Bilkent University Department Of Electrical and Electronics Engineering

EEE212 Circuit Theory

Lab 3

Waveform Generator

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Purpose:

Design a circuit that generates the voltage waveform shown in Figure 1. The design should be based on OPAMPs and RC circuits.

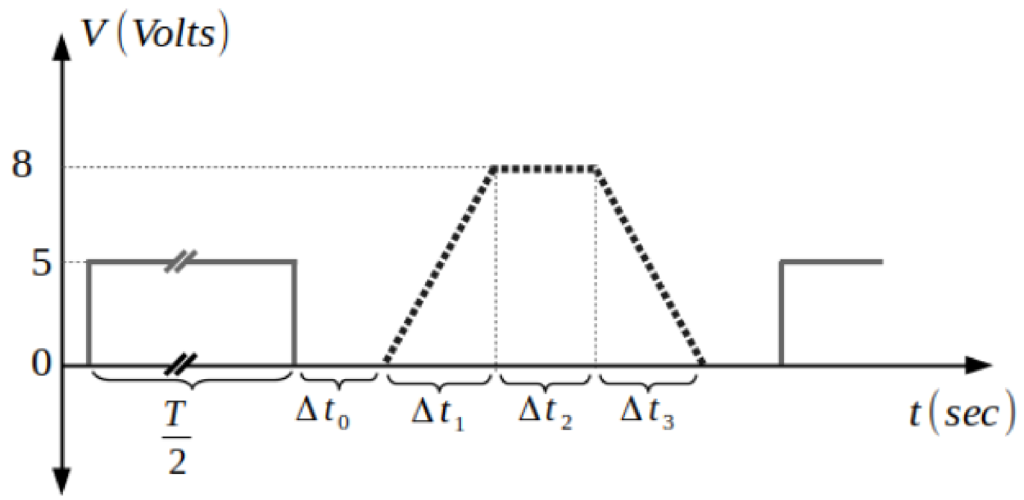


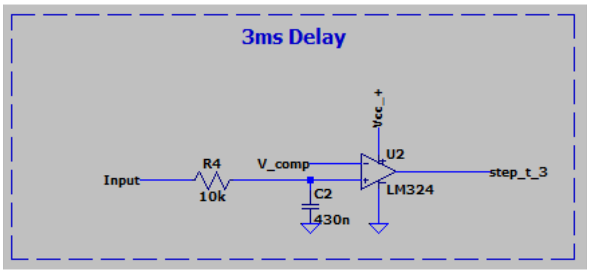
Figure 1 The Lab Task

The frequency is less than 50Hz, Δt0, Δt1, and Δt3 are 3ms, and Δt2 is 2ms. For the experiment, the frequency is selected as 20Hz.

Methodology:

There are three steps to generate such a waveform: Shifting the square wave for 3ms and 11ms, integrating both waveforms to create the skew line, and subtracting one from another. Throughout the design, LM324 OPAMP is used. The Vcc inputs for the OPAMPs are Vcc+=9.5V, Vcc-=0V, and Vcomp= 2.5V.

A delay circuit is needed for separate configurations for the first step, one for 3ms and 11ms(3ms+ 3ms+ 2ms+3ms). A comparator OPAMP circuit is fit for this operation. The comparators can be seen in Figure 2. To the V+ input, an RC circuit is added, and for the reference input, V-, a threshold voltage is added. The working mechanism of the comparator circuit is that when the V+ voltage is smaller than the reference voltage, the OPAMP is negatively saturated; if the V+ voltage is greater than the reference voltage, the OPAMP is positively saturated. The following calculation is needed to decide when the V+ will be greater than V.



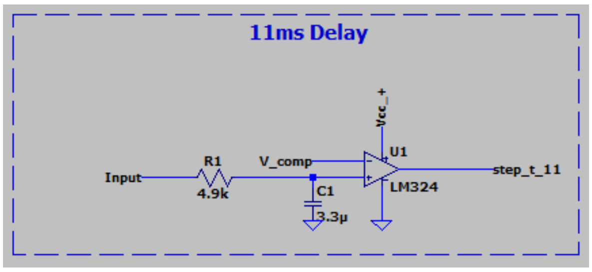


Figure 2 The Comparators

The calculations are as follows:

$$\frac{dV_c}{dt} * C = \frac{Input - V_c}{R}$$

$$\frac{dV_c}{dt} * C + \frac{V_c}{R} = \frac{Input}{R}$$

The Characteristic Equation:

$$\lambda * C + \frac{1}{R} = 0$$

$$\lambda = -\frac{1}{R * C}$$

The Natural Response:

$$c_1 * e^{-\frac{t}{R*C}} = V_{c_{natural}}$$

Basis and the General Solution for the Forced Response:

$$(1), A$$

$$\frac{A}{R} = \frac{Input}{R}$$

Solution for the Forced Response:

$$Input = V_{c_{forced}}$$

At t=0 V_c = 0:

$$c_1 = -5$$

The Solution for V_c(t):

$$-5 * e^{-\frac{t}{R*C}} + 5 = V_c$$

When t=3ms, the Vc must be 2.5V. This creates a 3ms delay and t=11ms for an 11ms delay.

