Circuits Lab 4

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3.3.13

Experiment 1

Our first experiment compared transistors on the same MAT14 transistor array. For each NPN transistor, we tied the collector to the +5V power rail and grounded the emitter. We swept the base voltage from .25V to .65V to characterize the transistor. We chose these values to sweep from a low current (one that the SMU could just barely source) to a current safely under the maximum the SMU could source. One way of measuring how well matched transistors are is to measure β and I_s. To do this, we calculated the collector current using KCL:

$$I_e = I_b + I_c$$

We then calculated β:

$$\beta = \frac{I_b}{I_c}$$

To calculate I_s, we used the following relationship:

$$I_c = I_s e^{\frac{V_{be}}{U_t}}$$

Where V_{be} is the base-emitter voltage that we sourced with the SMU. The results of our calculation are summarized in the table below.

β	I_s
875.52	$2.01 * 10^{-13}$
875.64	$2.07 * 10^{-13}$
877.97	$2.10 * 10^{-13}$
875.66	$2.07 * 10^{-13}$

Beta is very consistent across the four transistors. We calculated the standard deviation of β to be 1.18, which is about .1%. The standard deviation of I_s is $3.78*10^{-15}$, which is about 3.6%. These deviation values suggest that the transistors in the MAT14 transistor array are very well matched. To further investigate β across all 4 resistors, we plotted β as a function of base voltage in figure 1. The plot shows that β is well matched across all operation regions of the transistors.

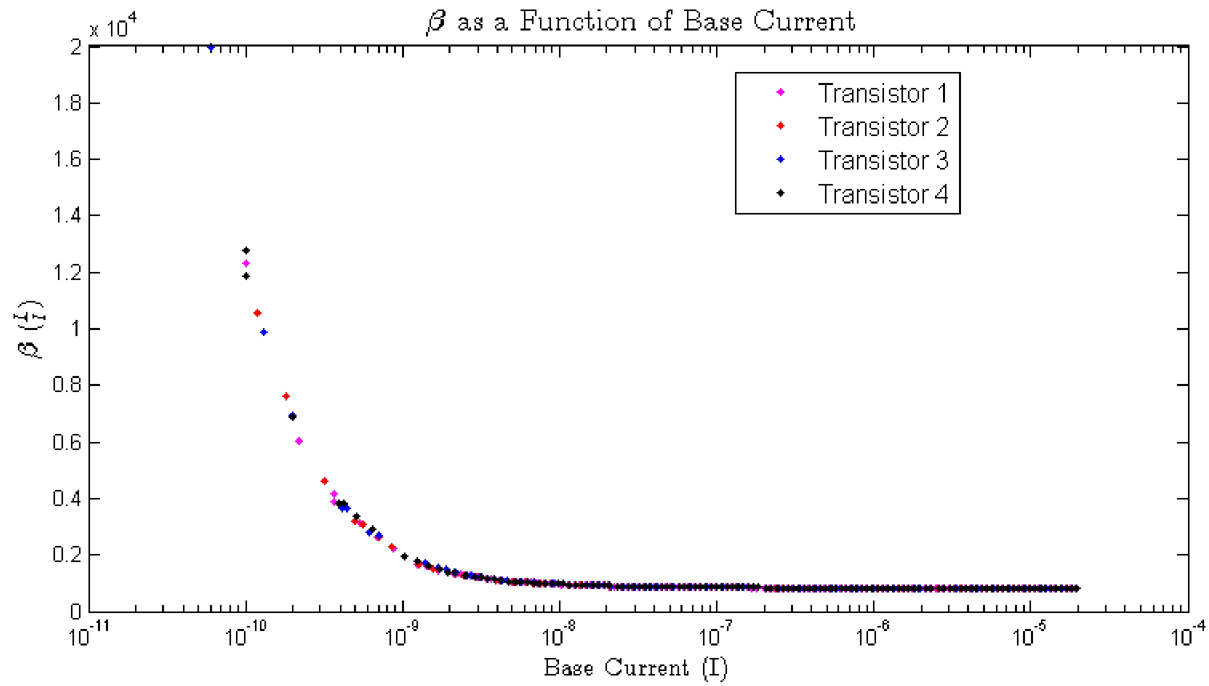

Figure 1: β as a function of V_{be} across all 4 devices.

