The Bipolar Junction Transistor (BJT): DC and AC Characterization

Ghassan Arnouk

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Instructor: Qi-Jun Zhang

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1 Introduction

1.1 Purpose

The purpose of this lab is to explore the device characterization of a Bipolar Junction Transistor (BJT). This process helps to obtain important device parameters which allows the designer to obtain information that the datasheet might not have and compare the results.

1.2 Experiment Overview

In day 1, the DC characterization of the transistor was analyzed. Data were measured and the I-V curves of the transistor were generated. As well, a current mirror circuit was assembled and tested which has given an idea of the way they work and where their limitations are.

In day 2, the AC characterization of the transistor was analyzed. Data were obtained with performing medium and higher frequency measurements. Then, useful parameters were calculated using the obtained measurements.

2 Background

2.1 BJT Construction

The basic structure, symbol, and practical structure for both the PNP and NPN bipolar junction transistor are given in Figure 1 below. The BJT is a three-terminal semiconductor device containing two PN junctions that can act as either an insulator or a conductor by the application of a small signal voltage [1]. The PN junctions behave like two diodes of opposite polarity connected in series. The direction of the arrow always points from the positive P-type region to the negative N-type region which defines the direction of the current flowing through the transistor. The transistor's ability to change between an insulator state and a conductor state enables it to have two basic function such as switching and amplifications. The BJT can be used to amplify since the base is small enough to allow the two sets of PN-junctions to interact with each other.

Figure 1 below shows the Basic, Symbol, and Practical structure of a bipolar junction transistor.

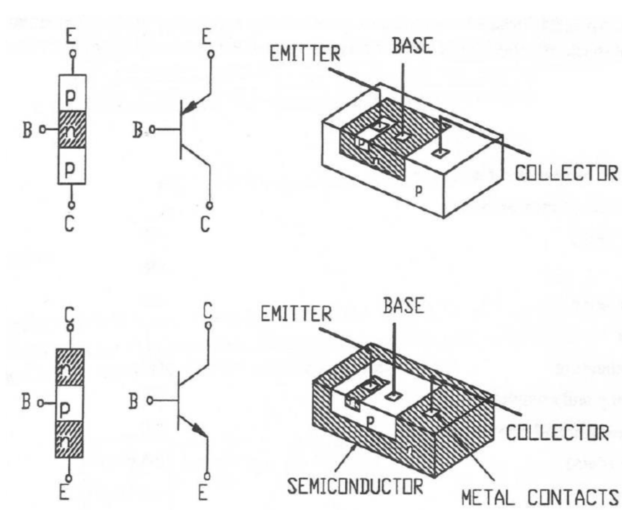


Figure 1: Different Structures of BJT [1]

2.2 BJT Operating Regions

As the BJT is a three-terminal device, there are basically three possible ways to connect it within an electronic circuit with one terminal being common to both the input and output. Figure 2 shows an example of an I-V curve of an NPN BJT transistor.
As observed in Figure 2, the effect of V_{CE} upon the collector current (I_C), when V_{CE} is greater than about 0.3 volts, is that I_C is largely unaffected by changes in V_{CE} and instead, it is almost entirely controlled by the base current [1].

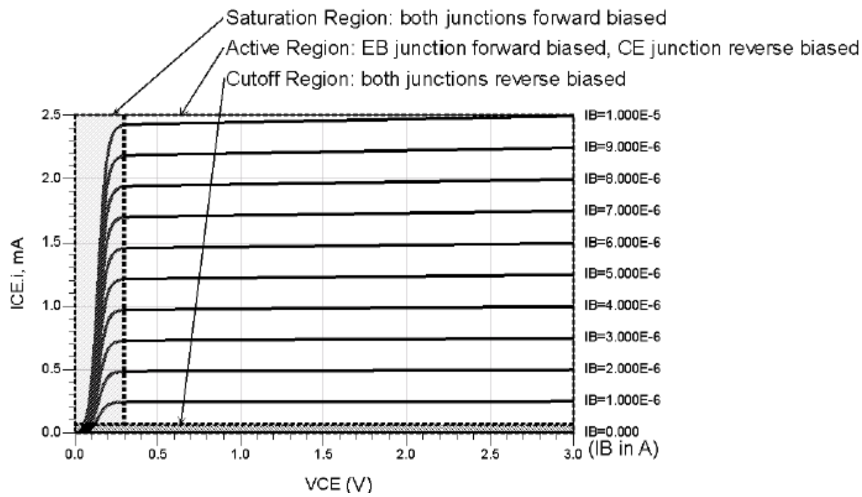


Figure 2: I-V Curves of a BJT Sweeping V_{CE} for different I_B [1]

Figure 3 below shows the opposite type of curve, with a plot of collector current as the base-emitter voltage is swept [1]. The collector-emitter voltage is held constant as this doesn't affect the family of curves significantly. As the collector-emitter voltage changes to another constant, i.e. 5 volts, the base current (I_B) is barely affected by the change of collector-emitter voltage (V_{CE}). However, the base-emitter voltage (V_{BE}) needs to be around 0.7 volts in order to forward the PN junction between the base and the emitter which results in increasing the base current (IB) and therefore, an increase in the collector current (I_C). It is important to notice that a small change in the base current (I_B) will have a significant change in the collector current (I_C).

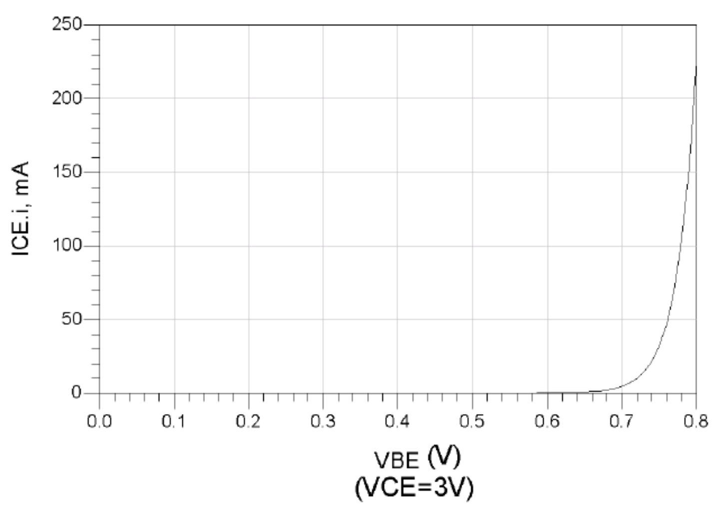


Figure 3: I-V Curves of a BJT Sweeping V_{BE} for a fixed V_{CE} [1]

2.2.1 Saturation Region

In this region, both BE and BC junctions are forward biased [1]. The collector-emitter voltage (V_{CE}) is small, a value of 0.2 volts or lower. However, a large collector and base currents (I_C and I_B) can flow.

2.2.2 Active Region

In this region, the BE junction is forward biased, but the BC junction is reversed biased [1]. That transistor is used in this region for amplification. Since the two junctions are very close together, the emitter emits carriers which shoot across the central base region and are collected by the collector region. This lets the collector current be controlled almost completely by the base-emitter junction voltage and is nearly independent on the collector node voltage [1]. They are governed by the following relation:

$$\beta = \frac{I_C}{I_B}$$

where,
β is the common-emitter current gain.
I_C is the collector current of the transistor.
I_B is the base current of the transistor.

2.2.3 Cutoff Region

In this region, both BE and BC junctions are reverse biased [1]. No current gain is available in this mode and there is a high resistance between the collector (C) and emitter (E) terminals.

Note that ***Multisim*** software was used to obtain all the presented data in this report.

3 BJT DC Characterization

3.1 Diode-Like Behavior of BJT Junctions, and BJT Type

Figure 4 illustrates the use of a Digital Volt Meter (DVM) on the *"diode"* setting to the measure the forward and reverse voltages of the B-E, B-C, and C-E junctions of both 2N3904 and 2N3906 transistors.

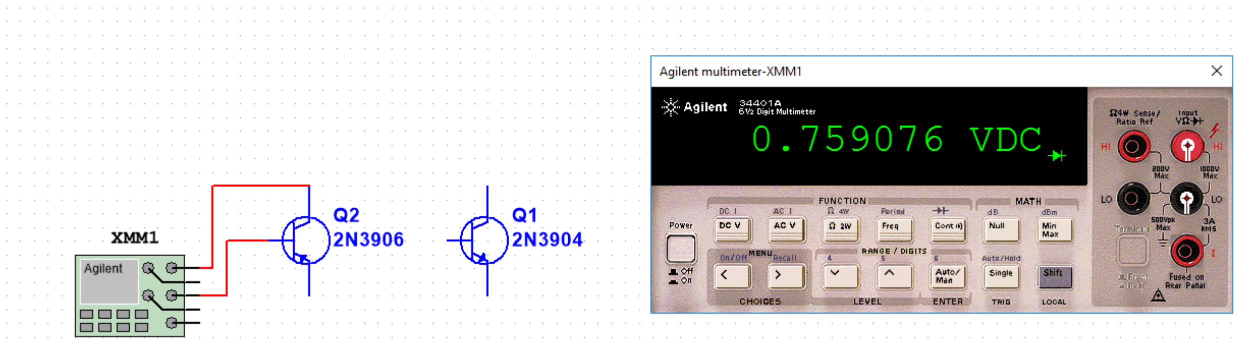


Figure 4: The Use of DVM to Measure Junction Voltages

The forward and reverse biases volatages are measured for both 2N3904 and 2N3906 transistors. Note that all collected data are measured in volts and can be seen in Tables 1 and 2 below.

Table 1: 2N3904 Transistor's Forward and Reverse Biases Voltages

2N3904		
VBE	VBC	VCE
0.689 V	0.668 V	—
VEB	VCB	VEC
—	—	—

Table 2: 2N3906 Transistor's Forward and Reverse Biases Voltages

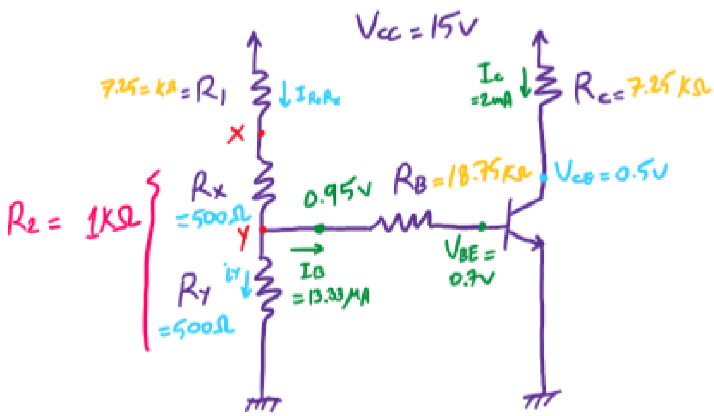
2N3906		
VBE	VBC	VCE
—	—	—
VEB	VCB	VEC
0.762 V	0.759 V	—

As observed from Table 1, the transistor is seen to have a base-emitter voltage, V_{BE}, of approximately 0.7 volts which means that the base-emitter junction is forward biased and acts as a diode when the transistor is in active mode. The transistor is also seen to have a base-collector voltage, V_{BC}, that is less than V_{BE} which means the the base-collector junction is reverse biased and acts like an open circuit blocking any current flow (only a very small leakage current). Due to that, the direction of the current is from the base to the emitter. Therefore, the 2N3904 transistor model is an NPN transistor.

As observed from Table 2, the transistor is seen to have an emitter-base voltage, V_{EB}, of approximately 0.7 volts which means that the emitter-base junction is forward biased and acts as a diode when the transistor is in active mode. The transistor is also seen to have a collector-base voltage, V_{CB}, that is less than V_{EB} volts which means the the collector-base junction is reverse biased and acts like an open circuit blocking any current flow (only a very small leakage current). Due to that, the direction of the current is from the emitter to the base. Therefore, the 2N3906 transistor model is an PNP transistor.

3.2 BJT I_C vs. V_{CE} Characteristic Curves -Point-by-Point- Plotting

3.2.1 Prelab Calculations



$I_C = 2mA$ $\quad R_1 = ?$

$V_{BE} = 0.7\ V$ $\quad R_B = ?$

$V_{CE,sat} = 0.5\ V$ $\quad R_C = ?$

$\beta = 150$

$V_{min,R} = 0.25V$

$R_x = 500\Omega$

$R_y = 500\Omega$

$$\alpha = \frac{\beta}{\beta+1} = \frac{150}{150+1} = 0.99$$

$V_B = 0.7\ V$

The voltage drop across a resistor is $0.25\ V$

The voltage across R_B is $0.25\ V$ leading to

$V_{Ry} = 0.7V + 0.25V = 0.95V$

$I_C = \beta I_B$

$$2mA = (150)\ I_B \rightarrow I_B = \frac{2mA}{150} = 0.01333mA = 13.33\ \mu A$$

$$\boxed{R_B = \frac{V_2 - V_1}{I_B} = \frac{0.95V - 0.7V}{13.33\ \mu A} = 18.75\ K\Omega}$$

$$I_{Ry} = \frac{V_Y - \phi V}{R_Y} = \frac{0.95V - \phi V}{500\Omega} = 0.0019\ A = 1.9\ mA$$

KCL @ Y :

$$I_{R_1R_x} = I_{RY} + I_B$$
$$= 1.9mA + 13.33\ \mu A = 0.00191333\ A = 1.91333\ mA$$

$$V_{Rx} = I_{R_1R_x} * R_x$$
$$= (1.91333\ mA)(500\Omega) = 956.665\ mV = 0.957\ V$$

$V_x = V_{Rx} + V_{Ry} = 0.957 + 0.95 = 1.907$

$$\boxed{R_1 = \frac{V_{cc} - V_x}{I_{R_1 Rx}} = \frac{15V - 1.907V}{1.91333\,mA} = 6.84\ K\Omega}$$

On the edge of saturation/active region: $V_{CE} = 0.5V$ with reference to the emitter at ϕV

$$\boxed{R_C = \frac{V_{cc} - V_{CE}}{I_c} = \frac{15V - 0.5V}{2mA} = 7.25\ K\Omega}$$

$$\boxed{V_{CE} = V_{cc} - R_c I_c}$$

Values of R_c in the Active Region:

Value of $R_c = 7.25 K\Omega$. However, 6.8$K\Omega$ will be used

$R\ (K\Omega)$

- ↳ 5.6
- ↳ 4.7
- ↳ 3.9
- ↳ 3.3
- ↳ 2.7

Values of R_C in the Saturation Region:

Value of $R_c = 7.25\,K\Omega$. However, $6.8\,K\Omega$ will be used

$R(K\Omega)$
↳ 8.2 $K\Omega$
↳ 10 $K\Omega$
↳ 12 $K\Omega$
↳ 15 $K\Omega$
↳ 18 $K\Omega$

3.2.2 Experiment

Figure 5 below illustrates the test circuit used in this part of the experiment.

