Introduction to Microcircuits
Lab 3: Resistors and Bipolar Transistors

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1 Experiment 1: Bipolar Transistor Matching

For each of the four transistors in the MAT14 npn array, we measured the emitter current and base current as the base voltage was swept, and then used these results to compute the bjt's collector current.

Below in figure 1 is a plot of the base and collector currents for all four of the MAT14 transistors. The currents for each transistor are so closely matched with eachother that the data points overlap on each graph.

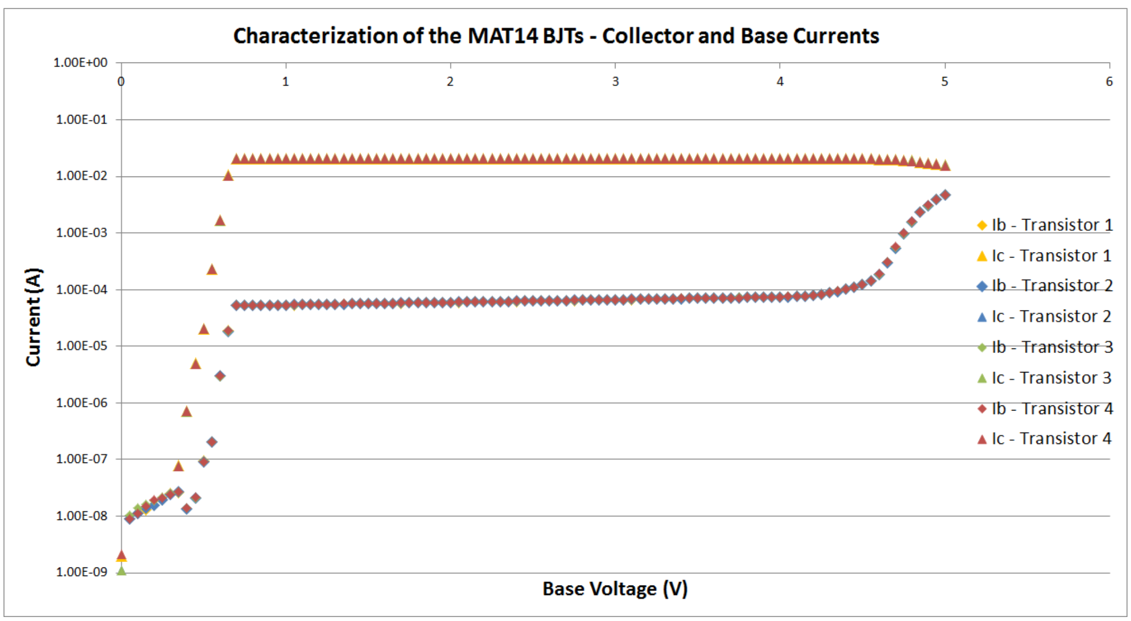

Figure 1: A semilog plot of the base and collector currents of the four BJT transistors on the MAT14 chip.

Then, we calculated the percent difference of each collector current when compared to the mean of all of the collector currents. The differences were plotted in the graph below, in figure 2.

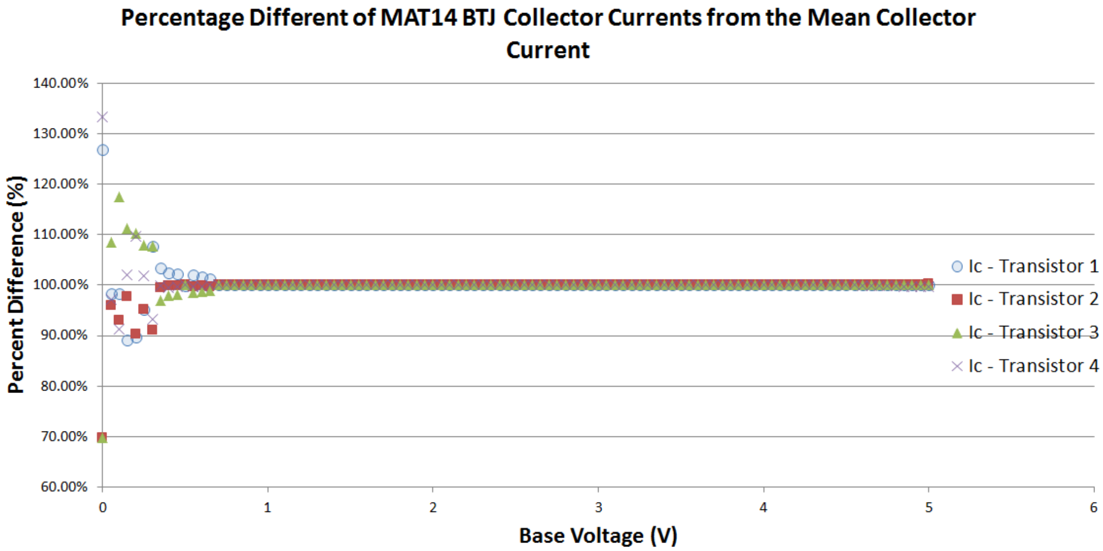

Figure 2: A plot showing the percentage difference between the transistors' collector currents and the mean collector current.