To better illustrate the slight differences between the 4 β values, we zoomed into the previous plot. Figure **??** shows that the β values are different, but they fluctuate by less than 10 in this region. Further, the values are generally consistent with our table, i.e. $\beta_3 > \beta_4 > \beta_2 > \beta_1$.

exp1c2.png

Figure 2: β as a function of I_b across all 4 devices, zoomed in to show slight differences between transistors.

Next, we wanted to investigate the similarity of currents between the devices. Figure 2 shows the base and collector currents for all 4 transistors on the same plot. The currents are almost identical.

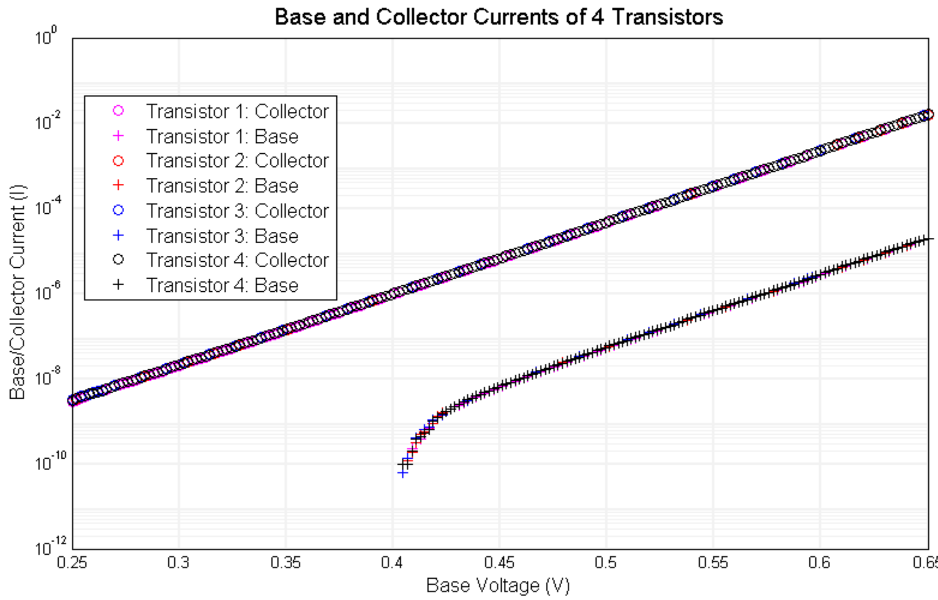

Figure 3: The base and collector currents of all 4 transistors in response to a base voltage sweep.

The similarity of the transistors' currents is better illustrated in figure 3. This plot shows the percentage difference of each transistor's collector current from the mean value. The collector currents are within a 2% tolerance of the mean.

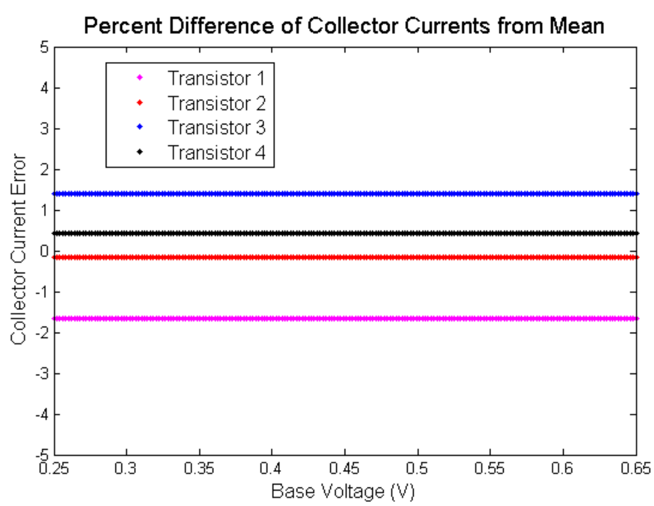

Figure 4: The percent error between each transistor's collector current and the mean value.

This experiment confirms that the transistors on the MAT14 are relatively very similar. This allows us to carry on with our experiments under the assumption that all 4 transistors are well matched.

Experiment 2

In experiment 2, we analyzed the first translinear circuit, shown in Figure 4.

