Lab 4: Translinear Circuits

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1 Experiment 1: Bipolar Transistor Matching

1.1 Background and Procedure

In Experiment 1, we obtained an MMPQ3904 quad NPN bipolar transistor array (shown in Figure 1) and measured the base current and emitter current as we swept the base voltage while the collector was tied to the +5V power supply. We then calculated the collector current (I_c) using $I_c = I_e - I_b$ where I_e is the emitter current and I_b is the base current. We then used theoretical fits to extract values for the collector saturation current (I_s) and the forward current gain (β).

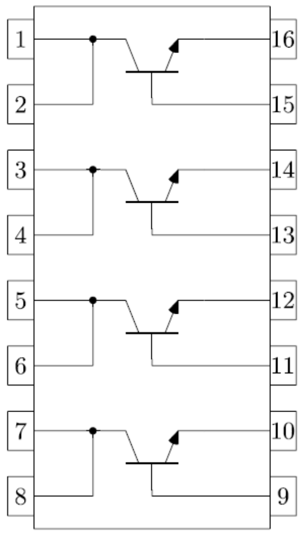

Figure 1: MMPQ3904 Quad NPN Bipolar Transistor Array

1.2 Expectations

We expect the transistors to be matched quite well. As the transistors were made at the same time and on the same equipment, it would make sense for the transistors to be matched very well.

1.3 Results and Discussion

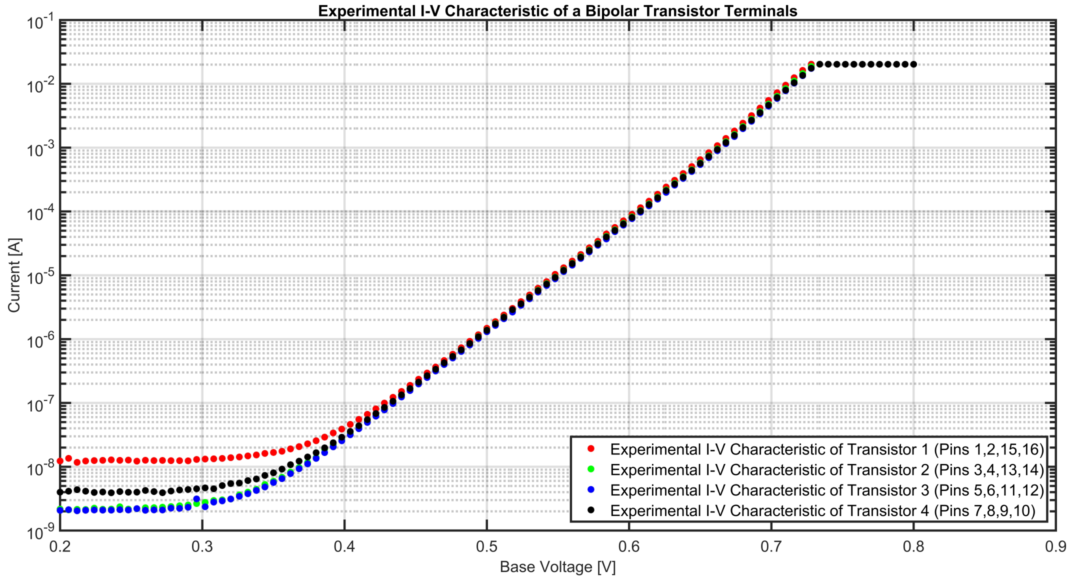

Figure 2: Experimental I-V Characteristics of Bipolar Transistor Terminals

To find the values of I_s and β we used the base voltage region of 0.4 V to 0.73 V. To find β, we averaged the β value over the range of 10^{-7} [A] to 10^{-4} [A] for the base current.

Transistor Parameters			
Transistor Number	I_s [A]	U_T [V]	β
1 (Pins 1, 2, 15, and 16)	$2.88 * 10^{-15}$ [A]	0.0248 [V]	185.28
2 (Pins 3, 4, 13, and 14)	$2.26 * 10^{-15}$ [A]	0.0247 [V]	184.00
3 (Pins 5, 6, 11, and 12)	$2.20 * 10^{-15}$ [A]	0.0247 [V]	185.52
4 (Pins 7, 8, 9, and 10)	$2.60 * 10^{-15}$ [A]	0.0248 [V]	185.12

