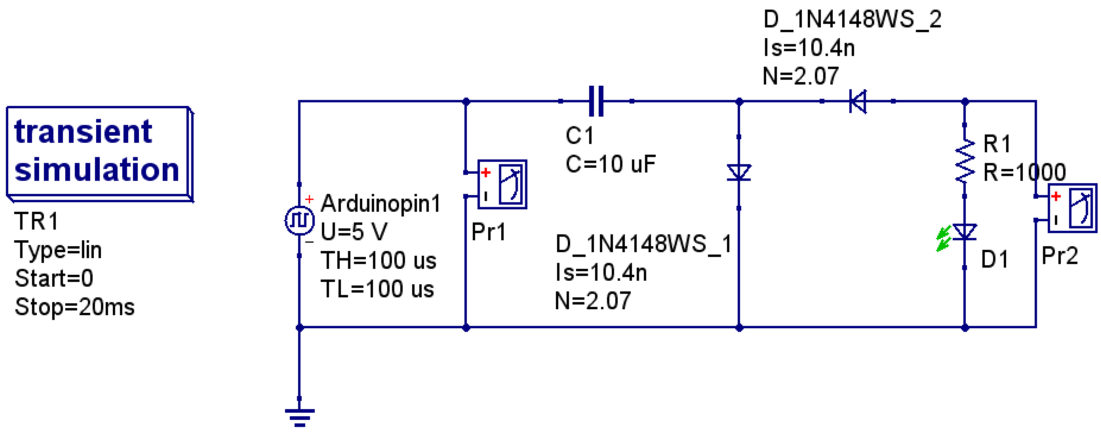

Figure 43: Simulation on QUCS

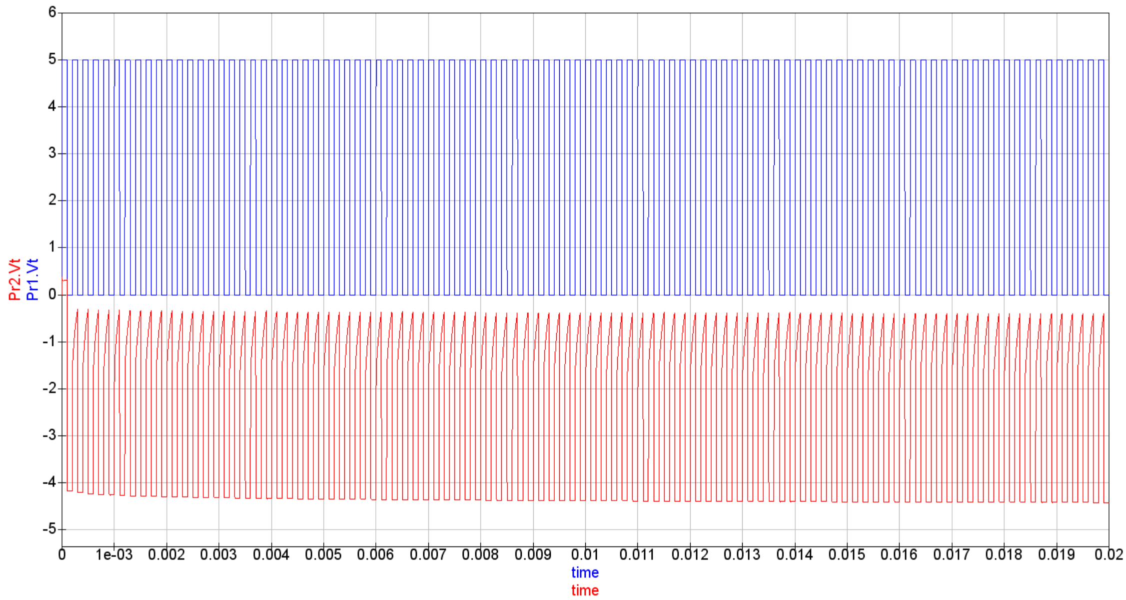

Figure 44: QUCS Curve

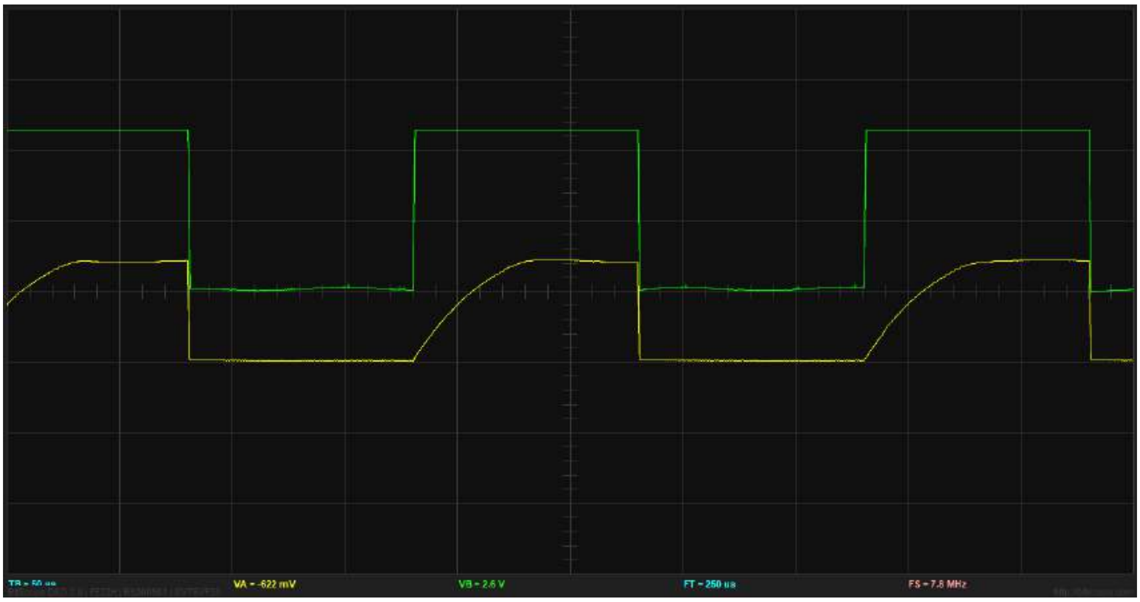

Figure 45: Bitscope Curve

2.4 Rectifier circuit with capacitor and resistor

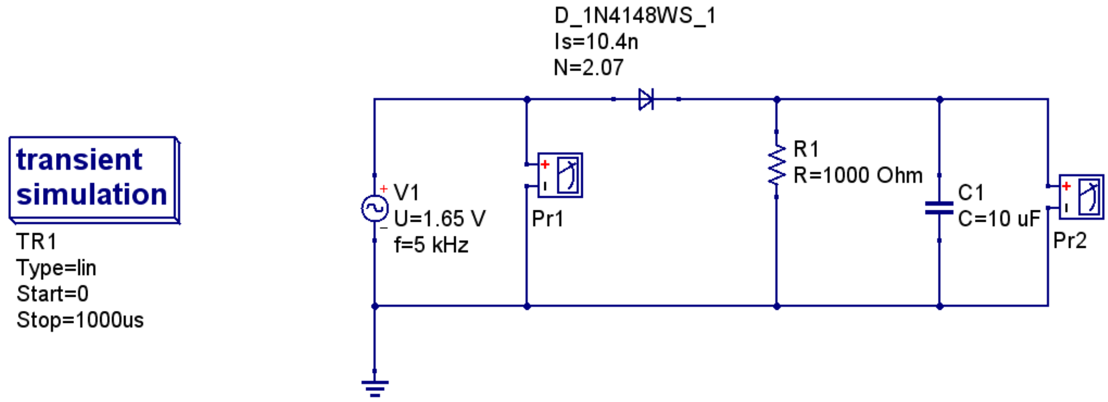

Figure 46: Rectifier Circuit with Capacitor

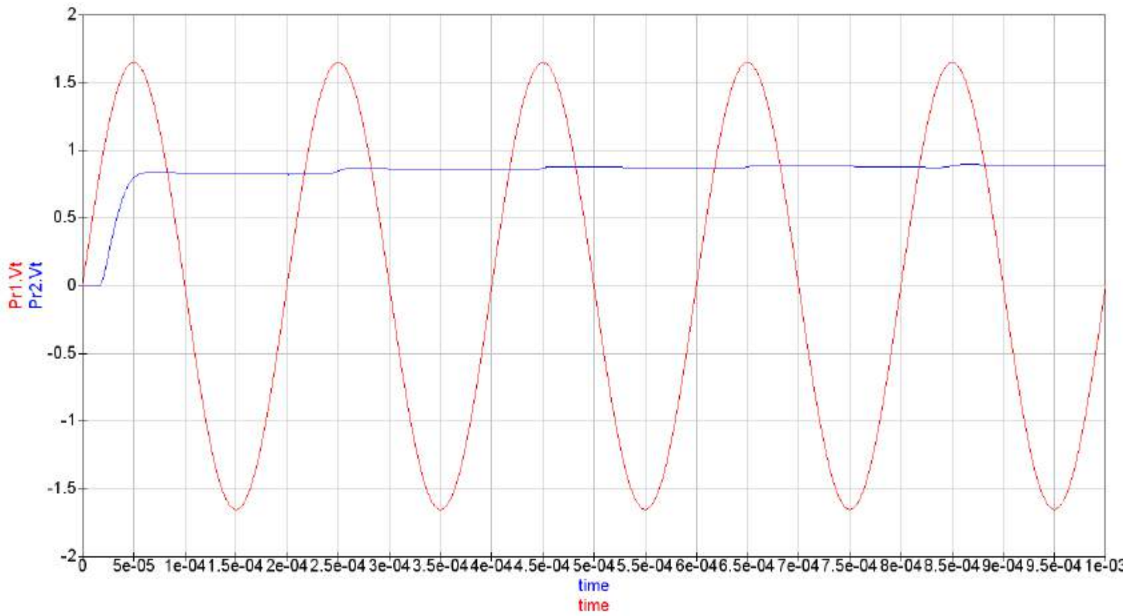

Figure 47: Rectifier Circuit Output with Capacitor

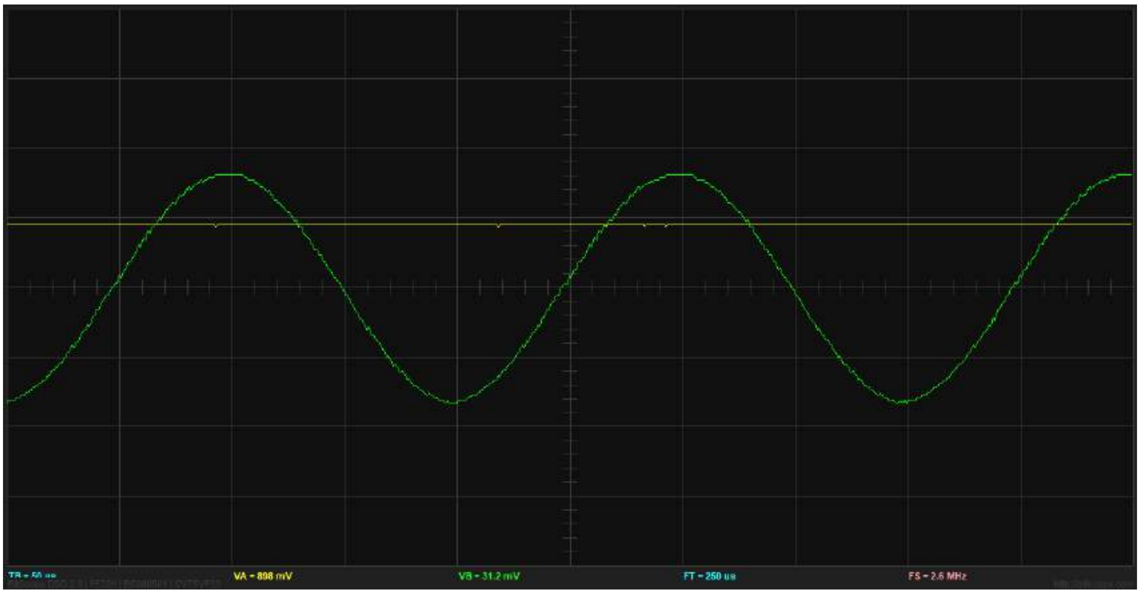

Figure 48: Rectifier Circuit Output with Capacitor

We can see that with a capacitor the rectifier acts as **AC to DC converter** as it maintains the output voltage even when the AC voltage keeps changing.

