

Bachelor of Engineering Electronic Engineering (HONS)

Headphone Amplifier Design



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Contents

1	Simple transistor circuit	4
1.1	Transistor basic property	4
1.2	Find R_e	5
1.3	Find R_o	6
1.4	Limit current gain	8
1.5	Add voltage divider	9
2	Negative Feedback	10
2.1	Simple Negative Feedback system	10
2.2	Implement Using Op-amp	10
2.3	Find the function of Feedback	12
2.4	Implement Using transistor	12
3	Current Source	16
3.1	Single current source circuit	16
3.2	Use current source to replace output resistor	17
4	Output Stage	18
4.1	Class A Output Stage	18
4.2	Class AB Output Stage	19
5	Final design	21
5.1	Final schematic	21
5.1.1	Voltage amplifier	21
5.1.2	Class AB output stage	22
5.1.3	Current source	22
5.1.4	Negative feedback part	24
6	PCB design	25
6.1	Draw PCB board	25

List of Figures

1.1	Single transistor circuit	4
1.2	Single transistor circuit simulation data	4
1.3	V_{be} and I_c curve	5
1.4	Re model	6
1.5	DC sweep on V3 in Figure 1.1	7
1.6	Ro model	7
1.7	Basic transistor circuit with R_c and R_e	8
1.8	Output of the circuit in Figure 1.7	8
1.9	Add voltage divider and capacitors	9
2.1	simple negative feedback system	10
2.2	Implement negative feedback circuit with Op-amp	11
2.3	Op-amp feedback simulation result curve	11
2.4	Feedback initail circuit	12
2.5	Feedback initail circuit output	12
2.6	Feedback circuit adding pull-push part	13
2.7	Feedback circuit adding pull-push part output	13
2.8	Feedback circuit after moving feedback point	13
2.9	Feedback circuit after moving feedback point output	14
2.10	Implement negative feedback circuit with transistor	14
2.11	transistor feedback circuit simulation result	15
3.1	single current source circuit	16
3.2	single current source circuit simulation result	17
3.3	the circuit after adding current source	17
4.1	Class A output stage	18
4.2	Class A output stage simulation result	19
4.3	Class A DC operating current simulation data	19
4.4	Class AB output stage	20
4.5	Class AB output stage simulation result	20
4.6	Class AB output stage DC operating current	20

5.1	Schematic of final Design	21
5.2	voltage amplifier part	22
5.3	Class AB outout stage	23
5.4	Current source	23
5.5	Negative feedback part	24
6.1	Layout components	25
6.2	Finsh autorout	26
6.3	PCB 3D view	26

Chapter 1

Simple transistor circuit

1.1 Transistor basic property

Figure 1.1 shows the basic NPN bipolar junction transistor circuit.

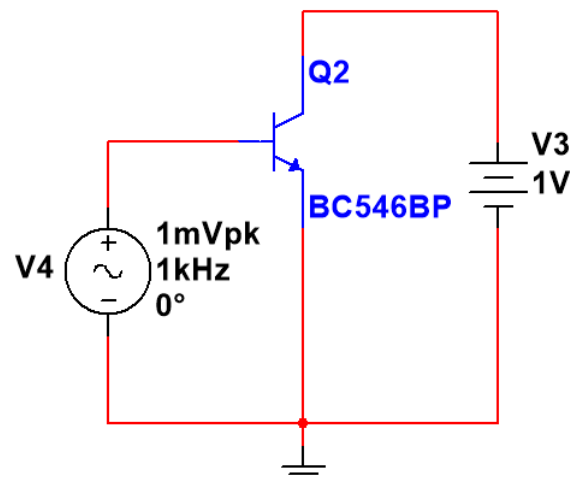


Figure 1.1: Single transistor circuit

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 β which is the most important parameter of transistor.

$$\beta = \frac{I_C}{I_B} \quad (1.1)$$

1.2 Find R_e

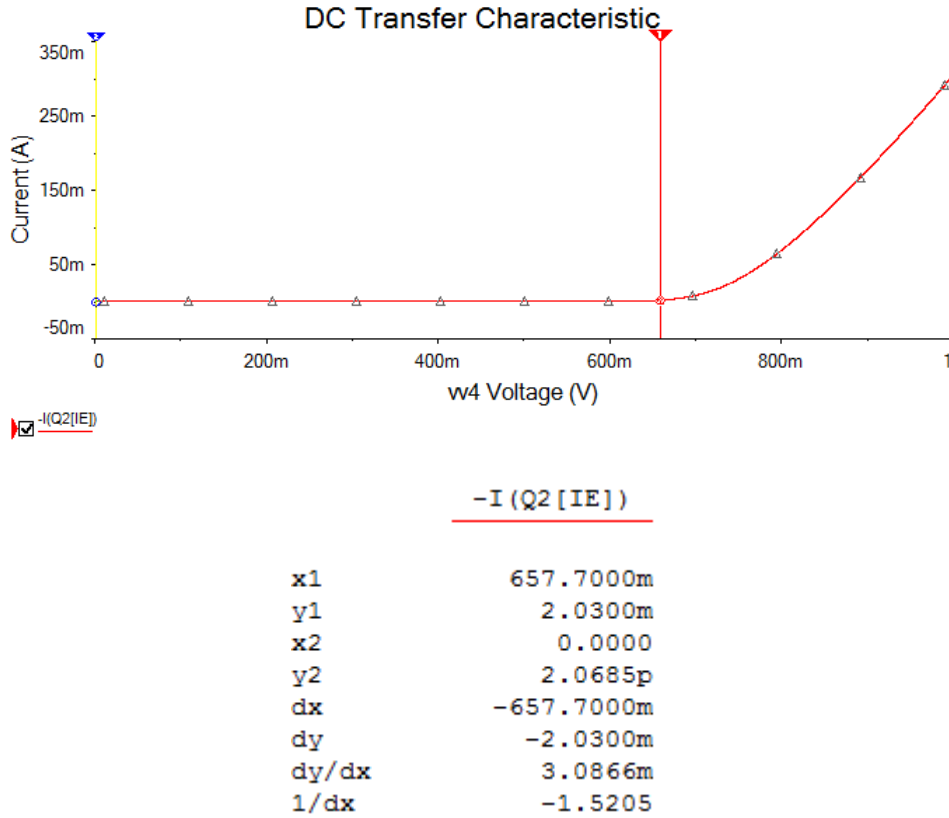


Figure 1.3: V_{be} and I_e curve

After running DC sweep command on V_4 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 $I_e = 2mA$,

