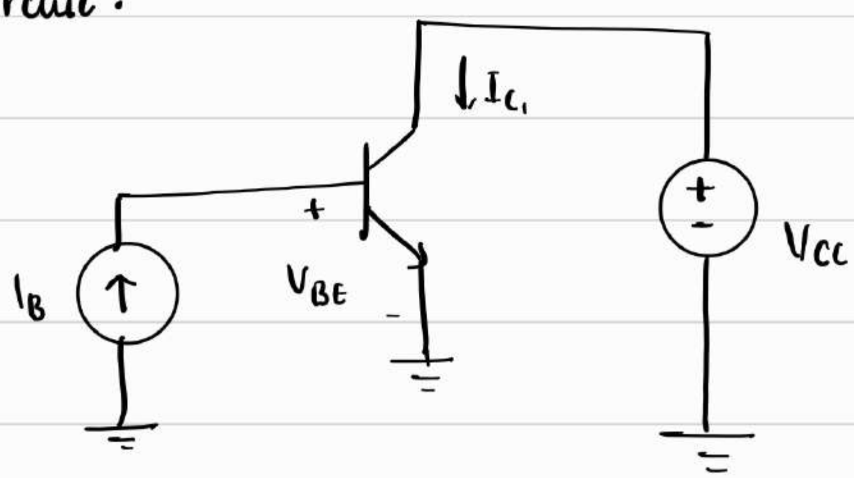
Analog Electronic Circuits

Assignment - 4

Question 1 : BJT Characterization

(a) Given, BC547B npn transistor

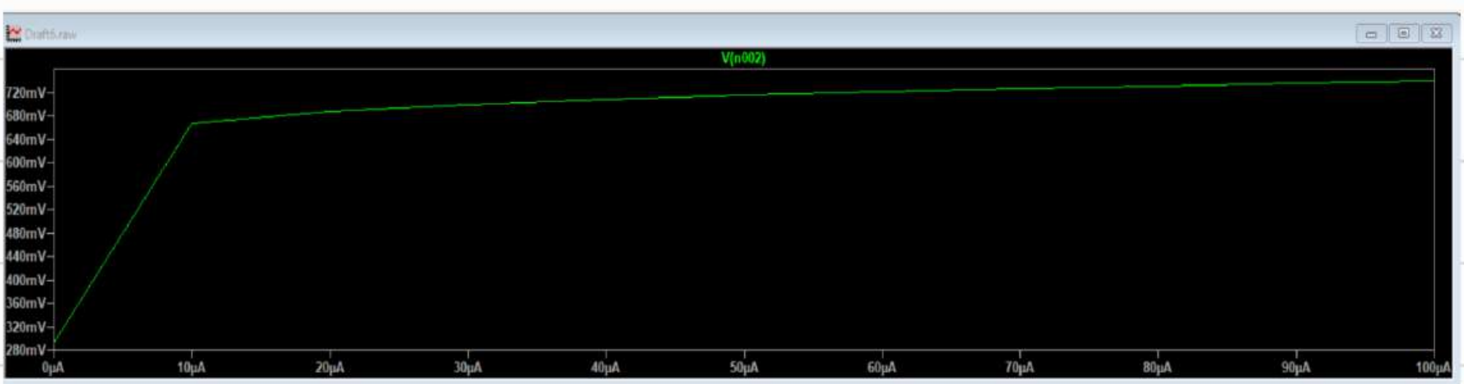
Circuit :

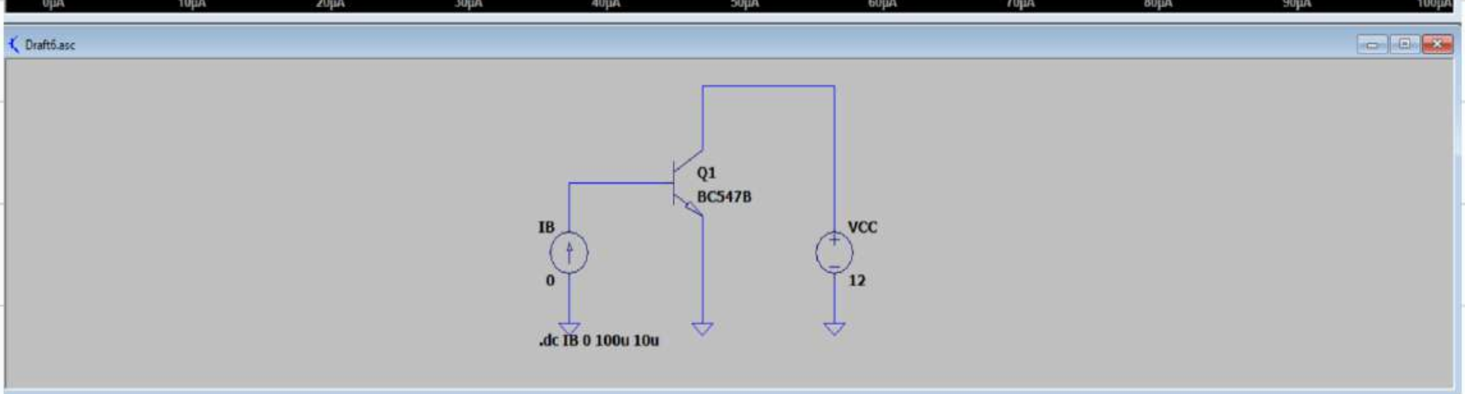


$V_{cc} = 12V$

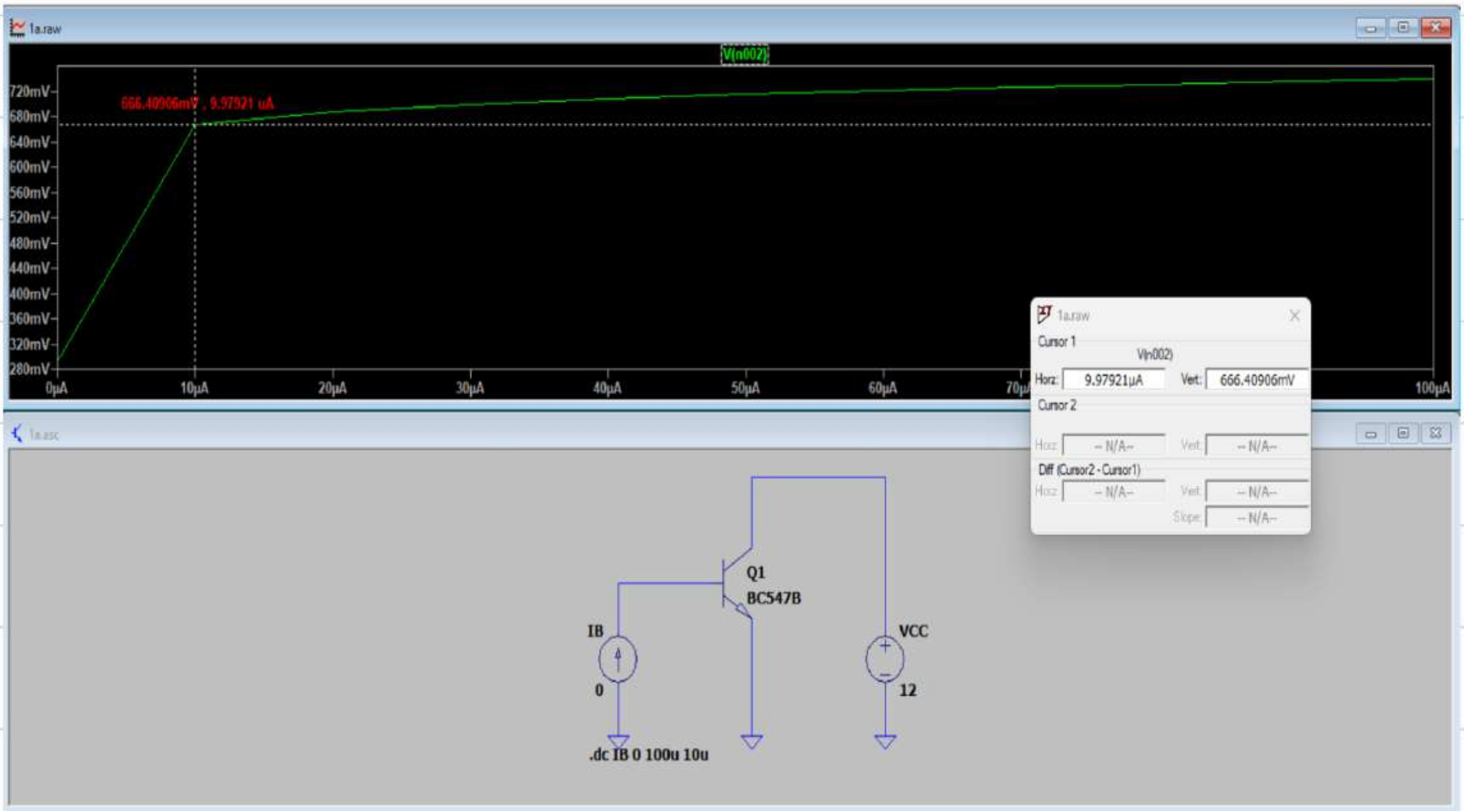
The required DC sweep from 0 to 100 µA with step 10 µA

Below is the plot between V_{BE} and I_B.

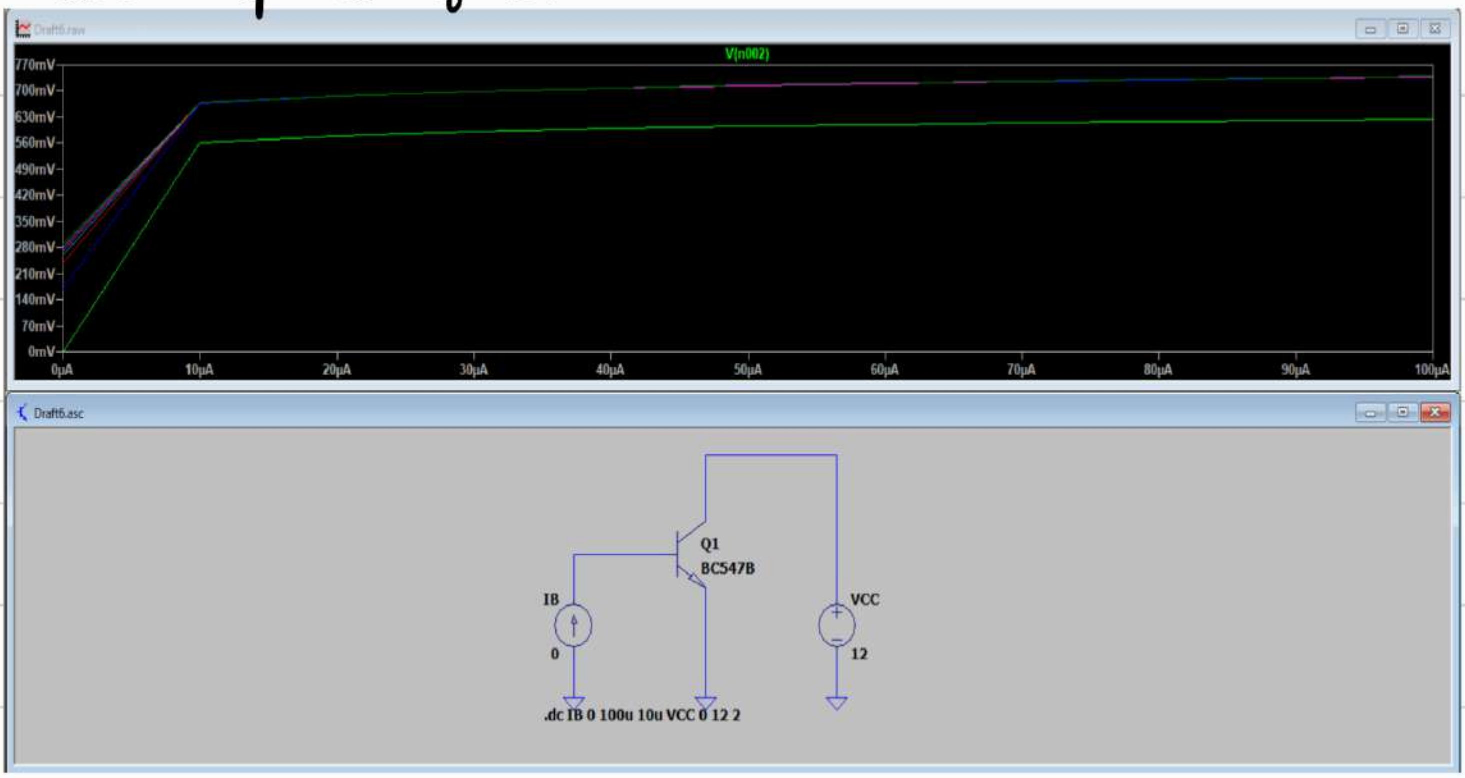




The forward-bias emitter-base junction (EBJ) voltage from the plot = 666.40906 mV

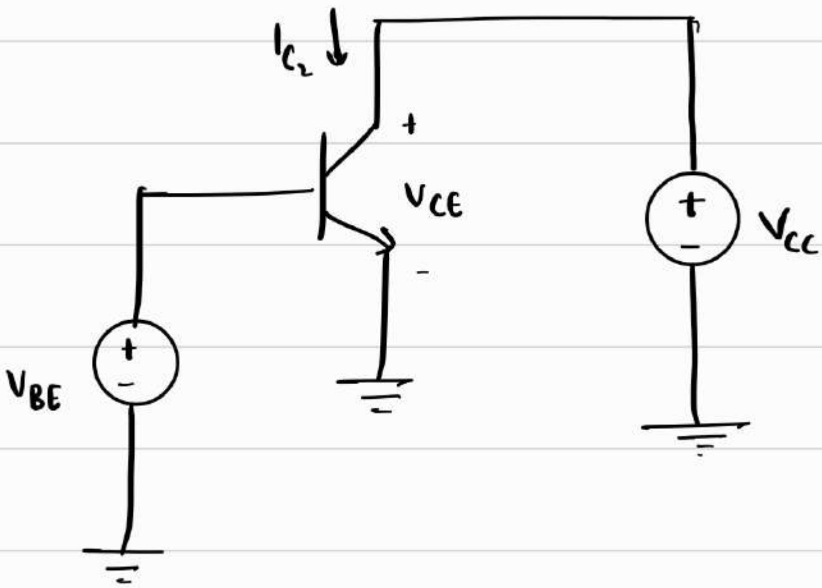


Now, dc sweep of I_B with V_{CC} varying from 0 to 12V and step size of 2V.

