第 6 講: BJT 電晶體共射(Common Emitter)放大電路分析

參考文獻與網頁:

[1]蕭敏學，大學電子學實習(一):電子電路分析篇，台科大圖書，2013

[2] YouTube: 吳順德，應用電子電實驗(L8 2 戴維寧等效電路在 BJT 分析的應用)
https://www.youtube.com/watch?v=kzIOvQeVfYA&list=PLXxs-fSMcpYfBBswuFSBfefLbeBmOUbZ2&index=23

[3] How To Calculate The Voltage Gain of a Transistor Amplifier，
https://www.youtube.com/watch?v=-MyVscG-Pew

[4]Basic BJT Amplifiers,
http://cdcpc.ce.ncu.edu.tw/classes/EEShortversion/Elect/Ch6%20Basic%20BJT%20Amplifiers.pdf

一、電路分析，請參考[1]~[3]

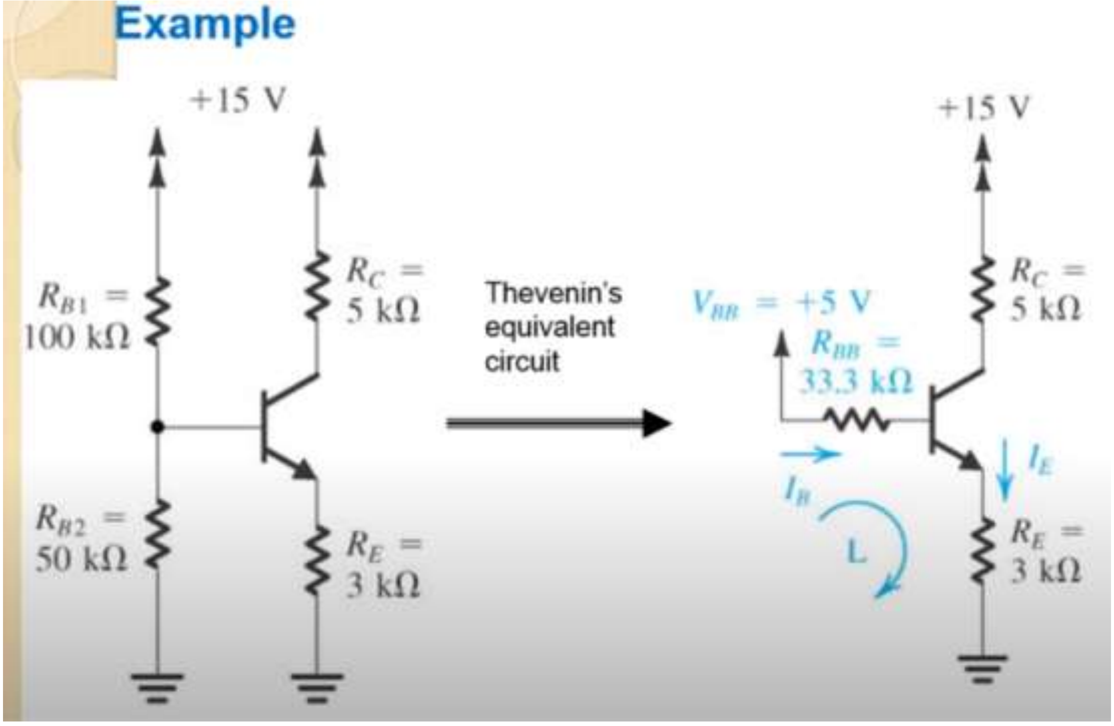


圖 6-1 BJT 電晶體共射電路之等效電路

$$R_{BB} = R_{B1} // R_{B2} = 100K // 50K = 33.3 K$$

$$V_{BB} = Vcc * \frac{R_{B2}}{R_{B1} + R_{B2}} = 15 * \frac{50}{100 + 50} = 5\ V$$

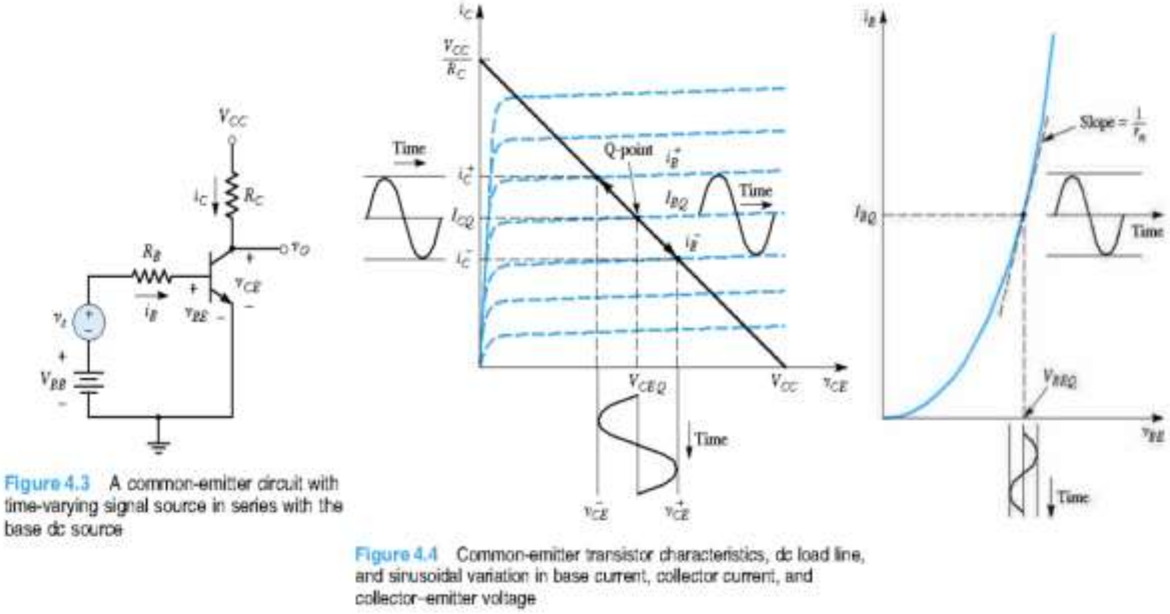


Figure 4.3 A common-emitter circuit with time-varying signal source in series with the base dc source

Figure 4.4 Common-emitter transistor characteristics, dc load line, and sinusoidal variation in base current, collector current, and collector-emitter voltage

圖 6-2 共射電路[4]

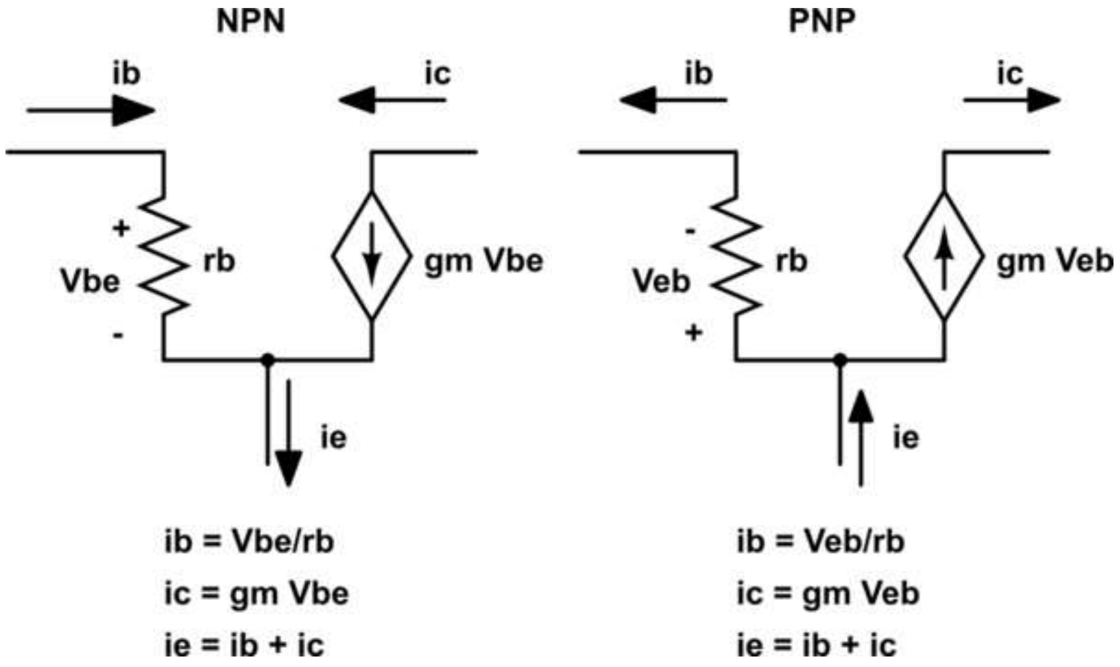


圖 6-3 NPN and PNP BJT Transistor hybrid π models, $r_b = r_\pi$ (sometimes using)