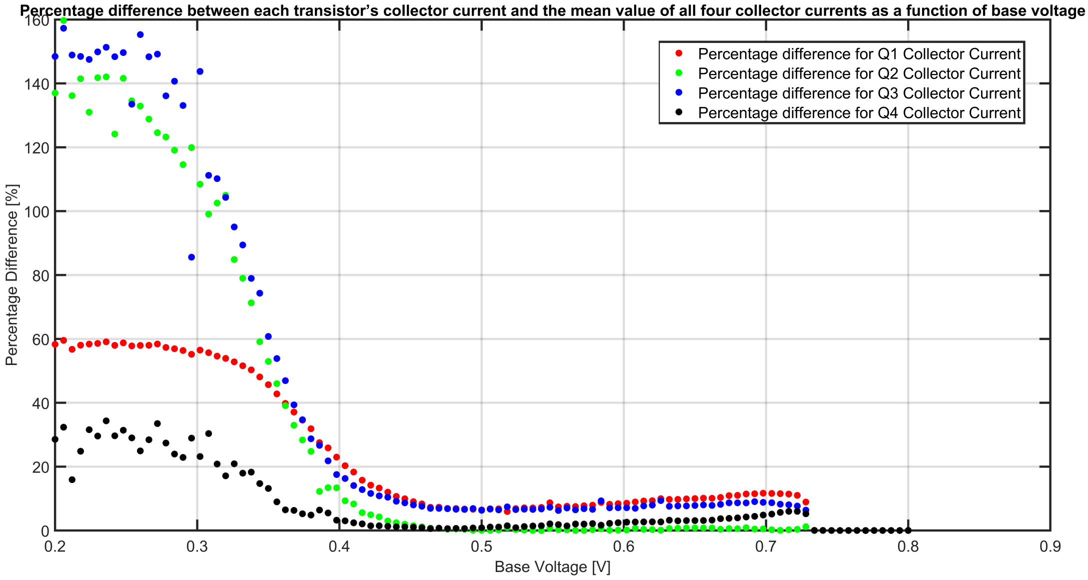

Figure 3: Percentage difference between each transistor's collector current and the mean value of all four collector currents as a function of base voltage

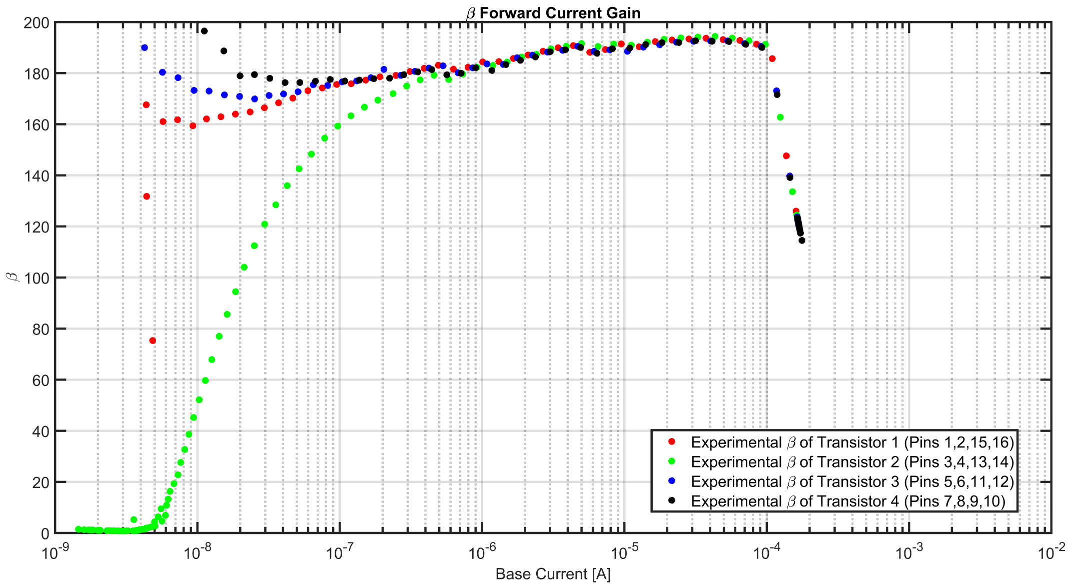

Figure 4: β Forward Current Gain for each Transistor

The transistors match quite well when the base voltage is above 0.4 V. We can see this in Figure 3, where the percent difference between the transistors is less than 20%. Further we can see within this region that transistor 4 and 2 match have about the same percent error from the mean. Similarly, we can see that transistor 1 and 3 match with their percent error from the mean in this region as well.

