BIPOLAR JUNCTION TRANSISTOR

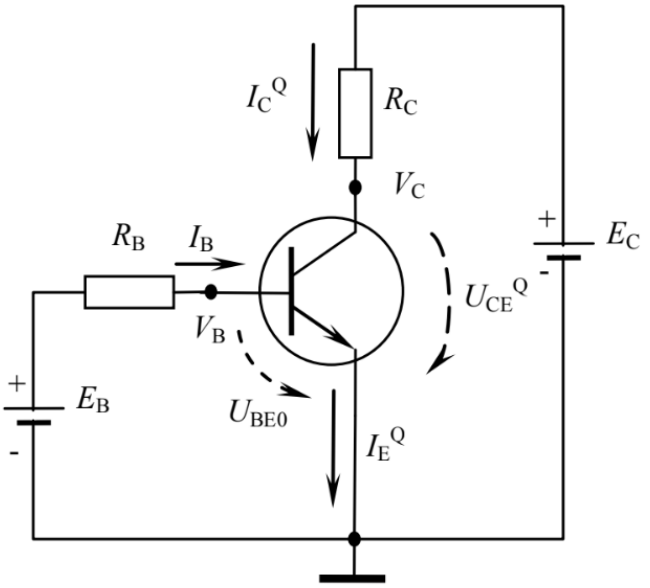
A Bipolar Junction Transistor (BJT) is a semiconductor device formed by two pn junctions. Therefore, it will have three alternating regions. It can be either a narrow n-type region placed between two p type layers (forming a pnp transistor), or a thin p-type region between two n-type layers (representing a npn transistor).

BJT OUTPUT CHARACTERISTIC

❖ ***Theoretical Summary***

The output characteristic relates the output current i_C with the output voltage v_{CE}, with the condition that the input current i_B is kept constant:

$$i_C = i_C(v_{CE}) \mid i_B = const.$$



- ***Components***
  a. *E_B , E_C – DC Voltage Sources*
  b. *npn Transistor*
  c. *R_B – Base Resistor*
  d. *R_C – Collector Resistor*

- ***Values***
  - R_B = 100kΩ
  - R_C = 1kΩ
  - $E_C \in [0V, 12V]$
  - I. E_B = 1.6V => (KVL – left loop) => I_{B1} = 10mA
  - II. E_B = 2.6V => … => I_{B2} = 20mA

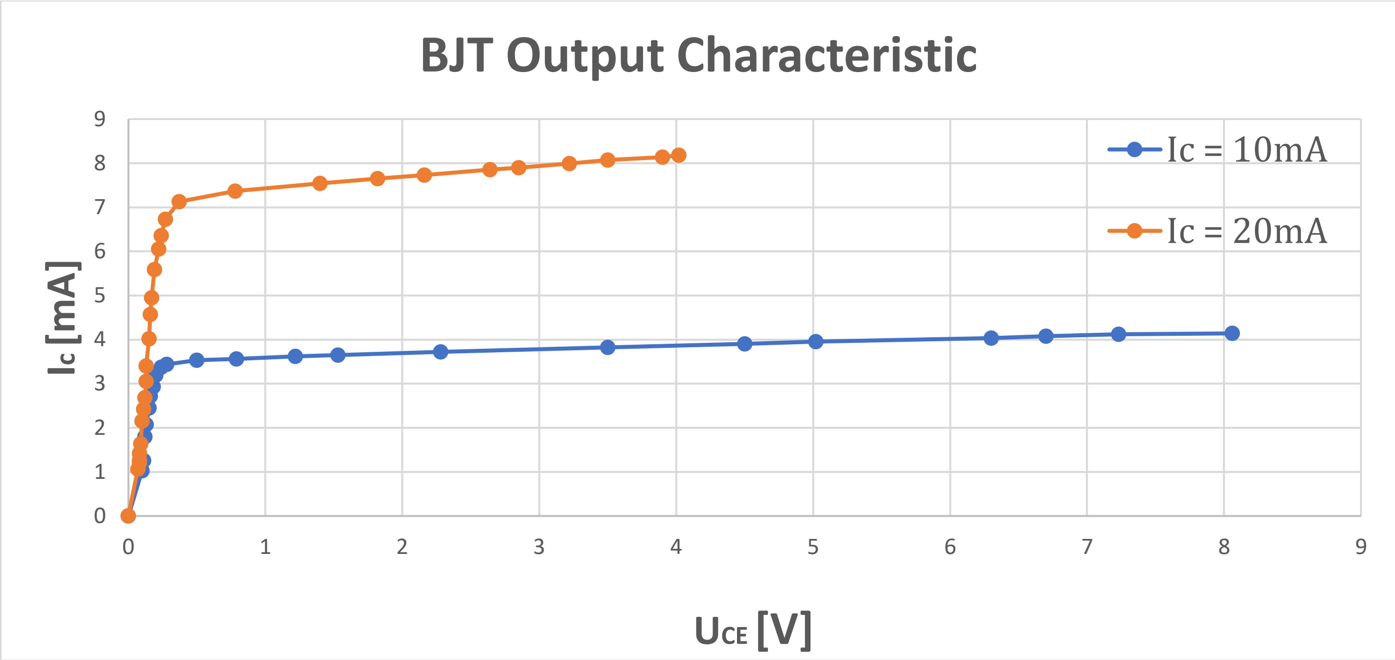
❖ *Measurements*

$I_{B1} = 10\,mA$ $I_{B2} = 20mA$

E_C[V]	U_{CE}[V]	I_C[mA]	E_C[V]	U_{CE}[V]	I_C[mA]
0	0	0	0	0	0
1.13	0.1	1.03	1.13	0.07	1.06
1.37	0.11	1.26	1.29	0.08	1.21
1.92	0.12	1.8	1.34	0.08	1.26
2.2	0.13	2.07	1.5	0.08	1.42
2.6	0.15	2.45	1.73	0.09	1.64
2.88	0.16	2.72	2.25	0.1	2.15
3.11	0.18	2.93	2.53	0.11	2.42
3.39	0.2	3.19	2.8	0.12	2.68
3.61	0.24	3.37	3.18	0.13	3.05
3.72	0.28	3.44	3.53	0.13	3.4
4.03	0.5	3.53	4.17	0.15	4.02
4.35	0.79	3.56	4.73	0.16	4.57
4.84	1.22	3.62	5.12	0.17	4.95
5.18	1.53	3.65	5.78	0.19	5.59
6	2.28	3.72	6.27	0.22	6.05
7.32	3.5	3.82	6.6	0.24	6.36
8.4	4.5	3.9	7	0.27	6.73
8.97	5.02	3.95	7.5	0.37	7.13
10.33	6.3	4.03	8.15	0.78	7.37
10.78	6.7	4.08	8.94	1.4	7.54
11.35	7.23	4.12	9.47	1.82	7.65
12.2	8.06	4.14	9.89	2.16	7.73
			10.49	2.64	7.85
			10.75	2.85	7.9
			11.21	3.22	7.99
			11.57	3.5	8.07
			12.04	3.9	8.14
			12.2	4.02	8.18

- ***KVL (right loop):***

$$E_C = R_C \cdot I_C + U_{CE} \Rightarrow I_C = \frac{E_C - U_{CE}}{R_C}$$



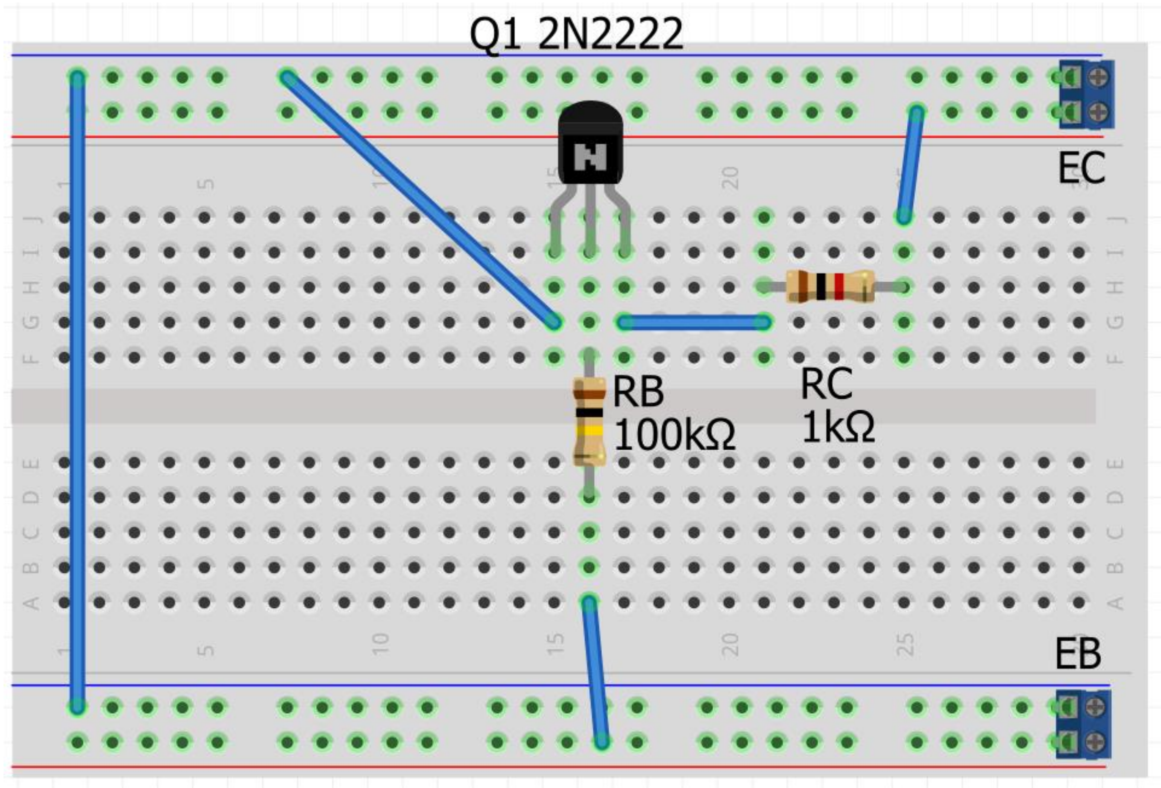
- ***Current Gain β***
  - ***I. I_B = 10mA***

