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

ELEC 3509A – L6

Lab 1 Report

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Part 1: Diode-Like Behavior of BJT Junctions, and BJT Type

Report:

1. Show your resulting bias voltages for the NPN and PNP BJT in a table and explain your conclusions. Which region is the transistor in for each bias?

NPN (2N3904)		
V_{BE}	V_{CE}	V_{BC}
0.689808	OPEN	0.668290
V_{EB}	V_{EC}	V_{CB}
OPEN	OPEN	OPEN

Table 1: NPN Forward and Reverse Bias Voltages

Table 1 shows that the NPN BJT has a base-emitter voltage of approximately 0.7 V, which means that the base-emitter junction is forward biased, and it acts as a diode when the BJT is in active mode. Also it is shown that the base-collector voltage is approximately 0.67 V, hence the voltage in the base-collector junction is less than the voltage in the base-emitter junction, which means that the base-emitter junction is in reverse bias and acts like an open circuit.

PNP (2N3906)		
V_{BE}	V_{CE}	V_{BC}
OPEN	OPEN	OPEN
V_{EB}	V_{EC}	V_{CB}
0.761639	OPEN	0.759076

Table 2: PNP Forward and Reverse Bias Voltages

Table 2 shows that the PNP BJT has an emitter-base voltage of approximately 0.76 V, which means that the emitter-base junction is forward biased, and it acts as a diode when the BJT is in active mode. Also it is shown that the collector-base voltage is approximately 0.76 V, hence the voltage in the collector-base junction is less than the voltage in the emitter-base junction, which means that the emitter-base junction is in reverse bias and acts like an open circuit.

Part 2: BJT IC vs. VCE Characteristic Curves - Point by Point Plotting

Report:

1. Plot the IC-VCE line for the base current that was used. Determine the IC/IB current ratio for the transistor at each point.

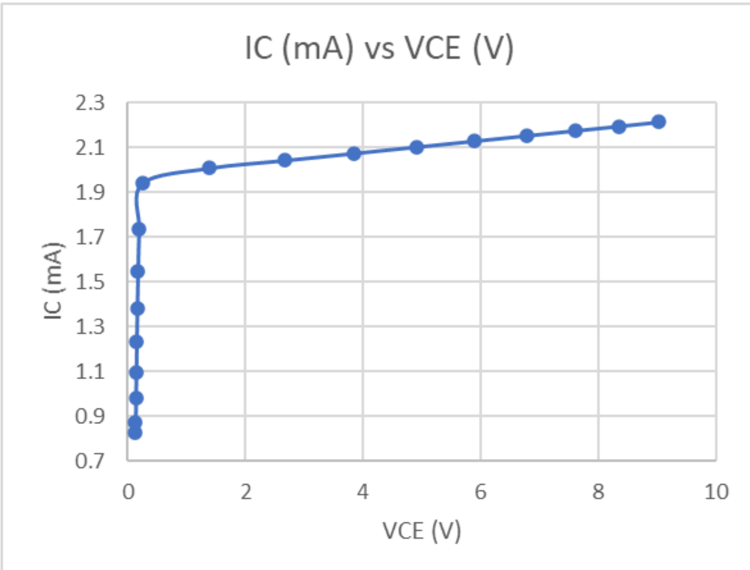


Figure 1: Collector Current vs Collector-Emitter Voltage

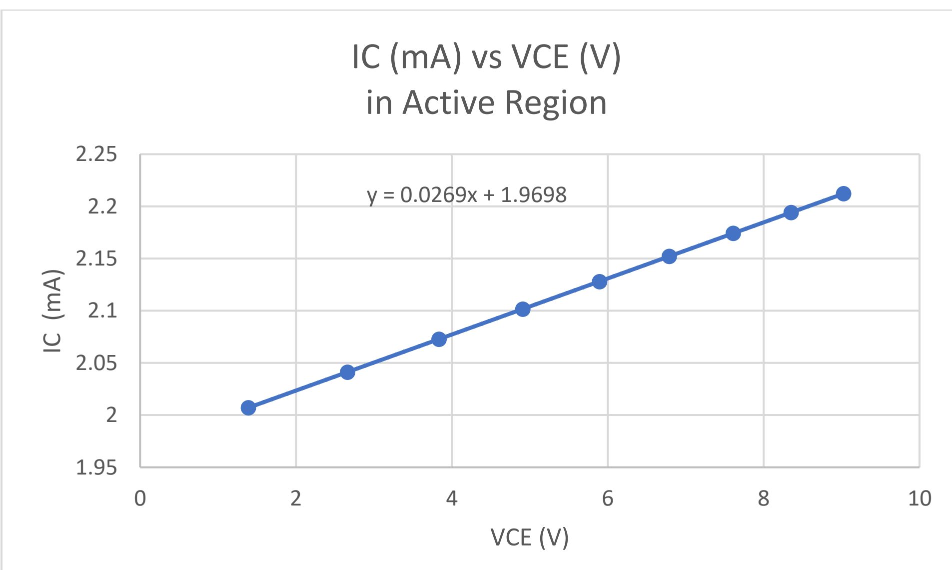


Figure 2: Collector Current vs Collector-Emitter Voltage in Active Region

RC (Ω)	IC (mA)	IB (mA)	VCE (V)	VBE (V)	β = IC/IB
2700	2.212255978	0.013808075	9.026908811	0.6839986	160.2146504
3029.449827	2.194154757	0.013808076	8.352917822	0.683998599	158.9037337
3399.098612	2.174194231	0.013808076	7.609696338	0.683998597	157.4581636
3813.85137	2.152226344	0.013808076	6.791731508	0.683998595	155.8672174
4279.21162	2.128100381	0.013808076	5.893411518	0.683998592	154.1199804
4801.354407	2.101666655	0.013808076	4.909162757	0.68399859	152.2056118
5387.20825	2.072778096	0.013808076	3.833509071	0.683998587	150.1134607
6044.547074	2.041295963	0.013808076	2.661284455	0.683998584	147.8334793
6782.093365	2.007092184	0.013808076	1.38772015	0.68399858	145.3563925
7609.633914	1.939383936	0.013833882	0.242005813	0.683502633	140.1908649
8538.149682	1.734544006	0.013985197	0.190203093	0.680594606	124.027137
9579.961509	1.547817691	0.01413954	0.171968419	0.677628394	109.467329
10748.8936	1.380601908	0.014293881	0.16004815	0.674662226	96.58692101
12060.45699	1.231218243	0.014447824	0.150892518	0.671703695	85.21825028
13532.05531	1.097886183	0.014601218	0.143294764	0.668755709	75.19141189
15183.21578	0.978930916	0.014753982	0.136697374	0.665819841	66.35028723
17035.8483	0.872821246	0.014906062	0.13079654	0.662897105	58.55478423
18000	0.826213078	0.014978529	0.12816459	0.661504407	55.15982728

Figure 3: Values of IC, IB, VCE, VBE, and β for Different Values of RC

2. Plot VBE vs. VCE. Does VBE change very much as VCE is changed? Why? What happens to this current ratio when the transistor goes into saturation?