We then used the measured collector and base currents to calculate the values of I_S and β. Figure 3 plots the value of the current gain, β, as voltage is swept from $0 - 5$V. Because β is not a constant value, but a curve, the average of the computed gain between 0.7 V and 4.1 V was calculated and compared to the average of the theoretical fits, in order to compute a single value for β. Because the theoretical fits were so close to their data (at R^2 values of 0.9976 or more), the two computed beta values were essentially the same for each transistor.

Figure 4 plots the value of the emitter current as the base voltage is swept. We used this data to extract the saturation current, by fitting a trendline to the emitter current curve.

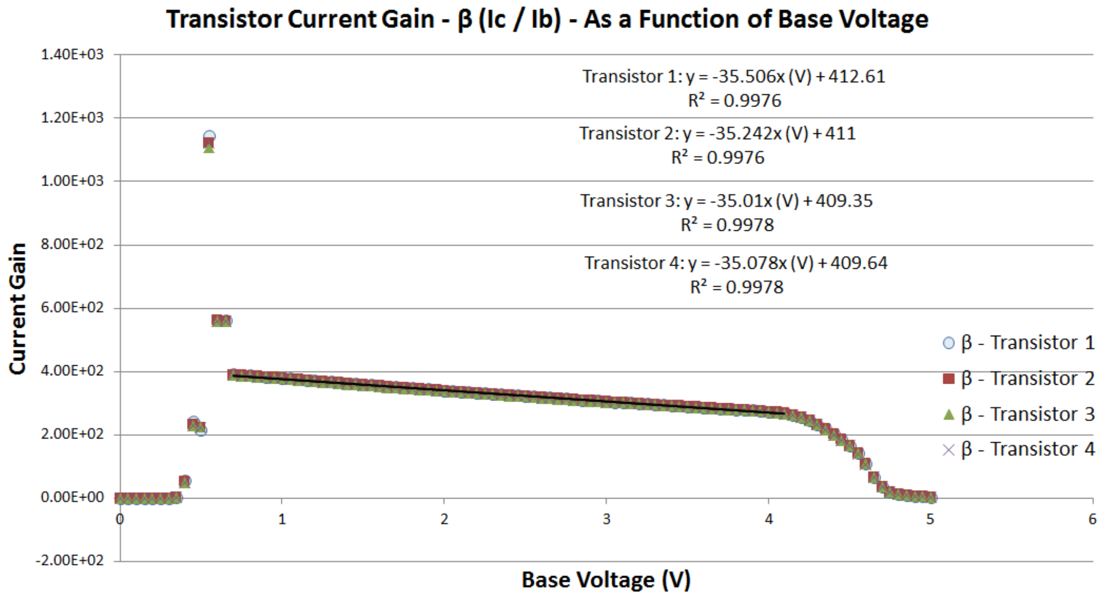

Figure 3: A plot of the current gain of all four MAT14 transistors as their base voltage was swept from 0V to 5V. Trendlines were fit to the data in order to extract equations that could be used to verify the average current gain values.