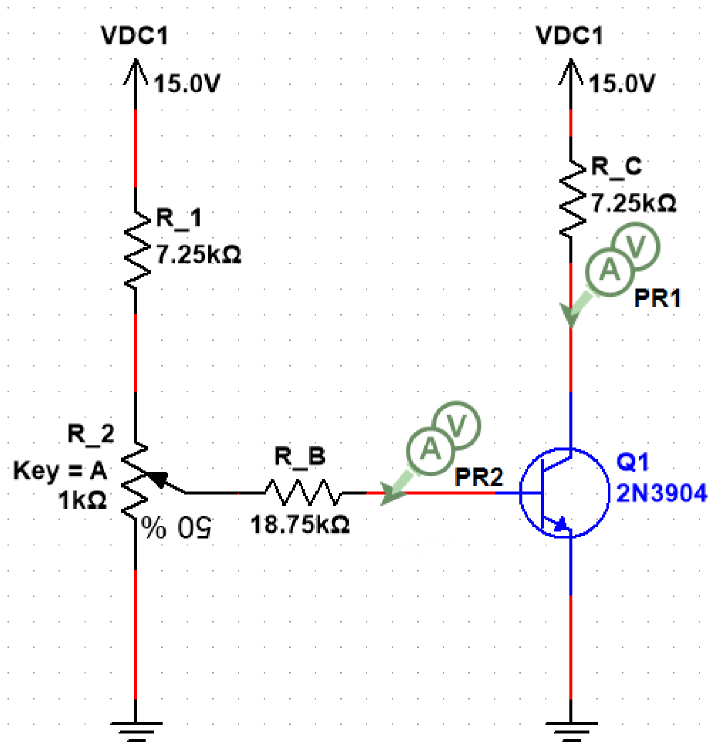


Figure 5: Test Circuit

Figure 6 below illustrates the DC operating sweep settings of the test circuit used in this part of the experiment.

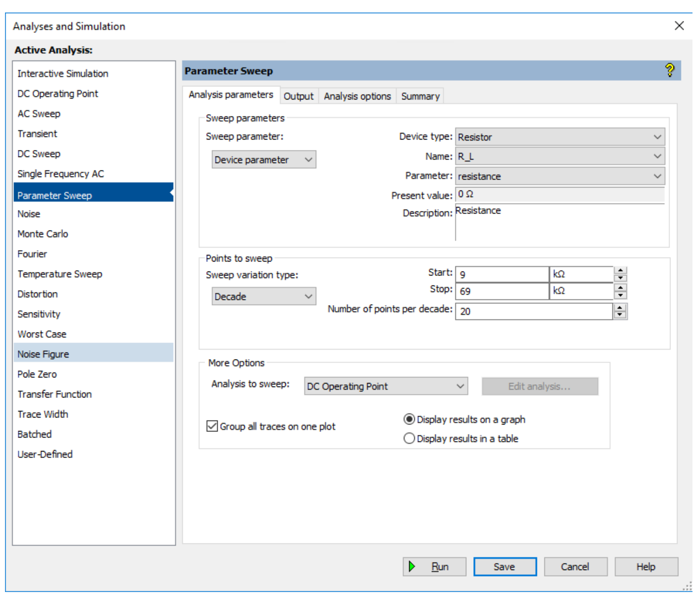


Figure 6: DC Operating Sweep Simulation Settings

Table 3 below shows the measured collector current, I_C,, the base-emitter voltage, V_{BE}, and the collector-emitter voltage, V_{CE}, for different collector resistance values, R_C. Also, the table shows the calculations of the current ration β for the transistor at each chosen R_C.

Table 3: Measured I_C, V_{BE}, and V_{CE} for Different R_C Values

VCE (V)	IC (mA)	RC (kOhm)	VBE (V)	IB (mA)	β = IC/IB
11.14596233	1.927018812	2	0.679638234	0.011938413	161.4133188
9.52855896	1.890132096	2.894736842	0.679638229	0.011938413	158.323565
7.971929818	1.854631419	3.789473684	0.679638224	0.011938413	155.3499105
6.472679747	1.820439347	4.684210526	0.67963822	0.011938413	152.4858692
5.02770941	1.787485196	5.578947368	0.679638215	0.011938414	149.7255205
3.634138732	1.755703282	6.473684211	0.679638211	0.011938414	147.0633622
2.289243544	1.725031475	7.368421053	0.679638207	0.011938414	144.4941904
0.990531616	1.695412937	8.263157895	0.679638203	0.011938414	142.0132439
0.221763425	1.61371632	9.157894737	0.67861823	0.011991483	134.5718673
0.189146002	1.4733356	10.05263158	0.676254851	0.01211445	121.6180352
0.174759748	1.354224763	10.94736842	0.674067281	0.012228269	110.7454172
0.165388998	1.252701041	11.84210526	0.672049811	0.012333238	101.5711398
0.158414856	1.165252272	12.73684211	0.670181033	0.01243047	93.74160703
0.152852659	1.089171289	13.63157895	0.668441655	0.01252097	86.987771
0.148225015	1.022405935	14.52631579	0.666815981	0.012605554	81.10757675
0.144261415	0.963338488	15.42105263	0.665290224	0.012684939	75.94348586
0.140795755	0.91072489	16.31578947	0.663853484	0.012759693	71.37514388
0.137716833	0.863559148	17.21052632	0.662496106	0.012830317	67.30614348
0.134947075	0.821033375	18.10526316	0.661209891	0.012897239	63.65962548
0.132430983	0.782503866	19	0.659988229	0.012960802	60.37465057

Figure 7 below shows the plot of I_C-V_{CE} line for the base current that was held constant.

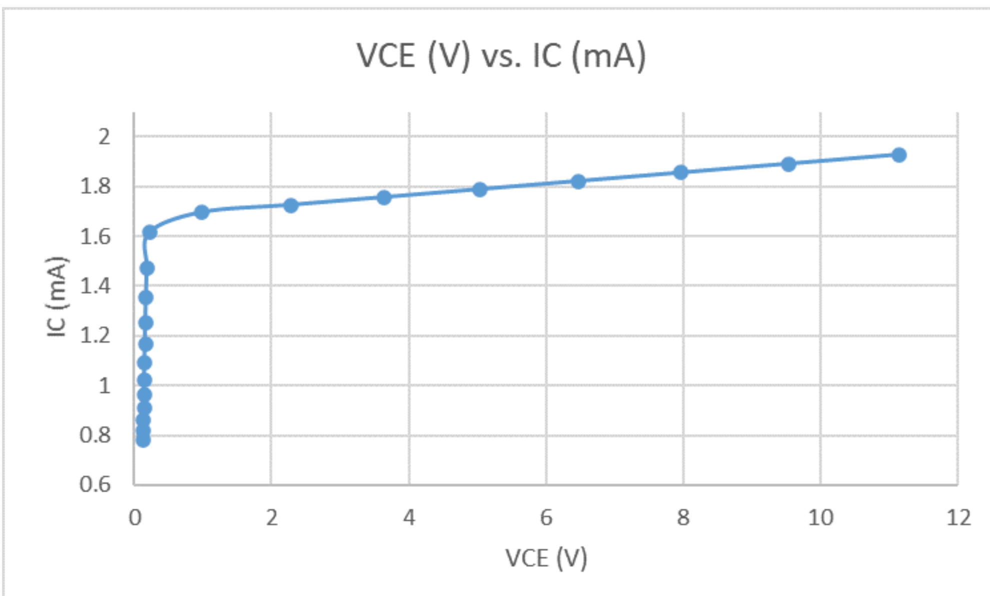


Figure 7: Collector-Emitter Voltage vs. Collector Current

Figure 8 below shows the plot of V_{BE} vs. V_{CE}.

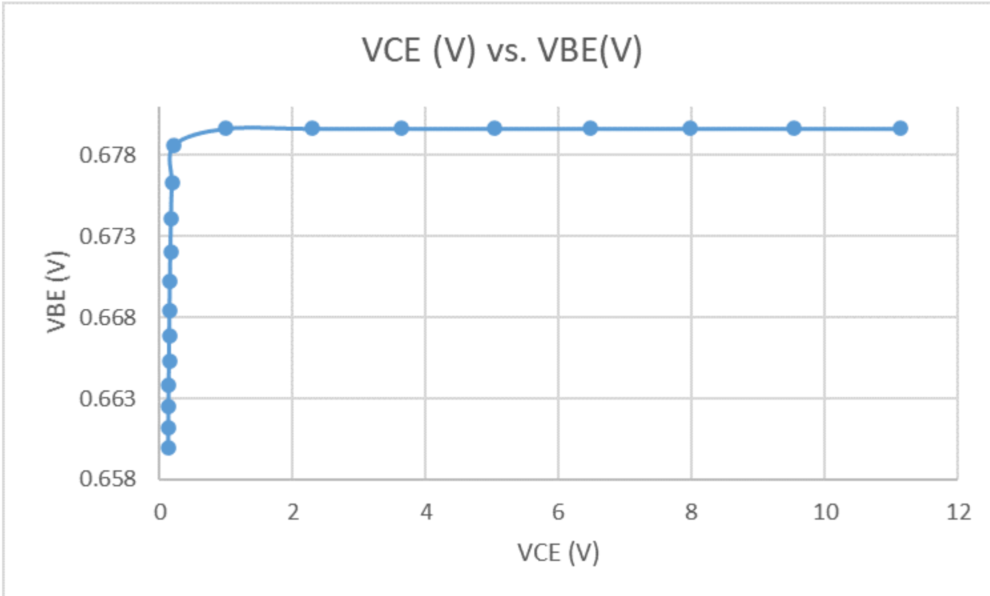


Figure 8: Collector-Emitter Voltage vs. Base-Emitter Voltage

As observed from Figure 8, the base-emitter voltage, V_{BE}, remains approximately constant as, V_{CE}, increases when the BJT is operating in the active region. While the BJT remains in the active mode, the base-emitter junction acts as a diode and thus will always have a voltage of approximately 0.7 volts across it. However, when the BJT operates in the saturation region, the base-emitter voltage, V_{BE}, slowly decreases.

As seen in Table 3 before, increasing the collector resistance values, R_C, to a value that is higher than 7.25 kΩ, the collector current, I_C, decreases while the base current, I_B, remains constant which results in a smaller current ratio.

As seen in Table 3 before, the current ration I_C/I_B was calculated for all the value of R_C, and the approximate β value when the transistor is operating in the active region is **147.06**.

In order to find the Early voltage (V_A), values are taken from Table 3 and plotted when the BJT is operating in the active region. The Early voltage is the x-intercept of the trendline in Figure 9.

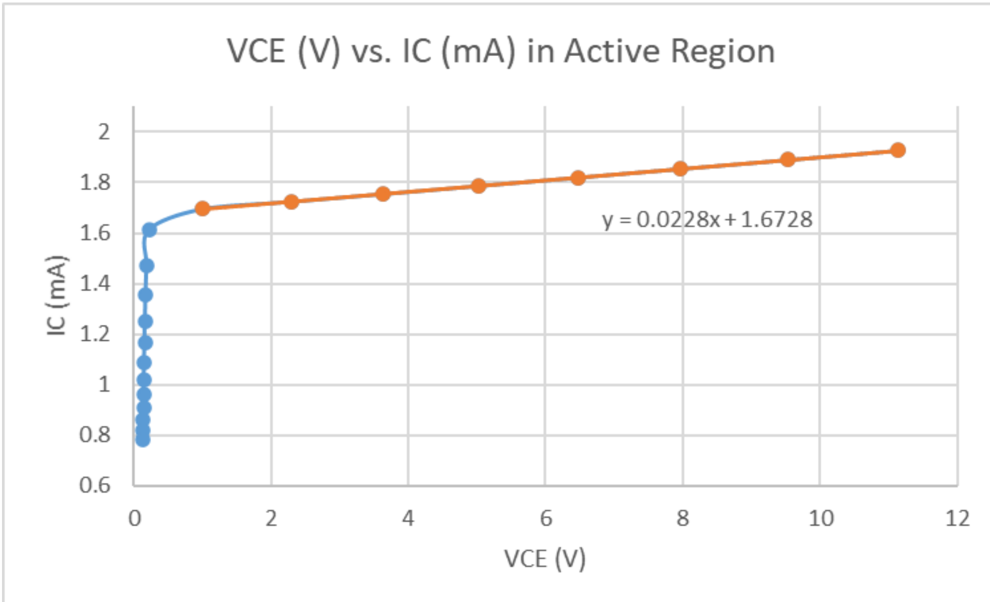


Figure 9: Collector-Emitter Voltage vs. Collector Current in the Active Region

The slope of Figure 9 is the value of the output admittance, $1/r_o$, and the x-intercept of the slope equation is the value of the Early voltage (V_A).

Using the slope equation of Figure 9:

$$y = 0.0228x + 1.6728$$

By setting the y-value to zero, the x-intercept is calculated as follows:

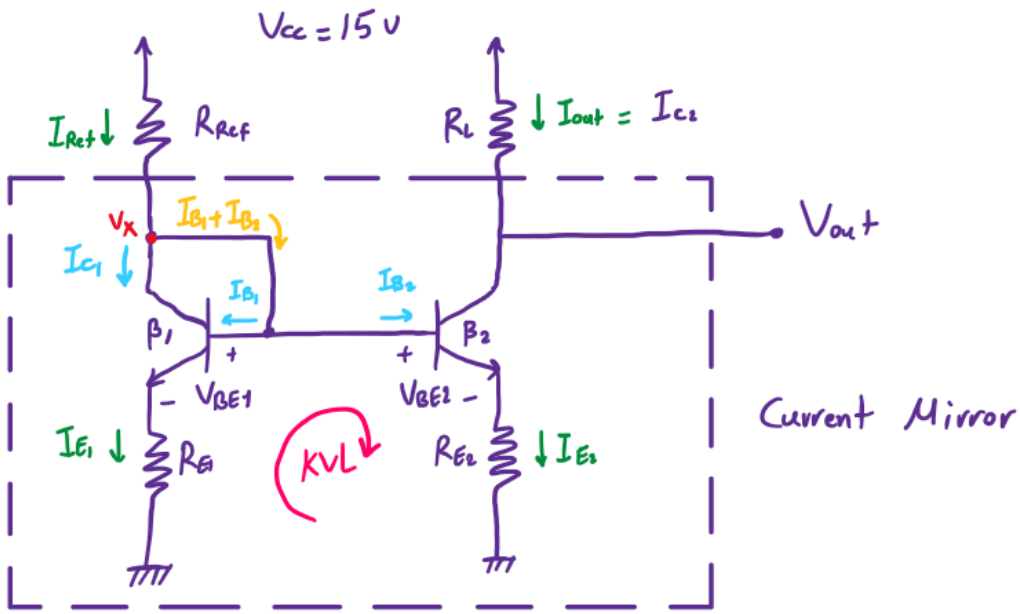
$$0 = 0.0228x + 1.6728$$

$$x = \frac{-1.6728}{0.0228} = -73.37$$

The Early voltage is the absolute value of **-73.37** volts.

