ELECENG 2EI4

DP #2: Voltage Controlled Switch

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Test Plan

Listed below are experiments to be conducted for each non-ideality. This will identify the performance of the design. For all cases $V_{supply} = +5V$.

Non-ideality 1: When switch is ON it has an internal resistance R_{ON}

Set Values:

- $V_{control} = 0$
    - SW1: to keep the switch closed
    - SW2: to connect V_1 to V_A
- V_1 = 3V
- $R_L = 400k\Omega$

Measure:

- SW1: Voltage drop across R_L (V_2).
- SW2: Voltage drop across R_{L1} (V_A).

Calculate:

- Resistance across the closed switch (R_{ON}).

Non-ideality 2: When switch is OFF it has a small leakage current I_{OFF}

Set Values:

- $V_{control} = 5V$
    - SW1: to keep the switch open
    - SW2: to connect V_1 to V_B
- V_1 = 3V
- $R_L = 2.2M\Omega$

Measure:

- SW1: V_2 (voltage drop across R_L)
- SW2: V_A (voltage drop across R_{L1})

Calculate:

- I_{OFF} (current through open switch)

Non-ideality 3: Switch has voltage limitations such that $V_{min} < V_1$, $V_2 < V_{max}$

Set Values:

- $V_{control} = 0V, 5V$
- $V_{supply} = 5V, V_{min} = 0V$
- Test boundary input values $V_1 = 1.1V, 4.9V$
- $R_L = 10k\Omega$

Measure:

- SW1: V_2 (output voltage)
- SW2: V_A, V_B (output voltages)

Non-ideality 4: When switch is ON, R_{ON} remains the same with input V_1 or V_2 (bidirectionality).

Set Values:

- $V_{control} = 0V$ (to keep the switch closed)
- $V_1 = 3V$
- $R_L = 2200k\Omega$

Measure:

- SW1: V_2 (voltage drop across R_L)
- SW2: Voltage drop across R_{L1} (V_A).

Calculate:

- R_{ON_1} in Direction 1 (normal polarity) and R_{ON_2}, when polarity is reversed.

Switch Type 1

i. Circuit Schematic

The circuit for switch 1 is a transmission MOSFET, with an input voltage V_1 an output voltage V_2. A load is attached to the output for testing purposes. Refer to Figure 1 for the schematic.

For the pMOS, the control voltage is applied to the gate, and the bulk is attached to the highest voltage in the circuit $V_{supply} = +5V$. Whereas, for the nMOS, the supply voltage is applied to the gate, and the bulk is attached to the lowest voltage in the circuit (ground).

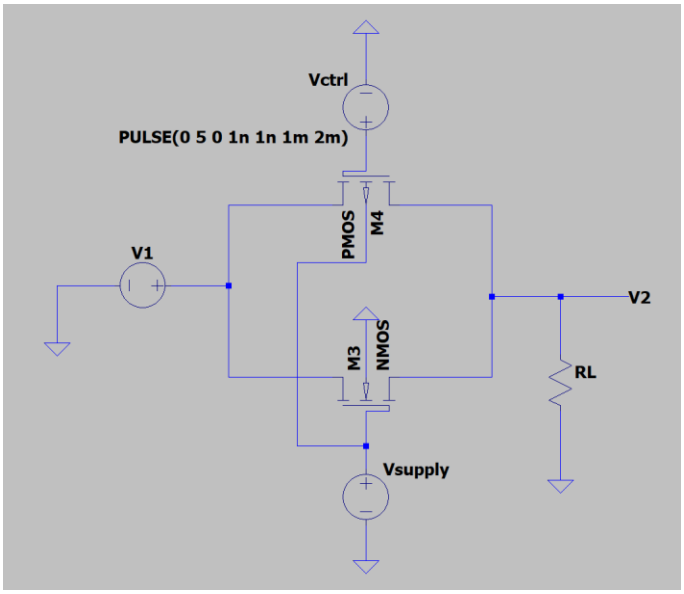

Figure 1. Switch 1 Schematic

ii. Measurements Performed

Verifying Circuit

To verify this circuit, the following conditions had to be met:

1. when $V_{ctrl} = 0$ the switch is closed, and thus $V_1 = V_2$
2. when $V_{ctrl} = 5V$ the switch is open, and thus $V_1 \neq V_2$

This circuit was simulated prior to the physical implementation for safety. Using a load resistor of 400kΩ and an input voltage $V_1 = 3V$, **Error! Reference source not found.** shows that when $V_{ctrl} = 0$, $V_1 \approx V_2$, and when $V_{ctrl} = 5V$, $V_1 \neq V_2$.