$$\beta = \frac{\sum \frac{I_C}{I_B}}{n} = 0.306$$

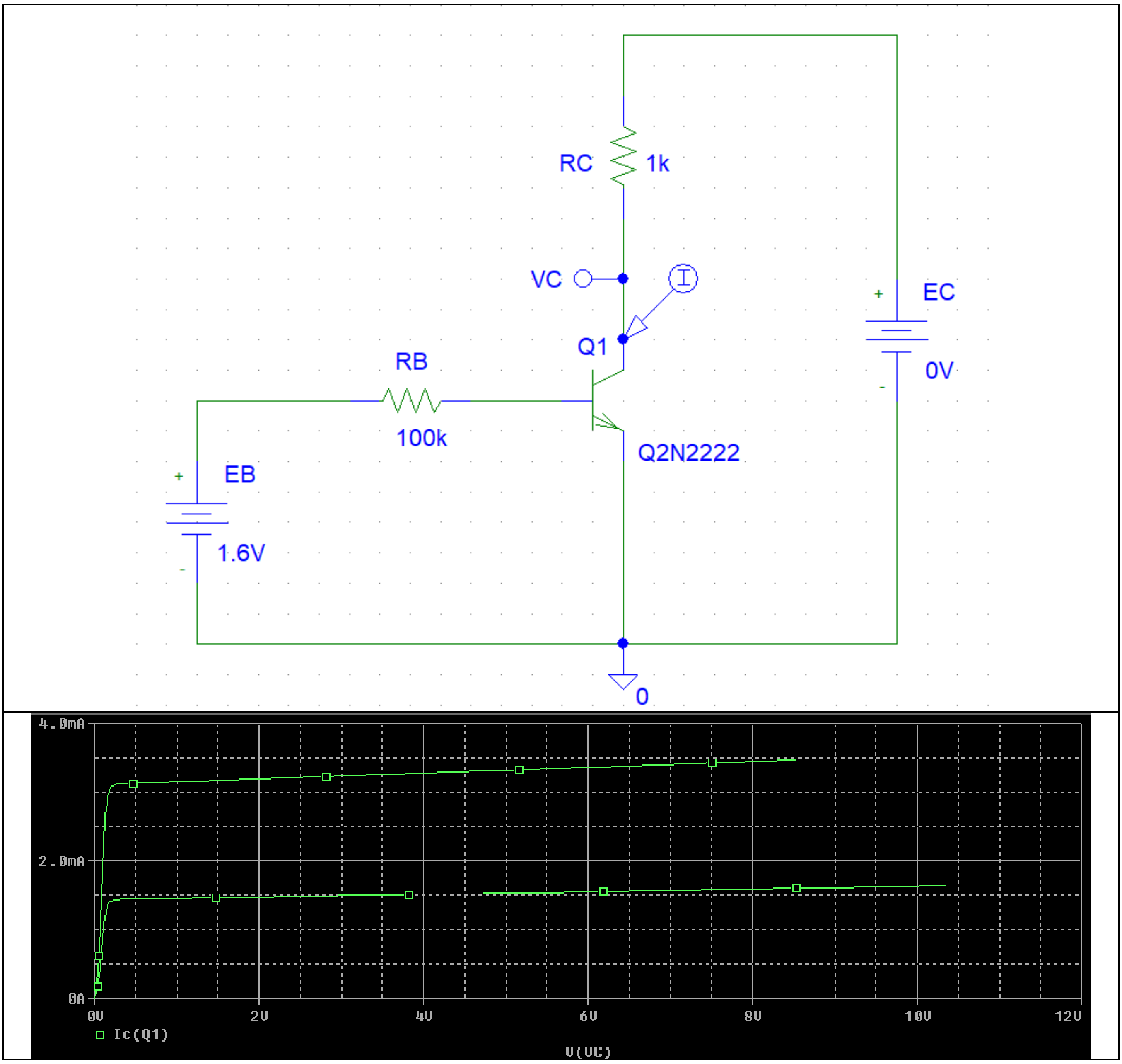
  - ***II. I_B = 20mA***

$$\beta = \frac{\sum \frac{I_C}{I_B}}{n} = 0.248$$

❖ ***Experimental Model***



❖ *Simulations*



❖ *Conclusion*

The collector current I_C, and in turn the Q point's current I_C^Q and voltage V_{CE}^Q, depends on the value of the base current I_B.

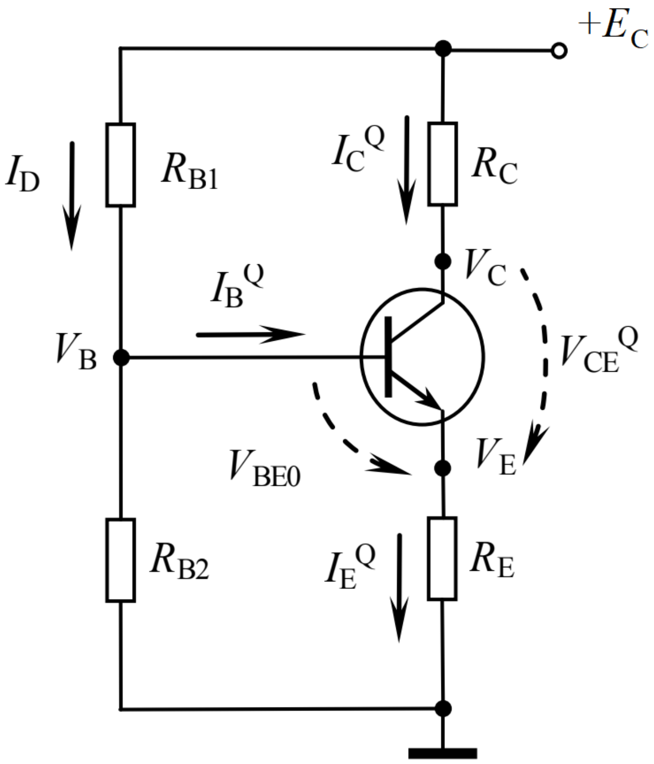
I_C is directly proportional with I_B.

BJT VOLTAGE DIVIDER (SELF-BIAS)

❖ *Theoretical Summary*

The operating point (Q point or bias point) of the BJT is defined as the DC component pair of the collector current I_C^Q and the collector – emitter voltage V_{CE}^Q.

Graphically, the operating point is situated at the intersection of the load line and the output I-V characteristic of the transistor.

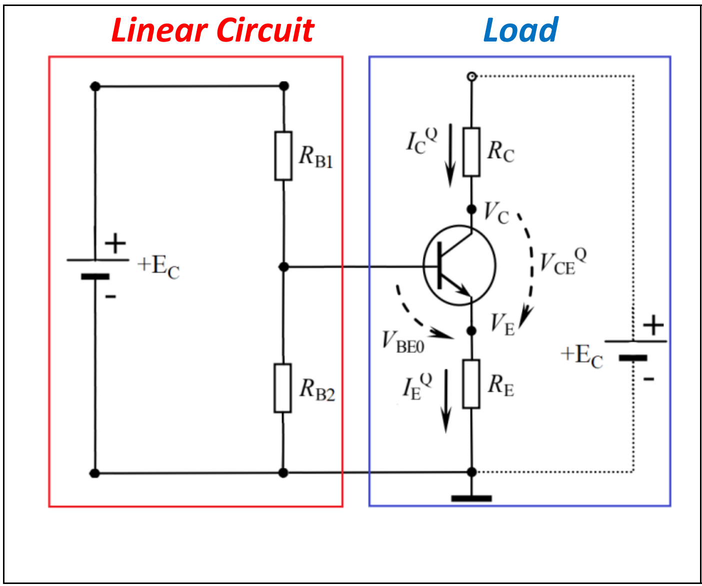


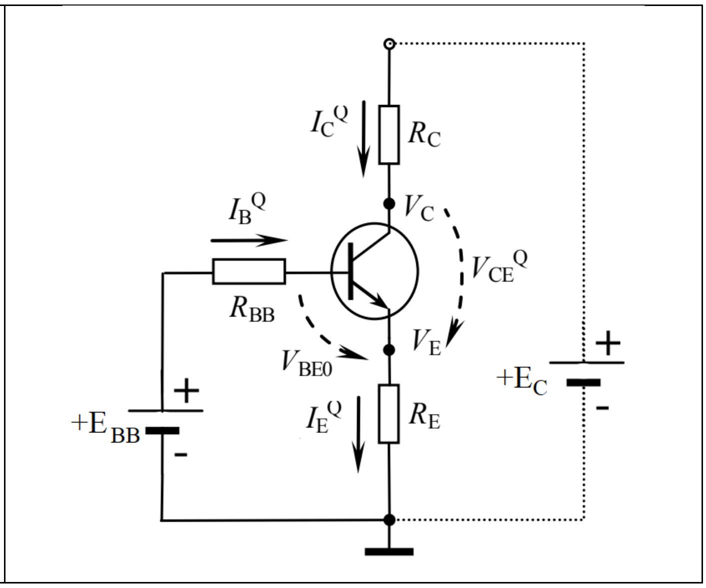
- ***Components***
  - *a. E_C – DC Voltage Sources*
  - *b. npn Transistor*
  - *c. R_{B1} , R_{B2} – Base Resistors*
  - *e. R_C – Collector Resistor*
  - *f. R_E – Emitter Resistor*

- ***Values***
  - E_C = 12V
  - R_C = 2.2kΩ
  - R_E = 1kΩ
  - Depending on the potentiometer:
    - I. P ⟶ M: R_{B1} = 47kΩ & R_{B2} = 20kΩ
    - II. P ⟶ N: R_{B1} = 57kΩ & R_{B2} = 10kΩ

❖ *Theoretical Analysis & Calculations*

- ***Thevenin Method***





$$Q: \begin{cases} I_C^Q \\ U_{CE}^Q \end{cases} \Rightarrow \begin{cases} I_E \cong I_C^Q \\ I_C^Q = \beta \cdot I_B \\ U_{BE0} = 0.6v \end{cases}$$

$$KVL: \begin{cases} E_{BB} = I_B \cdot R_{BB} + V_{BE0} + I_E \cdot R_E \\ E_C = I_C^Q \cdot R_C + V_{CE}^Q + I_E \cdot R_E \end{cases} \Rightarrow \begin{cases} I_C^Q = \beta \cdot \dfrac{E_{BB} - V_{BE0}}{R_{BB} + \beta \cdot R_E} \\ V_{CE}^Q = E_C - I_C^Q (R_C + R_E) \end{cases}$$

I. **P ⟶ M** : $R_{B1} = 47k\Omega$ & $R_{B2} = 20k\Omega$

$$E_{BB} = \frac{R_{B2}}{R_{B2} + R_{B1}} \cdot E_C = 3.58V$$
$$R_{BB} = R_{B1} \parallel R_{B2} = 14k\Omega$$