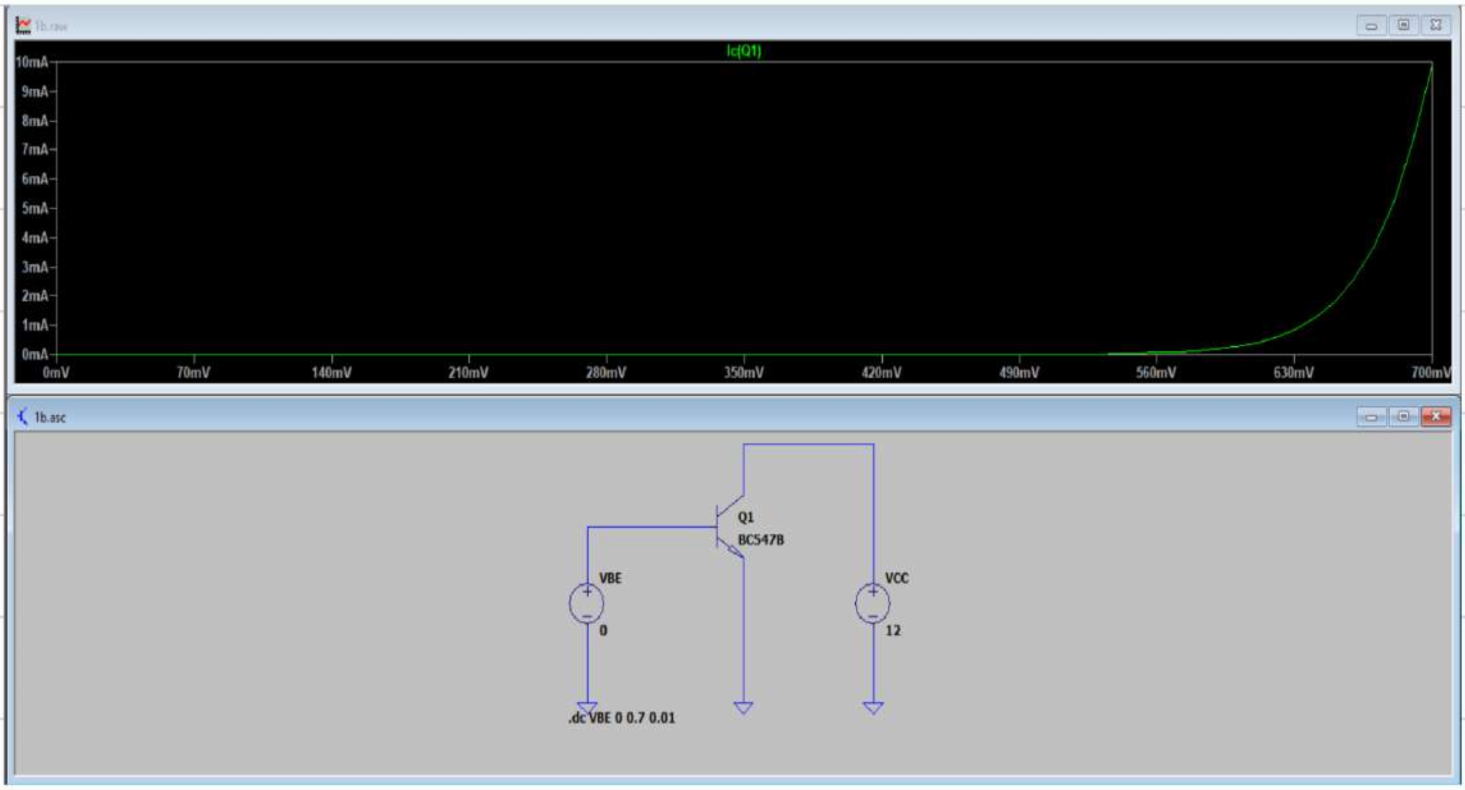


(b) BC547B npn transistor

Circuit :



Plot of I_c vs V_{BE} for $V_{CC} = 12V$



We know that, $I_{C_2} = I_S e^{V_{BE}/V_T}$

and $V_T = \frac{kT}{Q}$

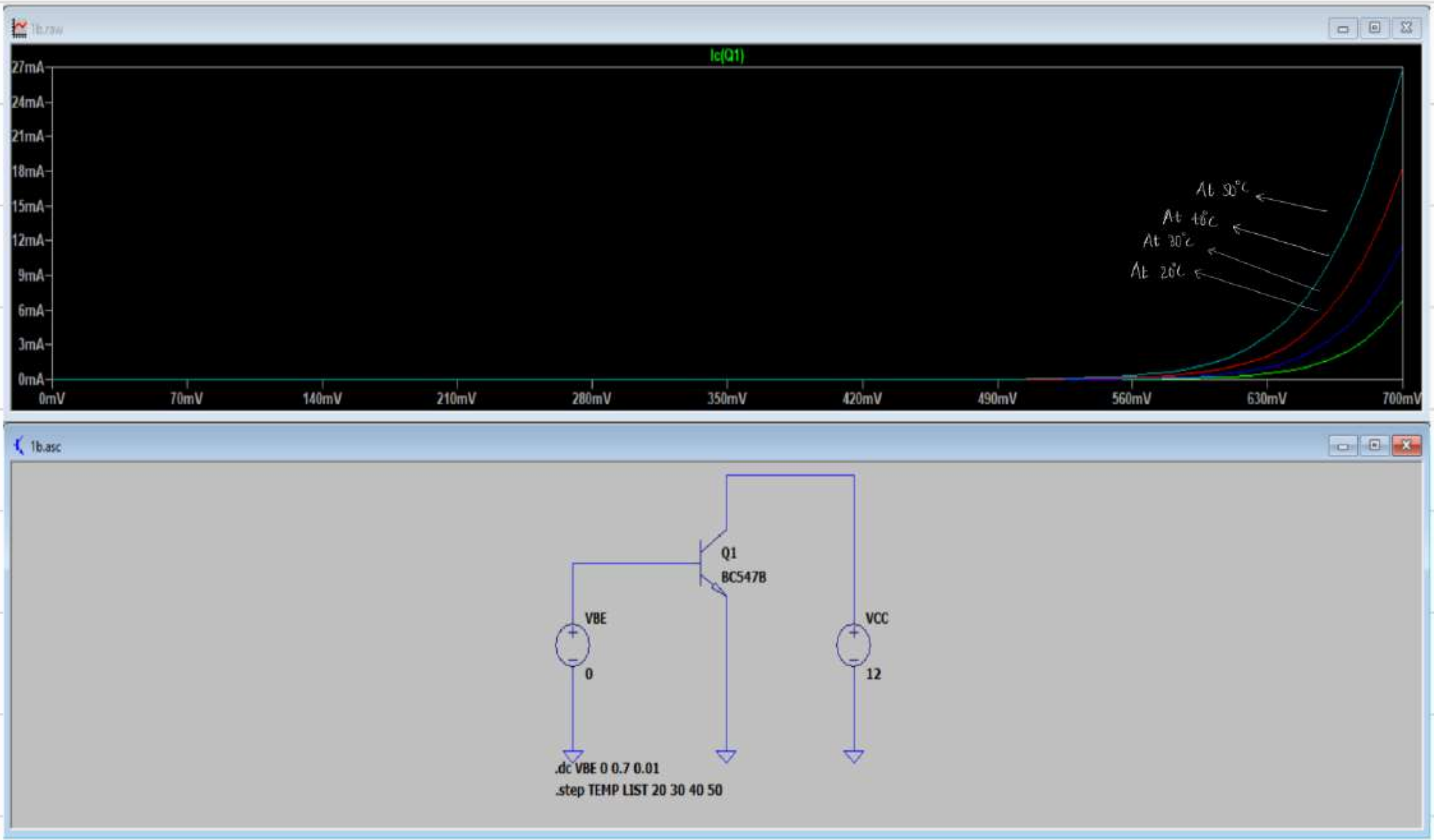
V_T

$\Rightarrow \quad I_{C_2} \propto e$

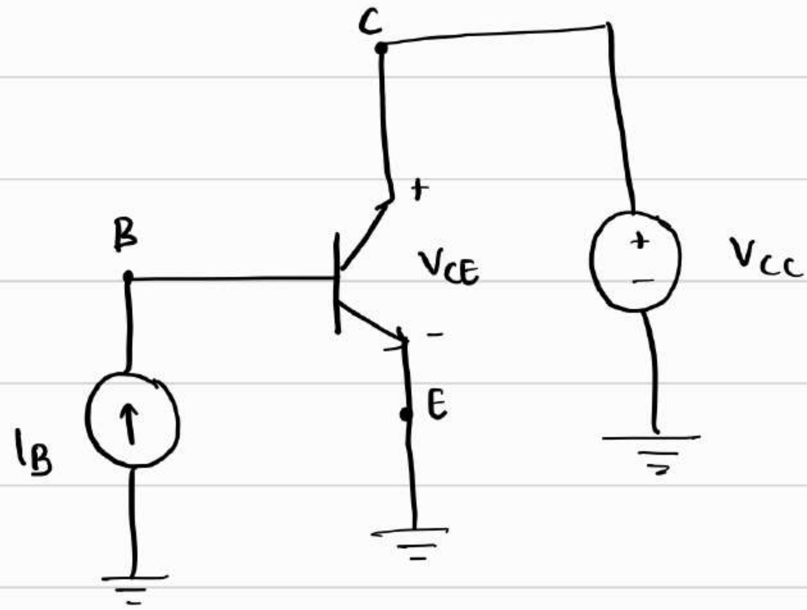
As temperature, $T \uparrow \Rightarrow \frac{1}{T} \downarrow$

$\therefore$ Collector current decreases

The below is the required LtSpice Simulation.



(c)



$\longrightarrow$

* At $V_{CE} = 100mV$ → Saturation Mode

I_B	I_C	$\beta = I_C/I_B$
50 uA	5.22 mA	104.4
60 uA	6.07 mA	101.16

→ Incremental Current Gain

* At $V_{CE} = 600mV$ → Active Mode

I_B	I_C	$\beta = I_C/I_B$
50 uA	12.95 mA	259
60 uA	15.2 mA	253.33

→ Incremental Current Gain

Reasons for the difference Observed :

* At $V_{CE} = 100 mV$ → The transistor is in saturation mode
  → The CB Junction is in forward bias
  → Collector current is very low
  $I_C = I_S$

* At $V_{CE} = 600 mV$ → The transistor is in

active mode

→ The CB Junction is in reverse bias

→ Collector current is high

$I_C = I_S e^{V_{BE}/V_T}$

→ At $V_{CE} = 1V$

I_B	I_C	$\beta = I_B / I_C$
0 A	−180.28 fA	-
10 μA	2.8 mA	280
20 μA	5.502 mA	275.1
30 μA	8.11 mA	270.33
40 μA	10.61 mA	265.25
50 μA	13.04 mA	260.8
60 μA	15.39 mA	256.5
70 μA	17.68 mA	252.25
80 μA	19.91 mA	248.87
90 μA	22.01 mA	244.56
100 μA	24.20 mA	242

The average β value from above is $\boxed{\beta = 259.56}$

Early Voltage:

The reverse-bias current in CB Junction increases

The reverse bias current in CB junction increases

i.e, as we increase V_{CE}, the width of the depletion region in CB junction increases.

$\Rightarrow$ Width of depletion increases

Because of this the no of $e^{\ominus}$ coming into collector wrt to time also increases. Hence collector current I_C increases.

Also, this trend is clearly seen in the simulation below.

Estimating V_A value :

Let's fix $I_B = 50\ \mu$

At $V_{CE} = 1V \Longrightarrow I_C = 12.94\ mA$

$V_{CE} = 2V \Longrightarrow I_C = 13.16\ mA$

Given, slope $= \dfrac{I_C}{V_A + V_{CE}}$

As slopes must be equal,

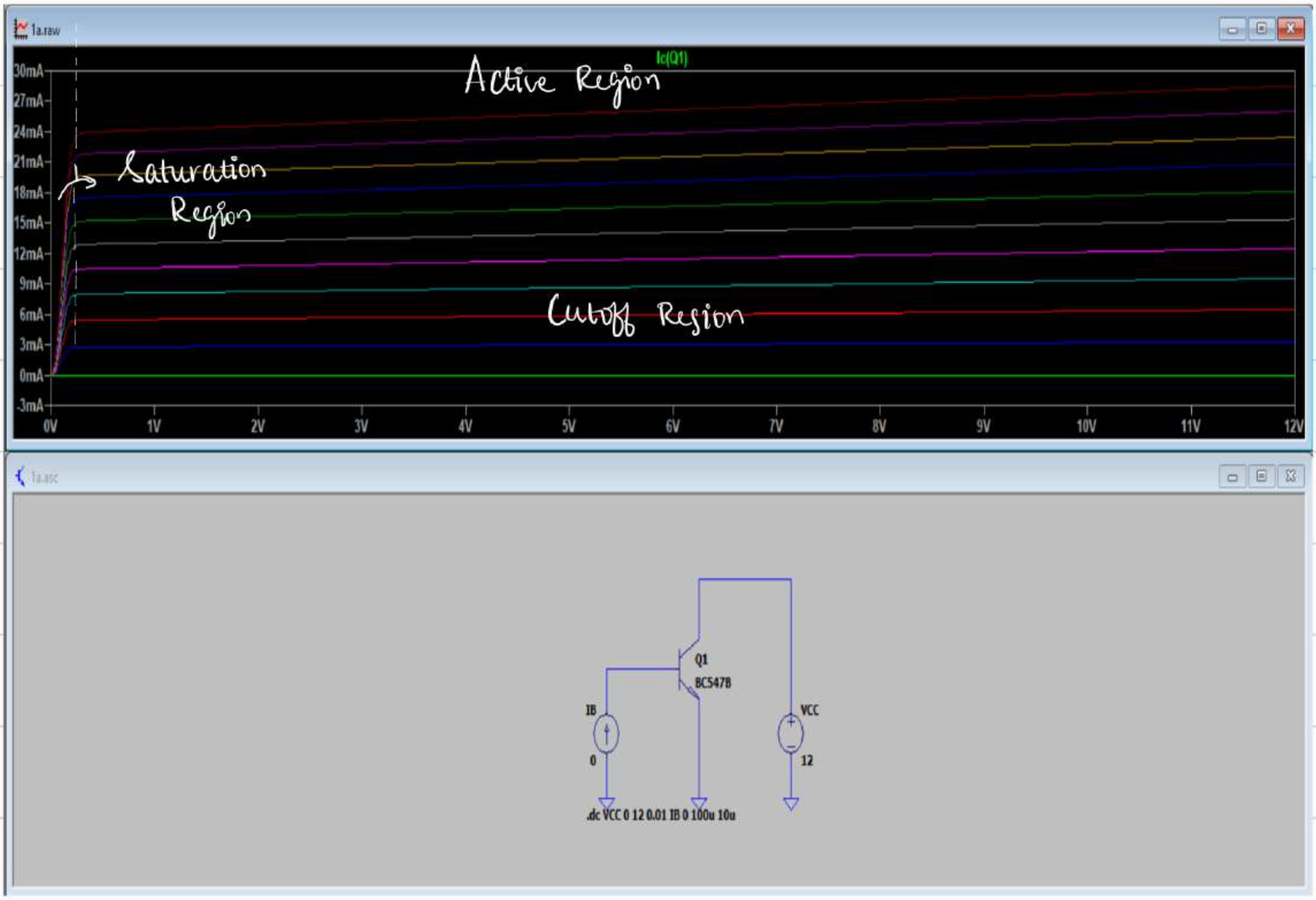
$$\frac{0 - 13.16}{V_A - 2} = \frac{12.92 - 13.16}{1 - 2}$$