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

Thermal voltage is

$$V_T = 2mA \times 13.459 \approx 26mV$$

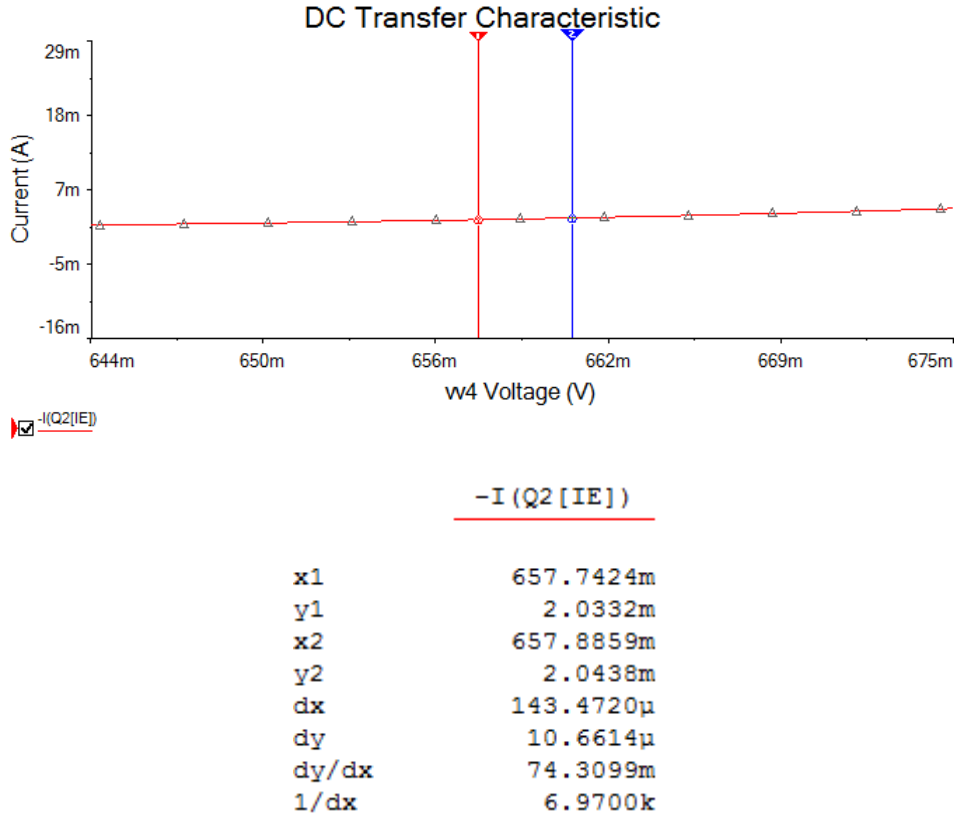


Figure 1.4: Re model

Therefore, we can calculate R_e with I_e in future using

$$R_e = \frac{26mV}{I_e} \quad (1.2)$$

1.3 Find R_o

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

In Figure 1.6, we can see the curve is almost linear when V3 is greater than 100mV. It means that there is an equivalent resistor cross between collector and emitter terminal ie. R_o .

$$R_o = \frac{\Delta V}{\Delta I} = \frac{697.8297m}{18.9471\mu} \approx 36.83 \times 10^3 \Omega$$

Because $I_e = 2mA$, Early voltage is

$$V_A = 2mA \times 36.83 \times 10^3 \Omega = 73.66 \approx 75$$

Therefore, We can calculate R_o using

$$R_o = \frac{75}{I_e} \quad (1.3)$$

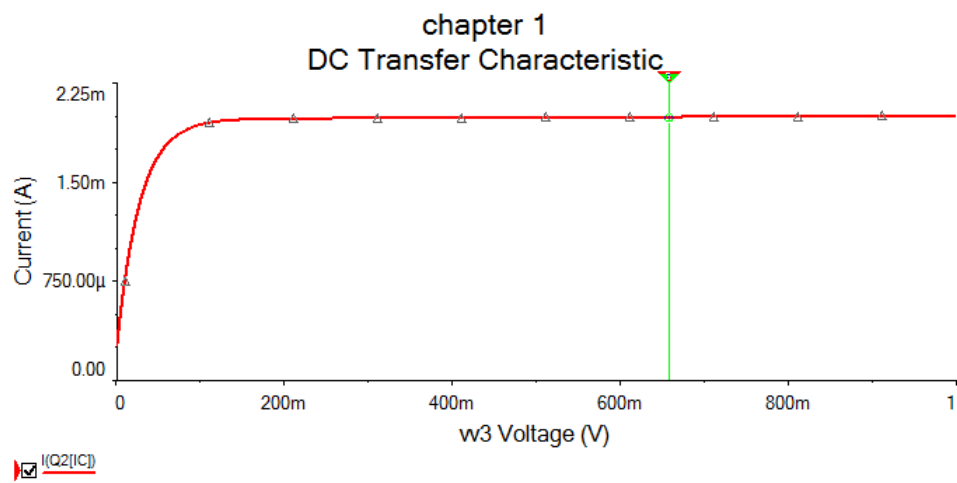
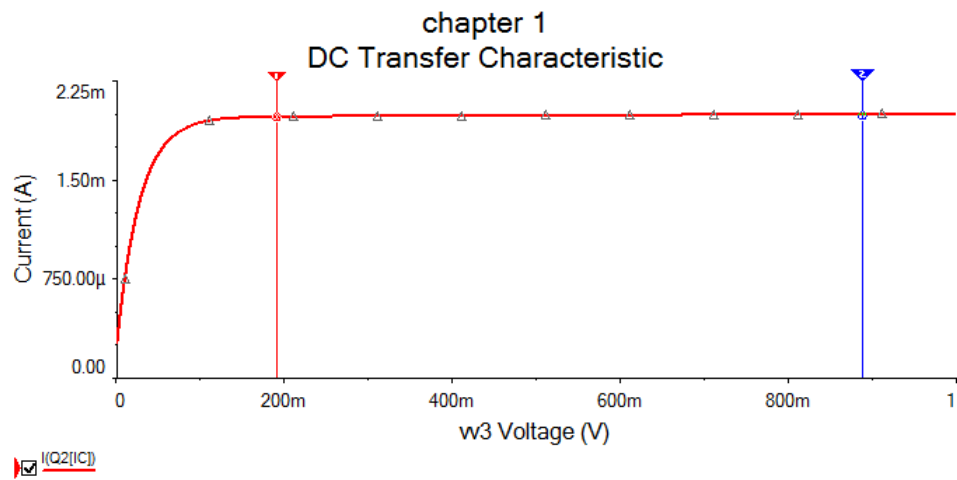


Figure 1.5: DC sweep on V3 in Figure 1.1



<u>I (Q2 [IC])</u>	
x1	190.3172m
y1	1.9761m
x2	888.1469m
y2	1.9951m
dx	697.8297m
dy	18.9471μ
dy/dx	27.1515μ
1/dx	1.4330

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 .

