Bachelor of Engineering Electronic Engineering (HONS)

Headphone Amplifier Design

By

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Abstract

The purpose of this project is designing a hign performance headphone amplifier.My headfore amplifier is designed for mobile phones or mobile players.These devices are powered by lithium-ion battery which cause they don't have enough ability to drive high impedence headphone.Therefore, the aim for my design to imporve headphone performance which used with mobile devices.

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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.

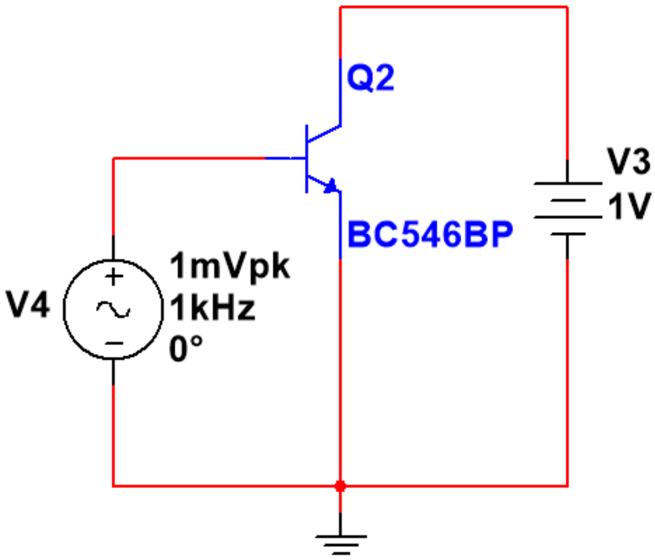


Figure 1.1: Single transistor circuit

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.

Equation 1.1 defines β which is the most important parameter of transistor.

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

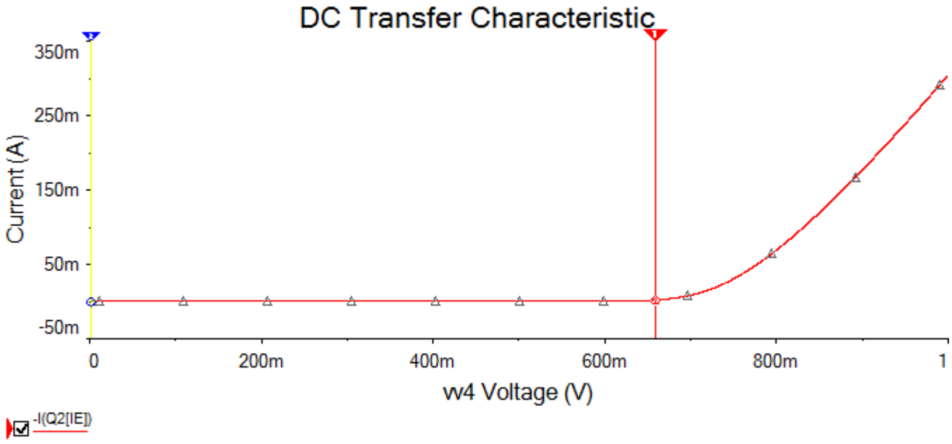
chapter 1

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

1.2 Find R_e



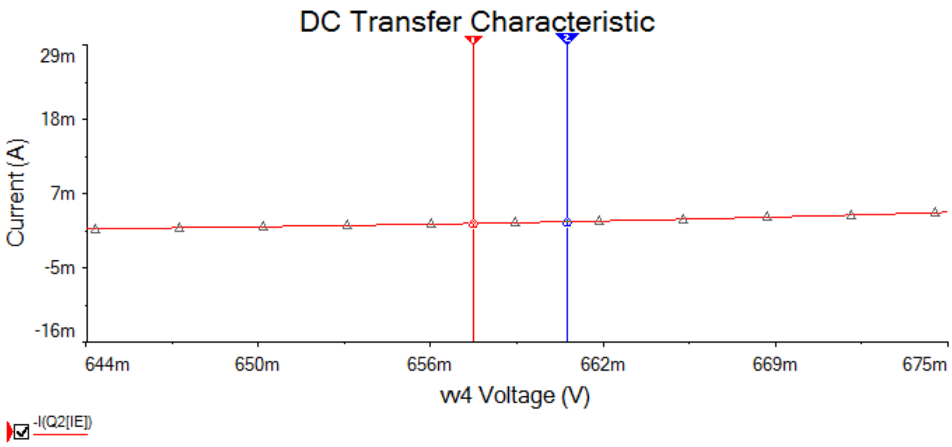
	-I(Q2[IE])
x1	657.7000m
y1	2.0300m
x2	0.0000
y2	2.0685p
dx	-657.7000m
dy	-2.0300m
dy/dx	3.0866m
1/dx	-1.5205

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

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



	-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

Because we know $I_e = 2mA$,

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

Thermal voltage is

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

Therefore,we can calculate R_e with I_e in future using

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

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 emiter terminal ie.R_o.

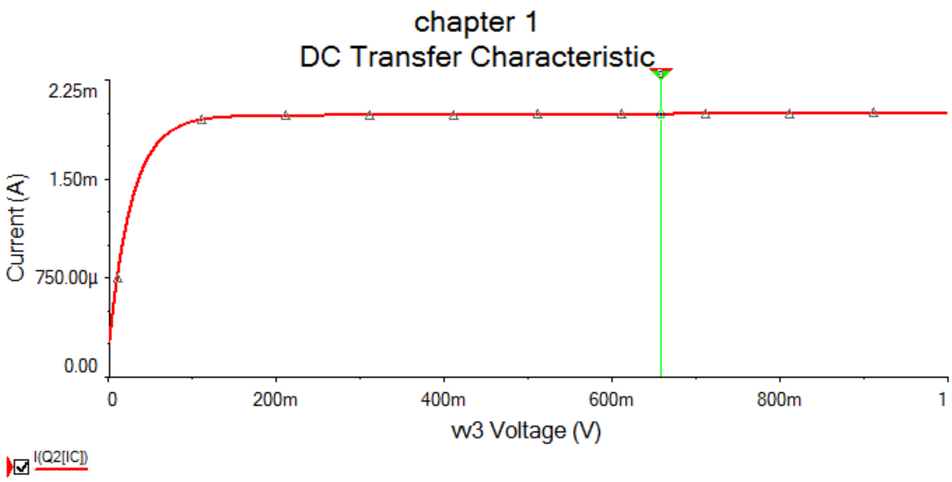


Figure 1.5: DC sweep on V3 in Figure 1.1

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

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

$$R_o = \frac{75}{I_e} \tag{1.3}$$

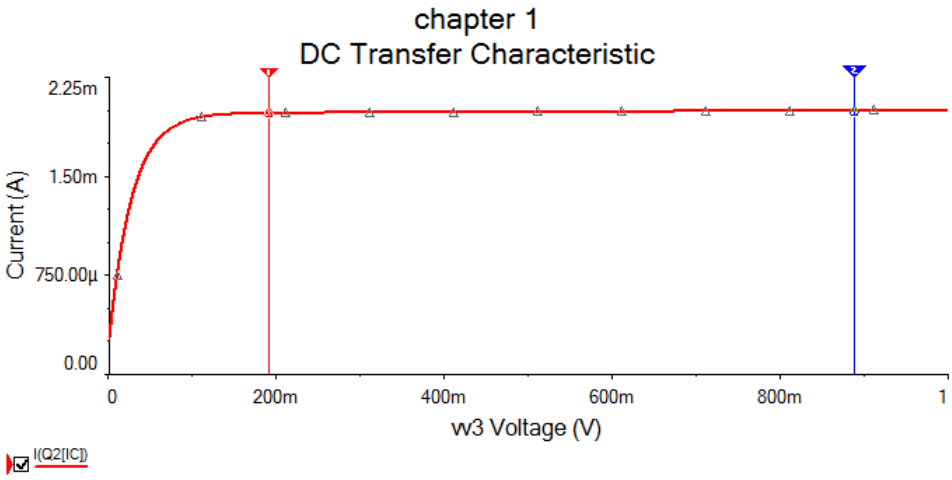
1.4 Limit current gain

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.