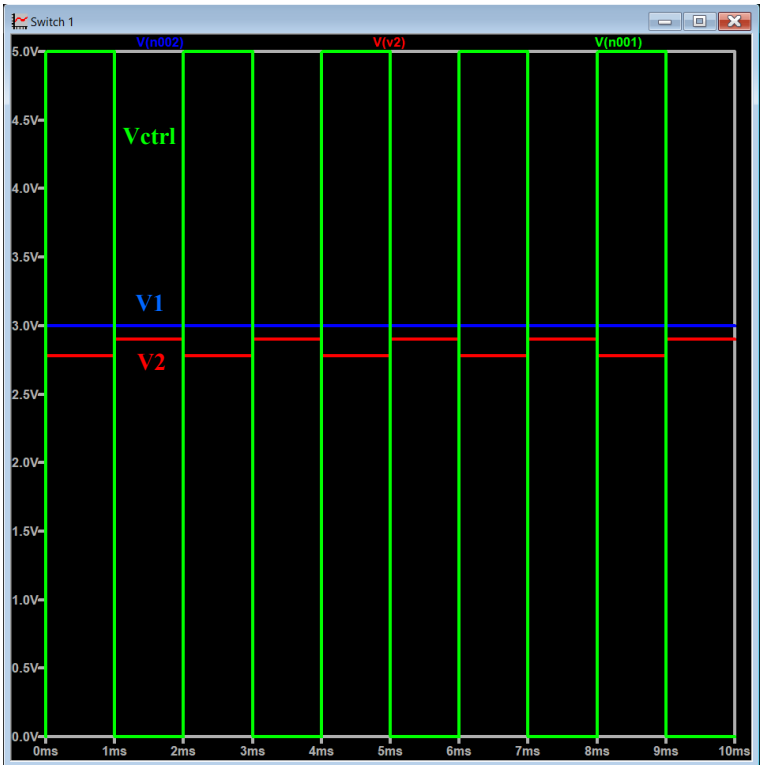

Figure 2. Switch 1 Simulation

These same results are shown from the physical circuit:

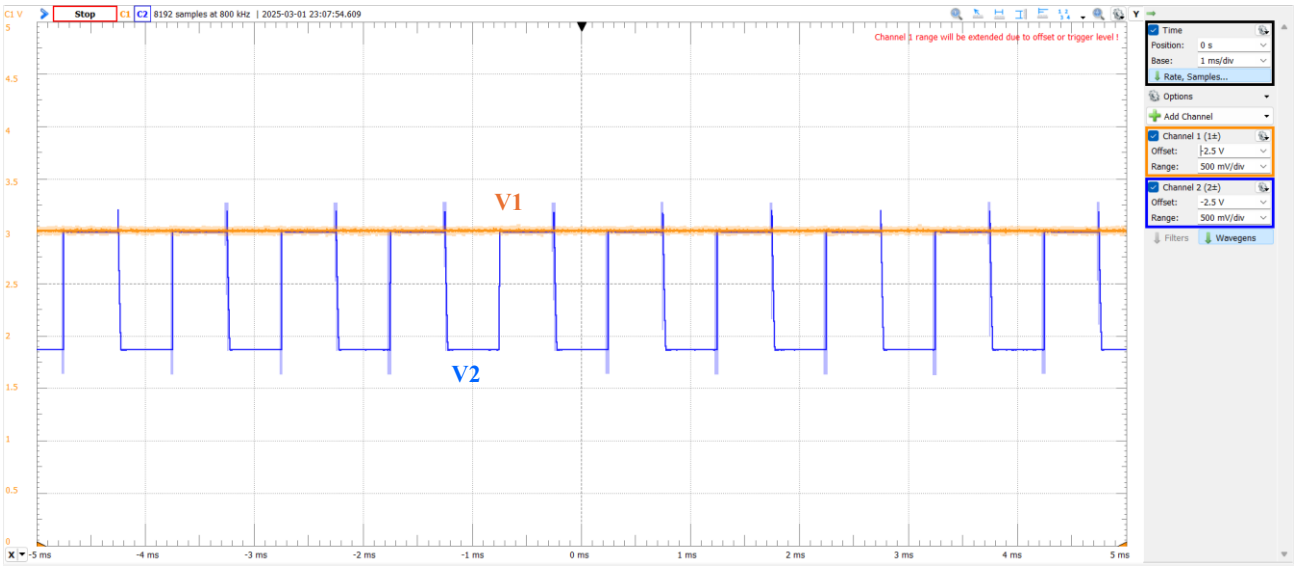

Figure 3. Switch 1 Measurement

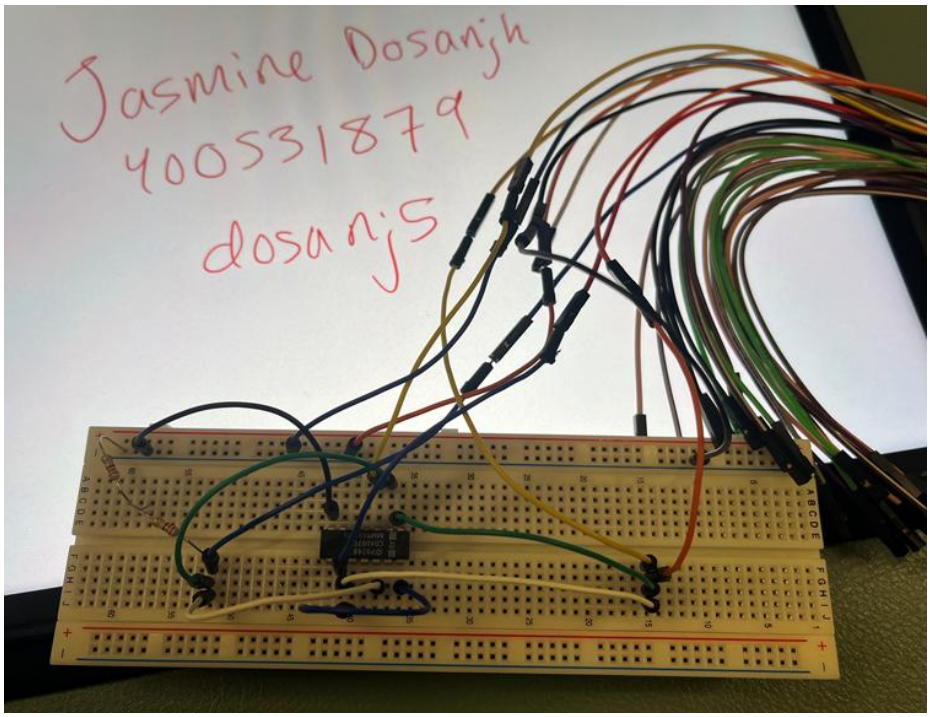

Figure 4. Switch 1 Physical Circuit

Non-ideality 1: When switch is ON it has an internal resistance R_{ON}

For switch 1, R_{ON} must be calculated by voltage division. This can be seen in Figure 55.