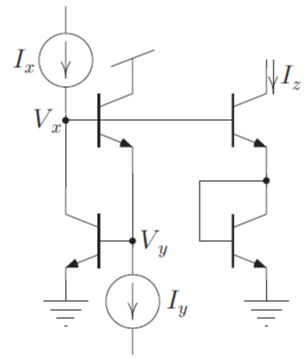

Figure 5: Translinear circuit 1.

Configuration 1: Sweeping I_x

For our first configuration of the first circuit, we held the current I_y constant using a current sink that we made using the circuit shown in Figure 5. We sourced I_x using the SMU and measured the current I_z with the SMU as well.

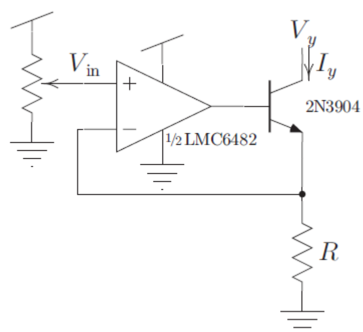

Figure 6: Our current sink.

The Current Sink

We held that current sink constant by choosing our V_{in} and our R values such that we could produce a wide range of currents. We knew from our prelab that the voltage at the base of the bottom-left transistor, V_y, will be approximately .6 V in forward-active mode. Since the voltage will wiggle around .6 V, we needed the sink collector voltage, held at V_{in} by the op-amp, to be underneath that by at least $V_{CEsat} \approx 200mV$, so we chose a voltage that was well underneath it, .1 V.

We generated .1 V at V_{in} by using a voltage divider with resistor values 200 Ohms and 10k Ohms. Since our voltage source was 5 V, our resulting voltage at V_{in} was .1 V.

We used that voltage to generate a current through the current sink. To generate 10 uA, by Ohm's law, we needed a resistor with resistance 10k Ω; for 100 uA, 1k Ω; for 1 mA, 100 Ω.

Measurement

We held I_y constant and used the SMU to sweep I_x over several orders of magnitude of current. We did this for three values of I_y that scaled three orders of magnitude.

From our prelab, we expect that this translinear circuit obeys the equation $I_x I_y = I_z^2$. As a result, when we hold I_y constant, we expect $I_z = \sqrt{I_x I_y}$.

Our experiment result, and our theoretical expectation, are shown in Figure 6.