3.3 The Current Mirror

3.3.1 Prelab Calculations



KVL:

$$\emptyset = (R_{E_1})(-I_{E_1}) + (-V_{BE_1}) + (V_{BE_2}) + (R_{E_2})(I_{E_2}) \quad (1)$$

$$I_{C_2} = I_{out} \quad (2)$$

$$I_{C_2} = \beta_2 I_{B_2} \quad (3)$$

$$I_{Ref} = I_{C_1} + I_{B_1} + I_{B_2} \quad (4)$$

$$I_{C_1} = \beta_1 I_{B_1} \quad (5)$$

$$I_{E_1} = I_{C_1} + I_{B_1} \quad (6)$$

$$I_{E_2} = I_{C_2} + I_{B_2} \quad (7)$$

$$I_{B_2} = \frac{I_{C_2}}{\beta_2} \quad (8)$$

↳ from (4), (6) and (8):

$$I_{Ref} = I_{E_1} + \frac{I_{C_2}}{\beta_2} \rightarrow I_{E_1} = I_{Ref} - \frac{I_{C_2}}{\beta_2} \qquad (9)$$

↳ Substitute in (1):

$$\phi = (R_{E_1})\left(\frac{I_{C_2}}{\beta_2} - I_{Ref}\right) - V_{BE_1} + V_{BE_2} + (R_{E_2})\left(I_{C_2} + \frac{I_{C_2}}{\beta_2}\right)$$

$$\phi = \underline{R_{E_1} \cdot \frac{I_{C_2}}{\beta_2}} - R_{E_1} I_{Ref} - V_{BE_1} + V_{BE_2} + \underline{R_{E_2} I_{C_2}} + \underline{R_{E_2} \frac{I_{C_2}}{\beta_2}}$$

$$R_{E_1} I_{Ref} + V_{BE_1} - V_{BE_2} = \frac{R_{E_1}}{\beta_2} I_{C_2} + R_{E_2} I_{C_2} + \frac{R_{E_2}}{\beta_2} I_{C_2}$$

$$R_{E_1} I_{Ref} + V_{BE_1} - V_{BE_2} = I_{C_2}\left[\frac{R_{E_1} + R_{E_2}}{\beta_2} + R_{E_2}\right]$$

$$\boxed{I_{out} = I_{C_2} = \frac{R_{E_1} I_{Ref} + V_{BE_1} - V_{BE_2}}{R_{E_2} + \dfrac{R_{E_1} + R_{E_2}}{\beta_2}}}$$

Assuming: ↳ $V_{BE_1} = V_{BE_2}$

↳ $\beta_1, \beta_2 \rightarrow$ very large

The equation becomes:

$$\boxed{I_{out} = I_{C2} = \frac{R_{E1}}{R_{E2}} I_{Ref}}$$

with $R_{E1} = 2K\Omega$, $\boxed{R_{E2} \text{ should be } 2k\Omega}$ for 1:1 ratio

$I_{Ref} = 0.5\ mA$

Assuming $I_{Ref} = I_{E1}$

$$V_x = V_{BE1} + (I_{E1})(R_{E1}) = 0.7V + (0.5mA)(2K\Omega) = 1.7V$$

$$\boxed{R_{Ref} = \frac{V_{cc} - V_x}{I_{Ref}} = \frac{15V - 1.7V}{0.5mA} = 26.6\ K\Omega}$$

Since the current mirror ratio is 1:1, we have symmetry:

$$\left.\begin{matrix} V_{out} = 1.7V \\ I_{out} = 0.5mA \end{matrix}\right\} \rightarrow \boxed{R_L = R_{Ref} = 26.6\ K\Omega}$$

Values of R_L where the current mirror still operates:

Value of $R_L = 26.6\ K\Omega$. However, <u>27 KΩ</u> will be used

R_L (kΩ)	I_{out} (mA)	V_{out} (V)
↳ 22	0.5	4
↳ 18	0.5	6
↳ 15	0.5	7.5
↳ 12	0.5	9
↳ 10	0.5	10

$$I_{out} = \frac{V_{cc} - V_{out}}{R_L}$$

$$V_{out} = V_{cc} - (I_{out})(R_L)$$
$$= 15V - (0.5mA)\ R_L$$

Values of R_L where the current mirror fails to operate:
Value of R_L = 26.6 kΩ. However, 27 kΩ will be used

R_L (kΩ)	I_{out} (mA)	V_{out} (V)
↳ 33	0.5	−1.5
↳ 39	0.5	−4.5
↳ 47	0.5	−8.5
↳ 56	0.5	−13
↳ 68	0.5	−19

$$I_{out} = \frac{V_{cc} - V_{out}}{R_L}$$

$$V_{out} = V_{cc} - (I_{out})(R_L)$$
$$= 15V - (0.5mA)\ R_L$$

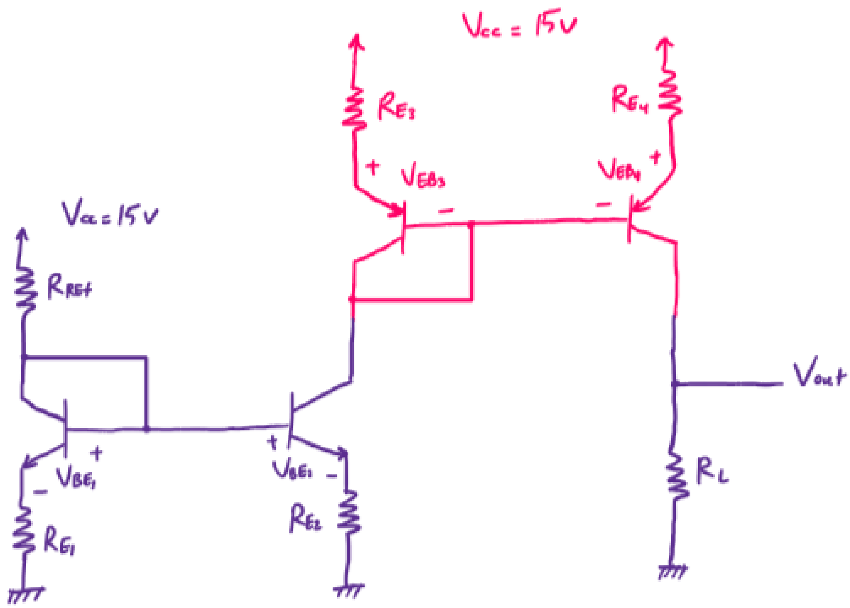
Conclusion: I_{out} can't be fixed at 0.5 mA as the output voltage is −ve indicating a failure in the design of the current source

In order to design a 1:2 current multiplier, the following eq. must be used

$$\boxed{I_{out} = \frac{R_{E_1}}{R_{E_2}} I_{Ref}}$$

we know that $R_{E_1} = 2k\Omega$, therefore $\boxed{R_{E_2} \text{ should be } 1k\Omega}$

The design of the PNP 1:1 ratio current mirror is as follows



3.3.2 Experiment: 1:1 NPN Current Multipllier

Figure 10 below illustrates the current mirror circuit used in this part of the experiment.

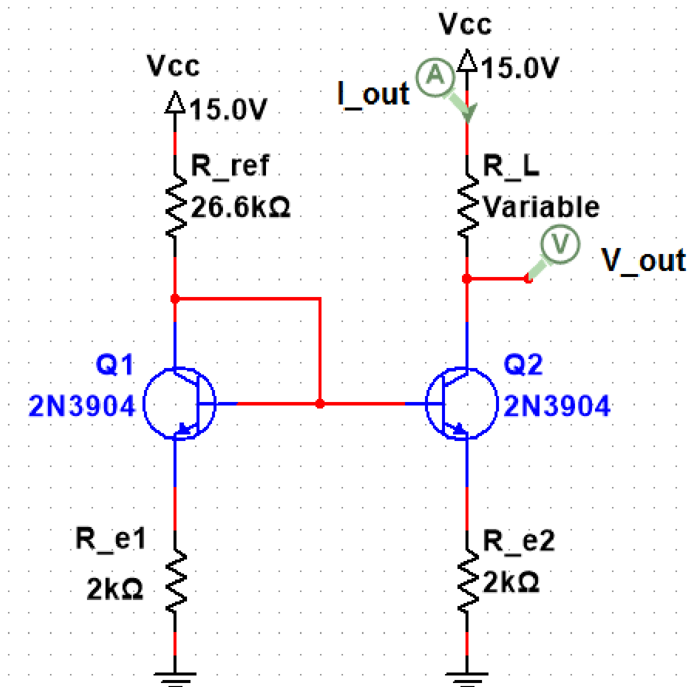


Figure 10: The 1:1 Ratio NPN Current Mirror Circuit

Figure 11 below illustrates the DC operating sweep settings of the 1:1 ratio current mirrior circuit used in this part of the experiment.

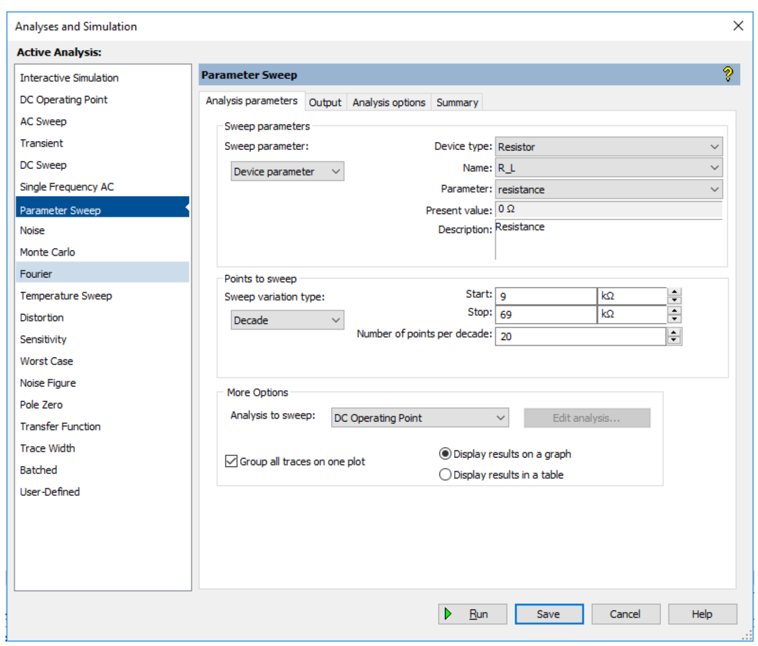


Figure 11: The 1:1 Ratio NPN DC Operating Sweep Simulation Settings

For the 1:1 ratio NPN current mirror, the reference resistance, R_{REF}, is set to be 26.6 kΩ and the reference voltage was measured and found to be 13.4 volts. Therefore, the reference current, I_{REF}, can be calculated as follows:

$$I_{REF} = \frac{V_{REF}}{R_{REF}} = \frac{13.4V}{26.6k\Omega} = 0.50$$

Therefore, the reference current, I_{REF}, for the 1:1 ratio multiplier is **0.50 mA**.

Table 4 below shows the output current of the 1:1 current mirror circuit with different values of the load resistor when the transistor is operating in both active and saturation regions.

Table 4: Measured I_{OUT} and V_{OUT} for Different R_L Values for 1:1 Ratio NPN

RL (kOhm)	VOUT (V)	IOUT (mA)	RREF (kOhm)
9	10.5351602	0.496093311	26.6
10.09816609	9.991583749	0.495971188	26.6
11.33032871	9.382063025	0.49583303	26.6
12.7128379	8.698563272	0.495676541	26.6
14.26403873	7.932201166	0.495499077	26.6
16.00451469	7.073010509	0.495297541	26.6
17.95736083	6.10986057	0.495068297	26.6
20.14849025	5.030379837	0.494807066	26.6
22.60697788	3.820641121	0.494508731	26.6
25.36544638	2.465251354	0.494167198	26.6
28.46049894	1.127944004	0.487414346	26.6
31.93320503	1.022984548	0.437695422	26.6
35.82964535	0.962388553	0.391788115	26.6
40.20152329	0.912877084	0.350412868	26.6
45.10685103	0.870329555	0.313248537	26.6
50.61071927	0.833116016	0.279918752	26.6
56.786161	0.80030082	0.250055457	26.6
63.71512059	0.771240549	0.223318483	26.6
69	0.753061761	0.206477366	26.6

Figure 12 below shows how the output current, I_{OUT}, remains constant and equals to the reference current, I_{REF}, for any load resistance values as long as the transistor is operation in the active region. The maximum load resistance value, $R_{L_{MAX}}$, is **26.6 kΩ**. Any chosen load resistance values, R_L, that are higher than $R_{L_{MAX}}$ will make the transistor operate in the saturation region. In this case, the current mirror fails and the output current, I_{OUT}, will decrease as observed in Table 4.

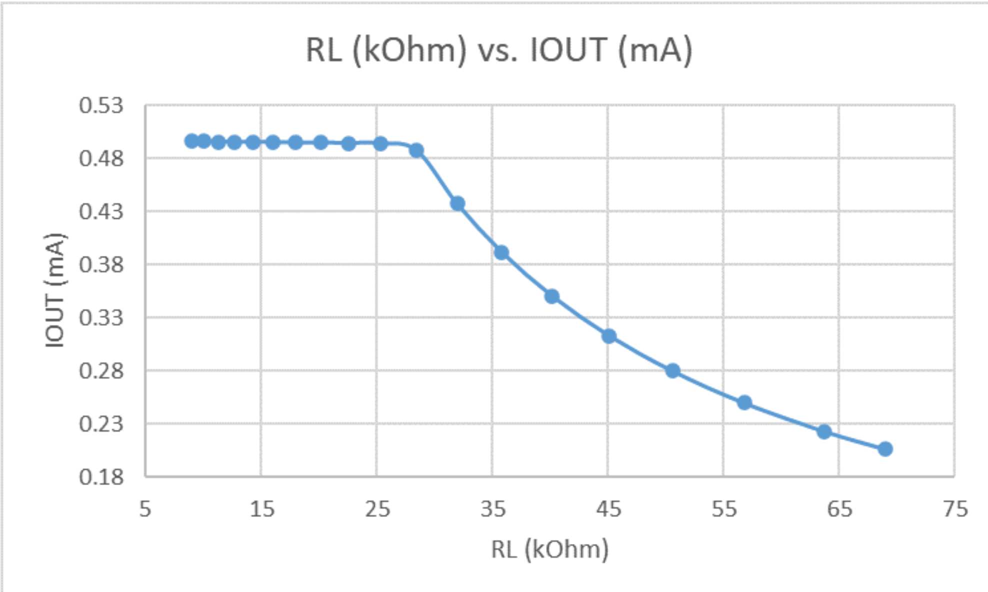


Figure 12: Load Resistor vs. Output Current for 1:1 Ratio NPN

Figure 13 below shows a plot of the output voltage vs. output current.

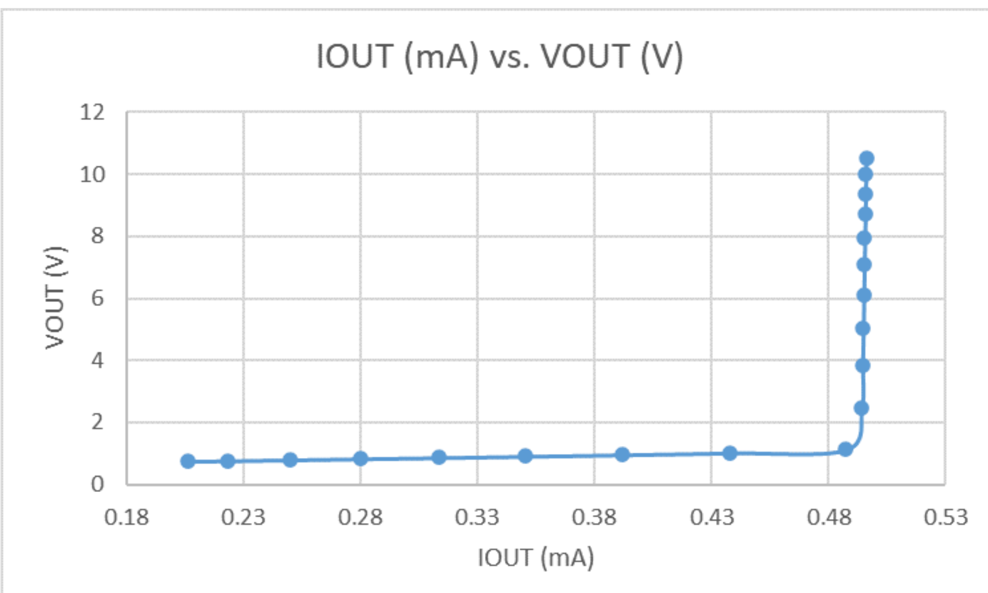


Figure 13: Output Current vs. Output Voltage for 1:1 Ratio NPN

In order to determine the output impedance, values are taken from Table 4 and plotted when the BJT is operating in the active region. The output impedance is 1 divided by the slope of the trendline in Figure 14.