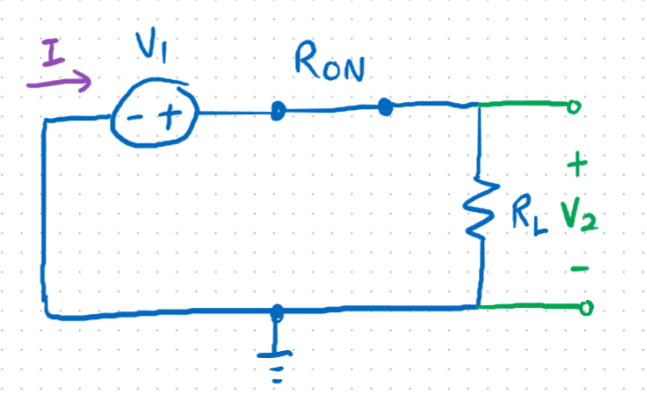

Figure 5. Circuit Diagram when Switch 1 ON

$$V_2 = V_1\left(\frac{R_L}{R_{ON} + R_L}\right)$$

$$\frac{V_2}{V_1} = \left(\frac{R_L}{R_{ON} + R_L}\right)$$

$$V_2(R_{ON} + R_L) = R_L V_1$$

$$V_2 R_{ON} + V_2 R_L = R_L V_1$$

$$V_2 R_{ON} = R_L V_1 - R_L V_2$$

$$R_{ON} = \frac{R_L V_1 - R_L V_2}{V_2}$$

$$R_{ON} = R_L \frac{V_1 - V_2}{V_2} \longrightarrow (1)$$

As seen in Figure 6, V_2 was found to be 2.979V and plugged it into Equation 1:

$$R_{ON} = 400k \frac{3V - 2.979V}{2.979V}$$

$$\therefore R_{ON} = 28.19k\Omega$$

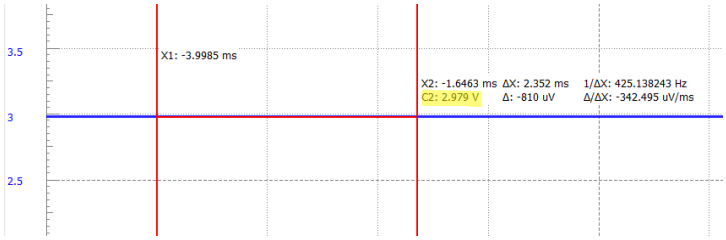

Figure 6. Switch 1 output voltage

Non-ideality 2: When switch is OFF it has a small leakage current I_{OFF}

For switch 1, I_{OFF} was calculated by using Ohm's Law. This can be seen in Figure 7.

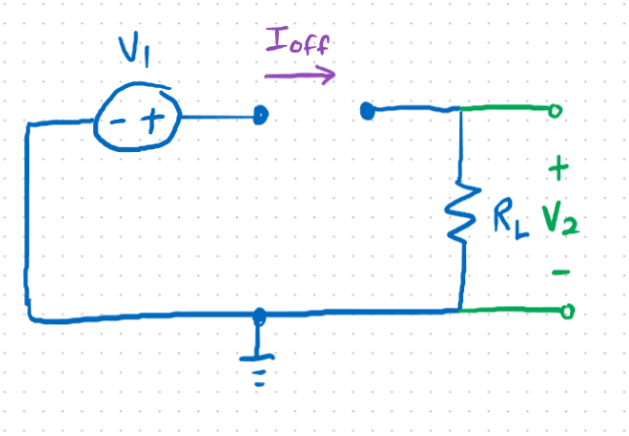

Figure 7. Circuit Diagram when Switch 1 OFF

$$I_{OFF} = \frac{V_2}{R_L} \longrightarrow (2)$$

V_2 was found to be 8.459V, and plugging it into Equation 2 gives:

$$I_{OFF} = \frac{8.459V}{2.2M\Omega}$$
$$\therefore I_{OFF} = 0.846\,\mu A$$

Non-ideality 3: Switch has voltage limitations such that $V_{min} < V_1$, $V_2 < V_{max}$

Boundary input voltages were tested, and the corresponding output voltages were inspected to ensure that the circuit functions correctly within its limit.

$V_{control}$ (V)	$V_1 > V_{min}$ (V)	$V_2 < V_{max}$ (V)
0	1.1	1.046 ✓
0	4.9	4.644 ✓
5	4.9	1.47 ✓
5	1.1	1.032 ✓

Non-ideality 4: When switch ON, R_{ON} remains same with input V_1 or V_2 (bidirectionality).

For direction 1, similarly to non-ideality 1, R_{ON_1} was calculated by voltage division. As seen in Figure 8, the input and output voltages were switched to calculate R_{ON_2}.