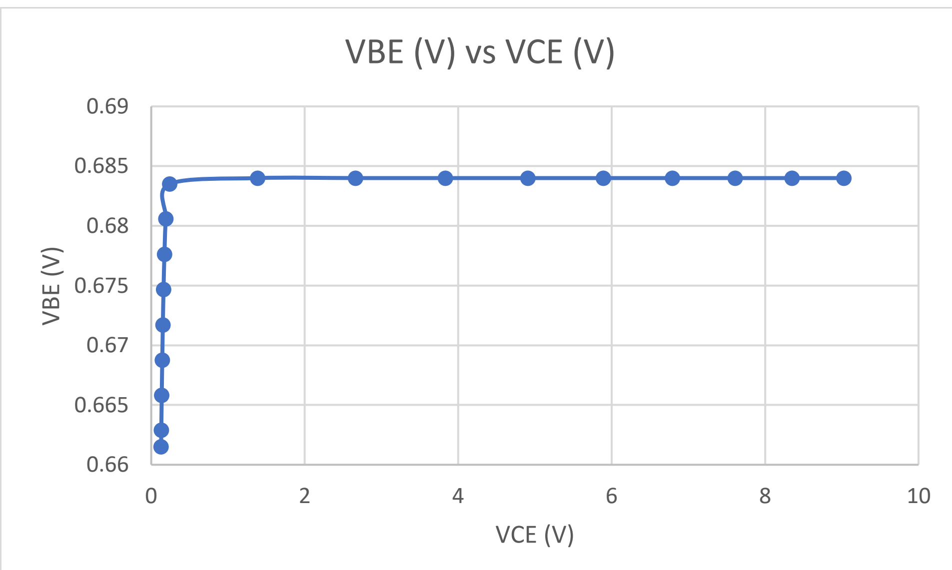


Figure 4: Base-Emitter Voltage vs Collector-Emitter Voltage

Figure 4 above shows that at active region VBE is approximately constant as VCE increases. But, when the BJT enters the saturation region, VBE starts to decrease. IC decrease while IB stays the same, hence decreasing the current ratio.

3. From your plot, determine the value of beta and a value for the Early voltage VA.

Figure 3 above shows the β for different RC values, and the approximate β value for the BJT in the active region is equal to 153.56.

To determine the Early Voltage, we must find the x-intercept of the equation of IC vs VCE from the Figure 2 above.

$$y = 0.0269x + 1.9698$$

By substituting y with zero, we get:

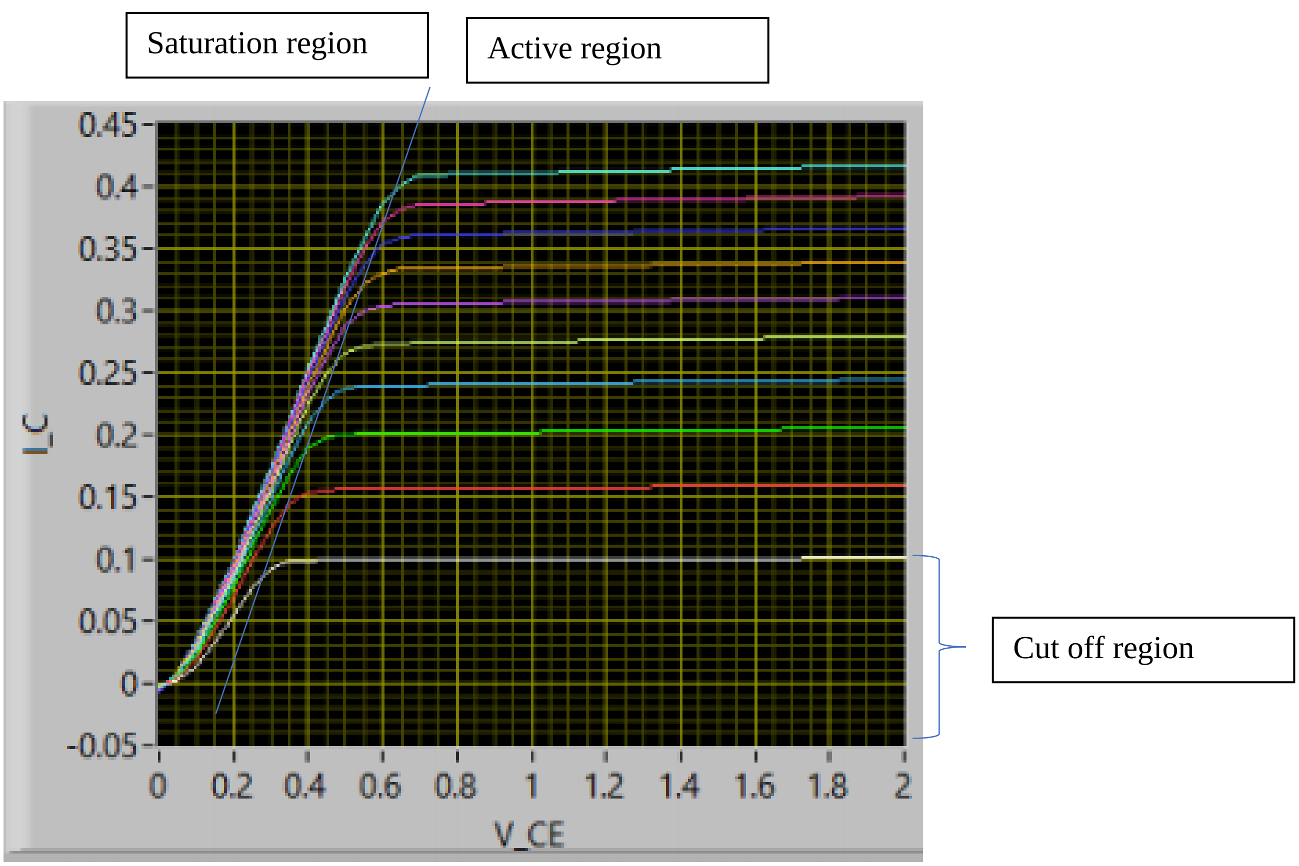
$$x = -1.9698/0.0269$$

$$x = -73.23 \text{ V}$$

Hence, the Early voltage VA is equal to -73.23 V.