i. $\boldsymbol{\beta = 333}$

$$I_C^Q = 2.85mA$$
$$V_{CE}^Q = 2.88V$$

ii. $\boldsymbol{\beta = 130}$

$$I_C^Q = 2.69mA$$
$$V_{CE}^Q = 3.39V$$

II. **P ⟶ N** : $R_{B1} = 57k\Omega$ & $R_{B2} = 10k\Omega$

$$E_{BB} = \frac{R_{B2}}{R_{B2} + R_{B1}} \cdot E_C = 1.79V$$

$$R_{BB} = R_{B1} \parallel R_{B2} = 8.5k\Omega$$

i. $\boldsymbol{\beta = 333}$

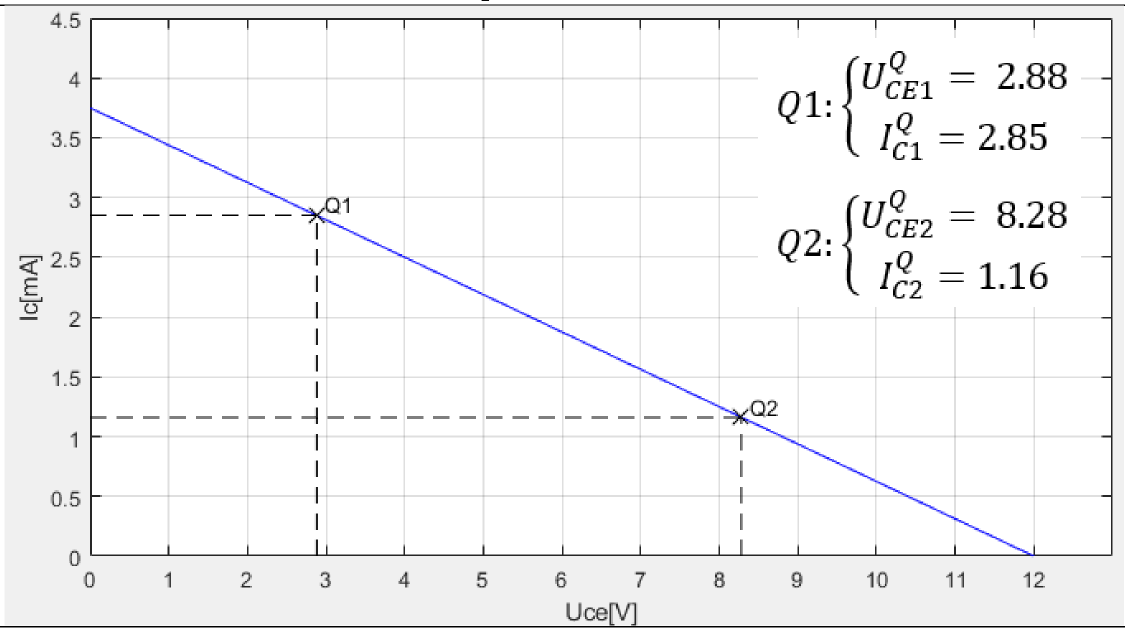
$$I_C^Q = 1.16mA$$
$$V_{CE}^Q = 8.28V$$

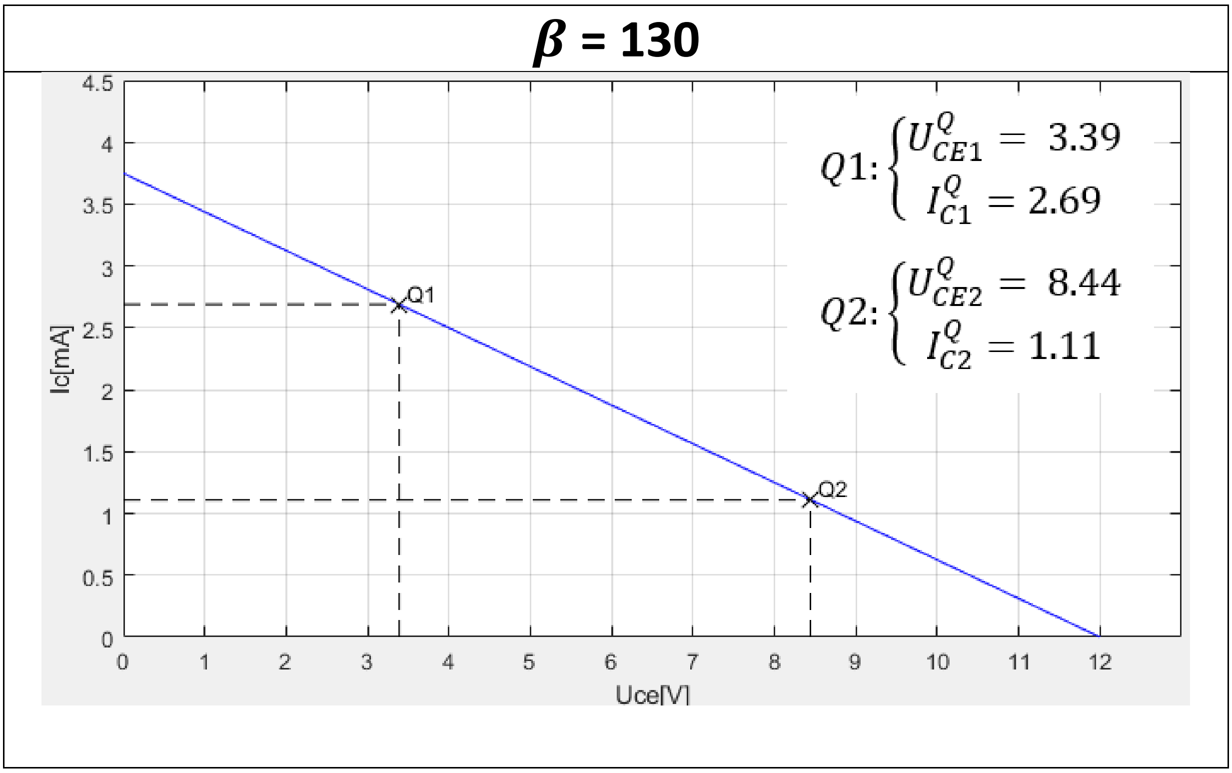
ii. $\boldsymbol{\beta = 130}$

$$I_C^Q = 1.11mA$$
$$V_{CE}^Q = 8.44V$$

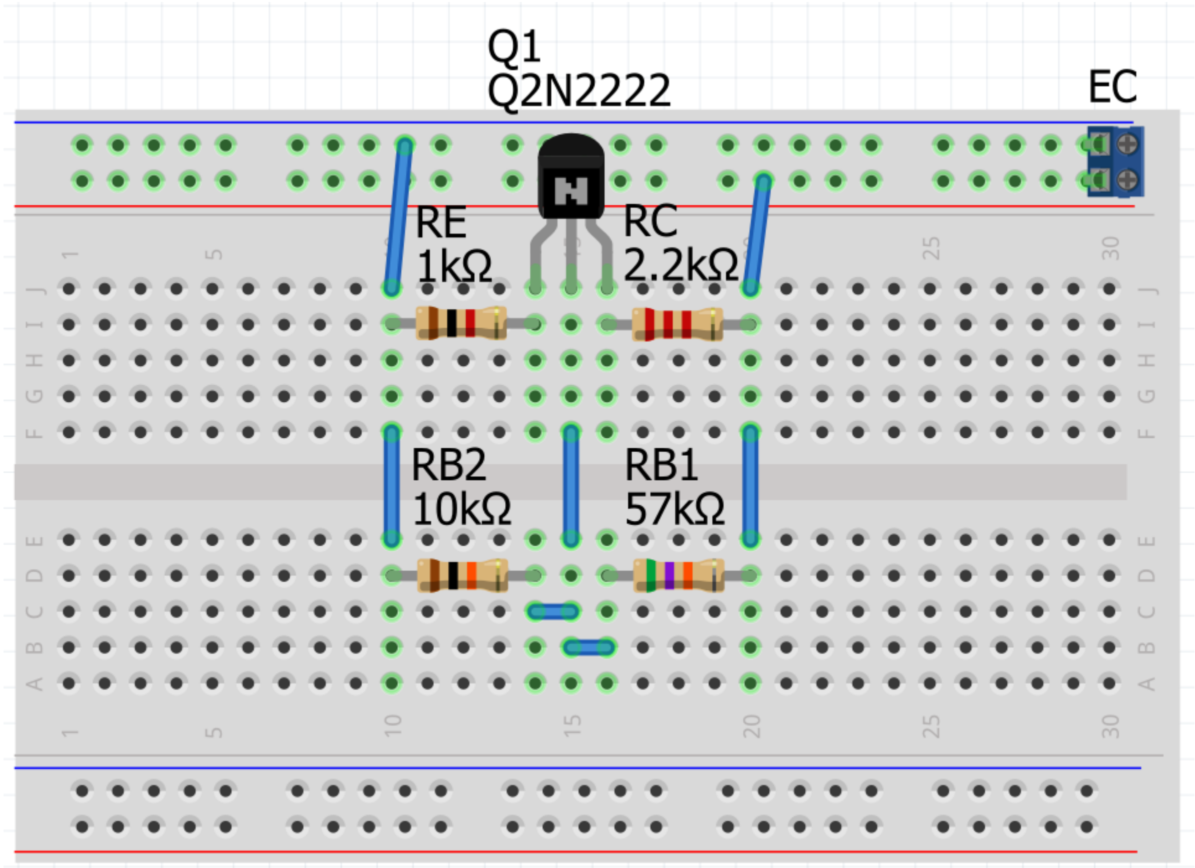
	β = 333		**β = 130**	
	I_C^Q [mA]	**U_{CE}^Q [V]**	**I_C^Q [mA]**	**U_{CE}^Q [V]**
P ⟶ M	**2.85**	**2.88**	**2.69**	**3.39**
P ⟶ N	**1.16**	**8.28**	**1.11**	**8.44**

β = 333





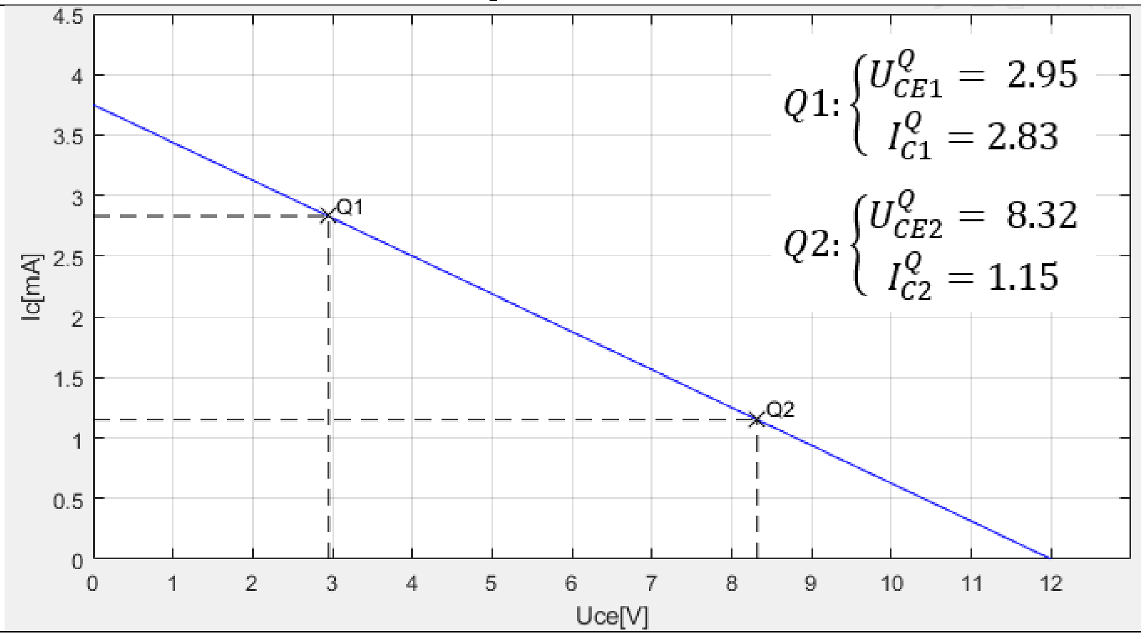
❖ ***Experimental Model***



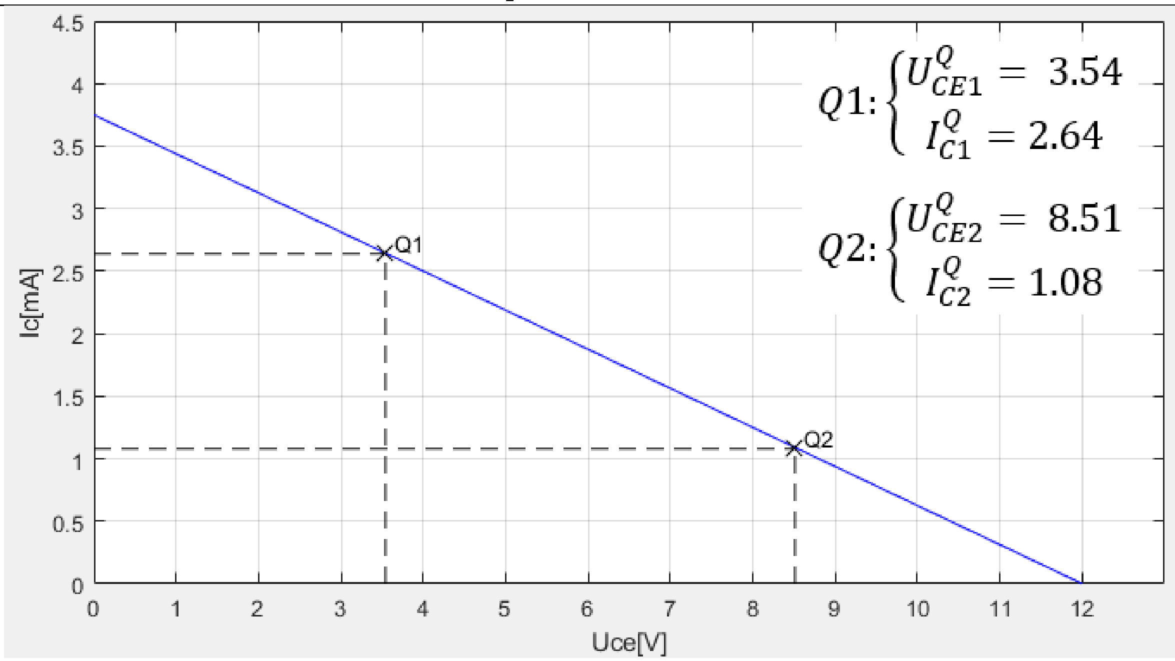
❖ ***Measurements***

θ = 25°C	T_1		T_2	
	β = 333		β = 130	
	I_C^Q [mA]	U_{CE}^Q [V]	I_C^Q [mA]	U_{CE}^Q [V]
P ⟶ M	2.83	2.95	2.64	3.54
P ⟶ N	1.15	8.32	1.08	8.51