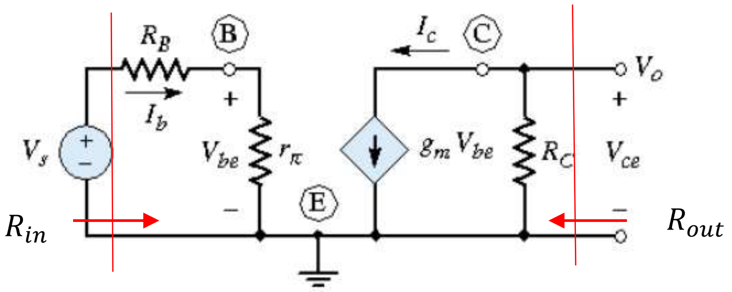


Figure 4.11 The small-signal equivalent circuit of the common-emitter circuit using the npn transistor hybrid-π model

$$V_o = -g_m V_{be} R_C \qquad V_o = -\beta I_b R_C$$

$$V_{be} = \left(\frac{r_\pi}{r_\pi + R_B}\right) V_s \qquad I_b = \frac{V_s}{r_\pi + R_B}$$

$$A_v = \frac{V_o}{V_s} = -g_m R_C \frac{r_\pi}{r_\pi + R_B} \qquad A_v = \frac{V_o}{V_s} = -\frac{\beta R_C}{r_\pi + R_B}$$

圖 6-4 共射電路小訊號模型[4]

輸入電阻 = R_{in} = $\frac{V_S}{i_b} = \frac{i_b(R_B+r_\pi)}{i_b} = R_B + r_\pi$

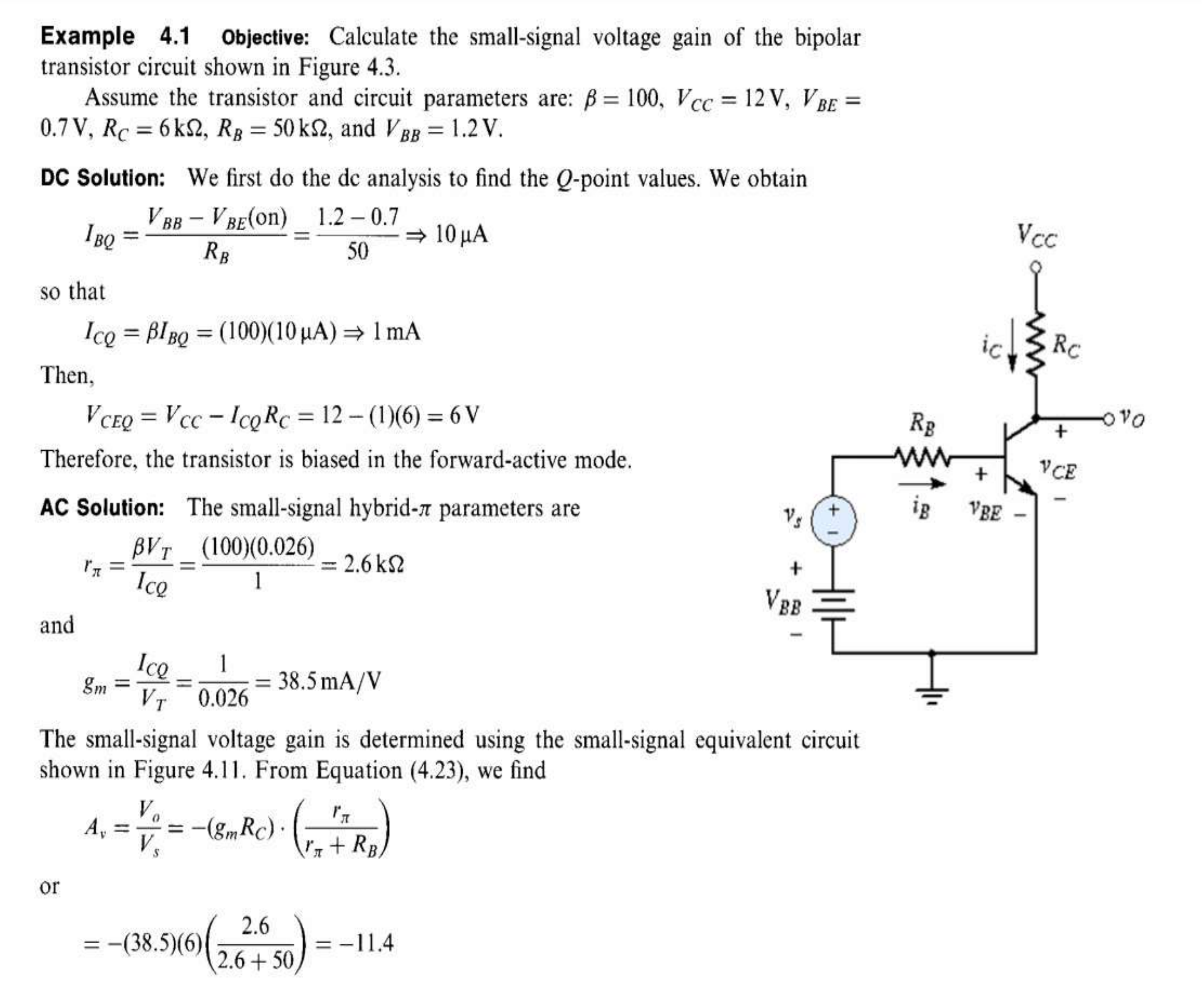
輸出電阻 = R_{out} = R_C

電壓放大率 = $A_v = \frac{V_o}{V_S} = \frac{-i_c*R_{out}}{i_b*R_{in}} = \frac{-\beta*R_{out}}{R_{in}} = -\frac{\beta R_C}{R_B+r_\pi}$

BE 導通電阻 $r_b = r_\pi = {}^{\beta V_T}\!/_{I_{CQ}}$ ， $V_T = 0.026$ ， I_{CQ} = Q-point I_C

電流放大率 = β = ${}^{i_c}\!/_{i_b} = \frac{g_m*V_{be}}{V_{be}/r_\pi} = g_m*r_\pi$

- 共射電路小訊號放大電路範例 1 [4]



Example 4.1 **Objective:** Calculate the small-signal voltage gain of the bipolar transistor circuit shown in Figure 4.3.

Assume the transistor and circuit parameters are: $\beta = 100$, $V_{CC} = 12\,\text{V}$, $V_{BE} = 0.7\,\text{V}$, $R_C = 6\,\text{k}\Omega$, $R_B = 50\,\text{k}\Omega$, and $V_{BB} = 1.2\,\text{V}$.

DC Solution: We first do the dc analysis to find the Q-point values. We obtain

$$I_{BQ} = \frac{V_{BB} - V_{BE}(\text{on})}{R_B} = \frac{1.2 - 0.7}{50} \Rightarrow 10\,\mu\text{A}$$

so that

$$I_{CQ} = \beta I_{BQ} = (100)(10\,\mu\text{A}) \Rightarrow 1\,\text{mA}$$

Then,

$$V_{CEQ} = V_{CC} - I_{CQ}R_C = 12 - (1)(6) = 6\,\text{V}$$

Therefore, the transistor is biased in the forward-active mode.

AC Solution: The small-signal hybrid-π parameters are

$$r_\pi = \frac{\beta V_T}{I_{CQ}} = \frac{(100)(0.026)}{1} = 2.6\,\text{k}\Omega$$

and

$$g_m = \frac{I_{CQ}}{V_T} = \frac{1}{0.026} = 38.5\,\text{mA/V}$$

The small-signal voltage gain is determined using the small-signal equivalent circuit shown in Figure 4.11. From Equation (4.23), we find

$$A_v = \frac{V_o}{V_s} = -(g_m R_C) \cdot \left(\frac{r_\pi}{r_\pi + R_B}\right)$$

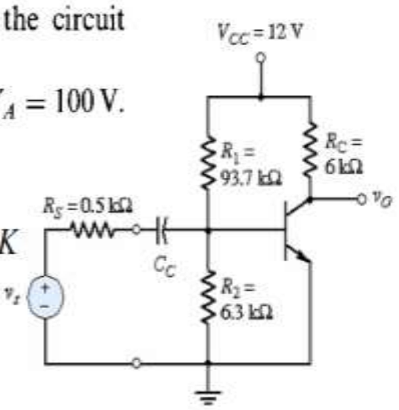
or

$$= -(38.5)(6)\left(\frac{2.6}{2.6 + 50}\right) = -11.4$$

- 共射電路小訊號放大電路範例 2 [4]

Example 4.4 **Objective:** Determine the small-signal voltage gain of the circuit shown in Figure 4.25.

Assume the transistor parameters are: $\beta = 100$, $V_{BE}(\mathrm{on}) = 0.7\,\mathrm{V}$, and $V_A = 100\,\mathrm{V}$.