4. Define each of the regions the from the IC-VCE for your graph and for figure 2 of the introduction.

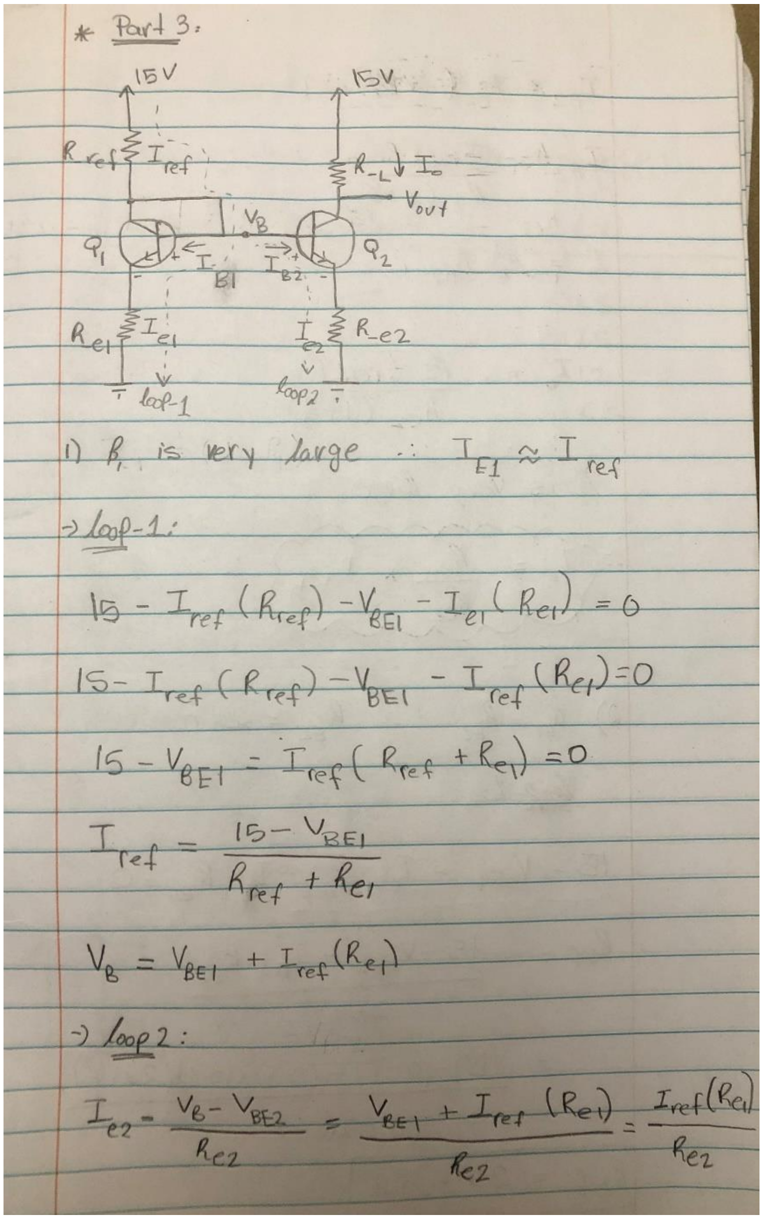
Active region is where the graph slope is almost flat. Saturation region is the region where the graph have a very steep slope



Part 3: The Current Mirror

Report:

1. Show your derivations for your equation for the current mirror's output current and the 1:2 current multiplier.



* Part 3:

1) β_1 is very large $\therefore$ $I_{E1} \approx I_{ref}$

→ loop-1:

$$15 - I_{ref}(R_{ref}) - V_{BE1} - I_{e1}(R_{e1}) = 0$$

$$15 - I_{ref}(R_{ref}) - V_{BE1} - I_{ref}(R_{e1}) = 0$$

$$15 - V_{BE1} = I_{ref}(R_{ref} + R_{e1}) = 0$$

$$I_{ref} = \frac{15 - V_{BE1}}{R_{ref} + R_{e1}}$$

$$V_B = V_{BE1} + I_{ref}(R_{e1})$$

→ loop 2:

$$I_{e2} = \frac{V_B - V_{BE2}}{R_{e2}} = \frac{V_{BE1} + I_{ref}(R_{e1})}{R_{e2}} = \frac{I_{ref}(R_{e1})}{R_{e2}}$$

$$I_{E2} = I_{B2}(1+\beta_2)$$

$$\therefore I_{B2} = \frac{I_{ref}(R_{e1})}{R_{e2}(1+\beta_2)}$$

$$I_o = \beta_2 I_{B2}$$

$$I_o = \frac{\beta_2 I_{ref} R_{e1}}{R_{e2}(1+\beta_2)}$$

β_2 is very large

$$\therefore \boxed{I_o = \frac{R_{e1}}{R_{e2}} \times I_{ref}}$$

4) $I_{out} = \frac{R_{e1}}{R_{e2}} \times I_{ref}$

$R_{e1} = 2k\Omega$

$\therefore$ R_{e2} should be equal to $1k\Omega$ to create a 1:2 current multiplyer

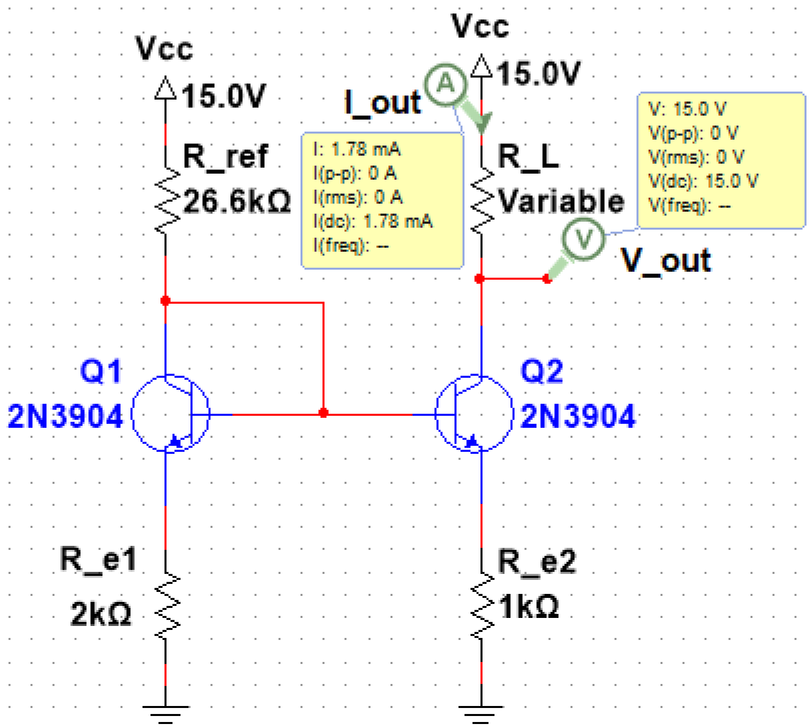


Figure 5: 1 to 2 Current Multiplier Circuit

2. With your measurements from your 1:1 mirror, plot output current vs. load resistance and output voltage vs output current. From the second plot, determine the output impedance. Keep in mind that a current mirror can be modeled as an ideal current source in parallel with a large resistance (which is its output resistance). Do this for both the simulation and the hardware circuits and compare.