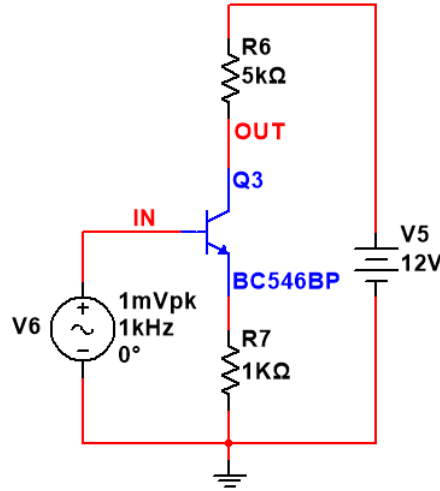


Figure 1.7: Basic transistor circuit with R_c and R_e

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

$$A_V \triangleq \frac{V_{out}}{V_{in}} \approx -\frac{R_C}{R_E} \quad (1.4)$$

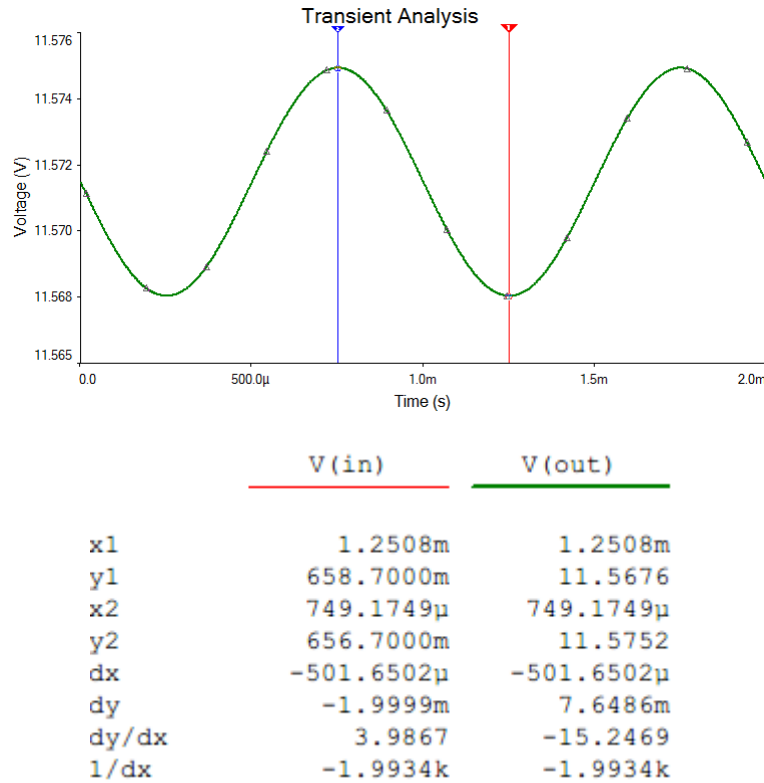


Figure 1.8: Output of the circuit in Figure 1.7

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.

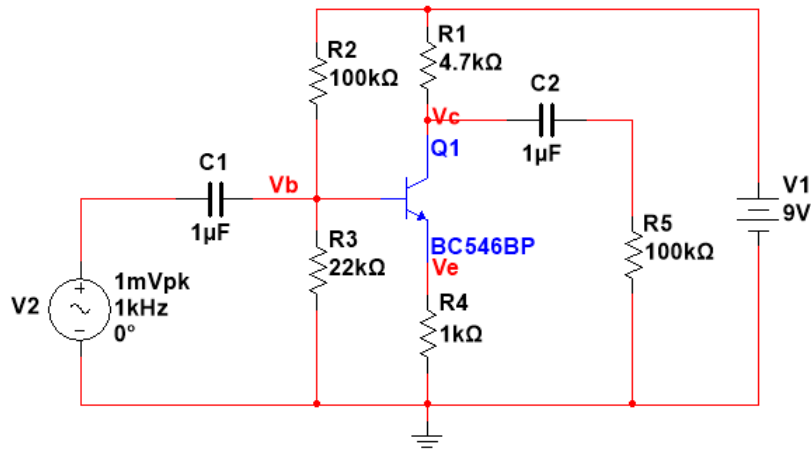


Figure 1.9: Add voltage divider and capacitors

Chapter 2

Negative Feedback

2.1 Simple Negative Feedback system

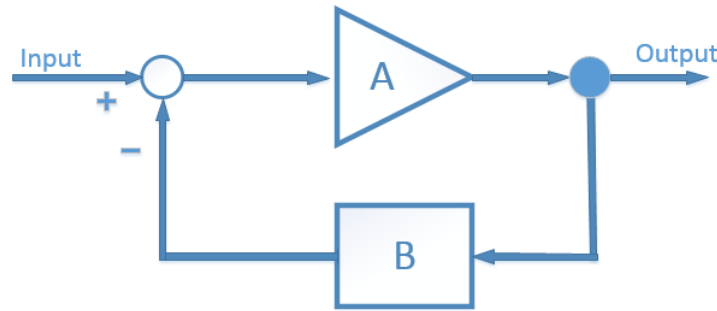


Figure 2.1: simple negative feedback system

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.

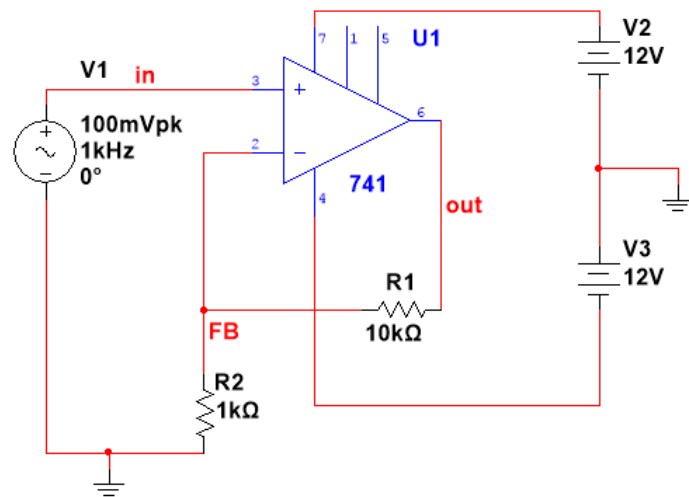
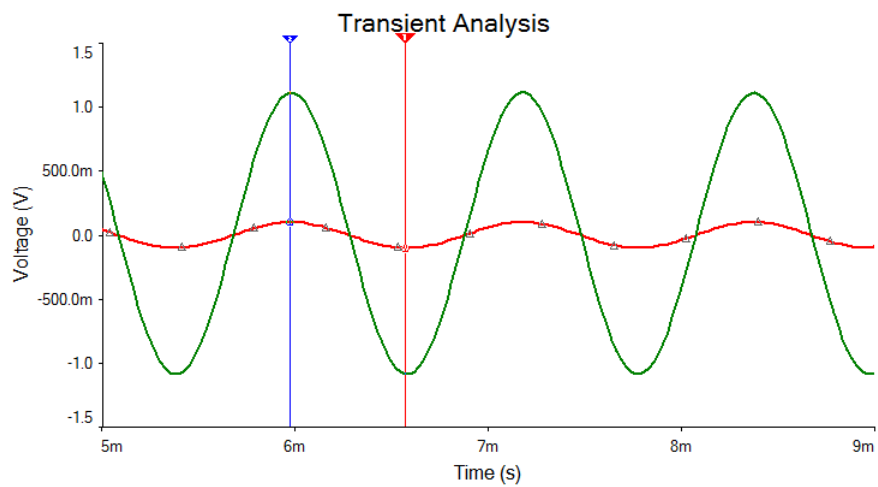


Figure 2.2: Implement negative feedback circuit with Op-amp



	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 Find the function of Feedback

At the beginning, our circuit in Figure 2.4 used is same as the circuit in Figure 2.2, the output signal is a smooth Sin wave shown as Figure 2.5.

