Circuits Lab 4

Daniel Connolly
William Fairman

March 14, 2019

1 Experiment 1: Bipolar Transistor Matching

For the first experiment, we measured the characteristics of a MAT14 quad NPN transistor array. This included finding the forward current gain(β), saturation current(I_s), and collector current(I_c) versus base voltage(V_b) relationship for all four transistors on the MAT14 chip. We also included figures comparing the values of each transistor within the transistor array chip.

1.1 Circuit

The following circuit diagram depicts the SMU setup we used to measure the emitter current(I_e) versus V_b. We repeated this measurement for each of the transistors within the integrated circuit. Pin 4, and subsequently pin 11, were connected to ground per the recommendation from the datasheet.

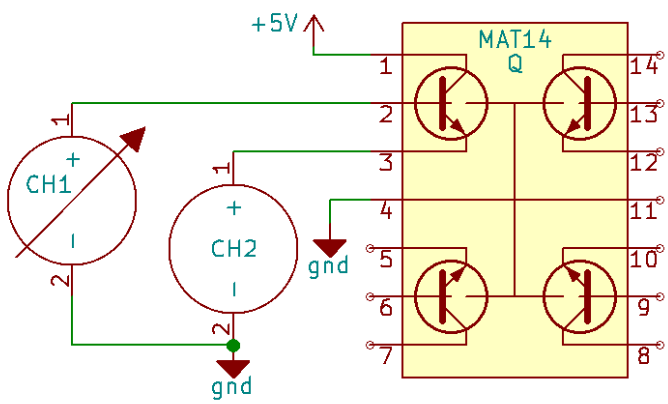

Figure 1: The setup used to measure the characteristics of a single transistor within the MAT14. This circuit was repeated for each of the transistors in the array.

1.2 Observations

From the previous lab we found that $I_c = I_e - I_b$ can be used to calculate the value for I_c. With I_c we can now calculate the values I_s from our I_c versus V_b plots.

$$\begin{aligned} I_c &= I_s * e^{\frac{V_b}{U_T}} \\ \ln I_c &= \ln I_s + \frac{V_b}{U_T} \\ \ln I_s &= \text{y-intercept} \end{aligned} \tag{1}$$

The forward current gain(β) is the relationship between I_c and I_b and is calculated as $\beta = \frac{I_c}{I_b}$. Table 1 shows the values of β and I_s for all four of transistors.

Q	β	I_s	U_T
Q1	600.69	2.83x$10^{-13}A$	26.7mV
Q2	598.16	2.13x$10^{-13}A$	26.6mV
Q2	597.47	2.29x$10^{-13}A$	26.6mV
Q2	597.86	2.81x$10^{-13}A$	26.7mV

Table 1: The values of β and I_s for each of the four transistors on the MAT14 transistor array.

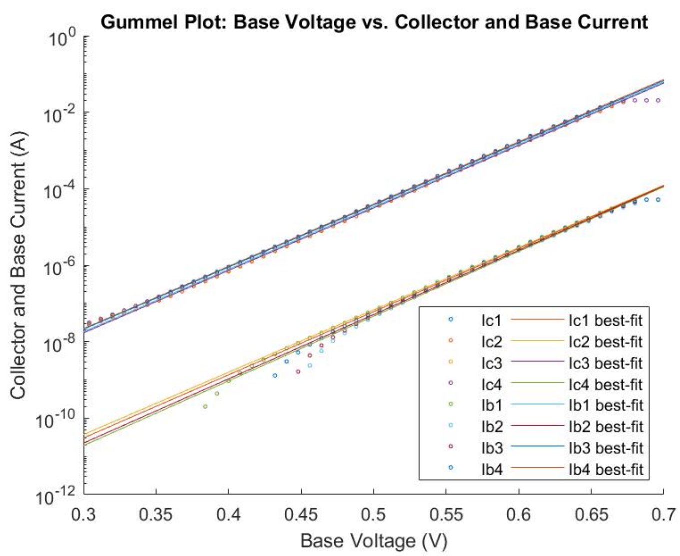

Figure 2: A Gummel Plot showing the base collector and base currents as a function of base voltage for each of the four transistors on the MAT14. In the legend, I_{c1} represents the collector current of the first transistor, and I_{b2} represents the base current of the second transistor.