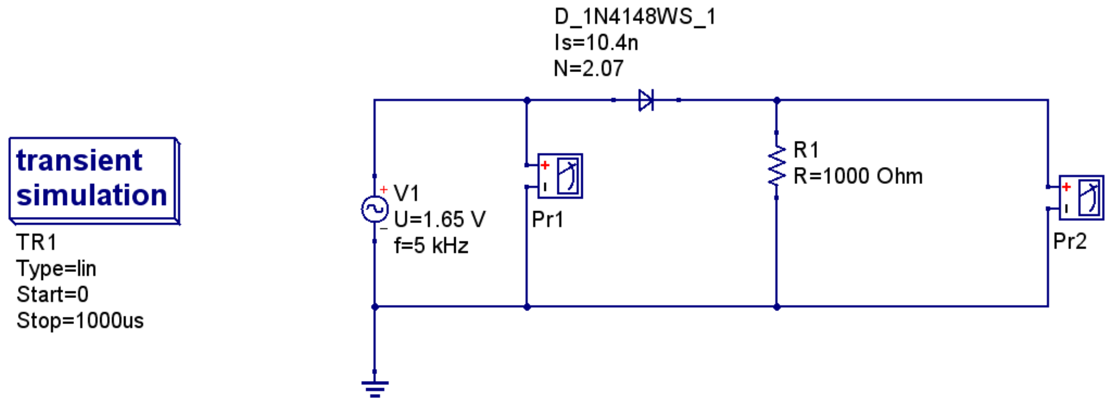

Figure 49: Rectifier Circuit without Capacitor

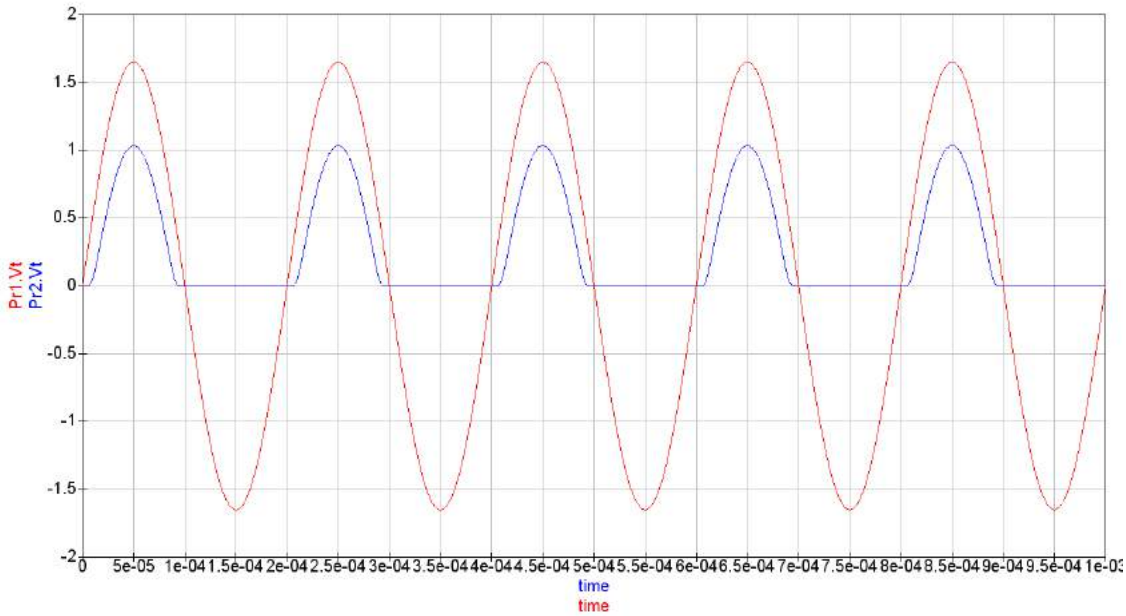

Figure 50: Rectifier Circuit Output without Capacitor

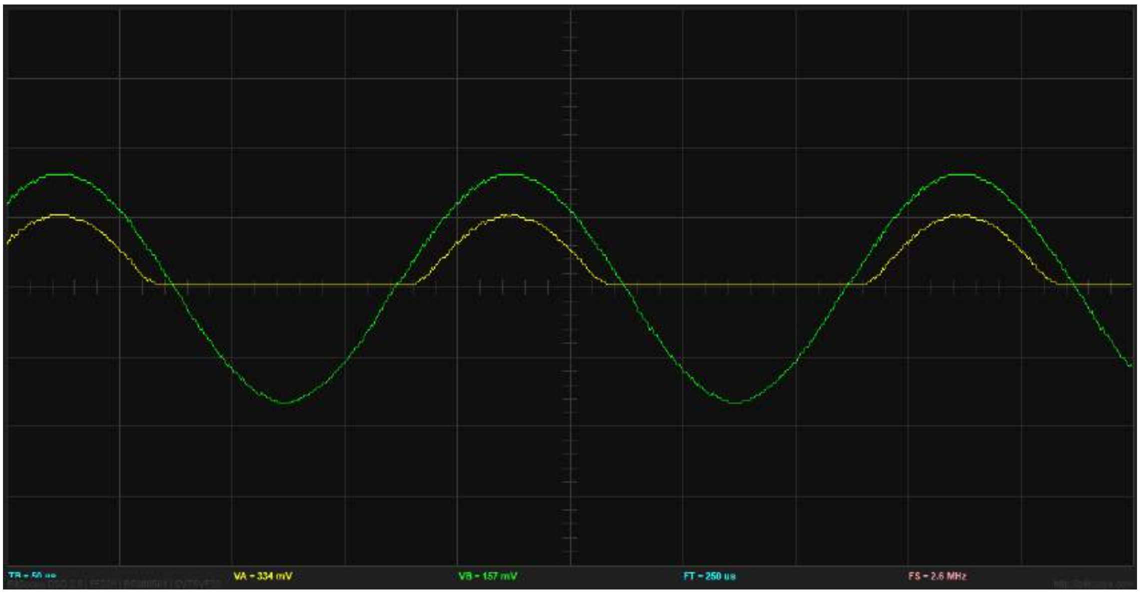

Figure 51: Rectifier Circuit Output with Capacitor

We can see that without a capacitor the rectifier acts as **half wave rectifier**.When the AC voltage becomes negative the output cancels it out and maintains the positive voltage.