A. DC analysis

$$V_{th} = \frac{6.3}{93.7+6.3}\times 12 = 0.756V$$

$$R_{th} = 93.7K // 6.3K = 5.9K$$

$$I_{BQ} = I_B = \frac{0.756-0.7}{5.9K} = 9.5\mu A$$

$$I_{CQ} = I_C = 100 I_B = 0.95mA$$

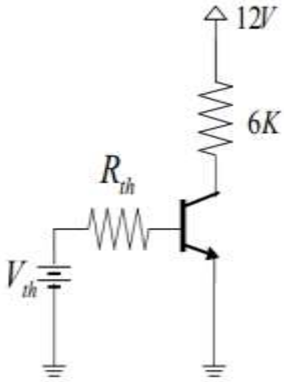
B. AC analysis

$$r_\pi = \frac{\beta V_T}{I_{CQ}} = 100\times\frac{0.026}{0.95}\times 10^3 = 2.736K$$

$$r_o = \frac{V_A}{I_{CQ}} = \frac{100}{0.95}\times 10^3 = 105K$$

$$i_b = \frac{v_\pi}{r_\pi} = \frac{1}{r_\pi}\times\frac{6.3//93.7//r_\pi}{6.3//93.7//r_\pi+0.5}v_s = 0.288v_s$$

$$v_o = -\beta\, i_b \times (r_o // R_C) = -100\times 0.288v_s\times 5.67 = -163.23v_s$$



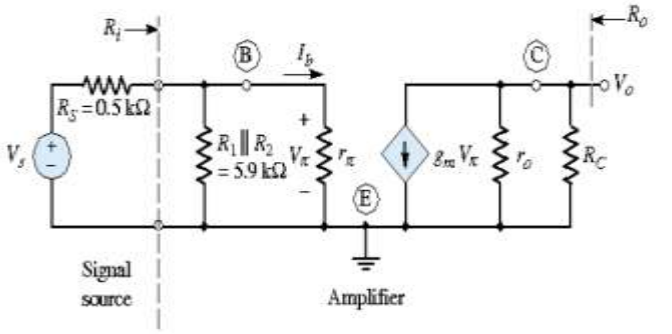
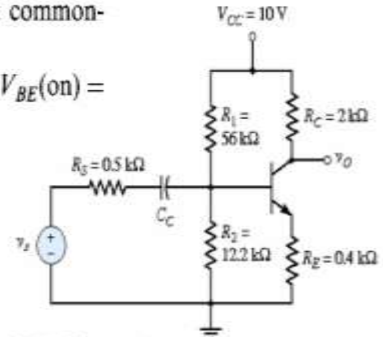


Figure 4.26 The small-signal equivalent circuit, assuming the coupling capacitor is a short circuit

- 共射電路小訊號放大電路範例 3 [4]

Example 4.5 **Objective:** Determine the small-signal voltage gain of a common-emitter circuit with an emitter resistor.

For the circuit in Figure 4.28, the transistor parameters are: $\beta = 100$, $V_{BE}(\text{on}) = 0.7\,\text{V}$, and $V_A = \infty$.



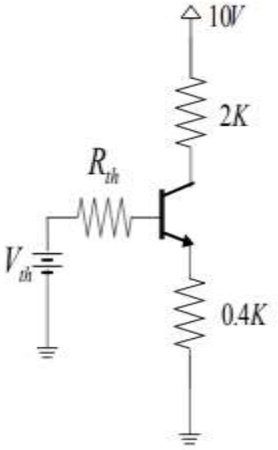
A. DC analysis

$$V_{th} = \frac{12.2}{56+12.2}\times 10 = 1.79V$$

$$R_{th} = 56K//12.2K = 10K$$

$$I_B = \frac{1.79-0.7}{10+(1+100)\times 0.4} = 0.0216mA$$

$$I_C = 100I_B = 2.16mA$$



B. AC analysis

$$r_\pi = \frac{\beta V_T}{I_{CQ}} = 100\times\frac{0.026}{2.16} = 1.2K$$

$$i_s = \frac{v_s}{10//(r_\pi+(1+\beta)\times 0.4)+0.5} = 0.1168v_s, mA$$

$$i_b = \frac{10}{10+(r_\pi+(1+\beta)\times 0.4)}\times i_s = 0.1938i_s, mA$$

$$v_o = -\beta\, i_b\times R_C = -100\times 0.1938\times 0.1168v_s\times 2 = -4.527v_s$$

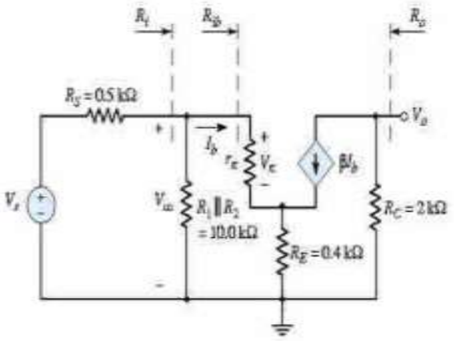


Figure 4.29 The small-signal equivalent circuit with an emitter resistor

The input resistance to the amplifier is now

$$\boxed{R_i = R_1 \| R_2 \| R_{ib}} \tag{4.48}$$

We can again relate V_{in} to V_s through a voltage-divider equation as

$$V_{in} = \left(\frac{R_i}{R_i + R_S}\right)\cdot V_s \tag{4.49}$$

Combining Equations (4.45), (4.47), and (4.49), we find the small-signal voltage gain is

$$A_v = \frac{V_o}{V_s} = \frac{-(\beta I_b)R_C}{V_s} = -\beta R_C\left(\frac{V_{in}}{R_{ib}}\right)\cdot\left(\frac{1}{V_s}\right) \tag{4.50(a)}$$

or

$$\boxed{A_v = \frac{-\beta R_C}{r_\pi + (1+\beta)R_E}\left(\frac{R_i}{R_i + R_S}\right)} \tag{4.50(b)}$$

From this equation, we see that if $R_i \gg R_S$ and if $(1+\beta)R_E \gg r_\pi$, then the small-signal voltage gain is approximately

$$\boxed{A_v \cong \frac{-\beta R_C}{(1+\beta)R_E} \cong \frac{-R_C}{R_E} \quad \text{..... independent of } \beta} \tag{4.51}$$

- 共射電路小訊號放大電路範例 4 [4]

Common Emitter Circuit with Emitter Bypass Capacitor

- We can use an emitter bypass capacitor to effectively short out a portion or all of the emitter resistance to enhance the small-signal voltage gain.

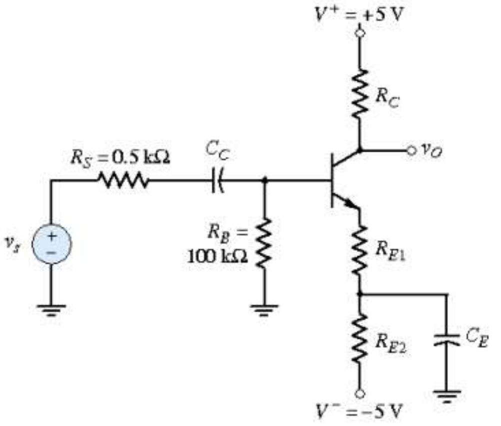
Design Example 4.6 **Objective:** An amplifier with the configuration in Figure 4.32 is to be designed such that a 12 mV sinusoidal signal from a microphone is amplified to a 0.4 V sinusoidal output signal. Standard resistor values are to be used in the final design.

Initial Design Approach: The magnitude of the voltage gain of the amplifier needs to be

$$|A_v| = \frac{0.4\,\text{V}}{12\,\text{mV}} = 33.3$$

From Equation (4.51), the approximate voltage gain of the amplifier is

$$|A_v| \cong \frac{R_C}{R_{E1}}$$



Noting from the last example that this value of gain produces an optimistically high value, we can set $R_C/R_{E1} = 40$ or $R_C = 40R_{E1}$.

The dc base-emitter loop equation is

$$5 = I_B R_B + V_{BE}(\text{on}) + I_E(R_{E1} + R_{E2})$$

Assuming $\beta = 100$ and $V_{BE}(\text{on}) = 0.7$ V, we can design the circuit to produce a quiescent emitter current of, for example, 0.20 mA. We then have

$$5 = \frac{(0.20)}{(101)}(100) + 0.70 + (0.20)(R_{E1} + R_{E2})$$

which yields

$$R_{E1} + R_{E2} = 20.5\,\text{k}\Omega$$

Assuming $I_E \cong I_C$ and designing the circuit such that $V_{CEQ} = 4\,\text{V}$, the collector–emitter loop equation produces

$$5 + 5 = I_C R_C + V_{CEQ} + I_E(R_{E1} + R_{E2}) = (0.2)R_C + 4 + (0.2)(20.5)$$

or

$$R_C = 9.5\,\text{k}\Omega$$

Then

$$R_{E1} = \frac{R_C}{40} = \frac{9.5}{40} = 0.238\,\text{k}\Omega$$

and $R_{E2} = 20.3\,\text{k}\Omega$.