RL (kΩ)	IOUT (mA)	VOUT (V)	RREF (kΩ)
7	0.496313291	11.52580697	26.6
7.85412918	0.496219724	11.10262578	26.6
8.812477883	0.496114069	10.62800469	26.6
9.887762812	0.495994664	10.09572381	26.6
11.09425235	0.495859587	9.498784978	26.6
12.44795587	0.495706635	8.829443802	26.6
13.9668362	0.495533234	8.078986433	26.6
15.67104797	0.495336358	7.237583935	26.6
17.58320502	0.495112482	6.294338215	26.6
19.72868052	0.494857451	5.237105805	26.6
22.13594362	0.494566334	4.052329082	26.6
24.83693725	0.494233204	2.724779328	26.6
27.86750194	0.49374681	1.240510766	26.6
31.26785145	0.446586326	1.036183422	26.6
35.08310635	0.399838341	0.972431496	26.6
39.36389276	0.35765401	0.921343317	26.6
44.16701411	0.319748269	0.877678207	26.6
49.55620491	0.285744854	0.839570864	26.6
55.60297643	0.255273899	0.80600537	26.6
62.38756567	0.22798924	0.776298484	26.6
70	0.203572362	0.749934684	26.6
73	0.19532777	0.741072758	26.6

Figure 6: Values for IOUT, and VOUT for Different values of RL

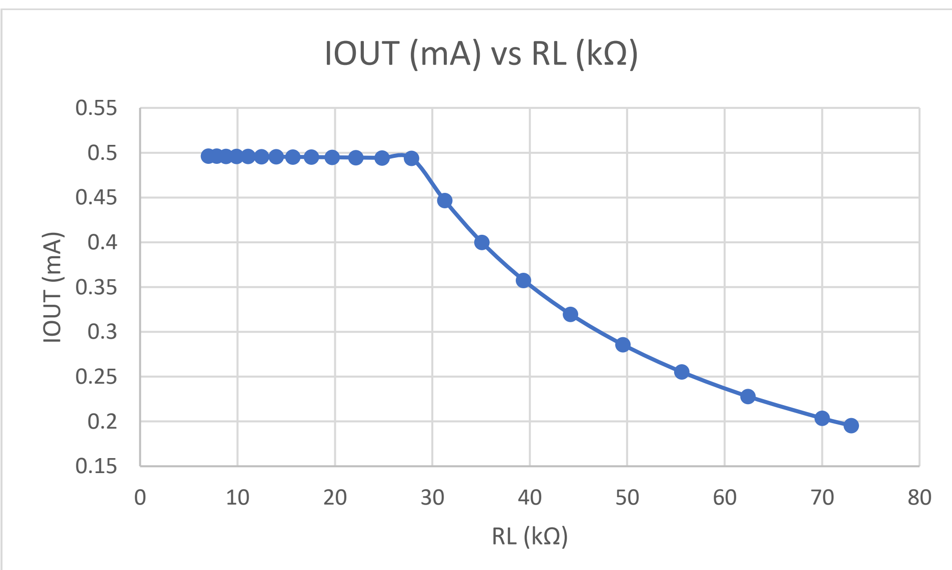


Figure 7: Output Current vs Resistive Load

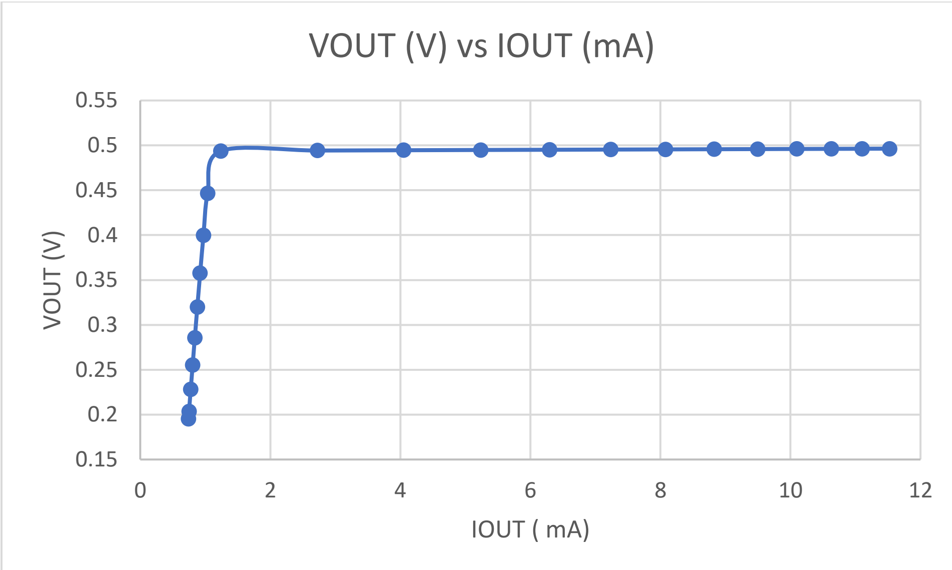


Figure 8: Output Voltage vs Output Current

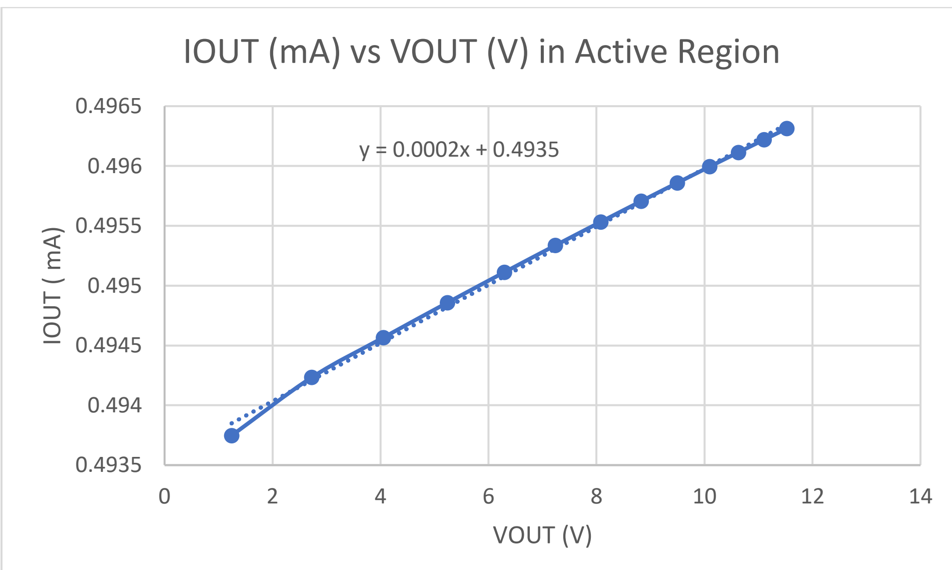


Figure 9: Output Current vs Output Voltage in Active Region

Output Impedance = 1/gradient

Output Impedance = $1/0.0002*10^{-3}$

Output Impedance = 5 MΩ