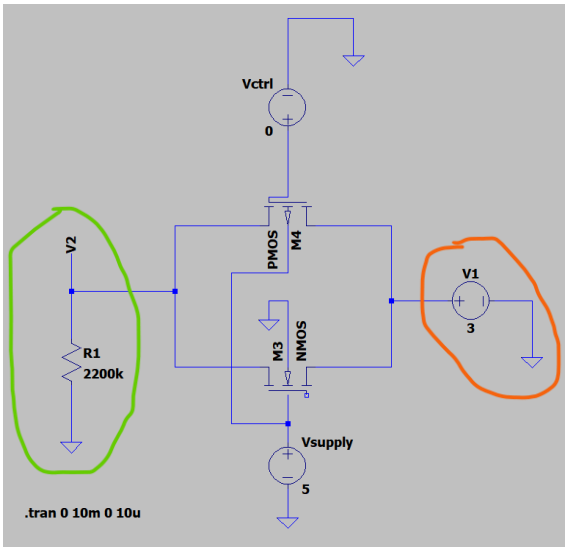

Figure 8. Switch 1 Schematic with V1 and V2 switched

As seen in Figure 9 and Figure 10, V_2 was found and plugged into Equations 3 and 4:

$$R_{ON\_1} = R_L \frac{V_1 - V_2}{V_2} \rightarrow (3)$$

$$R_{ON\_1} = 2200k \frac{3V - 2.998V}{2.998V}$$

$$R_{ON_1} = 1.467\text{k}\Omega$$

$$R_{ON\_2} = R_L \frac{V_2 - V_1}{V_2} \rightarrow (4)$$

$$R_{ON\_2} = 2200k \frac{3V - 2.991V}{2.7273V}$$

$$R_{ON\_2} = 6.619\text{k}\Omega$$

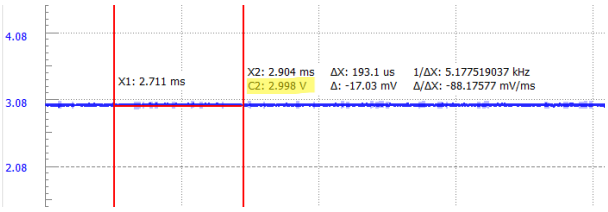

Figure 9. V2 when polarity same

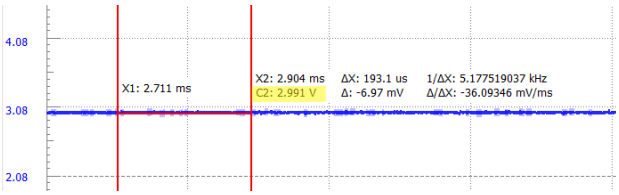

Figure 10. V2 when polarity flipped

iii. Theoretical Explanation

Verifying Circuit

Ideally, when $V_{ctrl} = 0$, V_1 should exactly equal V_2. However, in measurements, it was observed that V_1 was approximately equal to V_2. The accuracy of $V_1 = V_2$ improved as the load resistance increased. For example, with a 4400kΩ resistor and $V_1 = 3V$, V_2 was measured to be 2.997V. This behaviour can be explained using KVL in Figure 55, leading to Equation 5:

$$V_1 = V_{switch} + IR_L \longrightarrow (5)$$

When the load resistance is high, most of the voltage drops across R_L, leaving very little voltage to drop across the switch.

Non-ideality 1: When switch is ON it has an internal resistance R_{ON}

Ideally a closed switch behaves like a wire and thus should have a very small internal resistance. This was not the case with this design. Several load resistance values were tested to ensure a small R_{ON}, but two cases occurred for Equation 1:

$$R_{ON} = R_L \frac{V_1 - V_2}{V_2} \longrightarrow (1)$$

1. when R_L is large, $V_1 \approx V_2$ and thus $\frac{V_1 - V_2}{V_2}$ was small.
2. when R_L is small, $V_1 \gg V_2$ and thus $\frac{V_1 - V_2}{V_2}$ is large.

As a result, it was concluded that the switch was designed in such a way that it has a surplus of internal resistance. This could be due to the properties of the CD4007 MOSFET used.

Non-ideality 2: When switch is OFF it has a small leakage current I_{OFF}

As expected, non-ideal switches exhibit a small leakage current when open, with an expected value of 0.846 μA. It is important to note that as the load resistance increased, the leakage current decreased. This occurs because a higher resistance reduces the overall current flow in the circuit. To maximize this effect, a 2200MΩ load resistor was used

Non-ideality 3: Switch has voltage limitations such that $V_{min} < V_1$, $V_2 < V_{max}$

To verify that the switch operates within its voltage limitations, the output voltage was measured for boundary input voltages. Since $V_2 < V_{max}$ in all tested cases, the switch was confirmed to function correctly within its specified limits. If V_2 had exceeded V_{max}, the switch would have exhibited amplifier behaviour, indicating improper operation.

Non-ideality 4: When switch is ON, R_{ON} remains the same with input V_1 or V_2 (bidirectionality).