In Figure 2, we can see that the transistors match one another quite well when the base voltage is above 0.4 V. However, when the base voltage is less than that, we can note that transistors 2 and 3 match very well; whereas, transistors 1 and 4 have much more current through them at small base voltages.

In terms of the forward current gain (β), all of the transistors are well matched when the base current is 0.4 μA to 0.1 mA. However, we will note that transistors 1, 3, and 4 are matched when the base current is above 50 nA. β was found by dividing the experimentally measured values for $\frac{I_c}{I_b}$, where $I_c = I_b + I_e$

One possible reason for this would be due to the pin contact resistances and capacitance. Another reason there could be disparities is due to the manufacturing process inaccuracies such as inconsistent chemical deposits.

2 Experiment 2: Translinear Circuit 1

2.1 Background and Procedure

In Experiment 2, we made the the circuits depicted in Figure 5 and Figure 13 with the power supply rail connected to a +5V power supply. In addition, we constructed an adjustable current source and current sink, to supply the input required by the circuit. Using a voltage divider, we output a constant 0.247V for the current sink, and a constant 1.871V for the current source.

We then measured the output current I_z, as a function of first input current, I_x, for various values of the second input current, I_y, that are presented in the table below.

We also measured I_z, as a function of I_y for various values values of I_x, that are presented in the table below.