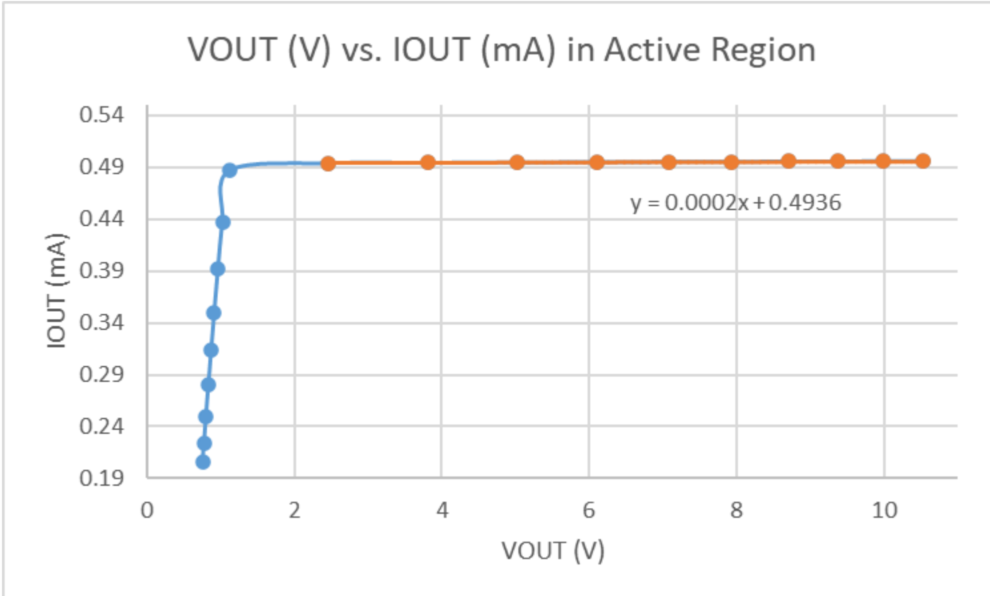


Figure 14: Output Voltage vs. Output Current in the Active Region for 1:1 Ratio NPN

Using Figure 14 above, when the transistor is in active mode, the I_{OUT} vs. V_{OUT} relationship appears to have a slope of approximately **0.000238** (the slope of the data when the BJT is only in active mode). The output impedance can be calculated as follows:

$$Output\ Impedance = \frac{1}{m} = \frac{1}{0.000238 * 10^{-3}} = 4,201,680.67$$

The output impedance is **4,201,680.67 mhos**.

3.3.3 Experiment: 1:2 NPN Current Multipllier

Figure 15 below illustrates the current mirror circuit used in this part of the experiment.

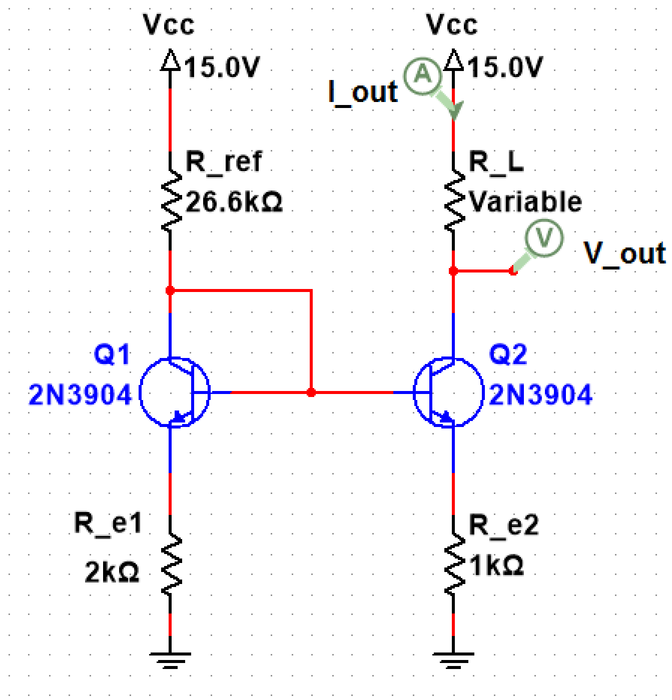


Figure 15: The 1:2 Ratio NPN Current Mirror Circuit

Figure 16 below illustrates the DC operating sweep settings of the 1:2 ratio current mirrior circuit used in this part of the experiment.

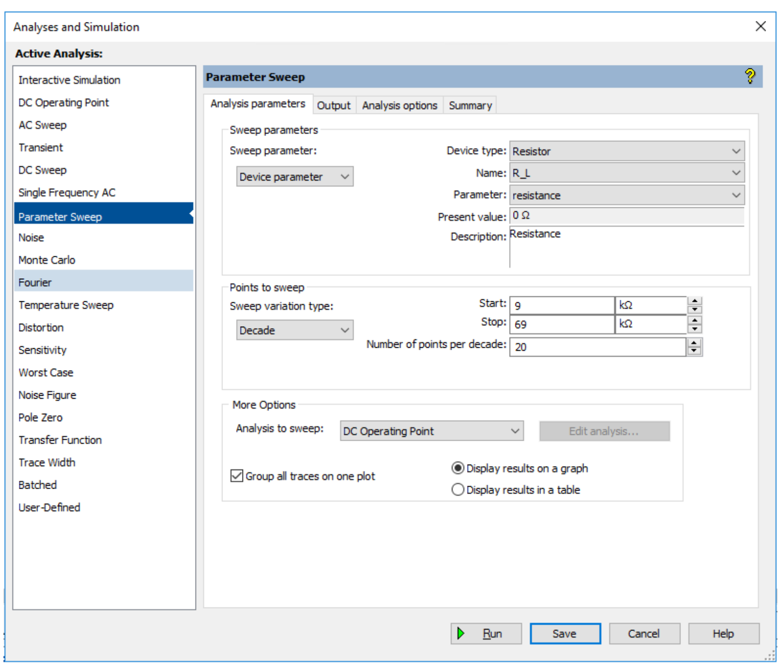


Figure 16: The 1:2 NPN DC Operating Sweep Simulation Settings

For the 1:2 ratio NPN current mirror, the reference resistance, R_{REF}, is set to be 26.6 kΩ and the reference voltage was measured and found to be 13.4 volts. Therefore, the reference current, I_{REF}, can be calculated as follows:

$$I_{REF} = \frac{V_{REF}}{R_{REF}} = \frac{13.4V}{26.6k\Omega} = 0.50$$

Therefore, the reference current, I_{REF}, for the 1:2 ratio multiplier is **0.50 mA**.

Table 5 below shows the output current of the 1:2 current mirror circuit with different values of the load resistor when the transistor is operating in both active and saturation regions.

Table 5: Measured I_{OUT} and V_{OUT} for Different R_L Values for 1:2 Ratio NPN

RL (kOhm)	VOUT (V)	IOUT (mA)	RREF (kOhm)
9	6.29064586	0.967706016	26.6
10.09816609	5.233651756	0.967137534	26.6
11.33032871	4.049398892	0.966488187	26.6
12.7128379	2.722682946	0.965744529	26.6
14.26403873	1.238679514	0.964758867	26.6
16.00451469	1.009627151	0.874152448	26.6
17.95736083	0.931286106	0.78344938	26.6
20.14849025	0.866966179	0.701443473	26.6
22.60697788	0.811311922	0.62762366	26.6
25.36544638	0.762363419	0.561301481	26.6
28.46049894	0.719006345	0.50178295	26.6
31.93320503	0.680469415	0.44842141	26.6
35.82964535	0.646151223	0.400614262	26.6
40.20152329	0.615556403	0.357808629	26.6
45.10685103	0.588264502	0.319501795	26.6
50.61071927	0.563911484	0.285237875	26.6
56.786161	0.542175987	0.254601012	26.6
63.71512059	0.522776067	0.2272181	26.6
69	0.510583011	0.209991551	26.6

Figure 17 below shows how the output current, I_{OUT}, is equal to approximately 1 mA which is ***double*** the reference current, I_{REF}, for any load resistance values as long as the transistor is operation in the active region. The maximum load resistance value, $R_{L_{MAX}}$, is appromximately **15 kΩ**. Any chosen load resistance values, R_L, that are higher than $R_{L_{MAX}}$ will make the transistor operate in the saturation region. In this case, the current mirror fails and the output current, I_{OUT}, will decrease as observed in Table 5.

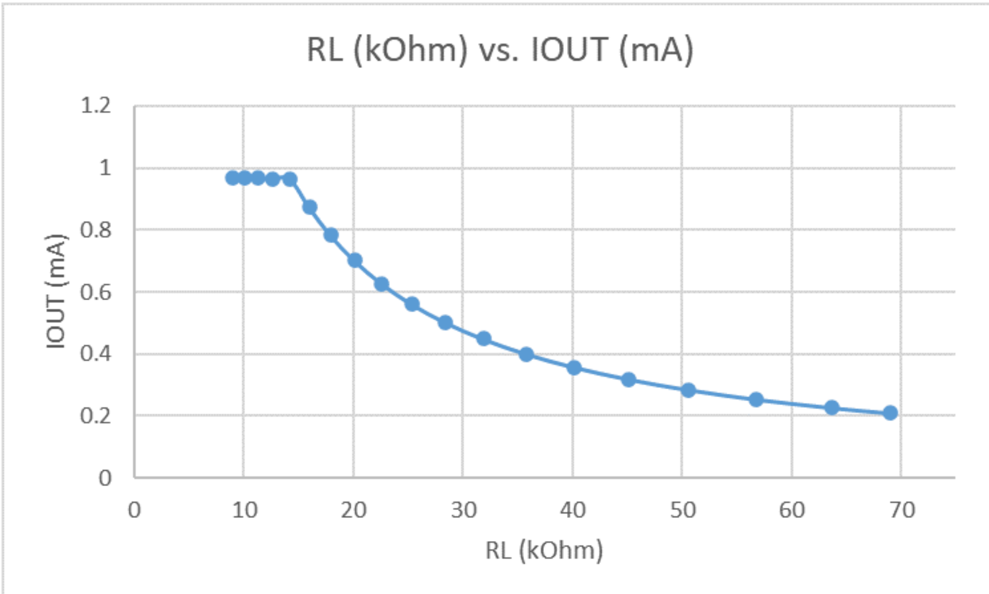


Figure 17: Load Resistor vs. Output Current for 1:2 Ratio NPN

3.3.4 Experiment: 1:1 NPN-PNP Current Multipllier

Figure 18 below illustrates the current mirror circuit used in this part of the experiment.

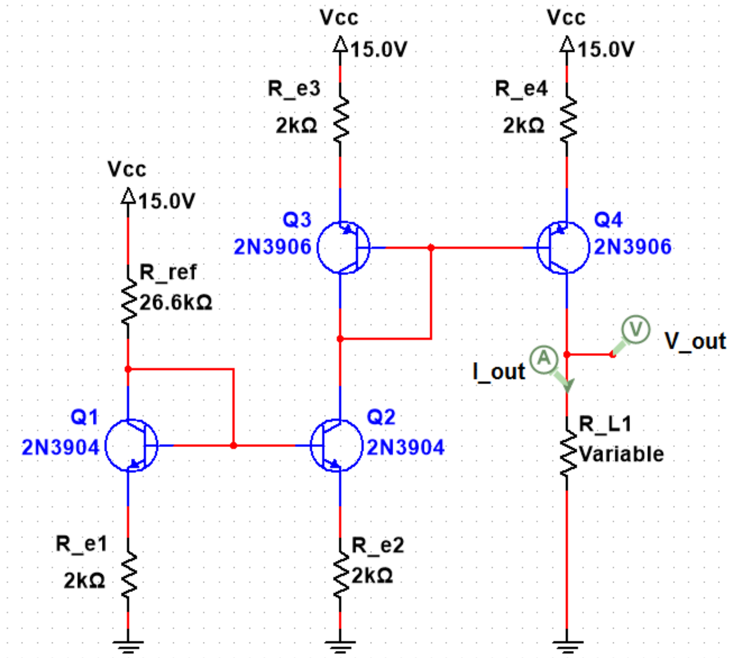


Figure 18: The 1:1 Ratio NPN-PNP Current Mirror Circuit

Figure 19 below illustrates the DC operating sweep settings of the 1:2 ratio current mirrior circuit used in this part of the experiment.

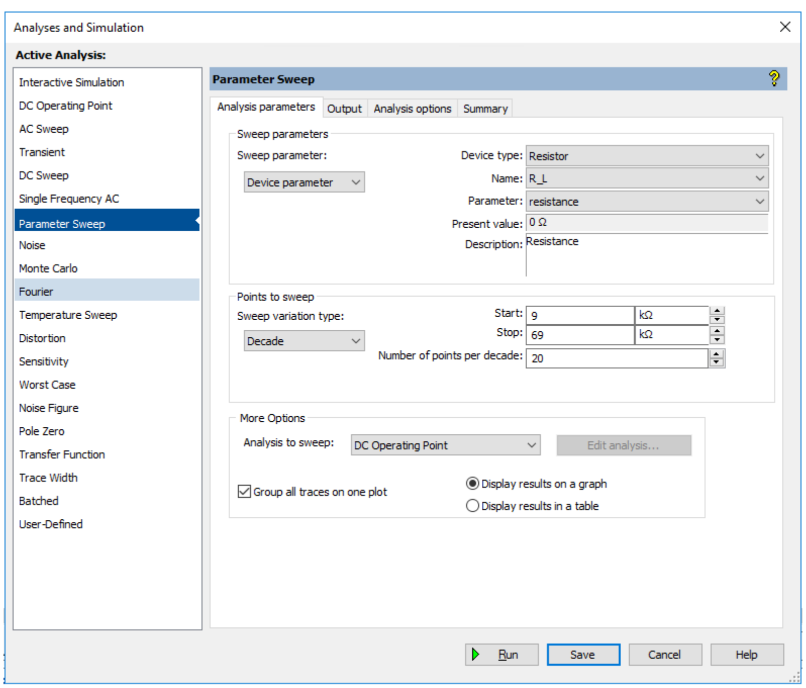


Figure 19: The 1:1 NPN-PNP DC Operating Sweep Simulation Settings

For the 1:1 ratio NPN-PNP current mirror, the reference resistance, R_{REF}, is set to be 26.6 kΩ and the reference voltage was measured and found to be 13.4 volts. Therefore, the reference current, I_{REF}, can be calculated as follows:

$$I_{REF} = \frac{V_{REF}}{R_{REF}} = \frac{13.4V}{26.6k\Omega} = 0.50$$

Therefore, the reference current, I_{REF}, for the 1:1 ratio multiplier is **0.50 mA**.

Table 6 below shows the output current of the 1:1 NPN-PNP current mirror circuit with different values of the load resistor when the transistor is operating in both active and saturation regions.