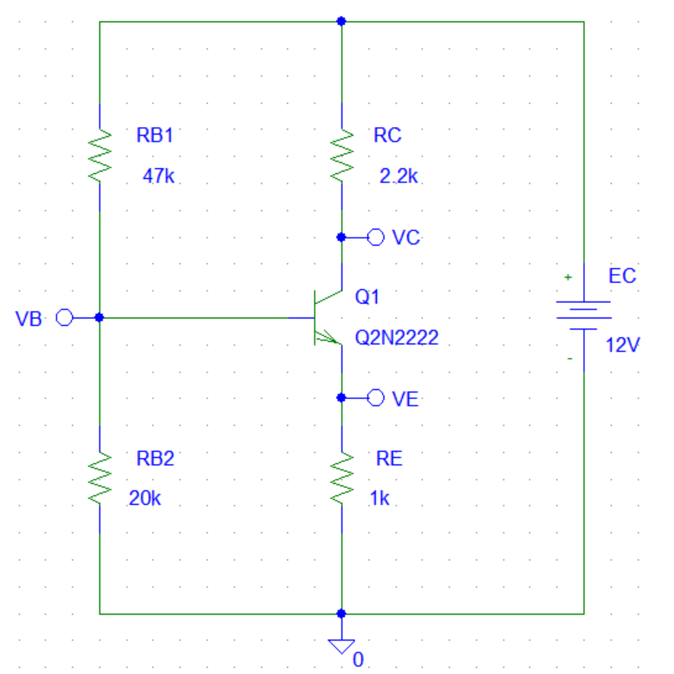
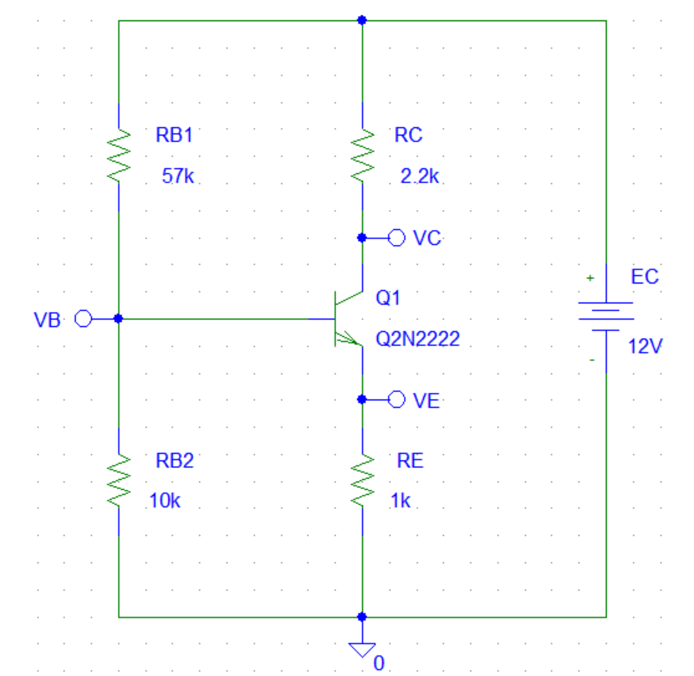
β = 333

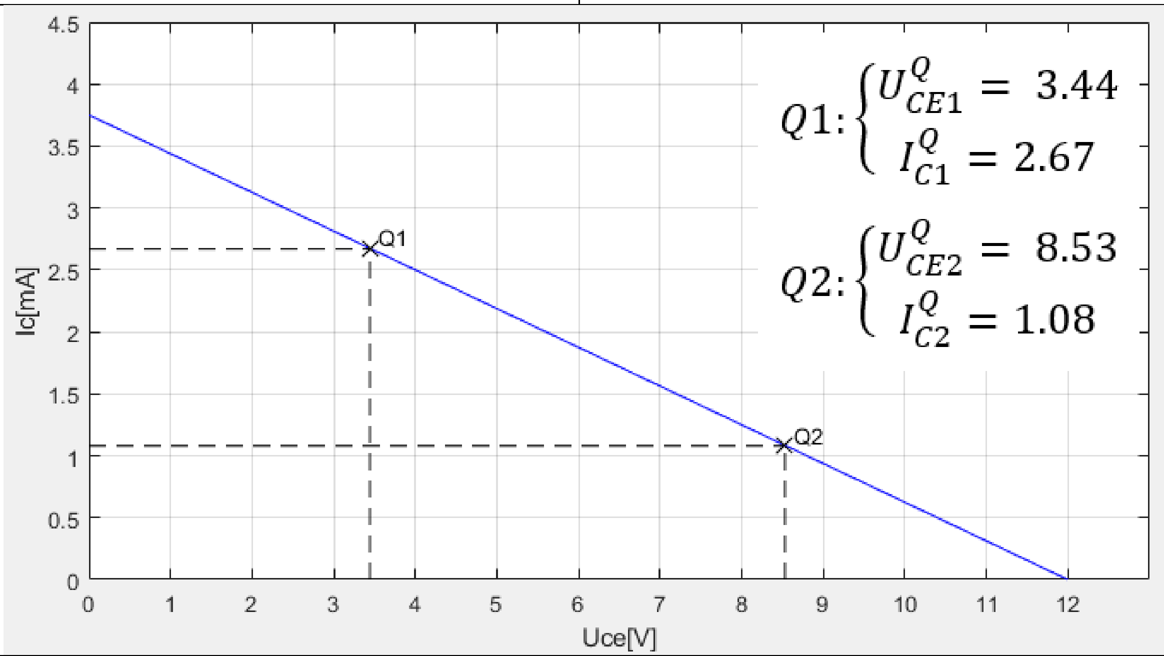


β = 130



- ***Simulations***

$P \longrightarrow M$	$P \longrightarrow N$
	
$\beta = 166$ $I_C^Q = 2.67mA$ $U_{CE}^Q = 3.44V$	$\beta = 163$ $I_C^Q = 1.08mA$ $U_{CE}^Q = 8.53V$



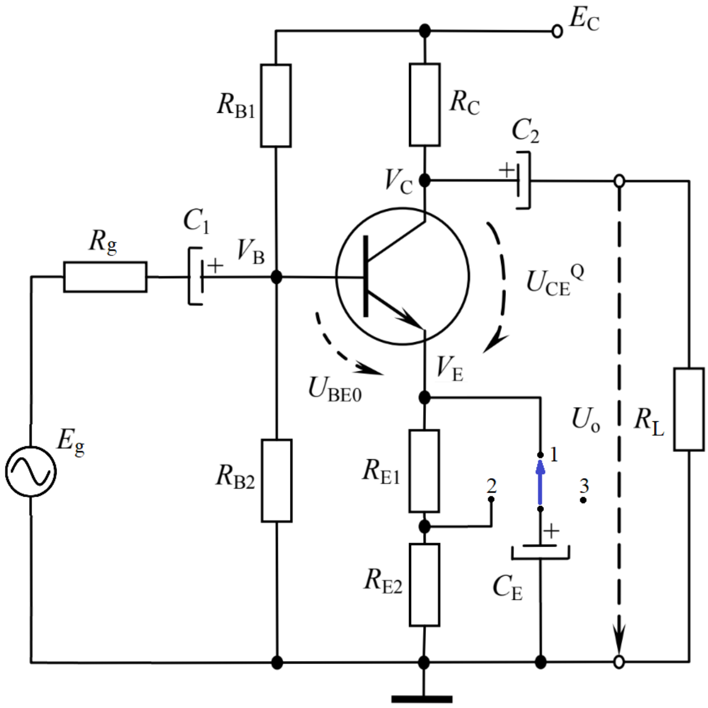
- ***Conclusion***

The Q point of the self-bias voltage divider circuit depends more on the resistances at the base of the transistor, R_{B1} and R_{B2}, than the variation of the transistor's current gain, β.

BJT AMPLIFIER

❖ *Theoretical Summary*

The typical voltage amplifier using a single BJT – common emitter connection. It can be observed that this circuit contains two voltage sources. The DC voltage source E_C is required for biasing the transistor in the active region so that it can work as an amplifier. On the other hand, the AC source E_g provides the variable signal to be amplified.



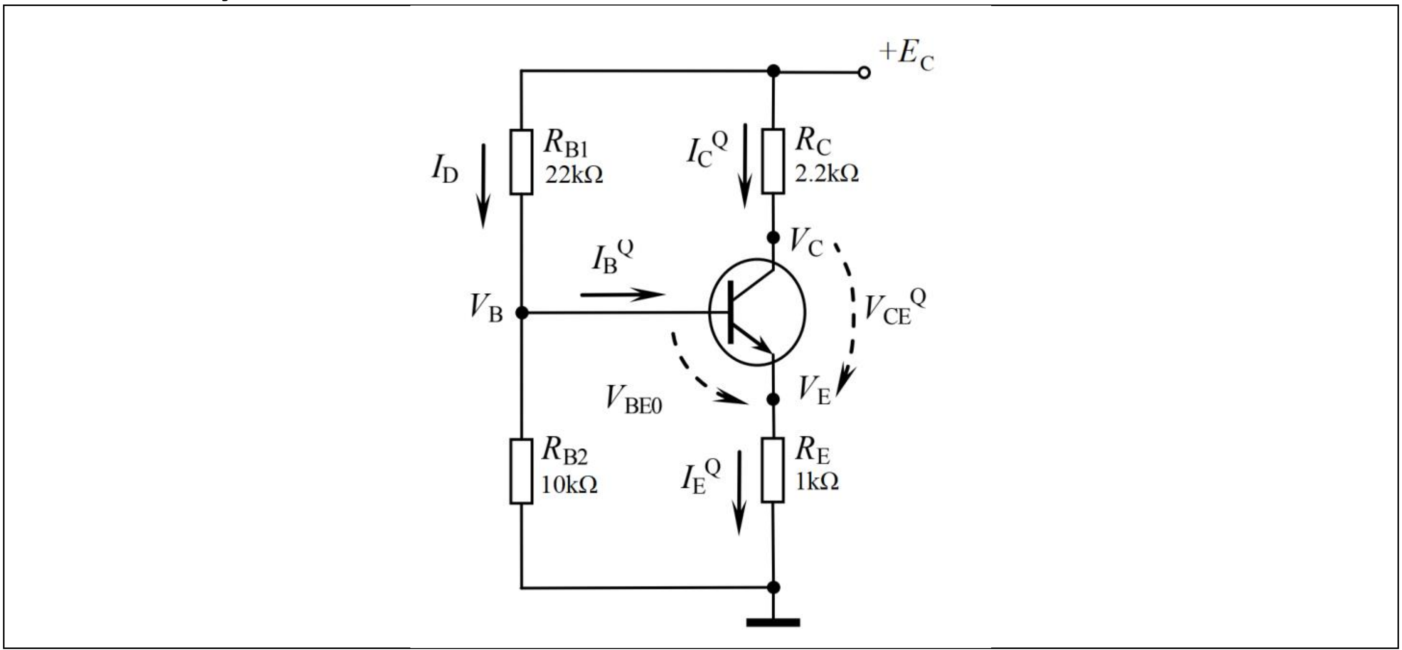
- ***Components***
  a. *E_C – DC Voltage Source*
  b. *E_g – AC Voltage Source*
  c. *npn Transistor*
  d. *C_1 , C_2 – Capacitors*
  e. *C_E – Emitter Capacitor*
  f. *R_{B1} , R_{B2} – Base Resistors*
  g. *R_C – Collector Resistor*
  h. *R_{E1} , R_{E2} – Emitter Resistors*
  i. *R_g – Input Internal Resistor (E_g)*
  j. *R_L – Load Resistor*

- ***Values***
  - E_C = +5V
  - $C_1 = C_2$ = 4.7µF
  - C_E = 470µF
  - R_C = 2.2kΩ
  - R_{B1} = 22kΩ
  - R_{B2} = 10kΩ
  - R_{E1} = 100Ω
  - R_{E2} = 900Ω
  - R_L = 10kΩ
  - R_g = 50Ω
  - β_{min} = 100
  - $\beta = h_{21e}$ = 307/25°C