In both cases the output voltages were very close (2.998V and 2.991V) which meant that

$$V_1 - V_2 \approx V_2 - V_1$$

Ideally they should have been the same, but non-ideal circuits have external factors that cause the slight variation in values. Another thing to note is since they were magnified by a large factor of 2200kΩ, the internal resistance was also magnified by that large amount. This caused R_{ON_1} and R_{ON_2} to vary by a large amount:

$$R_{ON_1} \gg R_{ON_2}$$

The same explanation from non-ideality 1 applies here: if a smaller load resistance was used then,

$$V_1 - V_2 \gg V_2 - V_1$$

which would be multiplied by a small factor R_L, essentially leading to the same results. This is why a measure of 1kΩ vs 6kΩ was obtained.

iv. Design Tradeoffs

There were two main tradeoffs in this design. The first tradeoff was simplicity, as it would have been easier to implement a single mosfet switch because it is easier to build and analyze. Unfortunately, it does not exhibit bidirectionality. Thus, a more complex double mosfet switch was implemented to obtain bidirectionality.

The second tradeoff was ideal load resistor values. Using smaller realistic values provide more accurate day to day results, but any resistor under 10kΩ did not provide the results needed, so larger less practical resistors were used as the load.

Switch Type 2

i. Circuit Schematic

The circuit for switch 2, shown in Figure 11, is an extension of switch 1. It is a double transmission MOSFET, with the same input voltage V_1 but two separate output voltages, V_A and V_B. It also has a CMOS inverter. Once again, a load is attached to the output of each transmission MOSFET for testing purposes.

This design required both a control and inverted control voltage, and thus a CMOS inverter was used. The input of the inverter was $V_{control}$ and the output was $\bar{V}_{control}$ (inverted). The top transmission MOSFET is switch 1: $V_{control}$ goes to pMOS gate and $\bar{V}_{control}$ goes to NMOS gate. The bottom transmission MOSFET is also a duplicate of switch 1 but this time: $V_{control}$ goes to nMOS gate and $\bar{V}_{control}$ goes to pMOS gate.

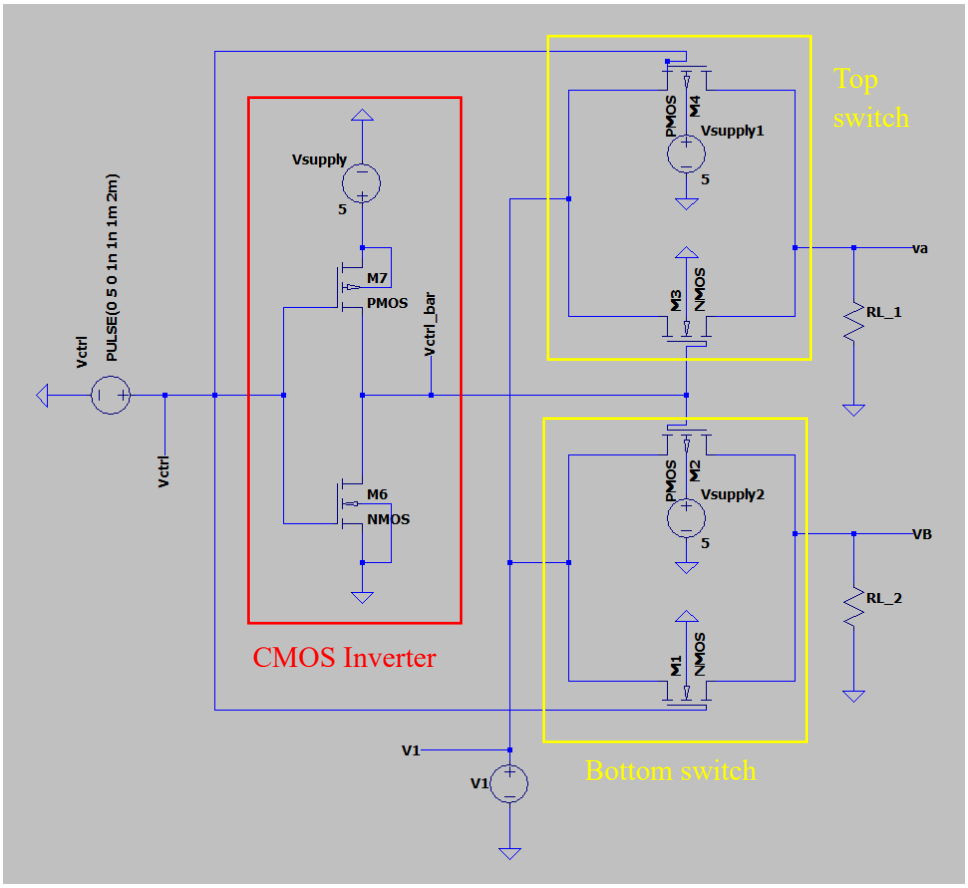

Figure 11. Switch 2 Schematic

ii. Measurements Performed (Test Plan)

Verifying Circuit

To verify this circuit, the following conditions had to be met:

1. when $V_{ctrl} = 0, V_1 = V_A$
2. when $V_{ctrl} = 5V, V_1 = V_B$

This circuit was simulated prior to the physical implementation for safety. Using load resistors of 2200kΩ and an input voltage $V_1 = 3V$, Figure shows that when $V_{ctrl} = 0, V_1 = V_A$, and Figure 13 shows that when $V_{ctrl} = 5V, V_1 = V_B$.