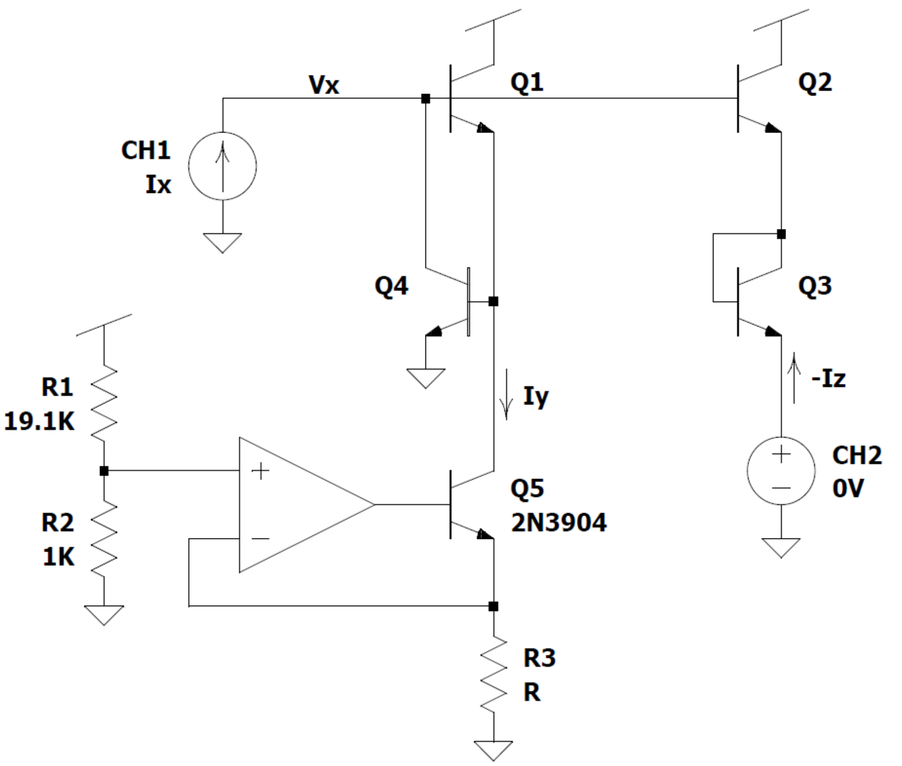

Figure 5: Circuit Diagram for Experiment 2 Part A

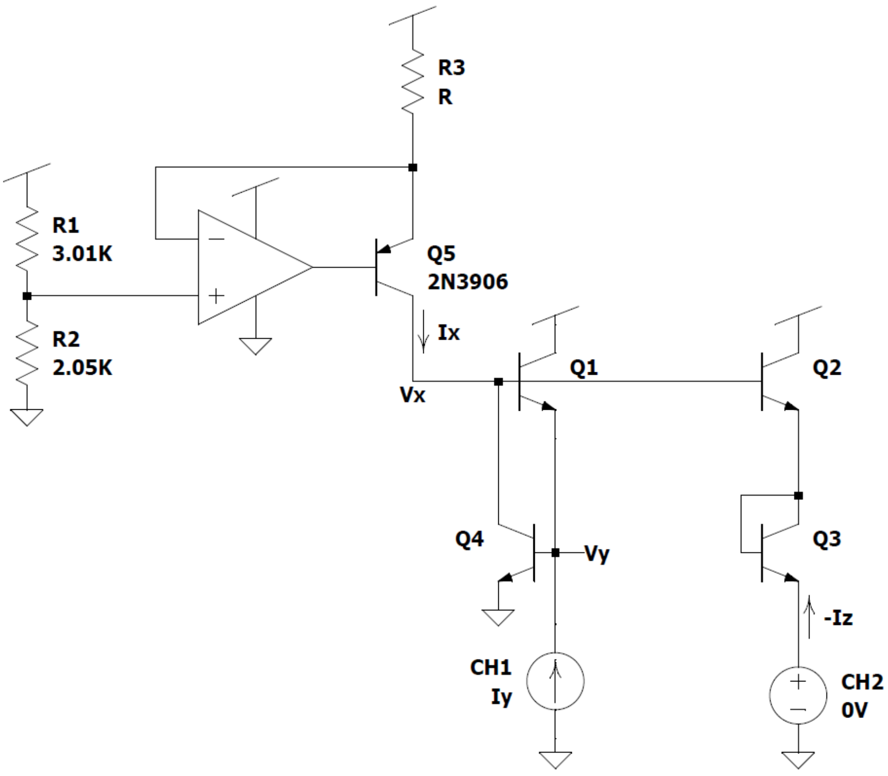

Figure 6: Circuit Diagram for Experiment 2 Part B

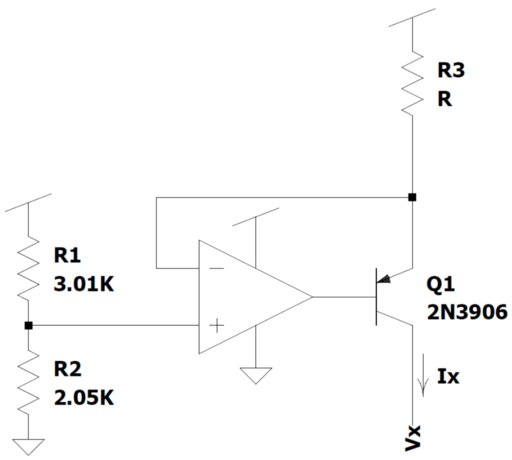

Figure 7: The Current Sink Circuit Schematic

Keeping in mind the experimental values for resistors (as presented below), we calculated the voltage input to the op-amp through the voltage divider ratio as 1.8711 V, acting as a current sink in this case.

Experimental Values for Resistors			
Manufacturer Provided Value	Measured Value	Error Percentage	Given Tolerance
2.05 $k\Omega$	1.99 $k\Omega$	-2.96%	+/-1%
3.01 $k\Omega$	3.01 $k\Omega$	-0.033%	+/-1%

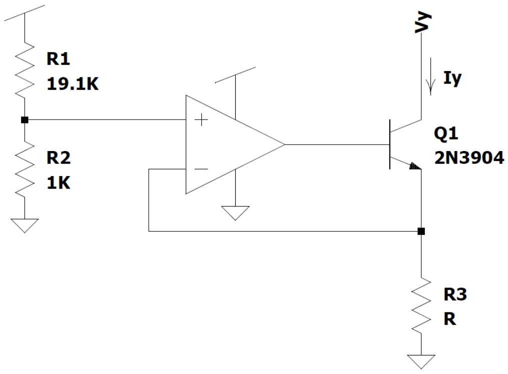

Figure 8: The Current Source Circuit Schematic

Keeping in mind the experimental values for resistors (as presented below), we calculated the voltage input to the op-amp through the voltage divider ratio as 0.247 V, acting as a current source in this case.

Experimental Values for Resistors			
Manufacturer Provided Value	Measured Value	Error Percentage	Given Tolerance
1 $k\Omega$	1 $k\Omega$	-0.33%	+/-1%
19.1 $k\Omega$	18.94 $k\Omega$	-0.871.%	+/-1%

For this circuit we used a MMPQ3904 quad NPN bipolar transistor array (shown in Figure 1) and LMC6482 dual rail-to-rail CMOS operational amplifier (shown in Figure 9).