$$\frac{-13.16}{V_A - 2} = 0.24$$

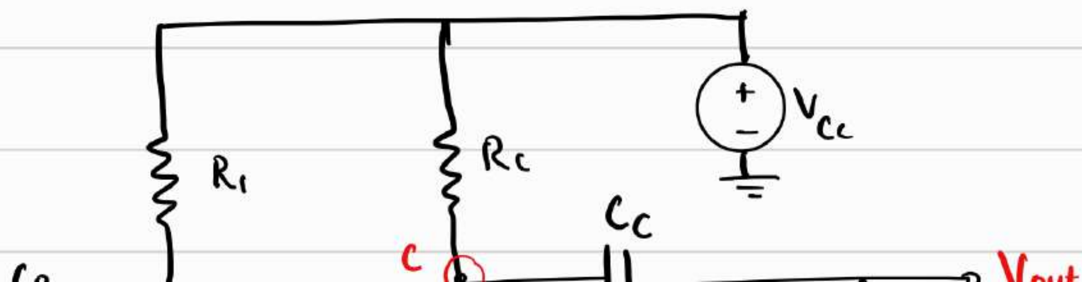
$$\boxed{V_A = -54.67\ V}$$

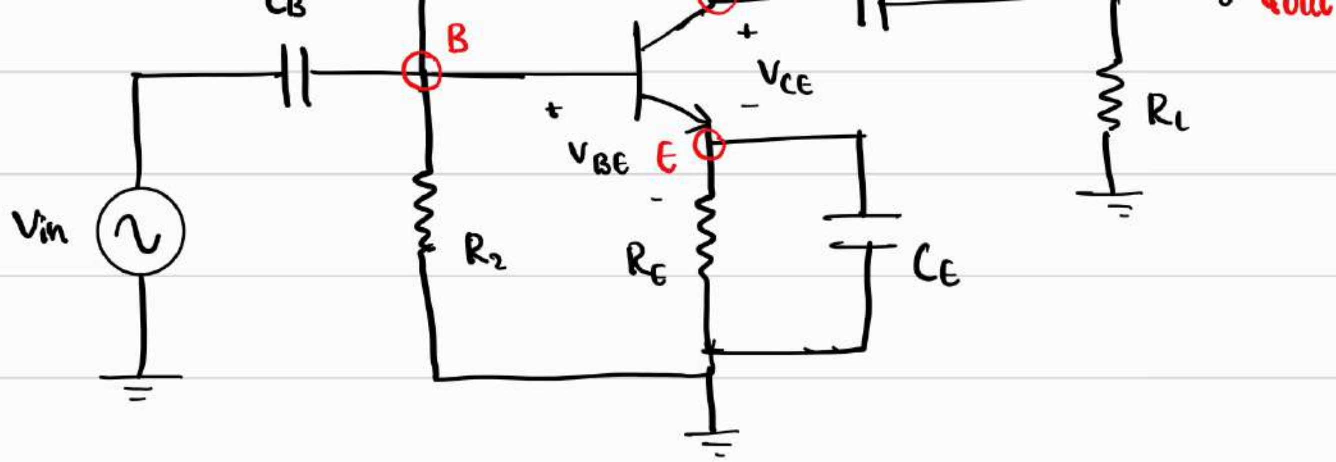
∴ The estimated early voltage is $-51.67\ V$

Below is the Lt Spice simulation with all the regions marked :



Question2: BJT Amplifier Analysis and Design

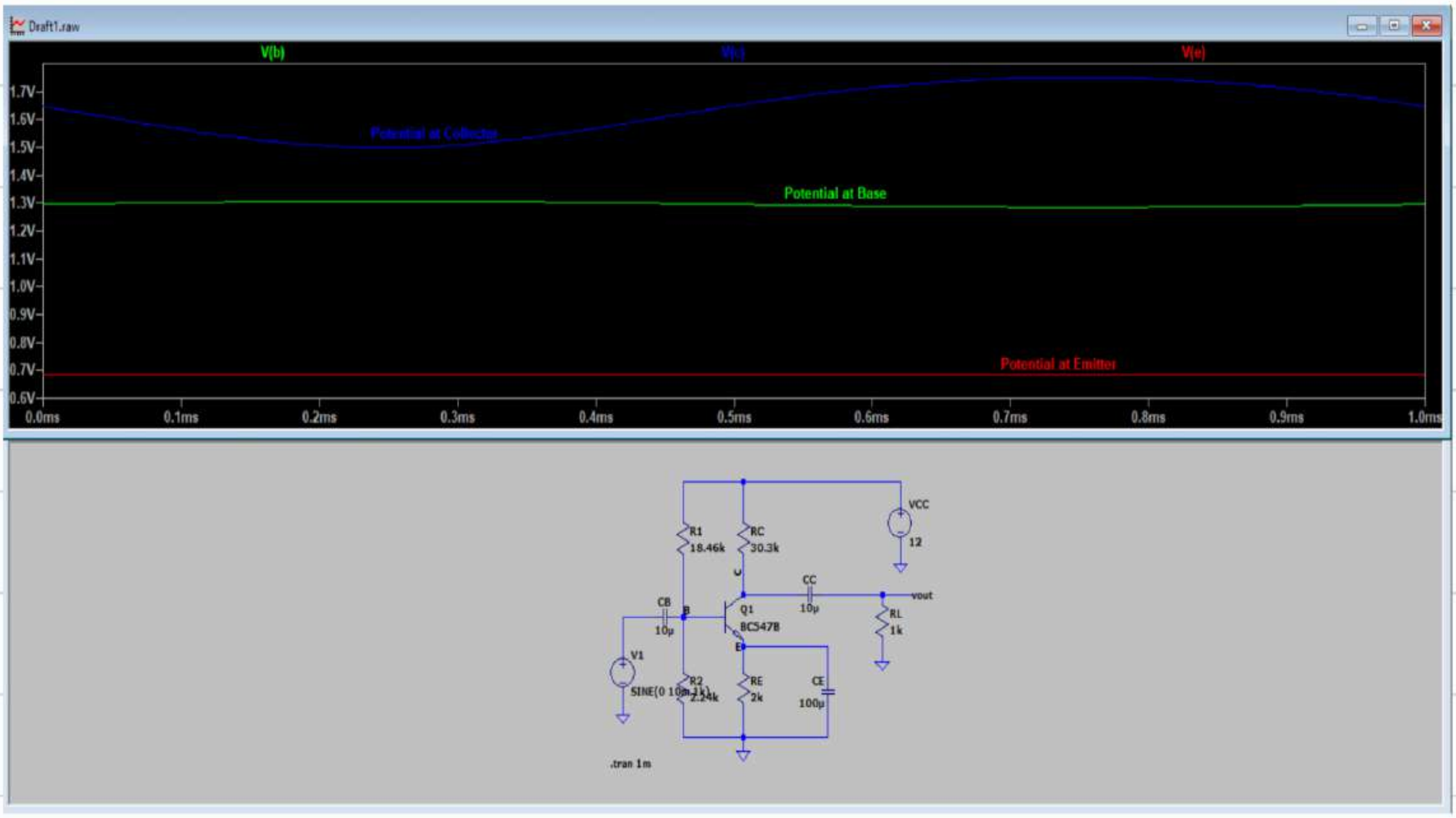


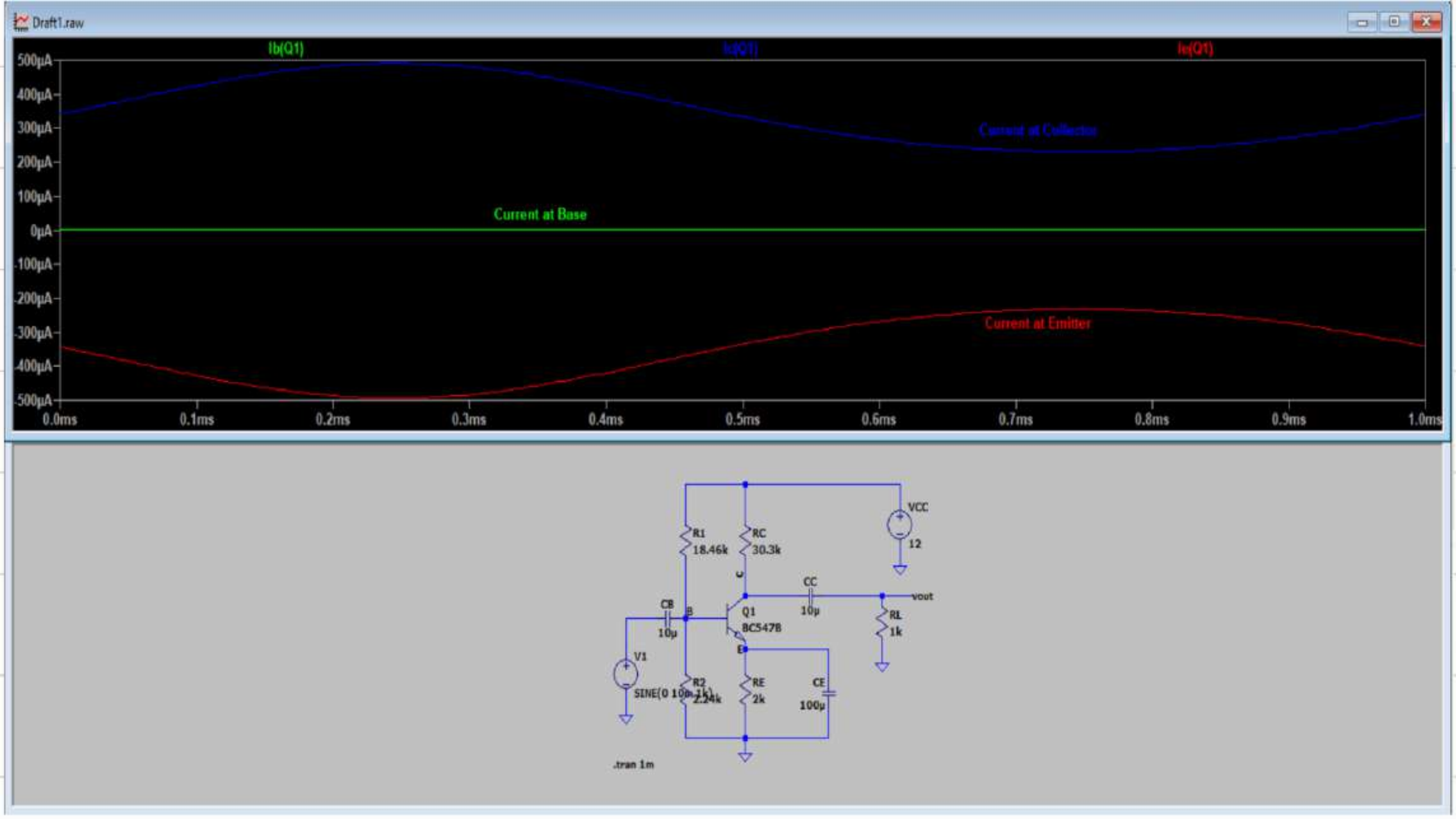


Given parameters,

V_{CC}	$= 12V$	R_1	$= 18.46\ k\Omega$
C_B	$= 10\ \mu F$	R_2	$= 2.29\ k\Omega$
C_C	$= 10\ \mu F$	R_E	$= 2\ k\Omega$
C_E	$= 10\ \mu F$	R_C	$= 30.3\ k\Omega$
f_0	$= 1kHz$	R_L	$= 1\ k\Omega$

$$v_{in} = V_m \sin(2\pi f_0 t)$$





(a) <u>DC Picture</u>

When doing the DC analysis,

- All the AC voltage sources are shorted and all the AC current sources are opened.

- All the capacitors are open

<u>Because</u>: When a DC signal is sent in

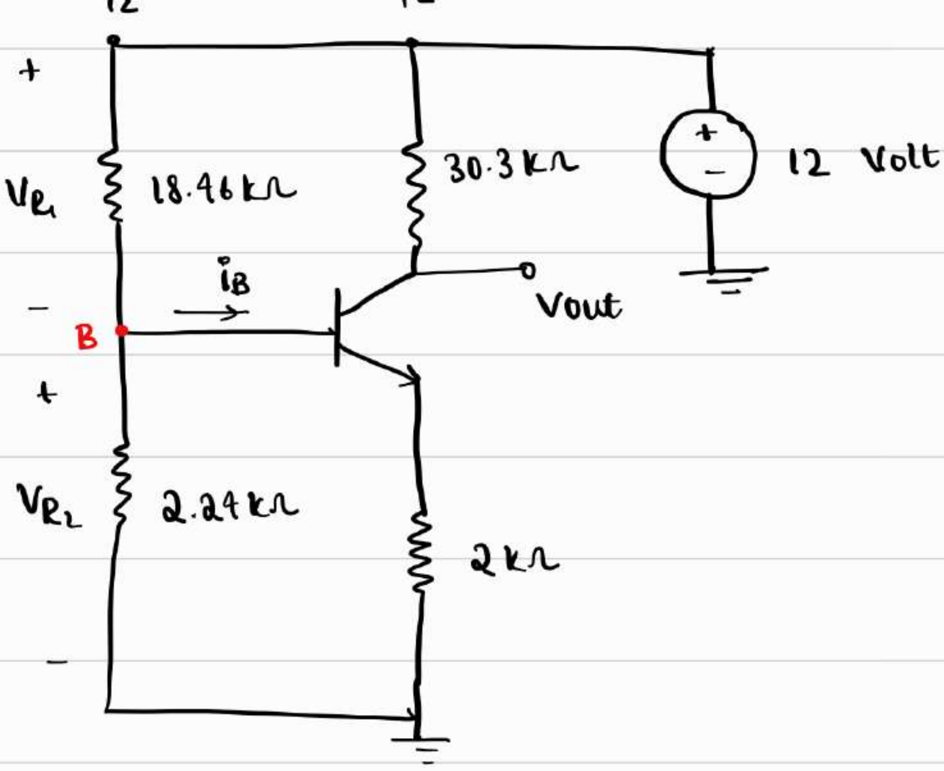
$$\omega \longrightarrow 0 \quad \Rightarrow \quad \frac{1}{\omega} \to \infty$$

$$X_c = \frac{1}{j\omega c} = \infty$$

Impedance of capacitor $= \infty$

$\Rightarrow$ Open circuit

<u>Large Signal Model</u>



The value of i_B is very small.