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

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

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



	I(Q2[IC])
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

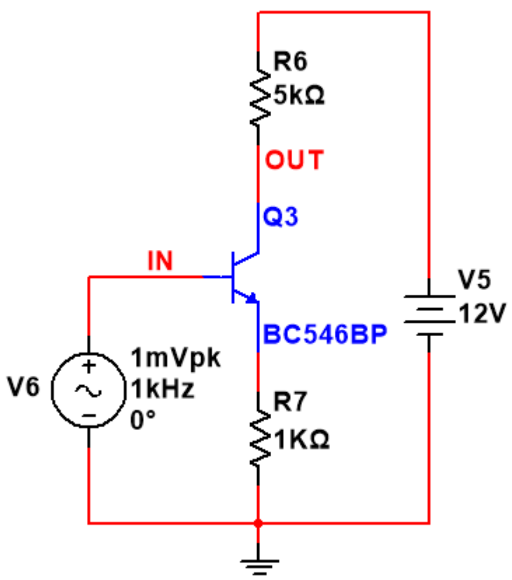
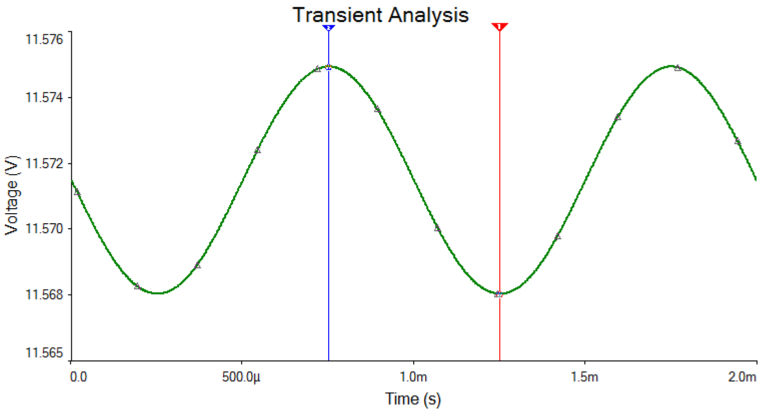


Figure 1.7: Basic transistor circuit with R_c and R_e



	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

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.

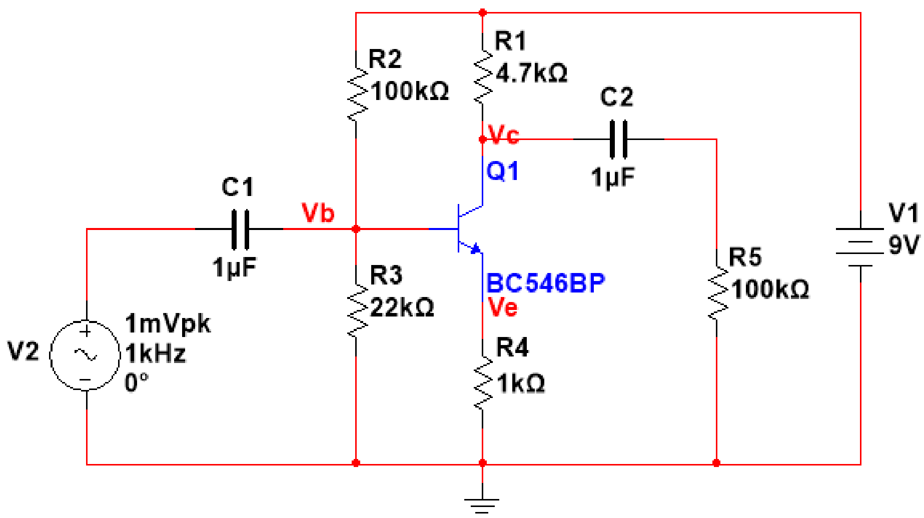


Figure 1.9: Add voltage divider and capacitors

Chapter 2

Negative Feedback

2.1 Simple Negative Feedback system

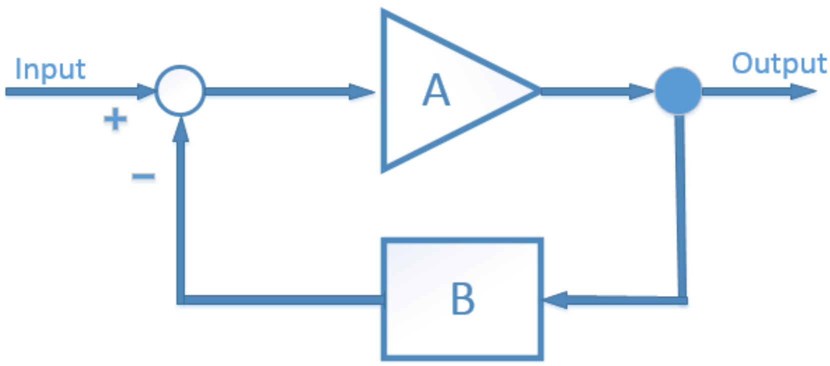


Figure 2.1: simple negative feedback system

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.

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

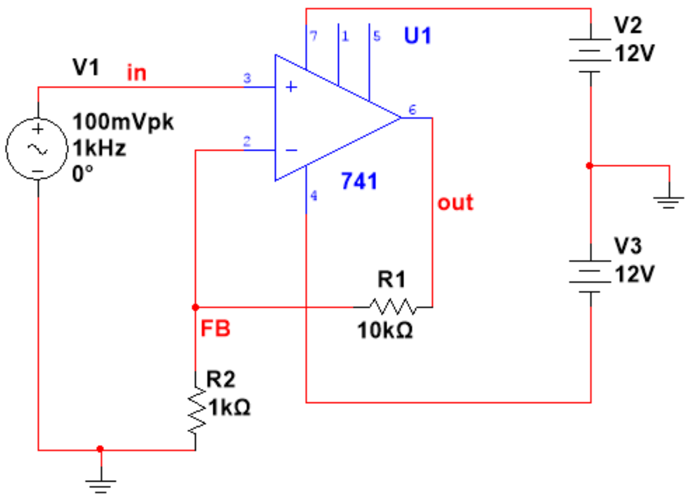
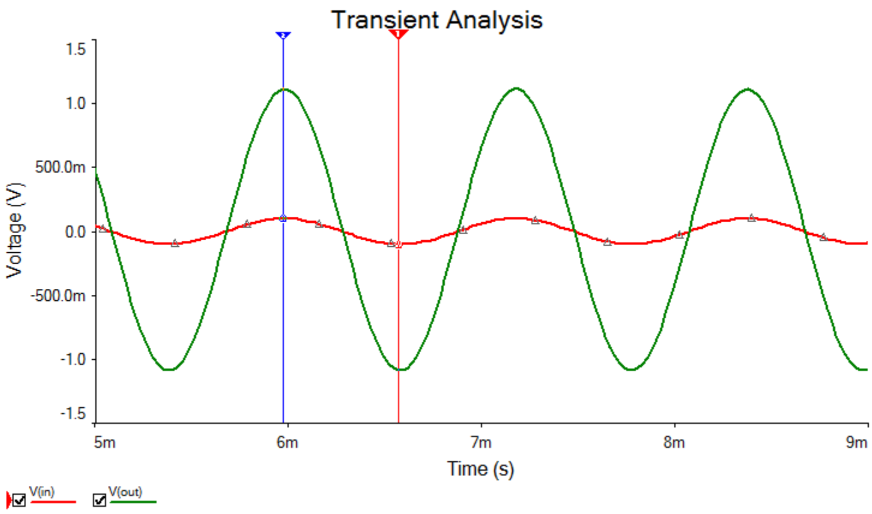


Figure 2.2: Implement negative feedback circuit with Op-amp



	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

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.

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 out put signal is a smooth Sin wave shown as Figure 2.5.

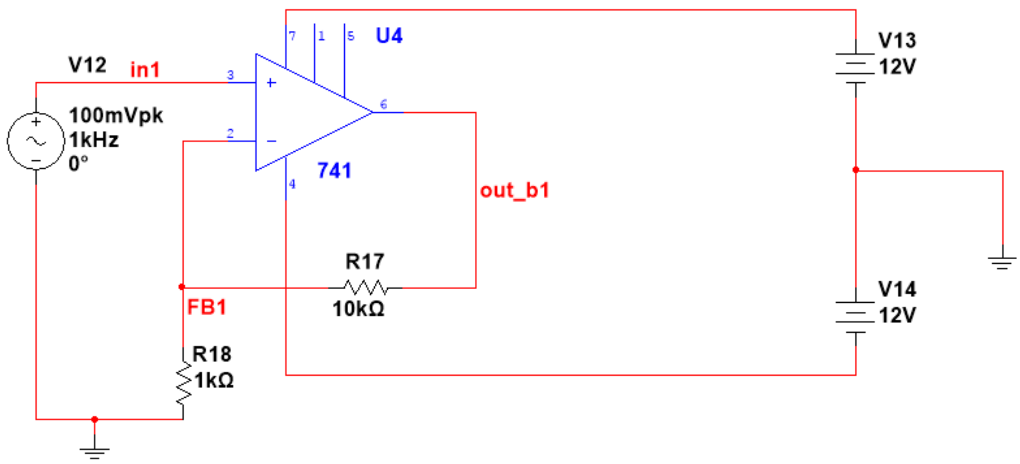


Figure 2.4: Feedback initail circuit

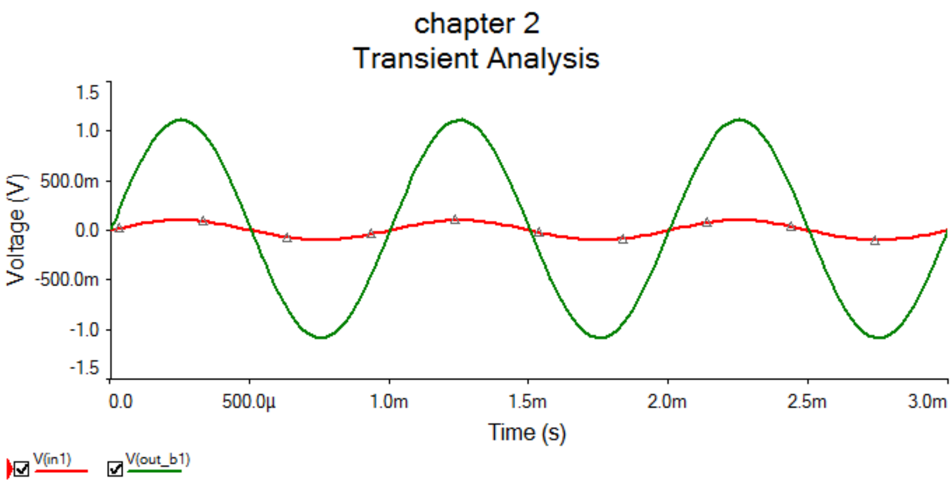


Figure 2.5: Feedback initail circuit output

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.