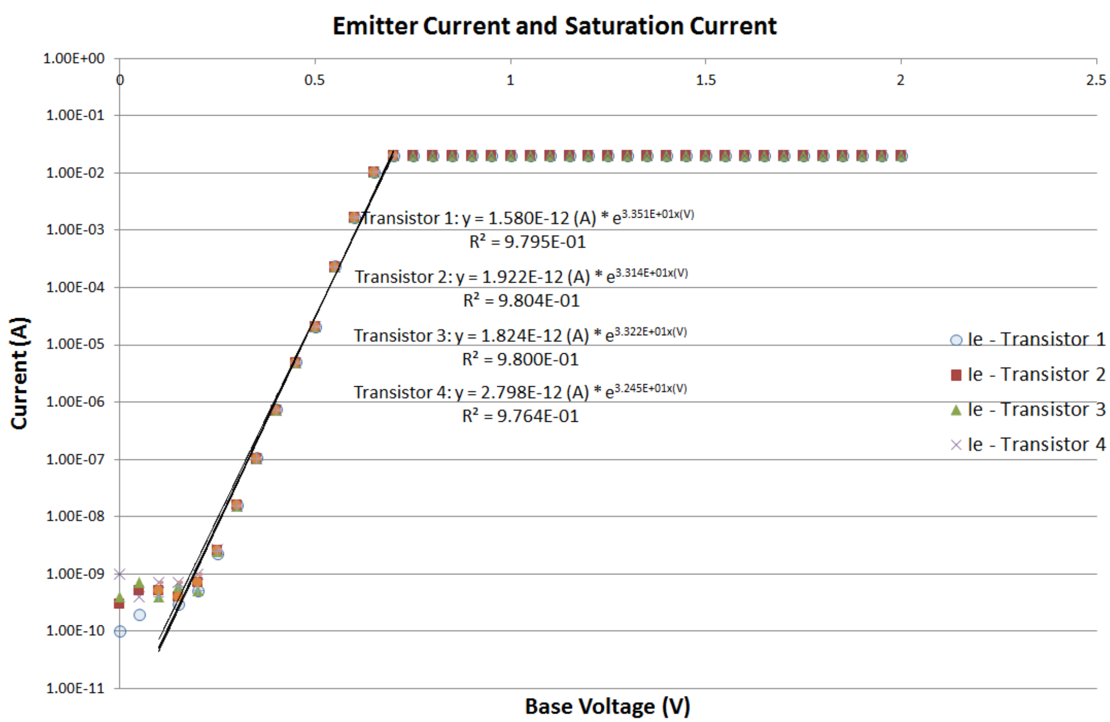

Figure 4: A semiplot of the emitter current of all four MAT14 transistors as their base voltage was swept from 0V to 5V. Trendlines were fit to the data in order to extract the saturation current of each transistor.

The results of the characterization of the four transistors are shown below:

BJT	1	2	3	4	mean
I_S	$1.58 * 10^{-12}$	$1.922 * 10^{-12}$	$1.824 * 10^{-12}$	$2.798E * 10^{-12}$	$2.031 * 10^{-12}$
%Δ I_S	-22.206	-5.367	-10.192	37.765	X
β	327.394	326.414	325.330	325.454	326.148
%$\Delta\beta$	0.381%	0.081%	-0.25%	-0.214%	X

Based on the data shown in table 1 and figure 2, we see that the transistors are in fact extremely well matched. Their beta values differ by little to nothing (less than 0.5%), while their saturation current values differ slightly more (in the range of $-22\% - 37\%$) but are all on the same order of magnitude.

Finally, we plotted the current gain β against the base current for all four of the MAT14 transistors. As shown in figure 5, the beta values for each transistor seemingly overlap, as if on the same curve, suggesting that the transistors are very well matched.