Apply Voltage divider,

$$V_B = \frac{R_2}{R_1 + R_2} V_{cc}$$

$$= \frac{2.24\,k}{2.24k + 18.46\,k} \times 12$$

$$= \frac{12 \times 2.24}{20.07}$$

$$\boxed{V_B = 1.2986\ V}$$

103.171
9.988

Given that , $V_{BE} = 0.7\,V$ (fixed)

$$V_{BE} = V_B - V_E$$

$$V_E = 1.2986 - 0.7$$

$$\boxed{V_E = 0.5986\ V}$$

$$I_E = \frac{V_E}{R_E} = \frac{0.5986\ V}{2k\Omega}$$

$$\boxed{I_E = 0.2993\ mA}$$

$$I_C = \frac{\beta}{1+\beta} I_E$$

From Q1 part c) the value of $\beta = 259.56$

$$I_C = \frac{259.56}{260.56} \times 0.2993\ mA$$

$$\boxed{I_C = 0.298\ mA}$$

We know that, $I_E = I_B + I_C$

$$\Rightarrow \quad I_B = (0.2993 - 0.298)\ mA$$

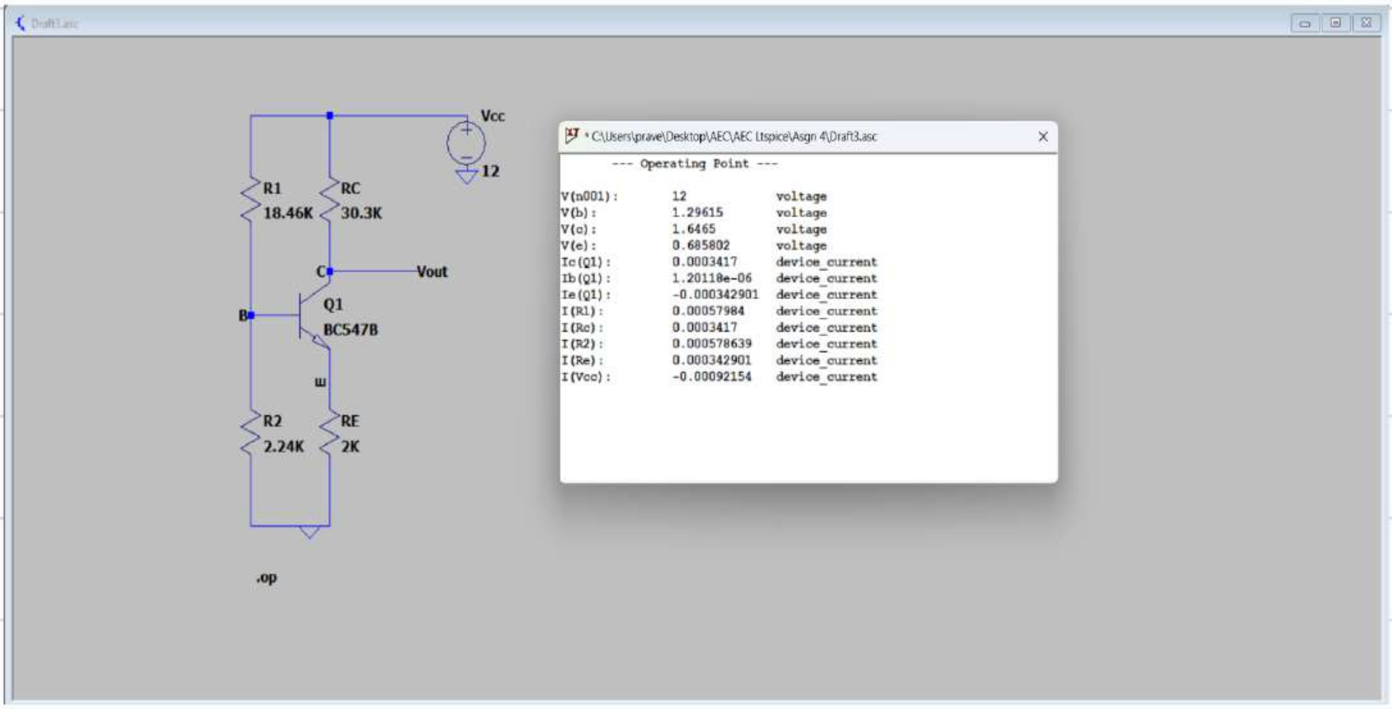
$$I_B = 0.0013\ mA$$

$$\boxed{I_B = 1.3\ \mu A}$$

$$V_C = V_{CC} - I_C R_C$$

$$= 12 - (0.298\ m)(20.2\ K)$$

$$\boxed{V_C = 2.9706\ V}$$



(b) Operation Point Simulation (.op)

	Theoretical Values	Simulated Values
V_b	1.2986 V	1.29615 V
V_c	2.9706 V	1.6465 V
V_E	0.5986 V	0.6858 V
I_b	1.3 uA	1.201 uA
I_c	298 uA	341.7 uA
I_E	299.3 uA	342.90 uA

(c) Calculation of small signal parameters

$$g_m = \frac{I_C}{V_T} = \frac{341.7 \times 10^{-6}}{25 \times 10^{-3}}$$

$$\boxed{g_m = 0.013668}$$

$$r_\pi = \frac{\beta}{g_m} = \frac{259.56}{0.013668}$$ 2k

$$\boxed{r_\pi = 18.99\ k\Omega}$$

$r_o \longrightarrow$ arises due to the Early Voltage

$$r_o = \frac{V_A}{I_C} = \frac{54.67}{298 \times 10^{-6}}$$ 18.99k

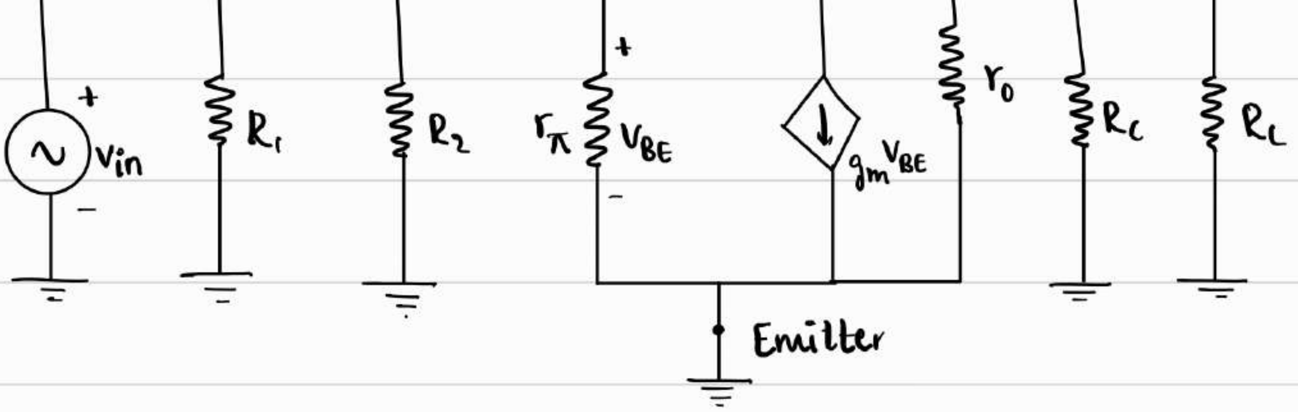
$$\boxed{r_o = 183.45\ k\Omega}$$

Early resistance

(d) Small-signal Equivalent Circuit :

All the DC sources are replaced by their AC equivalents.

All the capacitors are shorted to allow the AC signal.



(e) Small signal Voltage Gain :

$$V_{BE} = v_{in} \quad [\because R_1, R_2, r_\pi \text{ are all in parallel}]$$

Apply KVL at Vout

$$\frac{V_{out}}{R_L} + \frac{V_{out}}{R_C} + \frac{V_{out}}{r_0} + g_m V_{be} = 0$$

$$V_{out}\left[\frac{1}{R_L} + \frac{1}{R_C} + \frac{1}{r_0}\right] = -g_m V_{BE}$$

The value of r_0 is very high when compared to R_L and R_C. Hence, we can neglect it.

$$\Rightarrow \quad V_{out} = \left| \frac{-g_m v_{in}}{\left(\frac{1}{R_L} + \frac{1}{R_C}\right)} \right|$$

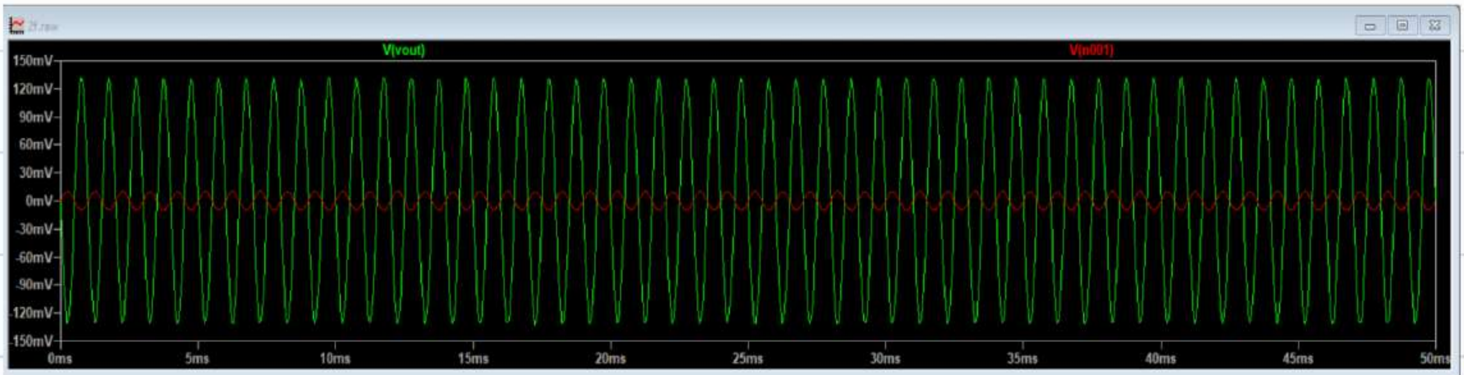
$$\frac{V_{out}}{V_{in}} = \left| -g_m \times \frac{R_C R_L}{(R_C + R_L)} \right|$$

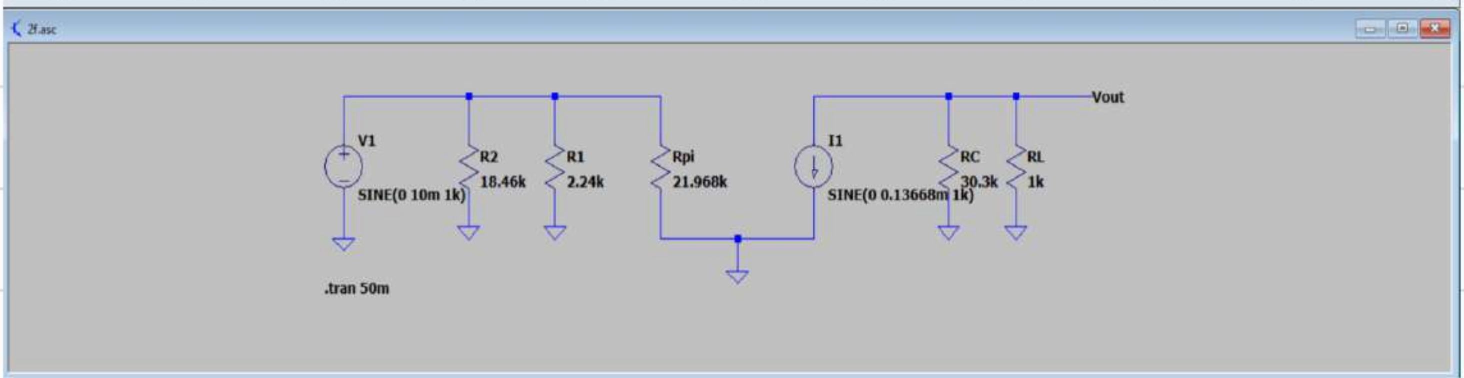
$$= 0.013668 \times \left(\frac{30.3k \times 1k}{1 + 30.3k} \right)$$

$$= 0.013668 \times 968.05\Omega$$

$$\boxed{A_v = \frac{V_{out}}{V_{in}} = 13.231}$$

(f) V_{in} and V_{out}





In the above plot, V_{pp} of V_{out} = 131.580 mV

From the given inQ, V_{pp} of V_{in} = 10 mV

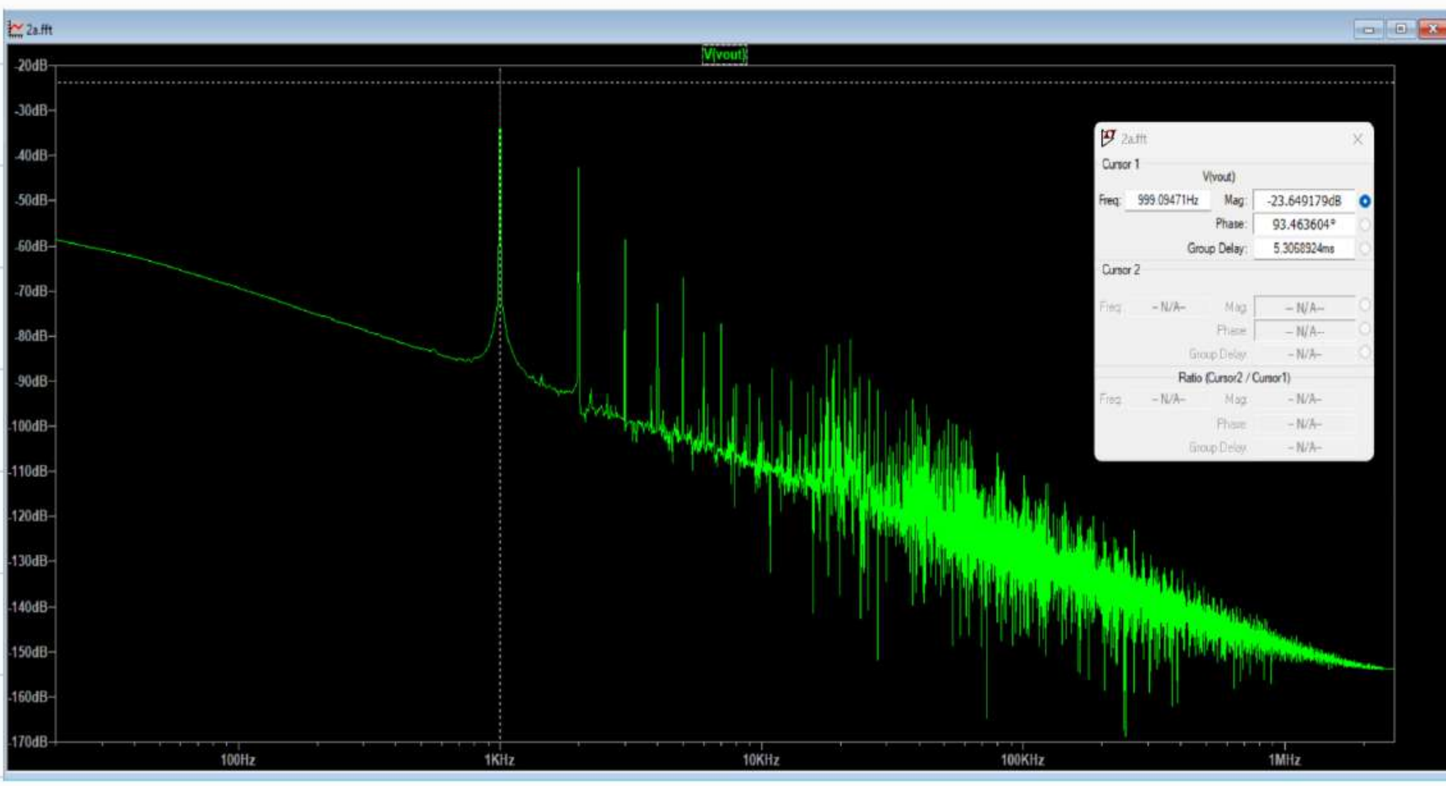
$$\text{Gain} = \frac{V_{out}}{V_{in}} = \frac{131.580\,m}{10\,m}$$