Table 6: Measured I_{OUT} and V_{OUT} for Different R_L Values for 1:1 Ratio NPN-PNP

RL (kOhm)	VOUT (V)	IOUT (mA)	RREF (kOhm)
9	4.480501088	0.497833454	26.6
10.09816609	5.023941172	0.497508583	26.6
11.33032871	5.63268939	0.497135062	26.6
12.7128379	6.314498456	0.496703988	26.6
14.26403873	7.07785923	0.496204377	26.6
16.00451469	7.932188319	0.495622376	26.6
17.95736083	8.887840285	0.494940263	26.6
20.14849025	9.956078352	0.494134965	26.6
22.60697788	11.14922083	0.493175602	26.6
25.36544638	12.48028318	0.492019963	26.6
28.46049894	13.89689905	0.488287242	26.6
31.93320503	14.02428037	0.43917554	26.6
35.82964535	14.08609492	0.393141283	26.6
40.20152329	14.13627649	0.351635548	26.6
45.10685103	14.17938234	0.314350628	26.6
50.61071927	14.2171107	0.280911165	26.6
56.786161	14.25041023	0.250948474	26.6
63.71512059	14.27992577	0.224121531	26.6
69	14.29840227	0.207223221	26.6

Figure 20 below shows how the output current, I_{OUT}, remains constant and equals to the reference current, I_{REF}, for any load resistance values as long as the transistor is operation in the active region. The maximum load resistance value, $R_{L_{MAX}}$, is **26.6 kΩ**. Any chosen load resistance values, R_L, that are higher than $R_{L_{MAX}}$ will make the transistor operate in the saturation region. In this case, the current mirror fails and the output current, I_{OUT}, will decrease as observed in Table 6.

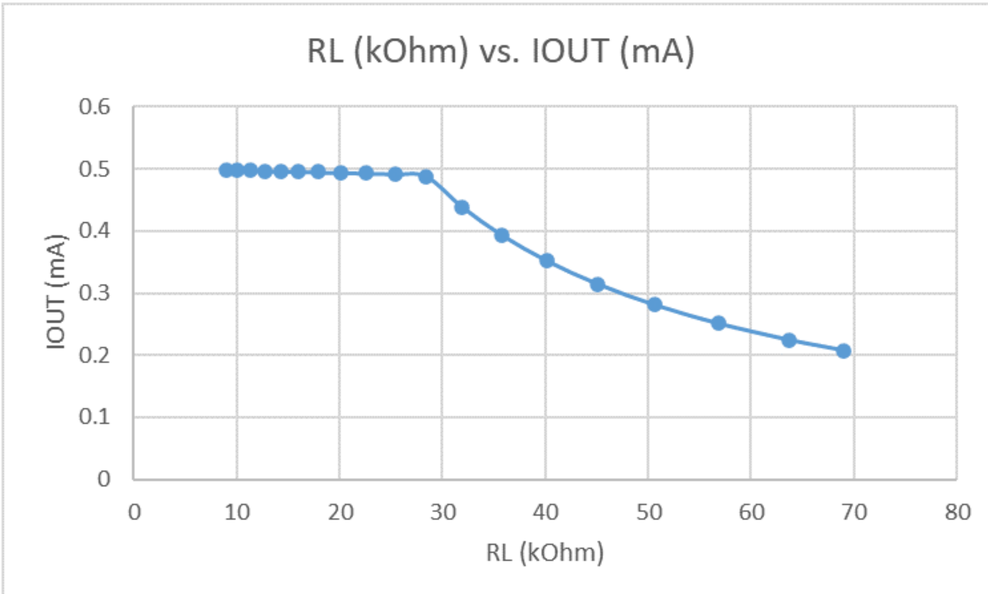


Figure 20: Load Resistor vs. Output Current for 1:1 Ratio NPN-PNP

4 BJT AC Characterization

4.1 The transistor's h-Parameters and Bandwidth

The four h-parameters describe all of a transistor's small-signal ac characteristics for a given set of dc bias conditions, at one frequency [1]. At low to medium frequencies, they are independent of frequency [1].

The four parameters are:

- h_{ie}: the ac input impedance with the output short-circuited
- h_{oe}: the output admittance with the input open-circuited
- h_{fe}: the ac forward current gain with the output short-circuited
- h_{re}: the reverse, or feedback, voltage ratio with the input open-circuited

The second subscript, **e**, indicates that these parameters are measured with respect to the emitter, the emitter being the terminal common to both the input circuit and the output circuit [1].

The one other transistor parameter of major interest is its unity-gain bandwidth, f_T, the frequency at which its ac current gain is reduced to one [1]. In this lab report, f_T will be calculated as the product of the low-frequency current gain, h_{fe}, and the beta cut-off frequency, f_β.

4.1.1 DC-Biasing Circuit

Figure 21 below illustrates the circuit used in this part of the experiment.

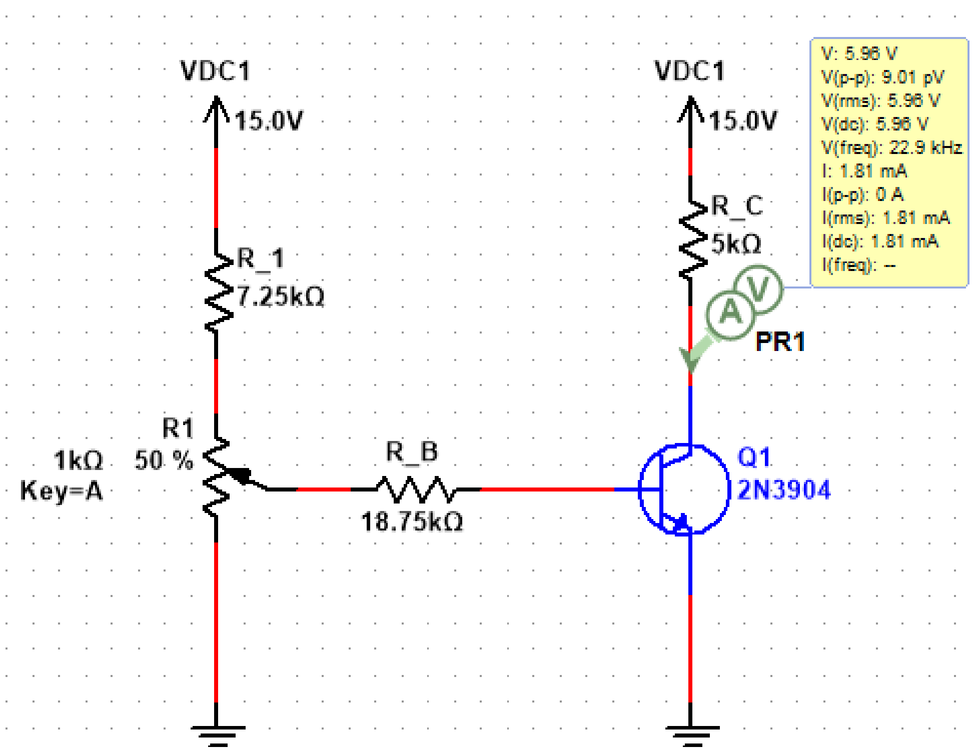


Figure 21: DC Bias Circuit for the AC Characterization Tests

Figure 22 below illustrates the interactive simulation settings of the DC Bias Circuit used in this part of the experiment.

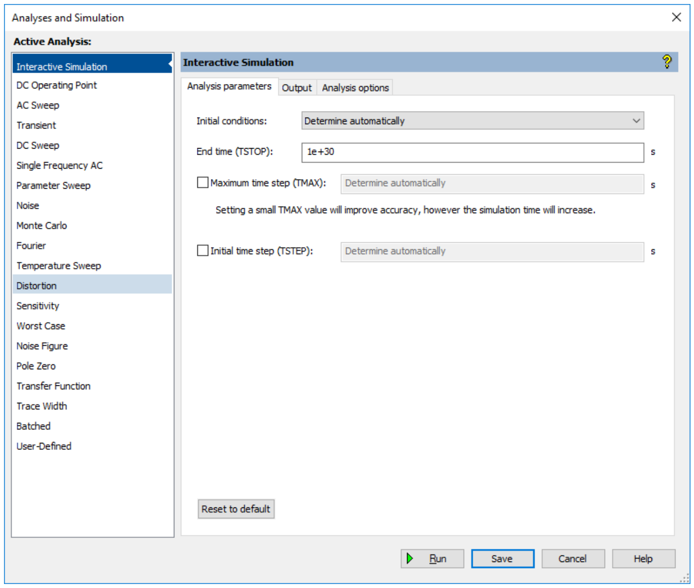


Figure 22: The Interactive Simulation Settings of the DC Bias Circuit

As shown in Figure 21 above, the collector resistor, R_C, was set to **5 kΩ** to maintain a collector-emitter voltage, V_{CE}, of approximately 6 volts.

Then, the potentiometer percentage was adjusted to 48% so that the collector current, I_C, is set to approximately 2 mA.

As shown in Figure 23 below, the actual collector-emitter voltage (V_{CE}) was measured and found to be **4.70 volts**.

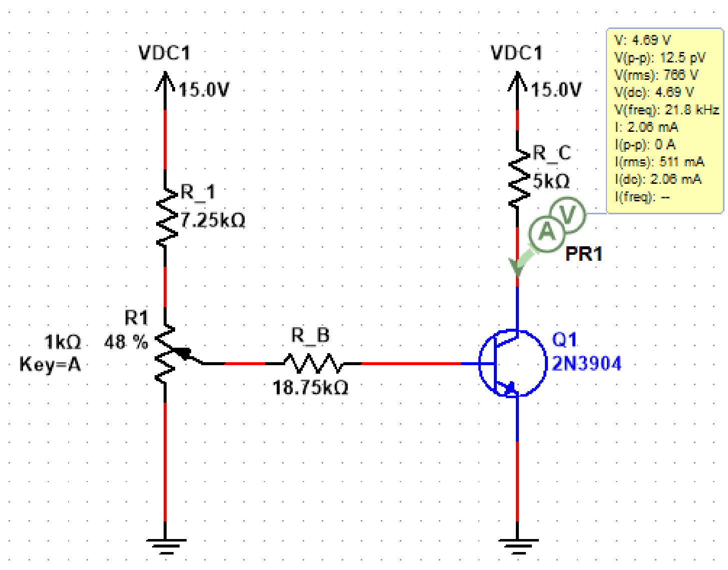


Figure 23: Measured V_{CE} After Adjusting I_C to 2 mA

4.1.2 AC-Coupling of Input and Output Signals

Figure 24 below illustrates the circuit used in this part of the experiment.

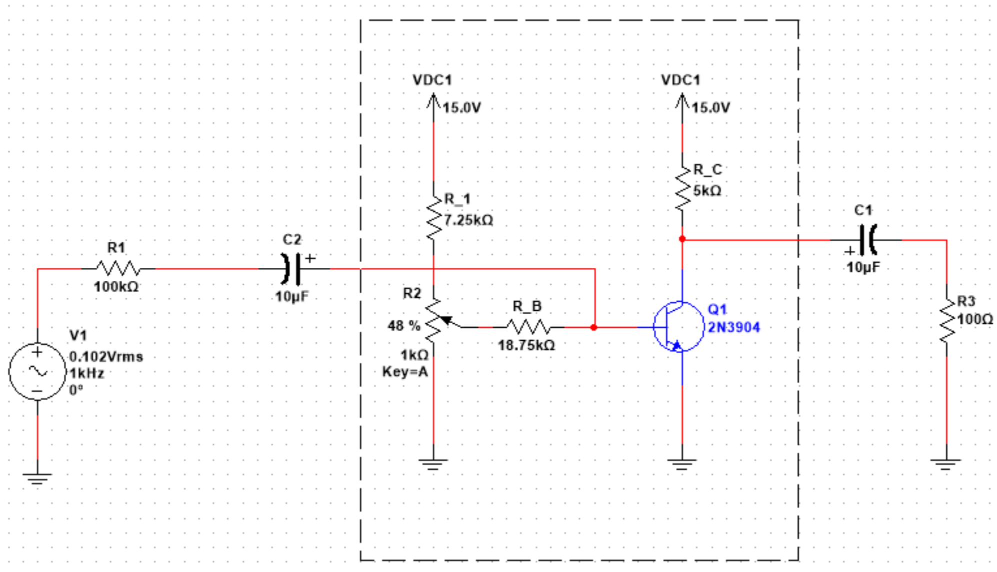


Figure 24: Additional Circuitry Added to The DC Bias Circuit

Figure 24 above shows the AC test circuit for the biased BJT which has two capacitors, C1 and C2. These capacitors are used to block the DC signal from going to the test circuit. If the capacitors were not present, the resistors, R_S and R_L, would experience DC voltage combined with the AC voltage signal. The DC voltage is only used to determining the biasing point of the ciruict and it is not desired when AC analysis is being done.

4.1.3 The AC Input Impedance, h_{ie}, and the AC Forward Current Gain, h_{fe}

Figure 25 below illustrates the interactive simulation settings of the test circuit, see Figure 24 above, used in this part of the experiment.

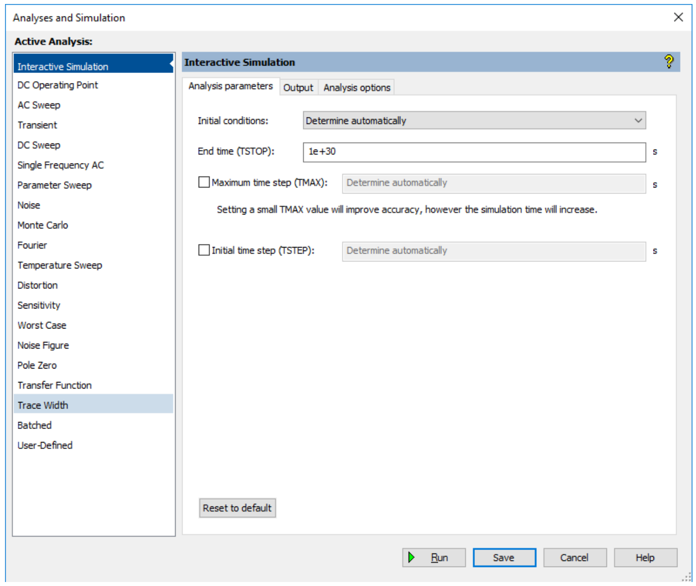


Figure 25: The Interactive Simulation Settings of the Test Circuit

As shown in Figure 26 below, the signal source is set to provide **1 kHz sinusoid**. The AC base current, I_B, is set to **1** μ**A RMS** by adjusting the amplitude of the singal generator to **0.102** V_{rms}.