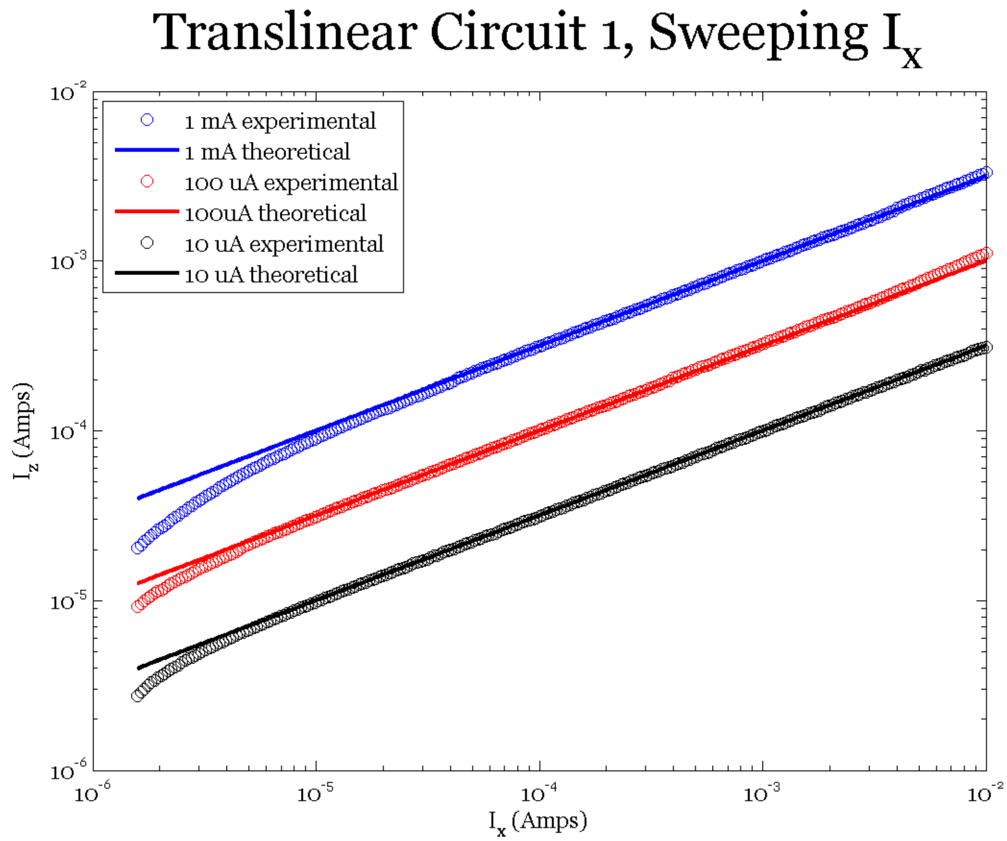

Figure 7: Translinear circuit 1, holding I_y at the values shown in the legend.

Error Analysis

In general, this circuit behaves as we would expect from our analysis. For many decades, we see the expected line. However, in the low-current regions, we see that the current deviates from that line. This could be the SMU, but I believe a SMU issue would look noisy, and this looks smooth. Our current sink might not be in forward-active mode, but we chose our voltages such that we can almost guarantee forward-active mode, so I believe it is not that. A feasible explanation is that this is the small-signal Early effect, which makes the transistor linear, rather than exponential, in the small signal region - which would appear logarithmic on a loglog plot, which is similar to what we see here. As the current increases, this becomes negligible.

Configuration 2

Next, we took the same circuit from before and replaced the current sink with one channel of the SMU, such that we could sweep I_y, and held I_x constant with a current source that we built. Our current source is shown in Figure 7.

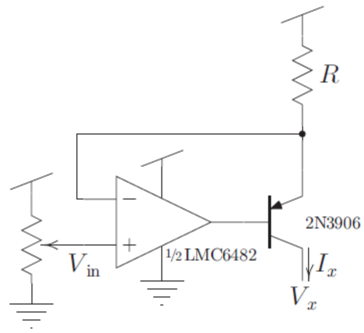

Figure 8: Our current source.

The Current Source

We chose appropriate values of V_{in} and R such that we could sweep our I_y over several orders of magnitude, as in configuration 1.

For our voltage divider, we used a 2k Ω and a 3k Ω resistor to generate a voltage divider ratio of .4, and an output voltage of 3 Volts.

From the prelab, we know that our output current is $\frac{5-V_{in}}{R}$. To generate 1 uA, we used a 2 MΩ resistor; for 10 uA, 200 kΩ; for 100 uA, 20 kΩ.

Measurement

Again, we expected, from the prelab, that $I_z = \sqrt{I_x I_y}$. Our results are shown in Figure 8.