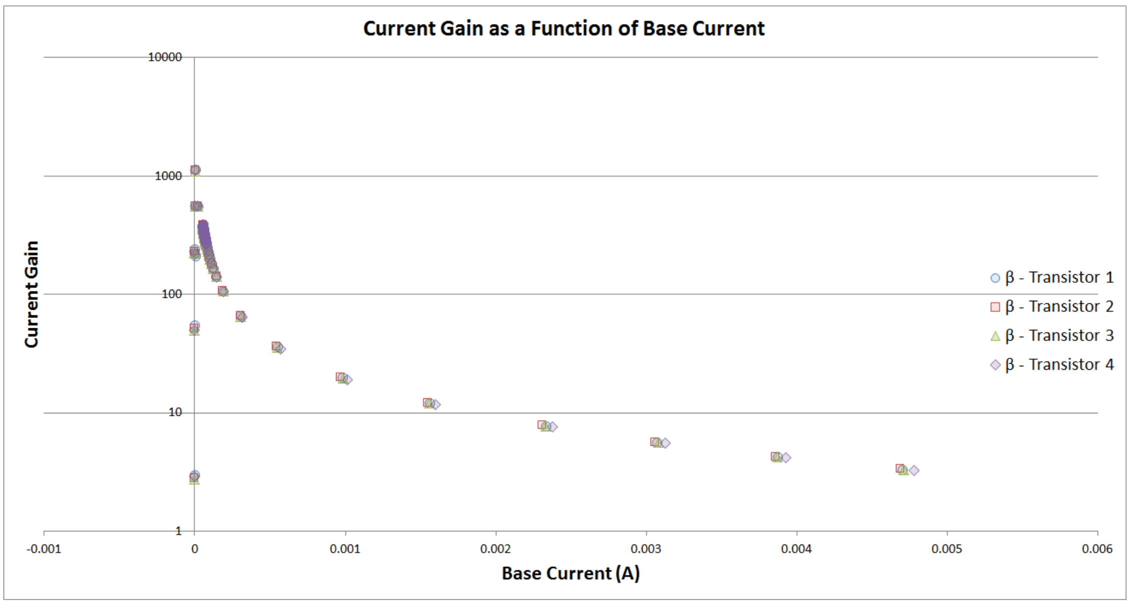

Figure 5: A plot of the current gain of each MAT14 transistor vs. the base current.

All of the data shown in the figure above suggest that these four transistors are very well matched. This is likely because they are seated on the same substrate; they experience the same temperatures, thus their current gain values and saturation current values are all very close.

2 Experiment 2: Translinear Circuit I

In this experiment, we constructed the square-rooting translinear circuit as shown in the prelab. We measured the output current as a function of the first input current, as a second input current was varied across three different values. Then, we measured the output current as a function of the second input current as the first was varied. The resistors used to vary the input currents were as follows:

- 197 Ohms,
- 1934 Ohms,
- $20k$ Ohms.

They were intentionally spaced across two orders of magnitude in order to achieve a 2 decibel range in source current from about 0.1mA to 10mA.

From our work done in the prelab, we determined that in this translinear circuit,

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

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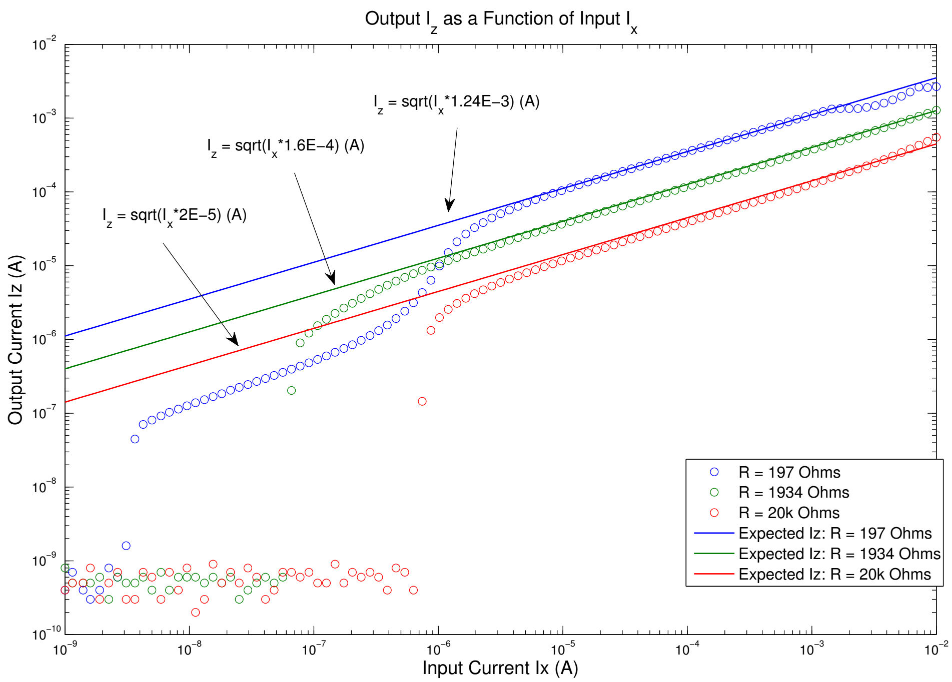

Figure 6: A log-log plot of the output current I_z as a function of the input current I_x as the second input current I_y was held at three different values determined by three resistor values for the sink circuit.

Figure 8 shows a plot of the output current I_z as the input current I_x is swept and the second input current I_y is varied across three values. We plotted these measured output current values, and then compared them to the expected output current values as calculated from the equation above (as solid lines). As shown in the graph, our measured current values are very close to the expected current values when the current exceeds approximately 1μA-10μA.