Buffer Circuit - Testing

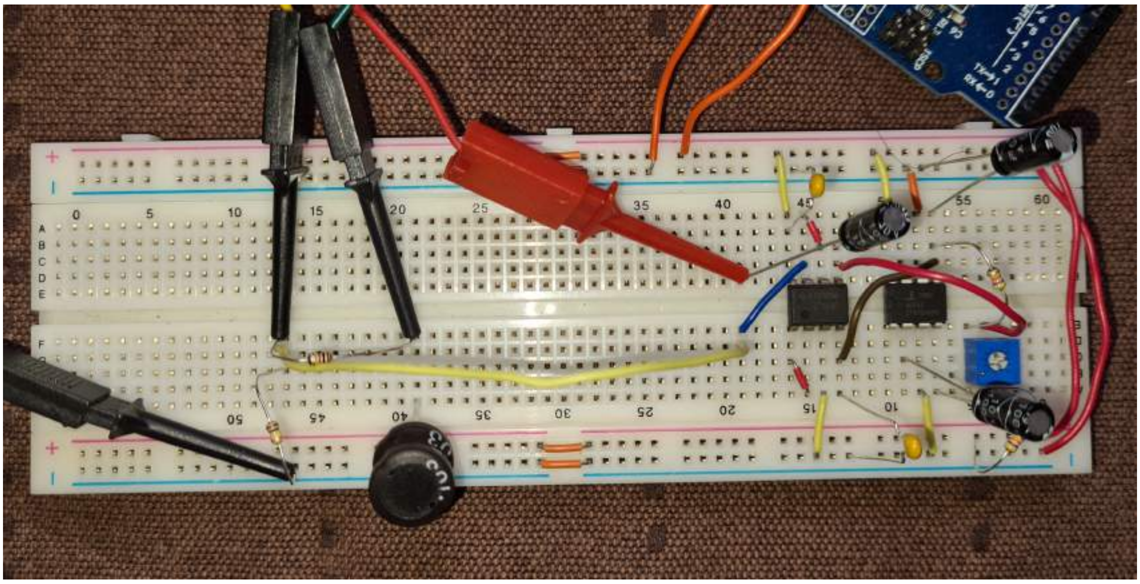

Figure 52: Buffer circuit connection

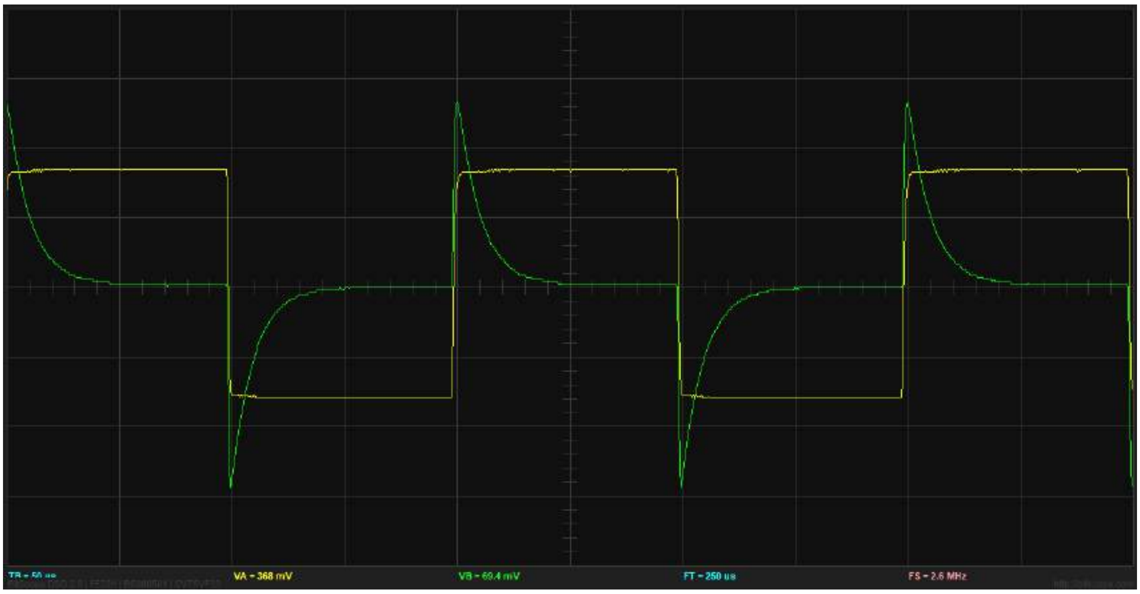

Figure 53: Buffer circuit curve

2.5 Voltage Doubler

– With Capacitor

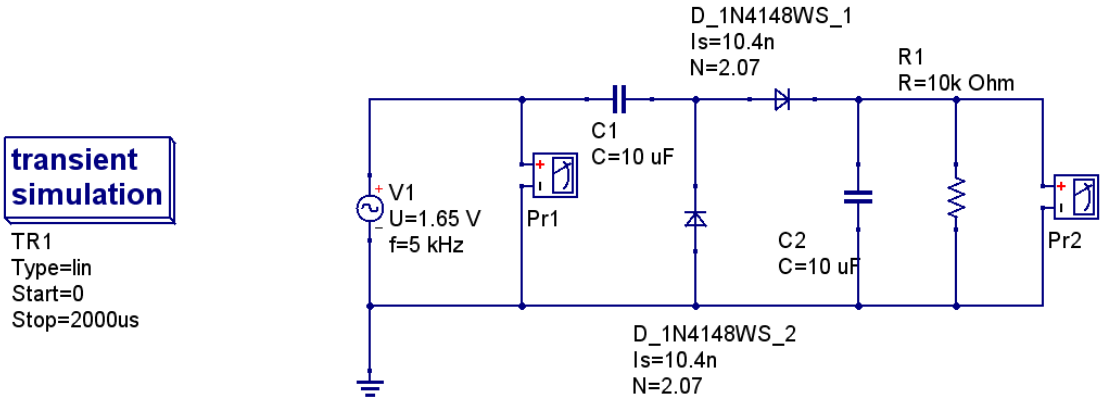

Figure 54: Circuit with Schematics - QUCS

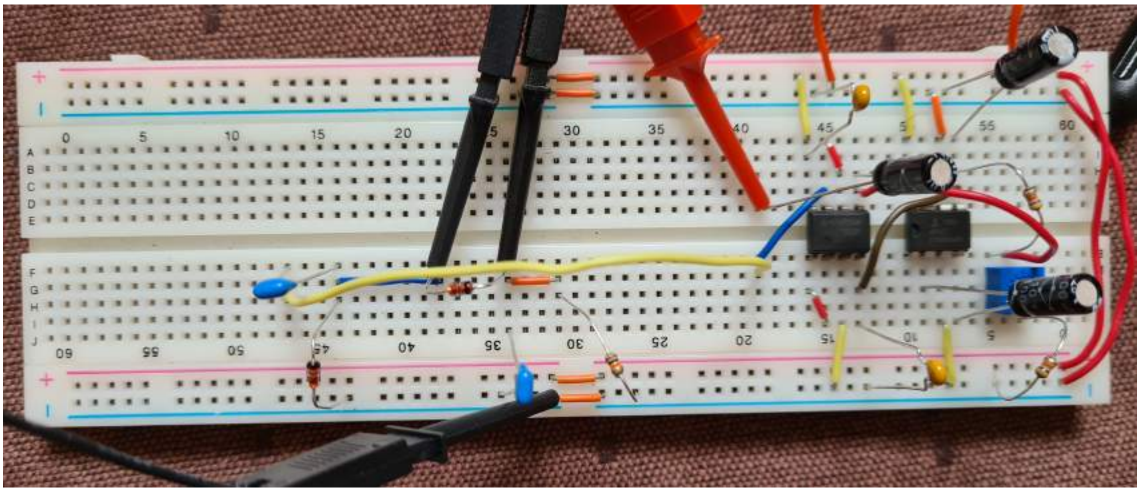

Figure 55: Connections on Breadboard

—- Curve

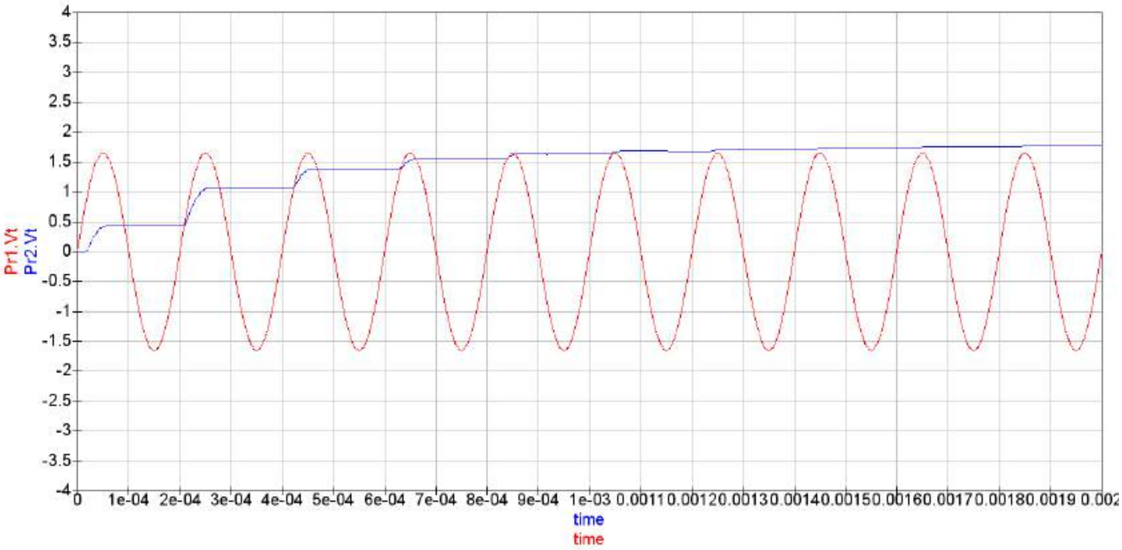

Figure 56: Curves - QUCS

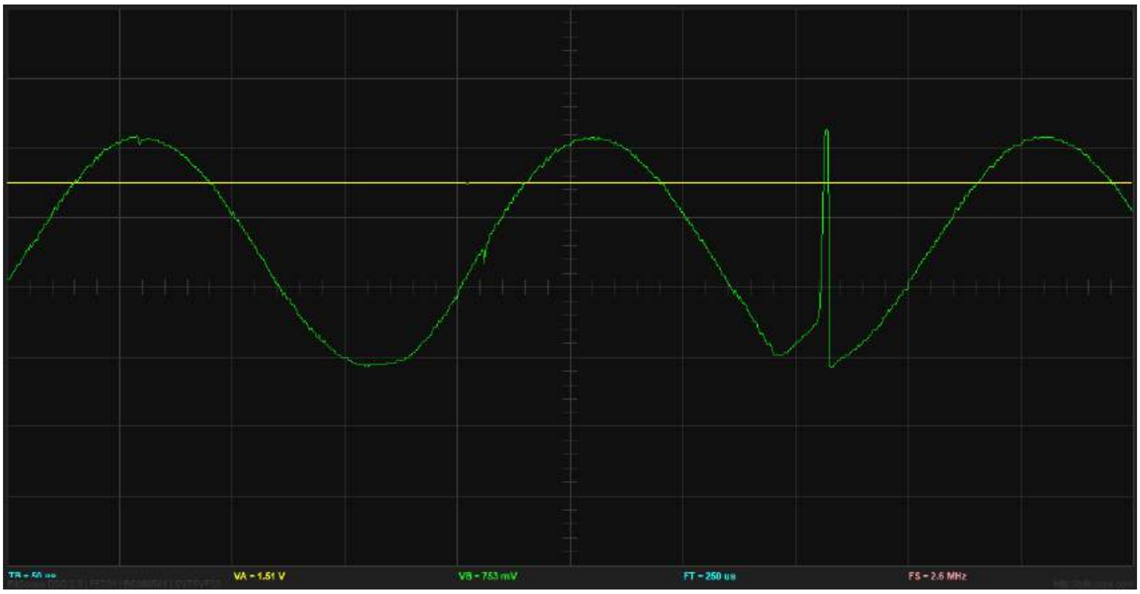

Figure 57: Curve - Bitscope

Here we notice that there is a slight difference in the graph. This difference exists as the diode used is not ideal and forward voltage might differ, also there’s a slight error in Bitscope which was shown to the lab assistant and approved.

– **Without Capacitor**

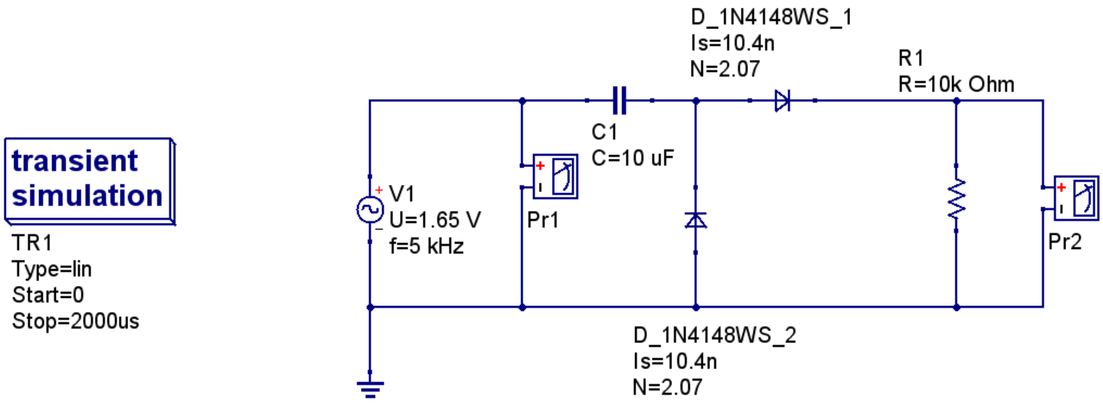

Figure 58: Circuit with Schematics - QUCS

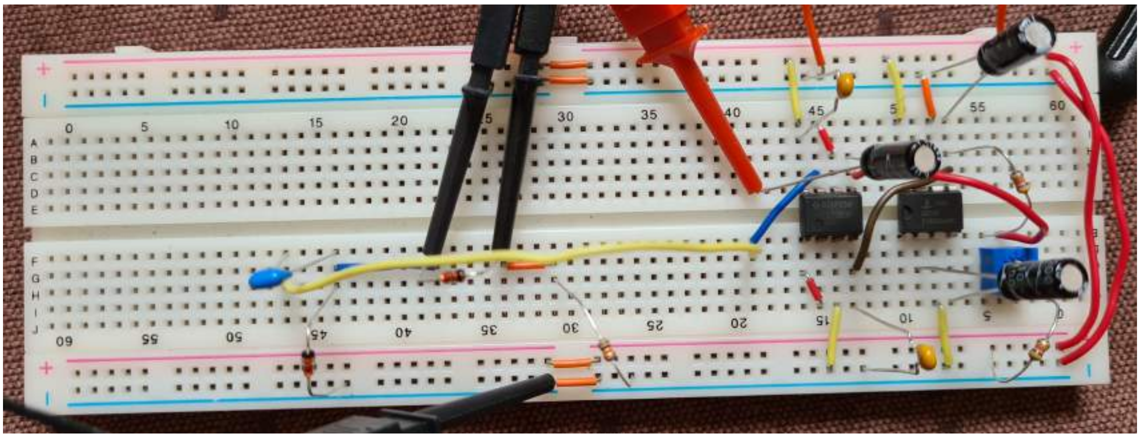

Figure 59: Connections on Breadboard

—- Curve

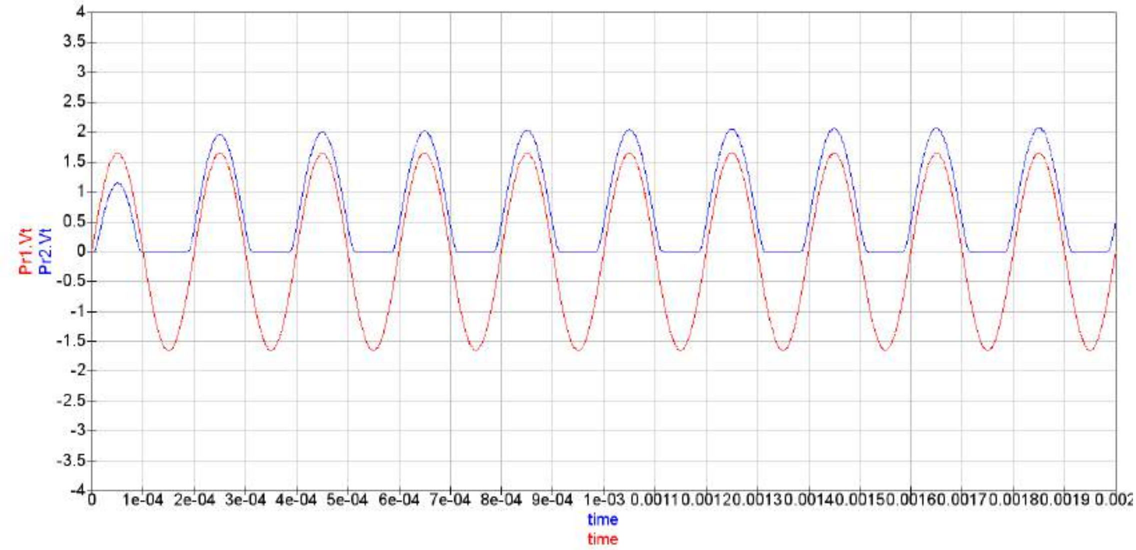

Figure 60: Curves - QUCS

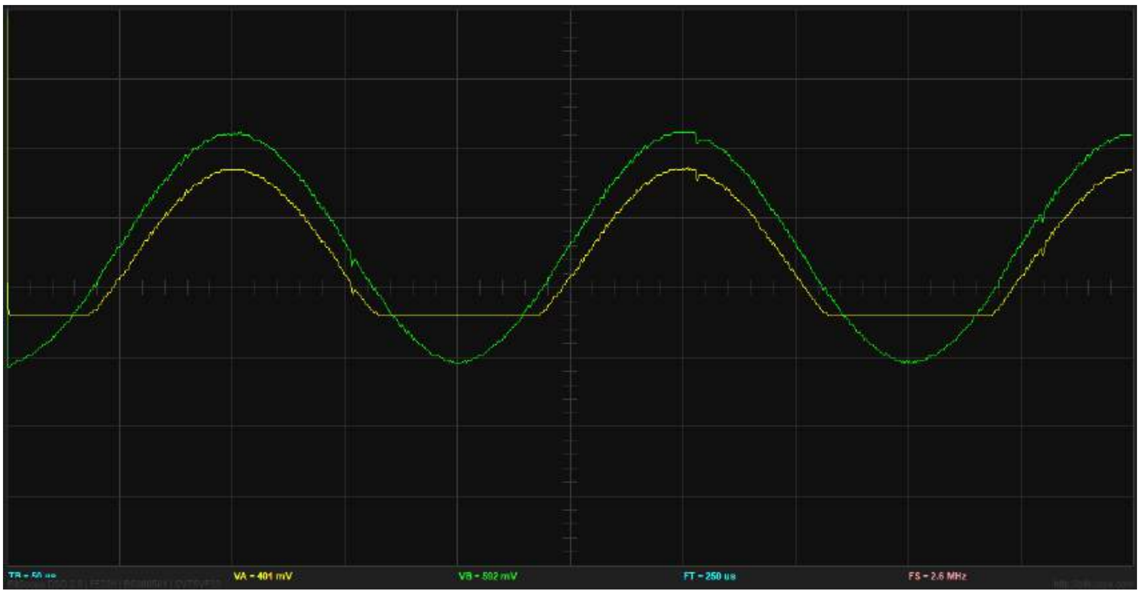

Figure 61: Curve - Bitscope

In both ways, with and without capacitor we notice that the behaviour is quite similar.

Module 3

3. AC MEASUREMENTS

3.1 Internal resistance of Bitscope waveform generator with Op amp buffer

Equation for Internal Resistance, R_i is

$$R_i = \frac{V_{pp,U} - V_{pp,L}}{V_{pp,L}} \cdot R_L$$

where $V_{pp,U}$ is unloaded voltage.
$V_{pp,L}$ is loaded voltage.
R_L is load Resistance.