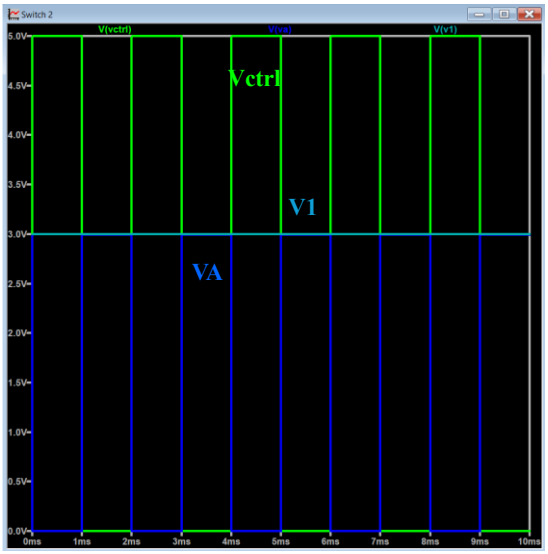

Figure 12. Switch 2 Simulation: V1 vs VA

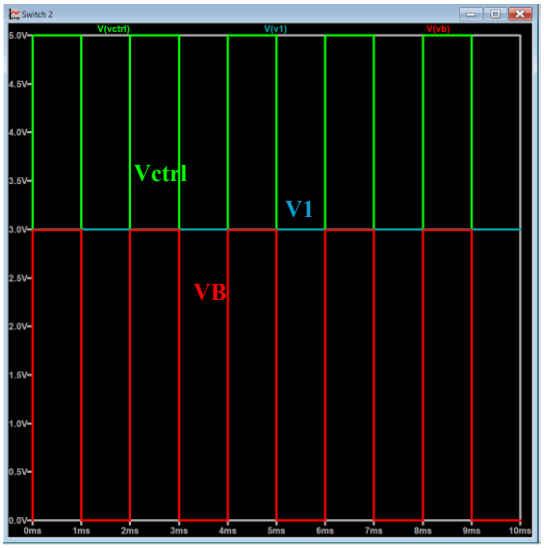

Figure 13. Switch 2 Simulation V1 vs VB

These same results are shown from the physical circuit:

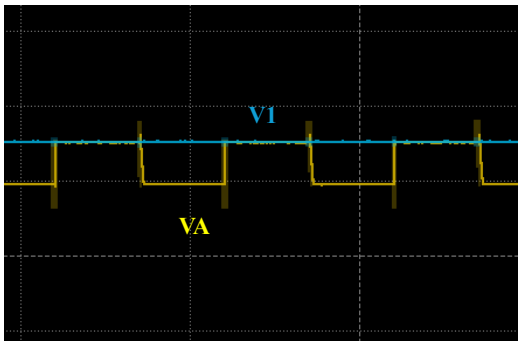

Figure 14. Switch 2 Measurement V1 vs VA

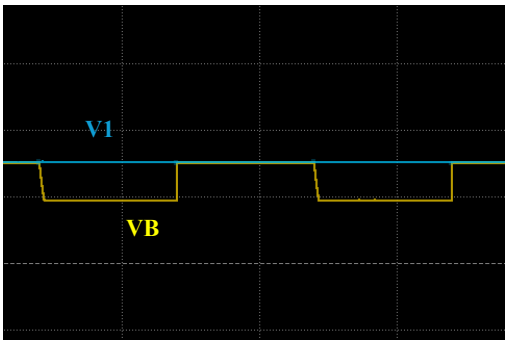

Figure 15. Switch 2 Measurement V1 vs VB

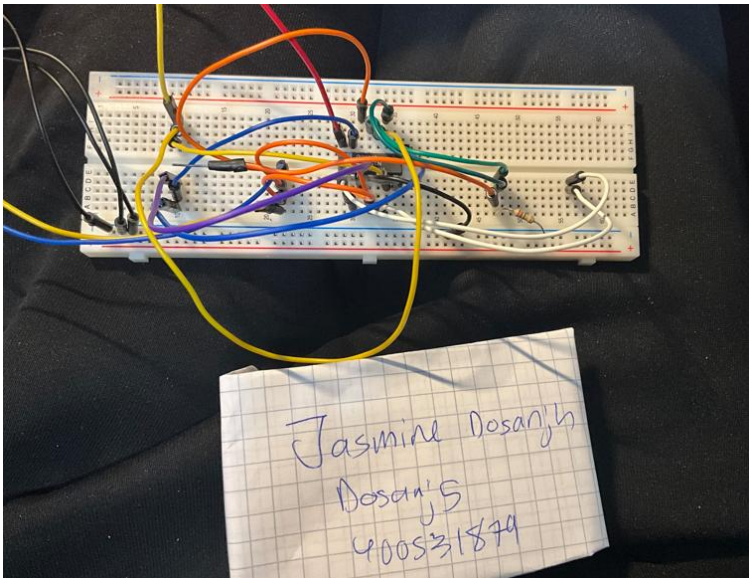

Figure 16. Switch 2 Physical Circuit

Non-ideality 1: When switch is ON it has an internal resistance R_{ON}

For switch 2, R_{ON} must be calculated by voltage division. When $V_{control} = 0$, $V_1 = V_A$. This can be seen in Figure :