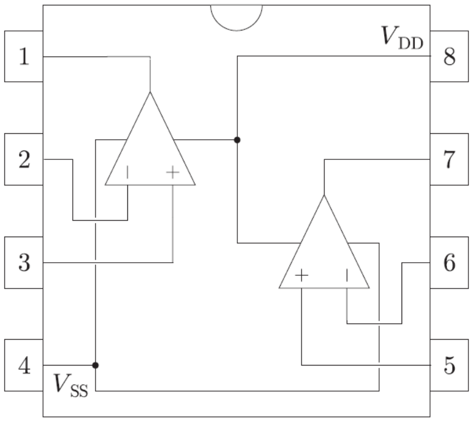

Figure 9: LMC6482 Dual Rail-to-Rail CMOS Operational Amplifier

2.2 Expectations

For this circuit we expect the output current to be related to the two input currents by,

$$I_z = \sqrt{I_x * I_y} \tag{1}$$

Where I_z is the output current, and I_x and I_y are the input currents.

2.3 Results and Discussion

Experimental Values for Resistors			
Manufacturer Provided Value	Measured Value	Error Percentage	Given Tolerance
2 $k\Omega$	1.99 $k\Omega$	-0.5%	+/-1%
20 $k\Omega$	19.68 $k\Omega$	-1.6%	+/-1%
200 $k\Omega$	200.64 $k\Omega$	0.31%	+/-1%
2 $M\Omega$	1.97 $M\Omega$	-1.52%	+/-5%

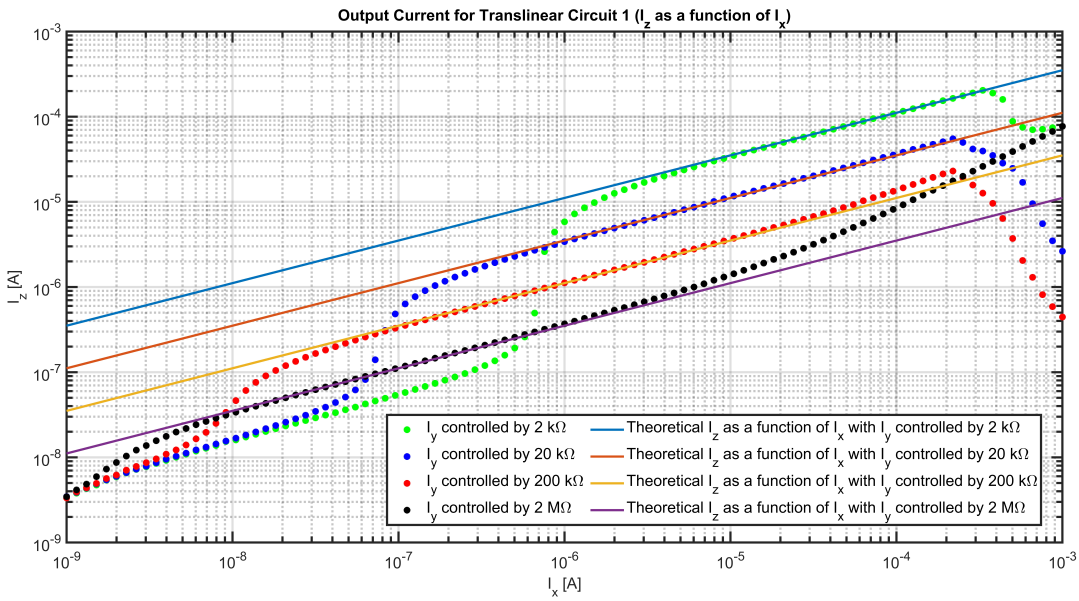

Figure 10: Output Current for Translinear Circuit 1 (I_z as a function of I_x)

The following table shows the ranges of I_x the theoretical output current is a good fit the experimentally measured data.

Fit Quality Range		
I_y	I_x Lower Bound	I_x Upper Bound
Controlled by 2 $k\Omega$	1 μA	1 mA
Controlled by 20 $k\Omega$	0.1 μA	0.1 mA
Controlled by 200 $k\Omega$	10 nA	0.1 mA
Controlled by 2M $k\Omega$	10 nA	1 μA

Theoretical I_y values	
Resistance Value	I_y
2 $k\Omega$	1.235e-04 [A]
20 $k\Omega$	1.235e-05 [A]
200 $k\Omega$	1.235e-06 [A]
2M $k\Omega$	1.235e-07 [A]