– Bitscope Waveform Generator

—- Observation

Resistance (R_L)	$V_{pp,L}$	R_i
1000	2.2V	509
2200	2.64V	566
4700	2.96V	571
10000	3.16V	506

Unloaded voltage, $V_{pp,U}$ is 3.32V.
We take average of these four measured R_i to get an approximate value.

$$R_i = 538\Omega$$

– Bitscope Waveform Generator with Op amp Buffer

—- Observation

Resistance (R_L)	$V_{pp,L}$	R_i
220	3.23V	6.8
470	3.29V	5.71
1000	3.28V	15.24
2200	3.299V	20.6

Unloaded voltage, $V_{pp,U}$ is 3.33V.
We take average of these four measured R_i to get an approximate value.

$$R_i = 12.08\Omega$$

3.2 RL low pass and high pass

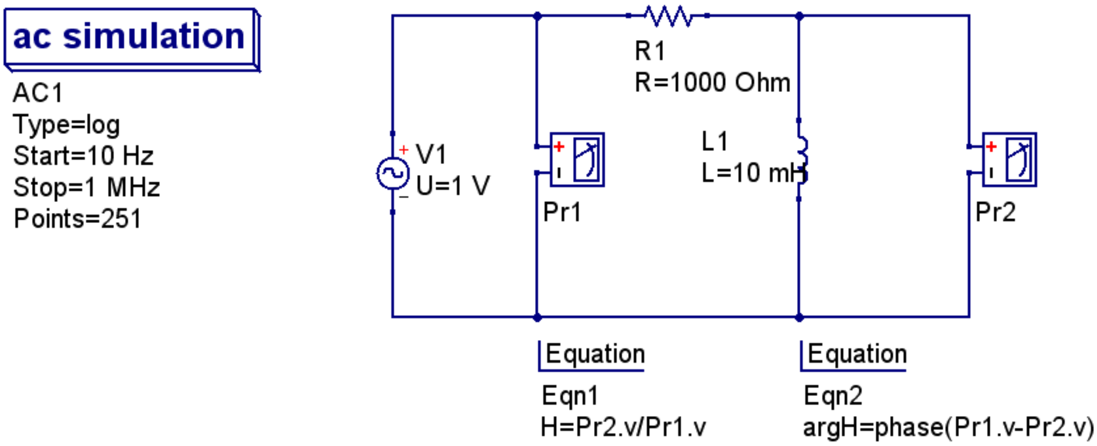

Figure 62: Circuit Schematics

1. Calculated f_c using R1 and L1

$$f_c = \frac{R}{2\pi L}$$
$$f_c = \frac{1000}{2\pi 10^{-2}}$$
$$f_c = 15.9 \cdot 10^3$$
$$f_c = 15.9kHz$$

2. For $f_c = 6kHz$, R1 and L1 should be

$$6kHz = \frac{R}{2\pi L}$$
$$6Khz = \frac{R}{2\pi L}$$
$$R = 377\Omega$$

As we have limited number of resistor values, for easy implementation we will approximate this value to 370Ω.This gives us a cutoff frequency $f_c = 5.89Khz$.

3.

$$V_{out} = \frac{X_L}{X_L + R} \cdot V_{in}$$
$$V_{out} = \frac{\omega L}{\omega L + R} \cdot V_{in}$$

Now, we can infer that as the frequency increases V_{out} tends to V_{in} and if we lower the frequency V_{out} tends to 0.Thus we can say that this is a high pass filter.

4.

5. Cutoff Frequency by definition is the frequency where the output voltage is 0.707V_{in}. Using this information, we can check the peak of output voltage for various frequencies and check if it is 0.707V_{in}. We achieve this point at 5.89KHz. At this frequency, The output voltage lags behind input voltage by 45 degrees.

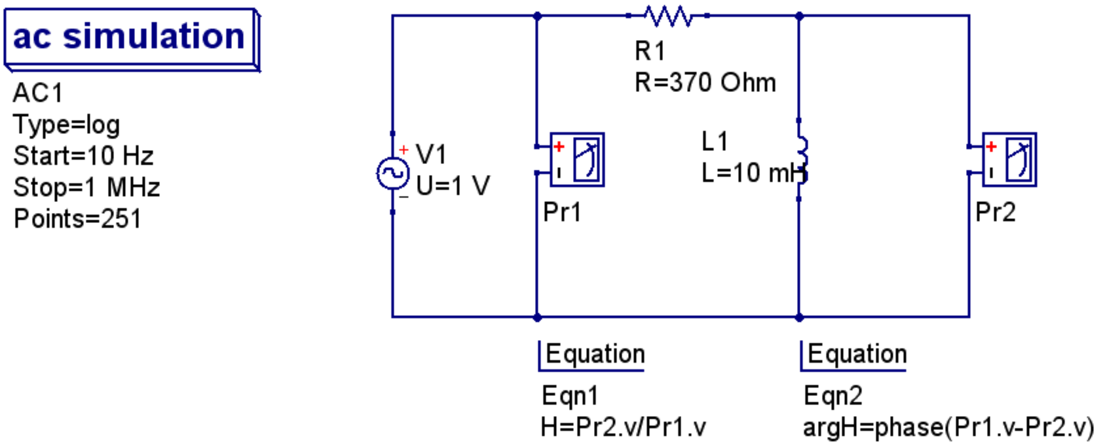

Figure 63: QUCS Circuit Schematics

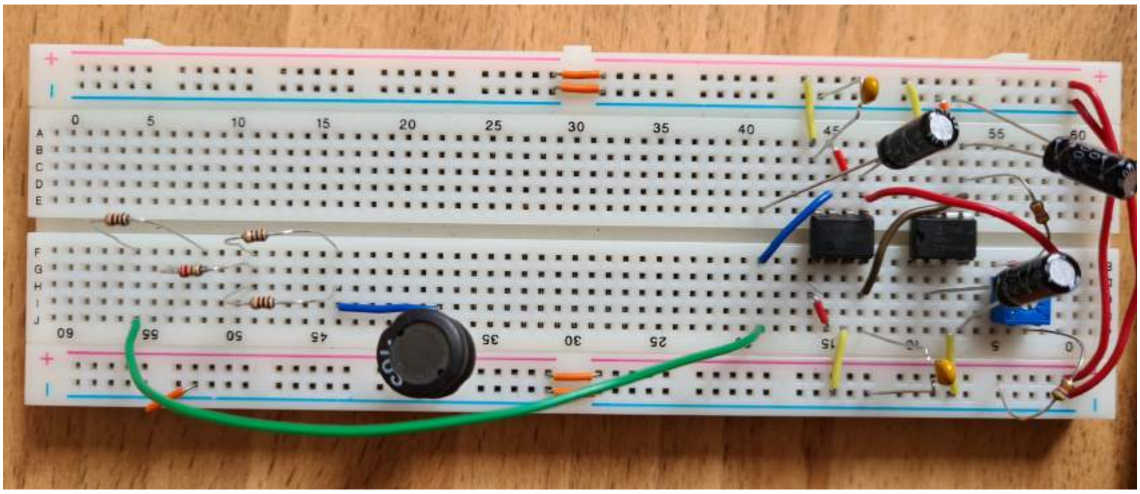

Figure 64: Connections on Breadboard

6. When Position of R1 and L1 is swapped,

$$V_{out} = \frac{R}{X_L + R} \cdot V_{in}$$

$$V_{out} = \frac{R}{\omega L + R} \cdot V_{in}$$

This shows that as the frequency increases V_{out} tends to 0 and if we lower the frequency V_{out} tends to V_{in}.Thus we can say that this acts as a low pass filter. The cutoff frequency will remain the same for this filter.