After inserting the values:

$$-5 * e^{-\frac{3m}{R_1*C_1}} + 5 = 2.5$$

$$-5 * e^{-\frac{11m}{R_2*C_2}} + 5 = 2.5$$

$$e^{-\frac{3m}{R_2*C_2}} = \frac{1}{2}$$

$$e^{-\frac{11m}{R_2*C_2}} = \frac{1}{2}$$

$$R_1 * C_1 = 0.043$$

$$R_2 * C_2 = 0.0159$$

After some trial and error, the given RC values satisfy the desired numbers.

$R_1: 10k\ Ohm \quad C_1: 430nF$

$R_2: 4.9k\ Ohm \quad C_2: 3.3uF$

The OPAMPs work in the nonlinear region. Hence they output the saturation voltages, 8V and 0V.

Now, we have two waveforms shifted for 3ms and 11ms. The next step is to generate the skew line at the ends of the square waveforms. A skew line is obtained when the integral of a step function is taken. Hence, an integrator OPAMP configuration is used(Figure 3).

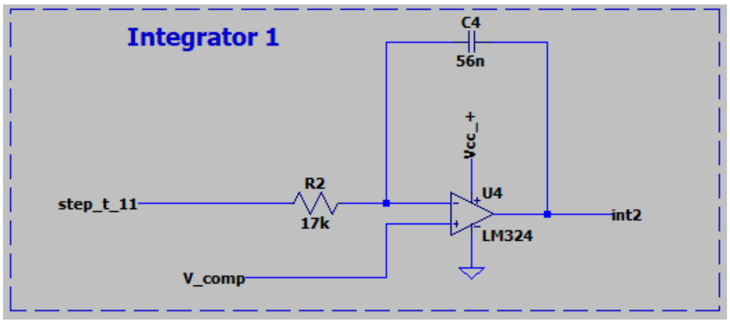


Figure 3 The Integrator

The calculations are as follows:

KCL at V^-:

$$\frac{Input - V^-}{R} = C\frac{dV_c}{dt}$$

$$\frac{Input - V^+}{R * C}dt = dV_c$$

Taking the integral of both sides:

$$\int \frac{Input - V^+}{R * C}dt = V_c$$

$$\frac{Input - V^+}{R * C} * t \ + A = V_c$$

Since at t=0, V_c =0; A=0:

$$\frac{Input - V^+}{R * C} * t = V_c$$

$$\frac{2.5}{R * C} * t = V_c$$

At t=3ms, The Vc has to be 8V:

$$\frac{1}{R*C}*3m = 3.2$$

$$\frac{3m}{3.2} = R*C$$

$$9.375*10^{-4} = R*C$$

After some trial and error, the given RC values satisfy the desired numbers.

$$R: 17k\ Ohm \quad C: 56nF$$

Since the skew line is the same for both waveforms, the configuration is applied to both. The final step is to subtract them from each other to get the final waveform. To do so, a subtractor OPAMP configuration is used(Figure 4).

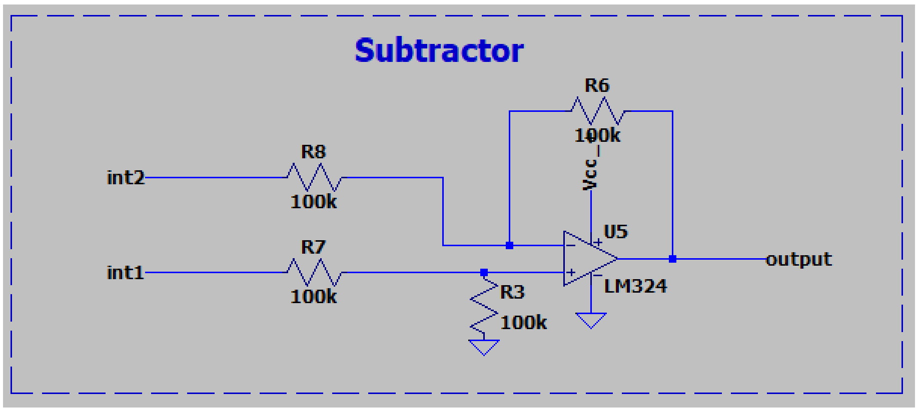


Figure 4 The Subtractor

The calculations are as follows:

$$\frac{Input_2 - V^-}{R_8} = \frac{V^- - V_{out}}{R_6}$$

$$\frac{Input_2}{R_8} - \frac{V^-}{R_8} = \frac{V^-}{R_6} - \frac{V_{out}}{R_6}$$

$$V^- = \left(\frac{Input_2}{R_8} + \frac{V_{out}}{R_6}\right) * \frac{1}{(\frac{1}{R_6} + \frac{1}{R_8})}$$

$$\frac{Input_1 - V^+}{R_7} = \frac{V^+}{R_3}$$

$$\frac{V^+}{R_3} + \frac{V^+}{R_7} = \frac{Input_1}{R_7}$$

$$V^+ = \frac{Input_1}{R_7 * (\frac{1}{R_3} + \frac{1}{R_7})}$$

Since $V^+ = V^-$:

$$\frac{Input_1}{R_7 * (\frac{1}{R_3} + \frac{1}{R_7})} = \left(\frac{Input_2}{R_8} + \frac{V_{out}}{R_6}\right) * \frac{1}{(\frac{1}{R_6} + \frac{1}{R_8})}$$

If all resistors have the same value, i.e., 100k Ohm:

$$Input_1 - Input_2 = V_{out}$$

Results:

In theory, when inputting the selected resistor and capacitor values, the Δt values are as follows:

Delay from proposed 3ms delay circuit:

$$\Delta t_0 = 3ms$$

Delay from proposed 11ms delay circuit:

$$\sum_{k=0}^{3} \Delta t_k = 10.97ms$$

The $\Delta t_{1,3}$ of the skew durations from the integrators and the Δt_2:

$$\Delta t_{1,3} = 3.05ms \quad \Delta t_2 = 1.87ms$$

Table 1 The Proposed Values vs Desired Values

	Δt_0	Δt_1	Δt_2	Δt_3
Expected Value	3ms	3ms	2ms	3ms
Proposed Value	3ms	3.05ms	1.87ms	3.05ms
Error	0%	1.67%	6.5%	1.67%

As seen in Table 1, the given values are in the 10% error margin, hence in compliance with the lab task.

Simulation Results:

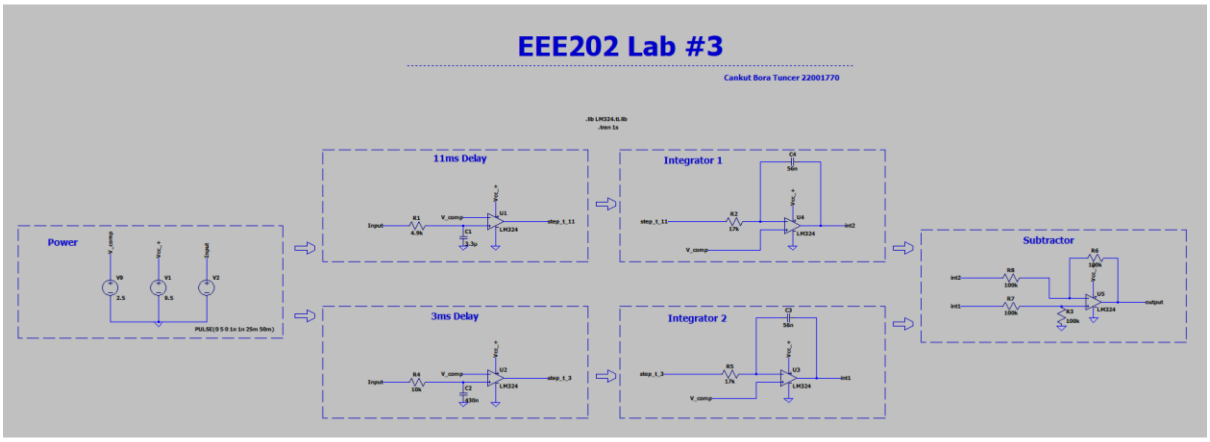


Figure 5 The Simulation Design

The simulation results from each OPAMP configuration is as follows:

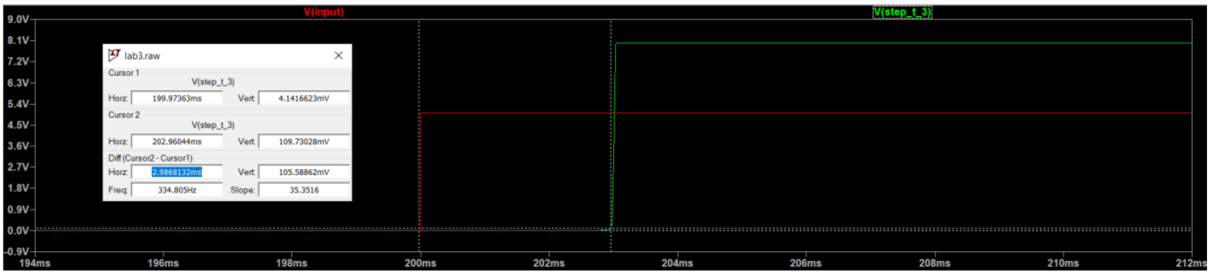


Figure 6 The Delay from 3ms Comparitor: 2.98ms

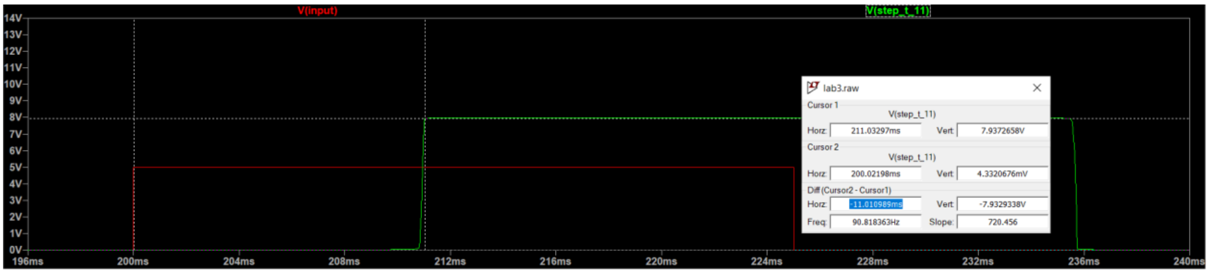


Figure 7 The Delay from 11ms Comparitor: 11.01ms

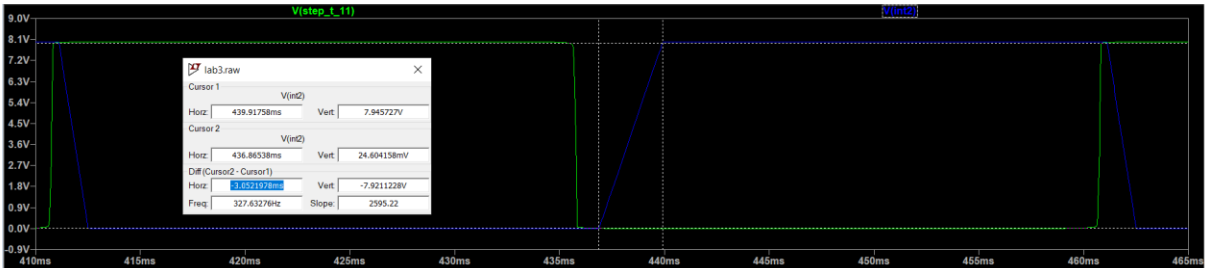


Figure 8 The Comparitor Results from 3ms shifted waveform: 3.05ms

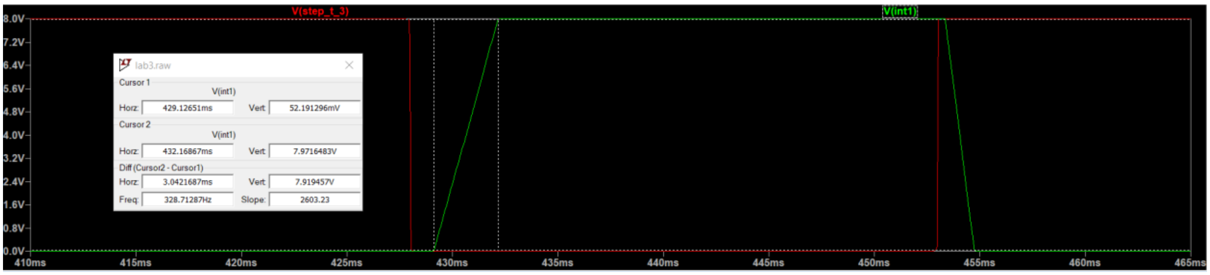


Figure 9 The Comparitor Results from 11ms shifted waveform: 3.04ms

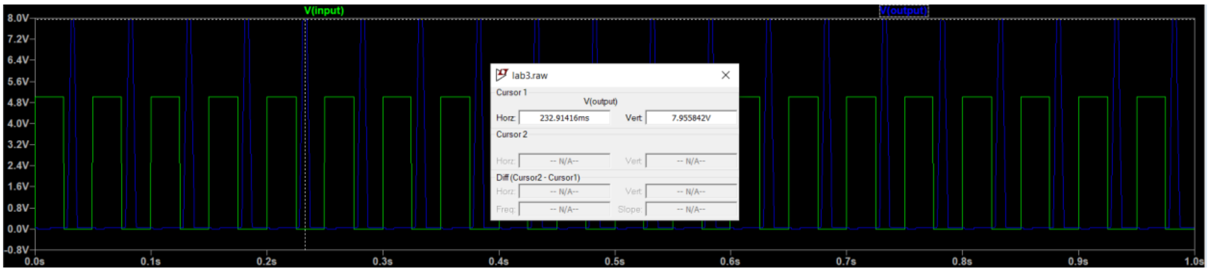


Figure 10 The Final Result the Software, Vout = 7.95V

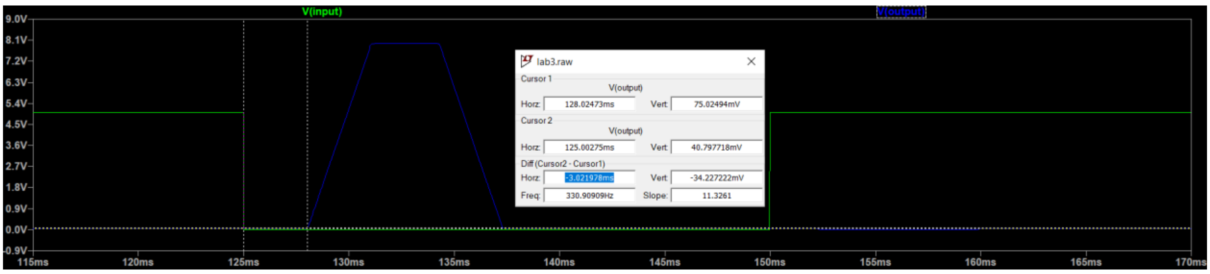


Figure 11 The Δt_0: 3.02ms