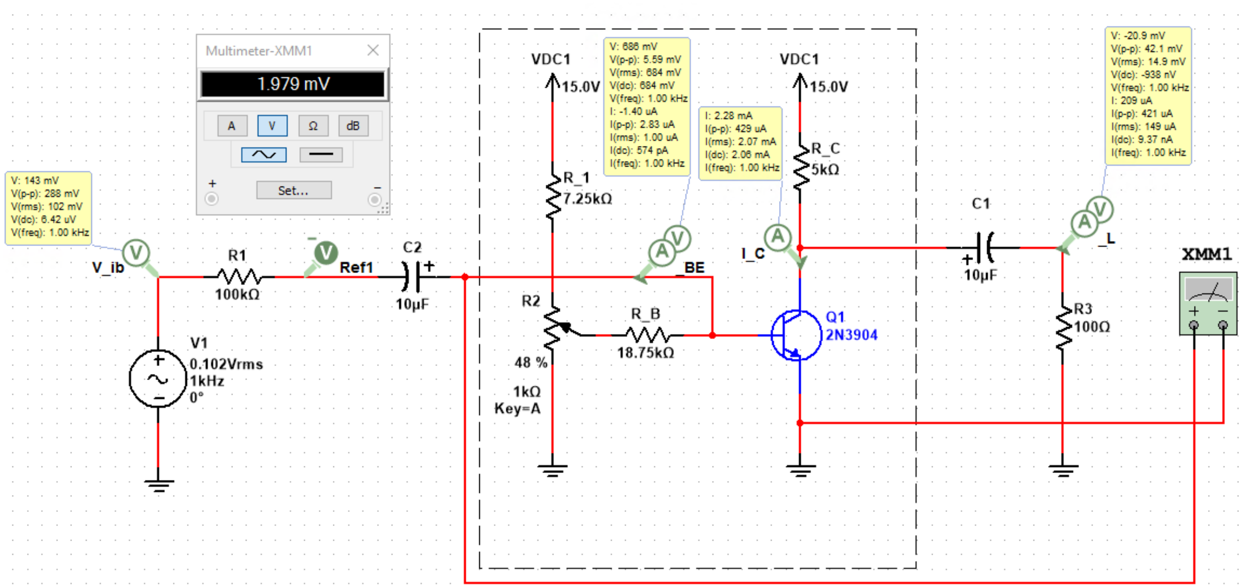


Figure 26: Measured Parameters to Calculate Input Impedance and Current Gain

Note that all measurements done in this part are RMS.

AC input impedance:

Table 7: Measured Parameters to Calculate AC Input Impedance

v_{be}	v_{i_b}	R_S
1.976 mV	100 mV	100 kΩ

Using the measured data in Table 7 above, the AC input impedance is calculated as follows:

$$h_{ie} = \frac{v_{be}}{i_b} = \frac{v_{be}}{v_{i_b}} R_S = \frac{1.976mV}{100mV}(100k\Omega) = 1.976$$

The AC input impedance is approximately **2 kΩ**.

AC forward current gain:

Table 8: Measured Parameters to Calculate AC Forward Current Gain

i_b	v_o	R_L
1 μA	14.9 mV	100 Ω

Using the measured data in Table 8 above, the AC forward current gain is calculated as follows:

$$h_{fe} = \frac{i_c}{i_b} = \frac{v_o}{R_L * i_b} = \frac{14.9mV}{100\Omega * 1\mu A} = 149$$

The AC forward current gain is **149 *A/A***.

A load resistance value of zero is effectively grounding the transistor's collector during AC analysis. The load resistor, R_L, must be present in the circuit since the AC current and AC voltage of a purely resistive impedance are in phase. Regarding that, the output current, I_L, can be directly calculated using Ohm's law wihtout accounting for phase differences.

4.1.4 The AC Output Admittance, h_{oe}, and the AC Reverse, or Feedback, Voltage Ratio, h_{re}

From Figure 9 above, the slope of the I_C vs. V_{CE} characteristics curve is 0.0228 mA/V. Therefore, the AC output admittance, h_{oe}, is **22.8 μmhos**.

4.1.5 The Unity-Gain Bandwidth, f_T, and The Beta Cut-Off Frequency, f_β

Figure 27 below illustrates the test circuit, for I_C = 2 mA, and the simulation probes used in this part of the experiment.

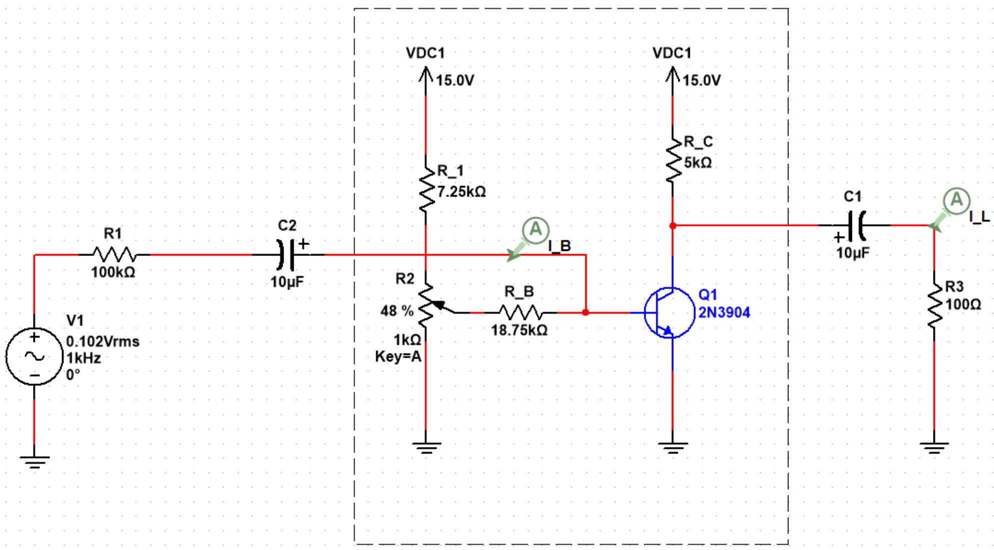


Figure 27: The Test Circuit for The Current Gain for $I_C = 2$ mA

Figure 28 below illustrates the AC sweep settings of the test circuit used in this part of the experiment.

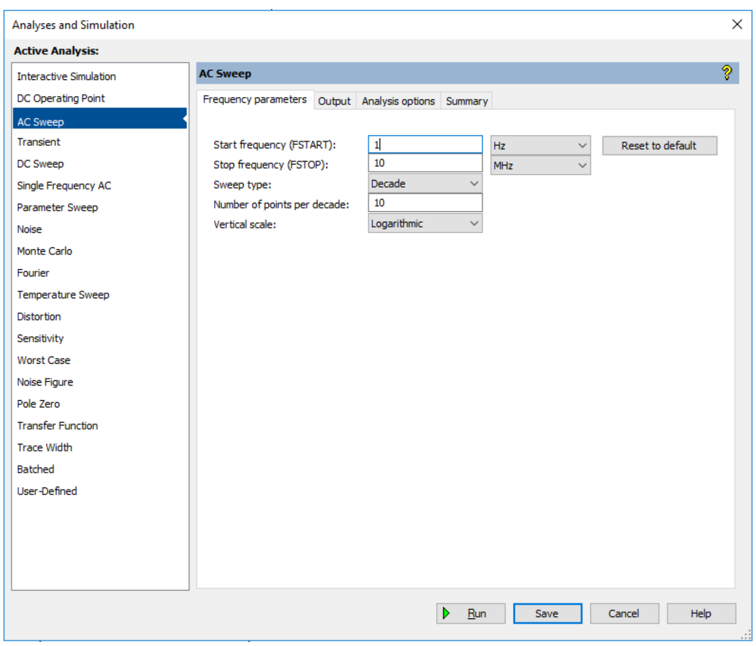


Figure 28: AC Sweep Simulation Settings for $I_C = 2$ mA

Table 9: Measured Data to Calculate The Current Gain with $I_C = 2$ mA

f (Hz)	IB (A)	IL (A)	hfe	20 Log (hfe)
1	9.68907E-06	0.000394062	40.67080911	32.18565625
1.258925412	9.73187E-06	0.000487769	50.12076129	34.00035318
1.584893192	9.75916E-06	0.000596363	61.10799976	35.72196137
1.995262315	9.7765E-06	0.000717629	73.40343457	37.31432762
2.511886432	9.78749E-06	0.000846362	86.47386521	38.73769743
3.16227766	9.79445E-06	0.000974556	99.50083934	39.95653488
3.981071706	9.79884E-06	0.001093101	111.5540567	40.94970737
5.011872336	9.80162E-06	0.001194519	121.8695656	41.71790526
6.309573445	9.80337E-06	0.001275101	130.0676208	42.28338392
7.943282347	9.80448E-06	0.001335166	136.1791437	42.68221198
10	9.80518E-06	0.00137772	140.5094144	42.95410848
12.58925412	9.80562E-06	0.001406753	143.4639765	43.13485729
15.84893192	9.8059E-06	0.001426042	145.4269564	43.2528983
19.95262315	9.80607E-06	0.001438627	146.7077734	43.32906251
25.11886432	9.80618E-06	0.001446741	147.5335419	43.37781538
31.6227766	9.80625E-06	0.001451931	148.0617976	43.40886036
39.81071706	9.8063E-06	0.001455235	148.3980386	43.42856322
50.11872336	9.80632E-06	0.001457331	148.6113747	43.44104103
63.09573445	9.80634E-06	0.001458659	148.746455	43.44893248
79.43282347	9.80635E-06	0.001459498	148.8318747	43.45391904
100	9.80636E-06	0.001460028	148.8858465	43.45706829
125.8925412	9.80637E-06	0.001460363	148.9199306	43.4590565
158.4893192	9.80637E-06	0.001460575	148.9414481	43.46031144
199.5262315	9.80637E-06	0.001460708	148.9550293	43.46110343
251.1886432	9.80637E-06	0.001460792	148.9636	43.46160319
316.227766	9.80637E-06	0.001460845	148.969008	43.46191851
398.1071706	9.80637E-06	0.001460879	148.9724195	43.46211743
501.1872336	9.80637E-06	0.0014609	148.9745708	43.46224286
630.9573445	9.80637E-06	0.001460913	148.9759259	43.46232186
794.3282347	9.80637E-06	0.001460922	148.9767773	43.4623715
1000	9.80637E-06	0.001460927	148.9773087	43.46240249
1258.925412	9.80637E-06	0.00146093	148.977635	43.46242151
1584.893192	9.80637E-06	0.001460932	148.9778264	43.46243267
1995.262315	9.80637E-06	0.001460933	148.9779243	43.46243838
2511.886432	9.80637E-06	0.001460933	148.9779499	43.46243987
3162.27766	9.80637E-06	0.001460933	148.9779086	43.46243747
3981.071706	9.80637E-06	0.001460932	148.9777916	43.46243064
5011.872336	9.80637E-06	0.00146093	148.9775736	43.46241793
6309.573445	9.80638E-06	0.001460926	148.9772075	43.46239659
7943.282347	9.80638E-06	0.001460921	148.9766143	43.462362
10000	9.80638E-06	0.001460912	148.975666	43.46230671
12589.25412	9.80638E-06	0.001460898	148.974158	43.46221879
15848.93192	9.80639E-06	0.001460875	148.9717647	43.46207925
19952.62315	9.8064E-06	0.001460839	148.9679698	43.46185798
25118.86432	9.80641E-06	0.001460783	148.9619546	43.46150724
31622.7766	9.80644E-06	0.001460693	148.9524217	43.46095137
39810.71706	9.80648E-06	0.00146055	148.9373165	43.46007049
50118.72336	9.80654E-06	0.001460324	148.9133854	43.45867474
63095.73445	9.80663E-06	0.001459967	148.8754805	43.45646352
79432.82347	9.80678E-06	0.001459401	148.8154644	43.45296128
100000	9.80702E-06	0.001458505	148.7204938	43.44741637
125892.5412	9.8074E-06	0.001457088	148.5703472	43.43864276
158489.3192	9.80799E-06	0.001454851	148.3333095	43.42477373
199526.2315	9.80892E-06	0.001451327	147.9599431	43.40288311
251188.6432	9.81038E-06	0.001445794	147.3739295	43.36841327
316227.766	9.81265E-06	0.001437153	146.4592574	43.31433656
398107.1706	9.81613E-06	0.001423769	145.0438533	43.22998658
501187.2336	9.82139E-06	0.001403303	142.8823007	43.09956869
630957.3445	9.82914E-06	0.0013726	139.6460396	42.90057247
794328.2347	9.84012E-06	0.001327816	134.9390098	42.60275038
1000000	9.85488E-06	0.001265026	128.3653909	42.16895895
1258925.412	9.87338E-06	0.00118152	119.6671921	41.55950202
1584893.192	9.8946E-06	0.001077526	108.9003884	40.74058857
1995262.315	9.91664E-06	0.000957388	96.54360489	39.69447022
2511886.432	9.93727E-06	0.000829005	83.42380617	38.42580001
3162277.66	9.95479E-06	0.000701499	70.46847471	36.95989743
3981071.706	9.96849E-06	0.000582555	58.43965774	35.33415328
5011872.336	9.9785E-06	0.000476944	47.79710382	33.58803164
6309573.445	9.98549E-06	0.000386526	38.70876058	31.75618532
7943282.347	9.9902E-06	0.000311071	31.13758412	29.86569828
10000000	9.99329E-06	0.000249183	24.93499933	27.93618722

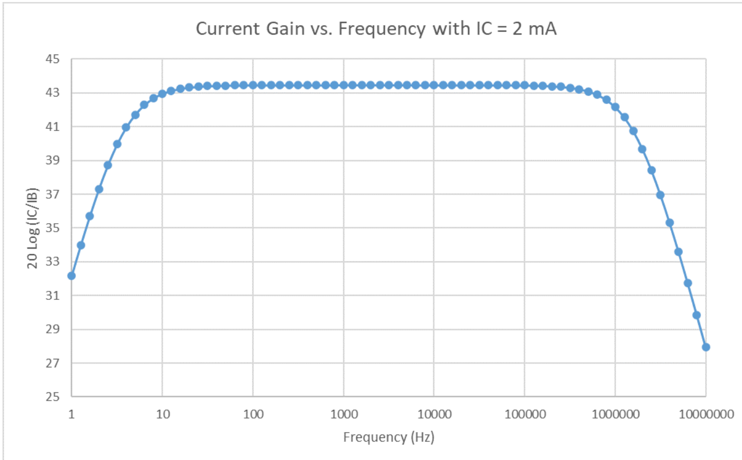


Figure 29: Frequency vs. Current Gain with $I_C = 2$ mA

Table 10: Measured and Calculated Parameters to Unity Gain Bandwidth

$h_{fe_{avg}}$	f_β
148.53	1.58 MHz

Using the measured data in Table 10 above, the unity-gain bandwidth is calculated as follows:

$$f_T = h_{fe} * f_\beta = (148.53)(1.58MHz) = 233.84$$

The Unity-Gain Bandwidth, f_T, is equal **233.84 MHz** when $I_C = 2$ mA.

Figure 30 below illustrates the test circuit, for $I_C = 0.50$ mA, and the simulation probes used in this part of the experiment.

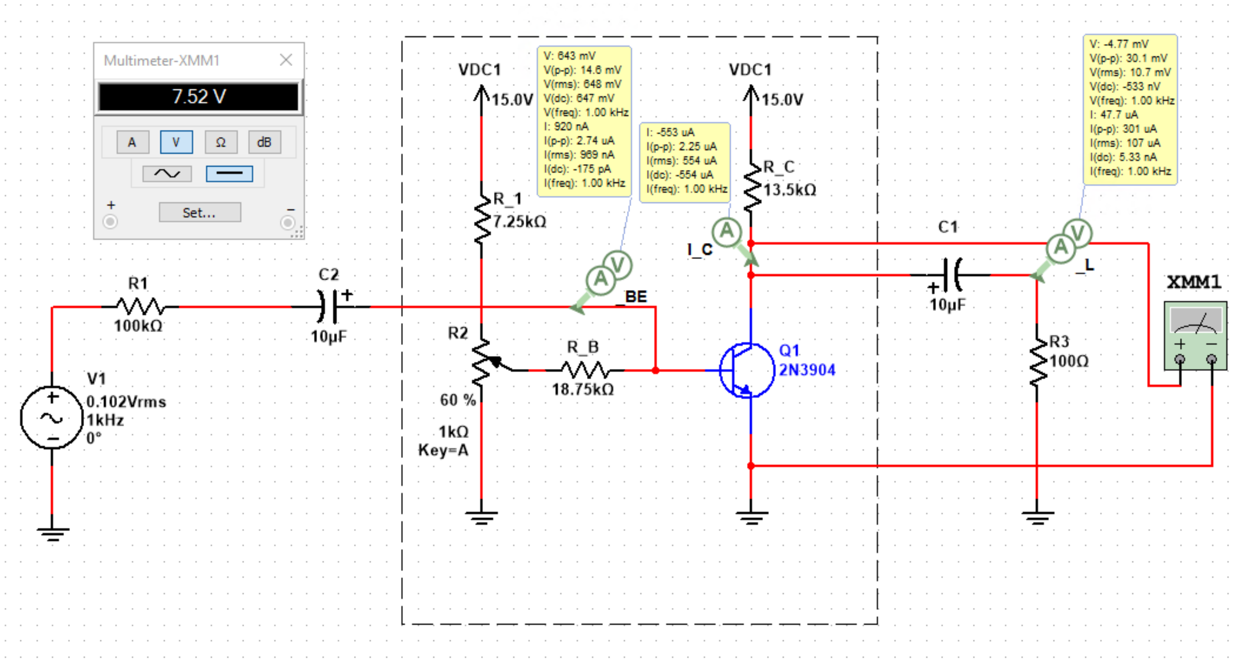


Figure 30: The Test Circuit for The Current Gain for $I_C = 0.50$ mA

Figure 31 below illustrates the AC sweep settings of the test circuit used in this part of the experiment.