As the Gummel Plot in Figure 2 displays, the I-V characteristics of the four transistors are remarkably similar. Throughout the range of base voltages between 0.3V and 0.8V, the collector and base currents are related exponentially to the base voltage. Our straight-line approximations, made using Matlab's polyfit function, to these exponential regions, further confirm the relationship between the currents and base voltage. From these straight-line fits, we obtained the values for I_s and U_T shown in Table 1. The four transistors exhibit matching I-V characteristics over the range of base voltages from $[0.3V, 0.7V]$ for their collector currents and from $[0.5V, 0.7V]$ for their base currents.

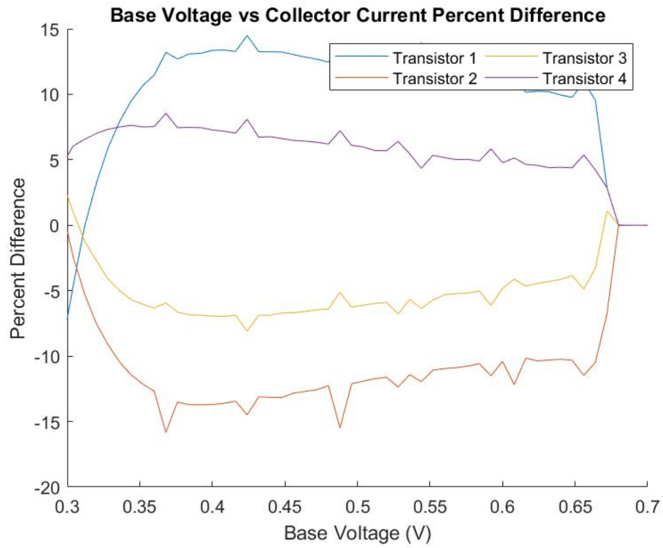

Figure 3: Plot showing the percentage difference between each transistor's collector current and the mean value of all four collector currents as a function of base voltage. The bumps occur as the SMU "changes gears," so to speak, as it adjusts the current and voltage it is supplying.

$$\text{Percent Difference Qn} = \frac{I_{c,n} - I_{c,mean}}{I_{c,mean}} \text{ x } 100 \tag{2}$$

In Figure 3, we plotted the the percent difference between each collector current and the mean collector current as a function of base voltage. We calculated this percent difference using Equation 2. As we can see, all of the transistors' collector currents remain within fifteen percent of the mean at all times, with two above and two below the mean at any given base voltage, as we expected to see given their were no outliers on the Gummel Plot. As the base voltage approaches 0.7V, we observed the transistors leaving the region of exponential growth on the Gummel Plot, and we now see the percent differences converging to zero as the collector currents perfectly match each other outside of the exponential region of the plot.

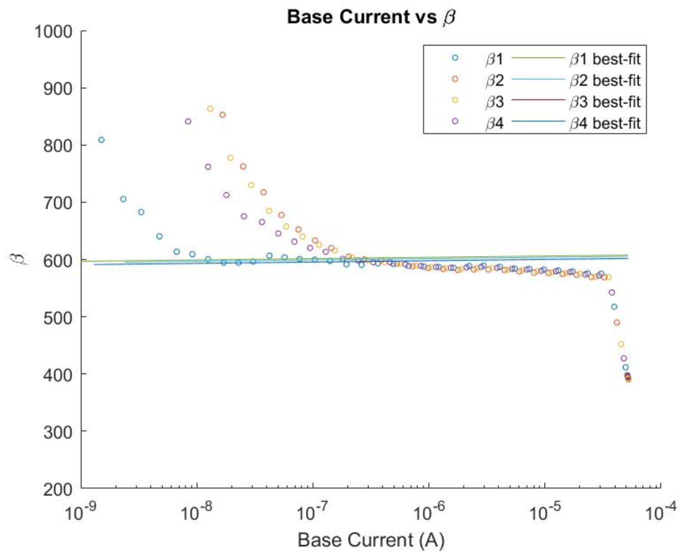

Figure 4: A plot showing forward current gain, β, as a function of base current for each of the four transistors.

$$\beta = \frac{I_{collector}}{I_{base}} \tag{3}$$

Our final plot in Experiment 1, shown in Figure 4, displays the values of the forward current gain, β, as a function of the base current. To obtain measured data points for β, we plugged our measured values of the base and collector currents into Equation 3. We then used Matlab's polyfit function to calculate the slope and y-intercept of a line of best fit for each measurement. After plotting the lines of best-fit and finding their slopes, we approximated β to be constant and equal to the y-intercepts of the lines, yielding the values shown in Table 1. All four β values are within three of each other and near the typical current gain for the MAT14, which is 600 according to its data-sheet, further indicating that the transistors on the MAT14 match one another rather well. Though the current gain is not actually constant with base current, we can reasonably assume it to be constant over the interval $[10^{-7}A, 10^{-4}A]$ for the base current. Additionally, it appears that our first transistor's ($Q1$) forward current gain is actually constant from when the base current is equal to $10^{-8}A$ to $10^{-4}A$, a slightly larger range than the other three transistors.