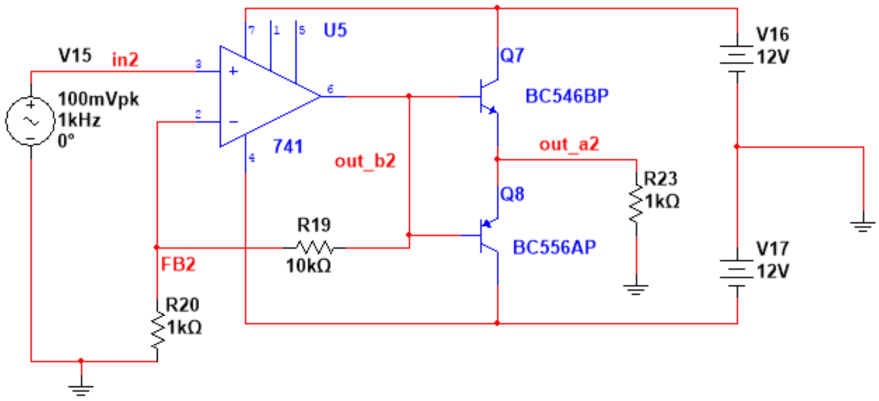


Figure 2.6: Feedback circuit adding pull-push part

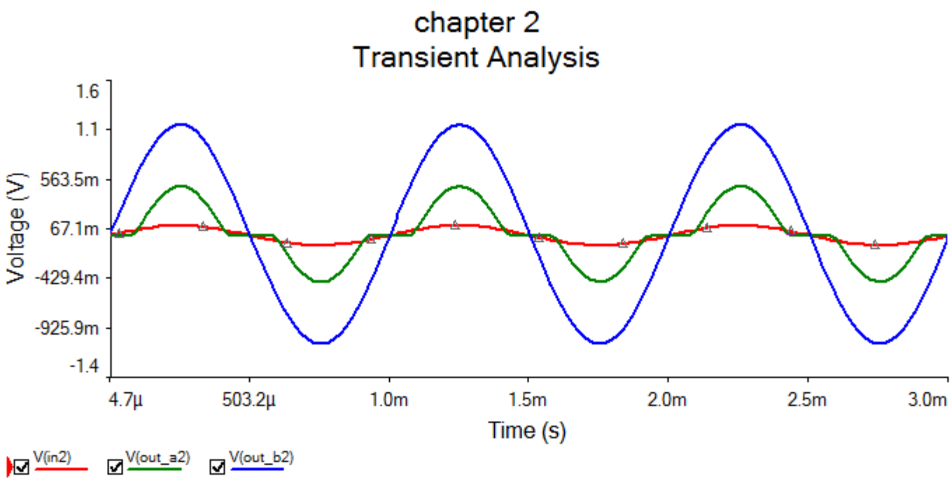


Figure 2.7: Feedback circuit adding pull-push part output

Next step, we move feedback point from Pin 5 of Op-Amp U6 to the emiter teminal of transister 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.

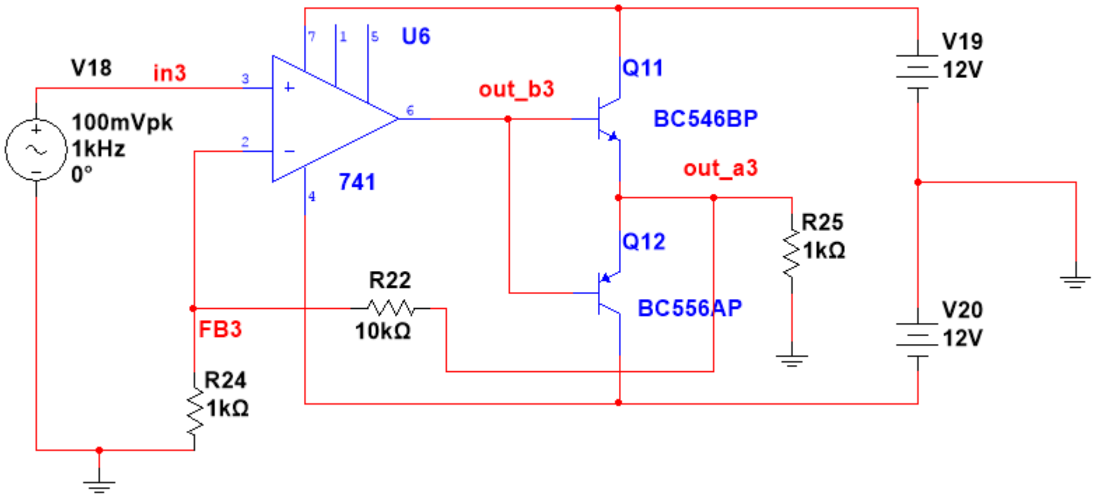


Figure 2.8: Feedback circuit after moving feedback point

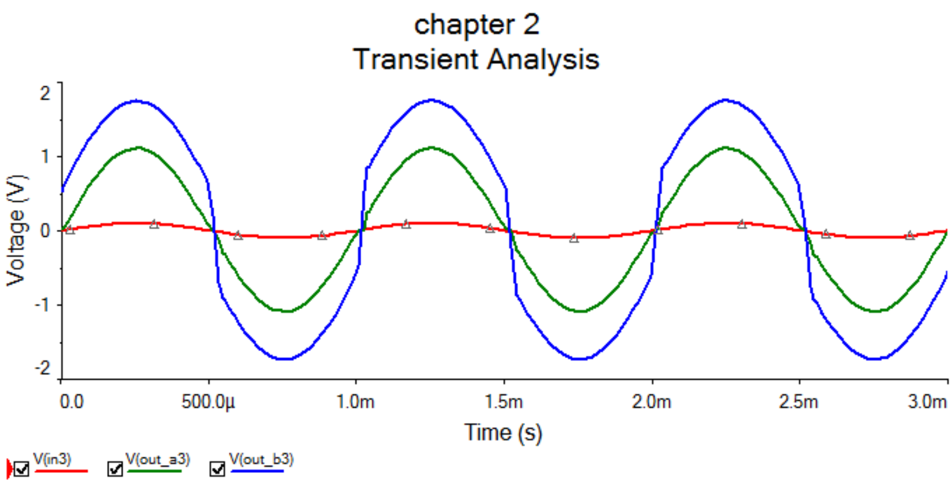


Figure 2.9: Feedback circuit after moving feedback point output

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

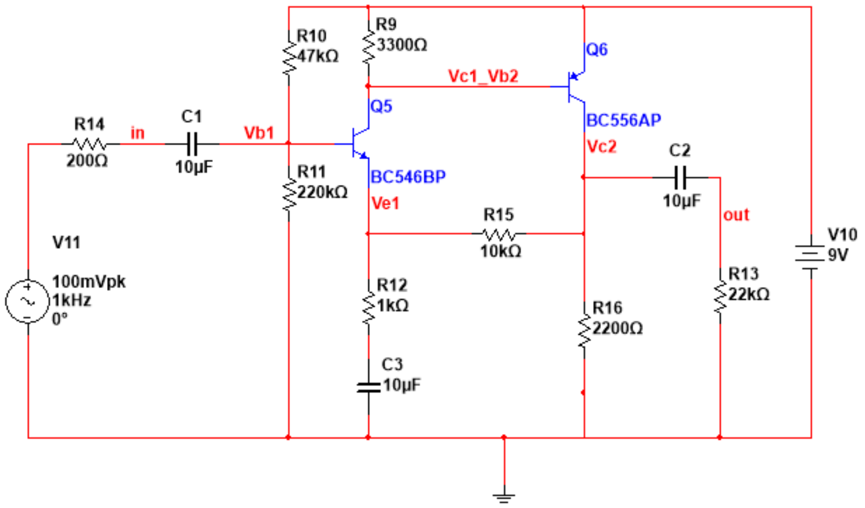
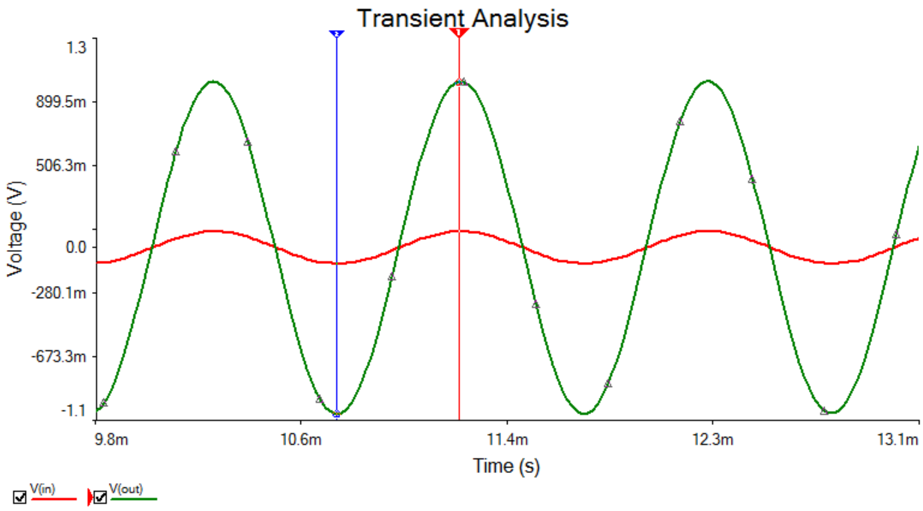