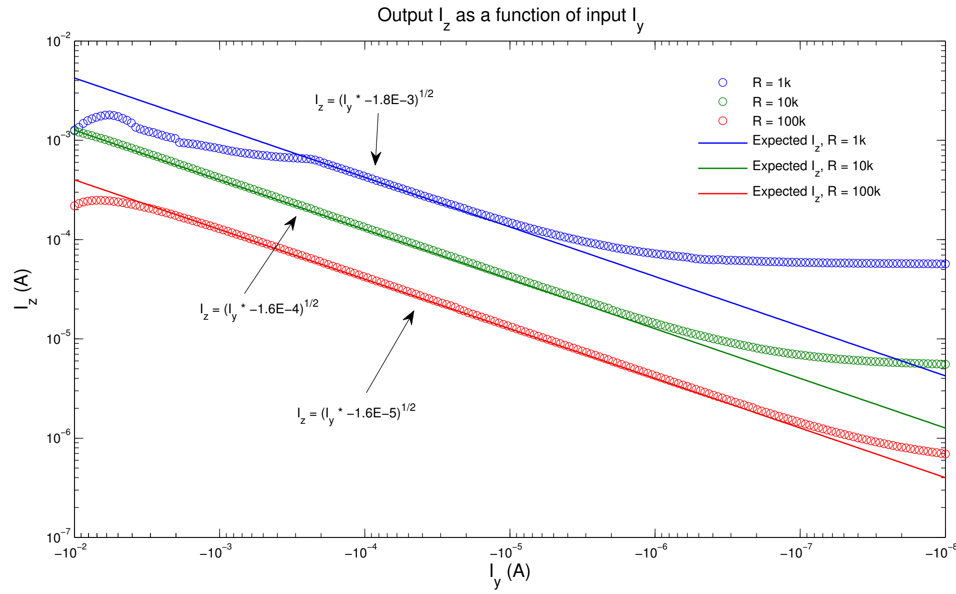

Figure 7: A log-log plot of the output current I_z as a function of the input current I_y, as the other input current, I_x, was held at three different values determined by three resitors we chose for the source circuit.

Figure 7 is a loglog plot of I_z as a function of I_y for three different values of I_x, which was determined by a current source circuit. The resistor values in the current source chosen in order to get a 2 decibel range of I_x, according to the equation:

$$I_x = \frac{V_{dd} - V_{in}}{R}$$

where $V_{dd} = 5V$. The theoretical fit for $R = 1k$ matches the data over a narrow range from about $-1E-3.5$ to $-1E-5$, but the other two values produced a good fit for almost the entire range of I_y.

3 Experiment 3: Translinear Circuit II

In this experiment, we constructed the squaring translinear circuit as shown in the prelab. We measured the output current as a function of the first input current, as a second input current was varied across three different values by constructing a current sink dependent on the value R of its resistor. Then, we measured the output current as a function of the second input current as the first was varied.

The resistors used to vary the input currents were picked to give us a two decibel range as dictated by the equation $I_y = fracV_{in}/R$, and were as follows:

- $2.86k$ Ohms,
- $30.1k$ Ohms,
- $301k$ Ohms.

They were intentionally spaced across two orders of magnitude.

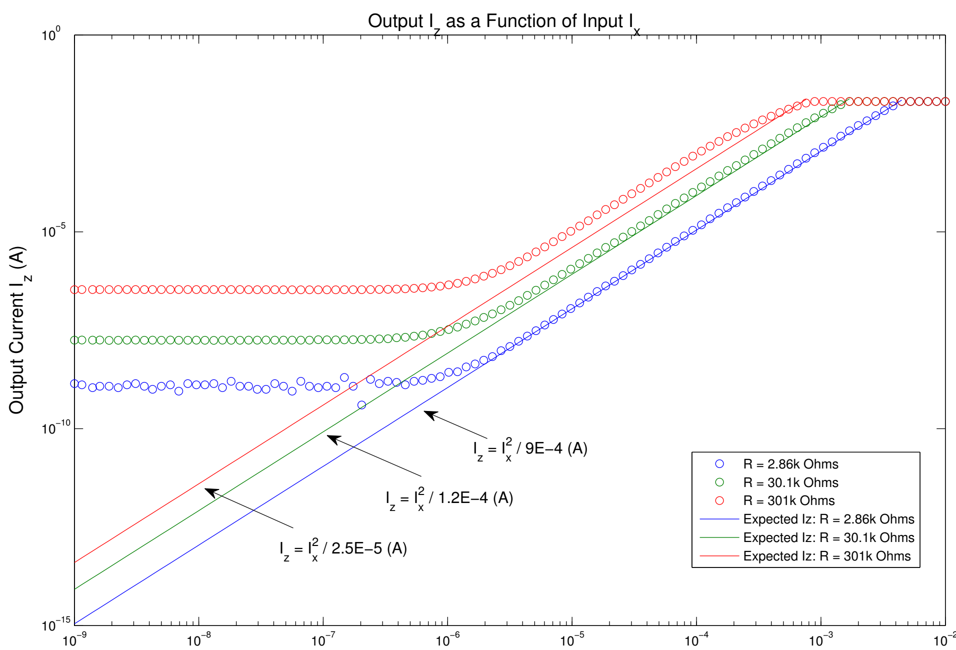

Figure 8: A log-log plot of the output current I_z as a function of the input current I_x, as the second input current I_y was varied across three values.

