Bachelor of Engineering Electronic Engineering (HONS)

# Headphone Amplifier Design


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Electronic Engineering Department

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# Chapter 1

# Simple transistor circuit

## 1.1 Transistor basic property

Figure 1.1 shows the basic NPN bipolar junction transistor circuit.

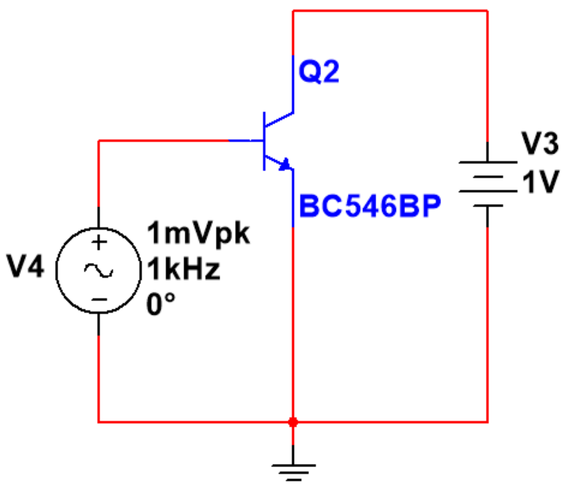



Figure 1.1: Single transistor circuit

We can get transistor operating state from simulation result as Figure 1.2. It's obvious that $I_C$ and $I_E$ is proximately 200 times greater than $I_B$ which is the main function of transistor.

chapter 1

DC Operating Point Analysis

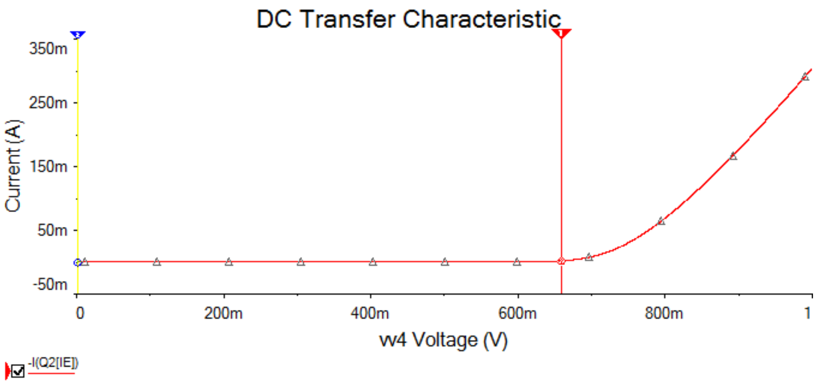
| | Variable | Operating point value |
|---|---|---|
| 1 | I(Q2[IB]) | 7.09789 u |
| 2 | I(Q2[IC]) | 2.02293 m |
| 3 | I(Q2[IE]) | -2.03003 m |

Figure 1.2: Single transistor circuit simulation data

Equation 1.1 defines $\beta$ which is the most important parameter of transistor.

$$\beta = \frac{I_C}{I_B} \tag{1.1}$$

## 1.2 Find $R_e$




| -I(Q2[IE]) | |
|---|---|
| x1 | 657.7000m |
| y1 | 2.0300m |
| x2 | 0.0000 |
| y2 | 2.0685p |
| dx | -657.7000m |
| dy | -2.0300m |
| dy/dx | 3.0866m |
| 1/dx | -1.5205 |

Figure 1.3: $V_{be}$ and $I_c$ curve

After running DC sweep command on $V4$ in circuit of Figure 1.1, We can get the curve of Figure 1.3. This illustrate that when $V_be = 657.7mV$, $I_e = 2mA$.

If we zoom in Figure 1.3 like shown in Figure 1.4, the relationship between $V_{be}$ and $I_e$ is linear which is same as resistor and we called $R_e$.Then we can get its value with