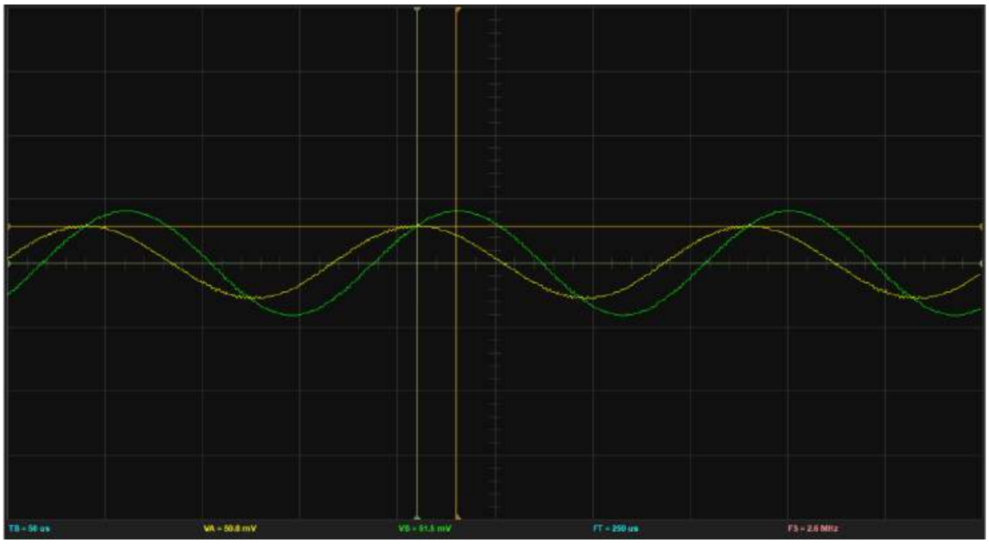

Figure 65: Connections on Breadboard

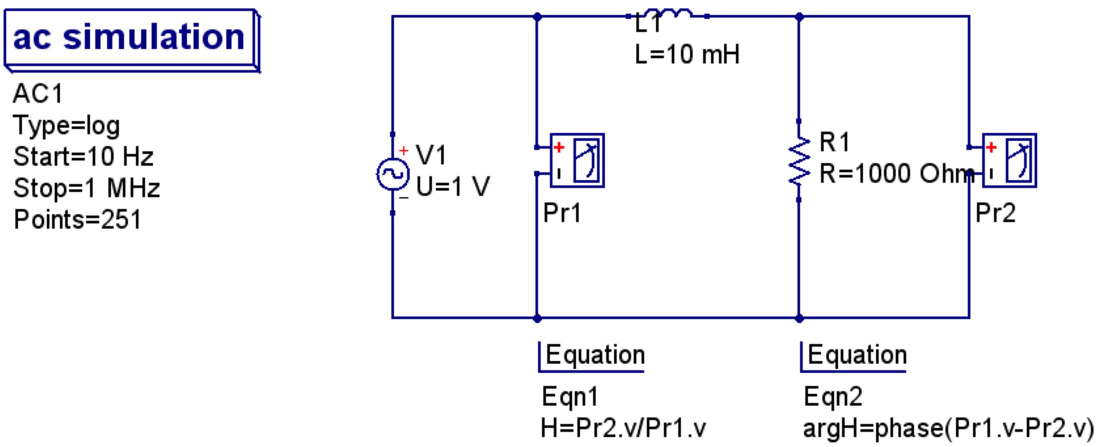

Figure 66: QUCS Circuit Schematics

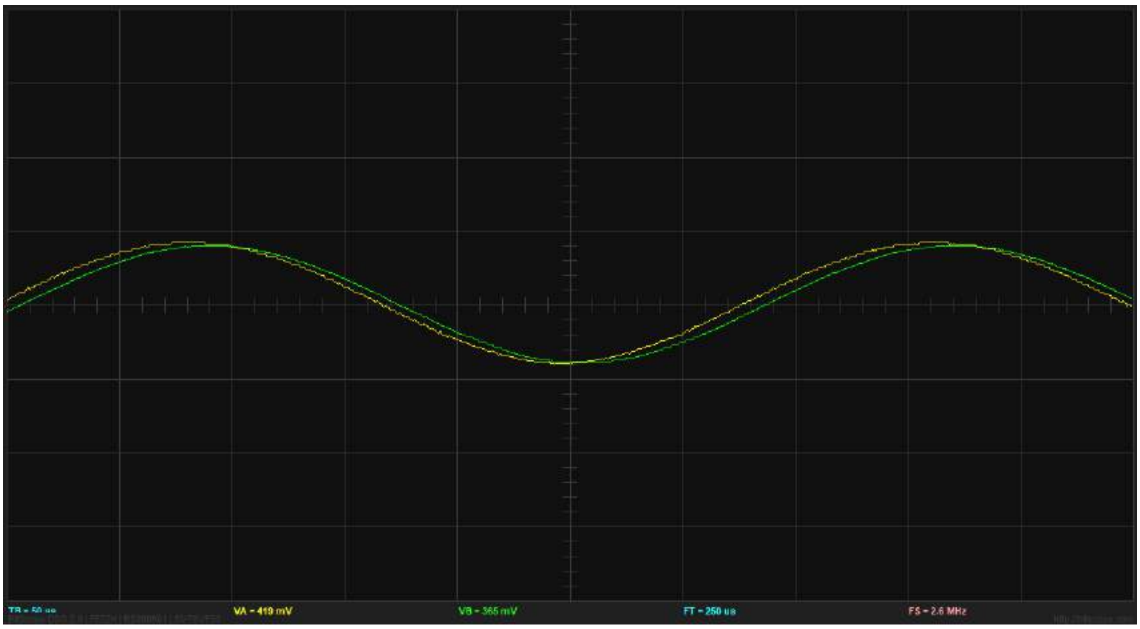

Figure 68: For low frequency, V_{out} tends to V_{in}

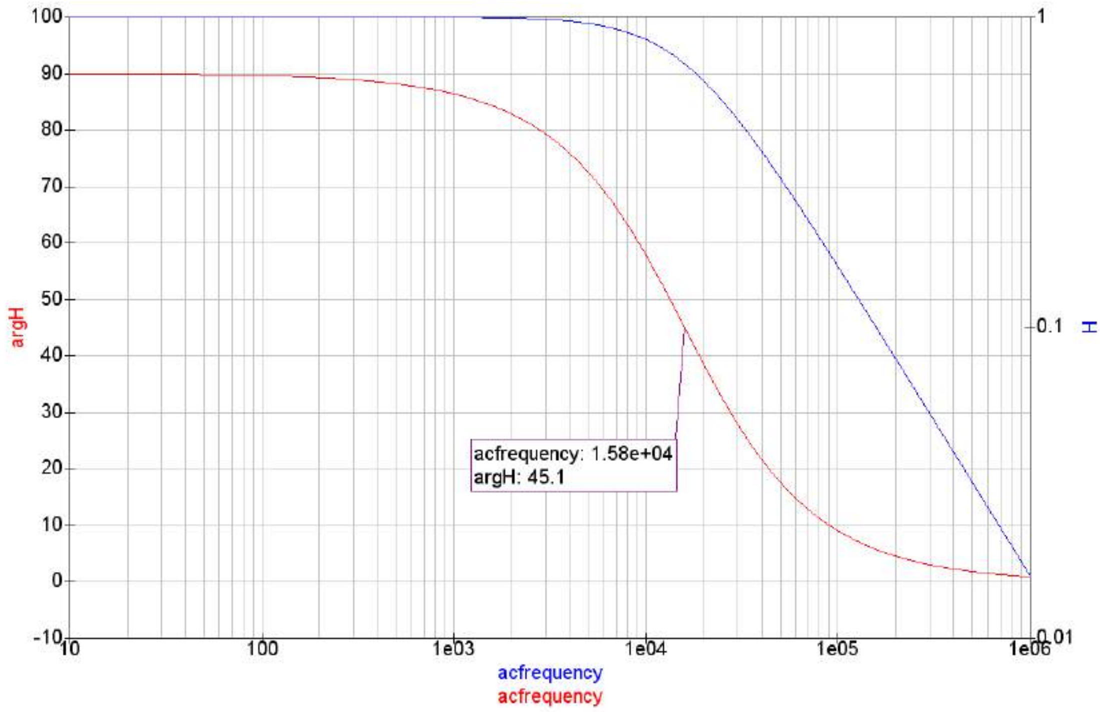

Figure 67: QUCS Simulation Curve

3.3 RC low pass and high pass

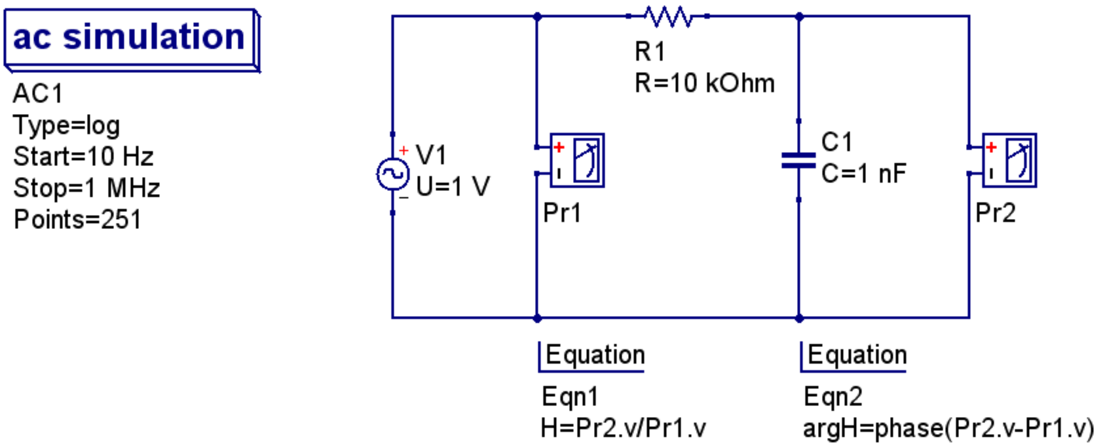

Figure 70: Circuit Schematics

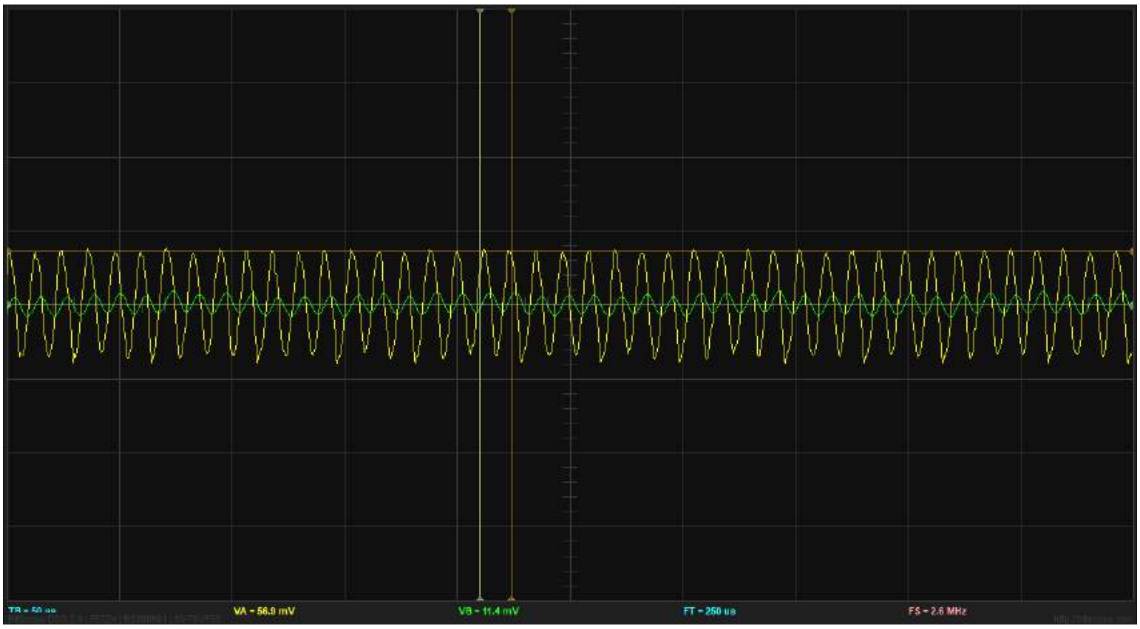

Figure 69: For high frequency, V_{out} tends to 0

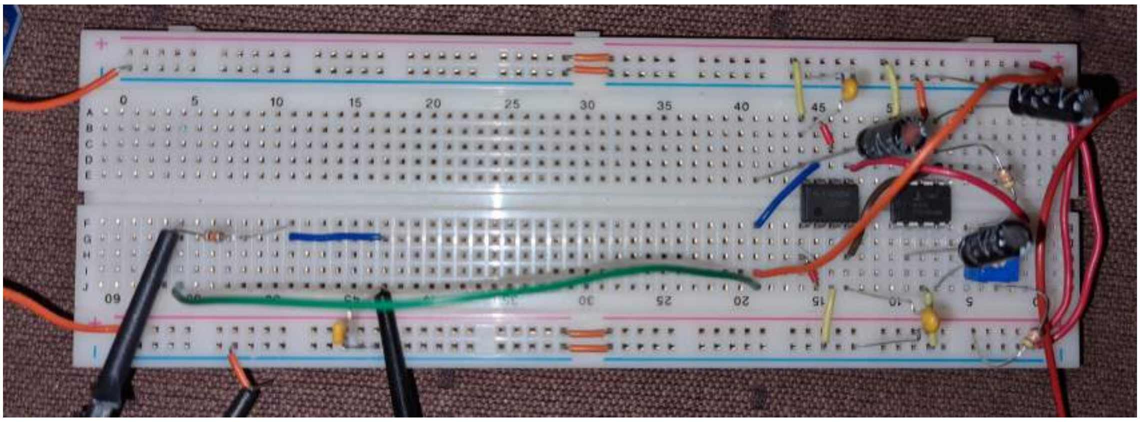

Figure 71: Circuit Schematics

1. Calculated f_c using R1 and C1

$$f_c = \frac{1}{2\pi RC}$$
$$f_c = \frac{1}{2\pi 10^5}$$
$$f_c = 15.9 \cdot 10^3$$
$$f_c = 15.9kHz$$

2. For $f_c = 18kHz$, R1/C1 should be

$$18 = \frac{R1}{C1}$$

   $R = 8800\Omega$ and $C = 1nF$

3.

$$V_{out} = \frac{X_c}{X_c + R} \cdot V_{in}$$
$$V_{out} = \frac{V_{in}}{1 + \omega RC}$$

We can see that as frequency tends to infinity, V_{out} tends to 0 and as we decrease the frequency the output voltage, V_{out} tends to V_{in}. Thus it is a low pass circuit.

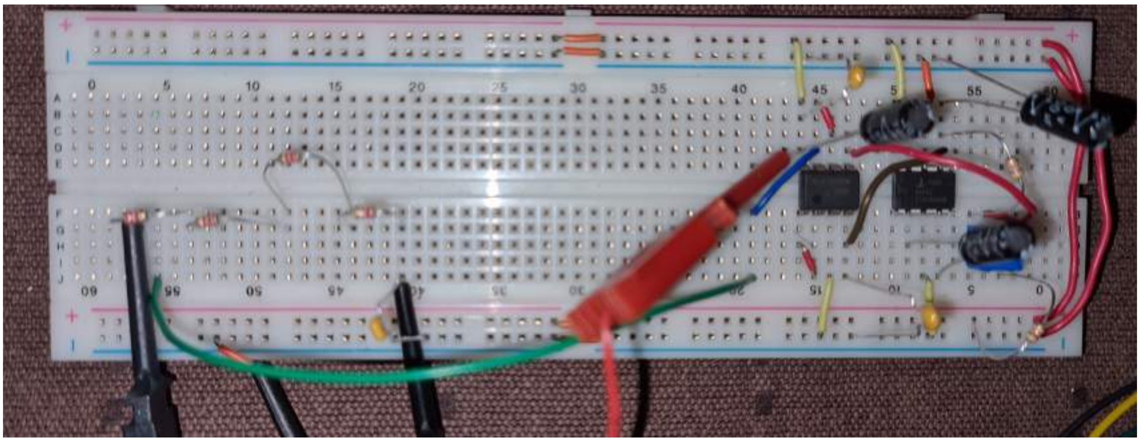

Figure 73: Circuit Schematics

4. Cutoff frequency by definition is the frequency where the output voltage is $0.707V_{in}$. Using this information, we can check the peak of output voltage for various frequencies and check if it is $0.707V_{in}$. We achieve this point at 18KHz. At this frequency, The output voltage lags behind input voltage by 45 degrees

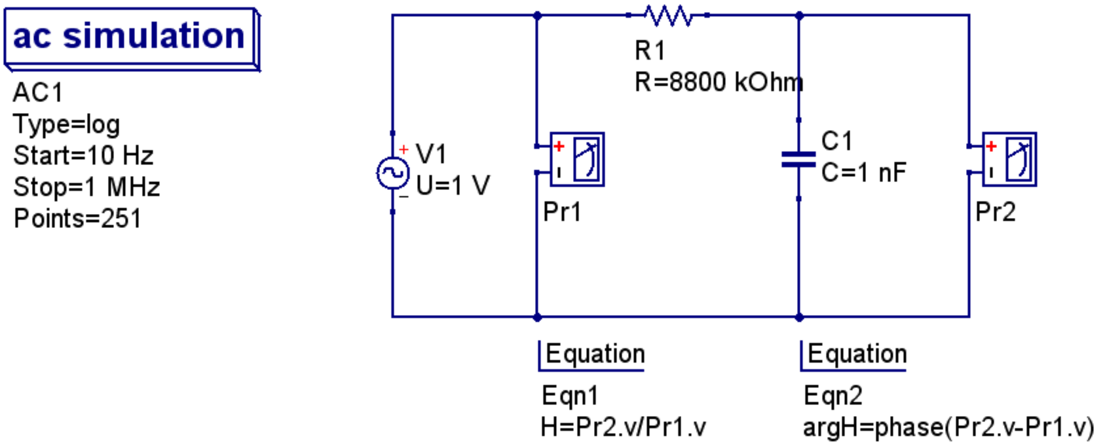

Figure 72: Circuit Schematics

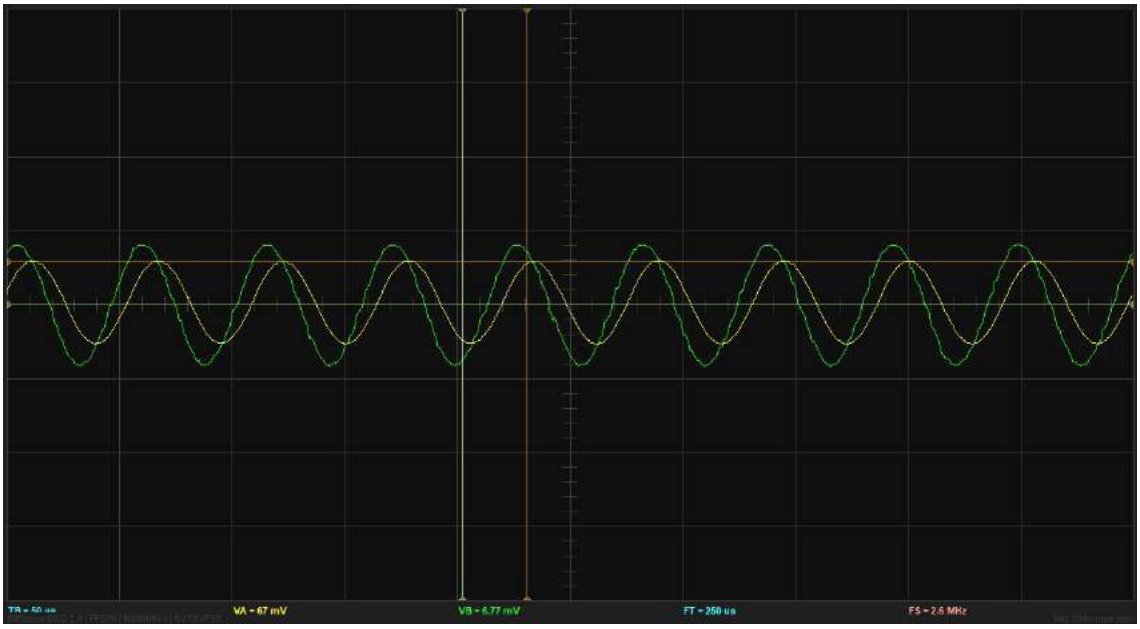

Figure 74: Circuit Schematics

5. When position of R1 and C1 is swapped,

$$V_{out} = \frac{R}{X_c + R} \cdot V_{in}$$

$$V_{out} = \frac{\omega CR}{\omega CR + 1} \cdot V_{in}$$

From this relation, we can see that if frequency tends to infinity, V_{out} tends to V_{in}. If we decrease the frequency, V_{out} tends to 0.