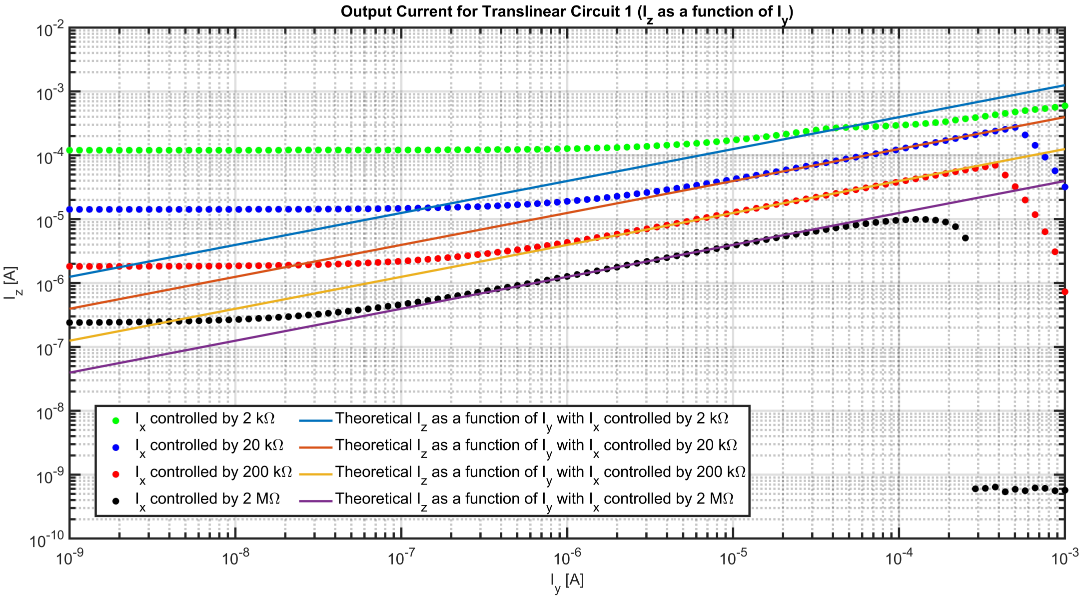

Figure 11: Output Current for Translinear Circuit 1 (I_z as a function of I_y)

Fit Quality Range		
I_x	I_x Lower Bound	I_x Upper Bound
Controlled by 2 $k\Omega$	10 μA	0.1 mA
Controlled by 20 $k\Omega$	10 μA	1 mA
Controlled by 200 $k\Omega$	1 μA	1 mA
Controlled by 2M $k\Omega$	0.1 μA	0.1 mA

The following table shows the ranges of I_y the theoretical output current is a good fit the experimentally measured data.

Theoretical I_x values	
Resistance Value	I_x
2 $k\Omega$	1.5644e-03 [A]
20 $k\Omega$	1.5644e-04 [A]
200 $k\Omega$	1.5644e-05 [A]
2M $k\Omega$	1.5644e-06 [A]

As we discussed in class, we believe the reason there is a region in which the transistor operates as expected is because of β being finite. With a finite β the output current will depend on it, and thus, the current through the transistors will change as the base current changes. This effect on each transistor propagates through the entire circuit, and will thus influence the output current. This dependence could be alleviated by using a β helper or op-amps to ensure the base current is negligible.

3 Experiment 3: Translinear Circuit 3

3.1 Background and Procedure

We then measured the output current I_z, as a function of first input current, I_x, for various values of the second input current, I_y, that are presented in the table included in Experiment 2 summary.

We also measured I_z, as a function of I_y for various values values of I_x, that are presented in the table included in Experiment 2 summary.