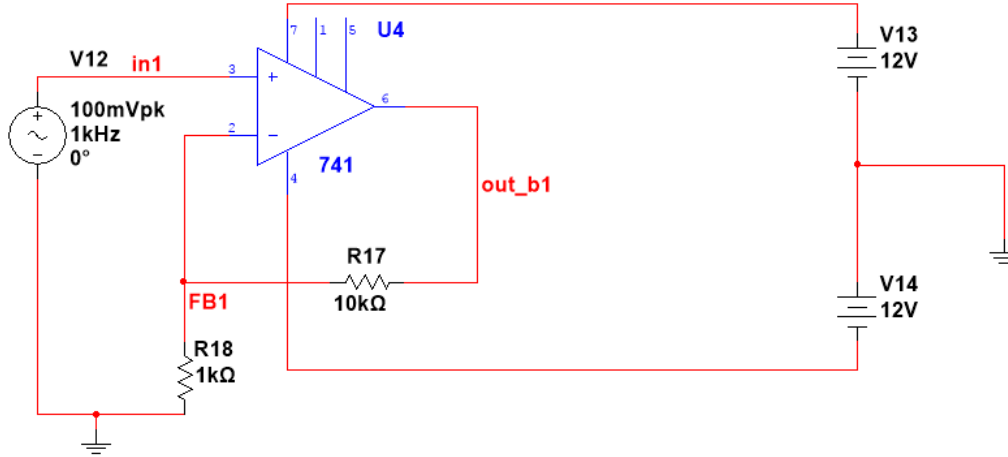


Figure 2.4: Feedback inital circuit

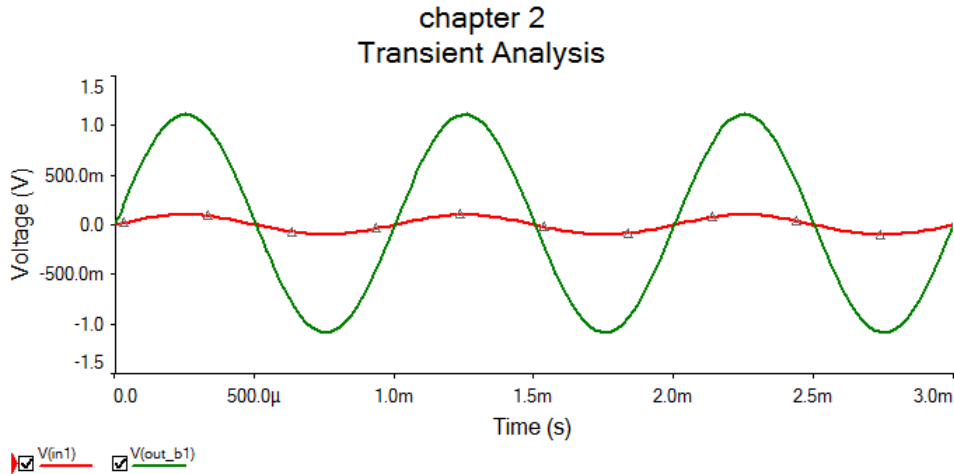


Figure 2.5: Feedback inital circuit output

Next we introduce some distortion to the output signal using pull-push output part. As expect, we could obviously observe crossover distortion for output wave shown in Figure 2.7.

Next step, we move feedback point from Pin 5 of Op-Amp U6 to the emitter terminal of transistor Q11 as show in Figure 2.8. From Figure 2.9, there's great improvement and we can hardly see any distortion of output signal. It proved that feedback is very useful in aspect of eliminating output distortion.