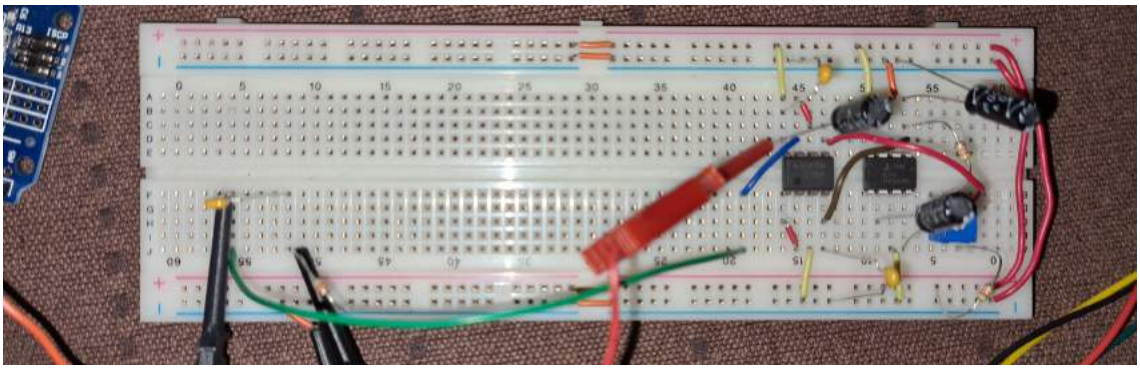

Figure 75: Circuit Schematics

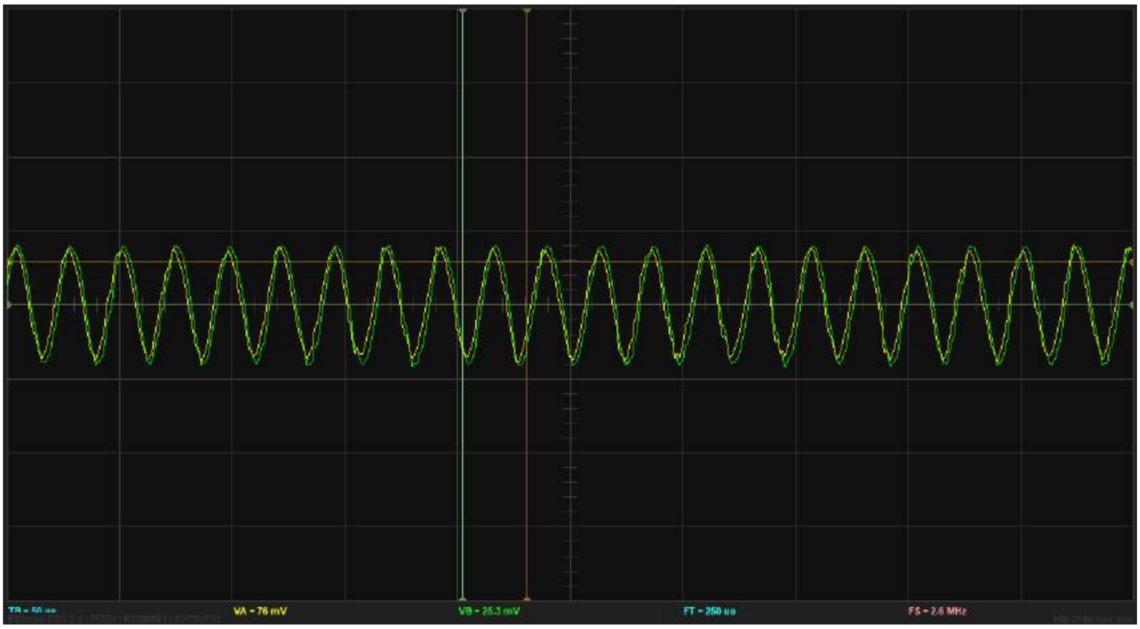

Figure 76: For High Frequency, V_{out} tends to V_{in}

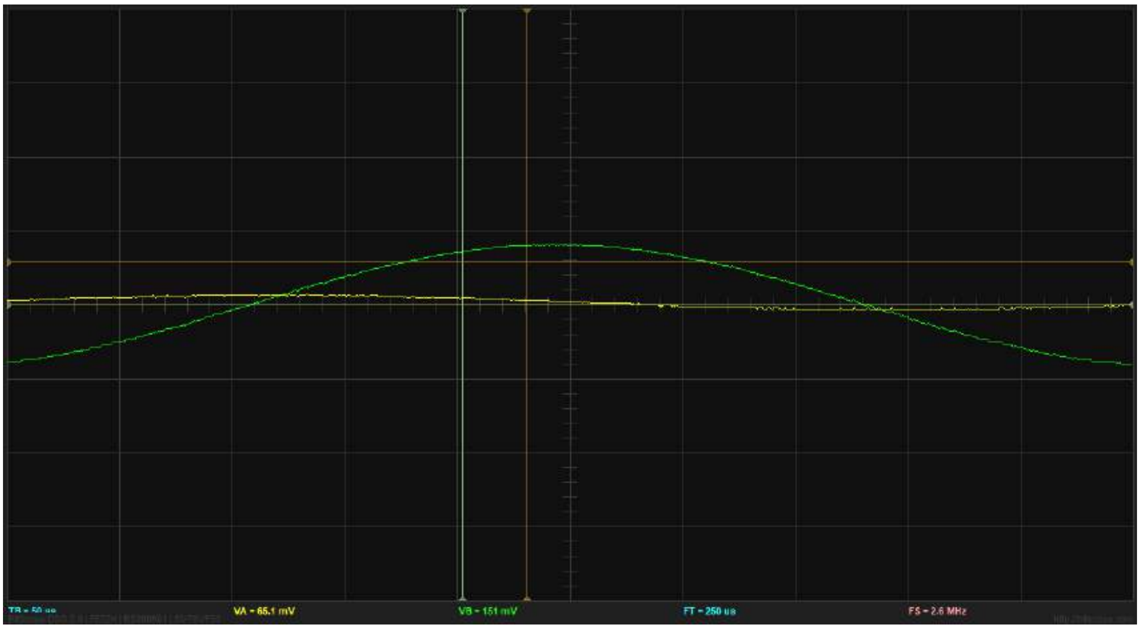

Figure 77: For High Frequency, V_{out} tends to 0

3.4 RLC Band Pass Filter

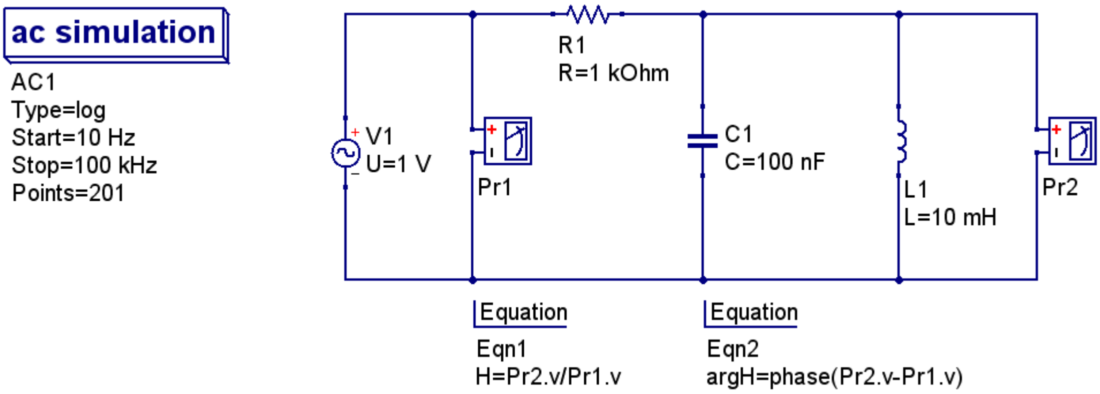

Figure 78: Circuit Schematics

1. Cutoff Frequency for band pass filter using L1 and C1 will have 2 frequencies, ω_1 and ω_2. By using Voltage divider rule,

$$V_{out} = \frac{Z_{LC}}{Z_{LC} + R} \cdot V_{in}$$

Let's start by calculating Z_{LC} first,

$$Z_{LC} = \frac{j\omega L \cdot \frac{1}{j\omega C}}{j\omega L + \frac{1}{j\omega C}}$$

$$Z_{LC} = \frac{j\omega L}{1 - \omega^2 LC}$$

Now we'll use this Z_{LC} in our original V_{out} equation. By simplifying we get

$$\frac{V_{out}}{V_{in}} = \frac{j\omega L}{j\omega L + R(1 - \omega^2 LC)}$$

2. To calculate ω_1 and ω_2,

$$\omega_1 = -\frac{\beta}{2} + \sqrt{(\frac{\beta}{2})^2 + {\omega_0}^2}$$

$$\omega_2 = \frac{\beta}{2} + \sqrt{(\frac{\beta}{2})^2 + {\omega_0}^2}$$

Where, $\beta = \frac{1}{RC}$ is the bandwidth of frequency allowed through the filter and $\omega_0 = \frac{1}{2\pi\sqrt{LC}}$ is the center frequency. Inserting the values, we get

$$\omega_1 = 2KHz$$

$$\omega_1 = 12KHz = 1.2 \cdot 10^4$$

At centre frequency the output and input signals are in-phase with each other. The bandwidth is $\beta = 10000$ and center frequency is $\omega_0 = 5KHz$.