Figure 2.10: Implement negative feedback circuit with transistor



	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 2.11: 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

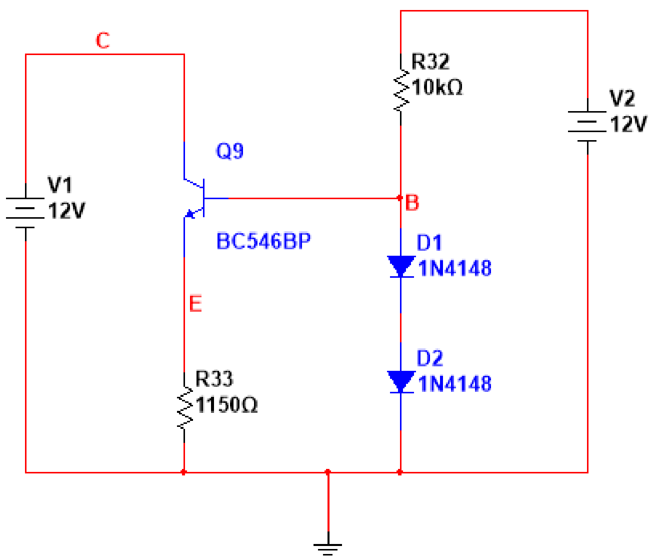


Figure 3.1: single current source circuit

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 $V_{be}oftransistor$.

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

Therefore:

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

$$I_e = \frac{V_{R33}}{R_{33}} = \frac{0.65V}{1150\Omega} = 565.217\mu A$$

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

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.

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.

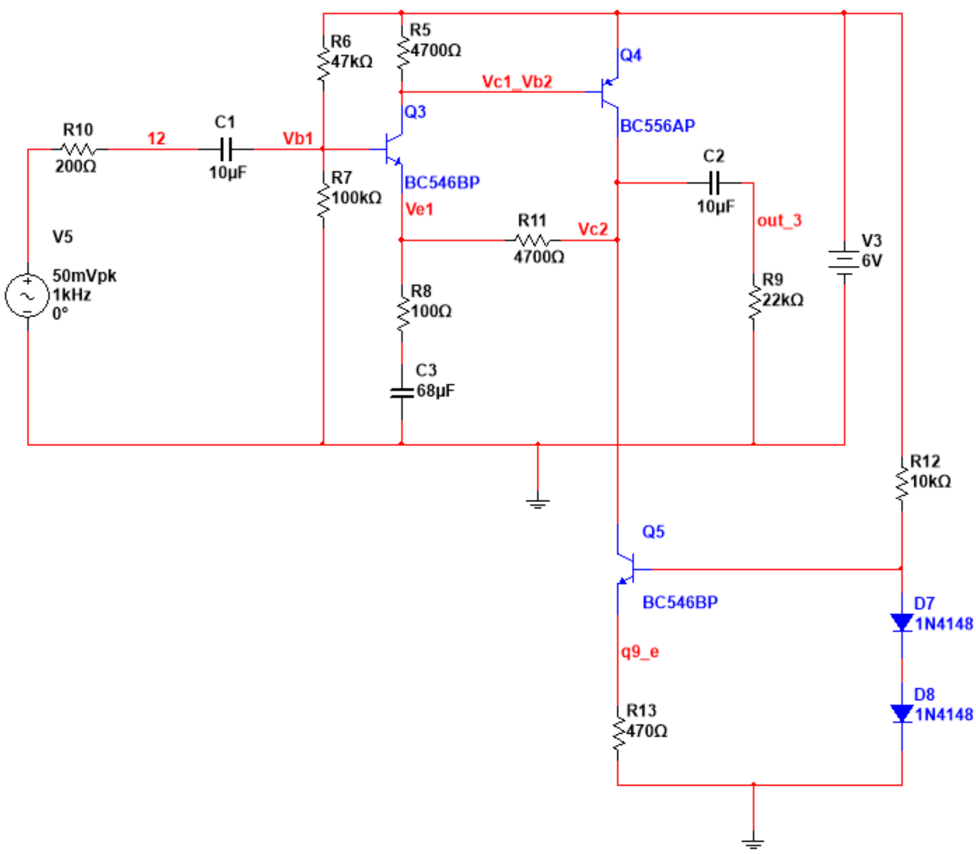


Figure 3.3: the circuit after adding current source

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.

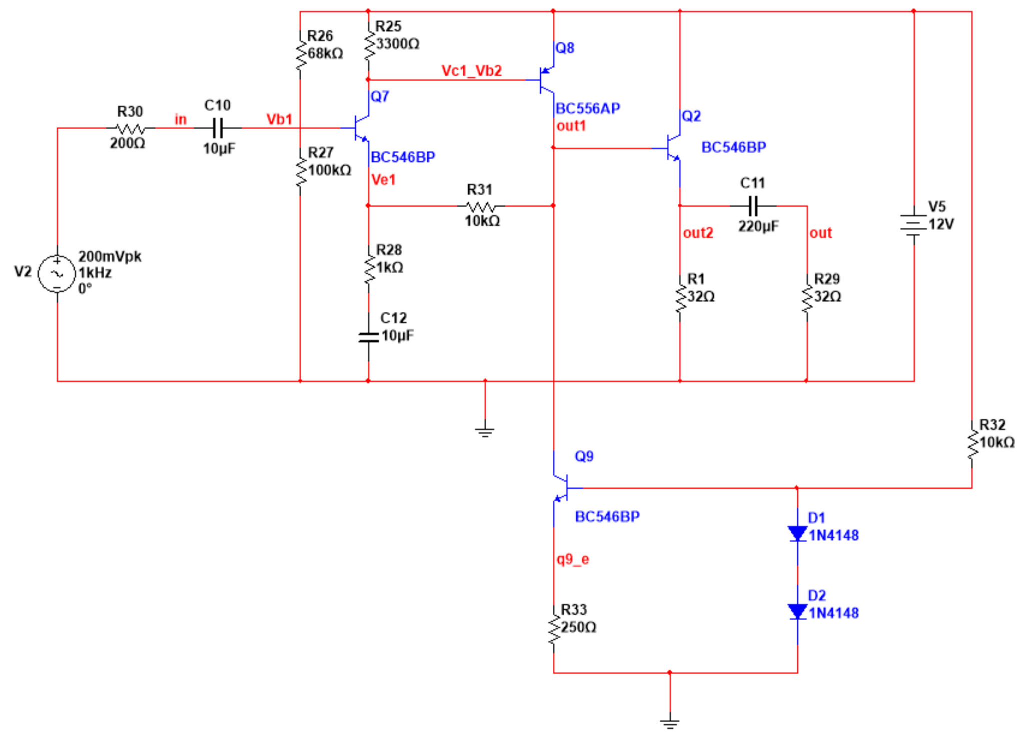


Figure 4.1: Class A output stage

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.

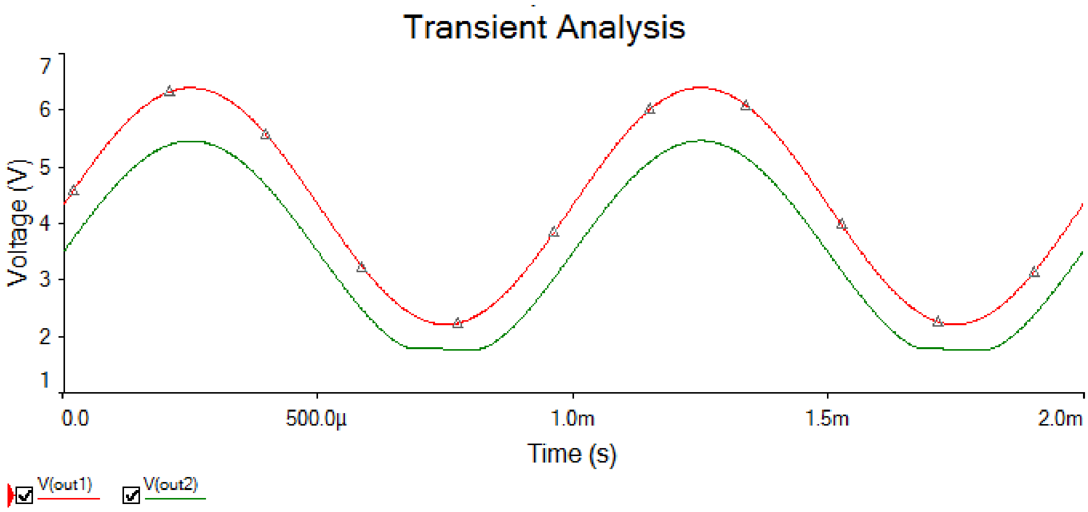


Figure 4.2: Class A output stage simulation result

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.