2 Experiment 2: Translinear Circuit 1

This experiment is focused on observing the current transfer characteristics of a translinear circuit made from four NPN transistors within a MAT14 chip. In order to observe the relationship between the output current(I_z) and input currents(I_x and I_y), we measured I_z while changing a singular input current and keeping the other input current at a constant current. This process was repeated for both I_x and I_y.

2.1 Circuit

This particular circuit is wired in a way to create the relationship in Equation 4 between the input and output currents, as calculated in the prelab assignment. As this relationship shows, the output current I_z is the geometric mean of the input currents.

$$\begin{aligned} I_z^2 &= I_x * I_y \\ I_z &= \sqrt{I_x * I_y} \end{aligned} \tag{4}$$

The schematic in Figure 5 reflects our setup to measure I_z while changing I_x with the SMU. The other input current I_y was connected to a current sink whose value is dictated by the R1 resistor and the voltage divider consisting of resistors R2 ($23.7k\Omega$) and R3 ($1k\Omega$). We used R2 and R3 to set the input to the positive terminal of our op-amp to 0.202V. Note that for purposes of our schematics, all resistor values are rounded to the nearest whole number. In this experiment we used three different R1 values to generate the 3 currents for I_y shown in Table 2. We measured these resistor values with the Keithley 2400 SourceMeter.

R1	I_y
497.2Ω	$407.14\mu A$
$4.975k\Omega$	$40.69\mu A$
$49.655k\Omega$	$4.08\mu A$

Table 2: The three resistor values we used to generate three currents that span two decades in our circuits for the first part of Experiments 2 and 3.

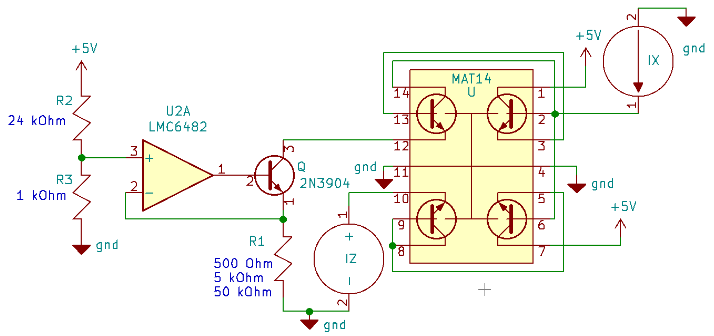

Figure 5: Translinear circuit used to measure I_z with respect to I_x. I_y was a constant value. We measured this circuit with three different values for I_y.

.

Similarly, Figure 6 exhibits our setup to measure I_z while changing I_y with the SMU. The other input current I_x was connected to a current source that had a value dictated by the R1 resistor and a potentiometer in series with the $1k\Omega$ resistor R2. Using the potentiometer, we adjust the input voltage to the positive terminal of the op-amp to be 3.47V, as measured with a handheld digital multimeter. We used the same three R1 values to generate the 3 currents for I_x shown in Table 3.

R1	I_x
497.2Ω	$3.1mA$
$4.975k\Omega$	$307.54\mu A$
$49.655k\Omega$	$30.813\mu A$

Table 3: The three resistor values we used to generate three currents that span two decades in our circuits for the second part of Experiments 2 and 3.

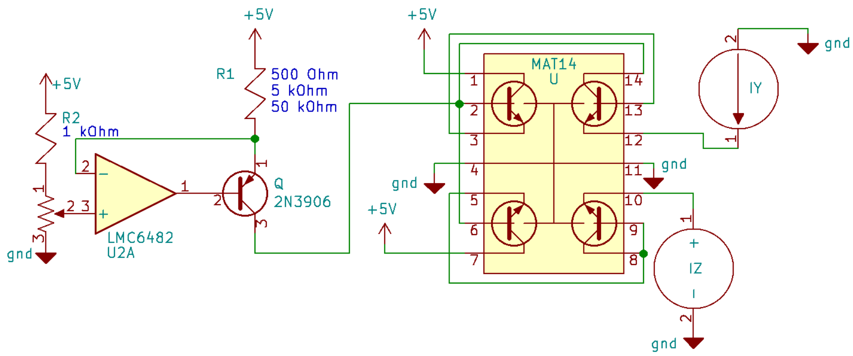

Figure 6: Translinear circuit used to measure I_z with respect to I_y. I_x was a constant value. We measured this circuit with three different values for I_x