$$R_e = \frac{dx}{dy} = \frac{143.472u}{10.66u} = 13.459\Omega$$

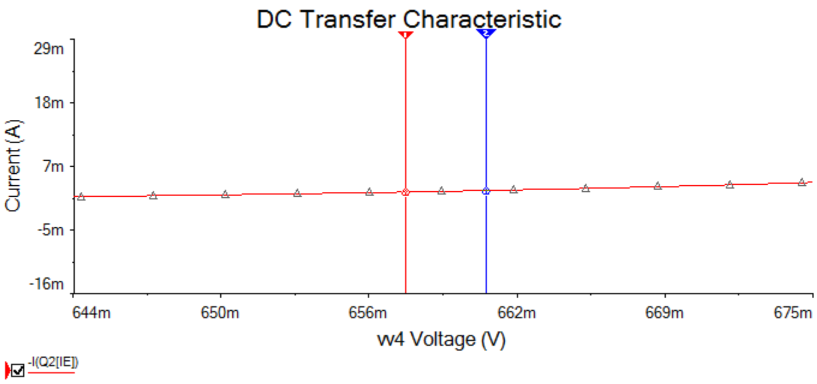
Because we know $I_e = 2mA$,

$$Re = \frac{V}{I_e} = \frac{V}{2mA} = 13.459\Omega$$

$$V = 2mA \times 13.459 \approxeq 26mV$$

Therefore,we can calculate $R_e$ with $I_e$ in future using

$$R_e = \frac{26mV}{I_e} \tag{1.2}$$




| | -I(Q2[IE]) |
|---|---|
| x1 | 657.7424m |
| y1 | 2.0332m |
| x2 | 657.8859m |
| y2 | 2.0438m |
| dx | 143.4720µ |
| dy | 10.6614µ |
| dy/dx | 74.3099m |
| 1/dx | 6.9700k |

Figure 1.4: Re model

## 1.3 Find $R_o$

If we run DC sweep on V3 and we can get a curve like Figure 1.5.

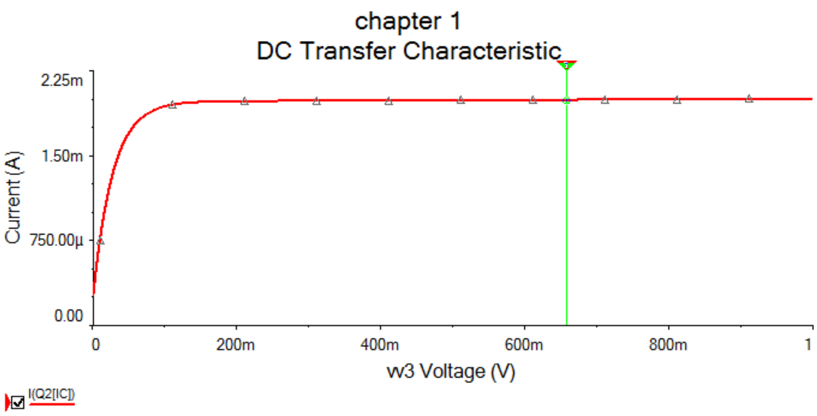



Figure 1.5: DC sweep on V3 in Figure 1.1

When we zoom in the curve and We can find that it's almost linear like Figure 1.6. It means that there is an equivalent resistor cross between collector and emiter terminal ie.$R_o$.

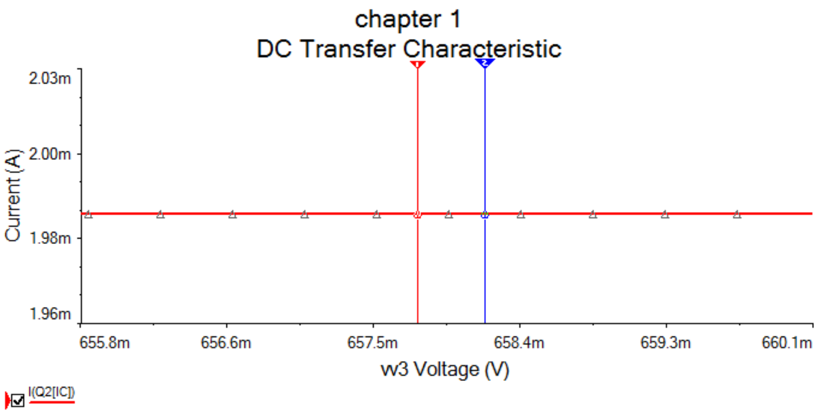
$$R_o = \frac{\Delta V}{\Delta I} = \frac{404.7665\mu}{10.1598n} \approx 39.84 \times 10^3 \Omega$$

Because $I_e = 2mA$,

$$V = 2mA \times 39.84 \times 10^3 \Omega = 79.68 \approx 80$$

Therefore, We can calculate $R_o$ using

$$R_o = \frac{80}{I_e} \tag{1.3}$$




| | I(Q2[IC]) |
|---|---|
| x1 | 657.7629m |
| y1 | 1.9893m |
| x2 | 658.1677m |
| y2 | 1.9893m |
| dx | 404.7665µ |
| dy | 10.1598n |
| dy/dx | 25.1004µ |
| 1/dx | 2.4706k |

Figure 1.6: Ro model

## 1.4 Limit current gain

Generally, we need a method to control the current gain as we want. Figure 1.7 is a simply solution by adding transistor $R_C$ and $R_E$.