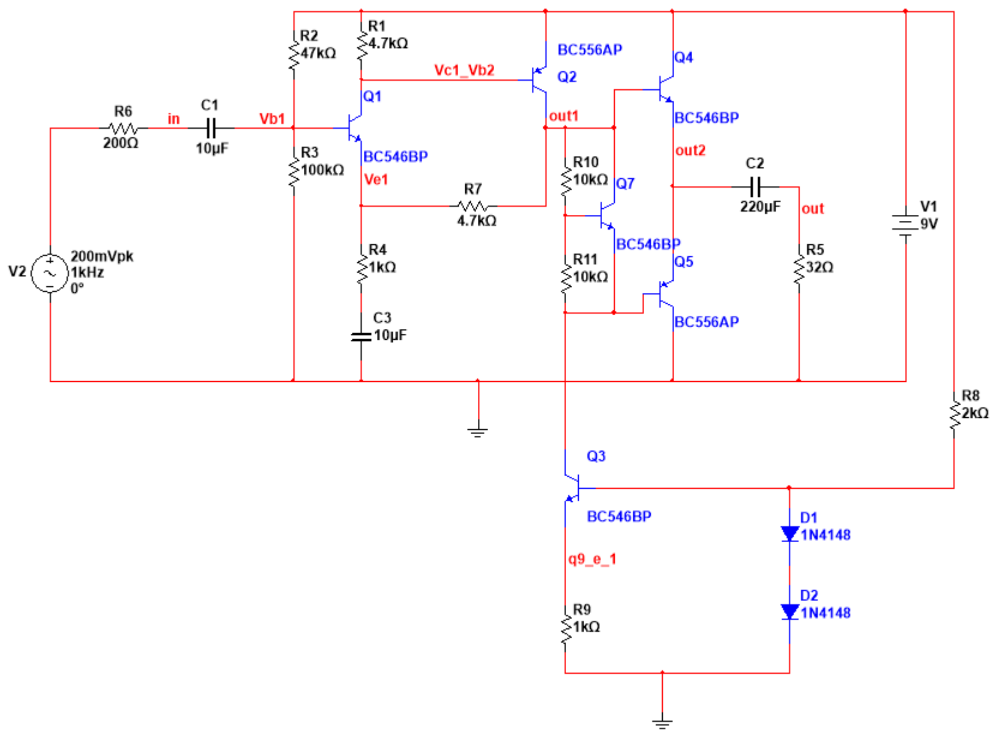


Figure 4.4: Class AB output stage

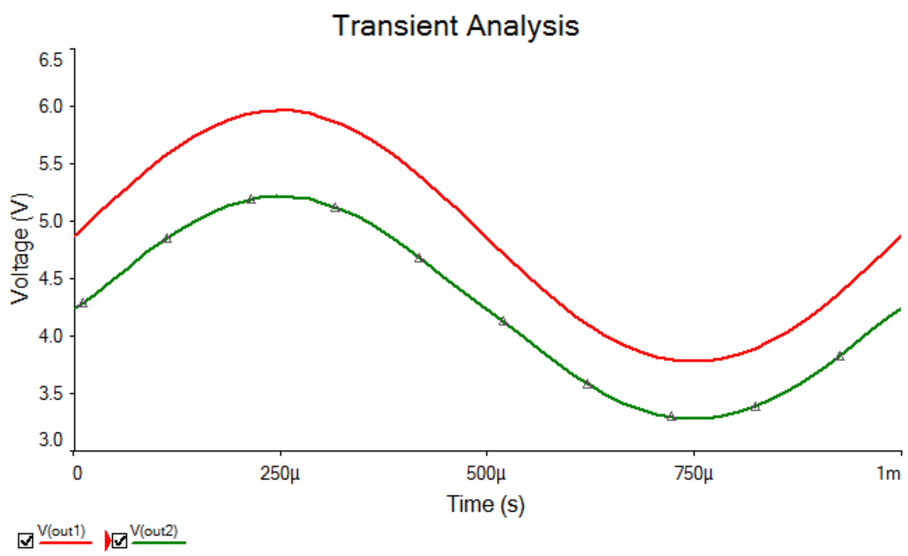


Figure 4.5: Class AB output stage simulation result

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

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 feeedback part.

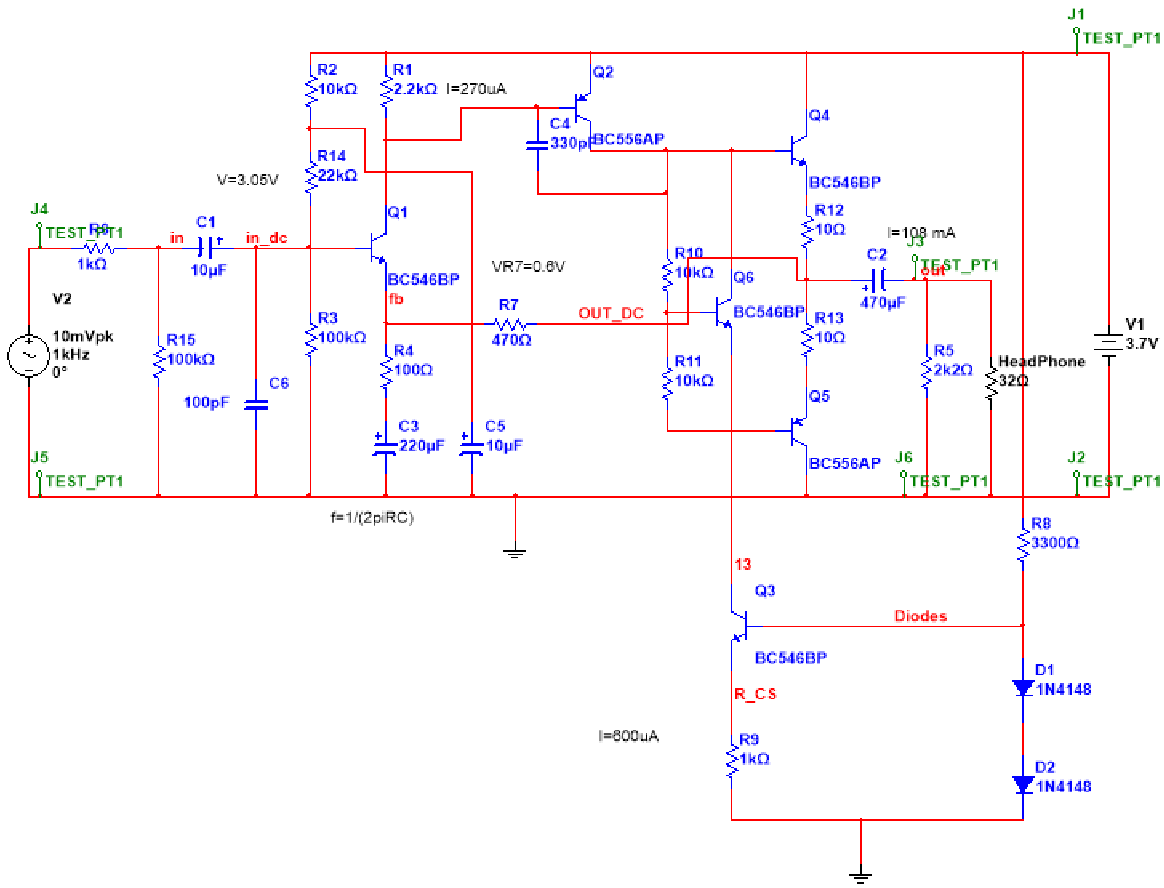


Figure 5.1: Schematic of final Design

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. Resister R14 and R3 consist of voltage diveder 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 makesure amplifier DC voltage gain is 1 which means circuit only amplify signal AC part.