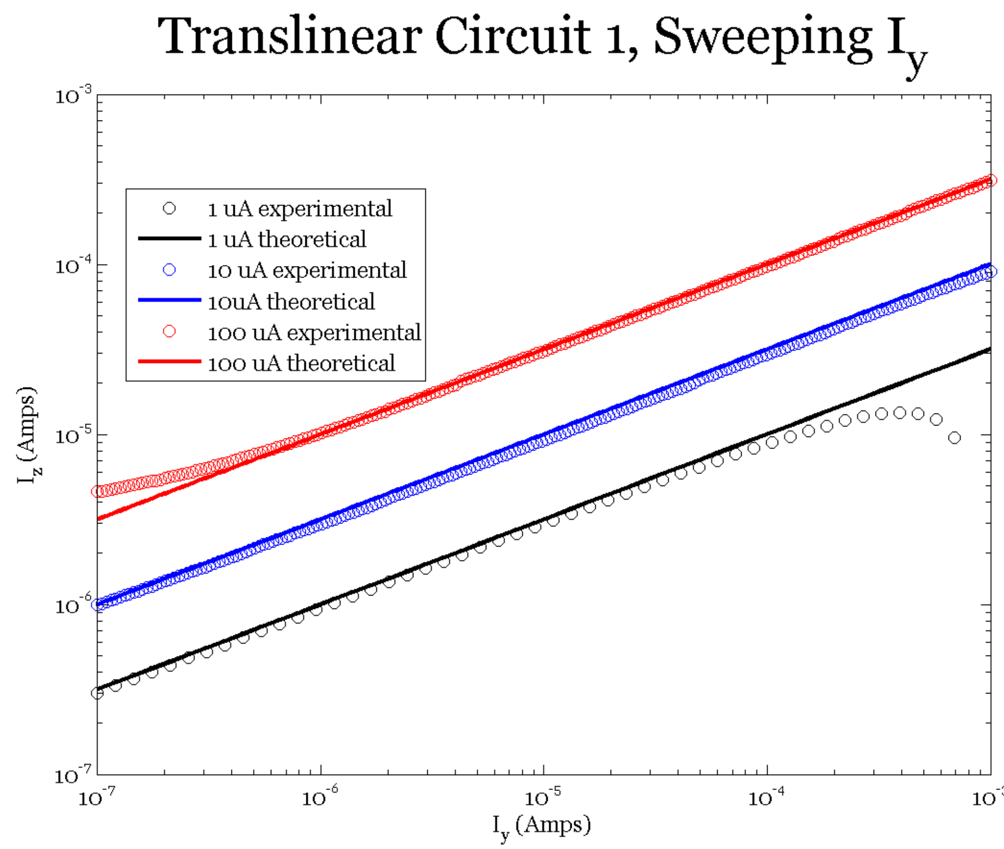

Figure 9: Translinear circuit 1, holding I_x at the values shown in the legend.

Error Analysis

This circuit behaved well for almost all I_x for all except one measurement. For that measurement, ith a high I_y we found that our circuit produced a very strange I_z for a low value of I_x. We think we might have actually damaged a transistor during that measurement, because we were unable to take another measurement with a higher data rate without the output current becoming completely unstable.

Translinear Circuit 2

We then repeated the experiments with a slightly different circuit, shown in Figure 9.

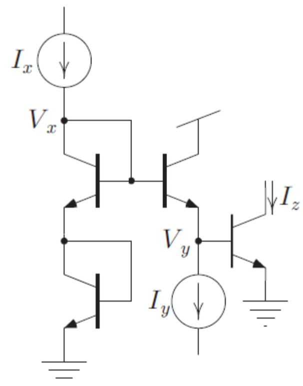

Figure 10: Translinear circuit 2.

As we did before, we used one channel of the SMU to sweep one of the currents in the circuit while holding the other current constant using current source or sink we built.

Configuration 1

In the first configuration, we held I_y constant with our hand-built current sink and swept I_x with the SMU.

The Current Sink

This current sink was almost identical from the current sink we used in Translinear Circuit 1, but we desired a slightly different range of currents to make the transistors behave over three decades. We used the same voltage divider to generate .1 V, but used a 200 kΩ resistor to generate 500 nA; for 5 uA, 20 kΩ; for 50 uA, 2 kΩ.

Measurement

From the prelab, we expect this circuit to follow $I_x^2 = I_z I_y$. As a result, holding I_y constant should yield $I_z = \frac{I_x^2}{I_y}$, which means that I_z will increase linearly on a log-log scale as we sweep I_x. Our results are in Figure 10.