From Appendix D, we can pick standard resistor values of $R_{E1} = 240\,\Omega$, $R_{E2} = 20\,\text{k}\Omega$, and $R_C = 10\,\text{k}\Omega$.

- 結論:
  BJT 電晶體共射放大電路、等效電路與小訊號模型如圖 6-5-1, 6-5-2, 6-5-3 所示，

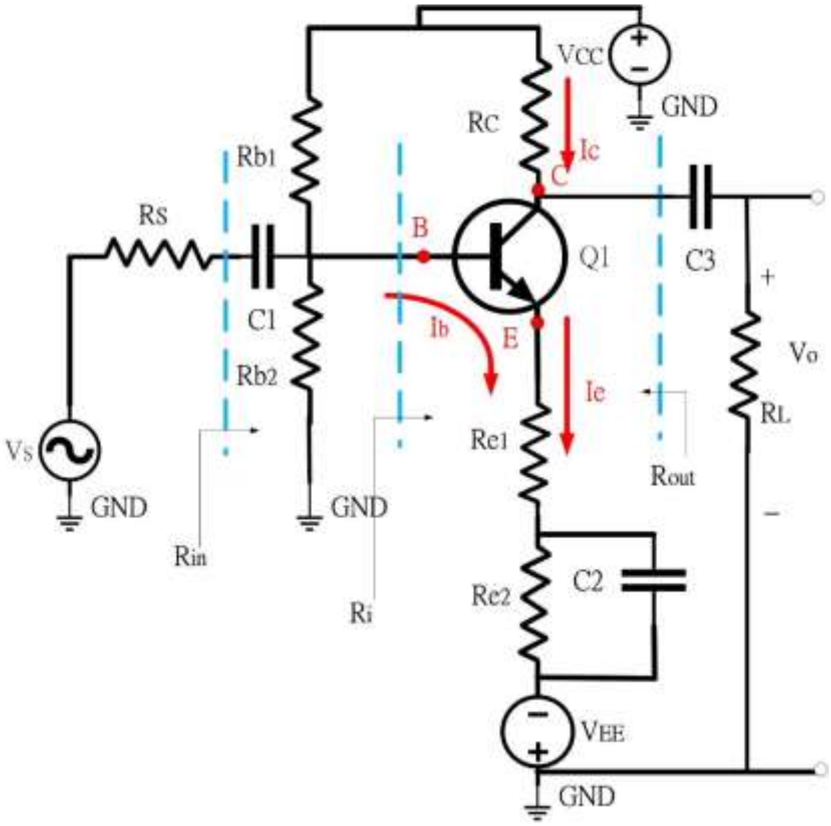


圖 6-5-1　BJT 電晶體共射放大電路

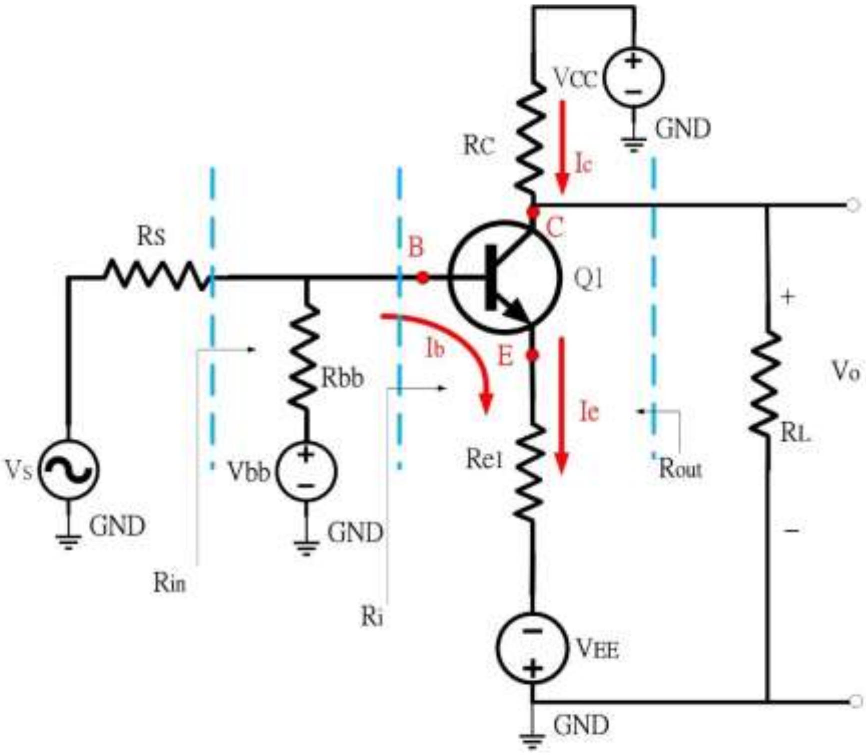


圖 6-5-2　等效電路

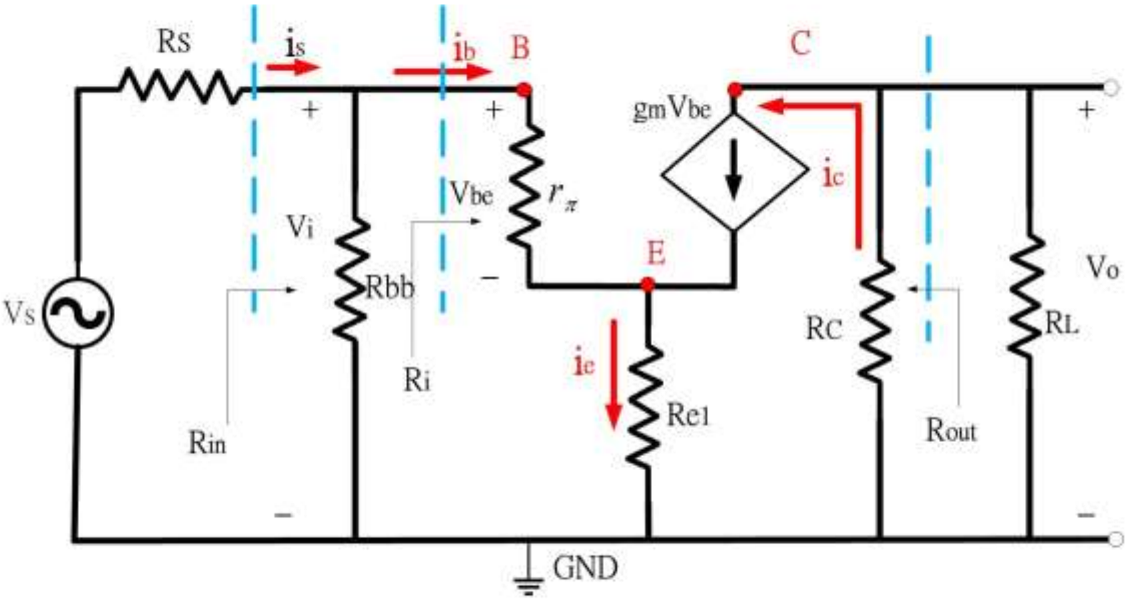


圖 6-5-3　小訊號模型

其中，流經電晶體三極的電流(I_b，I_c，I_e)與偏壓電流(I_{BQ}，I_{CQ}，I_{EQ})及訊號電流(i_b，i_c，i_e)關係如(6.1)所示:

1) $I_b = I_{BQ} + \ i_b, \quad I_c = I_{CQ} + \ i_c, \quad I_e = I_{EQ} + \ i_e,$ (6.1)

2) 電流放大率 => $\beta = {}^{I_{CQ}}\!\big/_{I_{BQ}} = \frac{g_m * V_{be}}{V_{be}/r_\pi} = g_m * r_\pi$ (6.2)

3) BE 間導通電阻 $r_b = r_\pi = {}^{\beta V_T}\!\big/_{I_{CQ}}$， $V_T = 0.026$， I_{CQ} = Q-point I_C (6.3)

$$R_{bb} = R_{b1} \ //R_{b2}$$

4) 輸入電阻 => $R_{in} = \frac{V_i}{i_s} = R_{bb}//(r_\pi \ + (1+\beta)R_{e1})$

$$\cong r_\pi \ + (1+\beta)R_{e1} = R_i \qquad (6.4)$$

5) 輸出電阻 => $R_{out} = R_C$ (6.5)

6) 電壓放大率 => $A_v = \frac{V_o}{V_s} = \frac{V_o}{V_i} * \frac{V_i}{V_s} = \frac{-i_c * R_c}{i_b * (r_\pi \ + (1+\beta)R_{e1})} * \frac{R_{in}}{R_{in}+R_s}$

$$= \frac{-\beta * R_c}{r_\pi \ + (1+\beta)R_{e1}} * \frac{R_{in}}{R_{in}+R_s} \cong -\frac{R_c}{R_{e1}} * \frac{R_{in}}{R_{in}+R_s} \qquad (6.6)$$