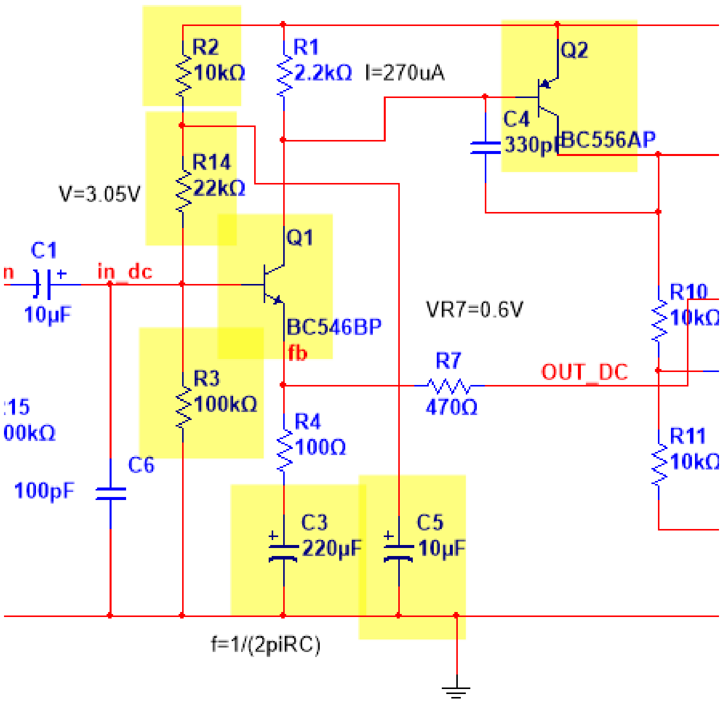


Figure 5.2: voltage amplifier part

5.1.2 Class AB output stage

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

Resistor R10, R11 and NPN transistor Q6 form a Vbe multiplier which use to eliminate the crossover distortion.

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

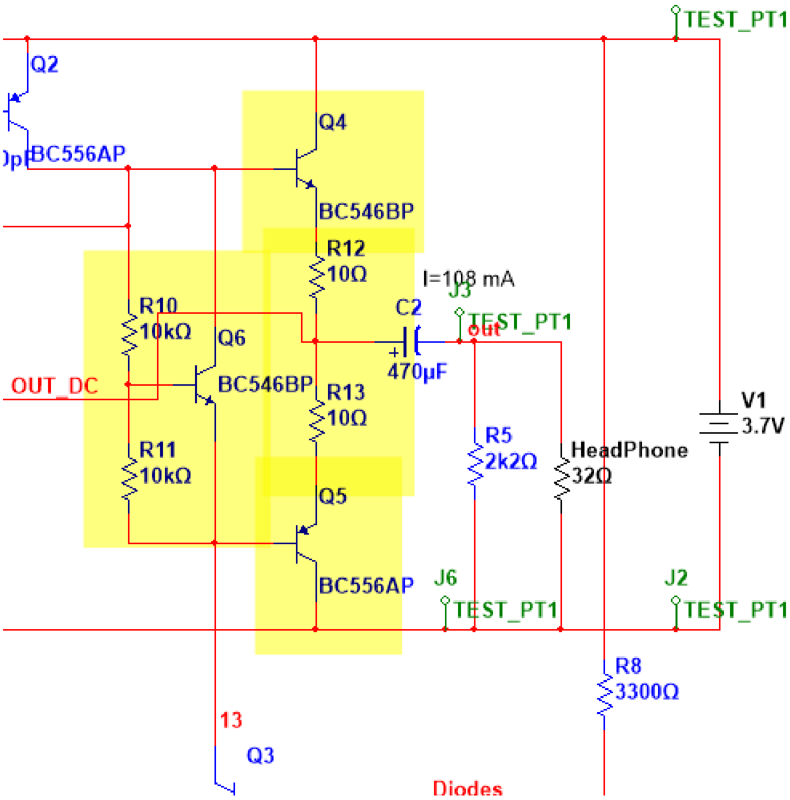


Figure 5.3: Class AB outout stage

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 cuurent of this 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.

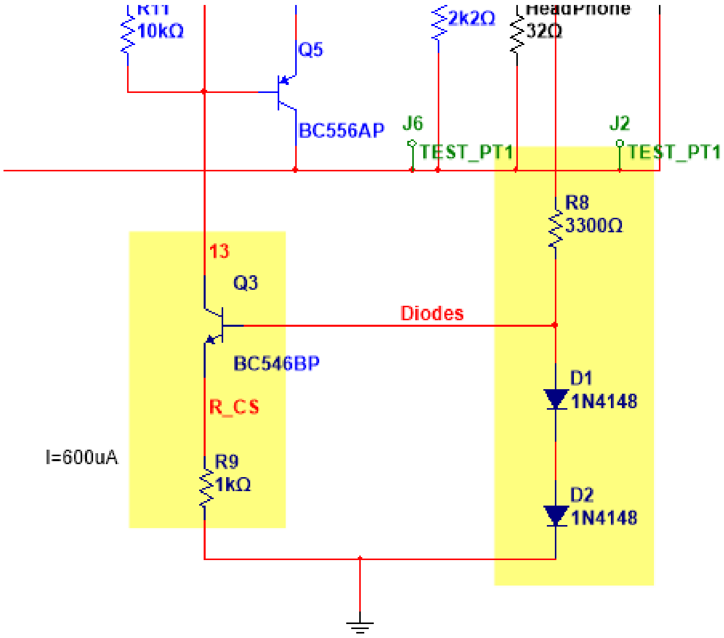


Figure 5.4: Current source

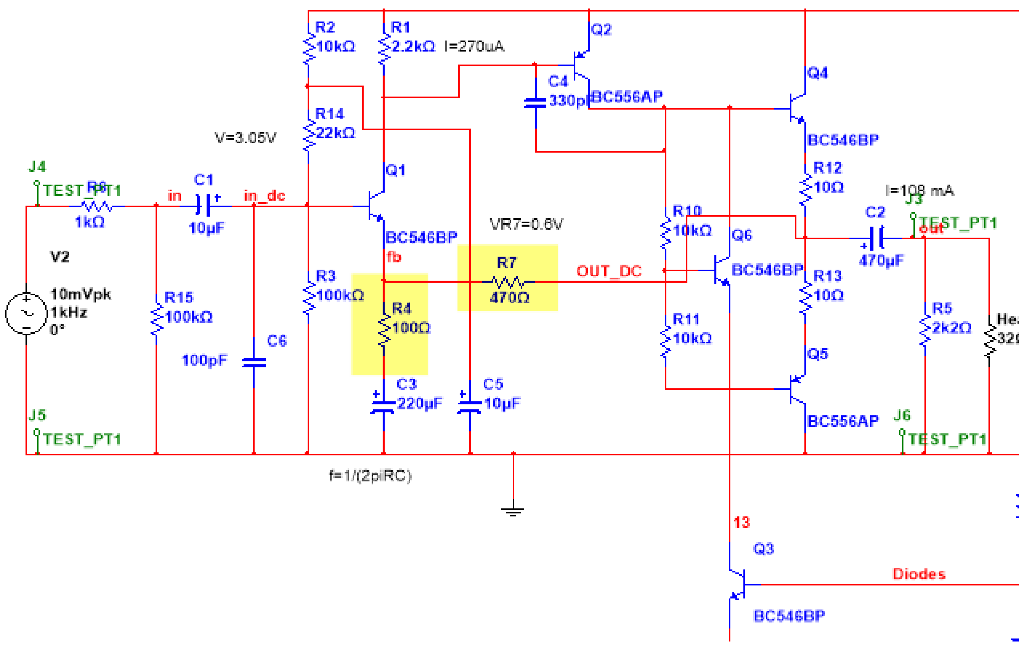


Figure 5.5: Negative feedback part

Chapter 6

PCB design

6.1 Draw PCB board

Step one, we transfer netlist data from multisim to Ultoboard and the result is shown in Figure 6.1.

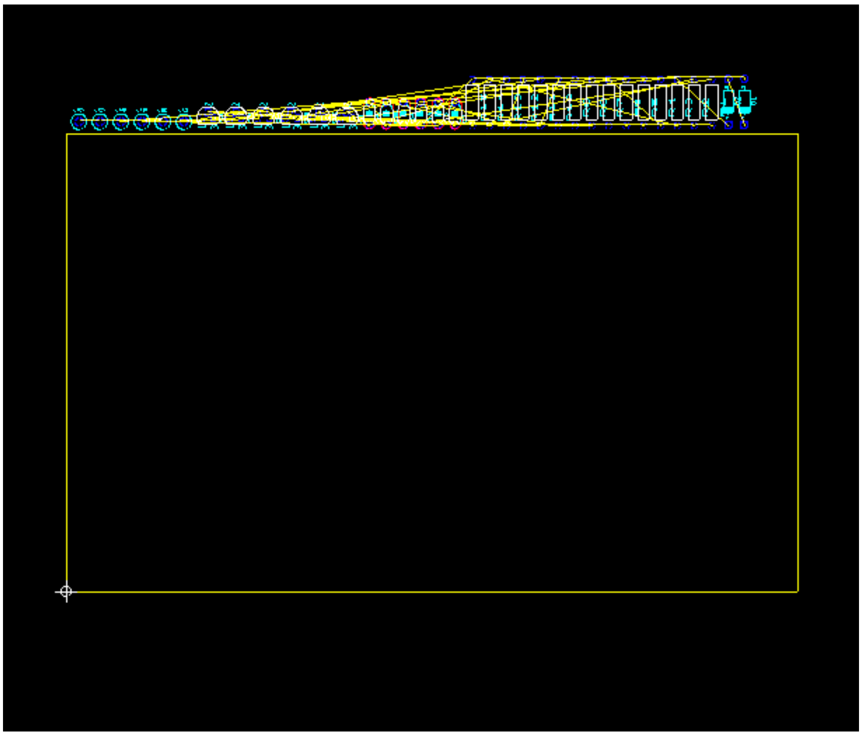


Figure 6.1: Step one transfer netlist data

Step two, we changed board size to 5cm x 5cm and the result is shown in Figure 6.2.