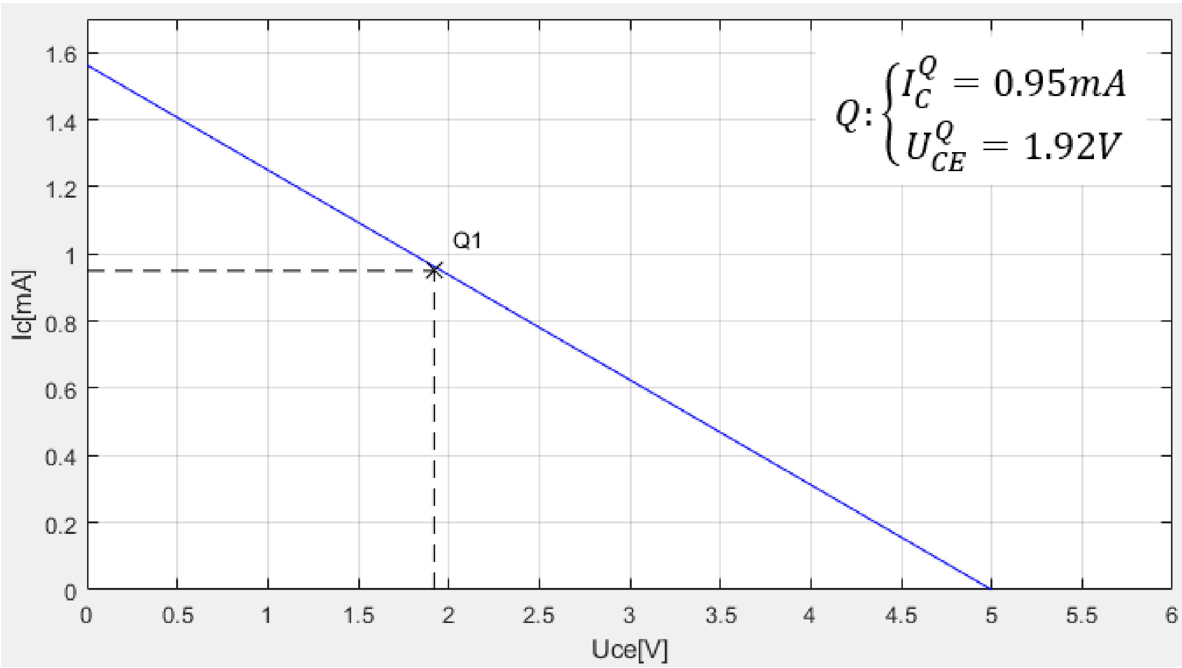
- SWITCH K: K⟶ 1, K⟶ 2, K⟶ 3

❖ ***Theoretical Analysis & Calculations***

- ***DC Analysis***



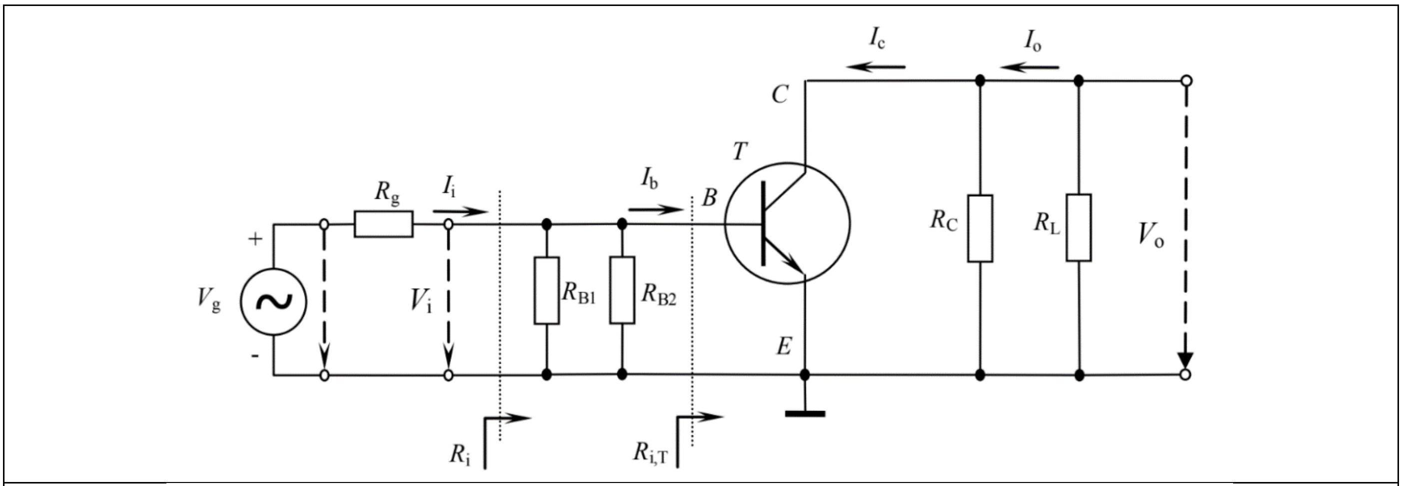
$$Q:\begin{cases} I_C^Q = 0.95mA \\ U_{CE}^Q = 1.92V \end{cases}$$

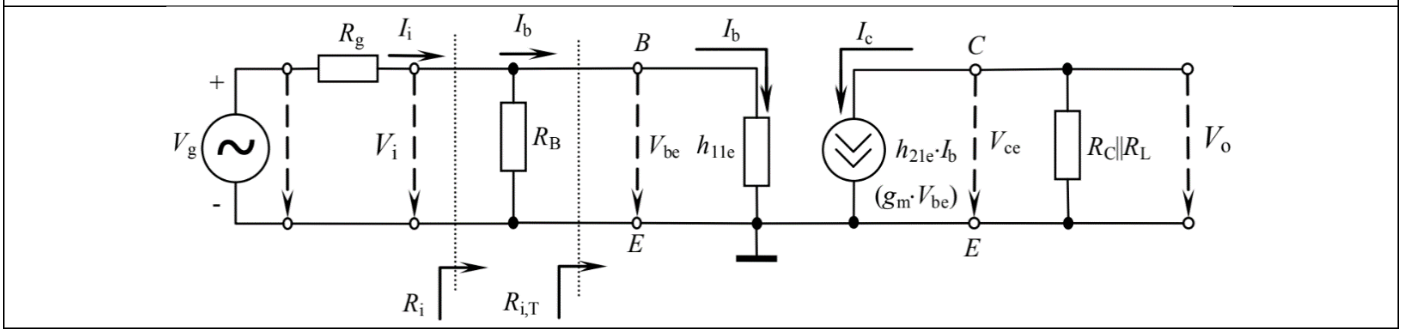


- ***AC Analysis***

$$g_m = \frac{h_{21e}}{h_{11e}} \cong 40 \cdot I_C^Q = 38 \cdot 10^{-3}$$
$$R_B = R_{B1} \parallel R_{B2} = 6.8k\Omega$$
$$R_C^I = R_C \parallel R_L = 1.8k\Omega$$
$$I_C = h_{21e} \cdot I_B$$

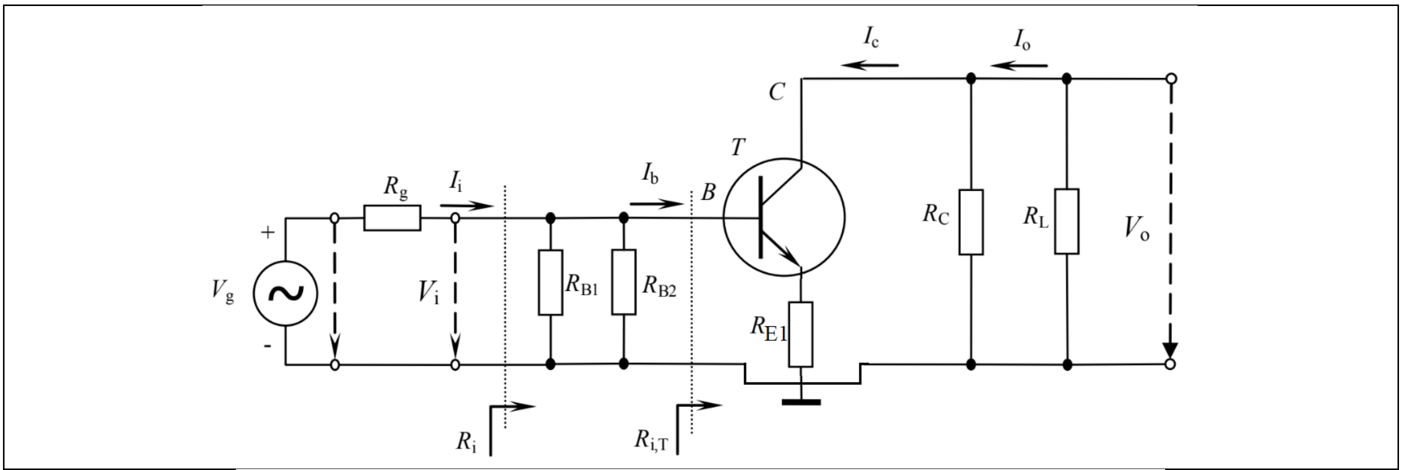
I. $K \longrightarrow 1$:

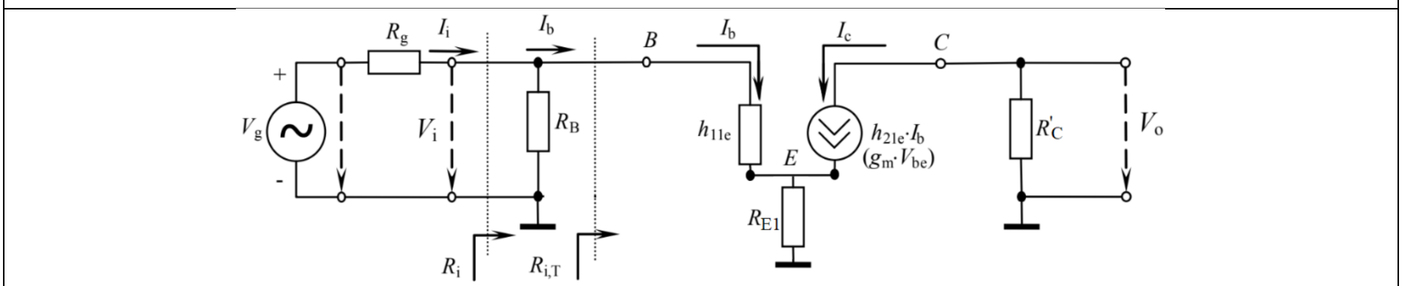




$$A_u = \frac{V_{out}}{V_{in}} = \frac{V_{out}}{I_c} \cdot \frac{I_c}{I_b} \cdot \frac{I_b}{V_{in}} = -R_C^I \cdot h_{21e} \cdot \frac{1}{h_{11e}} = -g_m \cdot R_C^I \cong -68.4$$