3. Make another plot showing the output current vs. load resistance for your multiplier.

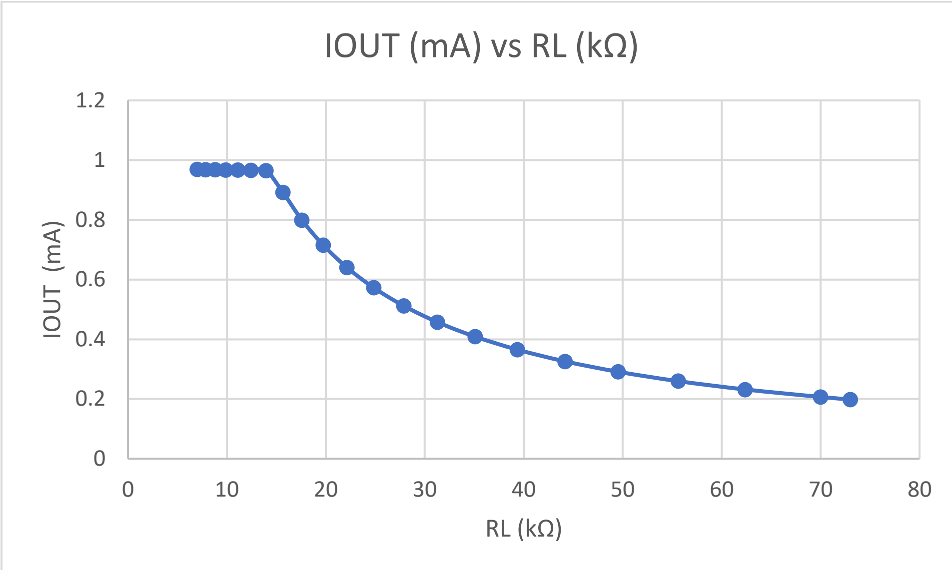


Figure 10: Output Current vs Resistive Load

4. Comment on the first transistor (the one with the base and collector shorted), what two-terminal device does it resemble the closest? With the transistor configured in this way, can it enter the saturation region of operation? If so, under what conditions? If not, why not?

A current source, if the RL value go beyond 26.6 kΩ it enters saturation mode.

5. Consider the range of loads over which the 1:2 mirror can deliver its rated current. How would you expect this range to change with the multiplier and why?

As RL increases, IOUT, and VOUT will decrease.

Part 4 The Transistor's h-Parameter and Bandwidth

Report:

(a). DC-Biasing Circuit

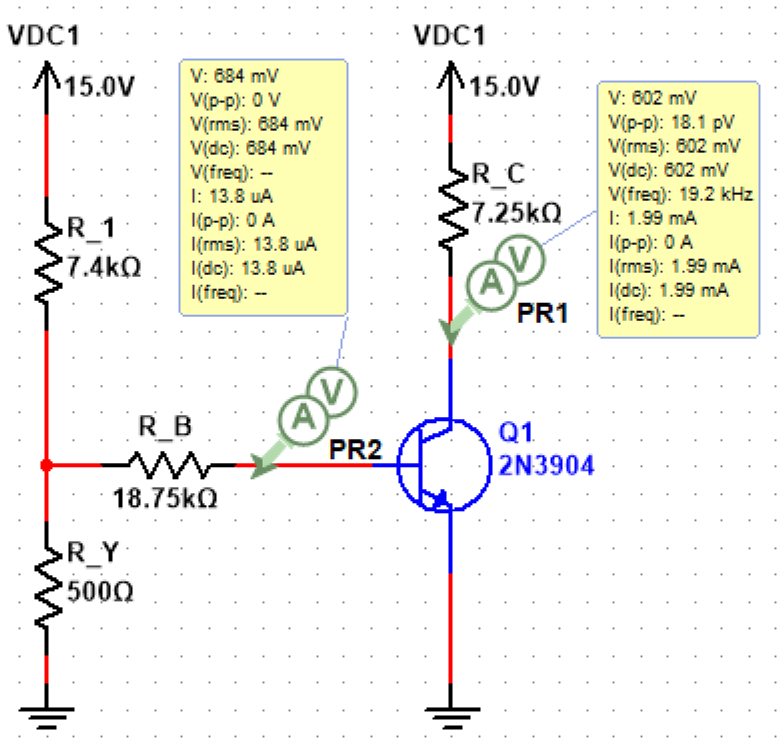
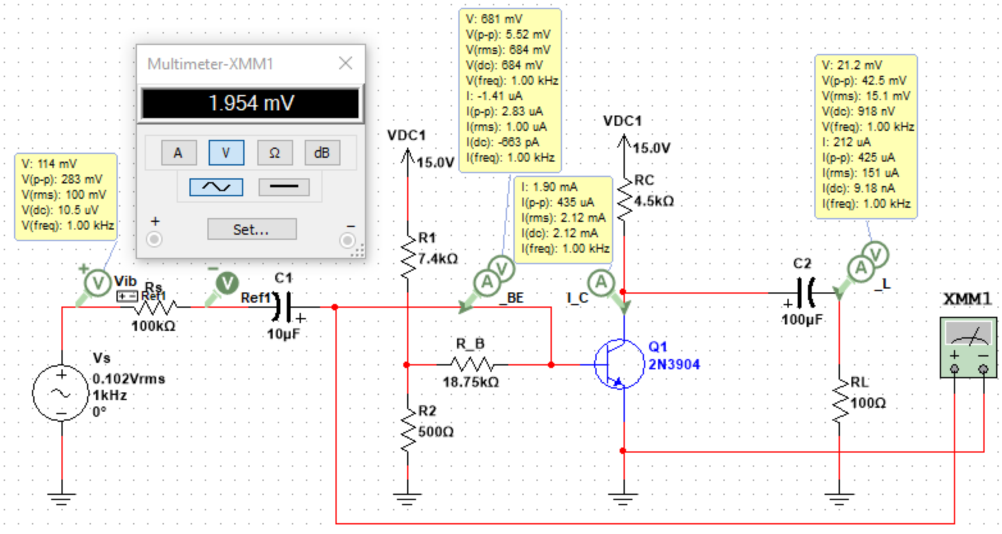


Figure 11: DC Bias Circuit

(b). AC-Coupling of Input and Output Signals

1. Explain the purpose of the capacitors C1 and C2, making sure to identify what would happen if they were absent.

Capacitors C1 and C2 are used to block DC signal from reaching to the test circuit. In case both capacitors were absent, a DC and AC voltages would effect RS and RL. DC voltage is only needed to find the bias points.