2.4 Implement Using transistor

In Figure 2.10 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

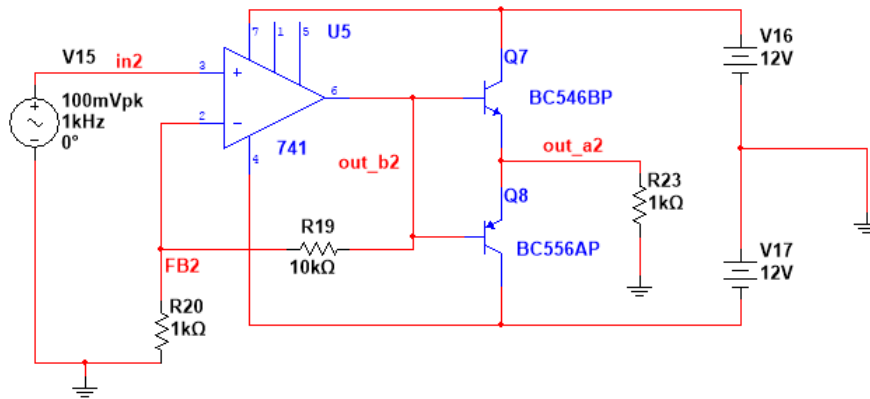


Figure 2.6: Feedback circuit adding pull-push part

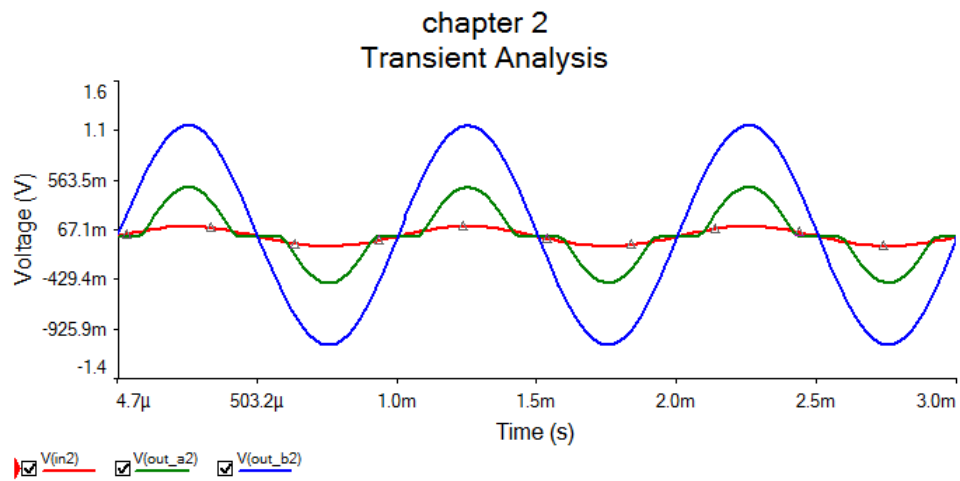


Figure 2.7: Feedback circuit adding pull-push part output

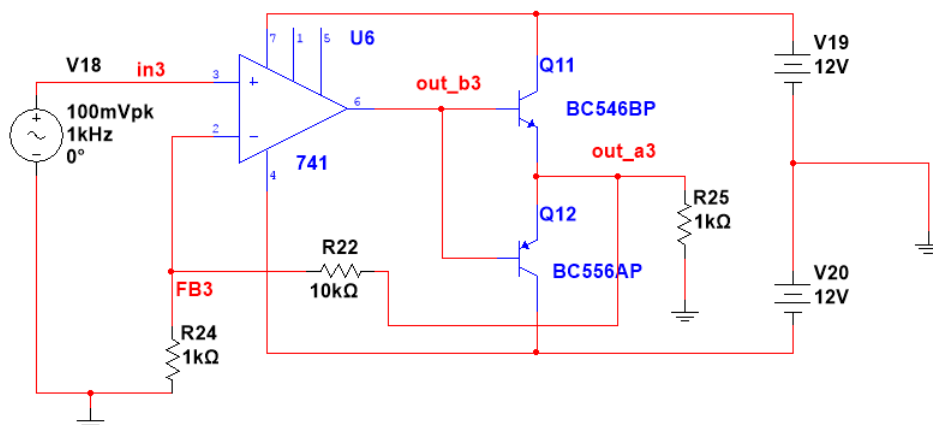


Figure 2.8: Feedback circuit after moving feedback point

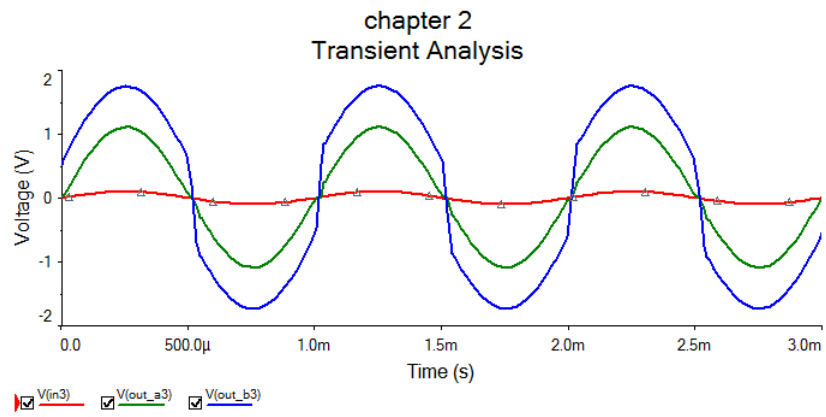


Figure 2.9: Feedback circuit after moving feedback point output

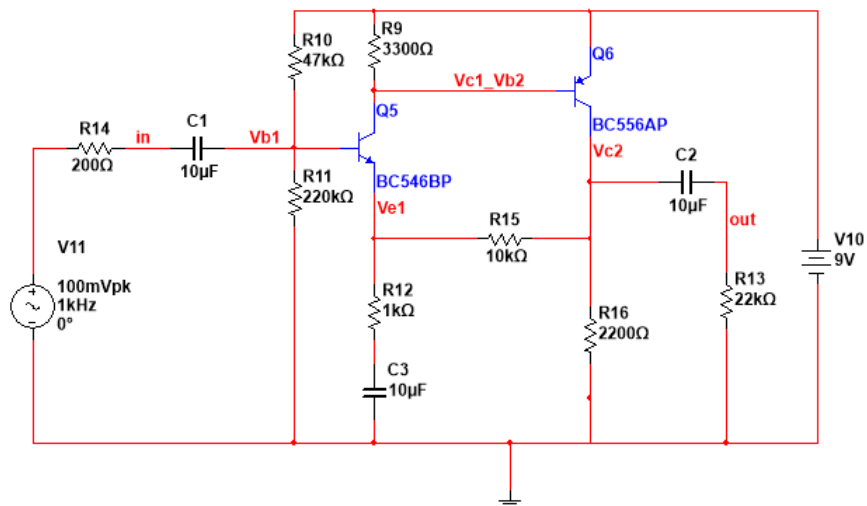


Figure 2.10: Implement negative feedback circuit with transistor

input. Therefore, we add another transistor Q6 to eliminate the phase difference of signal.

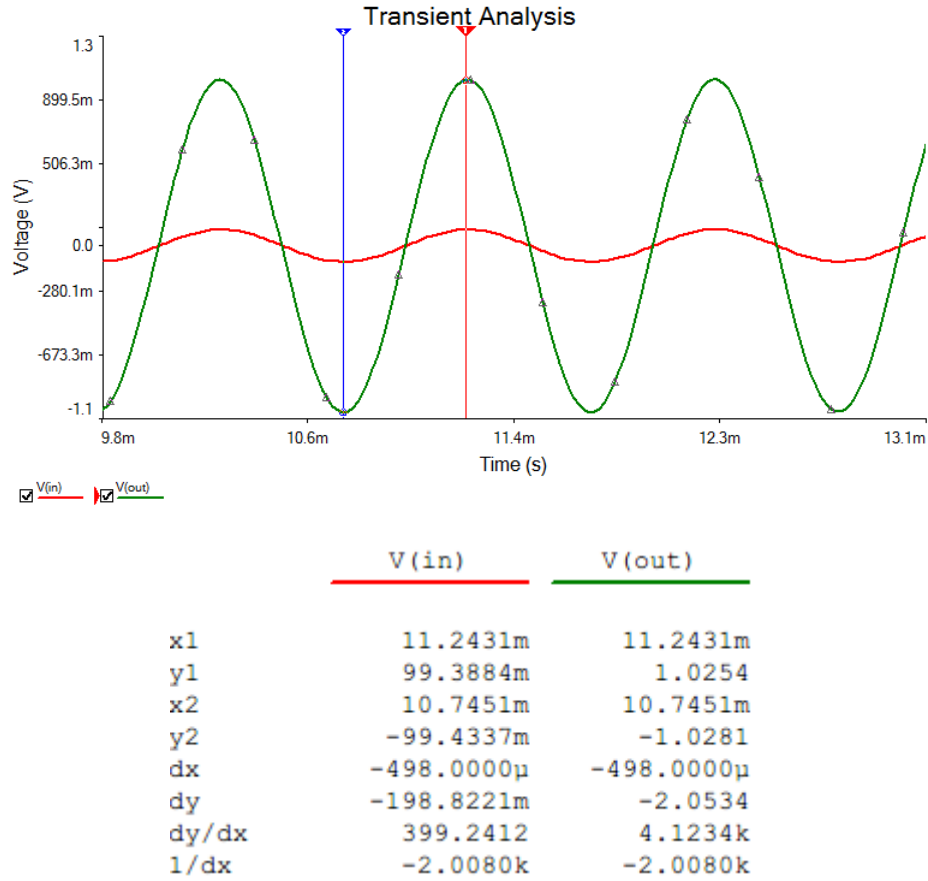


Figure 2.11: transistor feedback circuit simulation result

Apparently, there's no phase difference between input and output signal. The voltage gain of circuit in Figure 2.10 is $Gain = \frac{\Delta V_{out}}{\Delta V_{in}} = \frac{2.0534}{198.8221m} = 10.3707$. It's also very close to theory result.

Chapter 3

Current Source

3.1 Single current source circuit

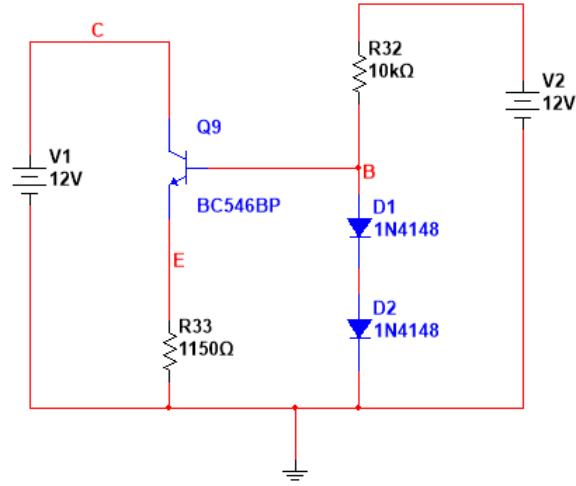


Figure 3.1: single current source circuit

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 2.10. 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.