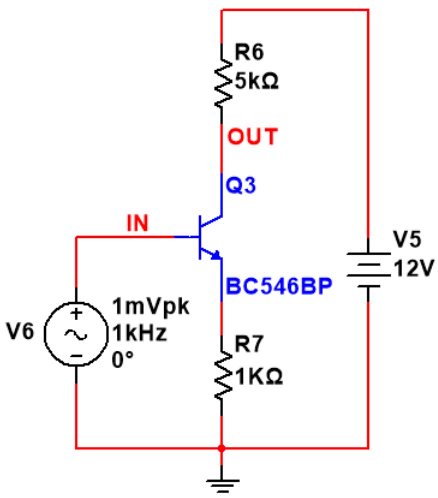
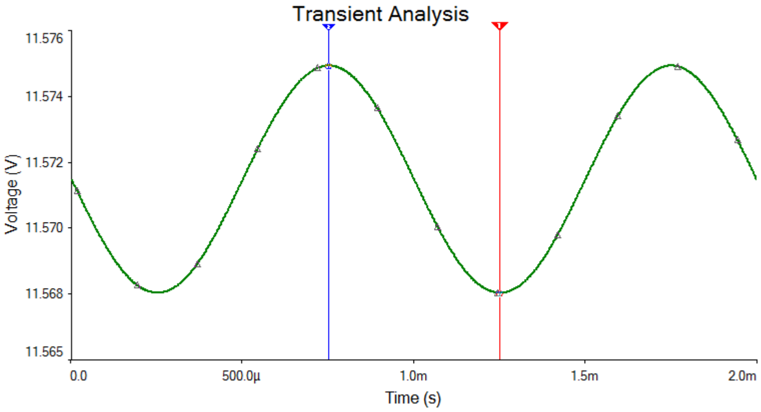



Figure 1.7: Basic transistor circuit with $R_c$ and $R_e$

We can derive voltage gain $A_V$ with Equation 1.4. And in circuit in Figure 1.7, $A_V$ is approximate 5 theoretically.

$$A_V \triangleq \frac{V_{out}}{V_{in}} \approx -\frac{R_C}{R_E} \tag{1.4}$$




| | V(in) | V(out) |
|---|---|---|
| x1 | 1.2508m | 1.2508m |
| y1 | 658.7000m | 11.5676 |
| x2 | 749.1749µ | 749.1749µ |
| y2 | 656.7000m | 11.5752 |
| dx | -501.6502µ | -501.6502µ |
| dy | -1.9999m | 7.6486m |
| dy/dx | 3.9867 | -15.2469 |
| 1/dx | -1.9934k | -1.9934k |

Figure 1.8: Output of the circuit in Figure 1.7

From simulation result in Figure 1.8, the practical $A_V = \frac{7.6486m}{2m} = 3.8243$ which is close to theoretic value.

## 1.5 Add voltage divider

As we know, we need make sure $V_{be} > 0.65V$ for transistor operating correctly. But in practical application, it's hard to keep input signal always meeting this requirement. So we can add capacitor and voltage divider solve this problem like Figure 1.9. In which, capacitor block the original DC voltage of input signal and voltage divider add the DC voltage which we require to signal. Finally, we use another capacitor for outputting pure AC signal form our circuit.