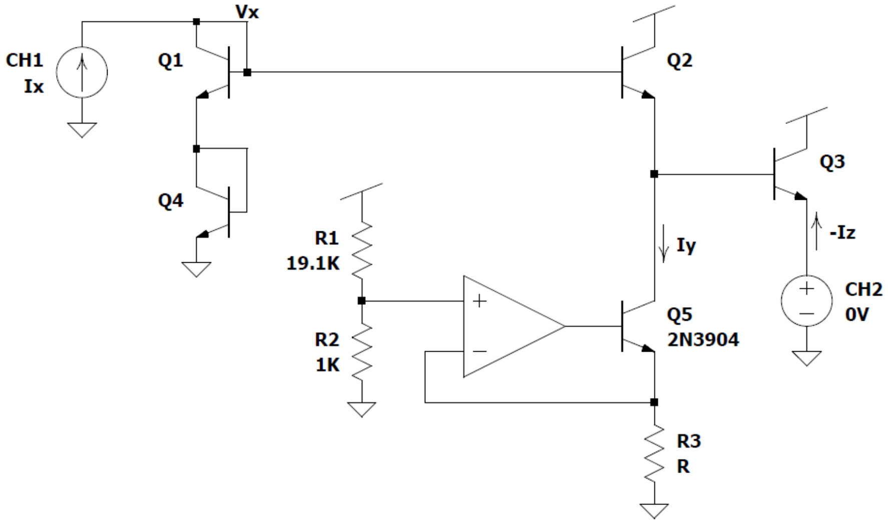

Figure 12: Circuit Diagram for Experiment 3 Part A

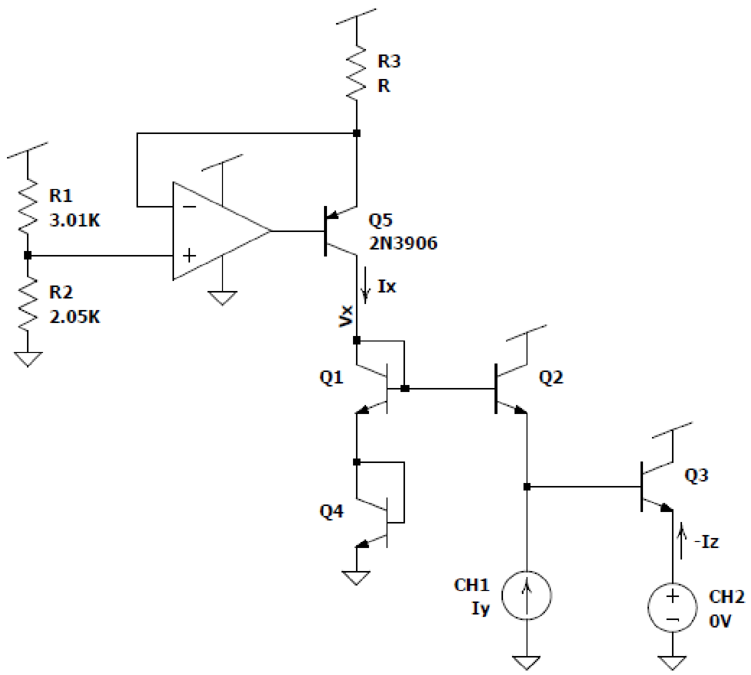

Figure 13: Circuit Diagram for Experiment 3 Part B

For this circuit we used a MMPQ3904 quad NPN bipolar transistor array (shown in Figure 1) and LMC6482 dual rail-to-rail CMOS operational amplifier (shown in Figure 9).

3.2 Expectations

For this circuit we expect the output current to be related to the two input currents by,

$$I_z = \frac{I_x^2}{I_y} \tag{2}$$

Where I_z is the output current, and I_x and I_y are the input currents.

3.3 Results and Discussion

Please refer to the tables in Experiment 2 to find the current source and sink values for each of the resistors added to the source/sink circuitry.