Step three, we layout all components and try arrange their position similar to where in schematic and we modified the locations of components.Then we added all

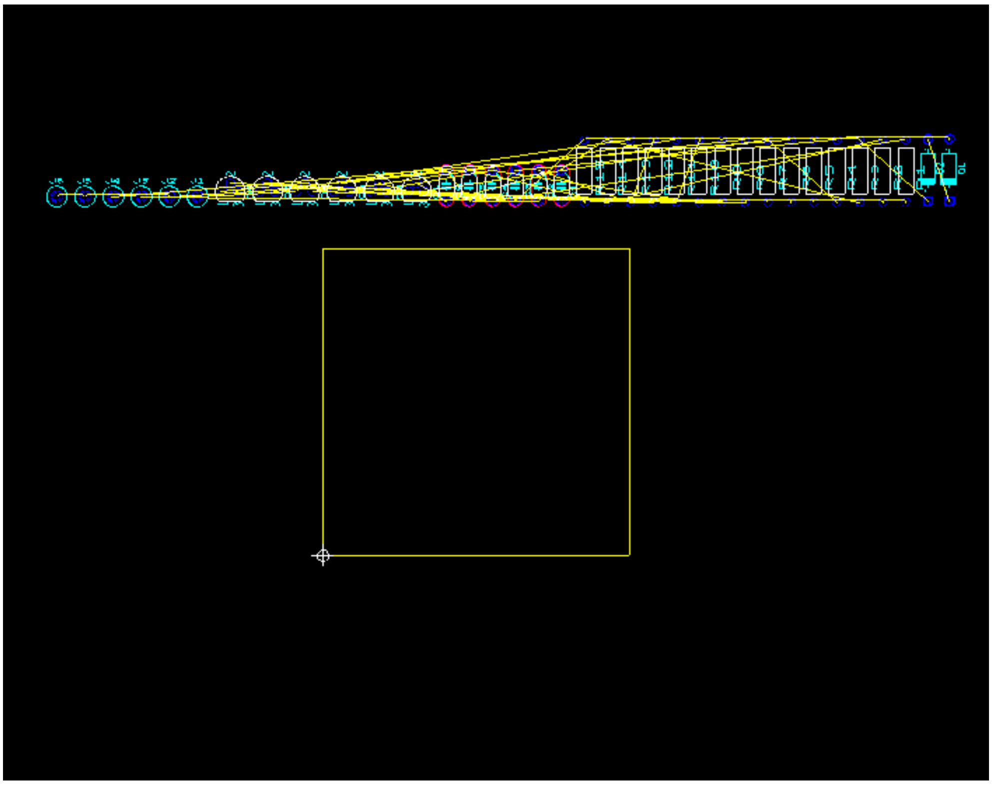


Figure 6.2: Step two change board size

value of resistors and capacitors which is useful when we solder this board.At the end of this step, we get result like Figure 6.3.

Step four, I added my name and student ID on the silkscreen layer.In the meanwhile, I marked the ground ports, input signal port, output signal port and the port need connected to battery because these silkscreen texts will help me connect this board to DC power source and ocilloscope.Ultil finish this step, the board is shown in Figure 6.4.

Step five, we run autoroute command to connect all components and the board is like the Figure 6.5.

It's obviouse that the traces routed by computer is not smooth enough, so we need modify them manually.For example, lets make ground line straight. Then I added teardrops to all pads to make pads more strongger.After finish doing all these, we can get result like Figure 6.6.

Finaly, we can view our board in 3D view which shown in Figure 6.7.By using this view mode, we can check whether there is any mistakes in our design and we can eliminate them before we send the Gerber file to manufacturer.