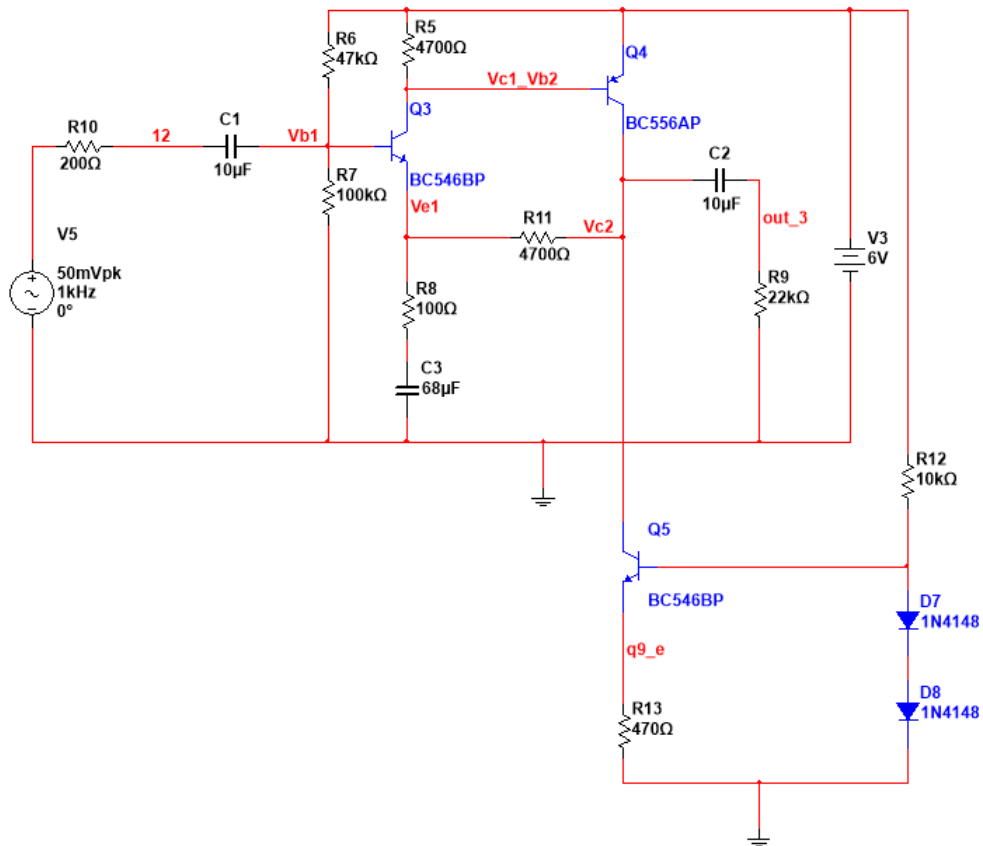


Figure 3.3: the circuit after adding current source

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.

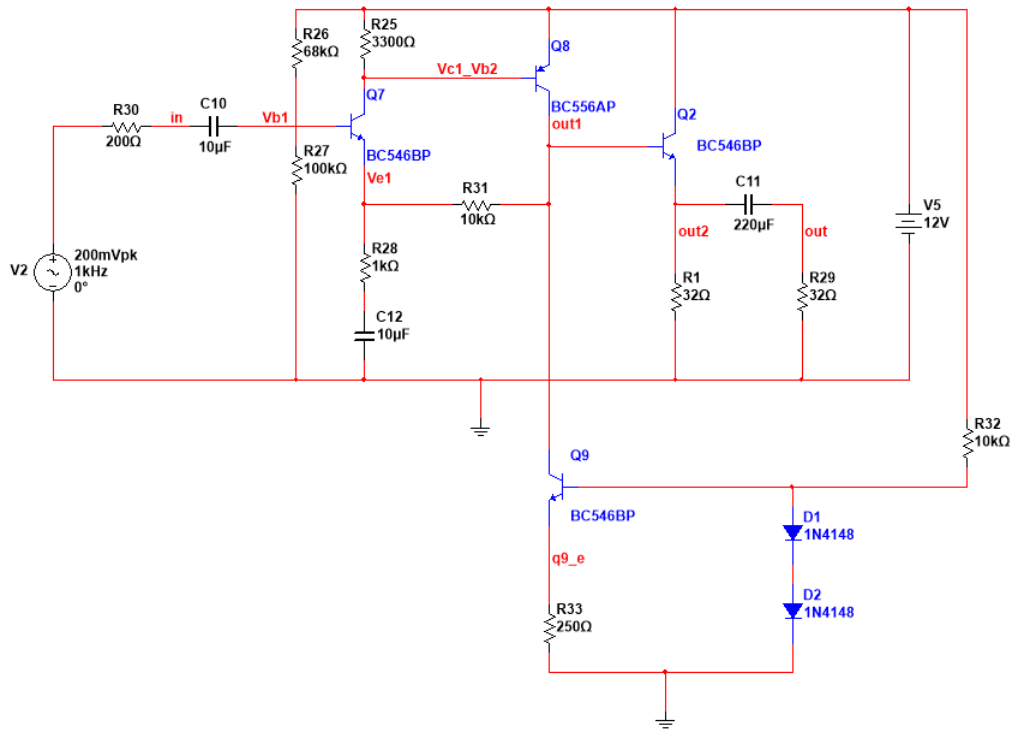


Figure 4.1: Class A output stage

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.

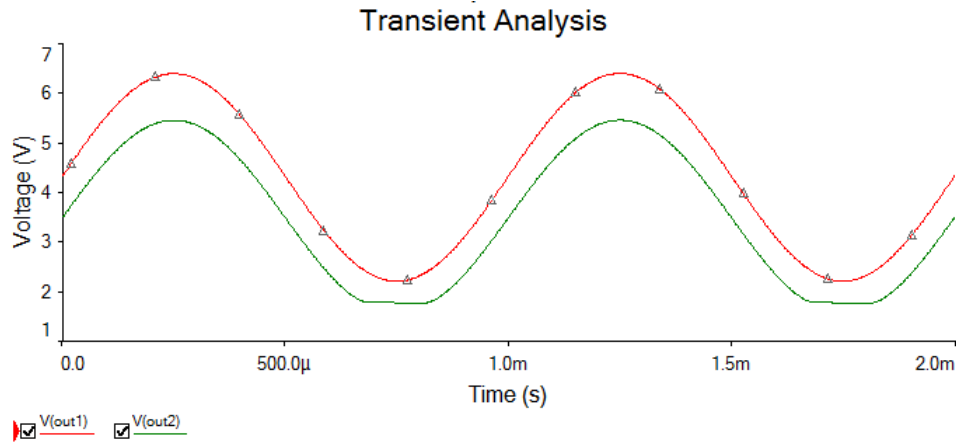


Figure 4.2: Class A output stage simulation result

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.

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

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.

Chapter 5

Final design

5.1 Final schematic

My final circuit is shown in Figure 5.1 which contains four parts. They are voltage amplifier, Class AB output stage, current source and negative feedback part.

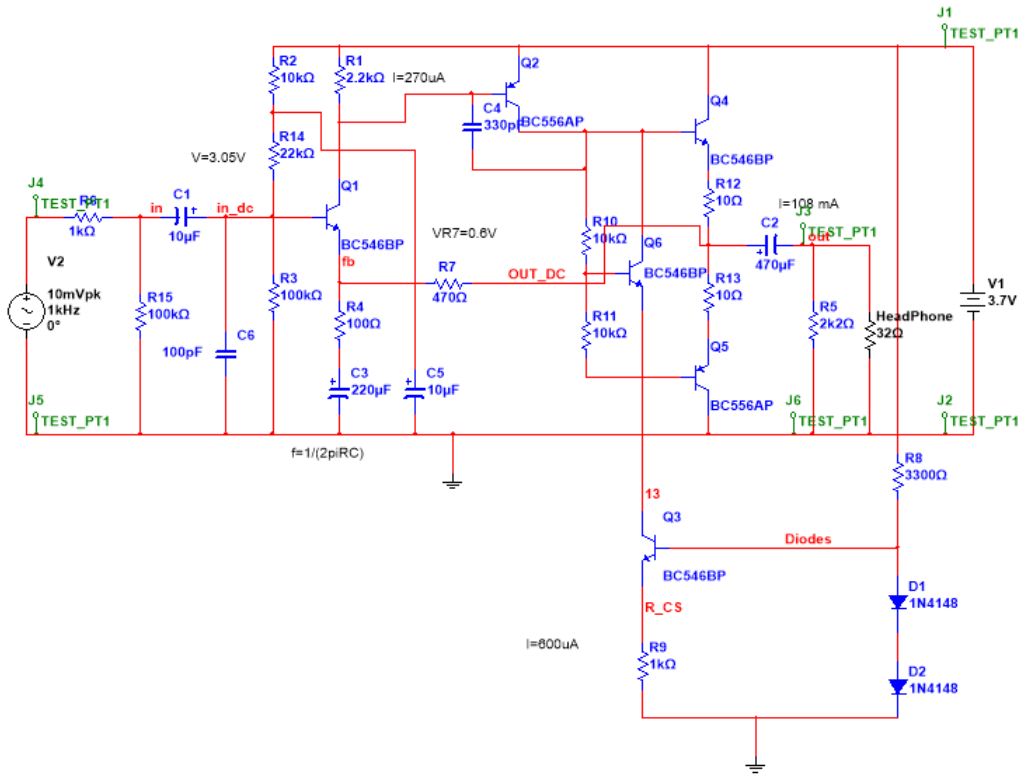


Figure 5.1: Schematic of final Design

5.1.1 Voltage amplifier

This part used to amplify input signal voltage, this means the output voltage of this part is hundreds times of input signal.