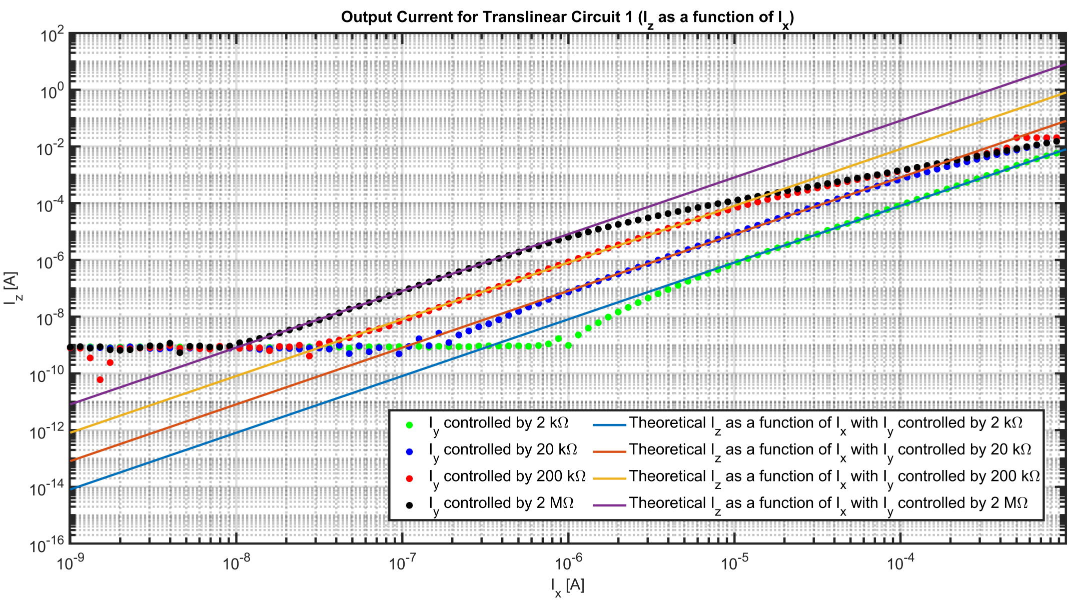

Figure 14: Output Current for Translinear Circuit 2 (I_z as a function of I_x)

Fit Quality Range		
I_y	I_y Lower Bound	I_y Upper Bound
Controlled by 2 $k\Omega$	10 nA	1 μA
Controlled by 20 $k\Omega$	10 nA	10 μA
Controlled by 200 $k\Omega$	0.1 μA	0.1 mA
Controlled by 2M $k\Omega$	1 μA	1 mA

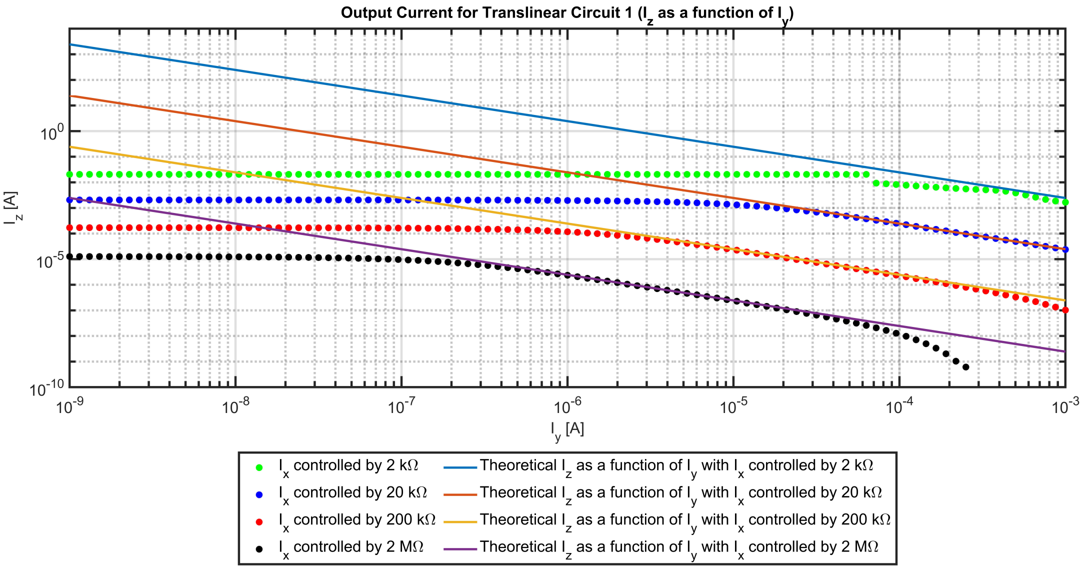

Figure 15: Output Current for Translinear Circuit 2 (I_z as a function of I_y)

Fit Quality Range		
I_x	I_x Lower Bound	I_x Upper Bound
Controlled by 2 $k\Omega$	0.1 mA	1 mA
Controlled by 20 $k\Omega$	10 μA	1 mA
Controlled by 200 $k\Omega$	1 μA	1 mA
Controlled by 2M $k\Omega$	0.1 μA	0.1 mA

We can see the current limit of the SMU (20 mA) in the experimental data for the 2 kΩ controlled current circuit. This is important to note if we were to use smaller resistance values (as the output current would be higher), but for the current values we set the source/sink to this limit did not play a large factor. For the 2 kΩ controlled current circuit, it appears the experimental behavior of the circuit would match the theoretical behavior for a higher currents than we input (possibly into the 1 A range for I_y). This also appears to be the case for the 20 kΩ controlled current circuit - but to a lesser degree (possibly 10^{-2} A for I_y).

Similar to Experiment 2, we believe the reason there is a region in which the transistor operates as expected is because of β being finite. With a finite β the output current will depend on it, and thus, the current through the transistors will change as the base current changes. This effect on each transistor propagates through the entire circuit, and will thus influence the output current. This dependence could be alleviated by using a β helper or op-amps to ensure the base current is negligible.