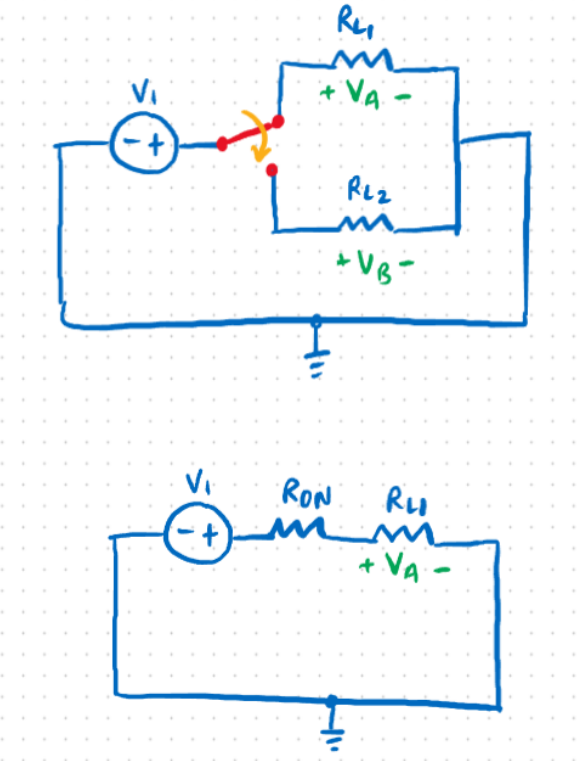

Figure 17. Circuit Diagram when Vctrl = 0

As seen in Figure 18, V_2 was found to be 3.012V and plugged it into Equation 1:

$$R_{ON} = R_L \frac{V_1 - V_A}{V_A} \longrightarrow (1)$$

$$R_{ON} = 400k \frac{3.044V - 3.012V}{3.012V}$$

$$\therefore R_{ON} = 4.24k\Omega$$

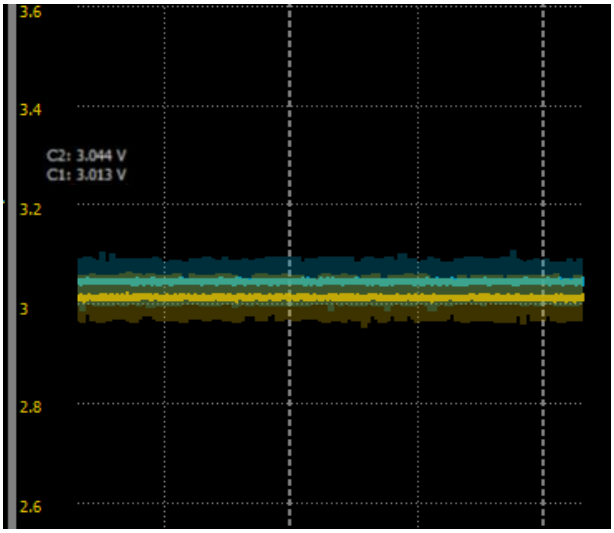

Figure 18. Switch 2 output voltage VA

Non-ideality 2: When switch is OFF it has a small leakage current I_{OFF}

For switch 2, I_{OFF} was calculated by using Ohm's Law. This can be seen in Figure 19.

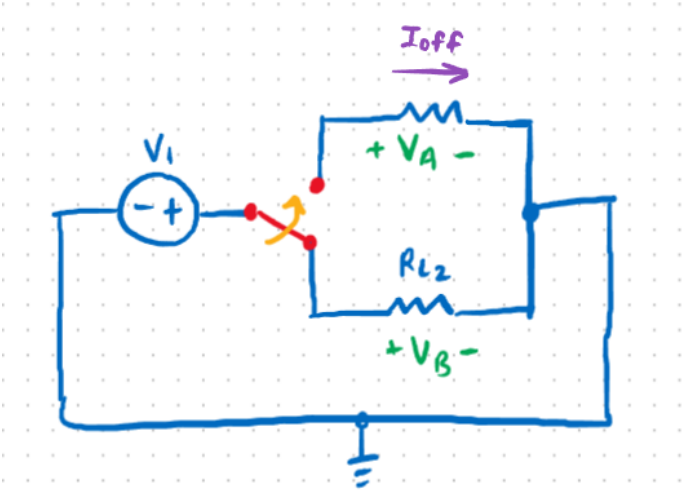

Figure 19. Circuit Diagram when Vctrl = 5V

V_A was found to be 1.406V, and plugging it into Equation 2 gives:

$$I_{OFF} = \frac{V_A}{R_{L1}} = \frac{1.406V}{2.2M\Omega}$$

$$\therefore I_{OFF} = 0.639\mu A$$

Non-ideality 3: $V_{min} < V_1$, $V_2 < V_{max}$

Boundary input voltages were tested, and the corresponding output voltages were inspected to ensure that the circuit functions correctly within its limit.

$V_{control}$ (V)	$V_1 > V_{min}$ (V)	$V_A < V_{max}$ (V)	$V_B < V_{max}$ (V)
0	1.1	43.18m✓	1.055✓
0	4.9	4.648✓	1.523✓
5	4.9	1.522✓	4.655✓
5	1.1	1.054✓	41.43m✓

Non-ideality 4: When switch ON, R_{ON} remains same with input V_1 or V_A/V_B (bidirectionality).

For direction 1, similarly to non-ideality 1, R_{ON_1} was calculated by voltage division. As seen in Figure 20, the input and output voltages were switched to calculate R_{ON_2}.