例題 5: 考量圖 6-6-1

- 找出 Q-point 的 V_{CEQ}、 I_{BQ} 與 I_{CQ}，$\beta = I_{CQ} / I_{BQ} = ?$
- 計算 Av = ? 比較理論值與模擬電路輸出入 Vp-p 波形比率值。
- 計算輸出入電阻 Rin , Rout，並修改該模擬圖 6-6 驗證該輸出入電阻計算值是否相近。

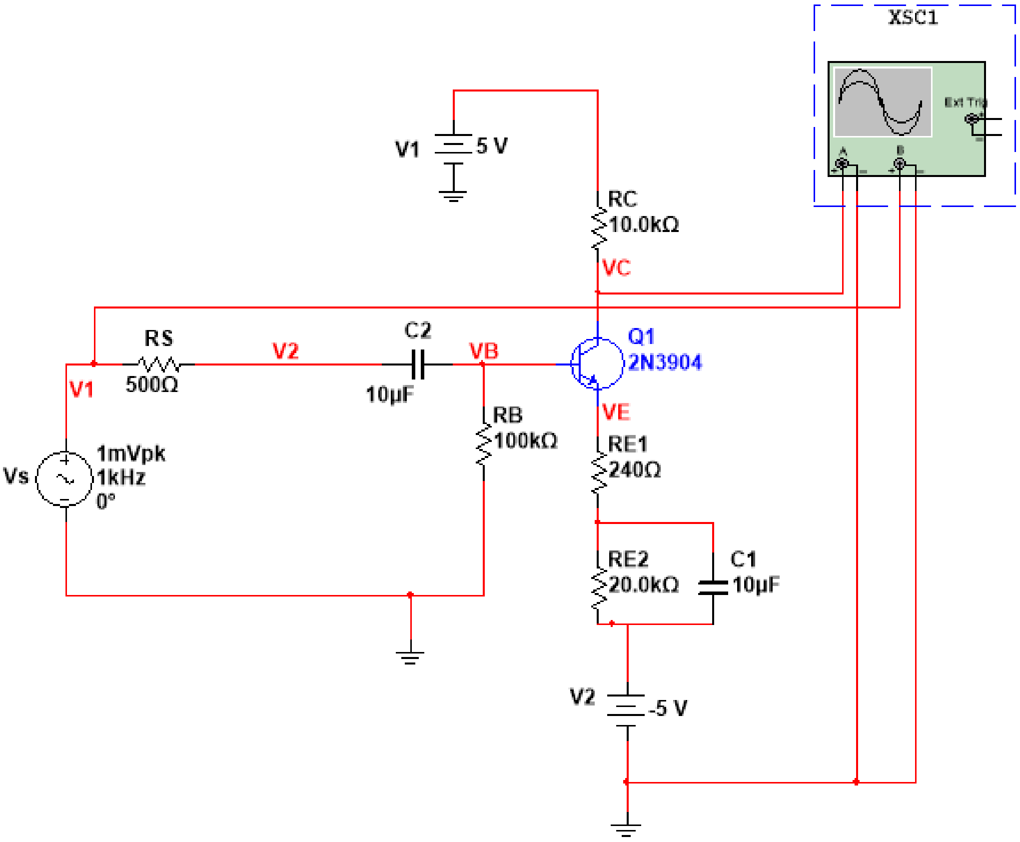


圖 6-6-1

- 使用 Simulate → Analyses → DC operating point，顯示 Q-point 電壓與電流

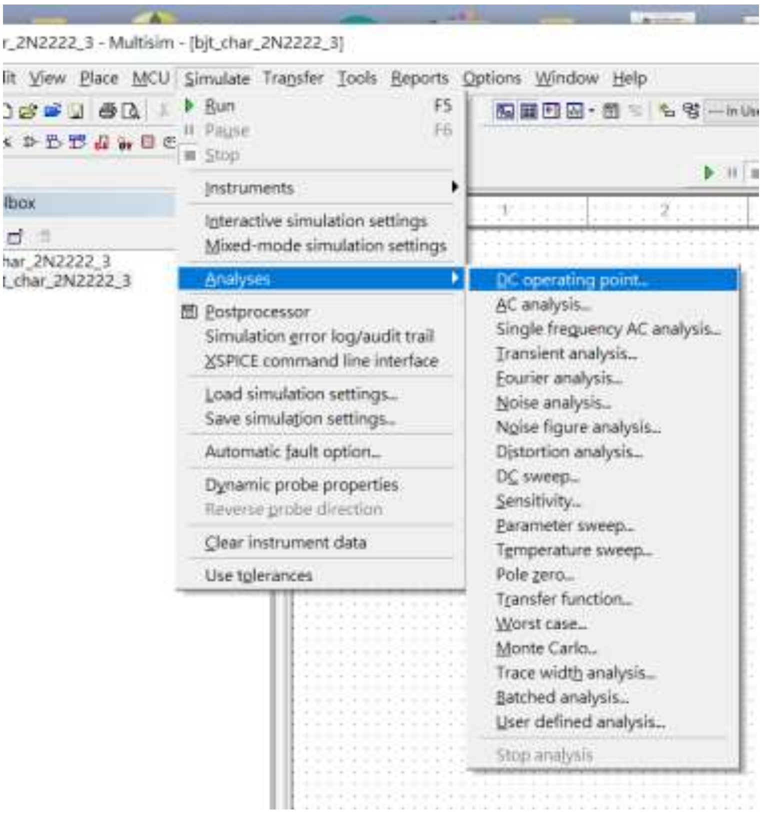
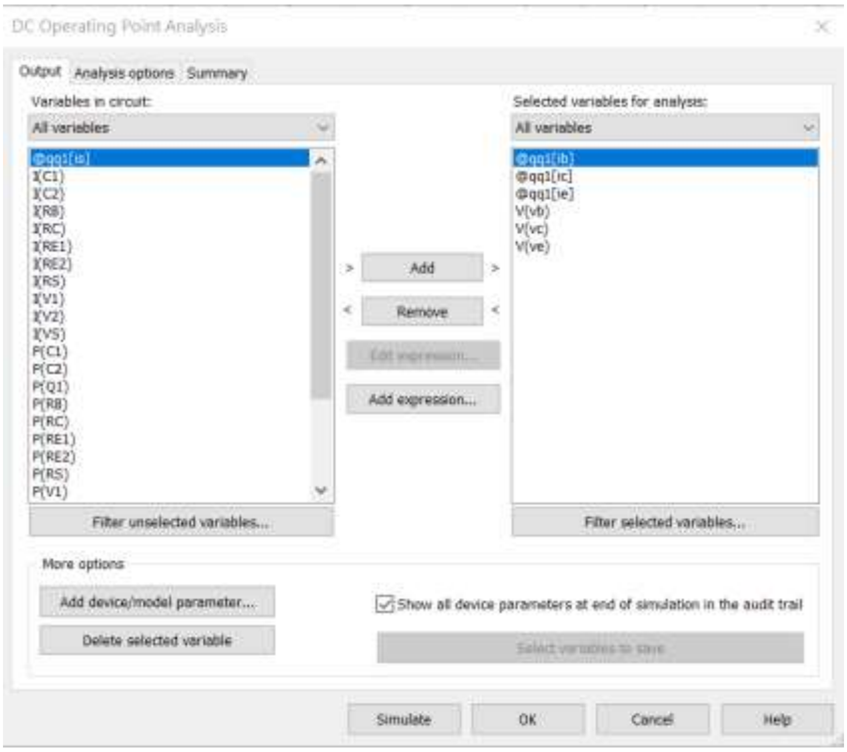


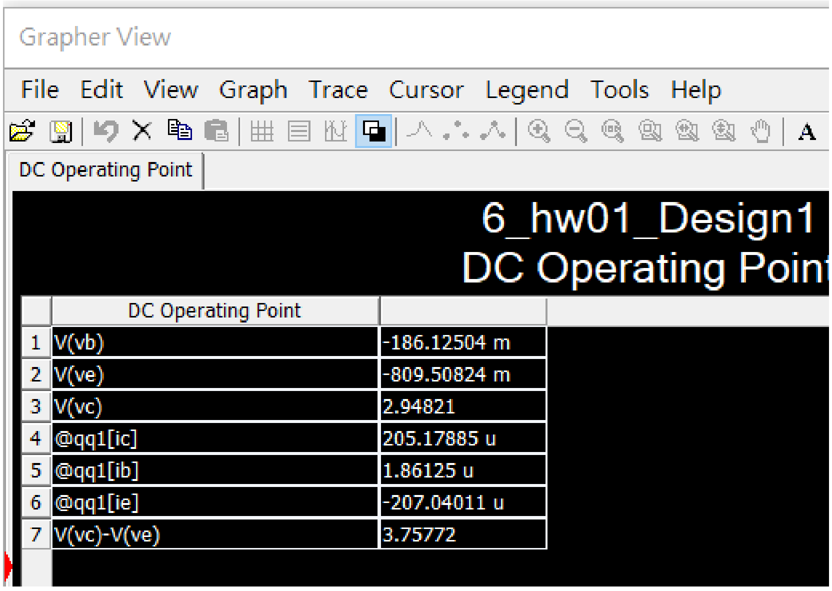
圖 6-6-2 操作程序



Selected variables for analysis:
All variables
@qq1[ib]
@qq1[ic]
@qq1[ie]
V(vb)
V(vc)
V(ve)