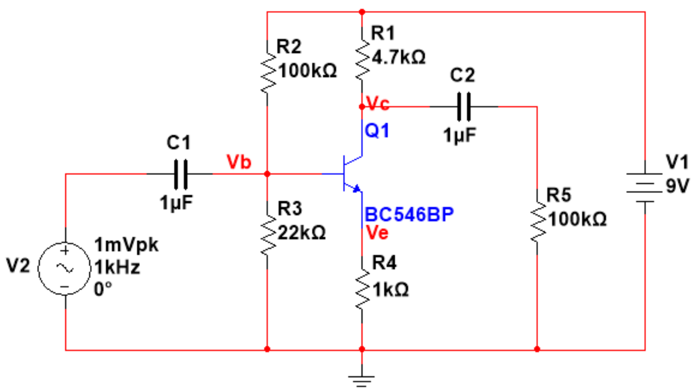



Figure 1.9: Add voltage divider and capacitors

# Chapter 2

# Negative Feedback

## 2.1 Simple Negative Feedback system

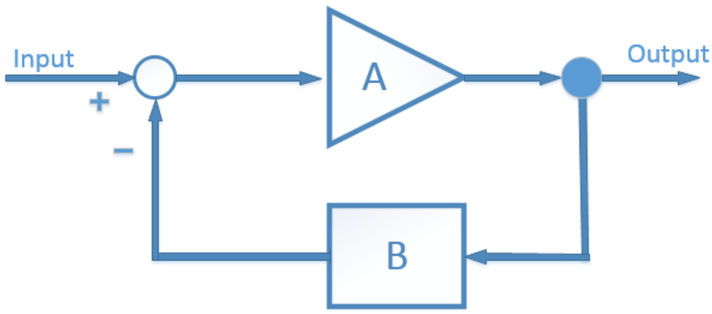



Figure 2.1: simple negative feedback system

Figure 2.1 show a simple negative feedback system in which A is ideal amplifier and B is feedback network.

$$\frac{V_{out}}{V_{in}} = B$$

## 2.2 Implement Using Op-amp

In Figure 2.2, an Op-amp 741 is used to implement the negative feedback circuit in Figure 2.1.

741 is part A while R1 and R2 form feedback network.

$$\frac{V_{out}}{V_{in}} = B = \frac{R1 + R2}{R2} = \frac{10K + 1K}{1K} = 11$$

From simulation result in Figure 2.3,

$$B = \frac{\Delta V_{out}}{\Delta V_{in}} = \frac{2.1972}{199.8674m} = 10.99328$$

Obviously, the simulation result is very close to our estimation.

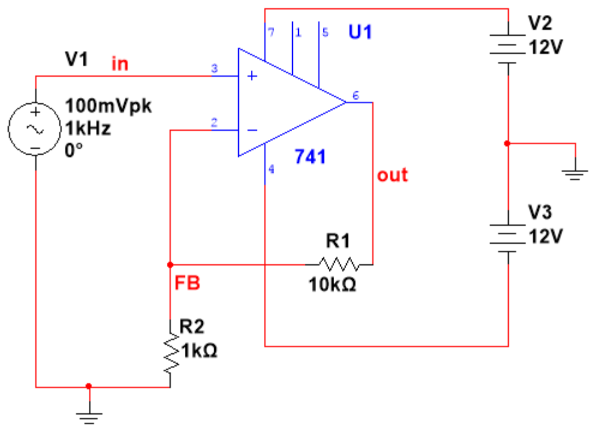
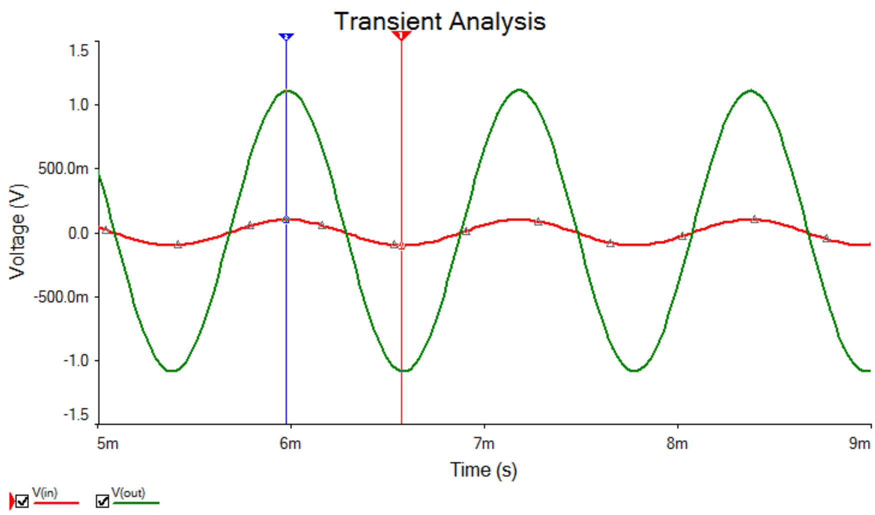