(c). The AC Input Impedance, hie, and the AC Forward Current Gain, hfe

1. In your report, show your results and calculations. Describe why the value of the load resistor cannot be made to be zero.

Load resistor RL cant be made zero, since doing this will ground the BJT collector during AC analysis c)

$i_b = 1\,\mu A$; $V_{be} = 1.954\ mV$; $V_{ib} = 102\ mV$

$R_s = 100\ k\Omega$; $V_o = 15.1\ mV$; $R_L = 100\ \Omega$

$$h_{ie} = \frac{V_{be}}{V_{ib}} R_s = \frac{1.954 \times 10^{-3}}{102 \times 10^{-3}} \times 100 \times 10^{3}$$

$$h_{ie} = 1915.69 = 1.915\ K\Omega$$

$$\therefore \boxed{\text{AC input impedance} \simeq 2\,K\Omega}$$

$$h_{fe} = \frac{i_c}{i_b} = \frac{V_o}{R_L \times i_b} = \frac{15.1 \times 10^{-3}}{100 \times 1 \times 10^{-6}}$$

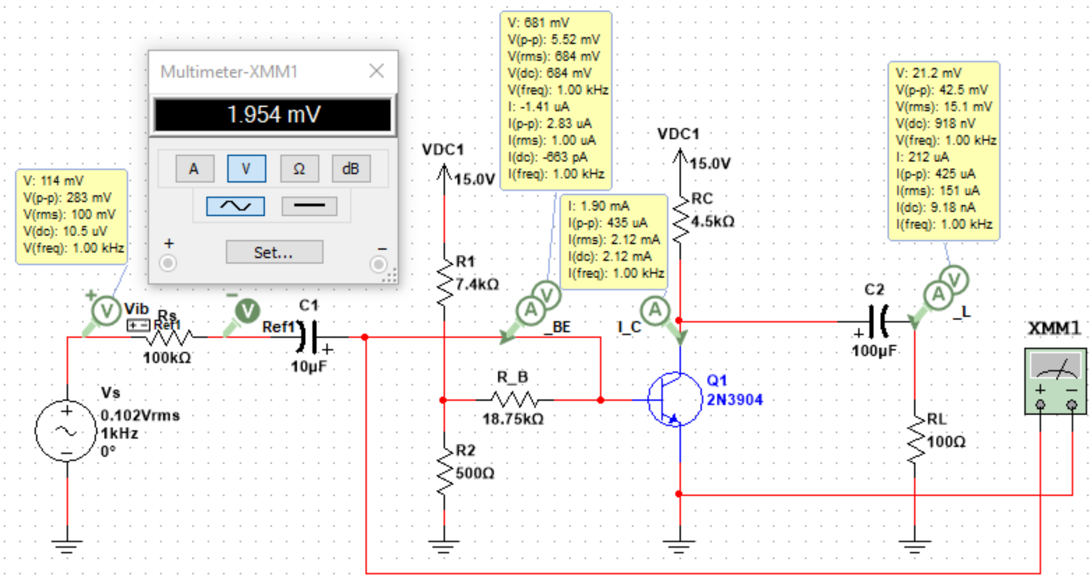
$$h_{fe} = 151\ A/A$$

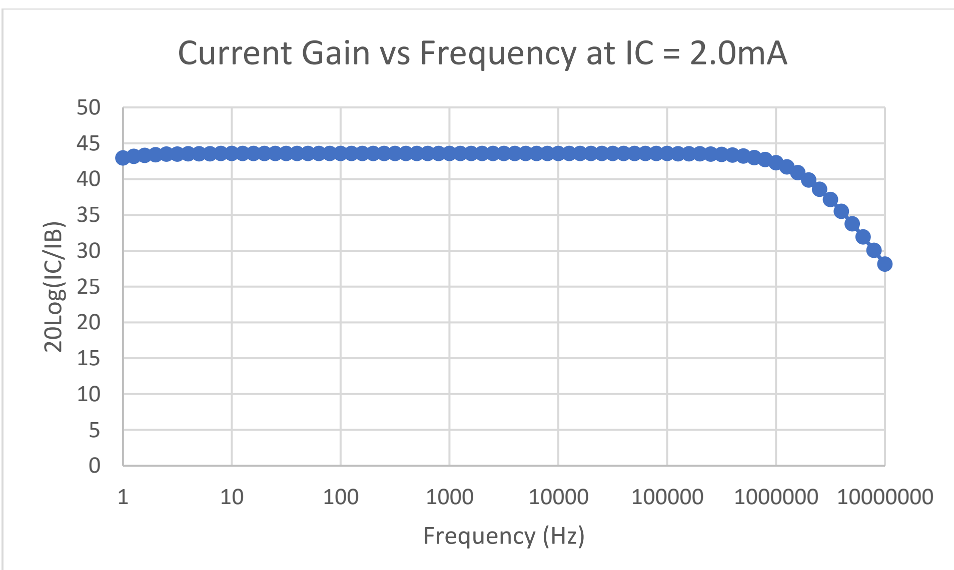
$$\therefore \boxed{\text{AC forwarding current gain} = 151\ A/A}$$

(e). The Unity-Gain Bandwidth, fT, and the Beta Cut-Off Frequency, fβ

1. For all three bias conditions, plot current gain (in dB) as a function of frequency (in a log scale). On the plot, show your values of hfe and fβ.