☑ Show all device parameters at end of simulation in the audit trail

圖 6-6-3 選擇變量 ib, ic, ie, Vb, Vc, Ve



6_hw01_Design1
DC Operating Point

	DC Operating Point	
1	V(vb)	-186.12504 m
2	V(ve)	-809.50824 m
3	V(vc)	2.94821
4	@qq1[ic]	205.17885 u
5	@qq1[ib]	1.86125 u
6	@qq1[ie]	-207.04011 u
7	V(vc)-V(ve)	3.75772

圖 6-6-4 VCEQ = Vc – Ve = 3.75V, $\beta = I_{CQ}/I_{BQ}$ = 205.17/1.86 = 110.3

- 使用示波器顯示 V1 與 VC 之波形，並連接相關接點如上電路圖

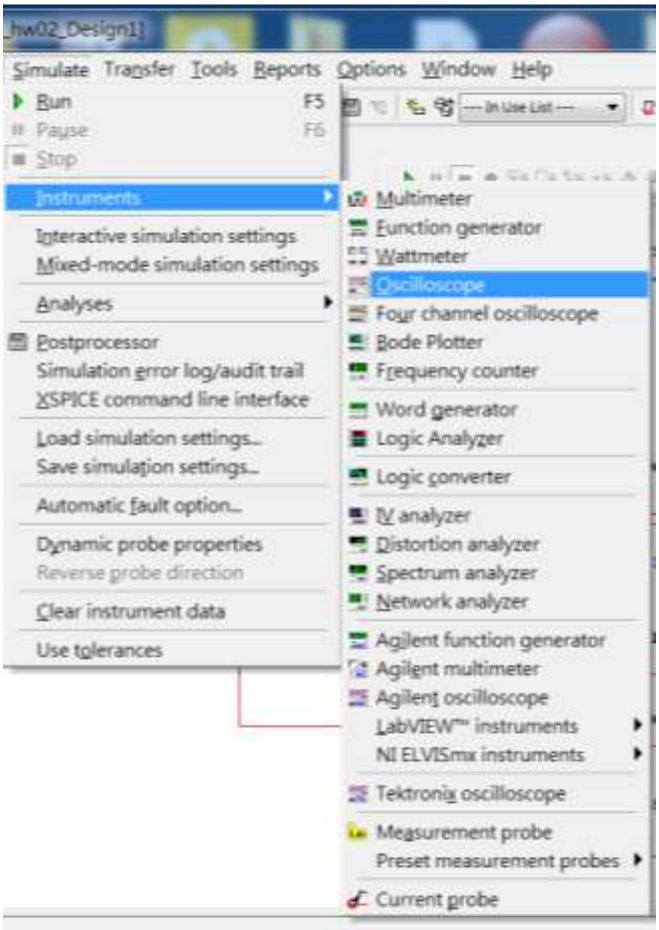
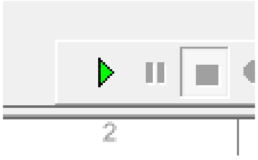


圖 6-6-5

Run → Stop



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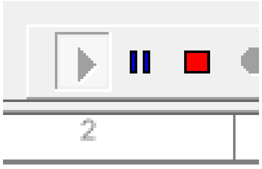
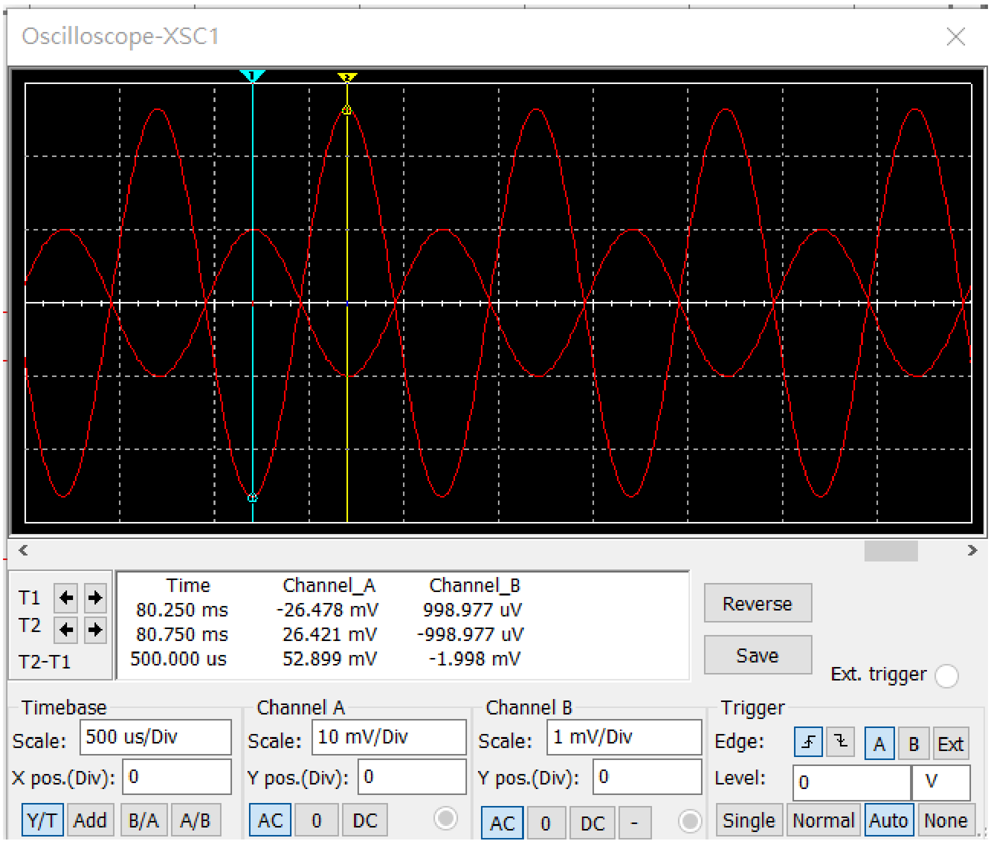



Oscilloscope-XSC1

	Time	Channel_A	Channel_B
T1	80.250 ms	-26.478 mV	998.977 uV
T2	80.750 ms	26.421 mV	-998.977 uV
T2-T1	500.000 us	52.899 mV	-1.998 mV

Timebase
Scale: 500 us/Div
X pos.(Div): 0

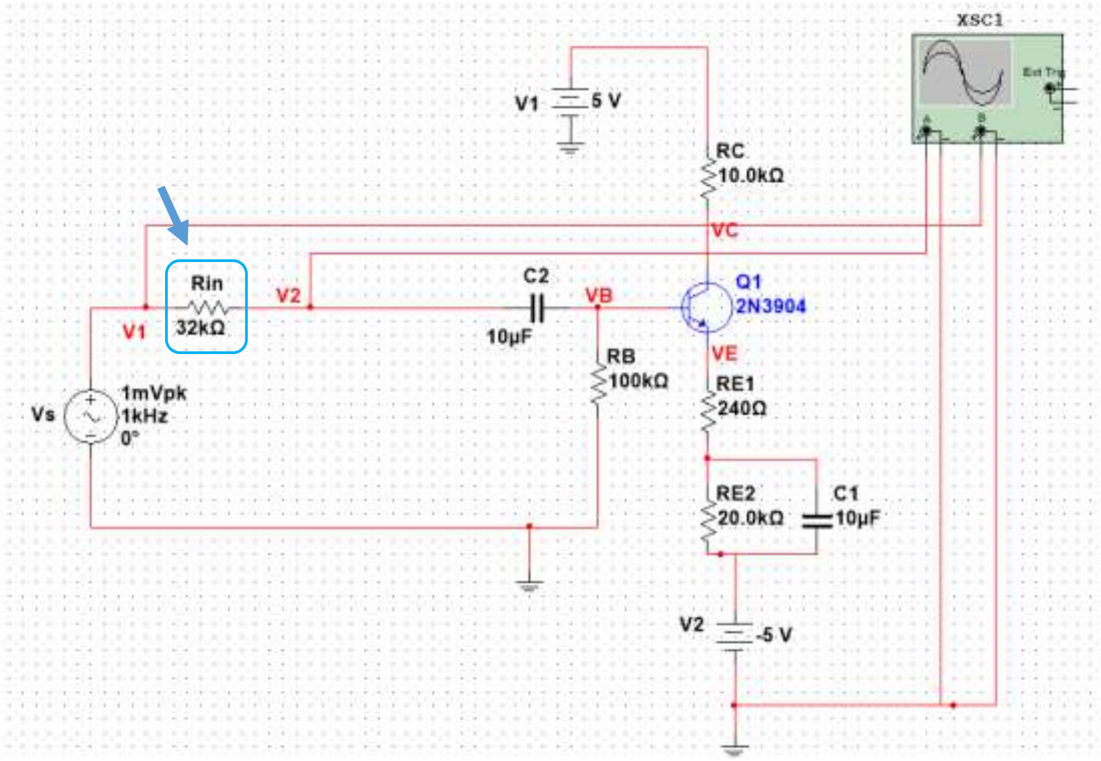
Channel A
Scale: 10 mV/Div
Y pos.(Div): 0