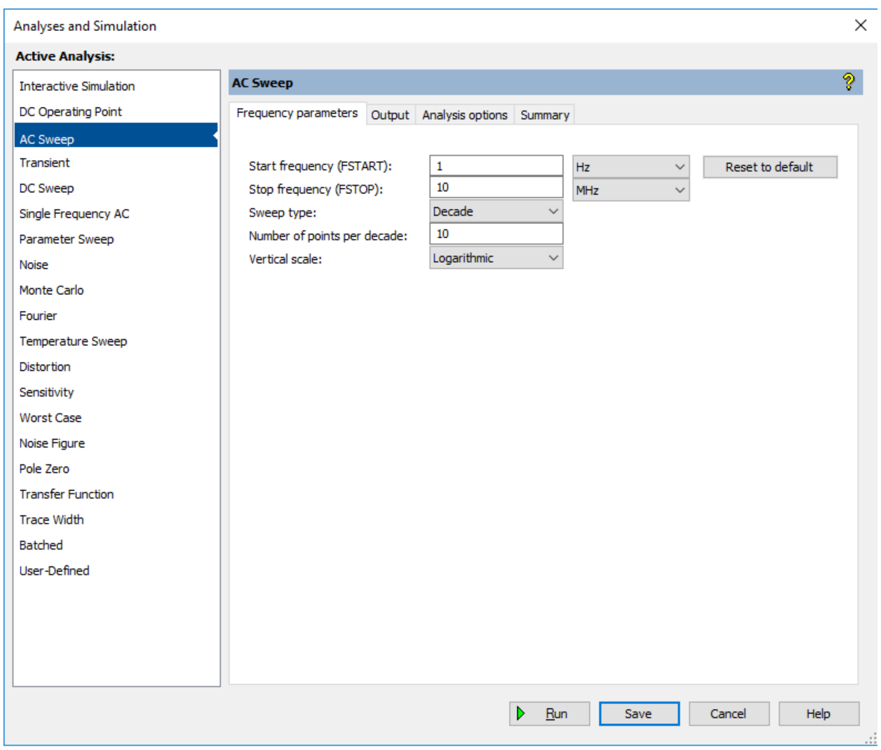


Figure 31: AC Sweep Simulation Settings for $I_C = 0.50$ mA

Table 11: Measured Data to Calculate The Current Gain with $I_C = 0.5$ mA

f (Hz)	IB (A)	IL (A)	hfe	20 Log (hfe)
1	9.39161E-06	0.000639934	68.13890004	36.66790237
1.258925412	9.43057E-06	0.000731697	77.58783938	37.79587316
1.584893192	9.4554E-06	0.000813695	86.05612853	38.69563608
1.995262315	9.47117E-06	0.000881587	93.08111752	39.37723177
2.511886432	9.48116E-06	0.000934008	98.5119441	39.8697778
3.16227766	9.48748E-06	0.00097219	102.4707451	40.21199788
3.981071706	9.49148E-06	0.000998775	105.2286369	40.4426789
5.011872336	9.494E-06	0.001016691	107.0877628	40.59479691
6.309573445	9.49559E-06	0.001028494	108.3127653	40.69359288
7.943282347	9.4966E-06	0.001036152	109.1076685	40.75710551
10	9.49723E-06	0.001041071	109.6183159	40.79766251
12.58925412	9.49763E-06	0.00104421	109.9442259	40.82344851
15.84893192	9.49789E-06	0.001046205	110.151363	40.83979751
19.95262315	9.49805E-06	0.00104747	110.2826617	40.85014479
25.11886432	9.49815E-06	0.00104827	110.3657475	40.85668619
31.6227766	9.49821E-06	0.001048776	110.4182679	40.8608186
39.81071706	9.49825E-06	0.001049096	110.4514446	40.86342801
50.11872336	9.49828E-06	0.001049297	110.472393	40.86507524
63.09573445	9.49829E-06	0.001049425	110.4856167	40.86611489
79.43282347	9.4983E-06	0.001049505	110.4939628	40.86677099
100	9.49831E-06	0.001049556	110.4992297	40.86718501
125.8925412	9.49831E-06	0.001049588	110.5025532	40.86744625
158.4893192	9.49832E-06	0.001049608	110.5046502	40.86761108
199.5262315	9.49832E-06	0.001049621	110.5059732	40.86771507
251.1886432	9.49832E-06	0.001049629	110.5068077	40.86778067
316.227766	9.49832E-06	0.001049634	110.5073338	40.86782202
398.1071706	9.49832E-06	0.001049637	110.5076651	40.86784805
501.1872336	9.49832E-06	0.001049639	110.5078729	40.86786439
630.9573445	9.49832E-06	0.00104964	110.5080023	40.86787456
794.3282347	9.49832E-06	0.001049641	110.508081	40.86788075
1000	9.49832E-06	0.001049642	110.5081262	40.8678843
1258.925412	9.49832E-06	0.001049642	110.5081476	40.86788598
1584.893192	9.49832E-06	0.001049642	110.5081497	40.86788615
1995.262315	9.49832E-06	0.001049642	110.5081331	40.86788484
2511.886432	9.49832E-06	0.001049641	110.5080941	40.86788178
3162.27766	9.49832E-06	0.001049641	110.5080243	40.86787629
3981.071706	9.49832E-06	0.00104964	110.5079088	40.86786721
5011.872336	9.49832E-06	0.001049638	110.5077224	40.86785256
6309.573445	9.49833E-06	0.001049636	110.5074251	40.86782919
7943.282347	9.49833E-06	0.001049632	110.5069525	40.86779205
10000	9.49834E-06	0.001049625	110.5062029	40.86773313
12589.25412	9.49835E-06	0.001049615	110.5050143	40.8676397
15848.93192	9.49836E-06	0.001049599	110.5031302	40.86749161
19952.62315	9.49839E-06	0.001049573	110.5001442	40.86725689
25118.86432	9.49843E-06	0.001049533	110.495412	40.86688491
31622.7766	9.49849E-06	0.001049468	110.4879132	40.86629542
39810.71706	9.49859E-06	0.001049366	110.4760314	40.8653613
50118.72336	9.49875E-06	0.001049205	110.4572079	40.86388122
63095.73445	9.499E-06	0.00104895	110.4273943	40.86153649
79432.82347	9.49939E-06	0.001048545	110.3801924	40.85782294
100000	9.50002E-06	0.001047904	110.3055062	40.85194384
125892.5412	9.50101E-06	0.001046892	110.1874465	40.84264237
158489.3192	9.50257E-06	0.001045293	110.0011085	40.82794123
199526.2315	9.50502E-06	0.001042774	109.7077093	40.80474295
251188.6432	9.50885E-06	0.001038818	109.2474742	40.7682281
316227.766	9.51481E-06	0.00103264	108.5297692	40.71097759
398107.1706	9.52396E-06	0.00102307	107.420703	40.62175981
501187.2336	9.53777E-06	0.001008434	105.7305463	40.48400952
630957.3445	9.55809E-06	0.000986471	103.2079556	40.27426351
794328.2347	9.58686E-06	0.000954423	99.55533865	39.96129108
1000000	9.62548E-06	0.000909467	94.48538925	39.50729313
1258925.412	9.67377E-06	0.000849639	87.82922314	38.87278083
1584893.192	9.72906E-06	0.000775075	79.66602498	38.02546296
1995262.315	9.78632E-06	0.000688861	70.39014802	36.95023757
2511886.432	9.83981E-06	0.000596651	60.63641659	35.65467056
3162277.66	9.88513E-06	0.000505001	51.08688051	34.16618769
3981071.706	9.92049E-06	0.000419451	42.28129848	32.52296632
5011872.336	9.94633E-06	0.000343456	34.53087468	30.76415159
6309573.445	9.96433E-06	0.000278371	27.93672882	28.92351104
7943282.347	9.97645E-06	0.000224044	22.45726006	27.02713536
10000000	9.98443E-06	0.000179479	17.97583726	25.09378255

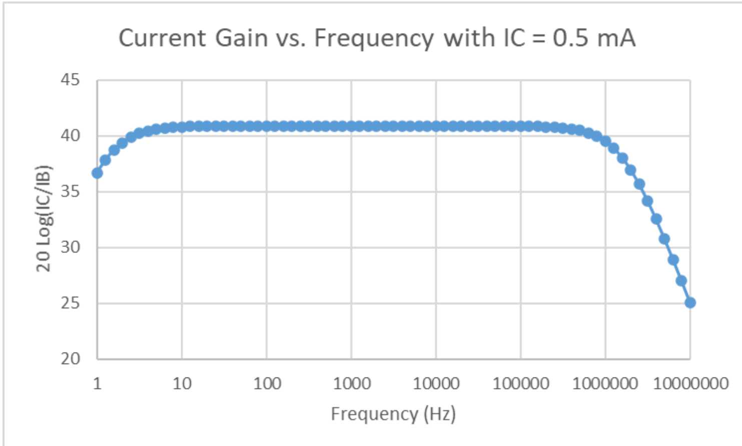


Figure 32: Frequency vs. Current Gain with $I_C = 0.5$ mA

As shown in Figure 30 above, the collector resistor (R_C) was set to **13.5 kΩ** to maintain a collector-emitter voltage (V_{CE}) of approximately 7.5 volts.

Then, the potentiometer percentage was adjusted to 60% so that the collector current (I_C) is set to approximately 0.5 mA.

As shown in Figure 30 above, the actual collector-emitter voltage (V_{CE}) was measured and found to be **7.52 volts**.

Table 12: Measured and Calculated Parameters to Unity Gain Bandwidth

$h_{fe_{avg}}$	f_β
110.30	1.58 MHz

Using the measured data in Table 12 above, the unity-gain bandwidth is calculated as follows:

$$f_T = h_{fe} * f_\beta = (110.30)(1.58MHz) = 174.27$$

The Unity-Gain Bandwidth, f_T, is equal **174.27 MHz** when $I_C = 0.5$ mA.

Figure 33 below illustrates the test circuit, for $I_C = 1$ mA, and the simulation probes used in this part of the experiment.

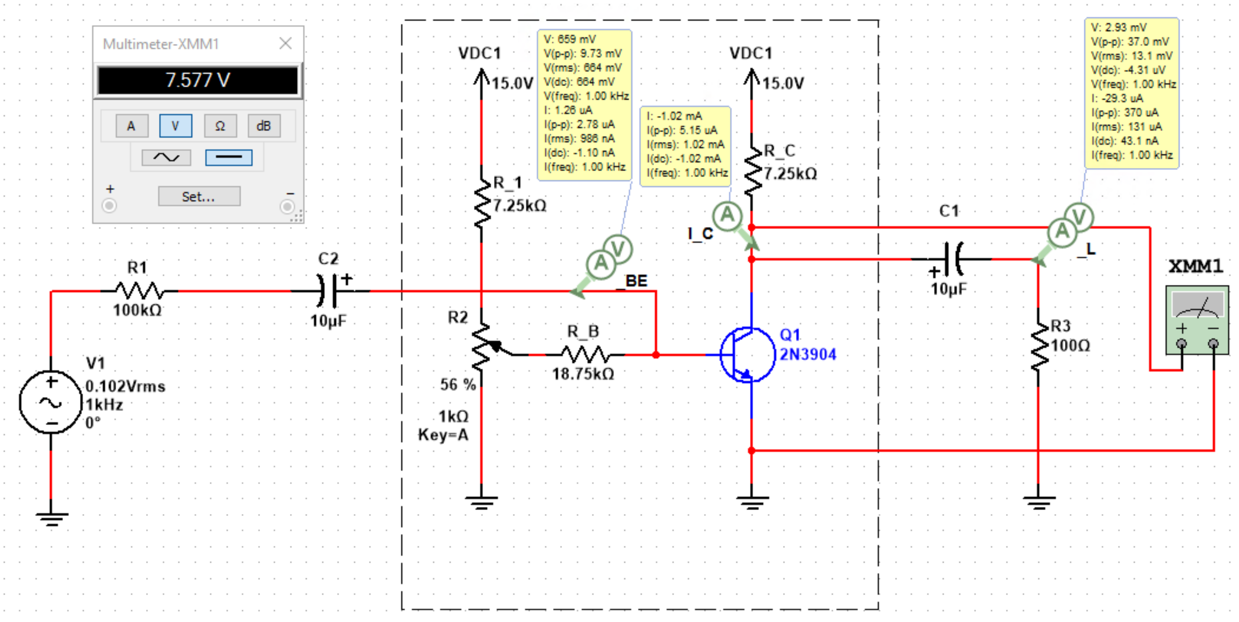


Figure 33: The Test Circuit for The Current Gain for $I_C = 1$ mA

Figure 34 below illustrates the AC sweep settings of the test circuit used in this part of the experiment.