2.2 Observations

Our first plot, shown in Figure 7, displays a current transfer characteristic in which we held I_y fixed at three unique amperages spanning two decades and swept I_x over the range $[10^{-8}A,10^{-2}A]$. As we can see in the figure, as we raise the value of I_y by each successive decade, we increase the value of I_x required for the data to follow the theoretical fit, calculated with Equation 5 where $V_{in} = 0.202V$, by approximately one decade. Each of the data-sets collected for each value of I_y follow the theoretical fit for approximately four and one half decades of current before peeling off on either end. Additionally, we can see that the theoretical fits each have a slope of one half, as expected from Equations 6 through 8.

$$I_y = \frac{V_{in}}{R1} \tag{5}$$

$$\begin{aligned} I_z &= \sqrt{I_x * I_y} \\ log(I_z) &= log((I_x * I_y)^{\frac{1}{2}}) \end{aligned} \tag{6}$$

$$log(I_z) = \frac{1}{2}log(I_x * I_y) \tag{7}$$

$$log(I_z) = \frac{1}{2}log(I_x) + \frac{1}{2}log(I_y) \tag{8}$$

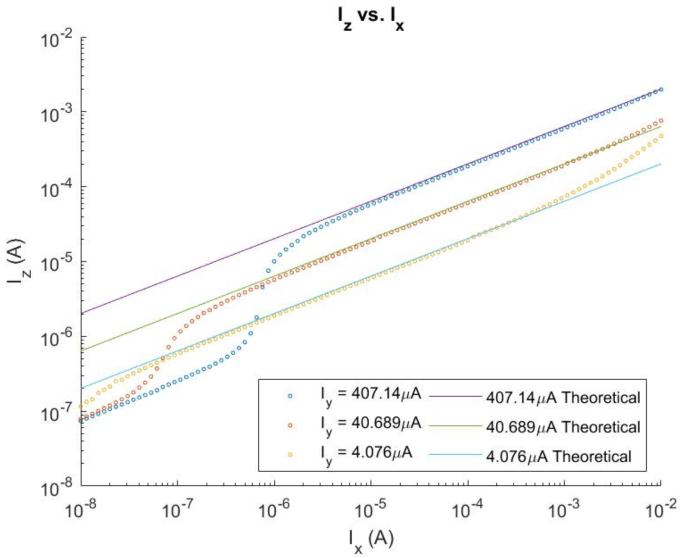

Figure 7: Plot showing I_z as a function of I_x for the circuit shown in Figure 5, which we used to calculate the output current to be geometric mean of the input currents I_x and I_y. The slopes of all three theoretical fits are 0.5.

Similarly, our second plot, shown in Figure 8, displays a current transfer characteristic in which we held I_x fixed at three unique amperages spanning two decades and swept I_y over the range $[10^{-8}A, 10^{-2}A]$. Again, as we raise the value of I_x by each successive decade, we increase the value of I_y required for the data to follow the theoretical fit, calculated with Equation 9 where $V_{in} = 3.47V$ and $V_{dd} = 5V$, by approximately one decade. In the case of when $I_x = 30.813\mu A$, the data follows the theoretical fit for approximately 3.5 decades of current before peeling off in the regions of higher and lower current. For our other two values of I_x, we observed unusual behavior in the regions of higher current, likely due to limitations in the SMU. Like Figure 7, the theoretical fits in Figure 8 all have slopes of one half. As a result, we know that this circuit did behave as expected from our prelab analysis.