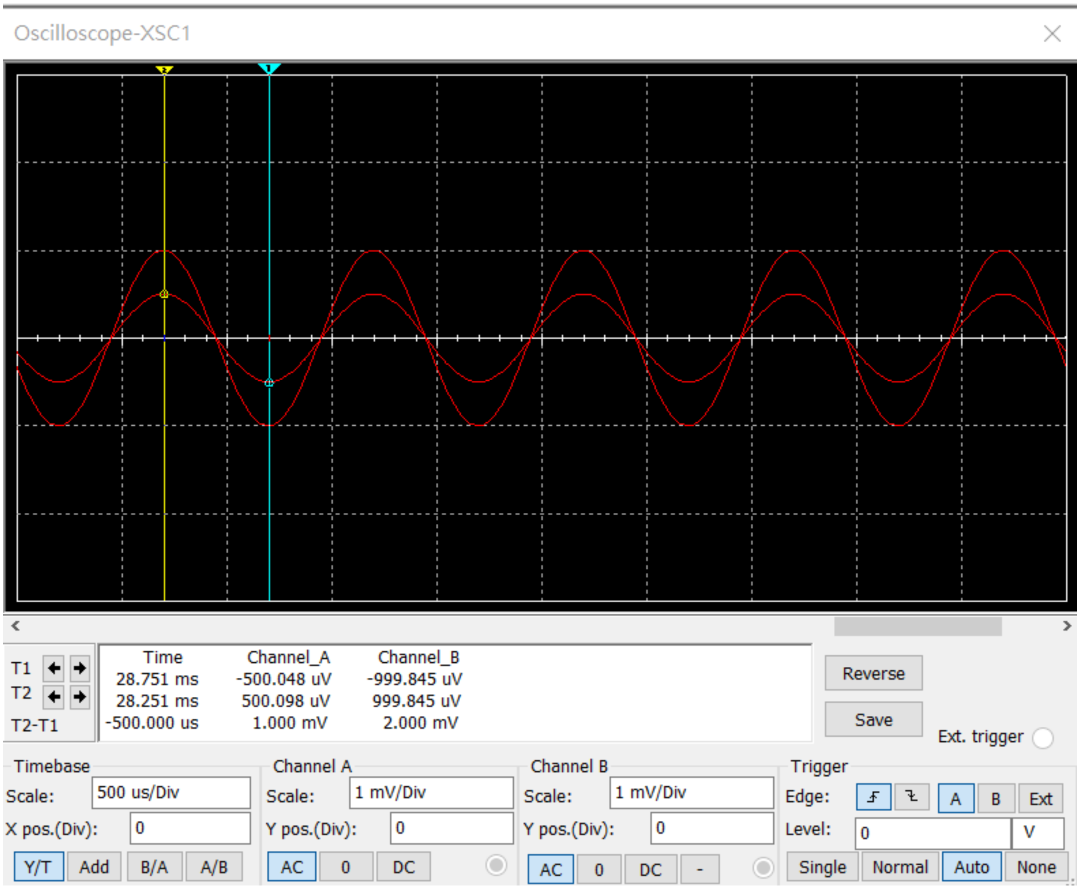
Channel B
Scale: 1 mV/Div
Y pos.(Div): 0

Trigger
Edge:
Level: 0 V

圖 6-6-6 Channel A V_C p-p = -26.478 ~ 26.421 mV =52.899 mv,
Channel B V_S p-p = -998.977 ~ 998.977 uV = 2mv

放大率計算 $|A_v| = |V_C|/|V_S| = 52.899/2 = 26.44 \ll R_C/R_{E1} = 10K/.24K = 41.66$





	Time	Channel_A	Channel_B
T1	28.751 ms	-500.048 uV	-999.845 uV
T2	28.251 ms	500.098 uV	999.845 uV
T2-T1	-500.000 us	1.000 mV	2.000 mV

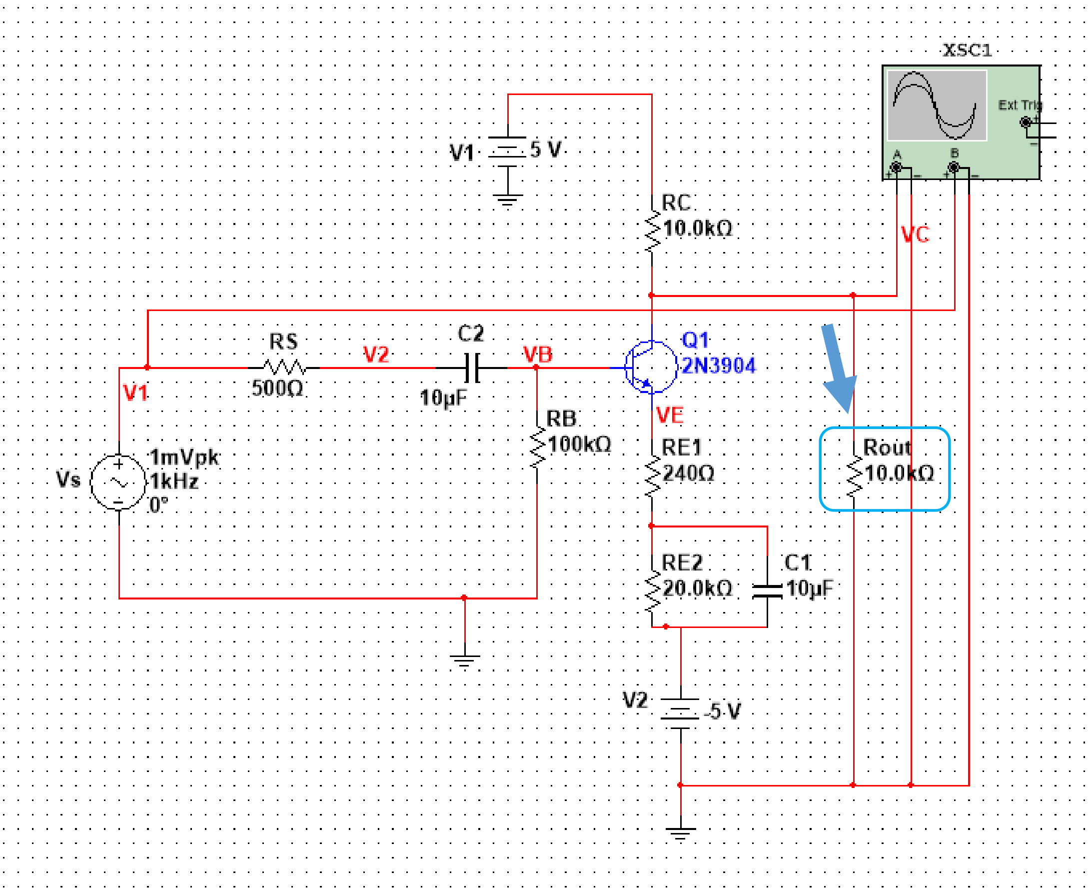
Timebase
Scale: 500 us/Div
X pos.(Div): 0
Y/T Add B/A A/B