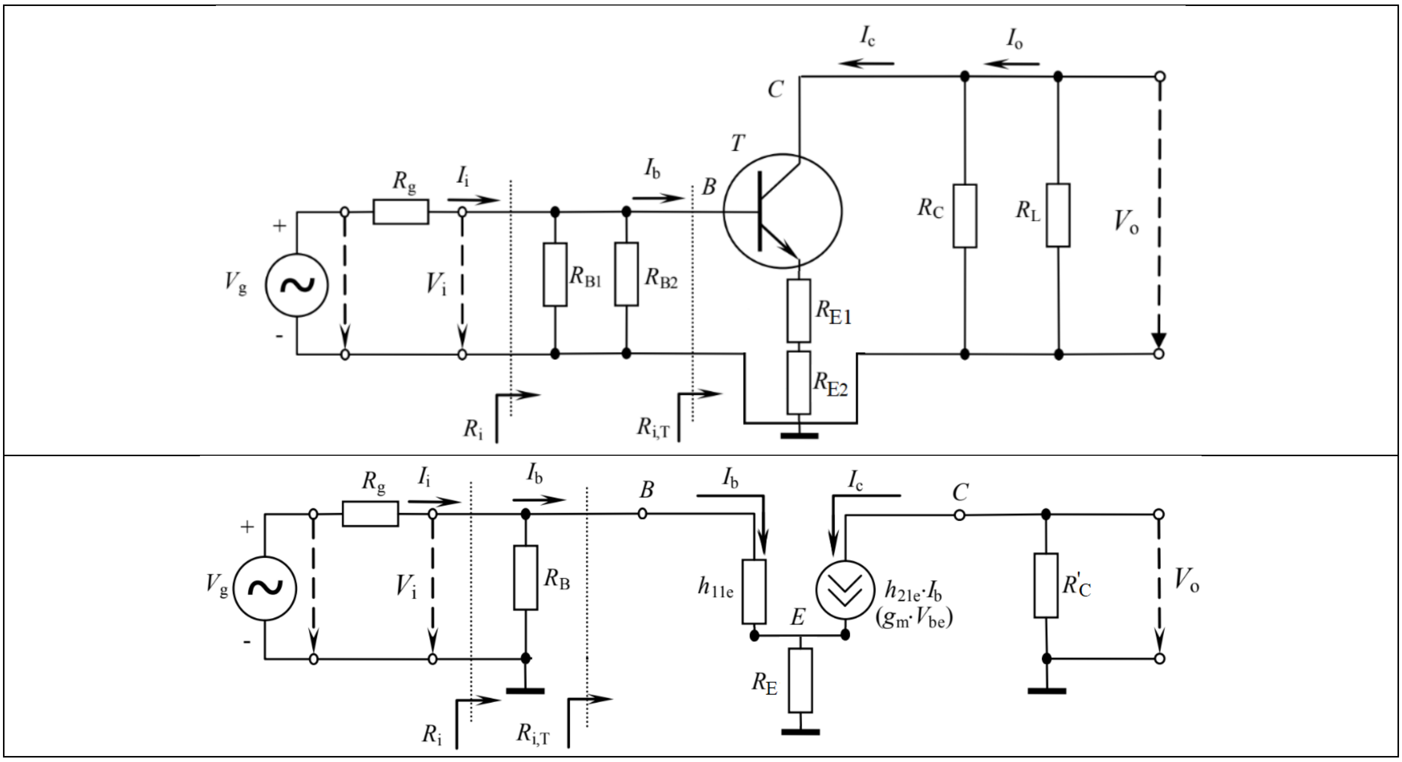
II. $K \longrightarrow 2$:





$$A_u = \frac{V_{out}}{V_{in}} = \frac{V_{out}}{I_c} \cdot \frac{I_c}{I_b} \cdot \frac{I_b}{V_{in}} = -R_C^I \cdot h_{21e} \cdot \frac{I_B}{h_{11e} \cdot I_B + R_{E1}(I_B + I_C)}$$
$$= -R_C^I \cdot h_{21e} \cdot \frac{1}{h_{11e} + R_{E1}(1 + h_{21e})} \cong -14.21$$

III. K ⟶ 3:

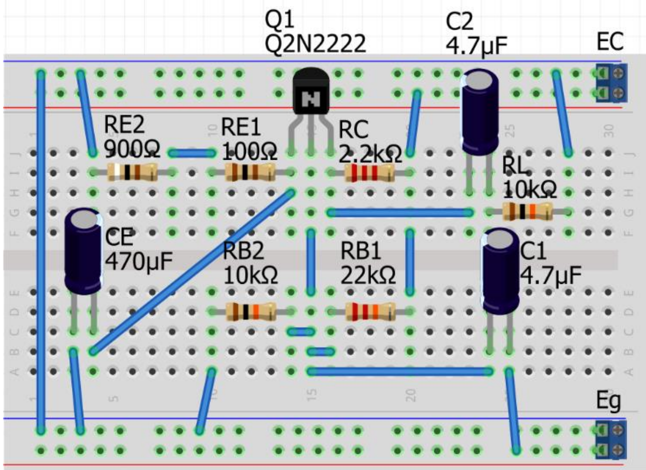


$$R_E = R_{E1} + R_{E2} = 1k\Omega$$

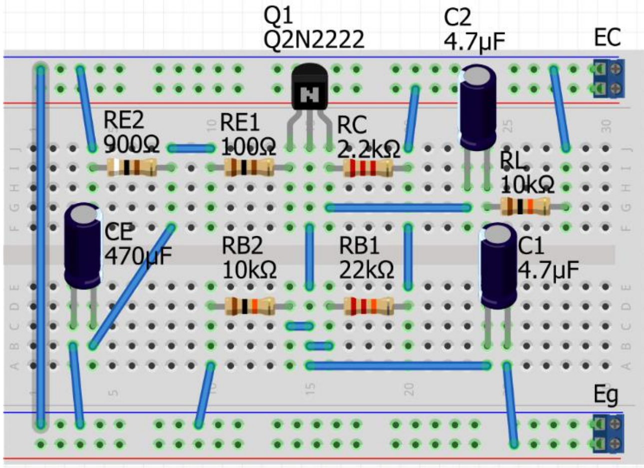
$$A_u = \frac{V_{out}}{V_{in}} = \frac{V_{out}}{I_c} \cdot \frac{I_c}{I_b} \cdot \frac{I_b}{V_{in}} = -R_C^I \cdot h_{21e} \cdot \frac{1}{h_{11e} + R_E(1 + h_{21e})} \cong -1.74$$