Figure 2.2: Implement negative feedback circuit with Op-amp




| | V(in) | V(out) |
|---|---|---|
| x1 | 6.7433m | 6.7433m |
| y1 | -99.9112m | -1.0862 |
| x2 | 6.2453m | 6.2453m |
| y2 | 99.9562m | 1.1110 |
| dx | -498.0000µ | -498.0000µ |
| dy | 199.8674m | 2.1972 |
| dy/dx | -401.3402 | -4.4121k |
| 1/dx | -2.0080k | -2.0080k |

Figure 2.3: Op-amp feedback simulation result curve

## 2.3 Implement Using transistor

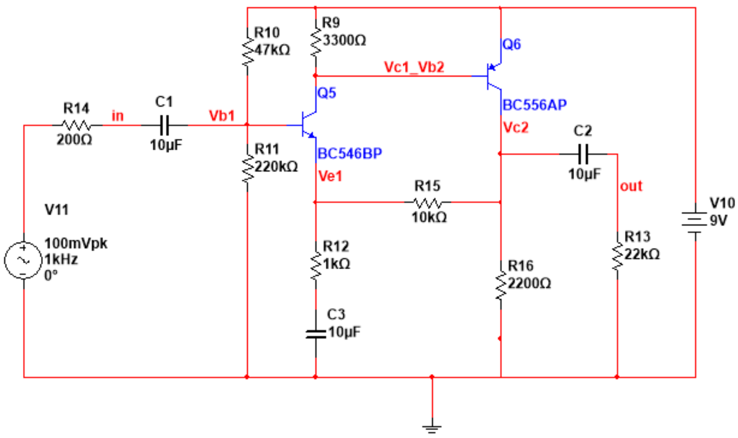
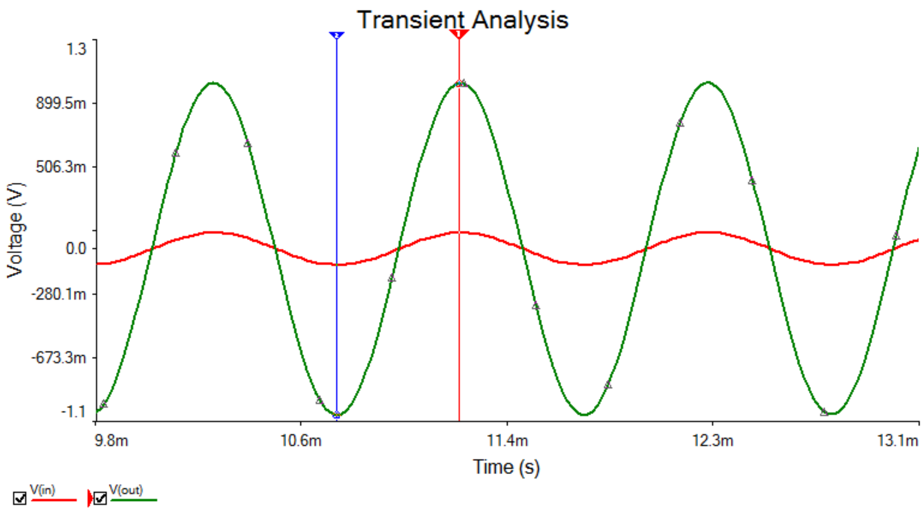



Figure 2.4: Implement negative feedback circuit with transistor

In Figure 2.4 circuit, Op-amp replaced by circuit in Figure 1.9. R12 and R15 make up feedback network which $B = \frac{R15+R12}{R12} = 11$. As we see in Figure 2.3, the output is reverse to input. Therefore, we add another transistor Q6 to eliminate the phase difference of signal.