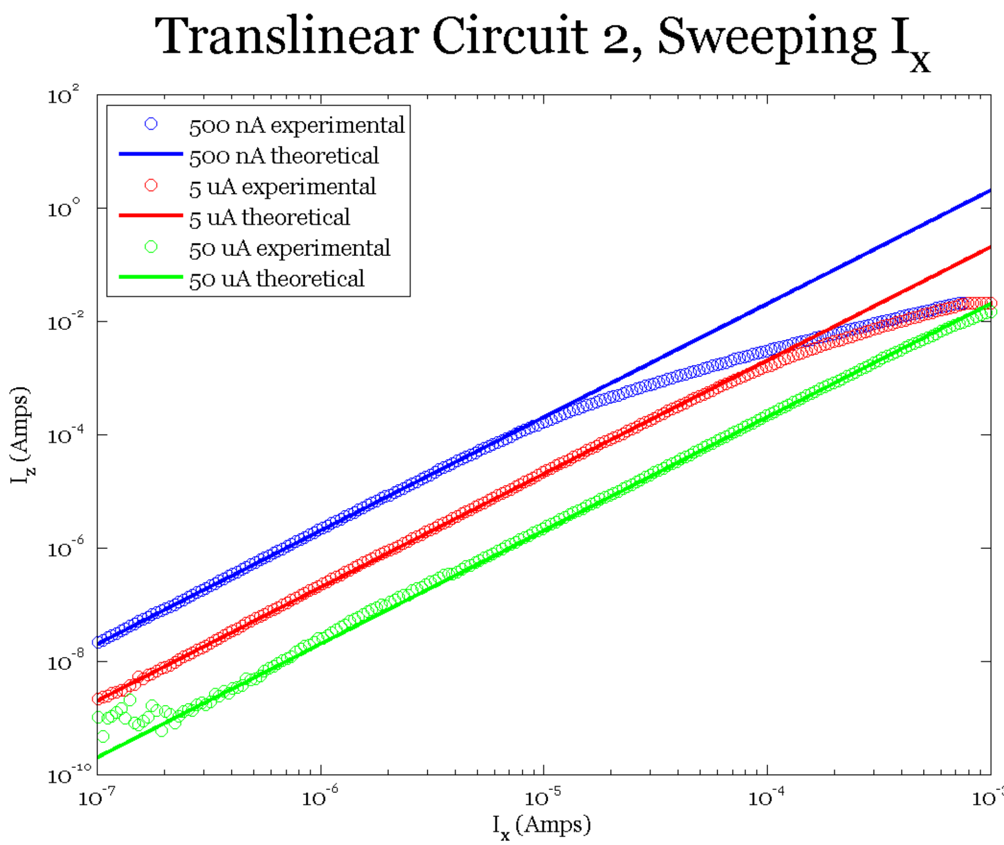

Figure 11: Translinear circuit 2, holding I_y at the values shown in the legend.

We swept over a high dynamic range (five orders of magnitude) and found that the data matched the theoretical expectation very well for the majority of the range of our input current values.

Error Analysis

We found that decreasing I_y caused the current to increase more slowly as we increased I_x, and that this effect seems to depend, on first glance, on I_y. There are many possible explanations for this error. We could chalk it up to the SMU, however the SMU would most likely create ugly, noisy data (like in the small-current region of the 50 uA measurement, which is almost certainly a SMU issue). This error is continuous and smooth, so is probably a circuit characteristic.

Another explanation is that our chosen current sink voltage is too low, and thus the current sink is not pulling enough current, however our choice of voltage should have protected us from any possible voltage that this circuit could produce.

Another explanation is a compounding Early effect. This would involve some or all of the transistors having an Early effect that adds up, causing the translinear property to hold a little less well. This might be reasonable.

However, we can get a deeper understanding by looking critically at the data itself. Though it seems that the effect is I_y dependent, on closer inspection, all of the data appears to flatten into a particular line when it intersects that line. It turns out that that line has slope 1, as seen in Figure 11.

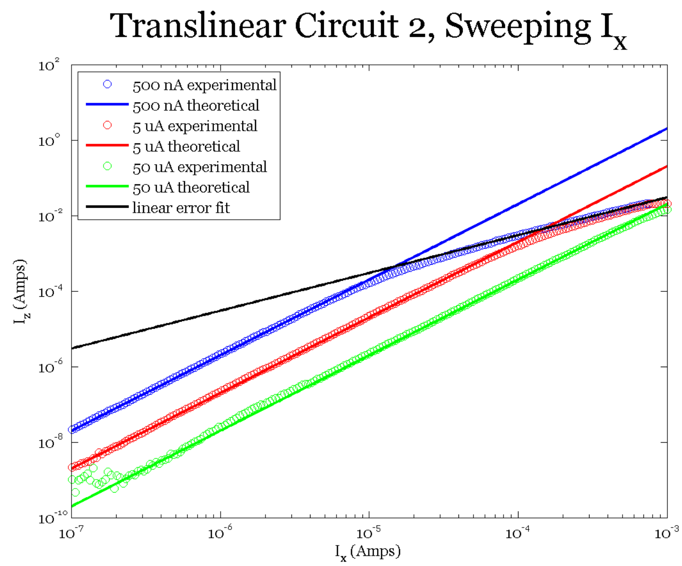

Figure 12: Translinear circuit 2, with a best-fit line plotted on the error region.