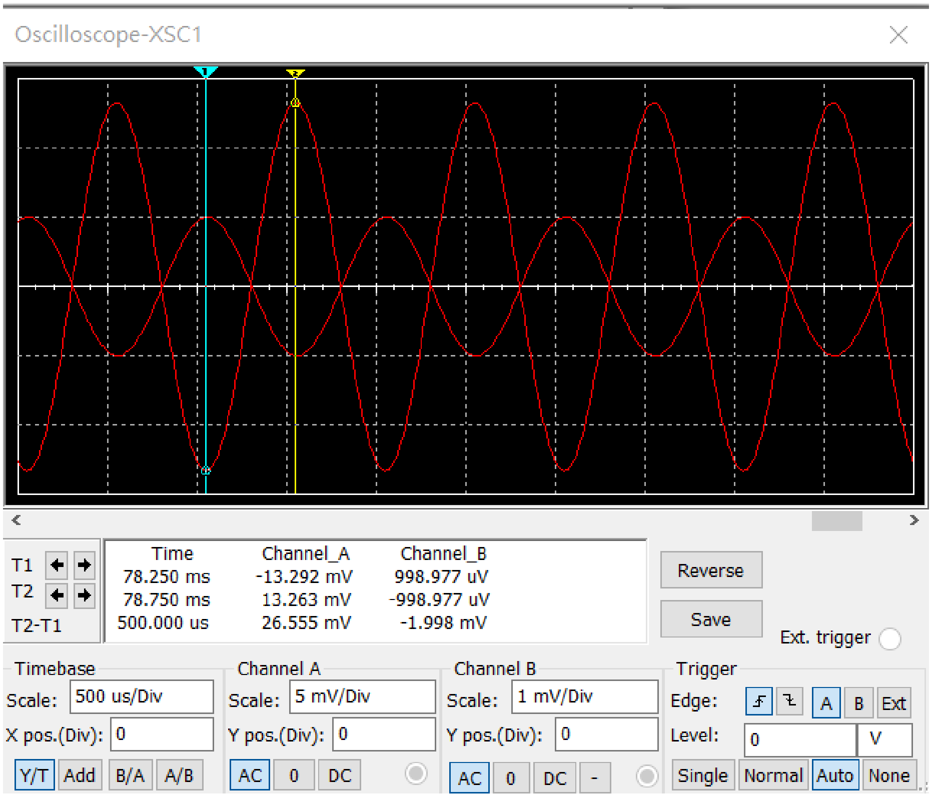
Channel A
Scale: 1 mV/Div
Y pos.(Div): 0
AC 0 DC

Channel B
Scale: 1 mV/Div
Y pos.(Div): 0
AC 0 DC -

Trigger
Edge: A B Ext
Level: 0 V
Single Normal Auto None

圖 6-6-7　設定輸入電阻 Rin = 32K，使得 |V2p-p| /|V1p-p| = 1mv/2mv = 0.5





	Time	Channel_A	Channel_B
T1	78.250 ms	-13.292 mV	998.977 uV
T2	78.750 ms	13.263 mV	-998.977 uV
T2-T1	500.000 us	26.555 mV	-1.998 mV

Timebase
Scale: 500 us/Div
X pos.(Div): 0

Channel A
Scale: 5 mV/Div
Y pos.(Div): 0

Channel B
Scale: 1 mV/Div
Y pos.(Div): 0

Trigger
Edge:
Level: 0 V

圖 6-6-8 設定輸出電阻 Rout = 10.0K，使得 |VRcp-p| /|V1p-p| = 26.5mv/2mv = 13.25 是原來 26.44 (圖 A-6)之半值。

理論值計算如下:

1) 電流放大率 => $\beta = \frac{I_{CQ}}{I_{BQ}} = 205.17/1.86 = 110.3$ (由圖 6-6-4 得知)

2) BE 導通電阻

$$r_b = r_\pi = {\beta V_T}/{I_{CQ}} = {110.3 * 0.026}/{205.17 * 10^{-6}} = 13.98\mathrm{K\Omega}$$

3) $R_{bb} = 100\mathrm{K\Omega}$

輸入電阻 => $R_{in} = \frac{V_i}{i_s} = R_{bb}//(r_\pi + (1+\beta)R_{e1})$

$$= 100 \ // \ (13.98 + (1 + 110.3) * 0.24)$$
$$= 100 \ // \ 40.69 = 28.92 \ \mathrm{K\Omega}$$

4) 輸出電阻 => $R_{out} = R_C = 10\mathrm{K\Omega}$

5) 電壓放大率 => $A_v = \frac{V_o}{V_s} = \frac{V_o}{V_i} * \frac{V_i}{V_s} = \frac{-i_c * R_c}{i_b * (r_\pi + (1+\beta)R_{e1})} * \frac{R_{in}}{R_{in} + R_s}$

$$= \frac{-\beta * R_c}{r_\pi + (1+\beta)R_{e1}} * \frac{R_{in}}{R_{in} + R_s}$$

$$= \frac{-110.3 * 10}{13.98 + (1 + 110.3) * 0.24} * \frac{28.92}{28.92 + 0.5} = -26.64$$

二、作業:

6-1: 參考圖 6-7 共射放大電路模擬圖:

- 找出 Q-point 的 V_{CEQ} 、 I_{BQ} 與 I_{CQ}，$\beta = I_{CQ} / I_{BQ} = ?$
- 計算 Av = ? 比較理論值與模擬電路輸出入 Vp-p 波形比率值。
- 計算輸出入電阻 Rin , Rout，並修改該模擬圖 6-7 驗證該輸出入電阻計算值是否相近。

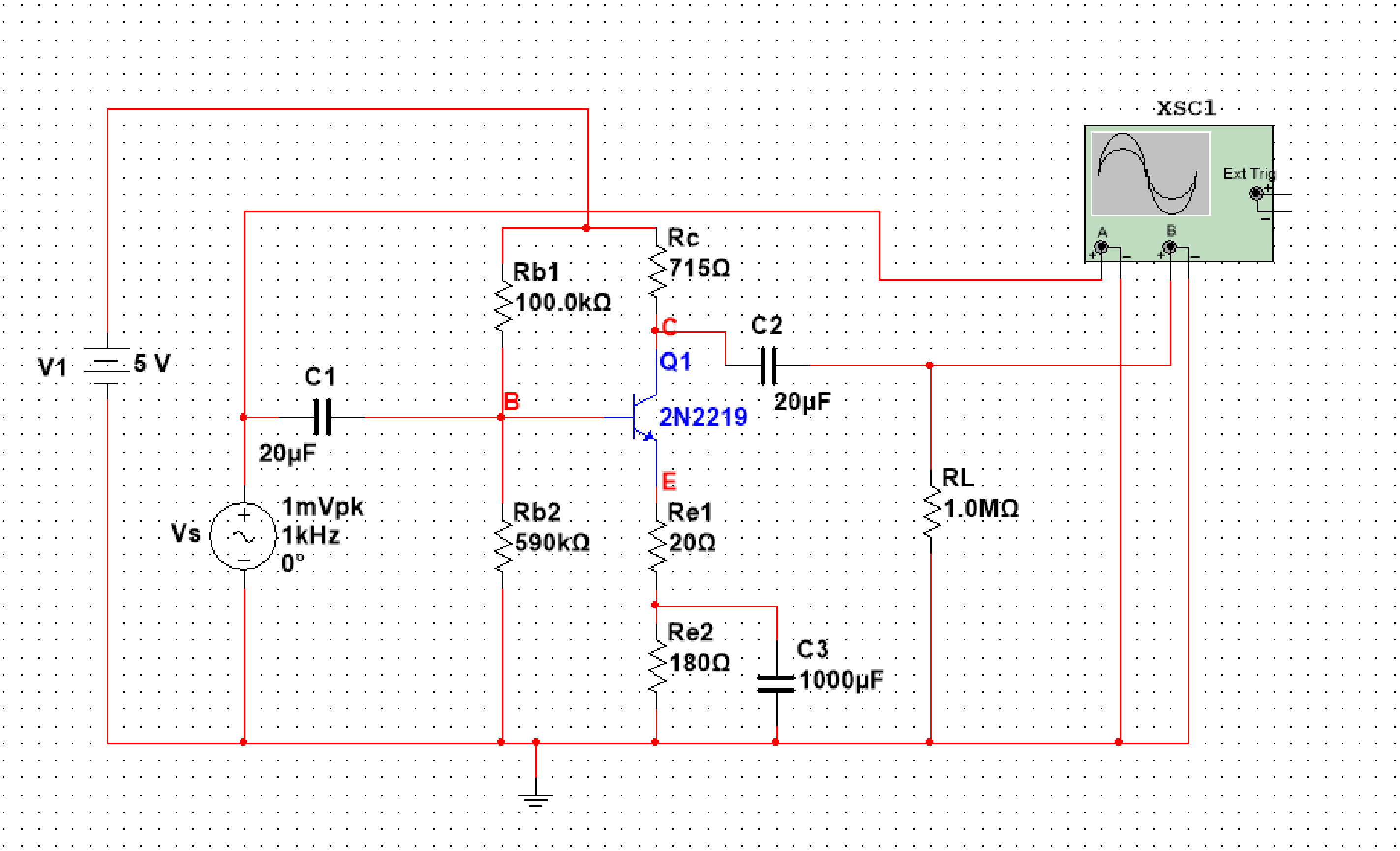


圖 6-7 作業電路圖

6-2: 續上題，可能因電容選擇不當(如 C1 , C2 = 10uF 修改為 0.1uF)，請選擇適當電容使得|Av|之值增加並接近期望值 $R_C / R_{E1} = 41.66$，並以 MultiSim ver. 12 驗證|Av| = ?