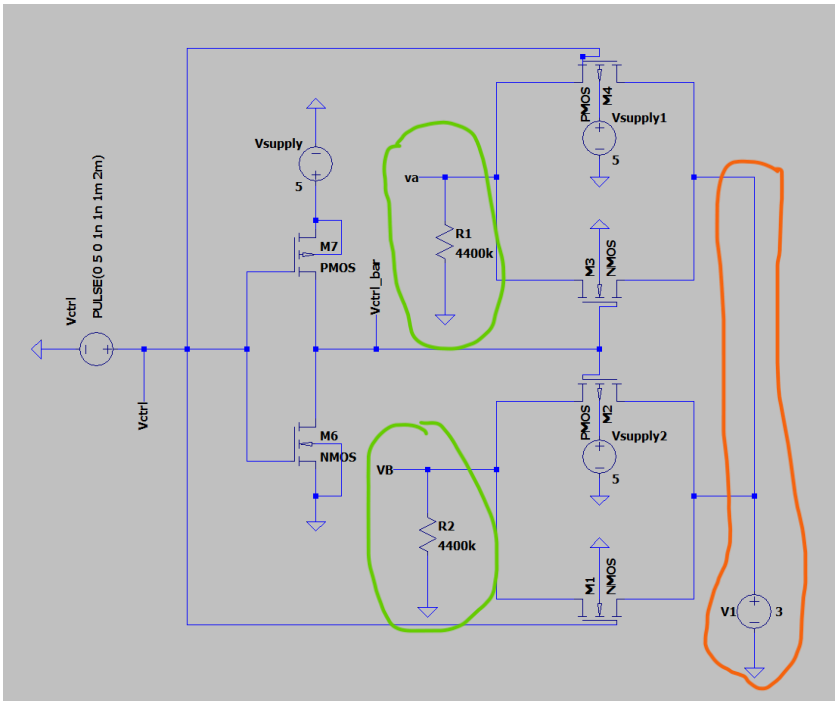

Figure 20. Switch 2 Schematic with V1 and VA + VB switched

As seen in Figure 21 and 22, V_A was found and plugged into Equations 3 and 4:

$$R_{ON\_1} = R_L \frac{V_1 - V_A}{V_A} \rightarrow (3) \qquad R_{ON\_2} = R_L \frac{V_A - V_1}{V_A} \rightarrow (4)$$

$$R_{ON\_1} = 2200k \frac{3.047V - 3.027V}{3.027V} \qquad R_{ON\_2} = 2200k \frac{3.049V - 3.025V}{3.025V}$$

$$R_{ON_1} = 14.53\text{k}\Omega \qquad R_{ON\_2} = 17.45\text{k}\Omega$$

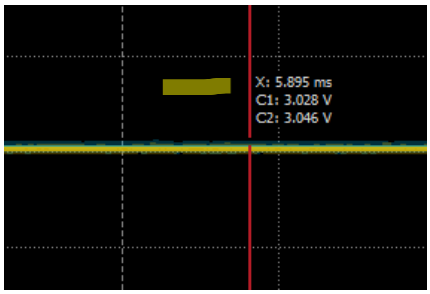

Figure 21. V2 when polarity same

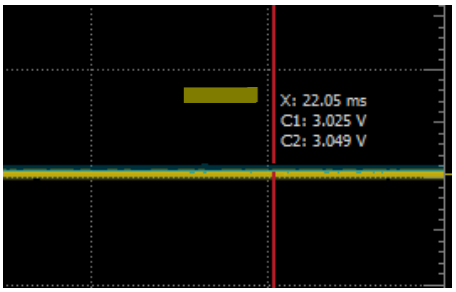

Figure 22. V2 when polarity flipped

iii. Theoretical Explanation

Verifying Circuit

The same explanation for switch 1 also applies here. The higher the load resistor, the greater the accuracy of $V_1 = V_2$, where V_2 equals V_A or V_B.

Non-ideality 1: When switch is ON it has an internal resistance R_{ON}

Just like Switch 1, Switch 2 also has a high internal resistance R_{ON} when turned ON. It deviates from the ideal behavior of a perfect conductor. Testing with various load resistance values revealed the same results as switch 1. This indicates that since Switch 2 is made from switch 1, it also possesses excess internal resistance, likely due to material properties or design constraints.

Non-ideality 2: When switch is OFF it has a small leakage current I_{OFF}

When switch 2 is OFF, it also exhibits a small leakage current, similar to switch 1, with an expected value of 0.639 µA. Once again, the leakage current decreased as the load resistance increased, and thus, a 2200MΩ load resistor was selected.

Non-ideality 3: $V_{min} < V_1$, $V_2 < V_{max}$

To verify that the switch operates within its voltage limitations, the output voltages at V_A and V_B were measured for boundary input voltages. Since they both remained within limits in all tested cases, the switch was confirmed to operate correctly within its specified voltage range. If either had exceeded V_{max}, the switch would have exhibited unintended behavior.

Non-ideality 4: When switch ON, R_{ON} remains same with input V_1 or V_A/V_B (bidirectionality).

Just like switch 1, both cases had similar output voltages (3.027V and 3.025V) which meant that

$$V_1 - V_\text{A} \approx V_\text{A} - V_1$$

Since they were magnified by a large factor of 2200kΩ, the internal resistance was also magnified by that large amount, causing R_{ON_1} and R_{ON_2} to vary by a large amount (14.53 kΩ vs 17.45 kΩ). If a smaller load resistance was used, the same results were obtained and the voltages varied significantly, leading to the same results.

iv. Design Tradeoffs

There were two main tradeoffs in this design. The first tradeoff was simplicity, as it would have been easier to build and measure a simpler circuit. Since switch 1 was already complex and needed twice in the design of switch 2, this combination with a CMOS inverter created a complicated design. The switch was tedious to build and theoretically analyze.

The second tradeoff was cost and performance. Higher-quality MOSFETs allow the switch to operate at higher speeds and greater accuracy, resulting in better performance. However, the only available MOSFET in the 2EI4 kit was the CD4007, which is generally cheaper and standard quality. Using this MOSFET may have led to higher on-resistance and slower switching speeds.