$$\boxed{\text{Gain} = 13.158}$$

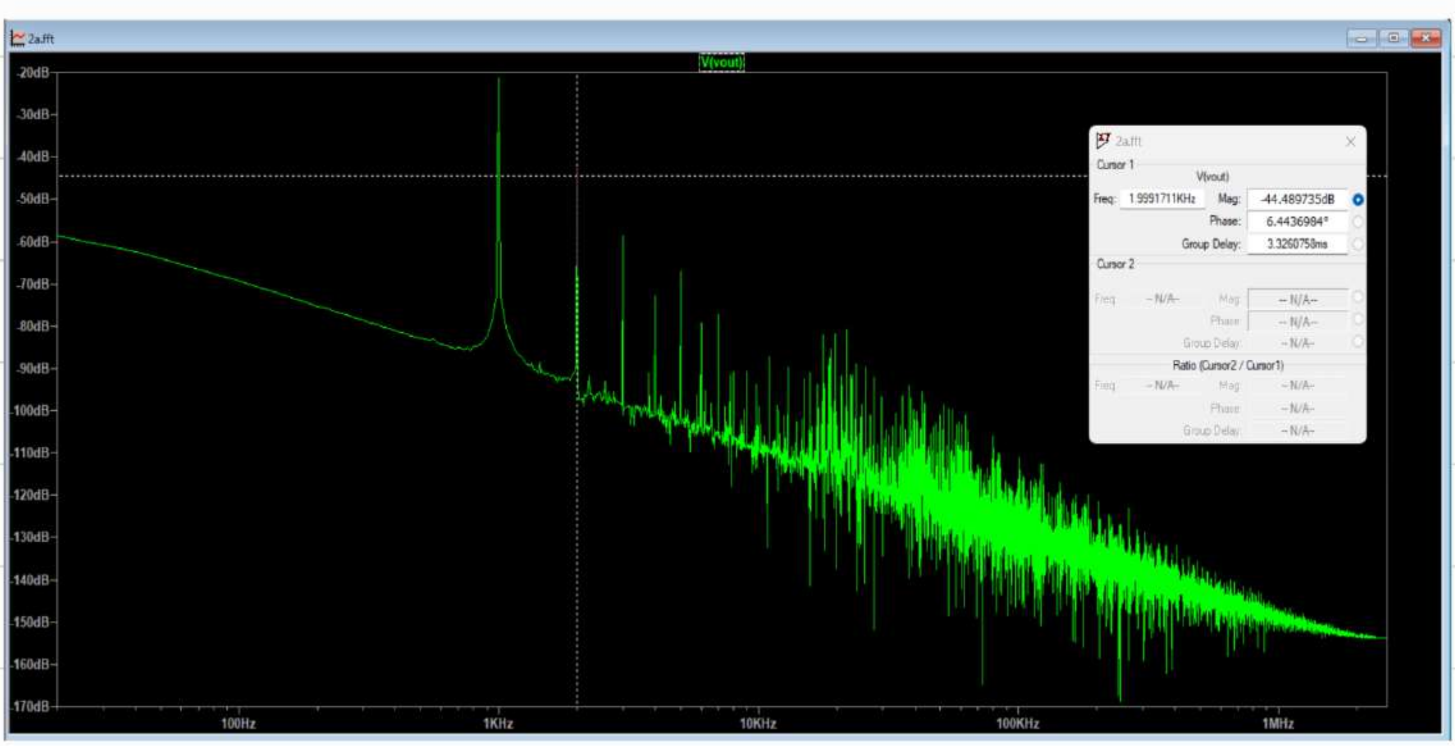
The gain calculated in the previous part = 13.231 which is almost similar.

(g) Fundamental frequency, f_0 = 1KHz

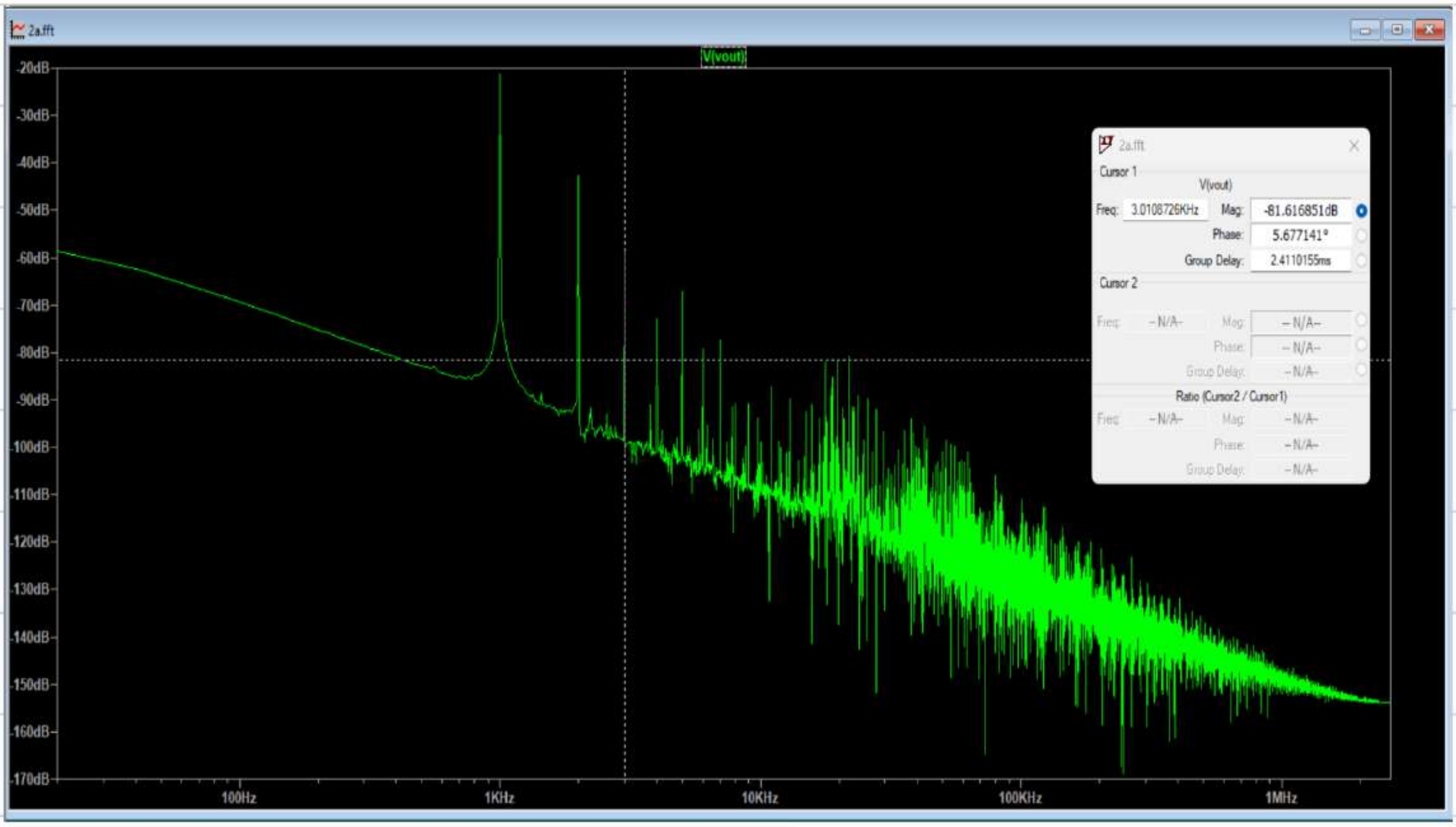
1st Harmonic



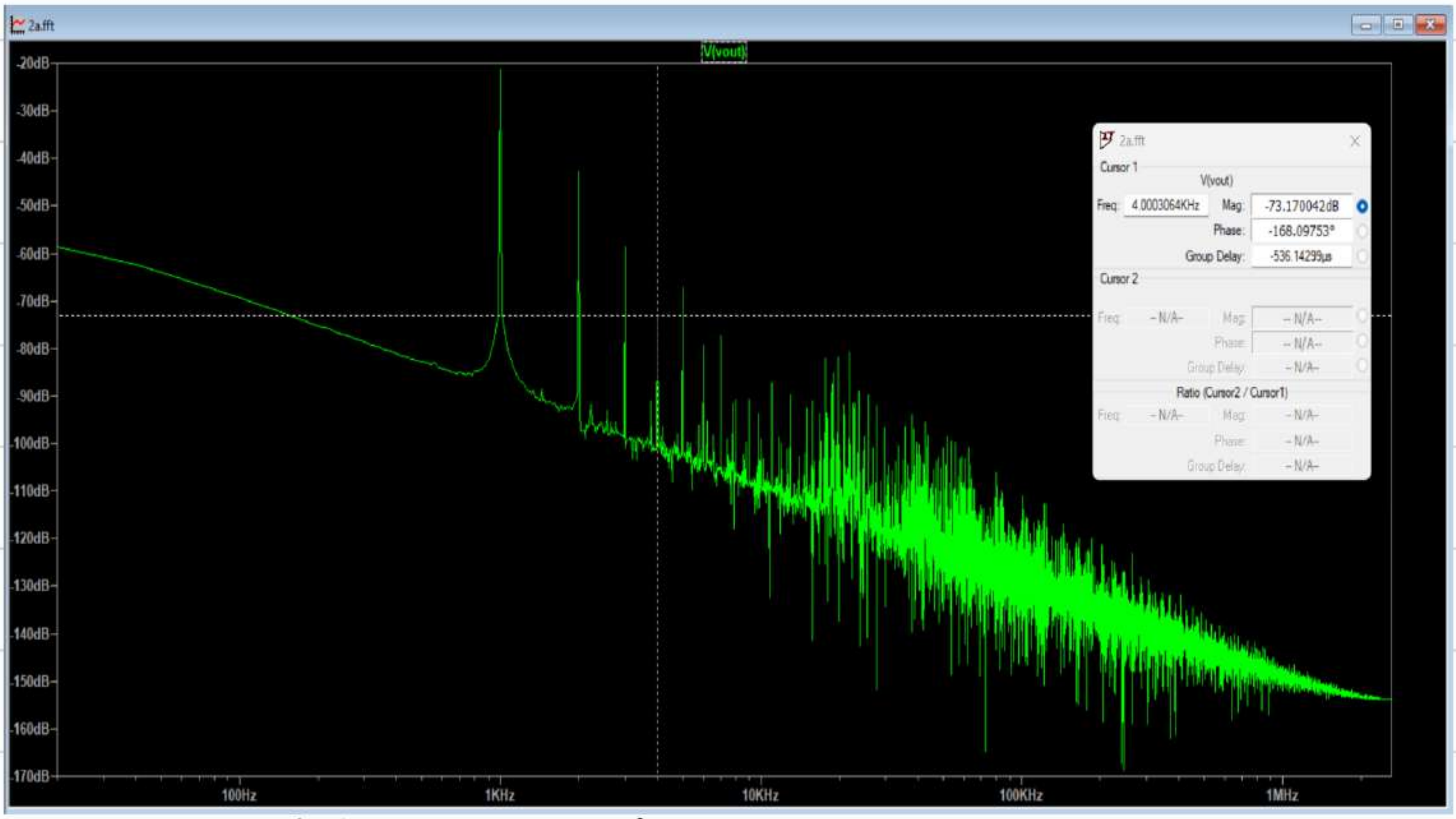
2nd Harmonic



3rd Harmonic



4th Harmonic



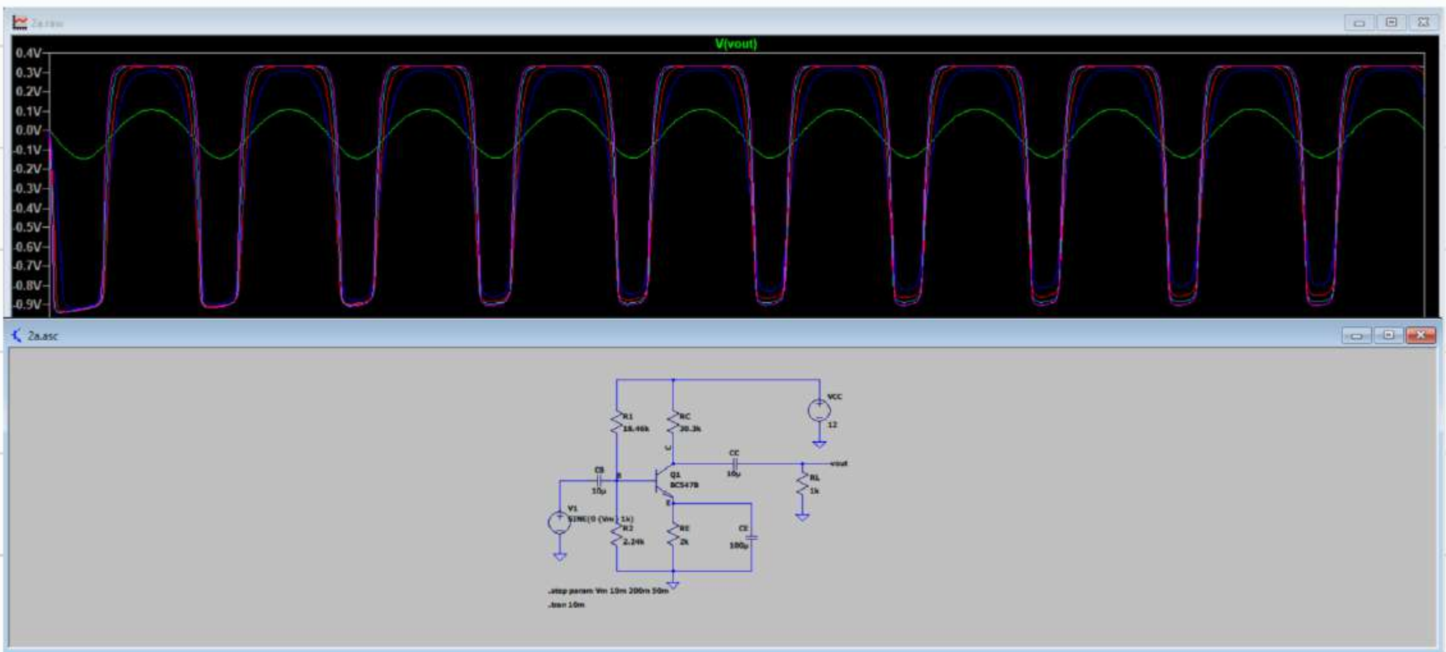
From the data in the photos,

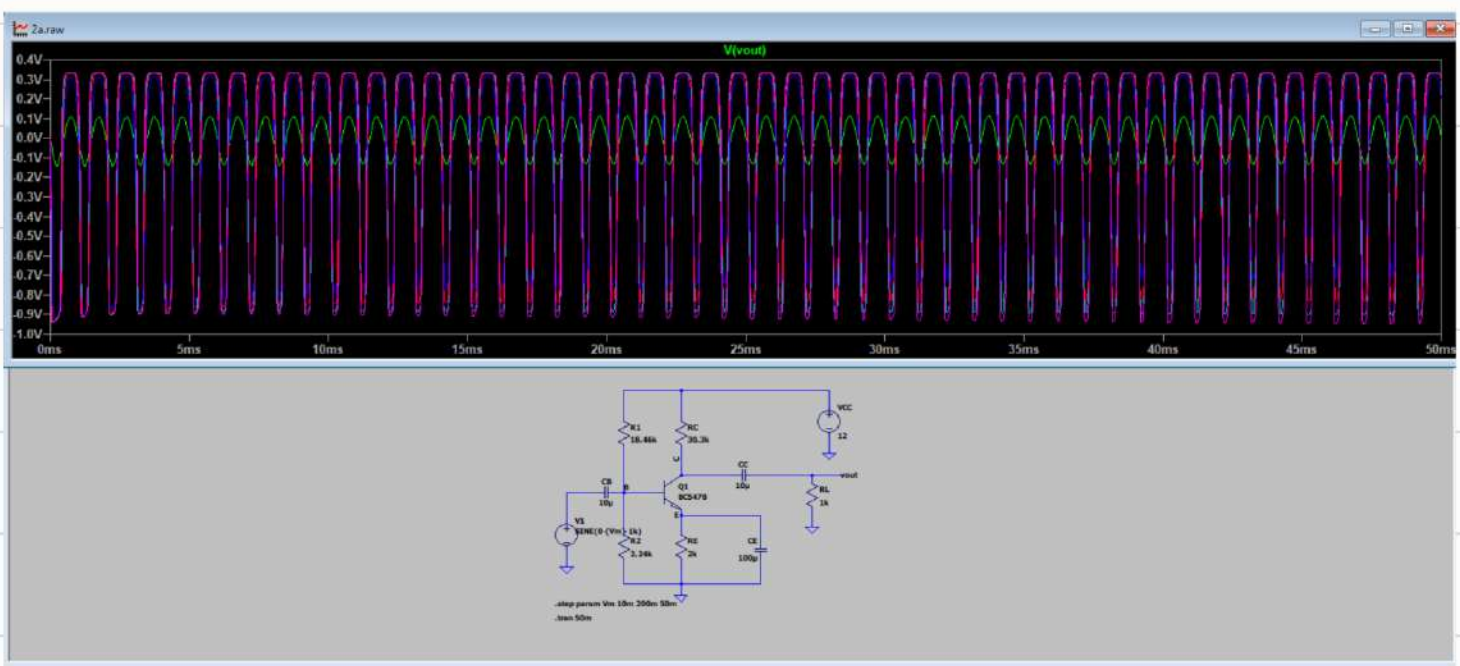
Difference can be reported.