From our work done in the prelab, we determined that in this translinear circuit,

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

Figure 8 shows a plot of the output current I_z as the input current I_x is swept and the second input current I_y is varied across three values. We plotted these measured output current values, and then compared them to the expected output current values as calculated from the equation above (as solid lines). As shown in the graph, our measured current values are very close to the expected current values from the prelab, within a certain current range (at 1μA to appriximately 1mA).

Then, we measured the output current I_z as the input current I_y is swept and the other input current I_x is varied across three values via a current source. The resistor values used for this current source were picked in order to give us a two decible range as dictated by the equation $I_x = \frac{V_{dd}-V_{in}}{R}$, and were as follows:

- $1k$ Ohms,
- $10k$ Ohms,
- $100k$ Ohms.

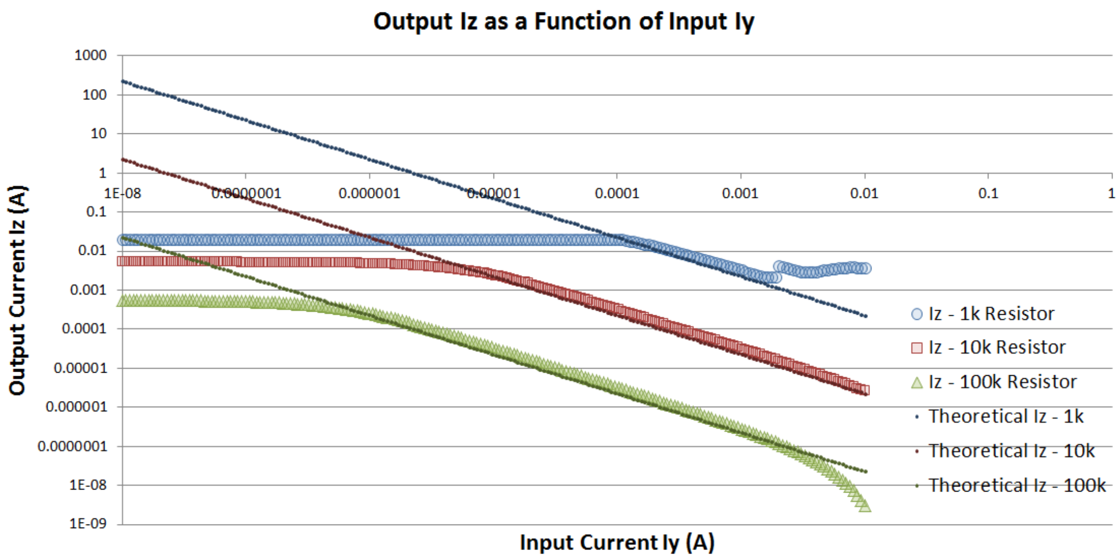

Figure 9: A log-log plot of the output current I_z as a function of the input current I_y, as the other input current I_x was varied across three values.

Figure 9 shows a plot of the output current I_z as I_x was swept. Again, we plotted these measured output current values, and then compared them to the expected theoretical output current values. As shown in the graph, our measured current values are very close to the expected current values within a certain range of current. This range changes with the resistor value used for the current source; the 100kΩ resistor-based source worked from 1μA onward, the 10kΩ based source worked from 10μA onward, and the 1kΩ based source worked from 100μA onward.

4 Discussion

In this lab, we were able to characterize four BJTs on a MAT14 array chip, examine the behavior of these matched transistors, and use them to construct two translinear circuits.

Experiment 1 allowed us to demonstrate how matched transistors had very close current gain and saturation current values–the characteristics that allow them to be used for translinear circuits.

Experiment 2 was an investigation of a square-rooting translinear circuit as two of the input currents were swept in turns. Experiment 3 was similar, instead investigating a squaring translinear circuit. Our physical circuits behaved as we theorized in the prelab, within certain current ranges, which usually changed depending on the resistor value used in the source/sink of the varied input current.