$$I_x = \frac{V_{dd} - V_{in}}{R1} \tag{9}$$

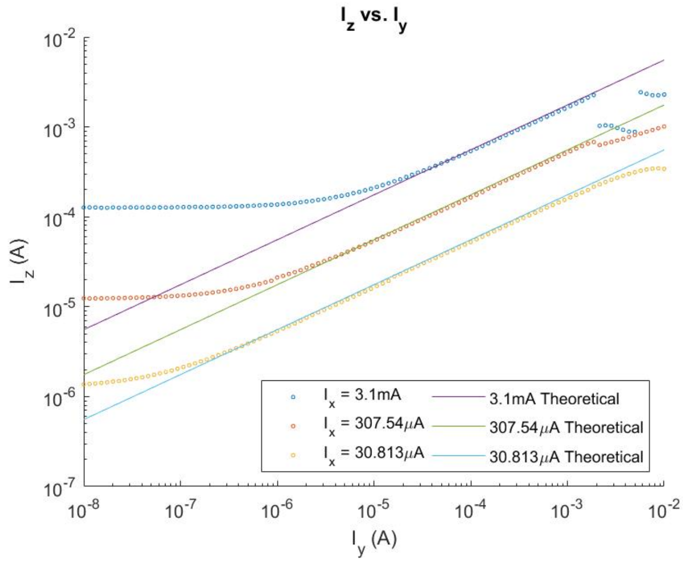

Figure 8: Plot showing I_z as a function of I_y for the circuit shown in Figure 6, which we used to calculate the output current to be geometric mean of the input currents I_x and I_y. The slopes of all three theoretical fits are 0.5.

3 Experiment 3: Translinear Circuit 2

As in Experiment 2, this experiment is focused on observing the current transfer characteristics of a translinear circuit made from four NPN transistors within a MAT14 chip. We measured and plotted the relationship between the output current(I_z) and input currents(I_x and I_y) in order to better understand the behavior of the circuit.

3.1 Circuit

This particular circuit is wired in a way to create the relationship in Equation 4 between the input and output currents, as calculated in the prelab assignment. In this circuit, the input and output currents follow the relationship in Equation 10, where the output current is the square of one input current multiplied by the reciprocal of the other.

$$\begin{aligned} I_x^2 &= I_y * I_z \\ I_z &= \frac{I_x^2}{I_y} \end{aligned} \tag{10}$$

The schematic in Figure 9 reflects our setup to measure I_z while changing I_x with the SMU. As in Experiment 2, we set the voltage at the positive terminal of the op-amp in our current sink to 0.202V with a simple voltage divider and adjusted the input current I_y by changing the R1 resistor. We utilized the same three different R1 values as in Experiment 2 to generate the 3 currents for I_y shown in Table 2.

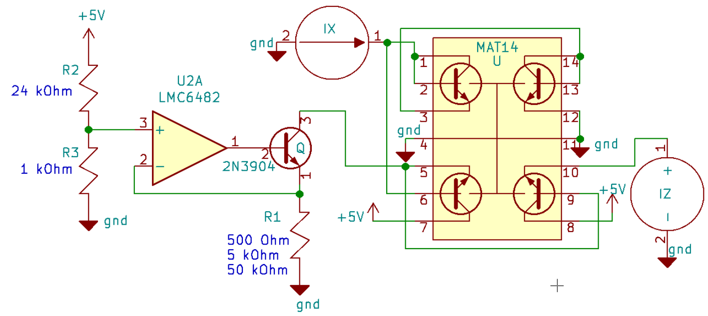

Figure 9: Translinear circuit used to measure I_z with respect to I_x. I_y was a constant value. We measured this circuit with three different values for I_y

.

Figure 10 shows our setup to measure I_z while changing I_y with the SMU. We adjusted the input current I_x by changing the R1 resistor and the potentiometer in series with the $1k\Omega$ resistor R2. We held the input voltage at the positive terminal of the op-amp at 3.47V, as measured with a handheld digital multimeter, for all data collection using the potentiometer. We used the same three R1 values to generate the 3 currents for I_x shown in Table 3, as we did in Experiment 2.

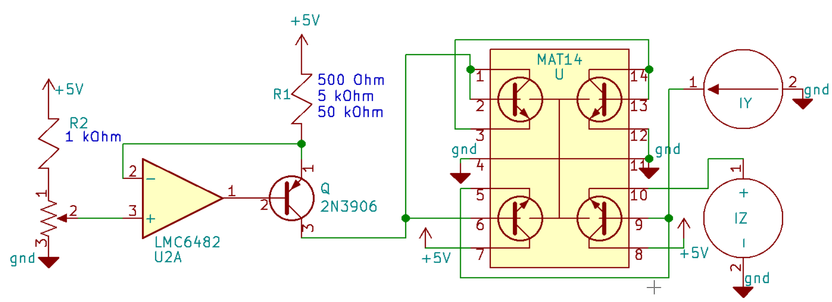

Figure 10: Translinear circuit used to measure I_z with respect to I_y. I_x was a constant value. We measured this circuit with three different values for I_x