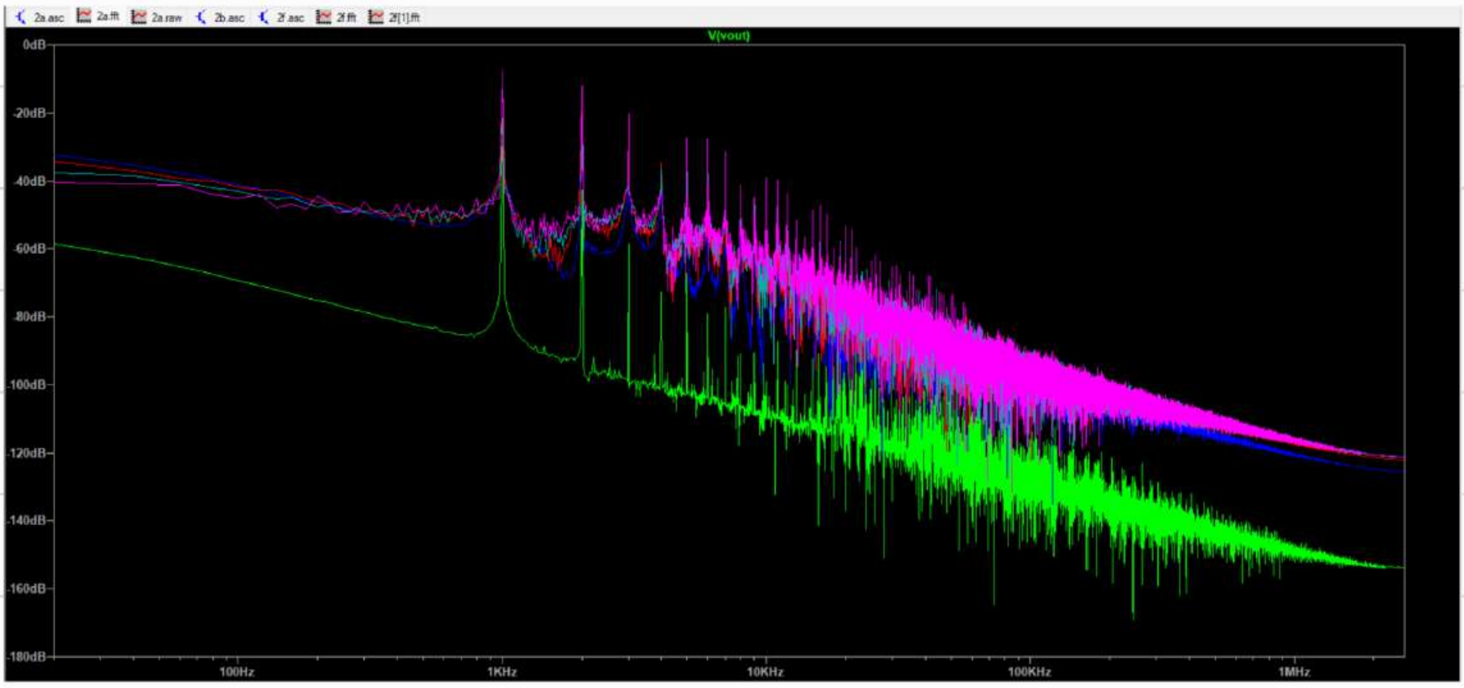
Magnitude of 1st Harmonic = - 23.649 dB

Harmonic	Frequency	Difference
2nd	1.99 kHz	$= -44.84 - (-23.649) = -21.191$
3rd	3.01 kHz	$= -61.616 - (-23.69) = -37.967$
4th	4.00 kHz	$= -73.170 - (-23.649) = -49.521$

(h) Total Harmonic Distribution (THD)







.step vm=0.06
N-Period=10
Fourier components of V(vout)
DC component:-0.0127641

Harmonic Number	Frequency [Hz]	Fourier Component	Normalized Component
1	1.000e+3	4.943e-1	1.000e+0
2	2.000e+3	2.039e-1	4.124e-1
3	3.000e+3	4.950e-2	1.001e-1
4	4.000e+3	8.030e-4	1.624e-3
5	5.000e+3	1.181e-2	2.390e-2
6	6.000e+3	1.273e-2	2.575e-2
7	7.000e+3	1.044e-2	2.112e-2
8	8.000e+3	6.900e-3	1.396e-2
9	9.000e+3	3.526e-3	7.133e-3
10	1.000e+4	1.203e-3	2.434e-3

Partial Harmonic Distortion: 42.668874%
Total Harmonic Distortion: 42.675338%

.step vm=0.11
N-Period=10
Fourier components of V(vout)
DC component:-0.00181328

Harmonic Number	Frequency [Hz]	Fourier Component	Normalized Component
1	1.000e+3	5.434e-1	1.000e+0
2	2.000e+3	2.843e-1	5.232e-1
3	3.000e+3	7.932e-2	1.460e-1
4	4.000e+3	1.350e-2	2.485e-2
5	5.000e+3	3.184e-2	5.859e-2
6	6.000e+3	2.332e-2	4.292e-2
7	7.000e+3	1.205e-2	2.217e-2
8	8.000e+3	4.514e-3	8.307e-3
9	9.000e+3	5.938e-4	1.093e-3
10	1.000e+4	1.495e-3	2.751e-3

Partial Harmonic Distortion: 54.908886%
Total Harmonic Distortion: 54.951963%

.step vm=0.01
N-Period=10
Fourier components of V(vout)
DC component:-0.000430312

Harmonic Number	Frequency [Hz]	Fourier Component	Normalized Component
1	1.000e+3	1.207e-1	1.000e+0
2	2.000e+3	1.047e-2	8.679e-2
3	3.000e+3	1.683e-3	1.395e-2
4	4.000e+3	3.284e-4	2.721e-3
5	5.000e+3	6.192e-4	5.131e-3
6	6.000e+3	1.621e-4	1.343e-3
7	7.000e+3	2.011e-4	1.666e-3
8	8.000e+3	4.755e-5	3.940e-4
9	9.000e+3	4.218e-5	3.495e-4
10	1.000e+4	1.813e-5	1.502e-4

Partial Harmonic Distortion: 8.812570%
Total Harmonic Distortion: 8.817012%

```
.step vm=0.16
N-Period=10
Fourier components of V(vout)
DC component:0.00275325
```

Harmonic Number	Frequency [Hz]	Fourier Component	Normalized Component
1	1.000e+3	5.596e-1	1.000e+0
2	2.000e+3	3.365e-1	6.014e-1
3	3.000e+3	1.215e-1	2.171e-1
4	4.000e+3	8.389e-3	1.499e-2
5	5.000e+3	5.026e-2	8.981e-2
6	6.000e+3	4.620e-2	8.256e-2
7	7.000e+3	2.731e-2	4.880e-2
8	8.000e+3	9.532e-3	1.703e-2
9	9.000e+3	4.315e-3	7.711e-3
10	1.000e+4	9.168e-3	1.638e-2

```
Partial Harmonic Distortion: 65.340304%
Total Harmonic Distortion:   65.649412%
```

```
.step vm=0.2
N-Period=10
Fourier components of V(vout)
DC component:0.00399901
```

Harmonic Number	Frequency [Hz]	Fourier Component	Normalized Component
1	1.000e+3	5.683e-1	1.000e+0
2	2.000e+3	3.672e-1	6.463e-1
3	3.000e+3	1.533e-1	2.699e-1
4	4.000e+3	7.492e-3	1.318e-2
5	5.000e+3	6.157e-2	1.084e-1
6	6.000e+3	6.791e-2	1.195e-1
7	7.000e+3	4.597e-2	8.089e-2
8	8.000e+3	1.793e-2	3.156e-2
9	9.000e+3	6.551e-3	1.153e-2
10	1.000e+4	1.809e-2	3.183e-2

```
Partial Harmonic Distortion: 72.482836%
Total Harmonic Distortion:   72.849067%
```

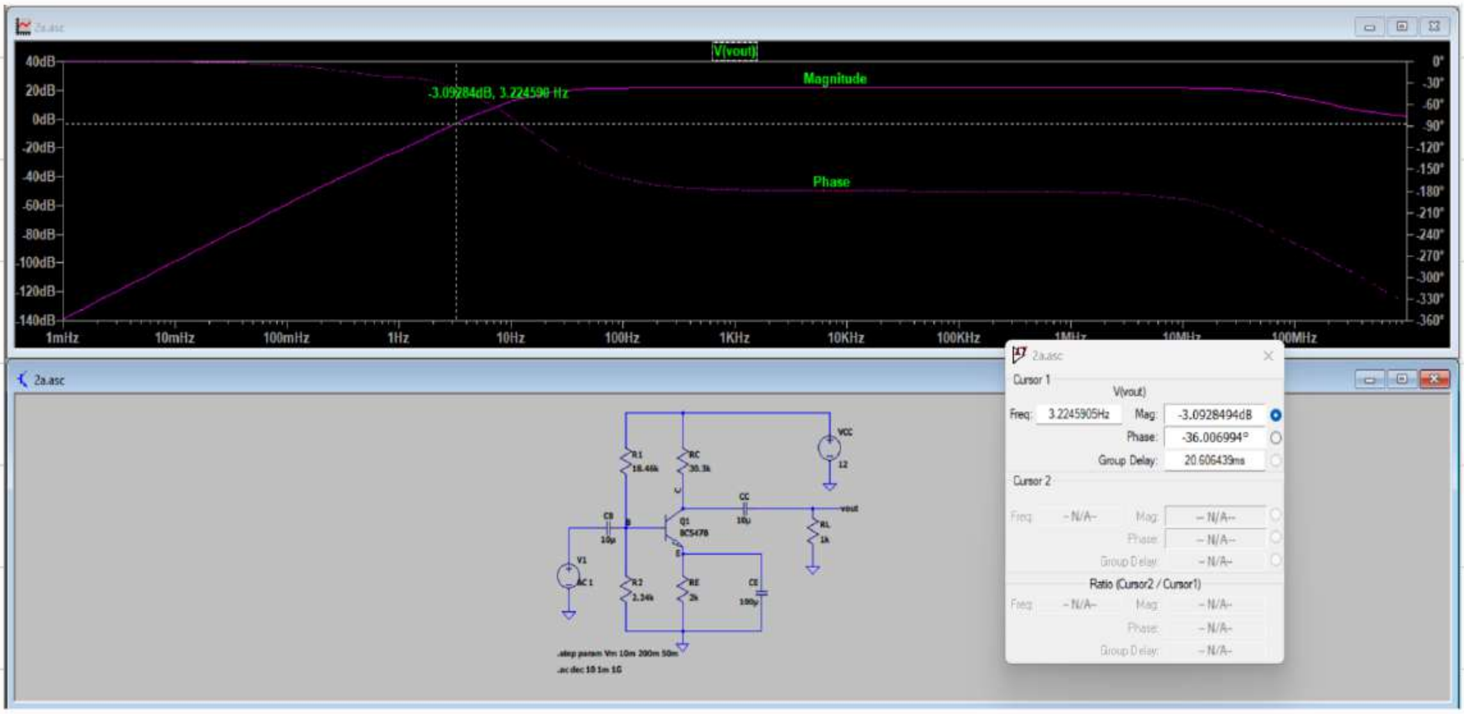
Vm	THD
0.01	8.817012 %
0.06	42.675338 %
0.11	54.951963 %
0.16	65.649412 %
0.2	72.849067 %

Yes, with increase in the value of Vm, there is also an increase in the THD.

There are also a few unwanted harmonics and distortions present in the signal.

→ As V_m increases, the value of output increases; that is, THD is directly proportional to the output of circuit. Thus we observed increasing values of THD's when V_m increases.

(i) AC Analysis and DC Gain

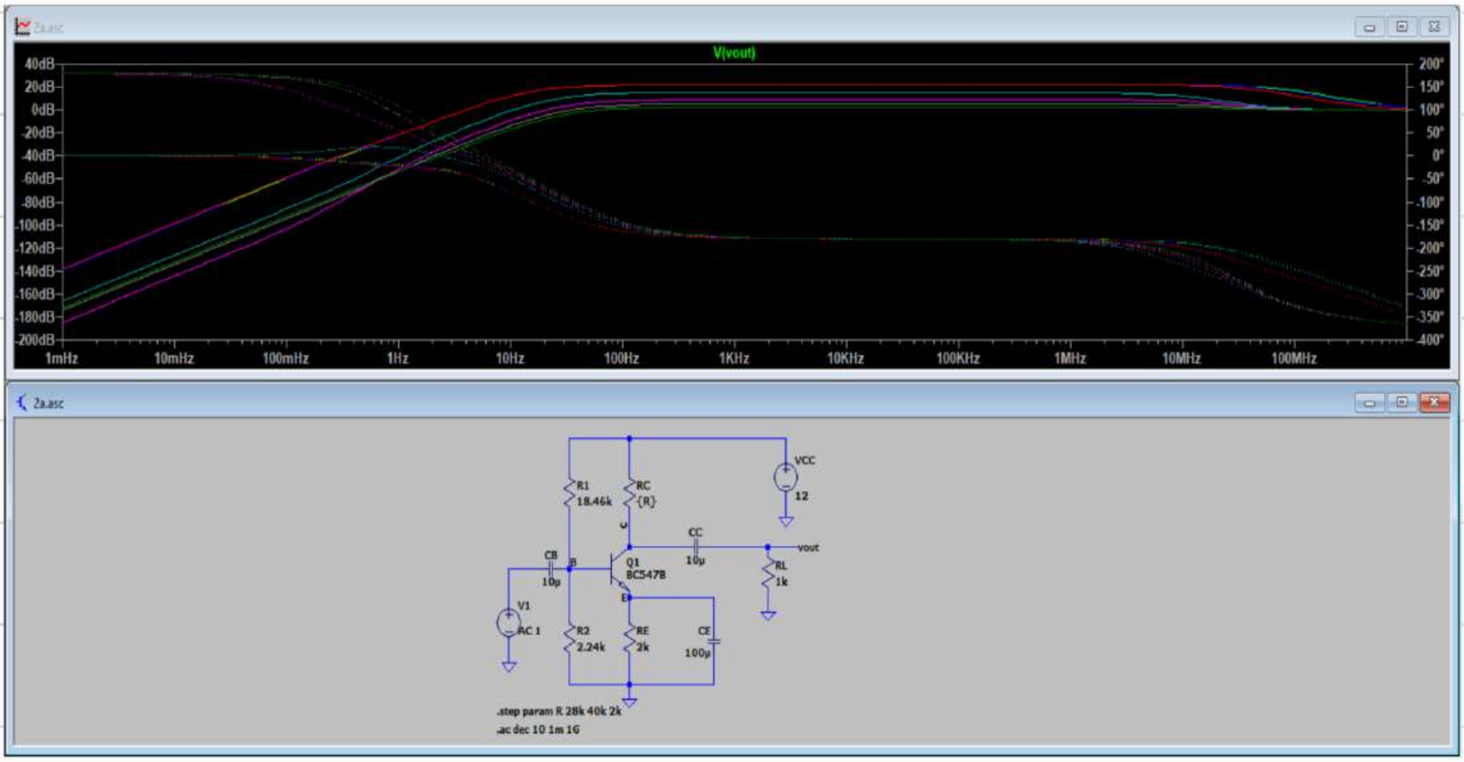


The -3 dB bandwidth is obtained at

at a frequency = 3.224590 Hz

Maximum gain is obtained at 21.393612 dB

(j) DC gain for different values of R_c



R_c	DC Gain
28 kΩ	21.913622 dB
30 kΩ	21.928602 dB
32 kΩ	21.940915 dB
34 kΩ	15.007594 dB
36 kΩ	8.7741936 dB
38 kΩ	5.0444321 dB
40 kΩ	2.3946224 dB

Comparision :

DC gain for R = 30kΩ is 21.929 dB

DC gain for R = 40kΩ is 2.394 dB

Justification:

As the value of R_L increases, then the output impedance increases accordingly.