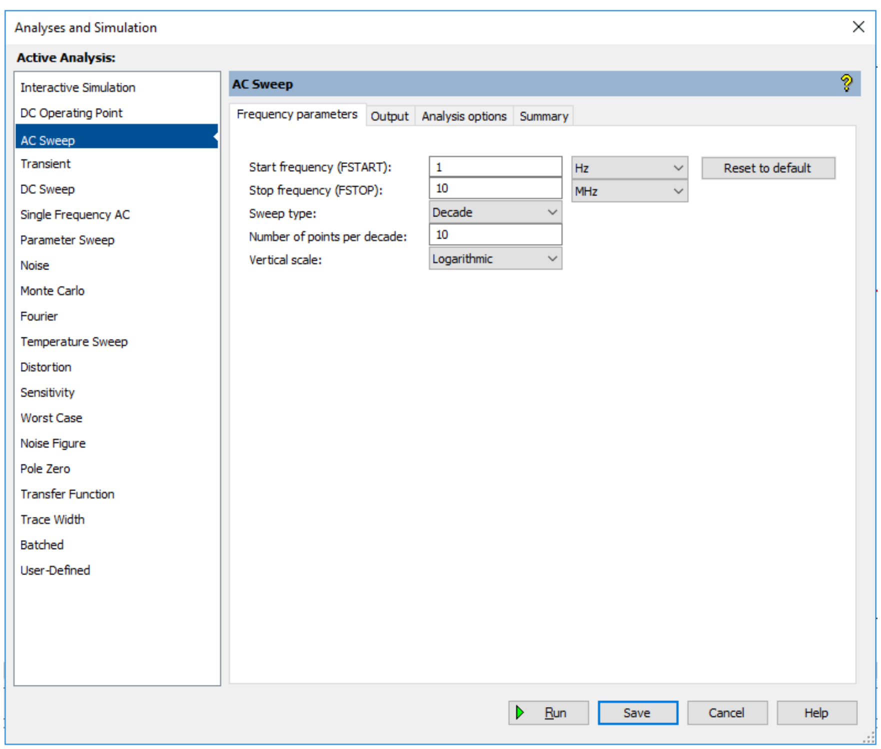


Figure 34: AC Sweep Simulation Settings for $I_C = 1$ mA

Table 13: Measured Data to Calculate The Current Gain with $I_C = 1$ mA

f (Hz)	IB (A)	IL (A)	hfe	20 Log (hfe)
1	9.55169E-06	0.000495924	51.92001708	34.30669653
1.258925412	9.59268E-06	0.000600843	62.63560812	35.93642597
1.584893192	9.61882E-06	0.000713666	74.19479098	37.40746831
1.995262315	9.63542E-06	0.000827909	85.92349636	38.68223882
2.511886432	9.64594E-06	0.000935602	96.99434593	39.73492838
3.16227766	9.6526E-06	0.001029569	106.6623478	40.56022278
3.981071706	9.65681E-06	0.001105599	114.4890898	41.17528205
5.011872336	9.65946E-06	0.001163139	120.4144706	41.61357362
6.309573445	9.66114E-06	0.001204388	124.6631113	41.91475923
7.943282347	9.6622E-06	0.001232772	127.5871176	42.11613652
10	9.66287E-06	0.001251742	129.5414624	42.24817591
12.58925412	9.66329E-06	0.001264169	130.8217818	42.3336012
15.84893192	9.66356E-06	0.001272202	131.6494126	42.38837851
19.95262315	9.66373E-06	0.001277349	132.1797659	42.42329957
25.11886432	9.66383E-06	0.001280629	132.5177127	42.44547862
31.6227766	9.6639E-06	0.001282711	132.7322811	42.45953116
39.81071706	9.66394E-06	0.00128403	132.8682022	42.46842117
50.11872336	9.66397E-06	0.001284865	132.9541777	42.47403976
63.09573445	9.66398E-06	0.001285392	133.0085105	42.4775886
79.43282347	9.66399E-06	0.001285725	133.0428264	42.47982925
100	9.664E-06	0.001285935	133.0644919	42.4812436
125.8925412	9.66401E-06	0.001286068	133.0781673	42.48213623
158.4893192	9.66401E-06	0.001286152	133.0867979	42.48269952
199.5262315	9.66401E-06	0.001286205	133.0922442	42.48305496
251.1886432	9.66401E-06	0.001286238	133.0956805	42.48327922
316.227766	9.66401E-06	0.001286259	133.0978483	42.48342069
398.1071706	9.66401E-06	0.001286272	133.0992154	42.48350991
501.1872336	9.66401E-06	0.001286281	133.1000767	42.48356612
630.9573445	9.66401E-06	0.001286286	133.1006181	42.48360145
794.3282347	9.66401E-06	0.001286289	133.1009566	42.48362353
1000	9.66401E-06	0.001286291	133.1011651	42.48363714
1258.925412	9.66401E-06	0.001286293	133.1012886	42.4836452
1584.893192	9.66401E-06	0.001286293	133.1013538	42.48364945
1995.262315	9.66401E-06	0.001286293	133.1013748	42.48365082
2511.886432	9.66401E-06	0.001286293	133.1013561	42.4836496
3162.27766	9.66401E-06	0.001286293	133.1012936	42.48364553
3981.071706	9.66401E-06	0.001286292	133.101174	42.48363772
5011.872336	9.66402E-06	0.00128629	133.1009713	42.48362449
6309.573445	9.66402E-06	0.001286287	133.1006418	42.48360299
7943.282347	9.66402E-06	0.001286282	133.1001144	42.48356857
10000	9.66402E-06	0.001286275	133.0992752	42.48351381
12589.25412	9.66403E-06	0.001286263	133.0979433	42.48342689
15848.93192	9.66404E-06	0.001286243	133.095831	42.48328904
19952.62315	9.66406E-06	0.001286213	133.0924827	42.48307053
25118.86432	9.66408E-06	0.001286165	133.087176	42.48272419
31622.7766	9.66412E-06	0.001286089	133.0787663	42.48217533
39810.71706	9.66419E-06	0.001285969	133.0654411	42.48130556
50118.72336	9.66429E-06	0.001285778	133.04433	42.47992741
63095.73445	9.66445E-06	0.001285477	133.0108916	42.47774409
79432.82347	9.6647E-06	0.001284999	132.9579469	42.47428601
100000	9.6651E-06	0.001284242	132.8741646	42.46881094
125892.5412	9.66573E-06	0.001283046	132.7417024	42.46014766
158489.3192	9.66673E-06	0.001281156	132.532573	42.44645259
199526.2315	9.6683E-06	0.001278179	132.2031405	42.42483544
251188.6432	9.67075E-06	0.001273503	131.6860203	42.39079346
316227.766	9.67457E-06	0.001266195	130.8787272	42.33738125
398107.1706	9.68044E-06	0.001254867	129.6291223	42.25405161
501187.2336	9.68932E-06	0.001237519	127.7199278	42.12517329
630957.3445	9.70242E-06	0.001211441	124.8596155	41.92843986
794328.2347	9.72106E-06	0.001173288	120.6954564	41.63381843
1000000	9.74623E-06	0.001119573	114.8724408	41.20431698
1258925.412	9.77795E-06	0.001047752	107.154562	40.60021331
1584893.192	9.81461E-06	0.000957731	97.58222621	39.78741444
1995262.315	9.85297E-06	0.000852998	86.57263766	38.74761299
2511886.432	9.88916E-06	0.000740288	74.8585381	37.48482683
3162277.66	9.92011E-06	0.000627641	63.26958622	36.02389988
3981071.706	9.94443E-06	0.000522013	52.49301972	34.40203114
5011872.336	9.9623E-06	0.000427855	42.94741341	32.65874026
6309573.445	9.9748E-06	0.000347015	34.78911675	30.82886805
7943282.347	9.98324E-06	0.00027942	27.98890102	28.93971693
10000000	9.98881E-06	0.000223907	22.41583098	27.01109687

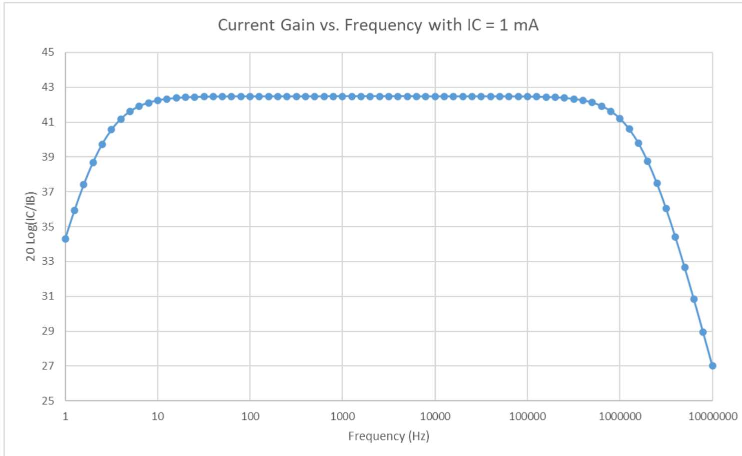


Figure 35: Frequency vs. Current Gain with $I_C = 0.5$ mA

As shown in Figure 33 above, the collector resistor (R_C) was set to **7.25 kΩ** to maintain a collector-emitter voltage (V_{CE}) of approximately 7.5 volts.

Then, the potentiometer percentage was adjusted to 56% so that the collector current (I_C) is set to approximately 1 mA.

As shown in Figure 33 above, the actual collector-emitter voltage (V_{CE}) was measured and found to be **7.577 volts**.

Table 14: Measured and Calculated Parameters to Unity Gain Bandwidth

$h_{fe_{avg}}$	f_β
132.53	1.58 MHz

Using the measured data in Table 14 above, the unity-gain bandwidth is calculated as follows:

$$f_T = h_{fe} * f_\beta = (132.53)(1.58MHz) = 209.39$$

The Unity-Gain Bandwidth, f_T, is equal **209.39 MHz** when $I_C = 1$ mA.

4.2 The BJT High-Frequency Hybrid-Pi Model

Figure 36 below shows the high-frequency hybrid-pi model of a BJT.

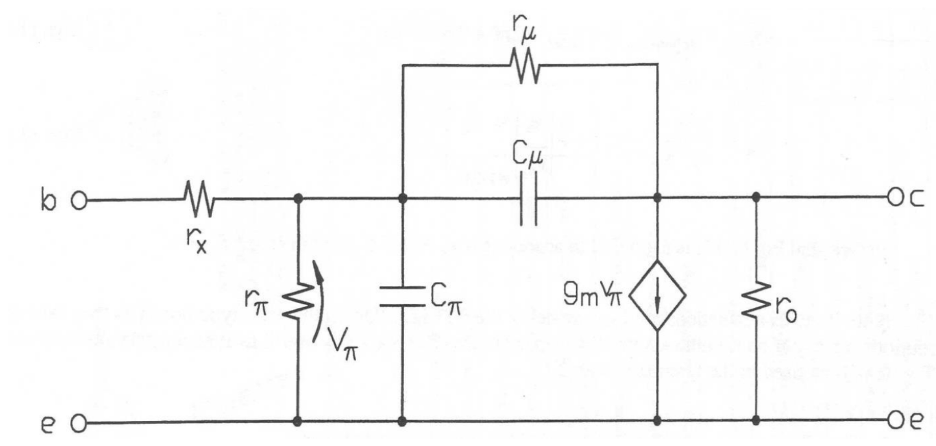


Figure 36: The High-Frequency Hybrid-Pi Model of a BJT

The equations below define its elemental values in terms of the previously measured circuit parameters.

4.2.1 Calculations given $I_C = 2$ mA

$$g_m = \frac{I_C}{V_T} = \frac{2mA}{25mV} = 80 \; milli \; mhos$$

$$r_\pi = \frac{h_{fe}}{g_m} = \frac{148.53}{0.08} = 1.856k\Omega$$

$$r_x = h_{ie} - r_\pi = 1.976k\Omega - 1.856k\Omega = 120\Omega$$

$$r_\mu = \frac{r_\pi}{h_{re}} \approx \infty$$

$$r_o = (h_{oe} - \frac{h_{fe}}{r_\mu})^{-1} \approx {h_{oe}}^{-1} \approx (22.8 \; \mu mhos)^{-1} \approx 44k\Omega$$

$$\omega_\beta = 2\pi f_\beta = (2\pi)(1.58MHz) = 9.93 \; Mrad/sec$$

$$C_\mu = C_{BC_{junction}} + C_{board} \approx 2pf + 2pf = 4pf$$

$$C_\pi = \frac{1}{r_\pi * \omega_\beta} - C_\mu \left[1 + \left| \frac{v_o}{v_{be}} \right|_{@1kHz} \right] = \frac{1}{(1.856k\Omega)(9.93 \; Mrad/sec)} - (4pf) \left[1 + \left| \frac{1.02\mu V}{684mV} \right|_{@1kHz} \right] \approx 50pf$$

4.2.2 Calculations given $I_C = 0.5$ mA

$$g_m = \frac{I_C}{V_T} = \frac{0.5mA}{25mV} = 20\ milli\ mhos$$

$$r_\pi = \frac{h_{fe}}{g_m} = \frac{110.30}{0.02} = 5.515k\Omega$$

$$r_x = h_{ie} - r_\pi = 1.976k\Omega - 5.515k\Omega = -3.539k\Omega \approx 0$$

$$r_\mu = \frac{r_\pi}{h_{re}} \approx \infty$$

$$r_o = (h_{oe} - \frac{h_{fe}}{r_\mu})^{-1} \approx {h_{oe}}^{-1} \approx (22.8\ \mu mhos)^{-1} \approx 44k\Omega$$

$$\omega_\beta = 2\pi f_\beta = (2\pi)(1.58MHz) = 9.93\ Mrad/sec$$

$$C_\mu = C_{BC_{junction}} + C_{board} \approx 2pf + 2pf = 4pf$$

$$C_\pi = \frac{1}{r_\pi * \omega_\beta} - C_\mu \left[1 + \left|\frac{v_o}{v_{be}}\right|_{@1kHz}\right] = \frac{1}{(1.856k\Omega)(9.93\ Mrad/sec)} - (4pf)\left[1 + \left|\frac{533nV}{647mV}\right|_{@1kHz}\right] \approx 50pf$$

4.2.3 Calculations given $I_C = 1$ mA

$$g_m = \frac{I_C}{V_T} = \frac{1mA}{25mV} = 40\ milli\ mhos$$
$$r_\pi = \frac{h_{fe}}{g_m} = \frac{132.53}{0.04} = 3.313k\Omega$$
$$r_x = h_{ie} - r_\pi = 1.976k\Omega - 3.313k\Omega = -1.337k\Omega \approx 0$$
$$r_\mu = \frac{r_\pi}{h_{re}} \approx \infty$$
$$r_o = (h_{oe} - \frac{h_{fe}}{r_\mu})^{-1} \approx {h_{oe}}^{-1} \approx (22.8\ \mu mhos)^{-1} \approx 44k\Omega$$
$$\omega_\beta = 2\pi f_\beta = (2\pi)(1.58MHz) = 9.93\ Mrad/sec$$
$$C_\mu = C_{BC_{junction}} + C_{board} \approx 2pf + 2pf = 4pf$$
$$C_\pi = \frac{1}{r_\pi * \omega_\beta} - C_\mu \left[1 + \left|\frac{v_o}{v_{be}}\right|_{@1kHz}\right] = \frac{1}{(1.856k\Omega)(9.93\ Mrad/sec)} - (4pf)\left[1 + \left|\frac{4.31\mu V}{664mV}\right|_{@1kHz}\right] \approx 50pf$$

5 Conclusion

In conclusion, a full DC and AC analysis was performed for several different BJT circuits. After discovering that the 2N3904 transistor is an NPN BJT type and the 2N3906 transistor is a PNP BJT type, the DC output characteristics were found for the NPN BJT. It was seen that V_{BE} remains constant while V_{CE} increases (only when BJT is operating in the active region). Once the BJT enters the saturation mode, V_{BE} starts to slowly decrease.

Two NPN BJTs were used to create both a 1:1 and 1:2 current mirror, which could be used as a current source. It was observed that the amplified output current (in the case of the 1:2 current mirror) did not change drastically in value for all load resistance values that kept the BJT in the active mode. This circuit will be useful in the future as a current source, as different circuits with varying "load resistances" will connect to it (while receiving the same current input).

A full AC analysis was performed on the BJT by attaching an AC source using capacitors. The capacitors blocked all DC signals, so a detailed AC analysis was possible to achieve. Many small signal model parameters were derived and calculated.

Finally, the values obtained in Part 4 were used to calculate the remaining small signal parameters, including g_m and C_π. The value of C_π was found to be 50pf, which will be useful in the future for the design of an amplifier circuit.

6 References

[1] "Lab 1: The Bipolar Junction Transistor (BJT): DC and AC Characterization," Carleton Univeristy, Ottawa, 2017.