In this part shown in Figure 5.2, NPN transistor Q1 and PNP transistor Q2 are key component which provide the capability of amplifying signal voltage. Resistor R14 and R3 consist of voltage divider which set the DC operating point. Resistor R2 and capacitor C5 consist of a low pass filter which eliminate noise in DC power.

Capacitor C3 used to make sure amplifier DC voltage gain is 1 which means circuit only amplify signal AC part.

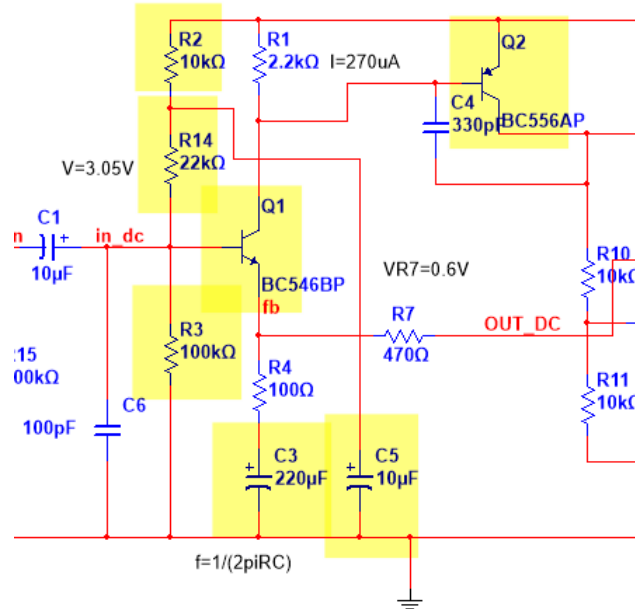


Figure 5.2: voltage amplifier part

5.1.2 Class AB output stage

In this part shown in Figure 5.3, Transistor Q4 and Q5 form a pull-push output stage which provide current gain and increase drive capability.

Resistor R10, R11 and NPN transistor Q6 form a V_{be} multiplier which use to eliminate the crossover distortion.

Resistor R12 and R13 is used to limit current which flow through transistors. Because too much current flow could burn the transistors.

5.1.3 Current source

In this part shown in Figure 5.4, Current source consist of NPN transistor Q3, resistor R9, R8 and two diodes D1, D2. Resistor R8 used to set base current of transistor Q3. Resistor R6 determine the constant current of this current source.

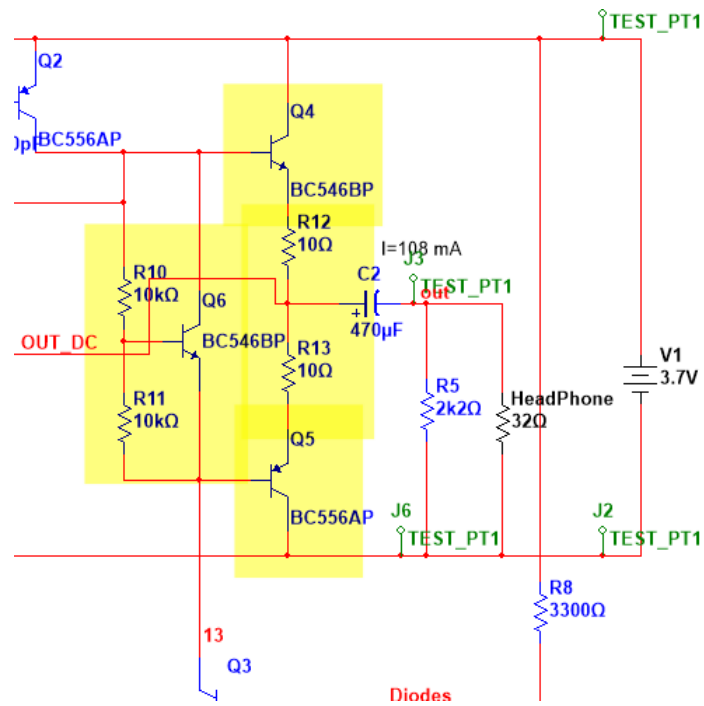


Figure 5.3: Class AB outout stage

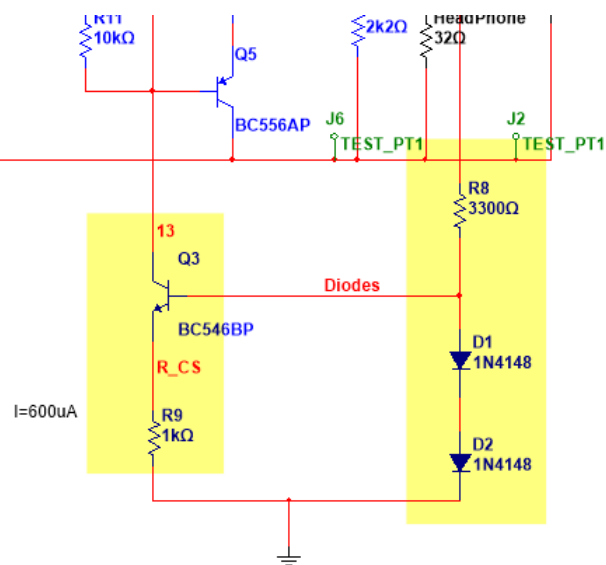


Figure 5.4: Current source

5.1.4 Negative feedback part

In this part shown in Figure 5.5, Resistor R4 and R7 make up negative feedback part. They control this headphone amplifier voltage gain and keep output signal follows the input signal.

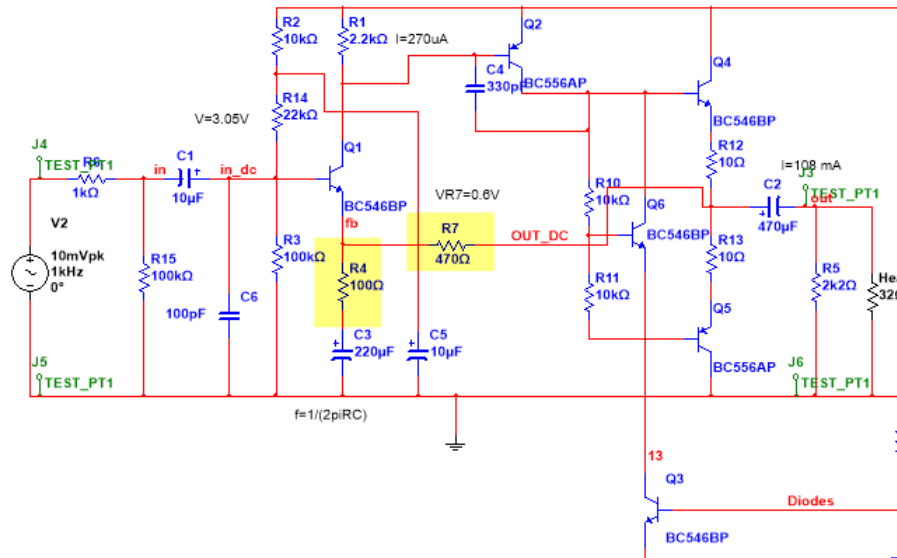


Figure 5.5: Negative feedback part

Chapter 6

PCB design

6.1 Draw PCB board

First of all, we layout all components and try arrange their position similar to where in schematic and we get result like Figure 6.1.