3.2 Observations

Our first plot, shown in Figure 11, displays a current transfer characteristic in which we held I_y fixed at three unique amperages, specified in Table 2, spanning two decades and swept I_x over the range $[10^{-8}A, 10^{-2}A]$. From Equations 11 through 14, we observe that the theoretical fits to this plot have a slope of two, which matches the data we collected.

$$I_z = \frac{I_x^2}{I_y} \tag{11}$$

$$log(I_z) = log(\frac{I_x^2}{I_y}) \tag{12}$$

$$log(I_z) = log(I_x^2) - log(I_y) \tag{13}$$

$$log(I_z) = 2log(I_x) - log(I_y) \tag{14}$$

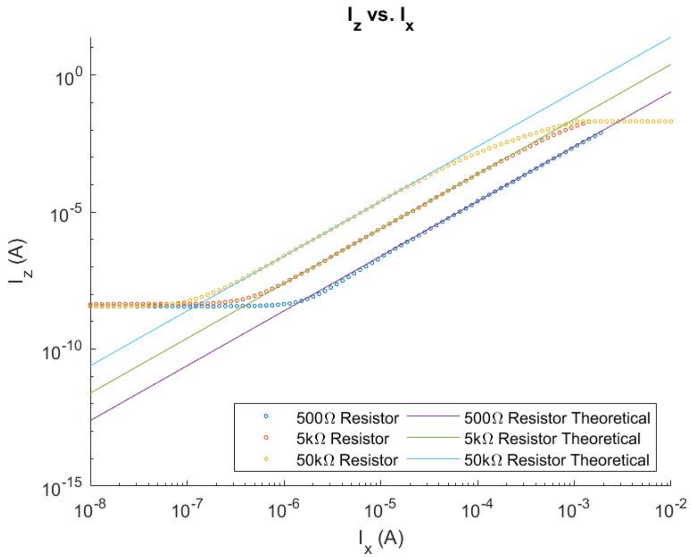

Figure 11: Plot showing I_z as a function of I_x for the circuit shown in Figure 9, which we used to calculate the output current to be the square of one input current, I_x multiplied by the reciprocal of the other, I_y. The slopes of the theoretical fits are two.

Likewise, our second plot, shown in Figure 12, displays a current transfer characteristic in which we held I_x fixed at three unique amperages, specified in Table 3, spanning two decades and swept I_y over the range $[10^{-8}A, 10^{-2}A]$. From Equations 11 through 14, we observe that the theoretical fits to this plot have a slope of negative one, which matches the data we collected. Due to unusual behavior in the SMU at higher currents, the data somewhat diverges from our theoretical fits when we utilized the 500Ω resistor in our current source, but follows the theoretical fit elsewhere. As a result, we can see that this circuit did behave as expected from our prelab analysis.

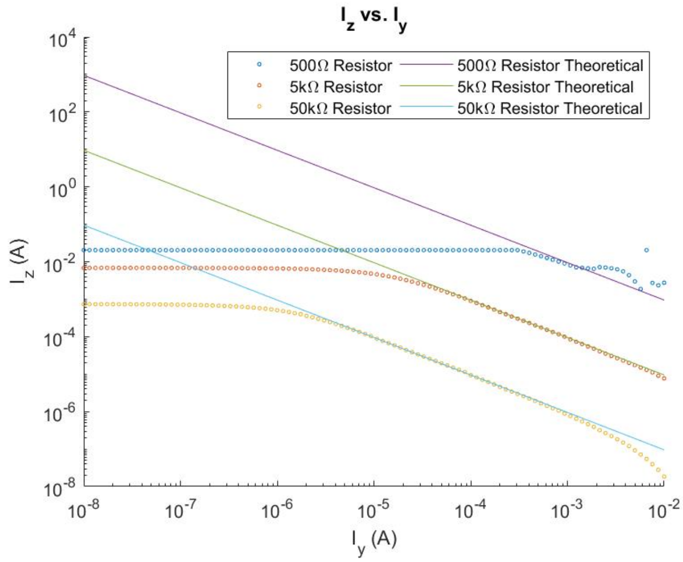

Figure 12: Plot showing I_z as a function of I_y for the circuit shown in Figure 10, which we used to calculate the output current to be the square of one input current, I_x multiplied by the reciprocal of the other, I_y. The slopes of the theoretical fits are negative one.