Apparently, there's no phase difference between input and output signal. The voltage gain of circuit in Figure 2.4 is $Gain = \frac{\Delta V_{out}}{\Delta V_{in}} = \frac{2.0534}{198.8221m} = 10.3707$. It's also very close to theory result.




| | V(in) | V(out) |
|---|---|---|
| x1 | 11.2431m | 11.2431m |
| y1 | 99.3884m | 1.0254 |
| x2 | 10.7451m | 10.7451m |
| y2 | -99.4337m | -1.0281 |
| dx | -498.0000μ | -498.0000μ |
| dy | -198.8221m | -2.0534 |
| dy/dx | 399.2412 | 4.1234k |
| 1/dx | -2.0080k | -2.0080k |

Figure 2.5: transistor feedback circuit simulation result

# Chapter 3

# Current Source

## 3.1 Single current source circuit

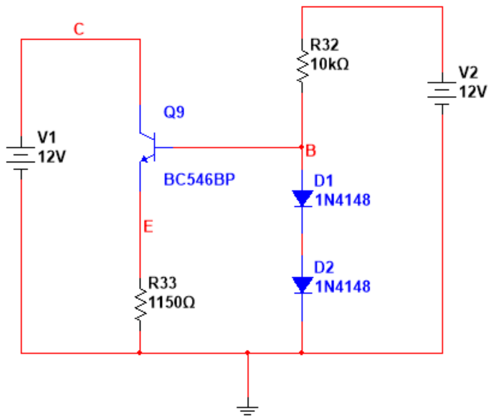



Figure 3.1: single current source circuit

Generally, we need a constant current source in circuit and the most classic one shows in Figure 3.1.

As we know the forward voltage cross a diode is about 0.65V which is approximately equal to $V_{be} of transistor$.

$$V_B = 2 \times V_{diode} = V_{be} + V_{R_{33}}$$

Therefore:

$$V_{R_{33}} = V_{diode} = 0.65V$$

$$I_e = \frac{V_{R_{33}}}{R_{33}} = \frac{0.65V}{1150\Omega} = 565.217\mu A$$

From Figure 3.2, we can see simulation result is close to the value we calculated. This simple circuit are able to supply constant current.

DC Operating Point Analysis

| | Variable | Operating point value |
|---|---|---|
| 1 | @qq9[ic] | 503.27881 u |
| 2 | @qq9[ie] | -505.07050 u |
| | | |

Figure 3.2: single current source circuit simulation result

## 3.2 Use current source to replace output resistor

Now we can use current source to replace the $R_{16}$ in circuit of Figure 2.4. Current source can supply stable current output. Till this step, we have finished the voltage amplifier part circuit but current of output is still enough to drive a headphone.

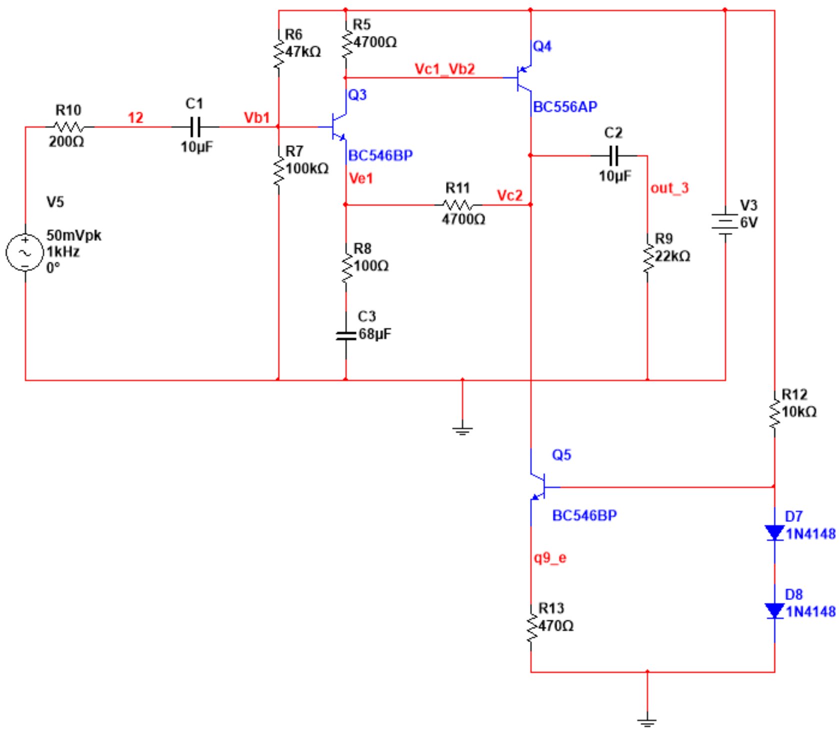



Figure 3.3: the circuit after adding current source

# Chapter 4

# Output Stage

## 4.1 Class A Output Stage

In Figure 4.1, transistor Q2 and resistor R1 made up of Class A output stage.