- IC = 2.0 mA:



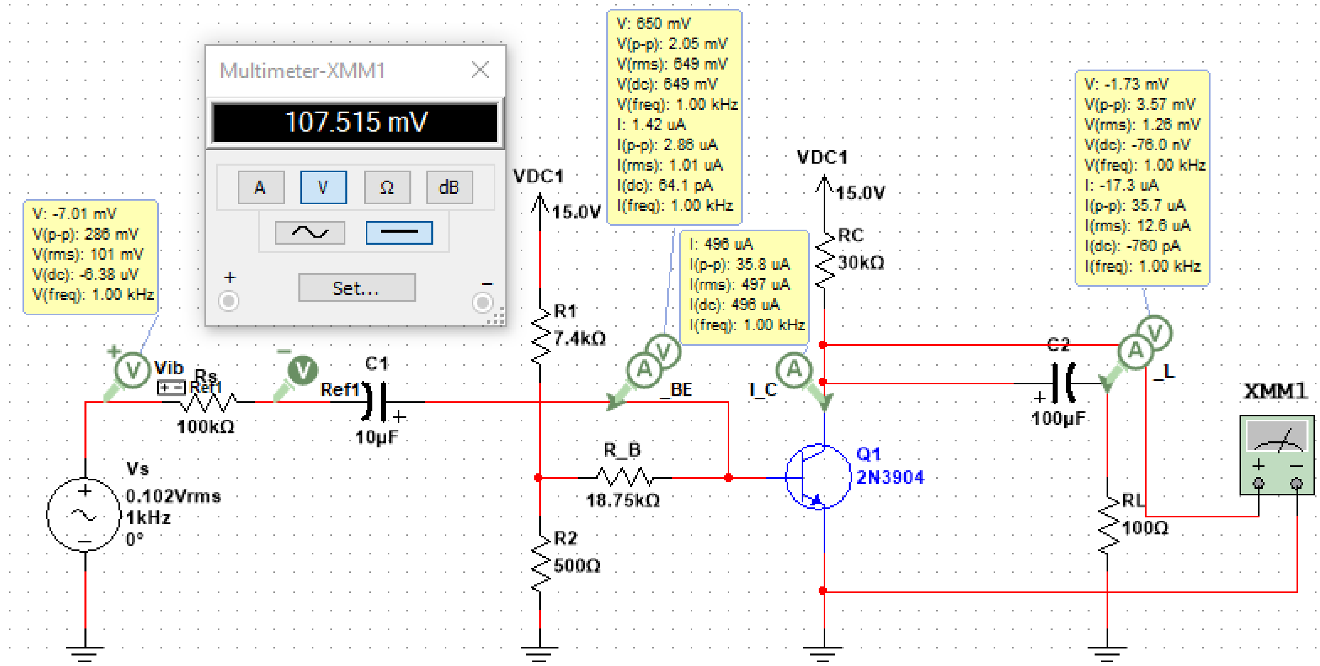


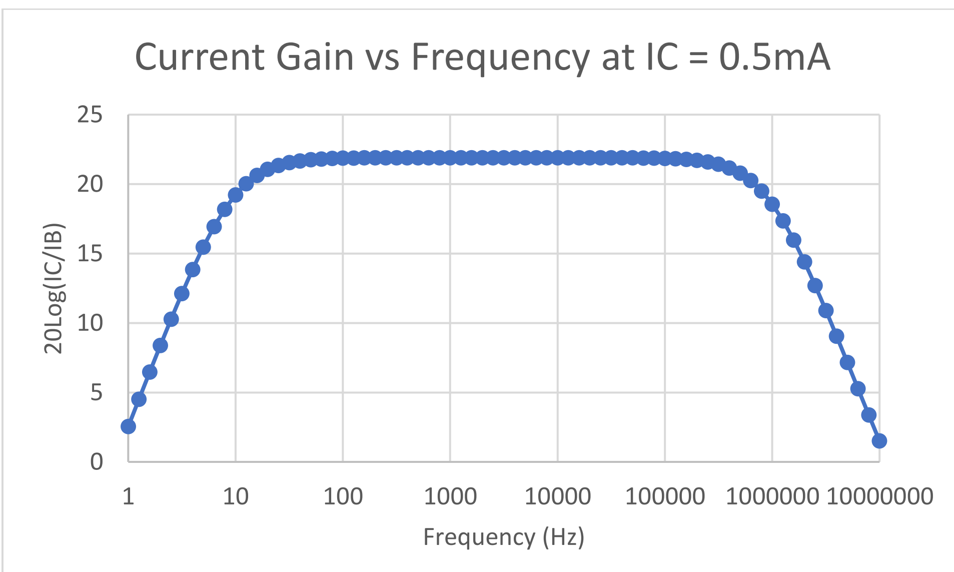
$$f_T = h_{fe}\text{ (low frequencies)} * f_\beta$$