In the log-log plot, this best-fit line has a slope of 1, meaning that is just a shifted version of I_x. This means that the output current, Z, no longer has a squared relationship with I_x but rather a linear one. This is interesting, but still confusing. It may be that our transistors are not perfectly matched and have trouble squaring the current after the output needs to be higher than the input. Honestly, we don't know for sure.

Configuration 2

We then switched our circuit around such that our current source was holding I_x constant and the SMU swept I_y over a high dynamic range. Again, we expect $I_z = \frac{I_x^2}{I_y}$, which means that I_z should decrease linearly on a log-log scale as we sweep I_y.

The Current Source

We used a similar current source to the one that we used in Translinear Circuit 1. However, we swept over a slightly tighter dynamic range (about one and a half orders of magnitude). To generate 22 uA, we used a 90 kΩ resistor; for 10 uA, 200 kΩ; and for 100 uA, 20 kΩ.

Measurement

Our results can be seen in Figure 12.

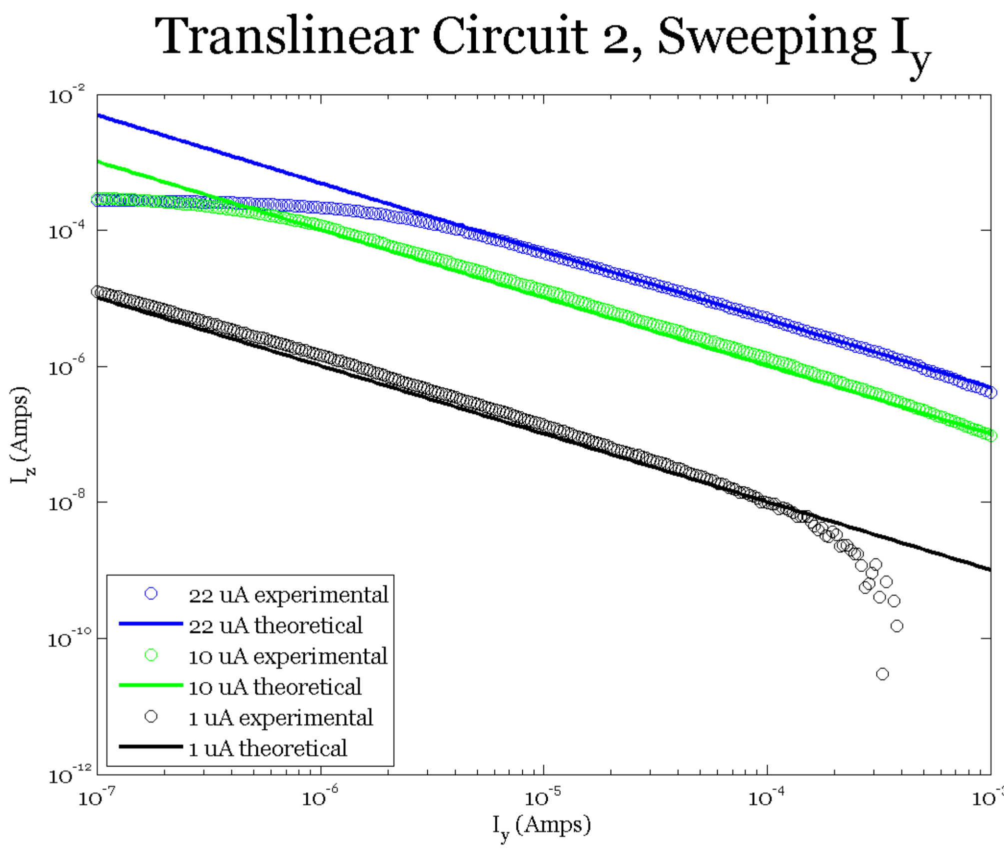

Figure 13: Translinear circuit 2, holding I_x at the values shown in the legend.

Error Analysis

This was our worst-behaved configuration. We found that we if we increased I_x above 20 uA, I_z was dominated by the non-linear region we discussed at length in configuration 1. If we decreased I_x to less than 100 uA, we found that I_z was very noisy for large input values, which we believe is SMU noise: the measured currents are very low, in the tens of nanoamps, and this is difficult to measure. As a result, we only measured I_y for I_x at values of 22 uA, 10 uA, and 100 uA because these produced a reasonable response over a reasonable range of currents.