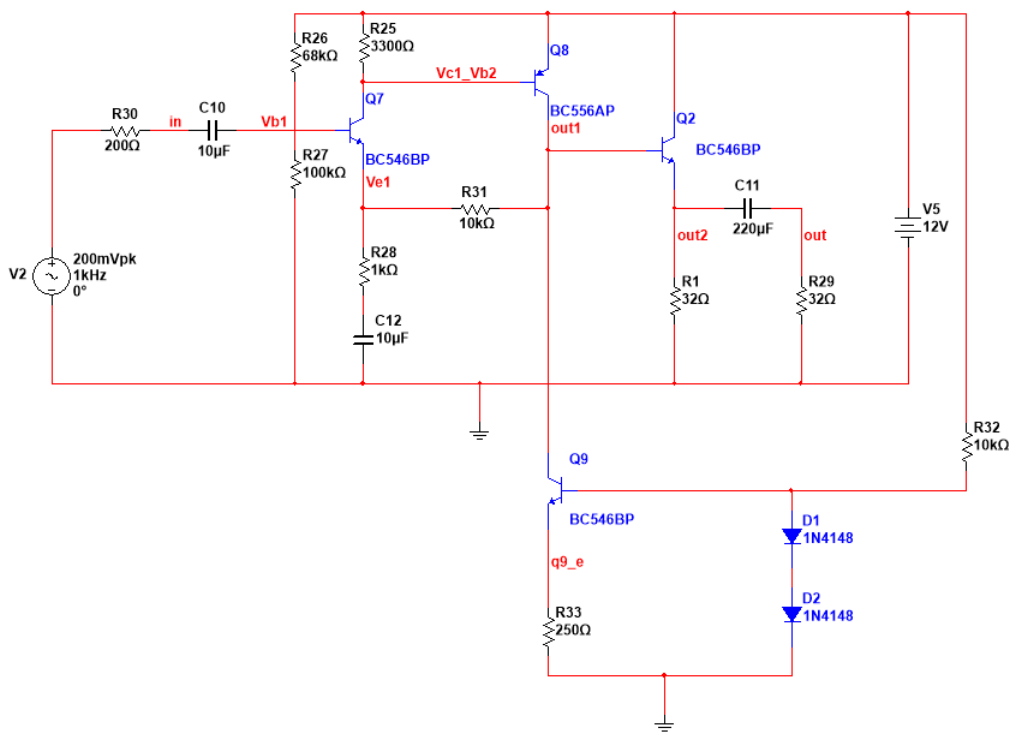



Figure 4.1: Class A output stage

As we can see in Figure 4.2, output signal of class A output stage is good enough to follow the input signal.

But from DC operating simulation result in Figure 4.3 we know Class A will consume a lot of current from battery and resistor R1 also waste a lot of power. It's can't acceptable because the final circuit is powered by battery.

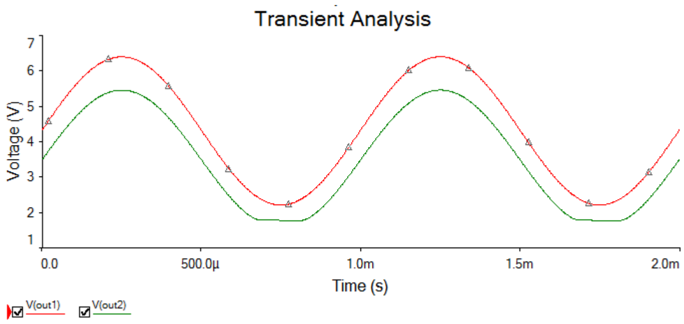



Figure 4.2: Class A output stage simulation result

**DC Operating Point Analysis**

| | Variable | Operating point value |
|---|---|---|
| 1 | I(Q2[IE]) | -109.82711 m |

Figure 4.3: Class A DC operating current simulation data

## 4.2 Class AB Output Stage

For better efficiency, we tried Class AB output stage which showed in Figure 4.4. Transistor Q4 and Q5 are used for amplifying upper and lower part of input signal. Resistor R10 and R11 and transistor Q7 are made up of $V_{be}$ multiplier. In this case, it generate $2V_{be}$ cross between collector and emitter of Q7 which eliminates the crossover distortion caused by $V_{be}$ of Q4 and Q5.