$$f_T = 137.8093 * 1584893.192$$

$$f_T = 218.41\text{ MHz}$$

- <u>IC = 0.5 mA:</u>



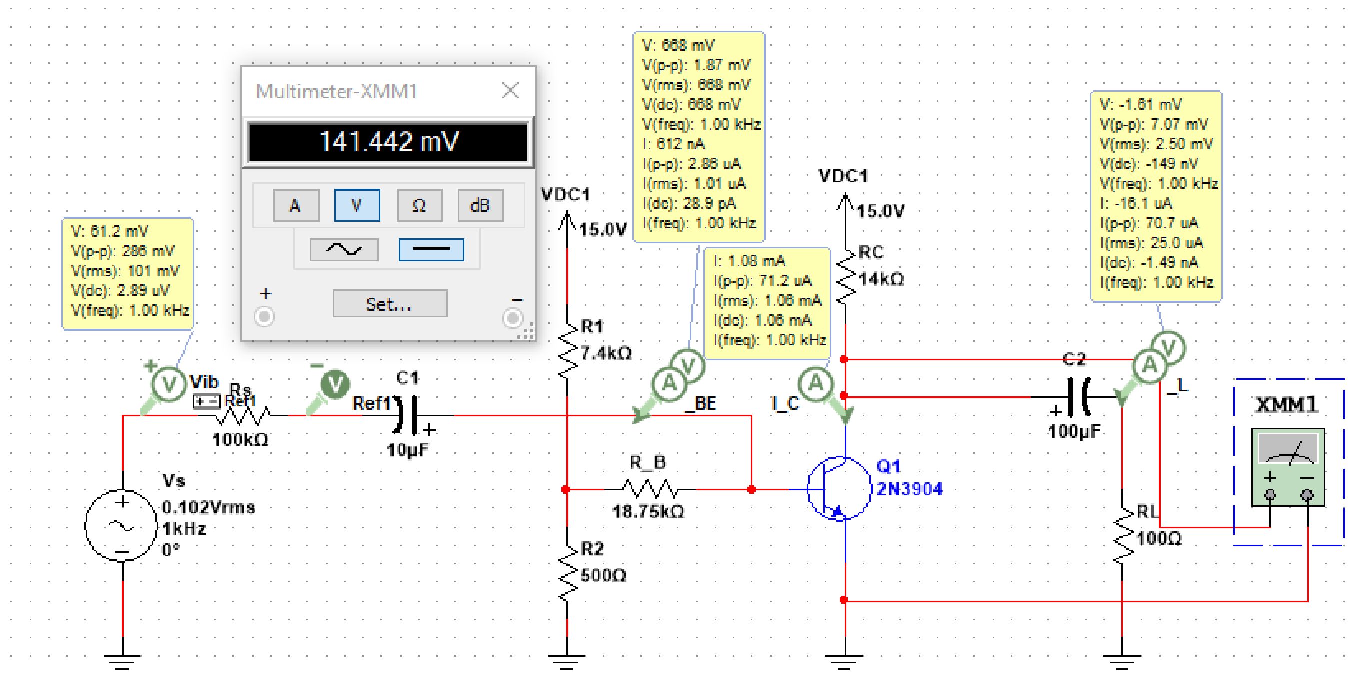


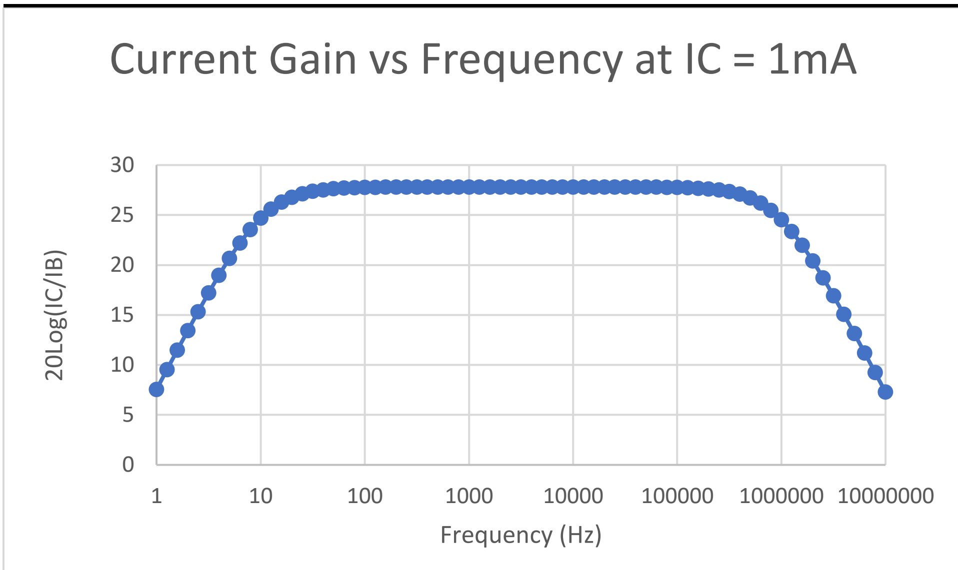
$$f_T = h_{fe}\,(\text{low frequencies}) * f_\beta$$

$$f_T = 9.6858 * 1584893.192$$

$$f_T = 15.35\ \text{MHz}$$

- <u>IC = 1.0 mA:</u>





$$f_T = h_{fe}\ (\text{low frequencies}) * f_\beta$$

$$f_T = 18.9785 * 1584893.192$$

$$f_T = 15.35\ \text{MHz}$$

Part 5: The BJT High-Frequency Hybrid-Pi Model

Report:

Part 5: $I_C = 2\,mA$

$$g_m = \frac{I_c}{V_T} = \frac{2mA}{25mV} = 80\,mS$$

$$r_\pi = \frac{h_{fe}}{g_m} = \frac{143}{0.08} = 1.788\,K\Omega$$

$$r_x = h_{ie} - r_\pi = 1.915\,k\Omega - 1.788\,k\Omega$$
$$= 127\,\Omega$$

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

$$r_o = \left(h_{oe} - \frac{h_{fe}}{r_\mu}\right)^{-1} \approx h_{oe}^{-1} \approx (2.69 \times 10^{-5})^{-1}$$
$$\approx 37.17\,k\Omega$$

$$\omega_\beta = 2\pi f_\beta = 2\pi(1584893.192)$$
$$= 9958177.617 \simeq 9.95M\ \text{rad/sec}$$

$$C\mu = C_{BC\ junction} + C_{board} \approx 4pf$$

$$C_\mu = \frac{1}{r_\pi \times W_\beta} - C_\mu\left[1 + \left|\frac{V_o}{V_{be}}\right|_{@1KHz}\right]$$

$$= \frac{1}{(1.788\,K\Omega)(9.95\,M\,rad/sec)} - (4pf)\left[1 + \frac{9.18nV}{684mV}\right]$$

$$= 52\,pf$$

$\rightarrow$ $\underline{I_c = 0.5mA}$

$$g_m = \frac{I_c}{V_T} = \frac{0.5mA}{25mV} = 20m\Omega$$

$$r_\pi = \frac{h_{fe}}{g_m} = \frac{9.6858}{20\,m\Omega} = 484.29\,\Omega$$

$$r_x = hi_e - r_\pi = 1.915\,k\Omega - 484.29\,\Omega = 1.43\,k\Omega$$

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

$$r_o = \left(h_{oe} - \frac{h_{fe}}{r_\mu}\right)^{-1} \approx h_{oe}^{-1} \approx 37.17K\Omega$$

$$\omega_\beta = 2\pi f_\beta = 2\pi(1584893.192) = 9.95M\ rad/sec$$

$C_\mu = 4\,pf$

$$C_\pi = \frac{1}{r_\pi \times \omega_\beta} - C_\mu\left[1 + \left|\frac{V_o}{V_{be}}\right|_{@1kHz}\right]$$

$$= \frac{1}{484.29 \times 9.95\ M\Omega} - (4\,pf)\left[1 + \frac{76\ mV}{649\ mV}\right]$$

$= 208\ f$

-) $\underline{I_C = 1\ mA}$

$$g_m = \frac{I_C}{V_T} = \frac{1\ mA}{25\ mV} = 40\ m\ \Omega$$

$$r_\pi = \frac{h_{fe}}{g_m} = \frac{18.9785}{40\ m\Omega} = 474.4625$$

$r_x = h_{ie} - r_\pi = 1.915\ k\Omega - 474.4625$

$= 1.44\ k\Omega$

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

$$r_o = \left(h_{oe} - \frac{h_{fe}}{r_\mu}\right)^{-1} \approx h_{oe}^{-1} \approx 37.17\ k\Omega$$

$\omega_\beta = 2\pi f_\beta = 9.95\ M\ rad/sec$

$C_\mu = C_{BC\ junction} + C_{board} \simeq 4\,pf$

$$C_\pi = \frac{1}{r_\pi \times W_\beta} - C_\mu \left[1 + \left| \frac{V_o}{V_{be}} \right|_{@1KHz} \right]$$

$$= \frac{1}{474.4625 \times 9.95 \text{ M rad/sec}} - (4pf) \left[1 + \frac{149 nV}{668 mV} \right]$$

$$= 212f$$