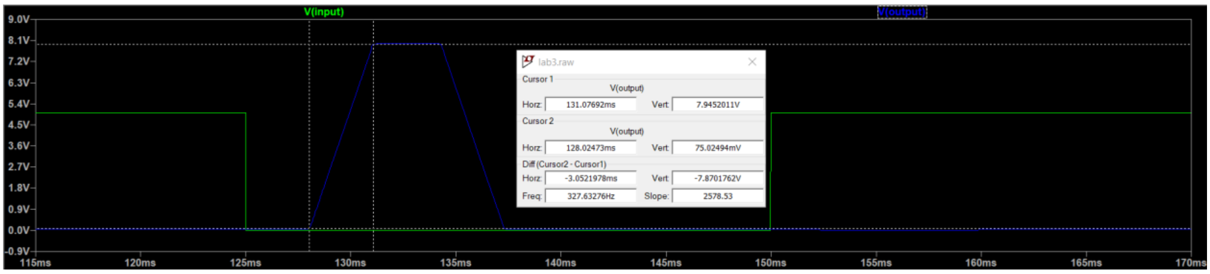


Figure 12 The Δt_1: 3.05ms

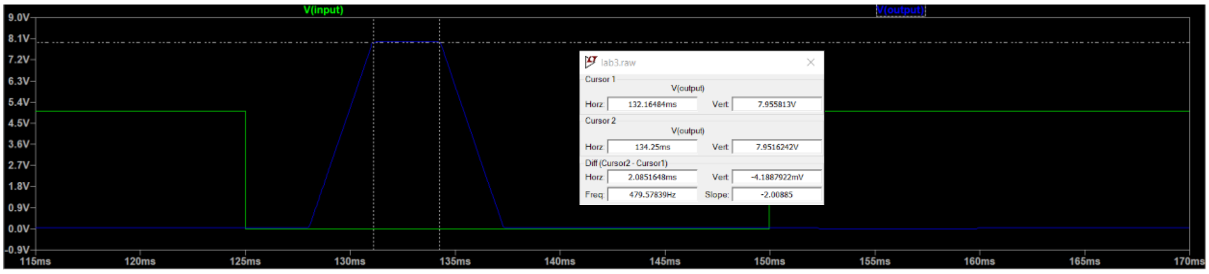


Figure 13 The $\Delta t_2: 2.08ms$

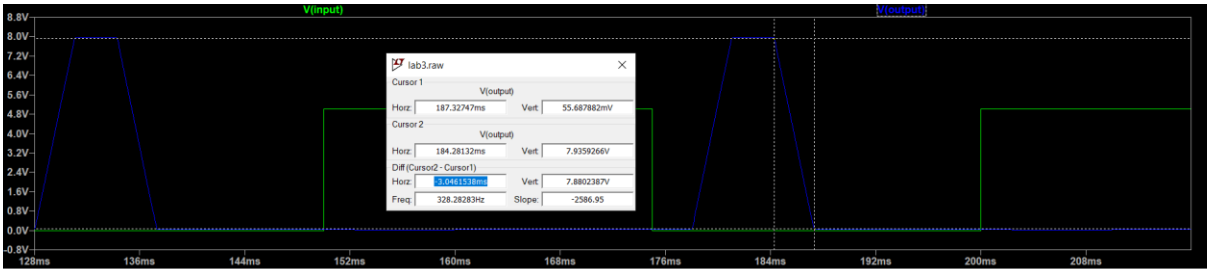


Figure 14 The $\Delta t_3: 3.04ms$

Table 2 The Expected Values and Simulation Values

	Δt_0	Δt_1	Δt_2	Δt_3
Expected Value	3ms	3ms	2ms	3ms
Simulation Value	3.02ms	3.05ms	2.08ms	3.04ms
Error	0.66%	1.67%	4%	1.33%

As seen in Table 2, the given values are in the 10% error margin, hence in compliance with the lab task.

Hardware Results:

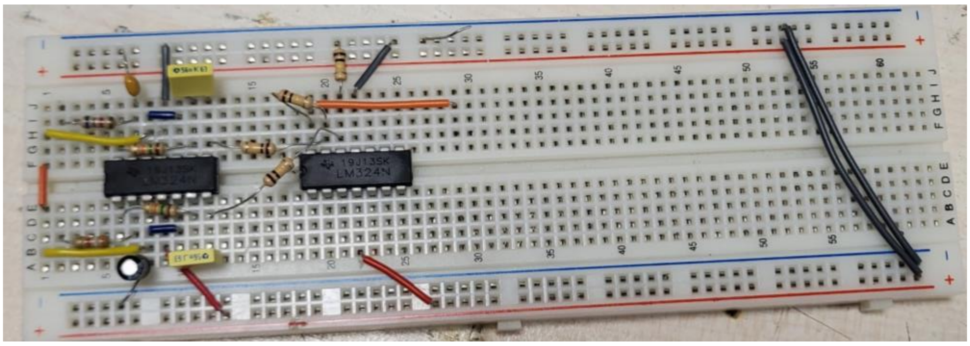


Figure 15 The Hardware Setup

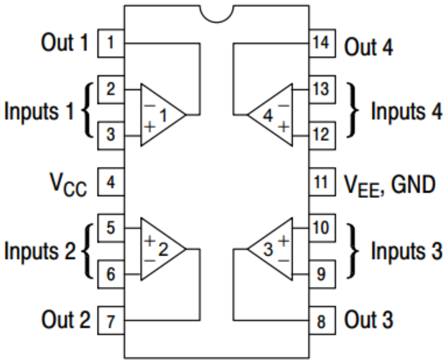


Figure 16 The LM324 Quad OPAMP IC

As for the hardware setup, I used 2 LM324 Quad OPAMP IC. The ICs are fed with 9.5V from their 11th pin, as seen in Figure 15 and Figure 16. The Comp input is given as 2.5V. The 4.9k resistor, 17k resistor, and 10k resistor are changed with 4.7k, 18k, and 8.2k resistors.

A signal generator generates the square wave with the configuration of 20Hz frequency, 2.5Vpp, and 1.26V offset voltage to carry the signal to the positive side(Figure 17).