❖ *Experimental Model*

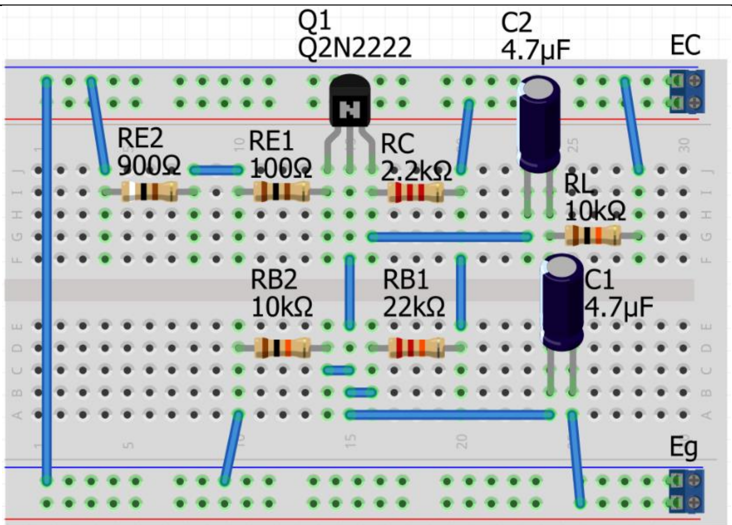
$K \longrightarrow 1$



$K \longrightarrow 2$

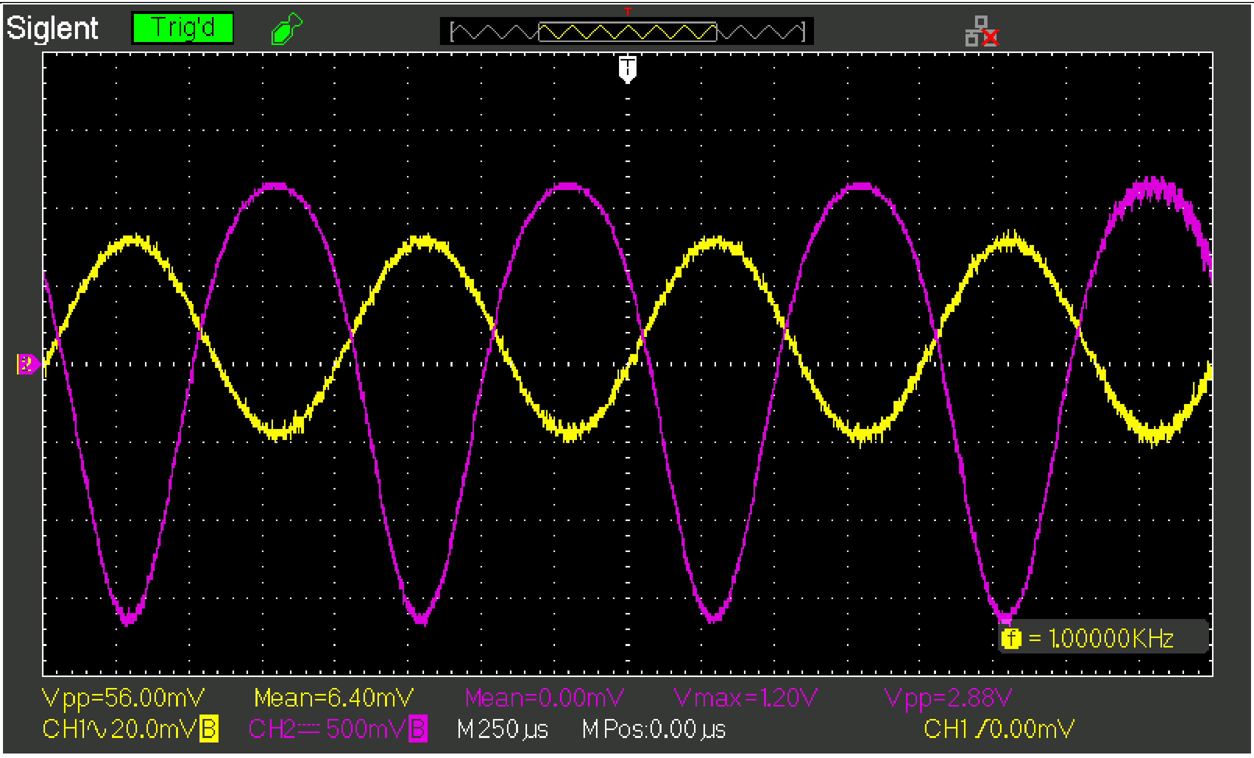


$K \longrightarrow 3$



❖ ***Measurements***

$K \longrightarrow 1$

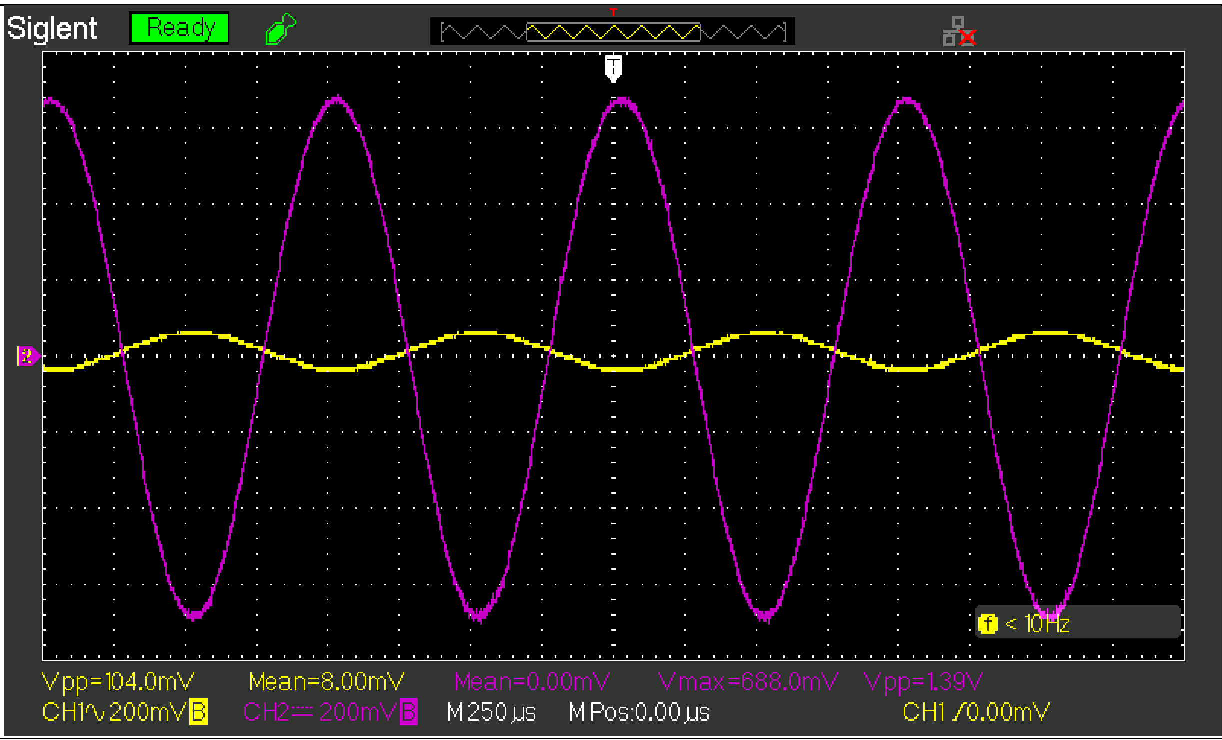


$$V_{p(in)} = \frac{V_{pp(yel)}}{2} = 28mV$$

$$V_{p(out)} = \frac{V_{pp(pur)}}{2} = 1.44V$$

$$A_u = -\frac{V_{p(out)}}{V_{p(in)}} = -51.43$$

$K \longrightarrow 2$

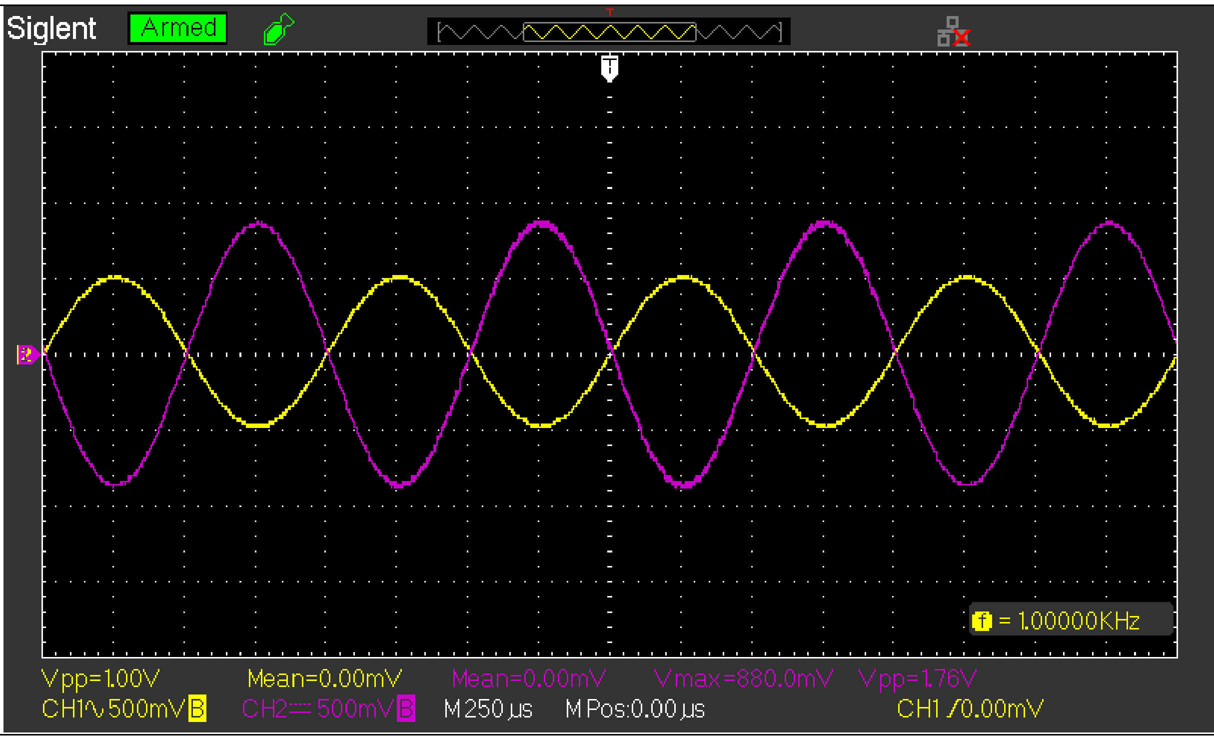


$$V_{p(in)} = \frac{V_{pp(yel)}}{2} = 52mV$$

$$V_{p(out)} = \frac{V_{pp(pur)}}{2} = 695mV$$

$$A_u = -\frac{V_{p(out)}}{V_{p(in)}} = -13.36$$

$K \longrightarrow 3$

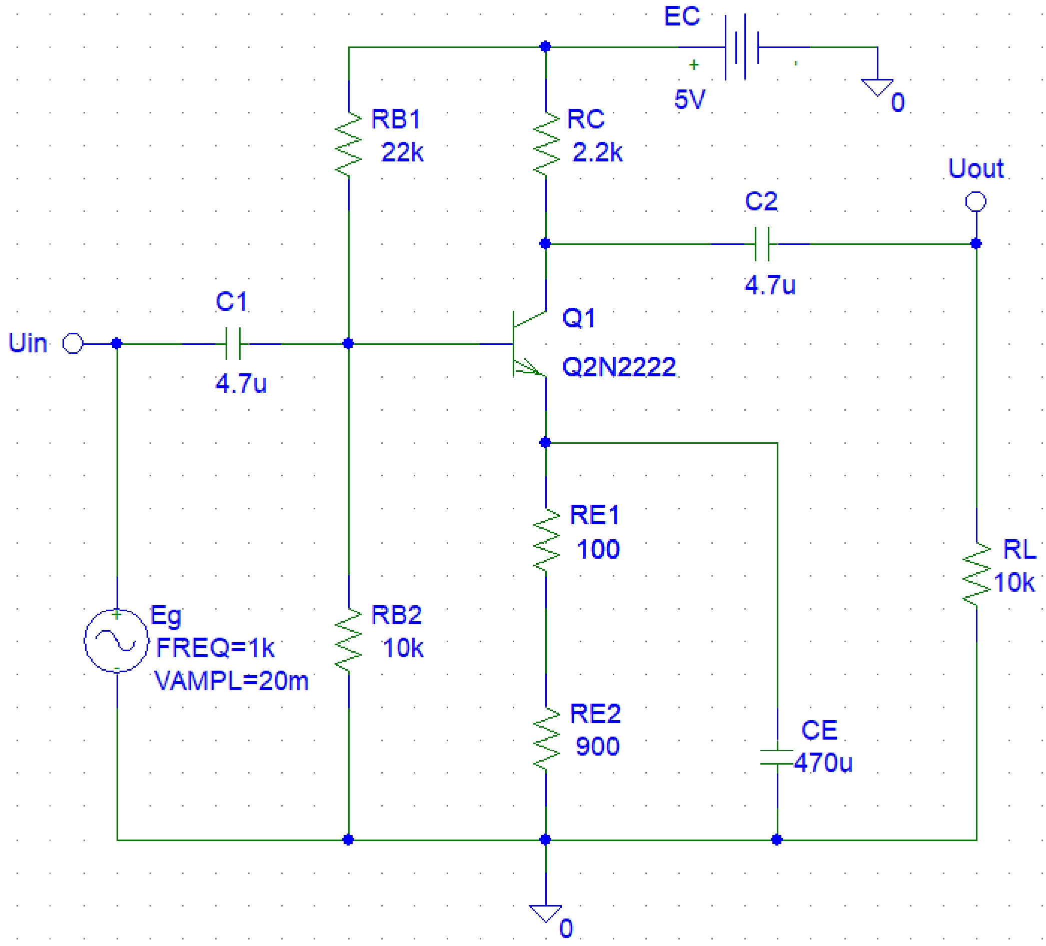
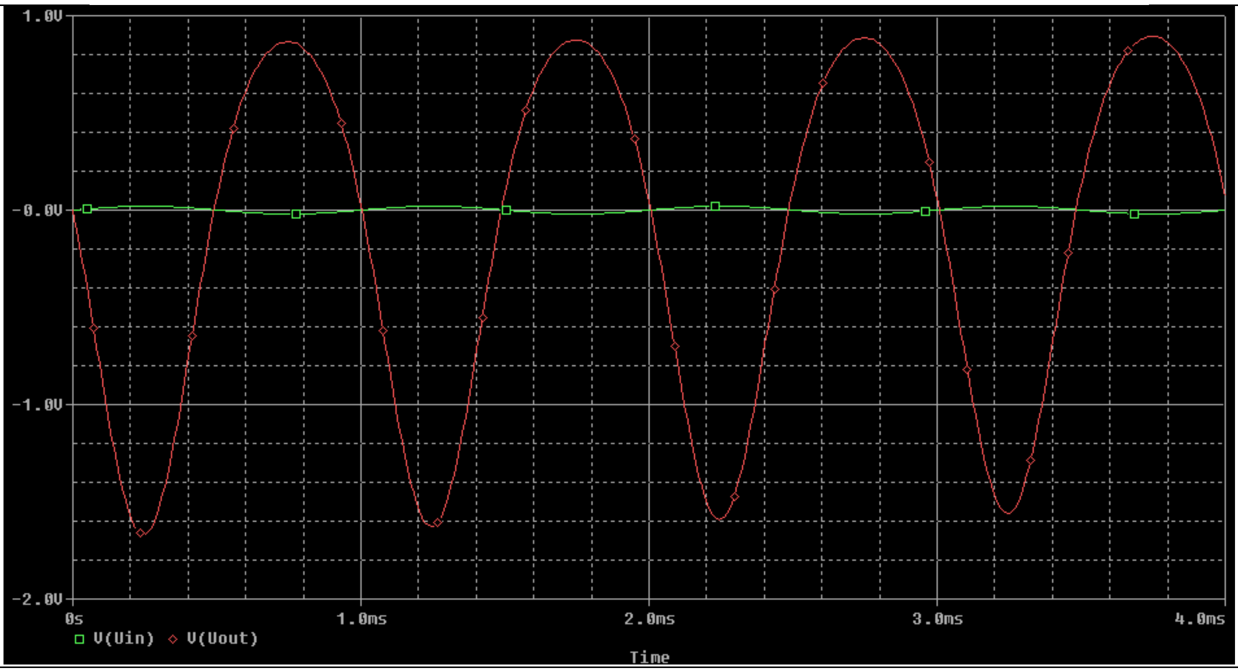


$$V_{p(in)} = \frac{V_{pp(yel)}}{2} = 500mV$$

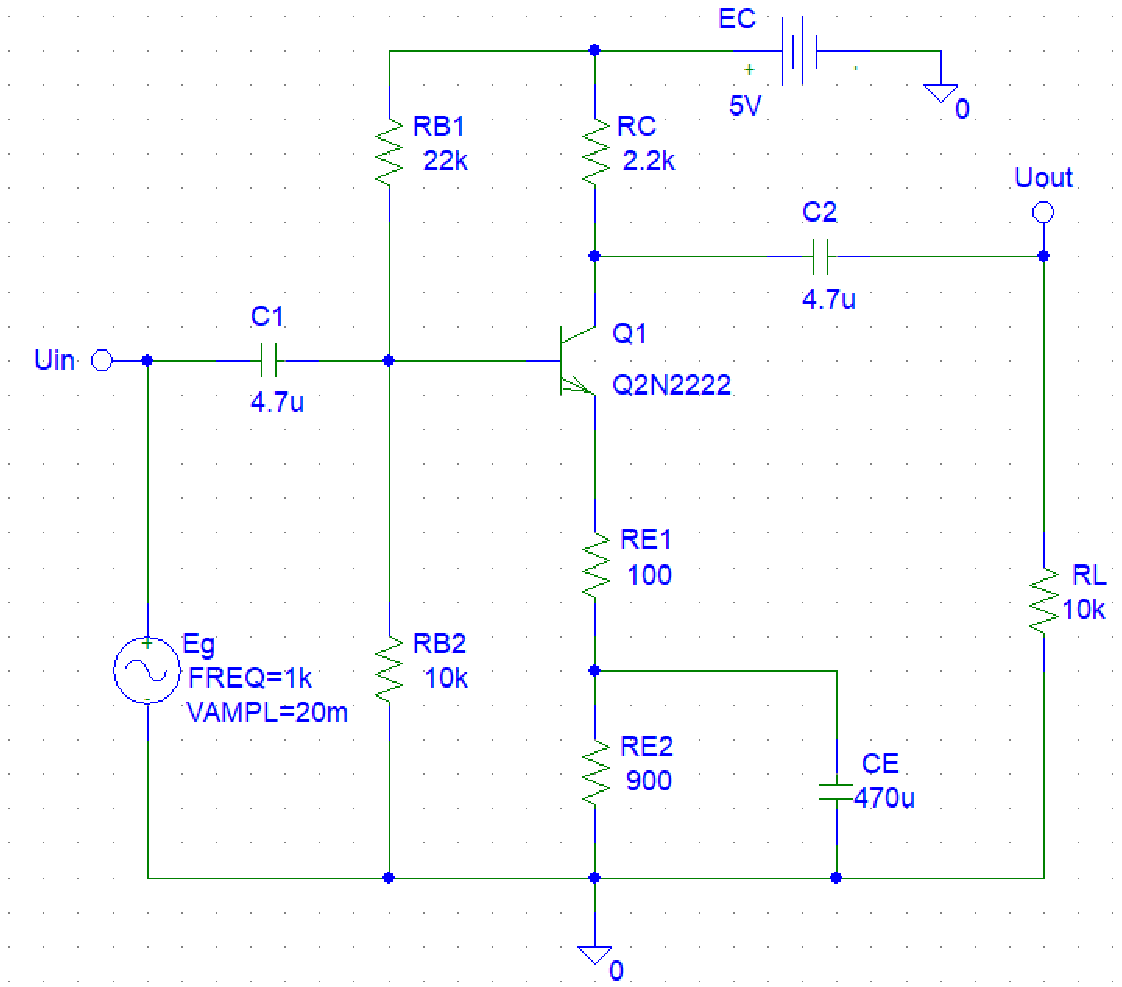
$$V_{p(out)} = \frac{V_{pp(pur)}}{2} = 880mV$$