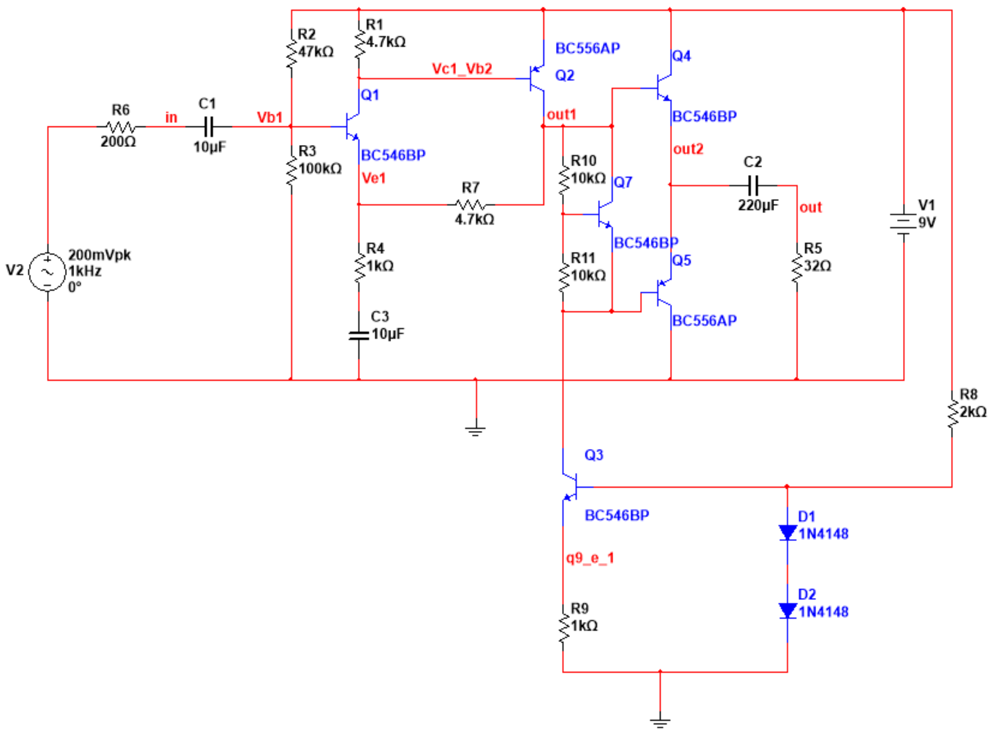



Figure 4.4: Class AB output stage

Finally, we can see from Figure 4.5 there is almost no distortion in output signal.

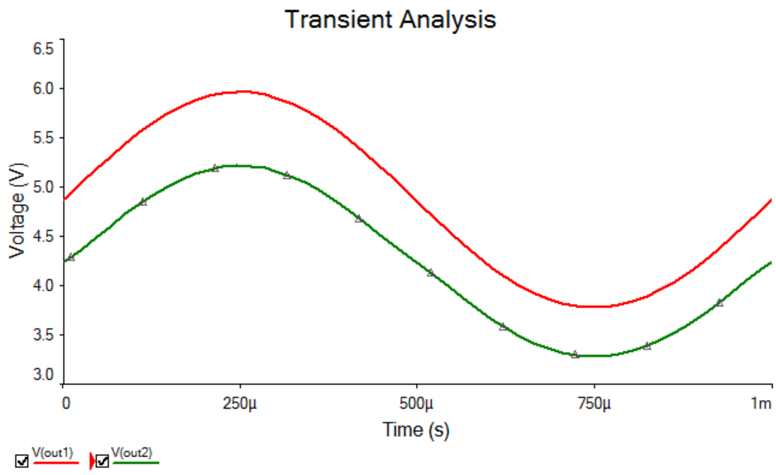



Figure 4.5: Class AV output stage simulation resut

**DC Operating Point Analysis**

| | Variable | Operating point value |
|---|---|---|
| 1 | I(Q4[IE]) | -809.46708 u |
| 2 | I(Q5[IC]) | 804.62548 u |

Figure 4.6: Class AB output stage DC operating current

In Figure 4.6, we know that DC operating current of Class AB output stage is much smaller than Class A. Therefore, Class AB output stage much more efficient and meet our requirement.