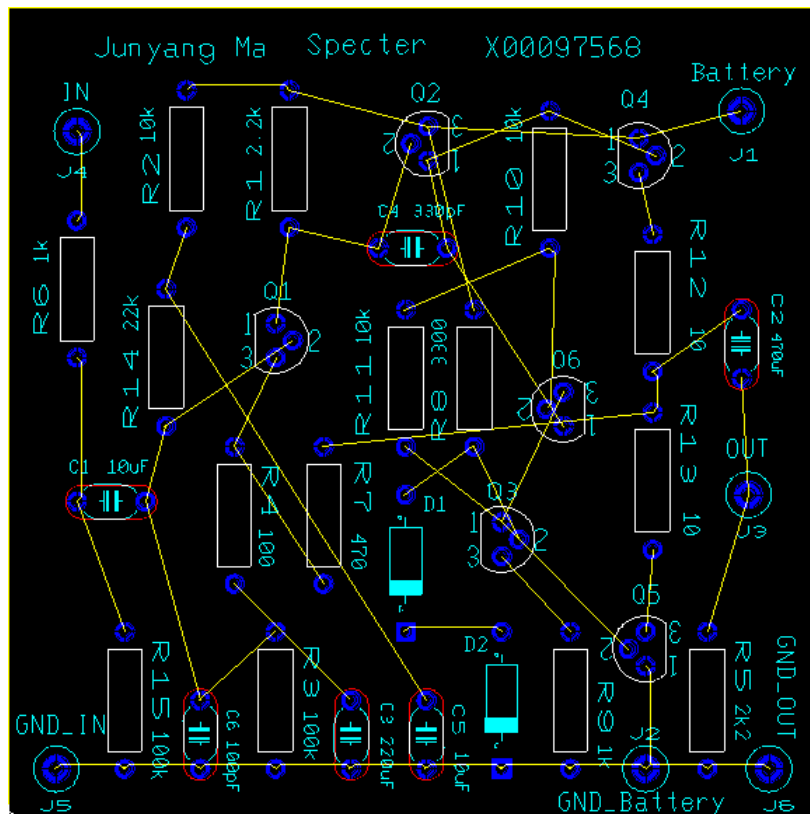


Figure 6.1: Layout components

Next step, we connect all pads using autorout tool and do some modification, we can get result like Figure 6.2.

Finally, I finish my PCB board design and 3D view shown in Figure 6.3.

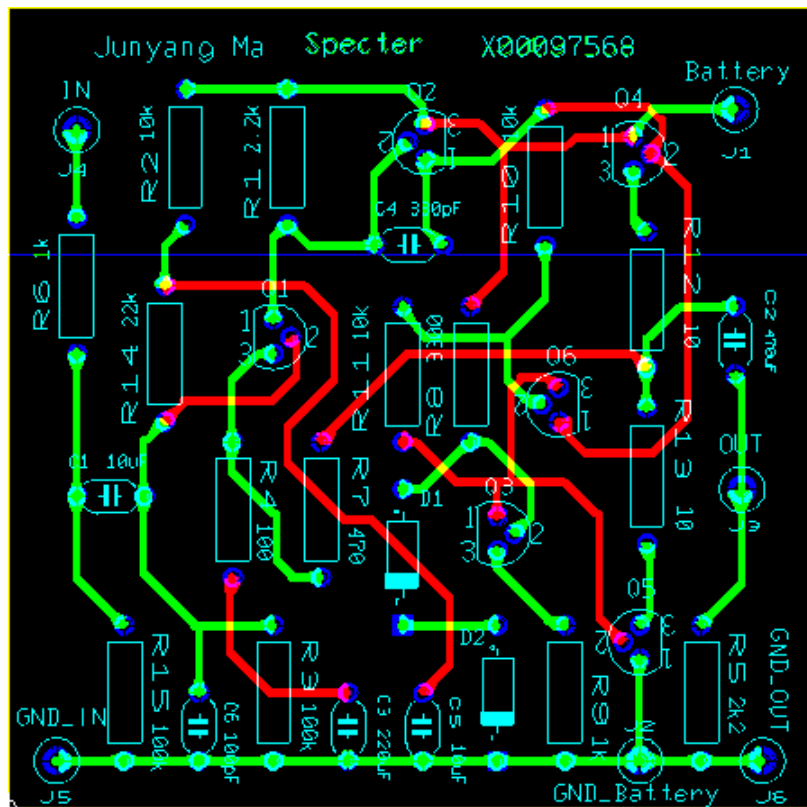


Figure 6.2: Finish autorout

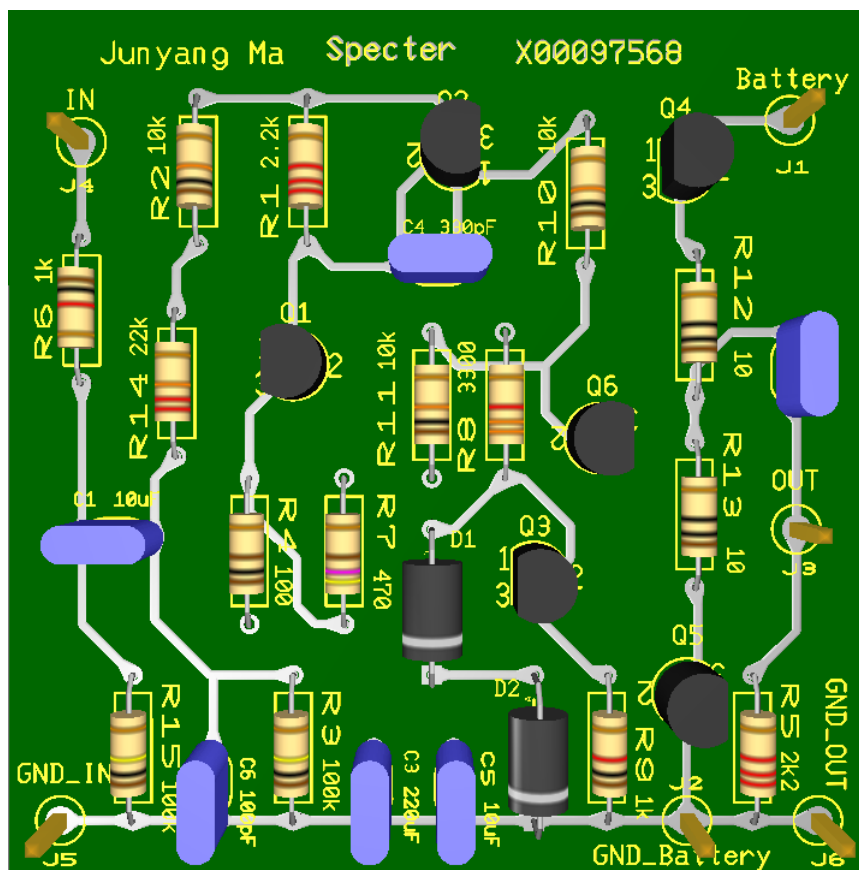


Figure 6.3: PCB 3D view