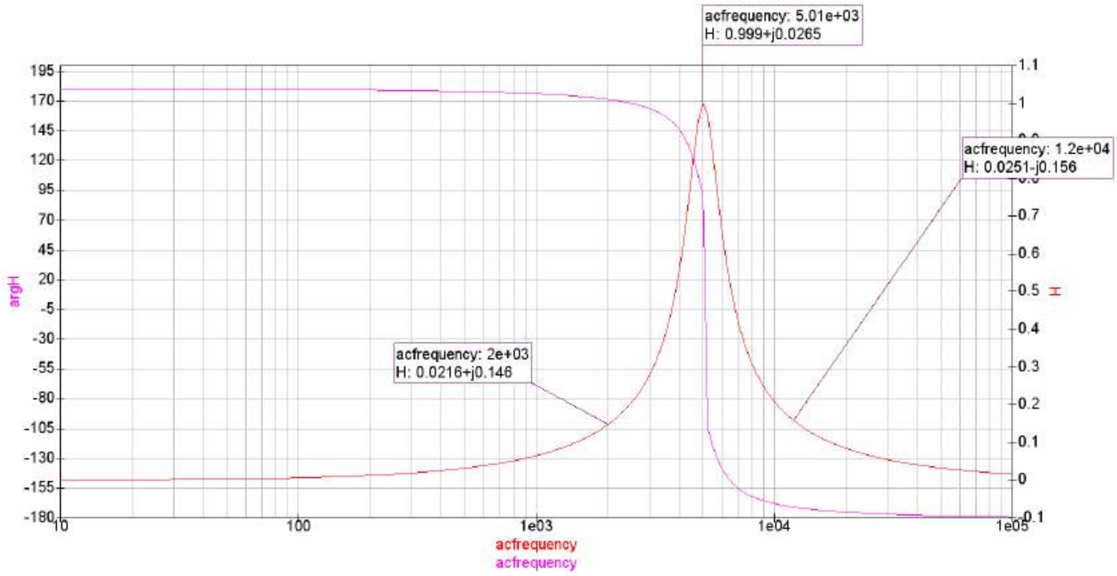

Figure 79: QUCS Curve

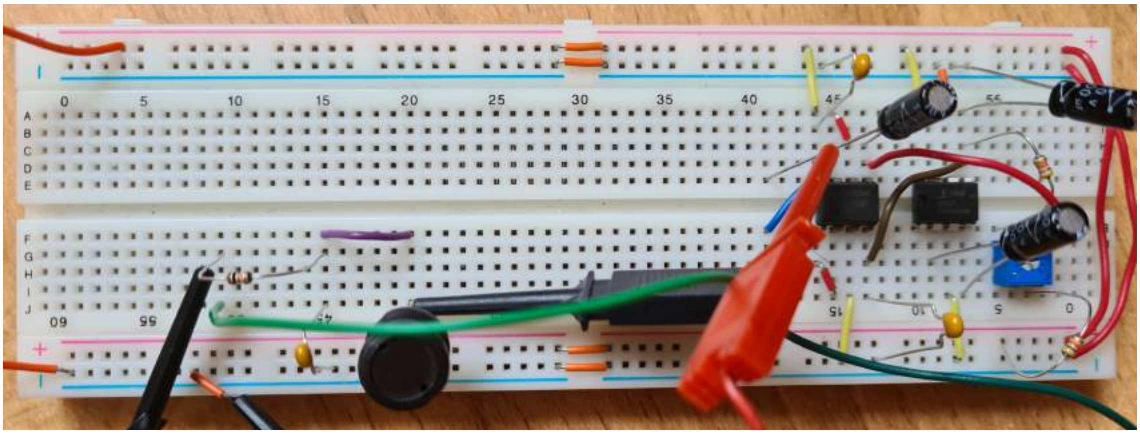

Figure 80: Connections on Breadboard

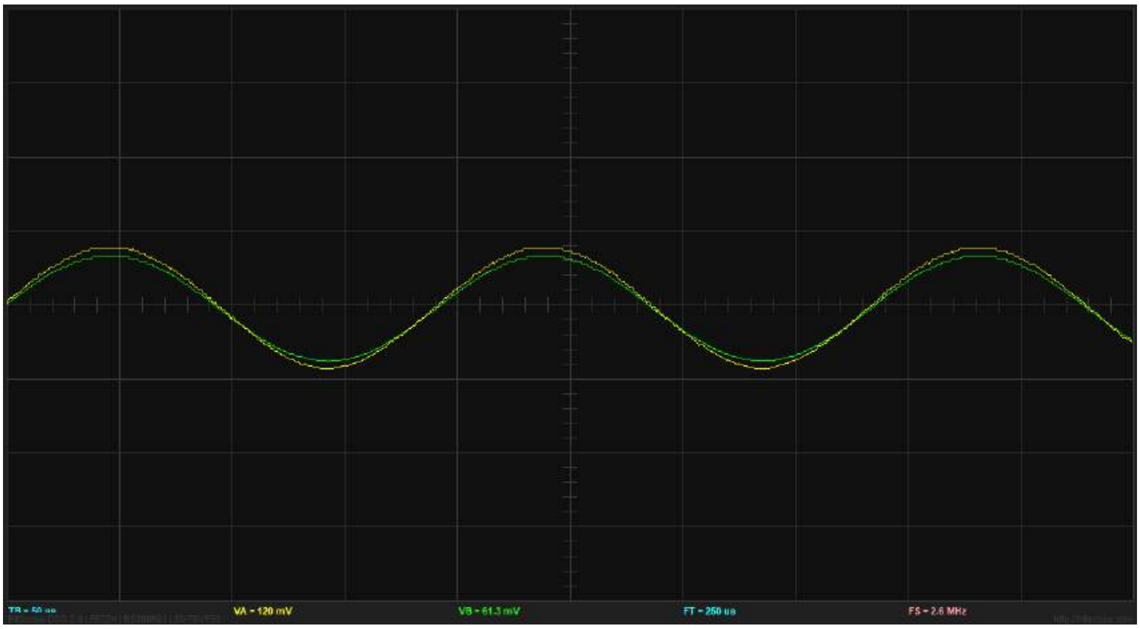

Figure 81: Curve on Bitscope at Center frequency 5kHz

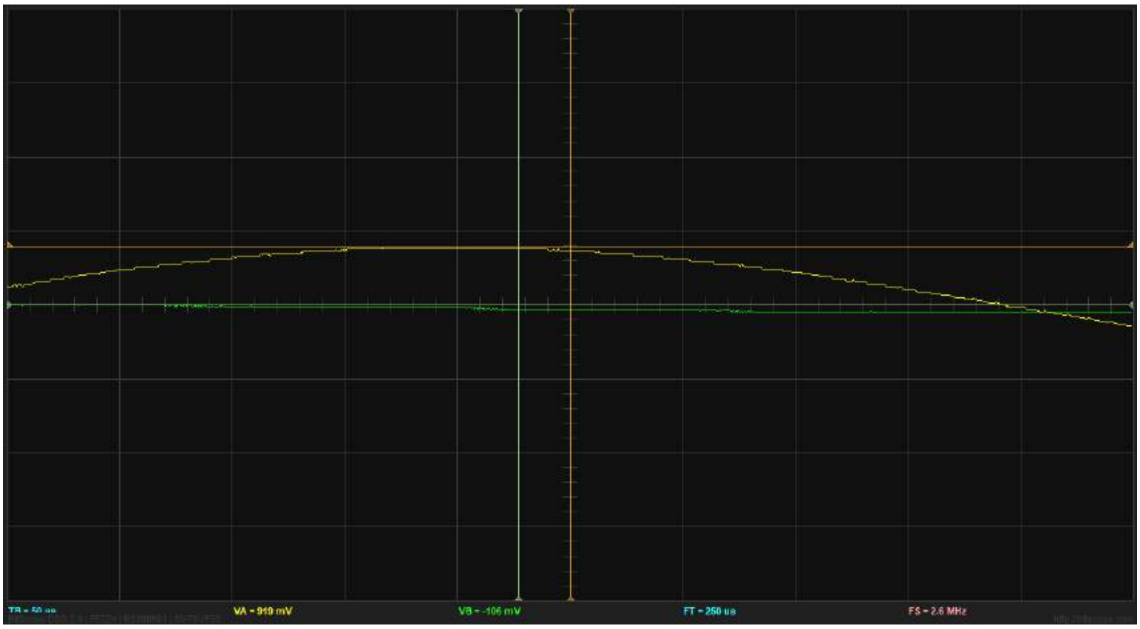

Figure 82: Curve on Bitscope at for frequency less than 2kHz

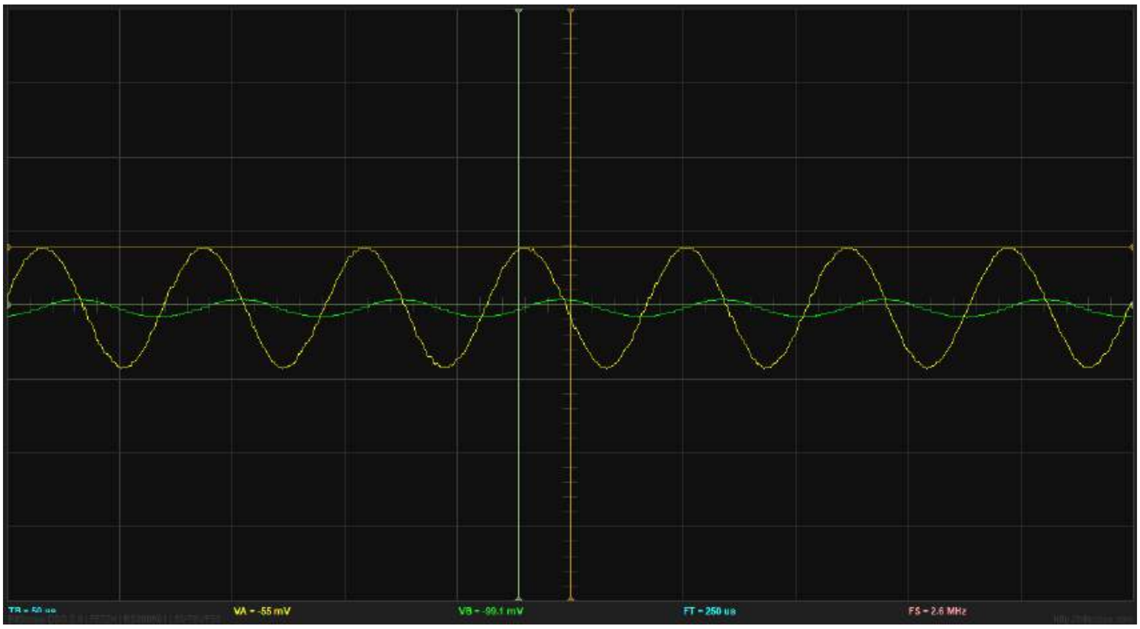

Figure 83: Curve on Bitscope at for frequency more than 12kHz

Module 4

4. OPERATIONAL AMPLIFIERS

4.1 Voltage regulator with a MOSFET, an Op amp and a LED as voltage reference

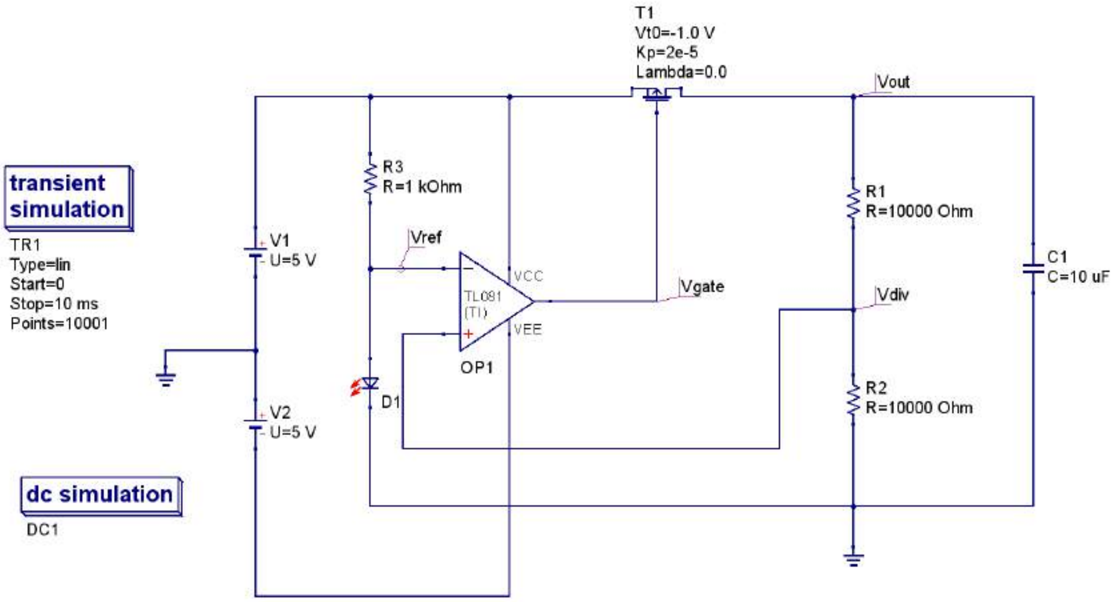

Figure 84: Schematics on QUCS

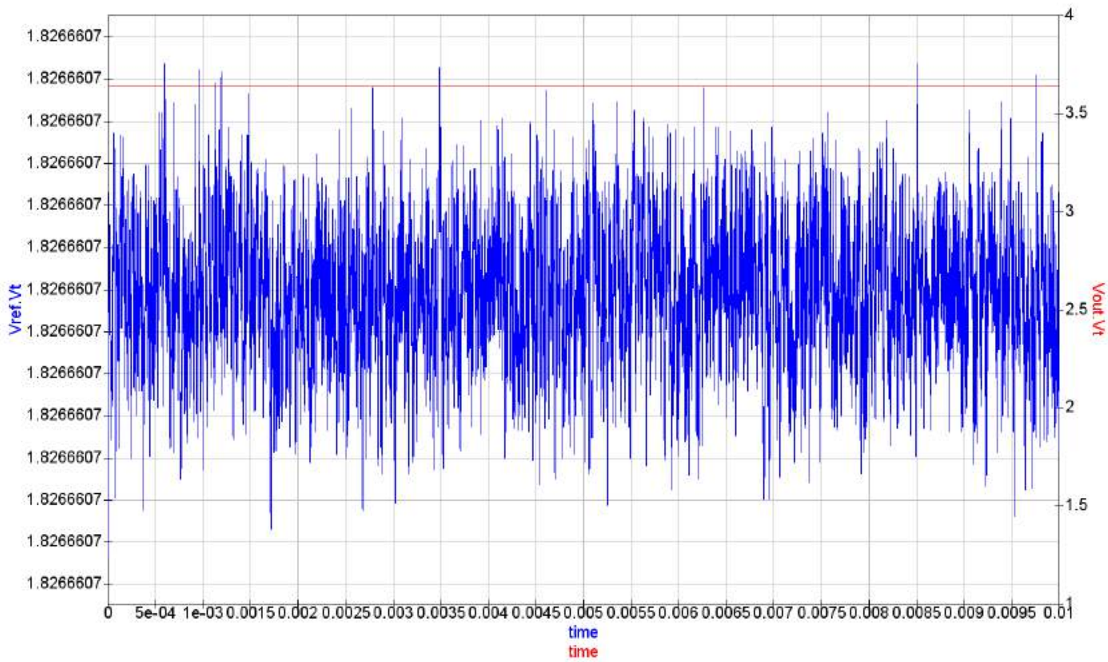

Figure 85: Simulated curve on QUCS

This complex voltage regulator is simply built on the voltage across the diode. In the breakdown region the voltage across diode is steady. We violate this property to build our voltage regulator. But the basic voltage regulator has several shortcomings, these are fixed in the voltage regulator we will be looking at.

R_1 acts as a current limiting resistor which controls the current through the LED. The voltage across the LED is will be our V_{ref}.

The op amp compares V_{div} and V_{ref}. The output from the op amp is then passed through current controlled device, PMOSFET. The current through the gate determines how much current will flow through source.

If V_{in} increases, V_{div} increases. The op amp compares V_{div} and V_{ref} and it will lower the output current through op amp. This causes the current through PMOSFET to lower and thus decreases V_{out}.

We can manipulate the value of R_1 and R_2 or use variable resistance to get the output we desire.

One thing to keep in mind is R_1 and R_2 should be kept high as we want to draw as minimum current as possible.