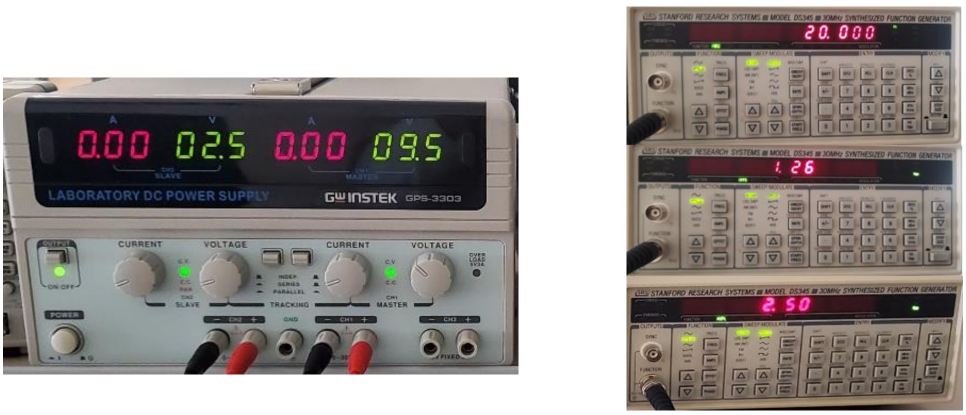


Figure 17 The Input Configurations

With the given inputs, the output results are as follows:

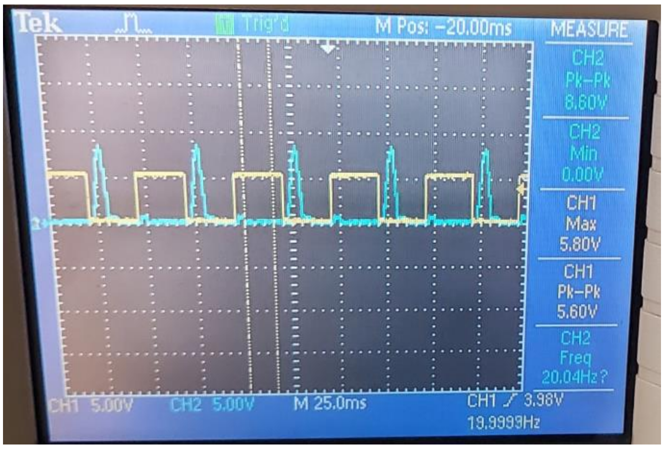


Figure 18 The Final Result of the Hardware, Vout = 8.6V

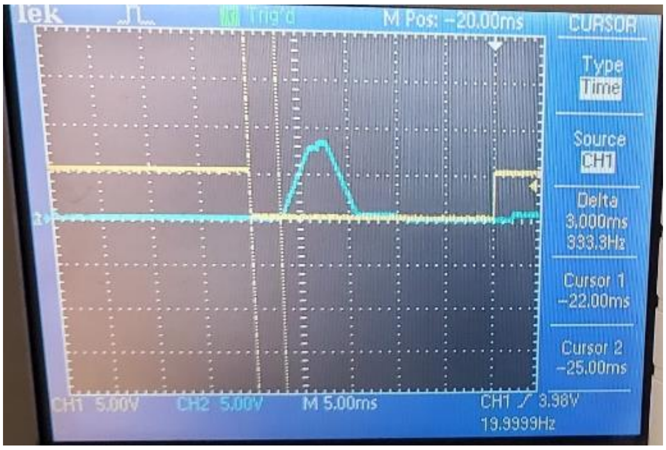


Figure 19 The Δt_0: 3.0ms

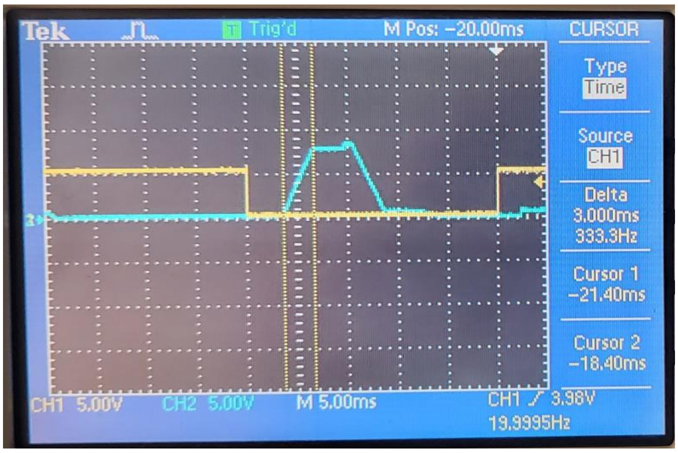


Figure 20 The Δt_1: 3.0ms

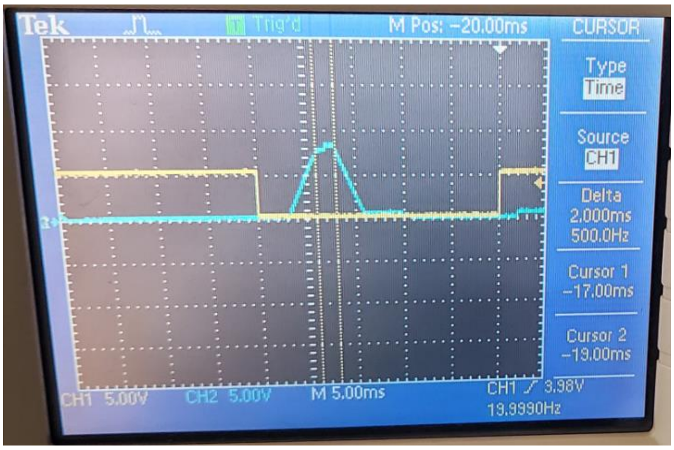


Figure 21 The Δt_2: 2.0ms

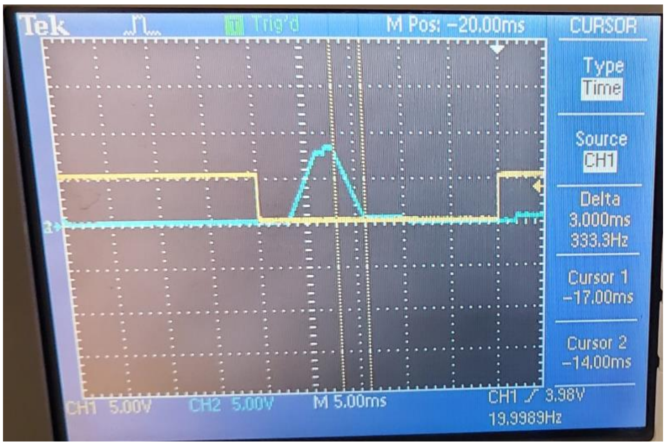


Figure 22 The Δt_3: 3.0ms

Table 3 The Expected Values and Hardware Values

	$\boldsymbol{\Delta t_0}$	$\boldsymbol{\Delta t_1}$	$\boldsymbol{\Delta t_2}$	$\boldsymbol{\Delta t_3}$
Expected Value	3ms	3ms	2ms	3ms
Hardware Value	3.0ms	3.0ms	2.0ms	3.0ms
Error	0 %	0%	0%	0%

As seen in Table 3, the given values are in the 20% error margin, hence in compliance with the lab task.

Conclusion:

This experiment aims to modify a given input waveform according to the desired specifications. The input voltage was a 5V 20Hz square wave, and the desired voltage is the 3ms shifted version with skew lines on each side with a duration of 3ms. In the proposed method, the final waveform is generated in 3 steps: Shifting, Integrating, and Subtracting. For the shift operation, a comparator OPAMP configuration is used. For integration, an integrator OPAMP configuration is designed. And for subtracting, a subtractor OPAMP circuit is constructed. After the mathematical derivations, the software simulation is created according to the theoretical values. For realistic results, the LM324 library is used. The simulation results were promising. Thus, I moved on to the hardware design. After fine-tuning some of the values, the hardware results match the desired results. The software and hardware lab's error values were between 4-0.66% and 0 respectively. However, if the stated changes were never made in the hardware lab and stuck with the simulation values, the error would be much higher. The possible error values are due to the fact that the OPAMP used is not ideal but the calculations are made with the assumption that the OPAMP is ideal. Furthermore, in real life, it is nearly impossible to have the exact resistance value written on the resistors. For instance, in the subtractor circuit, I assumed that the resistors were the same and 100k Ohm. However, in reality, they weren't the same. Thus it leads to some errors. Moreover, although the values fit with the expected values, the graph has distortion at the end of the second skew line. The defect occurs at the integrator circuit. When the defected waveforms are inputted to the subtractors a small spike occurs at the end of the second skew. This could be corrected if a resistor is added to the negative feedback loop as seen in Figure 23. To sum up, in this lab I learned to manipulate a given waveform in the desired configuration.

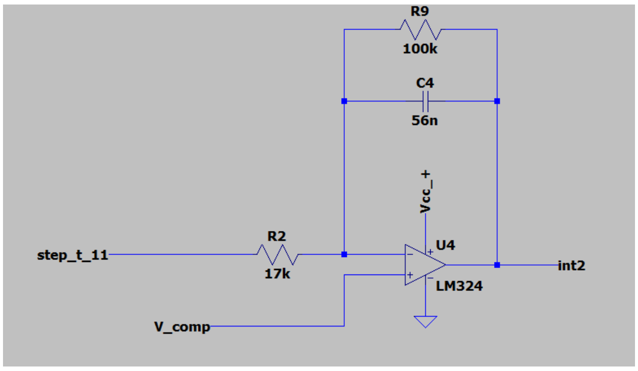


Figure 23 The corrected integrator circuit