Then the gain decreases.

Question 3 : Designing an Amplifier

Given that, $R_L = 1k\Omega$

$V_{CC} = 5$ Volts

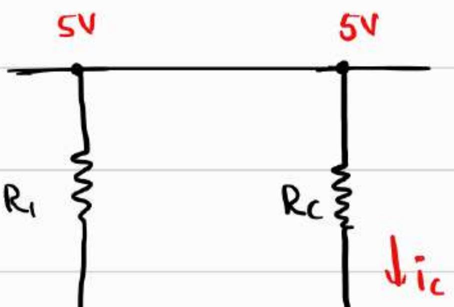
$A_v = 12.231$ (from prev Q)

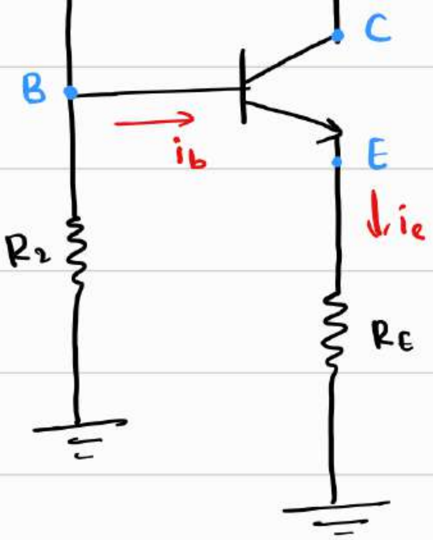
Bandwidth $= 17$ Hz (from previous problem)

We need to find,

$C_B, C_C, C_E, R_1, R_2, R_E, R_C, I_C, I_B$

Large Signal Model





Consider the following assumptions :

Let, $I_c = 3\,mA$

$$V_{CE} = \frac{V_{cc}}{2} = 2.5\ V$$

we know that,

$$\text{gain} = A_v = 13.231$$

$$A_v = g_m\,(R_L \| R_c) = 13.231$$

$$\frac{I_c}{V_T}\left(\frac{R_L \cdot R_c}{R_c + R_L}\right) = 13.231$$

$$\frac{1k \cdot R_c}{1000 + R_c} = \frac{13.231 \times 25 \times \cancel{10^{-3}}}{3 \times \cancel{10^{-3}}}$$

$$\frac{R_c}{1000 + R_c} = 110.25\ m$$

$$1 + \frac{1000}{R_c} = \frac{1000}{110.25}$$

$$\boxed{R_C = 123.91\ \Omega}$$

$$I_\beta = \frac{I_c}{\beta} = \frac{3m}{259.56}$$

$$\boxed{I_\beta = 11.55\ \mu A}$$

$$I_E = I_c + I_B$$

$$= 3mA + 11.55\ \mu A$$

$$\boxed{I_E = 3.0115\ mA}$$

Apply KVL on right half of circuit, i.e from collector to the emitter

$$5 - I_c R_c - V_{CE} - I_e R_e = 0$$

$$5 = 371.73 \times 10^{-3} + 2.5 + (3.0115 \times 10^{-3}) R_e$$

$$\boxed{R_e = 706.71\ \Omega}$$

$$V_E = I_E R_E$$

$$\boxed{V_E = 2.128\ V}$$

$$V_B = V_{BE} + V_E$$

$$= 0.7 + 2.128$$ [$\because V_{BE} = 0.7V$ given standard]

$$\boxed{V_B = 2.828 \text{ V}}$$

Let us also assume $\boxed{R_1 = 700\ \Omega}$

Then, $V_B = \dfrac{R_2}{R_1 + R_2} \times V_{cc}$

$$2.828 = \frac{R_2}{700 + R_2} \times 5$$

0.768

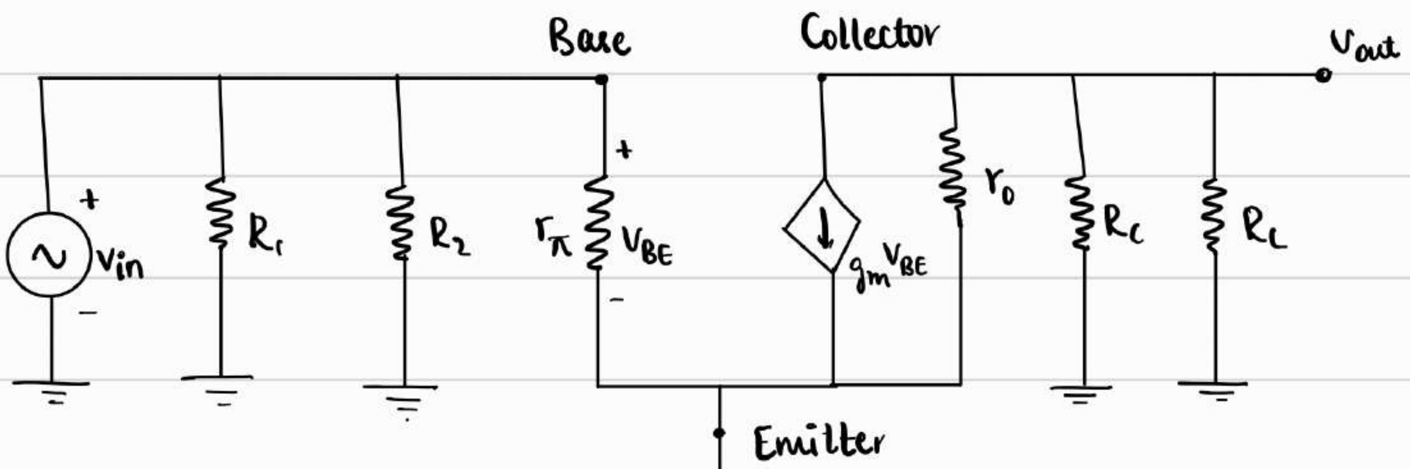
$$1 + \frac{700}{R_2} = \frac{5}{2.828}$$

$$\Rightarrow \boxed{R_2 = 911.458\ \Omega}$$

$$r_\pi = \frac{\beta}{g_m}$$

$$= \frac{\beta V_T}{I_C} = \frac{259.56 \times 25\cancel{m}}{3\cancel{m}}$$

$$\boxed{r_\pi = 2.163\ \text{k}\Omega}$$



At the input,

let $Z_{in} \rightarrow$ input impedance

$$Z_{in} = [R_1 \| R_2 \| r_\pi]$$

$$Z_{in} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{r_\pi}}$$

$$= \frac{1}{0.002556}$$

$$\boxed{Z_{in} = 391.236\ \Omega}$$

Since bandwidth in prev & new prob are the same

$$\frac{1}{\cancel{2\pi} Z_{in} C_{new}} = \frac{1}{\cancel{2\pi} R_{in} C_{old}}$$

$$C_{B_{new}} = \frac{R_{in} \times C_{old}}{Z_{in}}$$

R_{in} - input impedance in prev prob

$$= \frac{1803.88 \times 10 \times 10^{-6}}{391.236}$$

$$\boxed{C_B = 46\ \mu F}$$

Similarly,

$Z_{out} \longrightarrow$ Output Impedance at C_c

$$Z_{out} = R_c \parallel R_L$$

$$\boxed{Z_{out} = 110.24}$$

$R_{out} \to$ Output impedance in prev

$$\frac{1}{\cancel{2\pi} Z_{out} C_c} = \frac{1}{\cancel{2\pi} R_{out} C_{old}}$$

$$Z_{out} = \frac{968.05 \times 10\mu}{110.24}$$

$$Z_{out} = 87.80 \times \mu$$

$$\boxed{C_c = 87.8\ \mu F}$$

At the emitter,

Let $Z_E \longrightarrow$ emitter impedance

$$\frac{1}{Z_E} = \frac{1}{R_E} + \frac{\beta+1}{r_\pi}$$

5552.25

$$Z_E = R_E \parallel \frac{r_\pi}{\beta+1}$$

$$= \frac{706.71 \times 8.301}{715.011}$$

$$\boxed{Z_E = 8.204}$$

$$\frac{1}{\cancel{2\pi} Z_E C_{new}} = \frac{1}{\cancel{2\pi} R_{old} C_{old}}$$

R_{old} → Impedance at emitter in Q2)

$= 70.375\ \Omega$

$$Z_E = \frac{100\ \mu F \times 70.375}{8.204}$$

$$\boxed{C_E = 85.81\ \mu F}$$

∴ The required values are

$C_B = 46\ \mu F$	$R_1 = 700\ \Omega$
$C_C = 87.8\ \mu F$	$R_2 = 911.452\ \Omega$
$C_E = 85.81\ \mu F$	$R_E = 706.71$

$I_C = 3\ mA$	$R_C = 123.91\ \Omega$
$I_B = 11.55\ \mu A$	

Gain in the New Circuit:

$V_{in}(max) = 9.9823\ mA$

$V_{out}(max) = 131.566\ mA$

$Gain_{new} = \frac{131.566}{9.9823} = 13.179$ — Experimental

$$Gain_{theoretical} = g_m (R_C \| R_L) = \frac{I_C}{V_T}(R_C \| R_L)$$

$$= \frac{3\cancel{m}}{25\ \cancel{m}}(110.189) = 13.22$$ — Theoretical

DC Power Consumption:

At $V_C = 5V$

$I\ drawn = 6.1986\ mA$

$Power = V_C \times I\ drawn$

$= 30.993\ mW$

At $V_c = 12V$

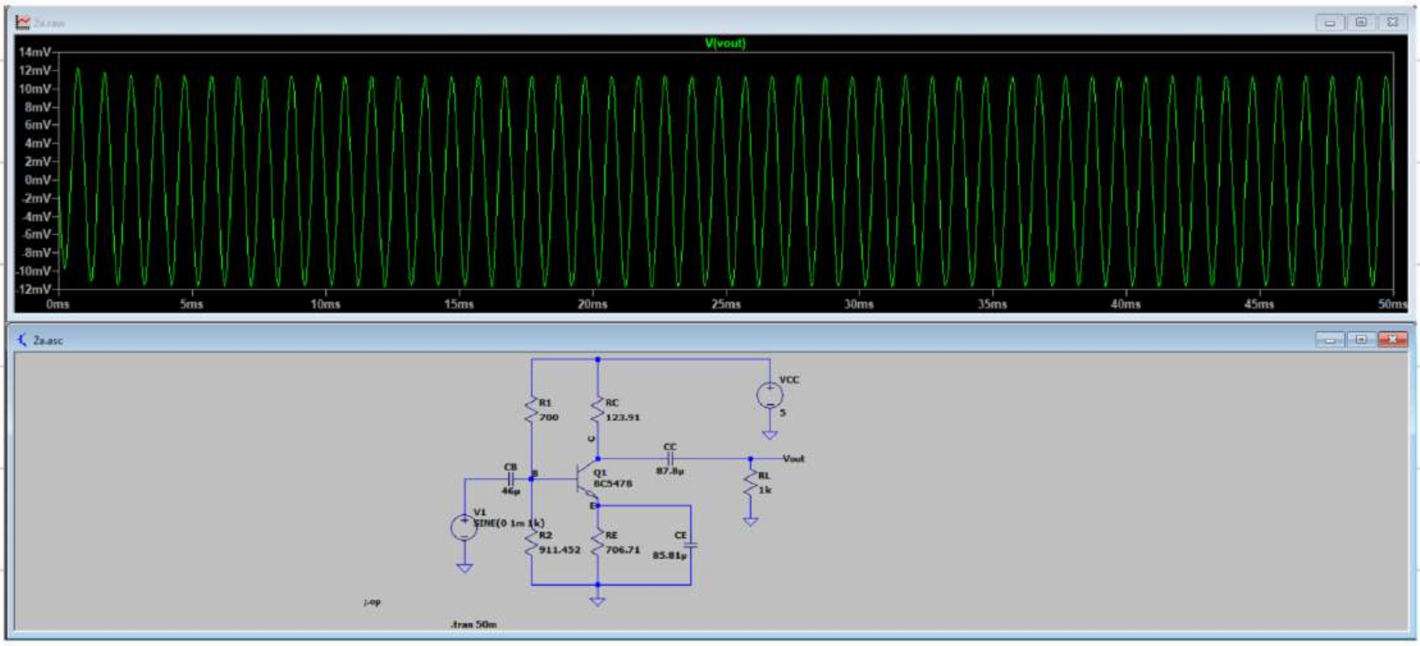
$$I_{drawn} = 0.9219 \text{ mA}$$

$$\text{Power} = V_c \times I_{drawn}$$

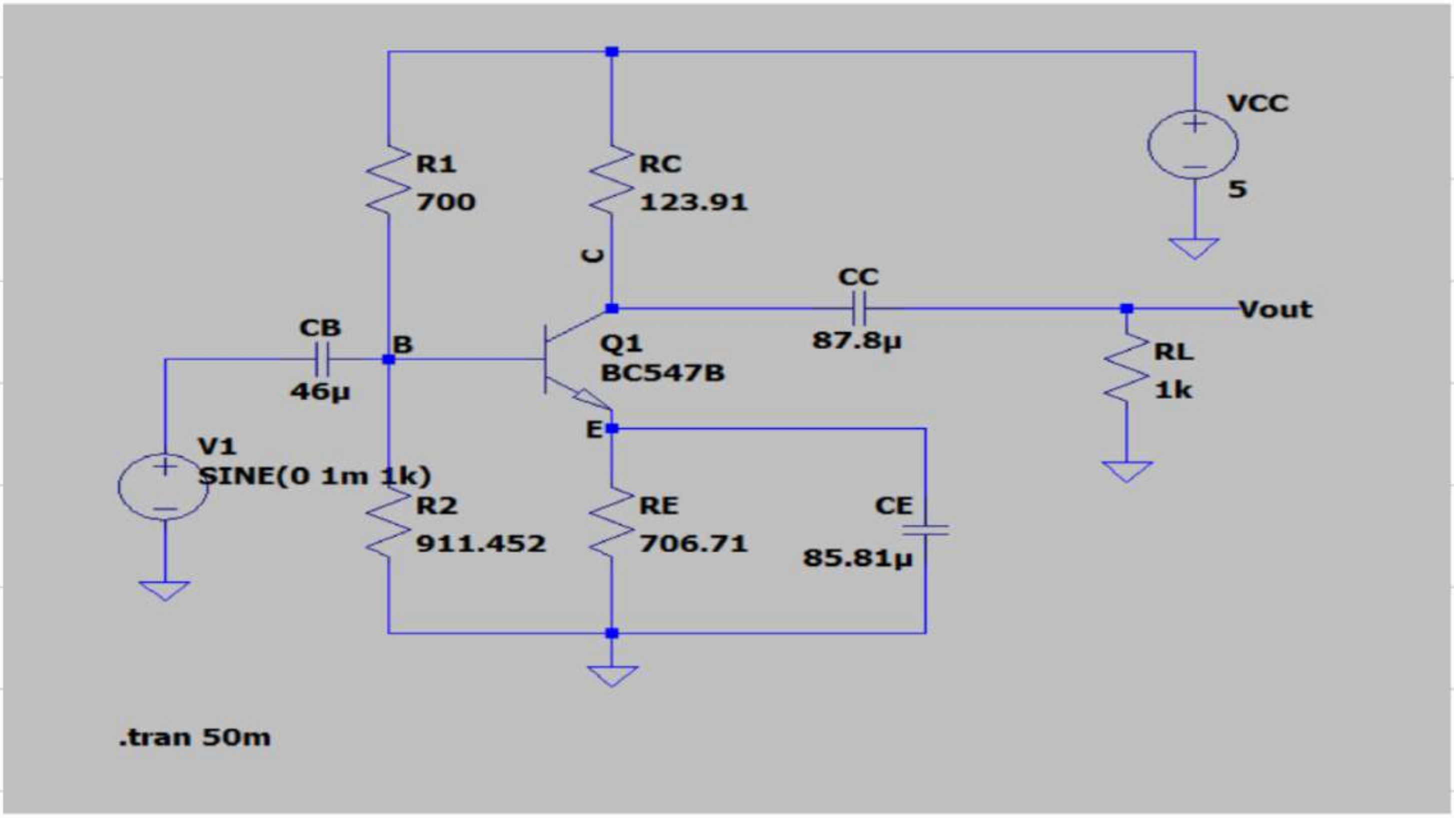
$$= 11.0628 \text{ mW}$$

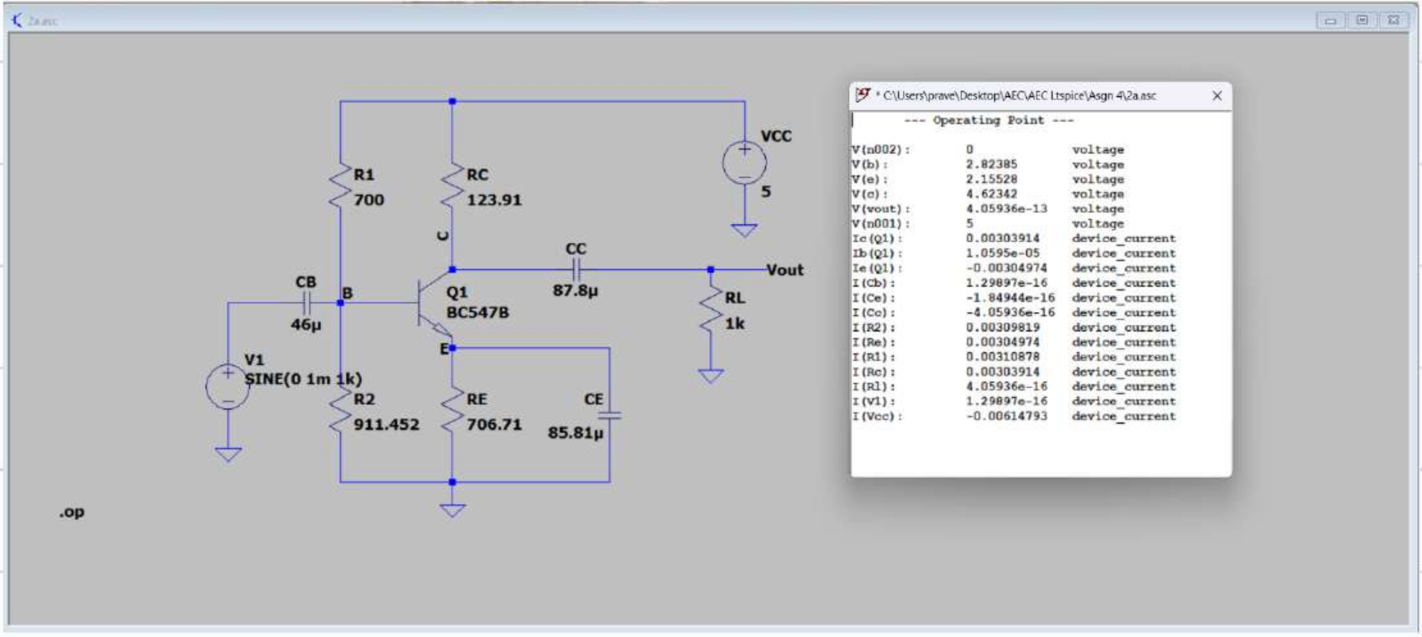
V_{CC}	I_{drawn}	P_{DC}
12 V	0.9219 mA	11.0628 mW
5V	6.1986 mA	30.993 mW

Vout

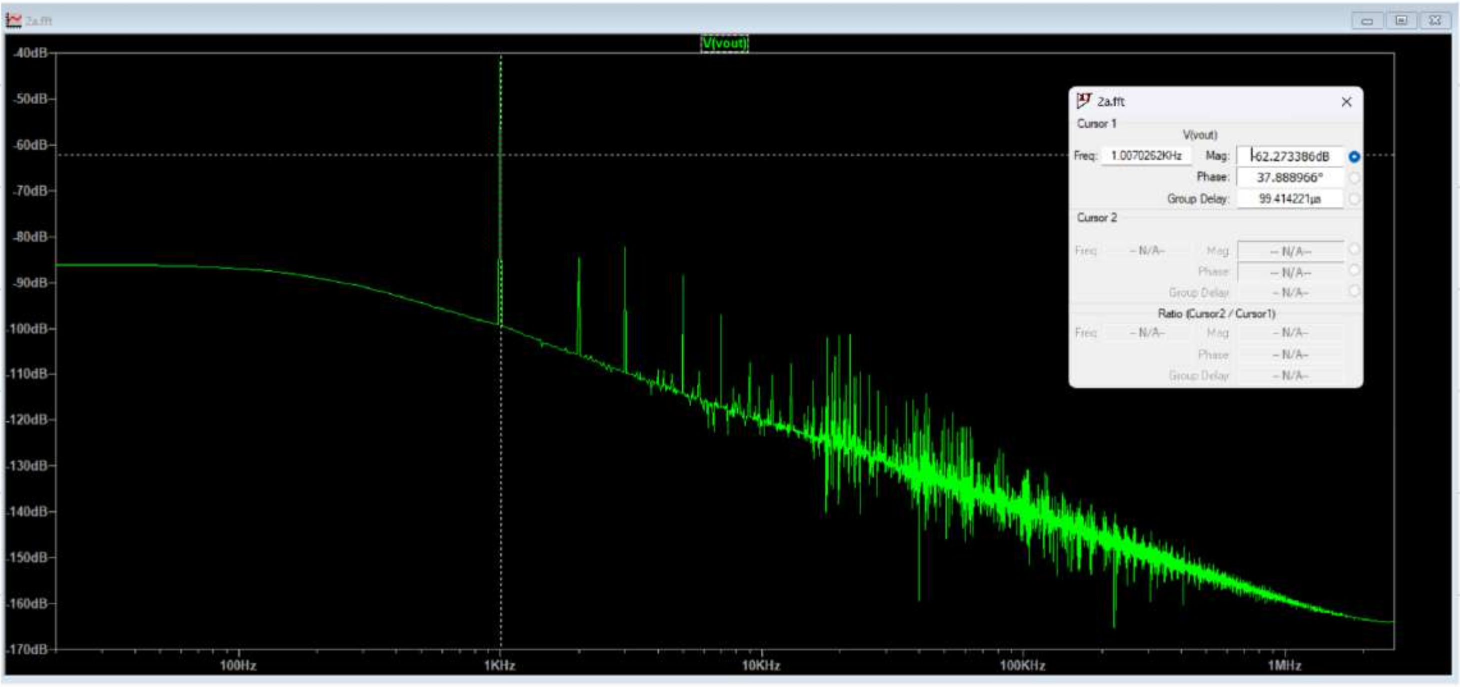


The New Designed Circuit

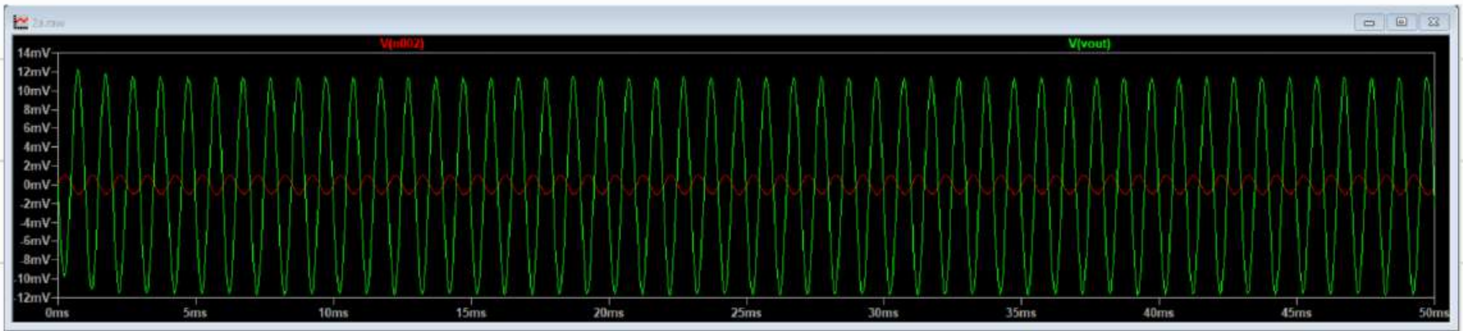


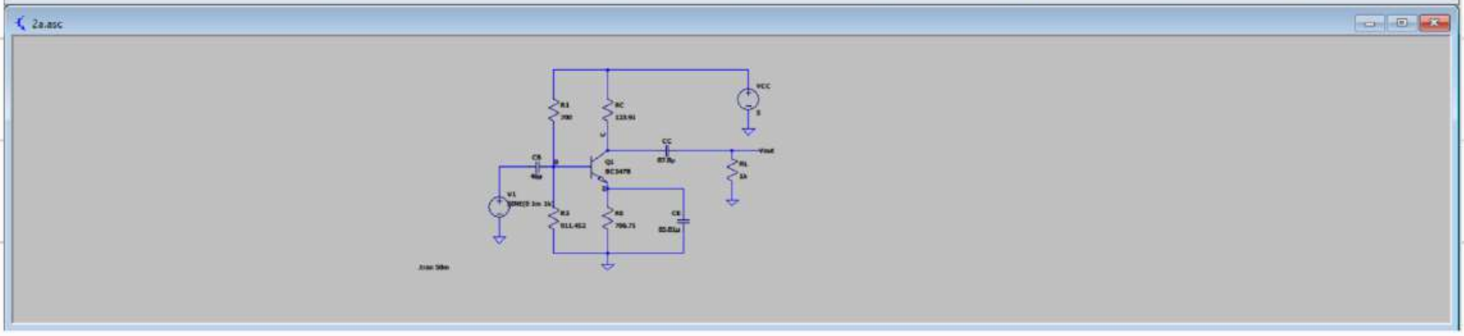


FFT :

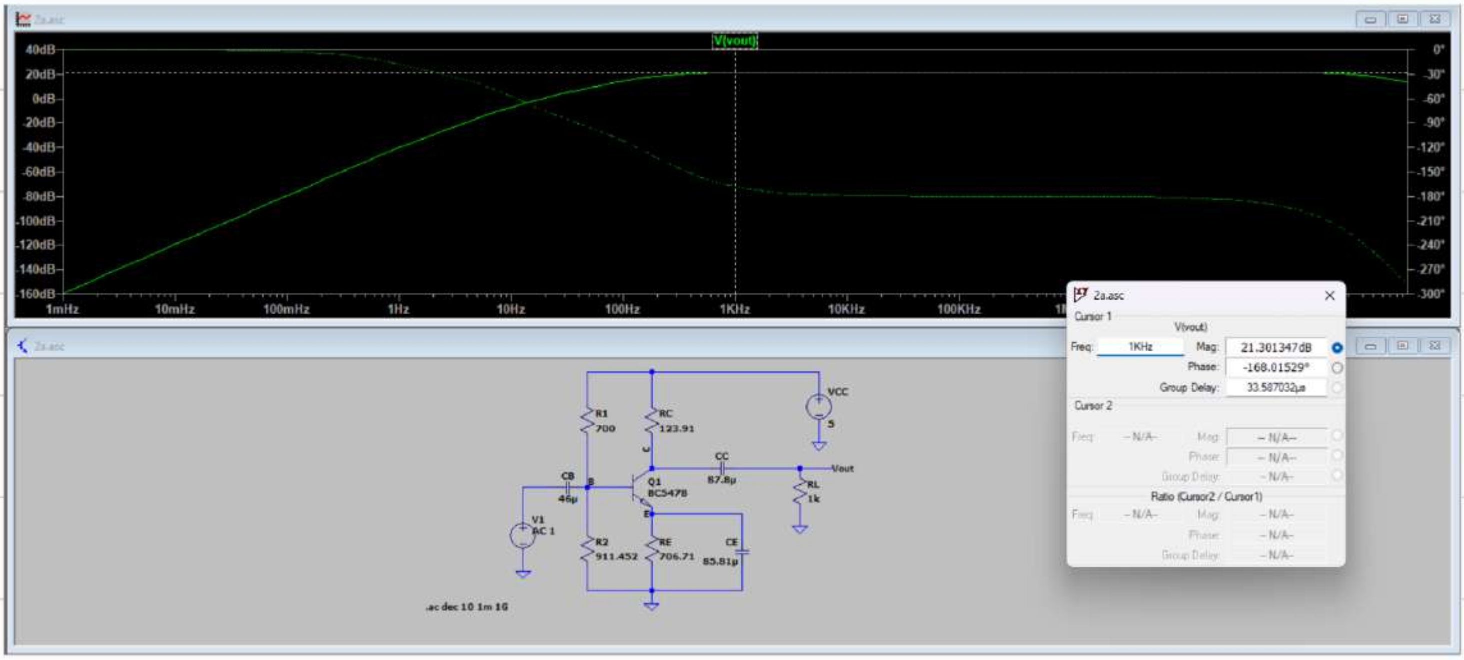


Vout and Vin





Bode Plot



−3dB Frequency in Bode Plot.