– Modified R1 and R2 to get 3.3V

This modification is done using the formula for V_{out},

$$V_{out} = V_{ref} \cdot (1 + \frac{R_1}{R_2})$$

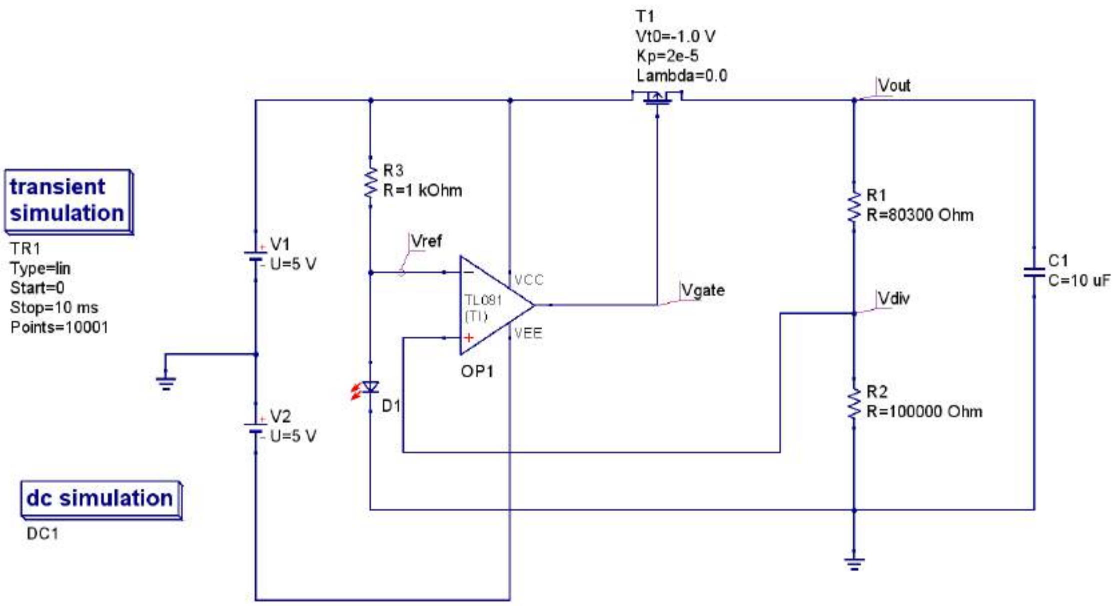

Figure 86: Schematics in QUCS

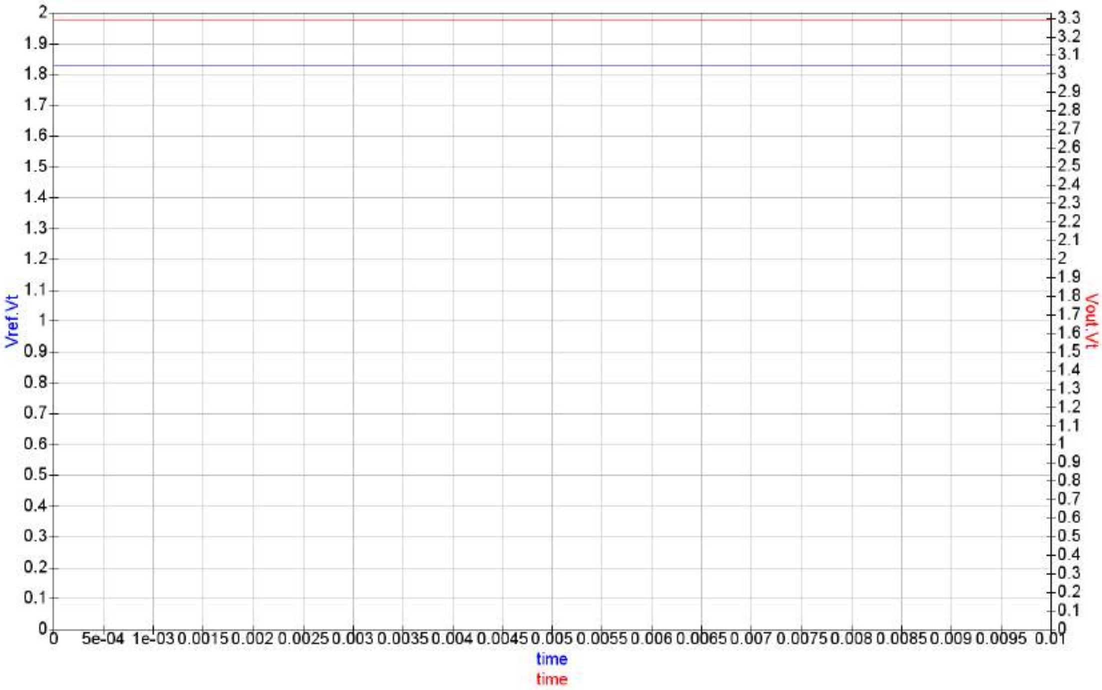

Figure 87: V_{out} and V_{ref} zoomed out curve

In this figure we can see that V_{out} is 3.3V while V_{ref} is around 1.8V. This is a zoomed out view.

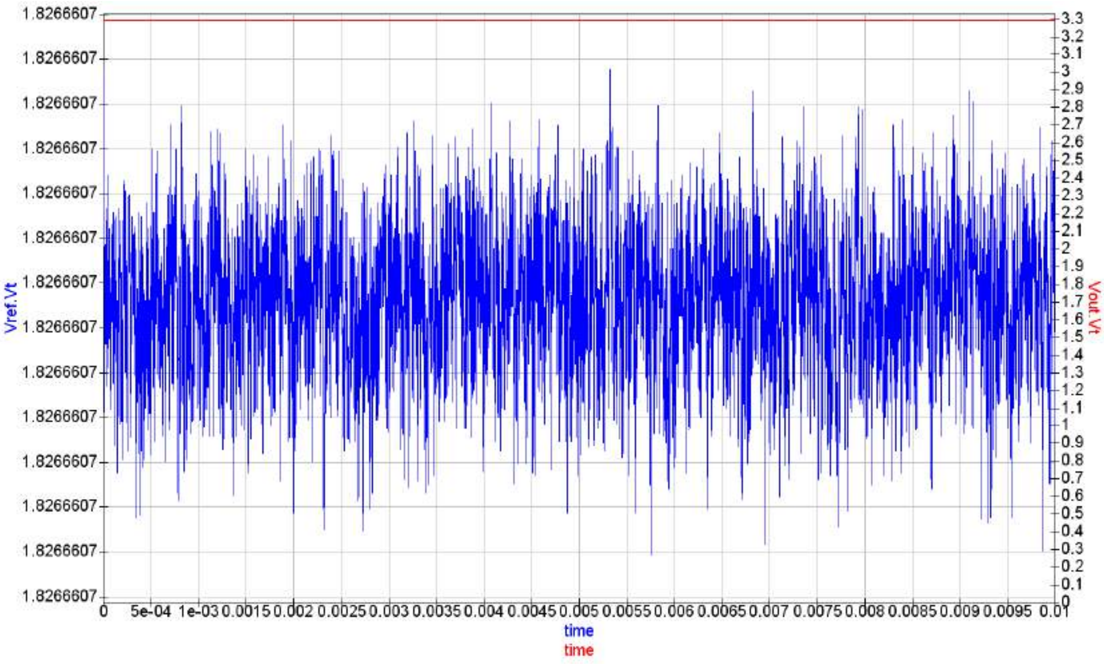

Figure 88: V_{out} focused curve

This is a zoomed in view where we can see that V_{ref} varies even though the change is very small but our V_{out} maintains the steady 3.3V.

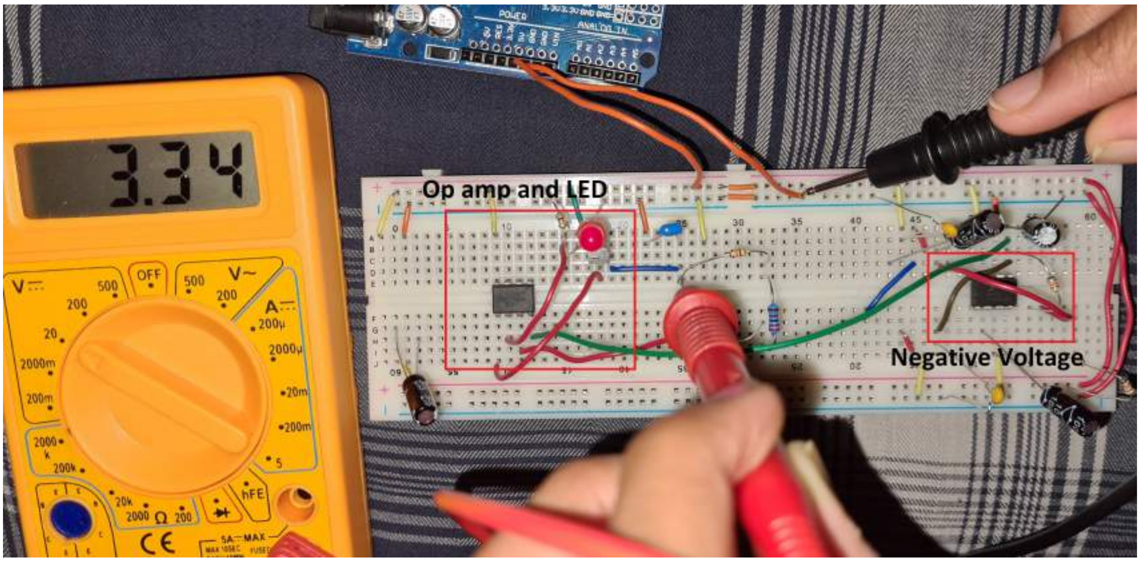

Figure 89: Circuit on Breadboard

– Replacing R1 and R2 by variable resistance

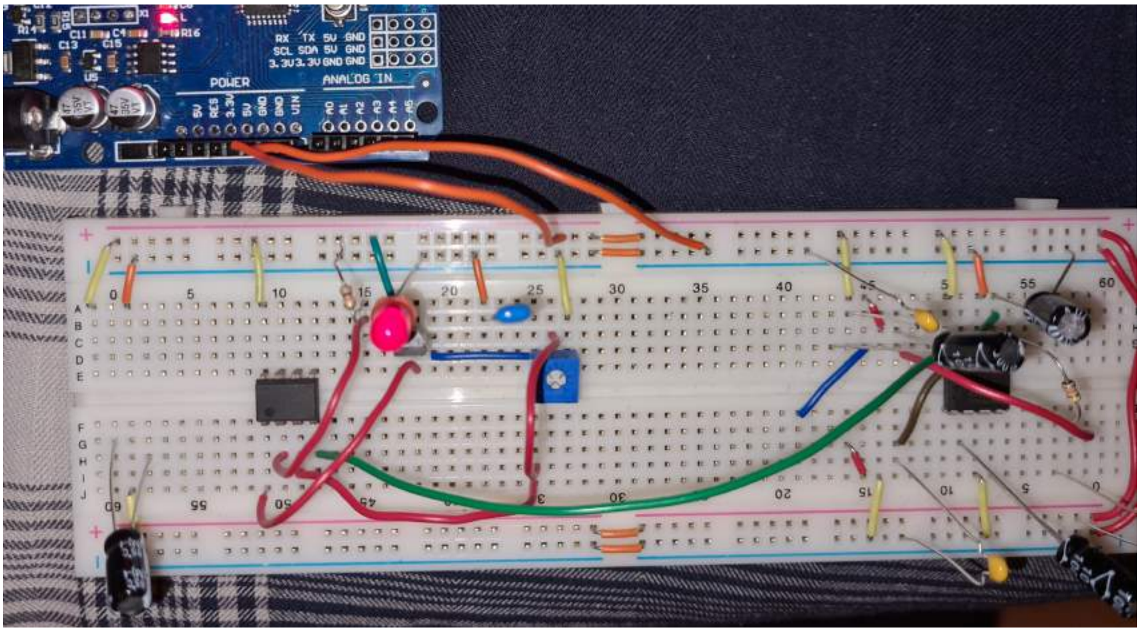

Figure 90: Trimmer at R1

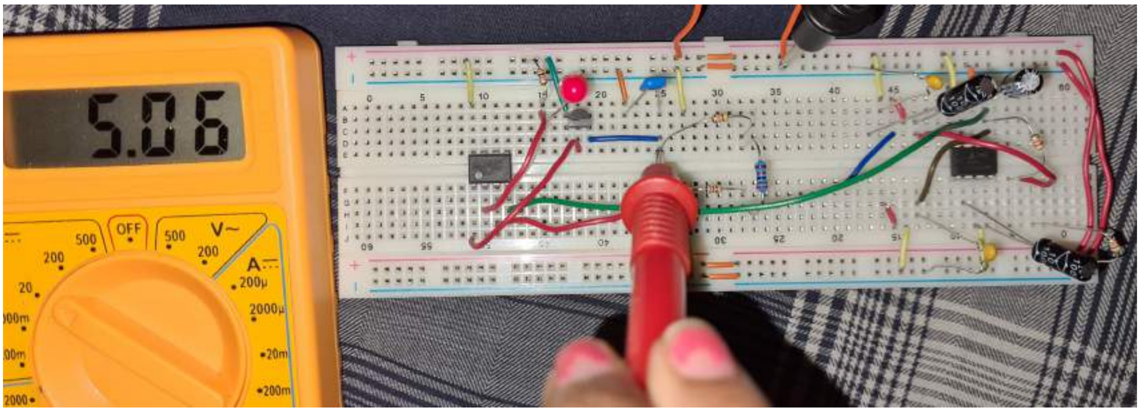

Figure 91: Trimmer at R2

As discussed above, R1 and R2 can be manipulated to get the voltage between V_{ref} and 5V.