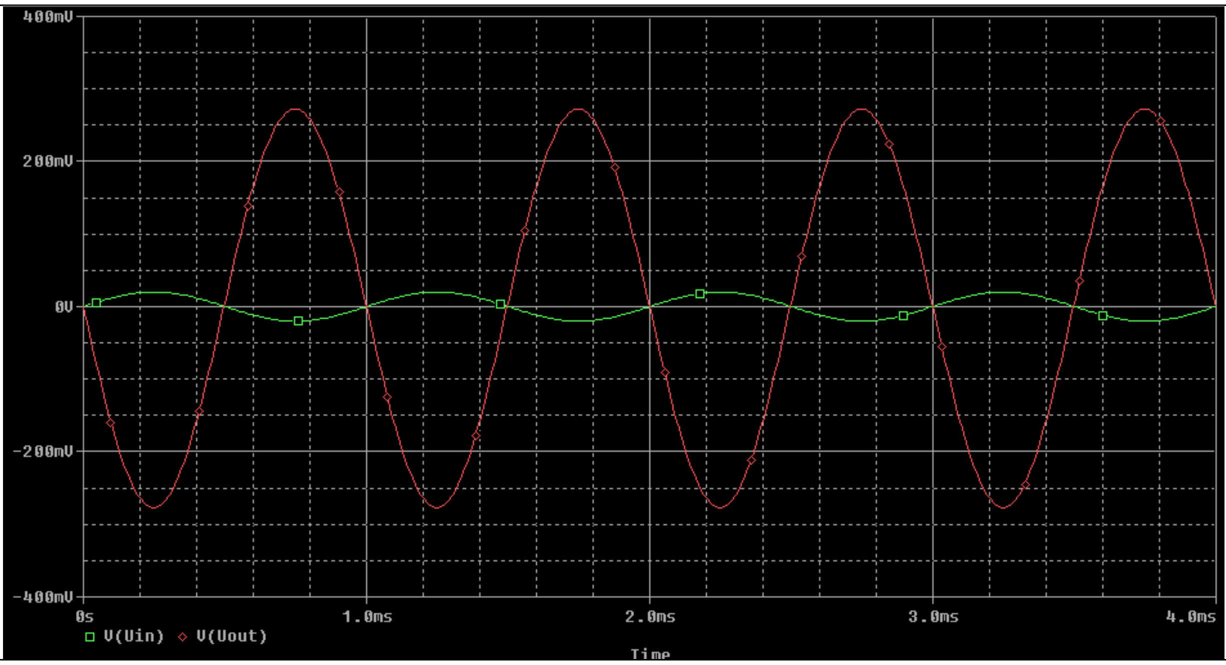
$$A_u = -\frac{V_{p(out)}}{V_{p(in)}} = -1.76$$

❖ ***Simulations***

$K \longrightarrow 1$


$$V_{p(in)} = 20mV$$ $$V_{p(out)} = \frac{V_{pp(out)}}{2} = \frac{2.73V}{2} = 1.37V$$ $$A_u = -\frac{V_{p(out)}}{V_{p(in)}} = -68.5$$

$K \longrightarrow 2$



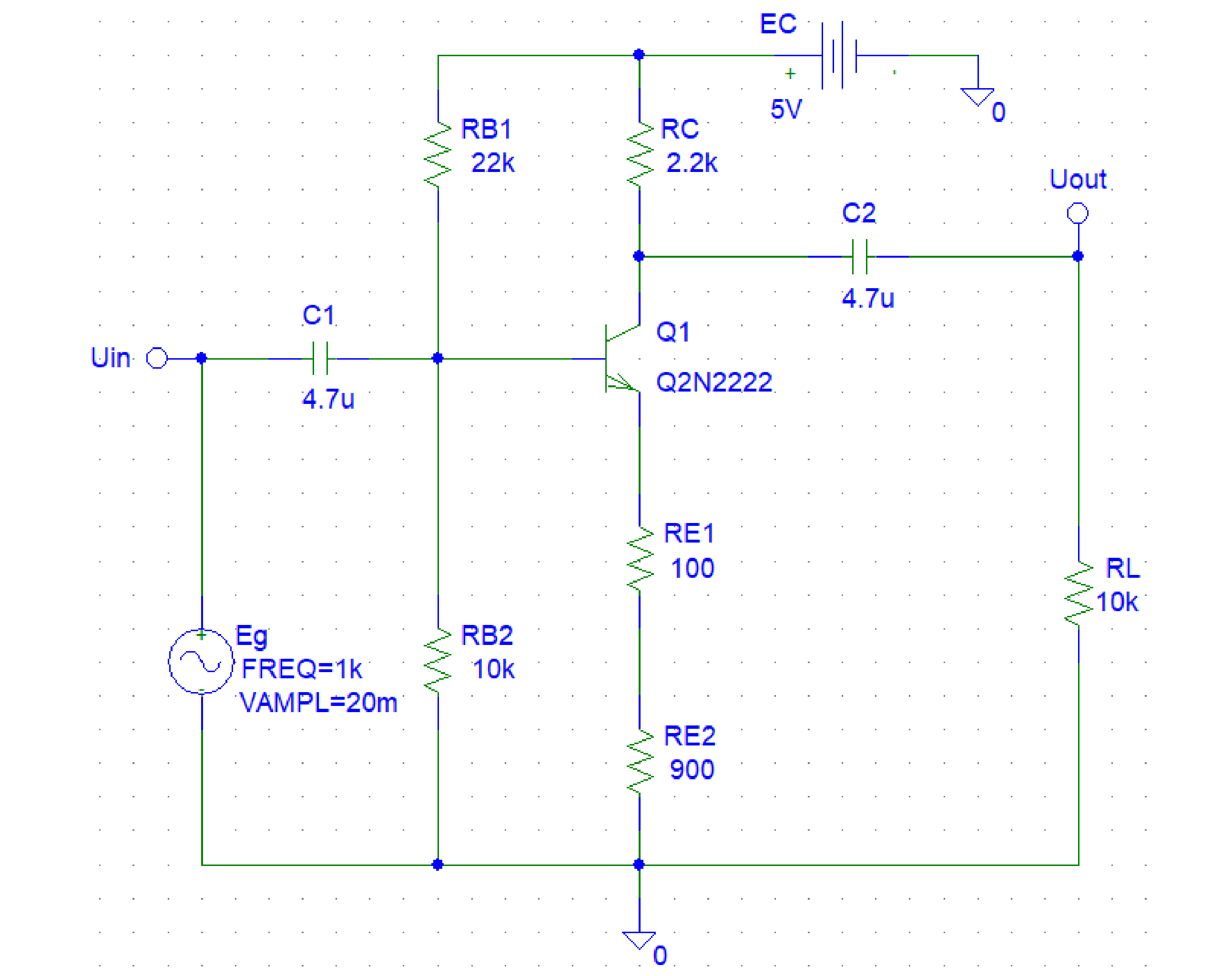


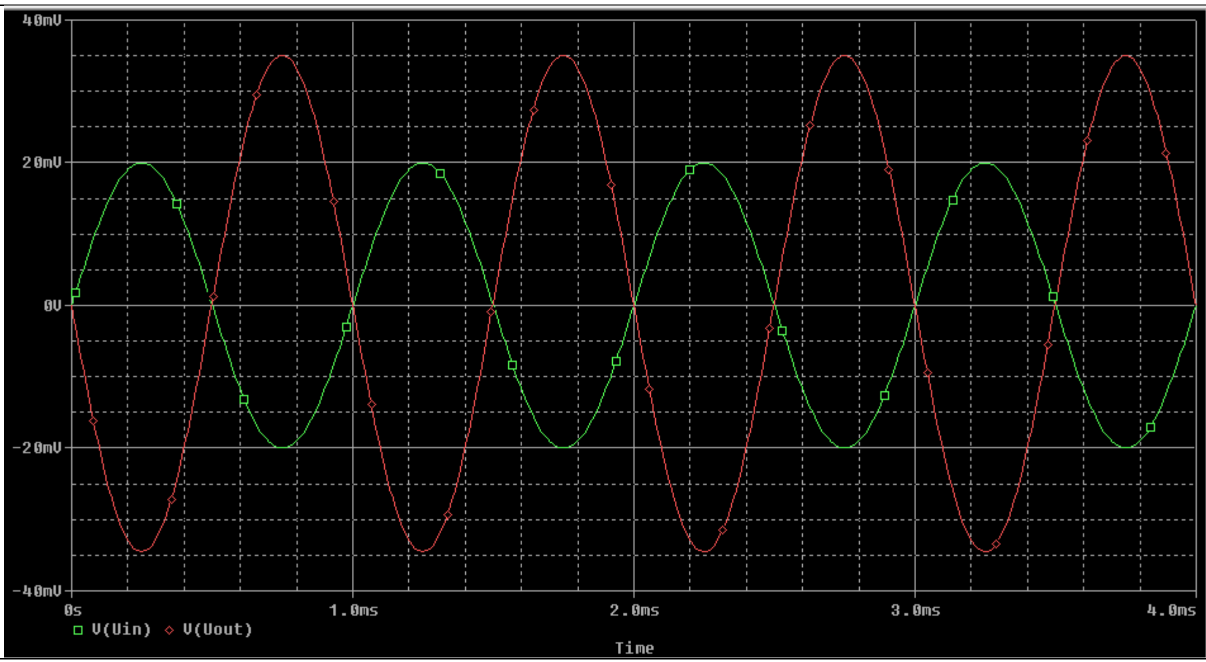
$$V_{p(in)} = 20mV$$

$$V_{p(out)} = \frac{V_{pp(out)}}{2} = \frac{546mV}{2} = 273mV$$

$$A_u = -\frac{V_{p(out)}}{V_{p(in)}} = -13.65$$

$K \longrightarrow 3$





$$V_{p(in)} = 20mV$$

$$V_{p(out)} = \frac{V_{pp(out)}}{2} = \frac{70mV}{2} = 35mV$$

$$A_u = -\frac{V_{p(out)}}{V_{p(in)}} = -1.75$$

❖ ***Table***

	K ⟶ 1	***K ⟶ 2***	***K ⟶ 3***
Calculation	***-68.4***	***-14.21***	***-1.74***
Experimental	***-51.43***	***-13.36***	***-1.76***
Simulation	***-68.5***	***-13.65***	***-1.75***

❖ ***Conclusion***

The BJT can be used as an AC voltage amplifier and depending on the resistance R_E before the emitter capacitor we can change the voltage gain from the input voltage to the output voltage, the lower the resistance the higher the absolute voltage gain and the higher the resistance the lower the absolute voltage gain($|A_u|\ i.p.R_E$).

As $R_E \to 0$ the output voltage waveform appears to deform from the input sinusoidal waveform.