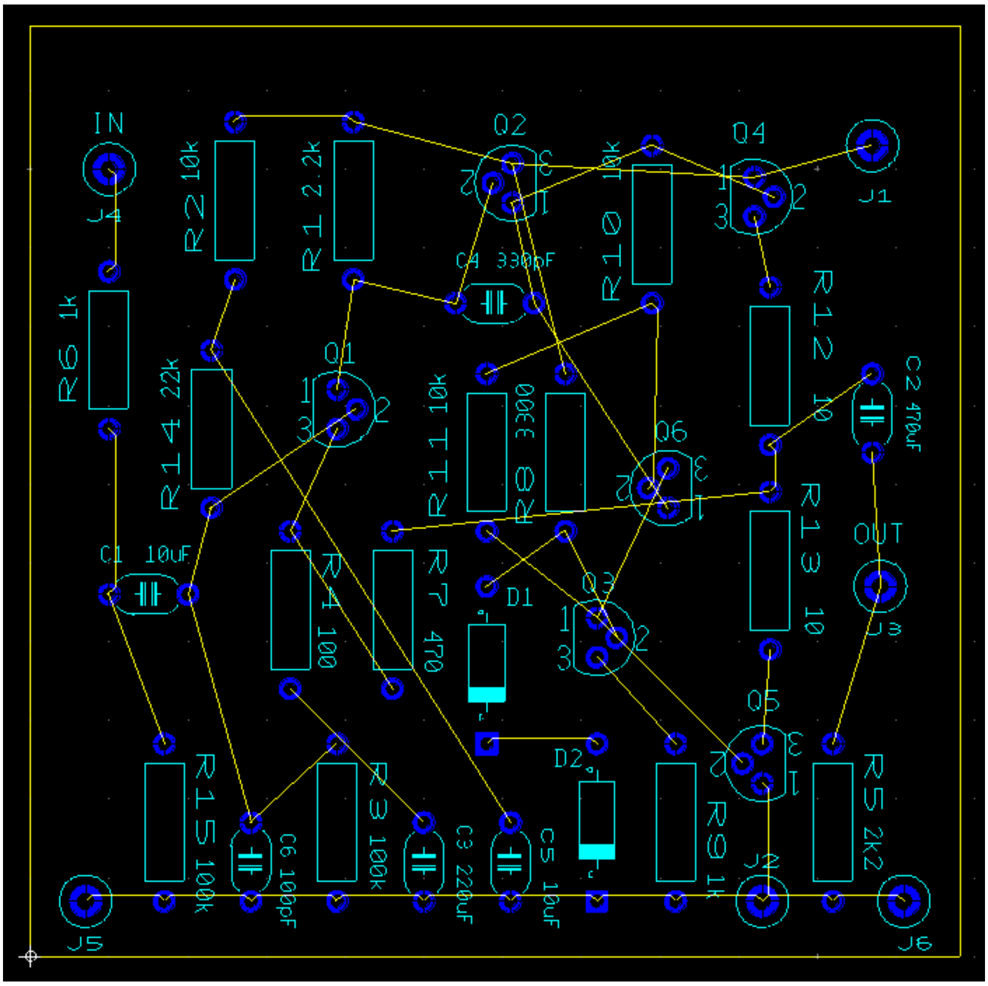


Figure 6.3: Step three arrange component

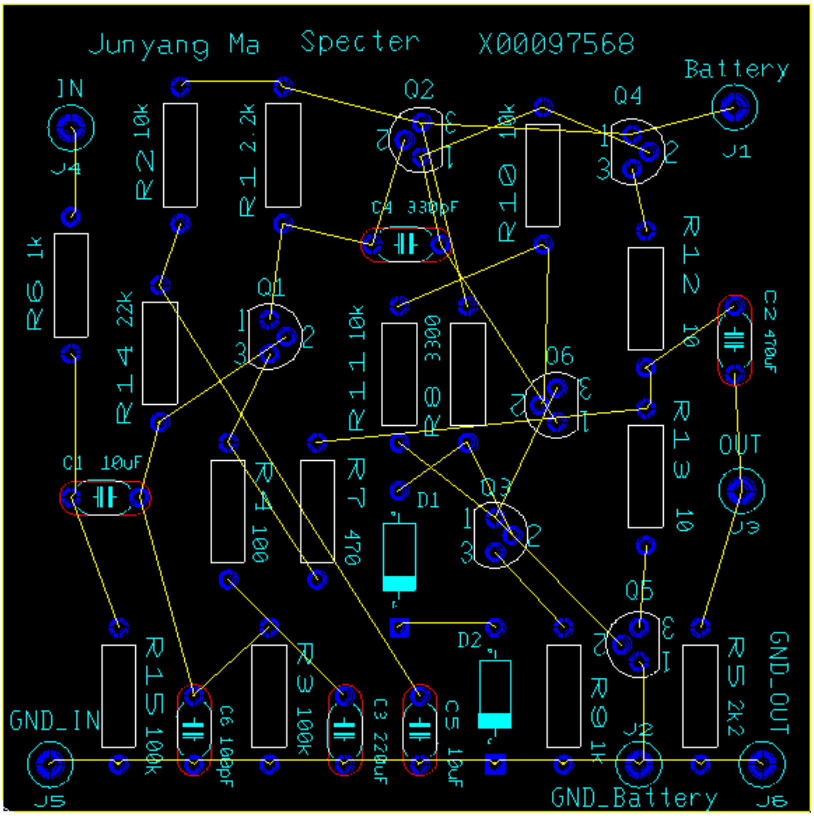


Figure 6.4: Step four add important information on silkscreen layer

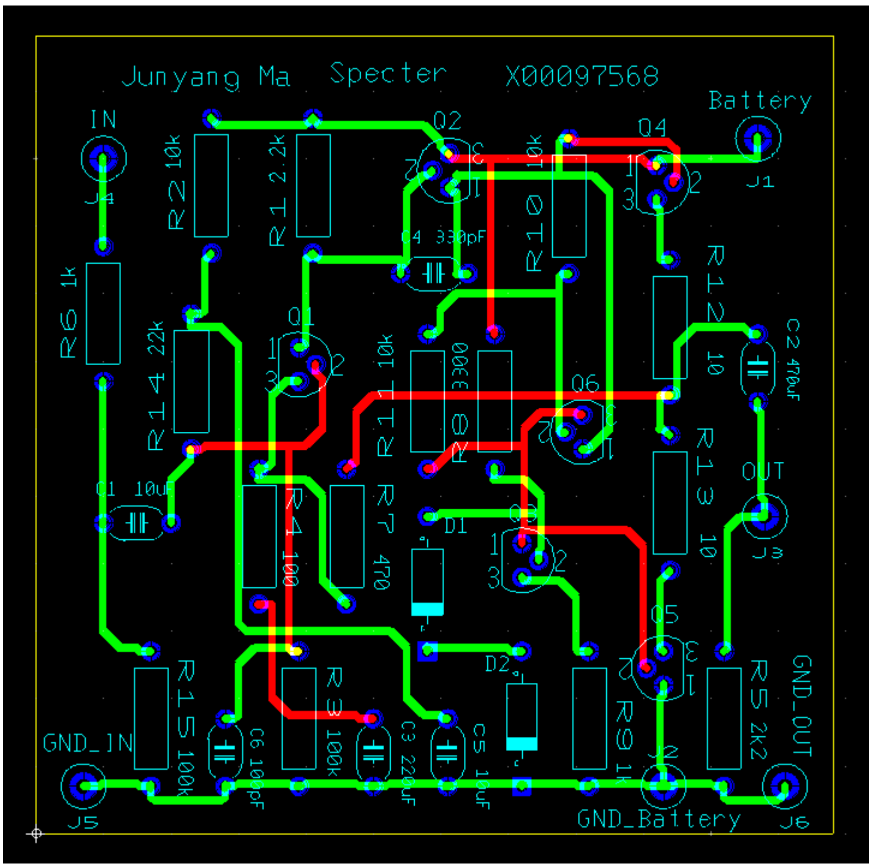


Figure 6.5: Step five connect all components

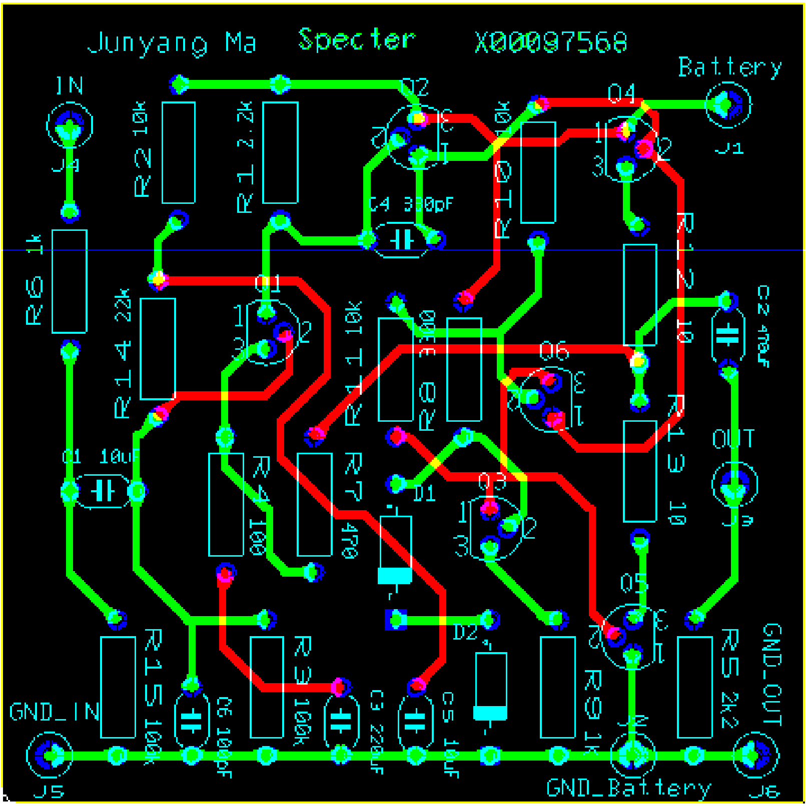


Figure 6.6: Finish autorout

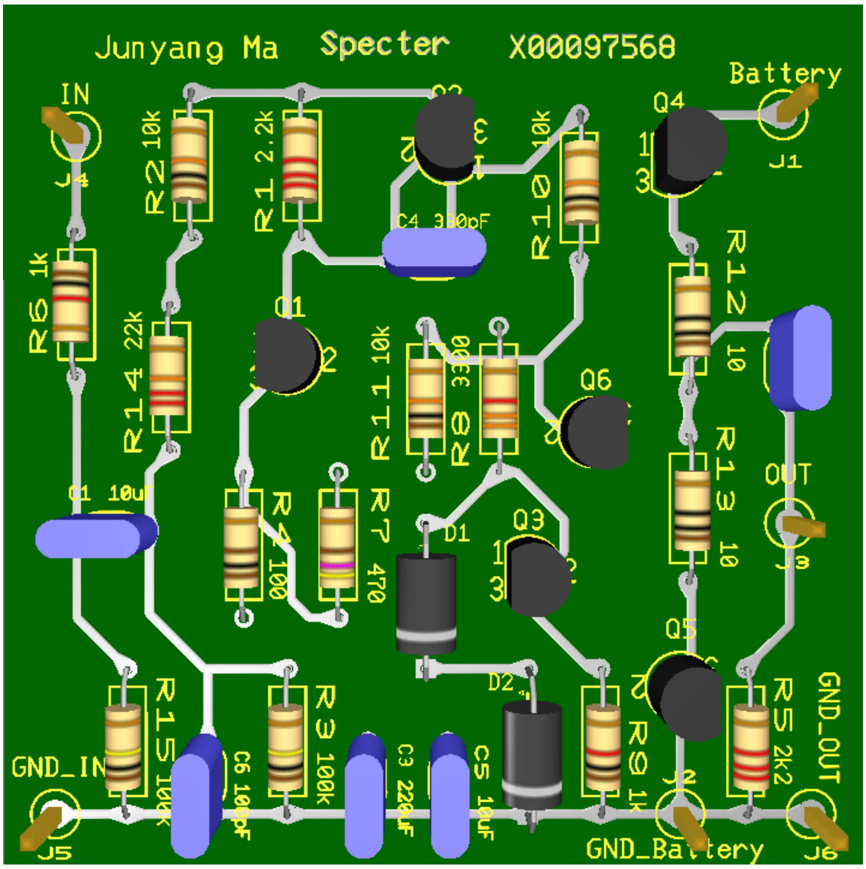


Figure 6.7: PCB 3D view

Chapter 7

Performance test

7.1 Bandwidth simulation test

For analysing bandwidth, we run the AC analyse in multisim and we get the curve like Figure 7.1.

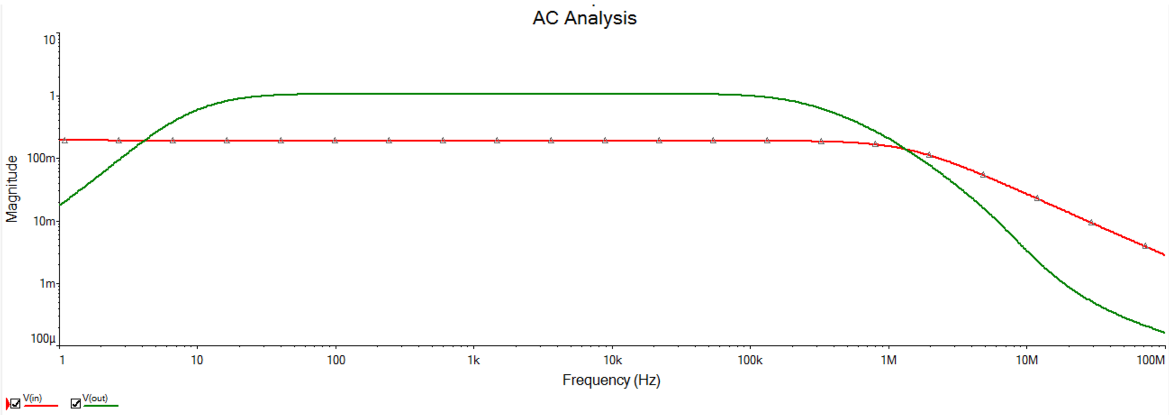


Figure 7.1: AC analyse

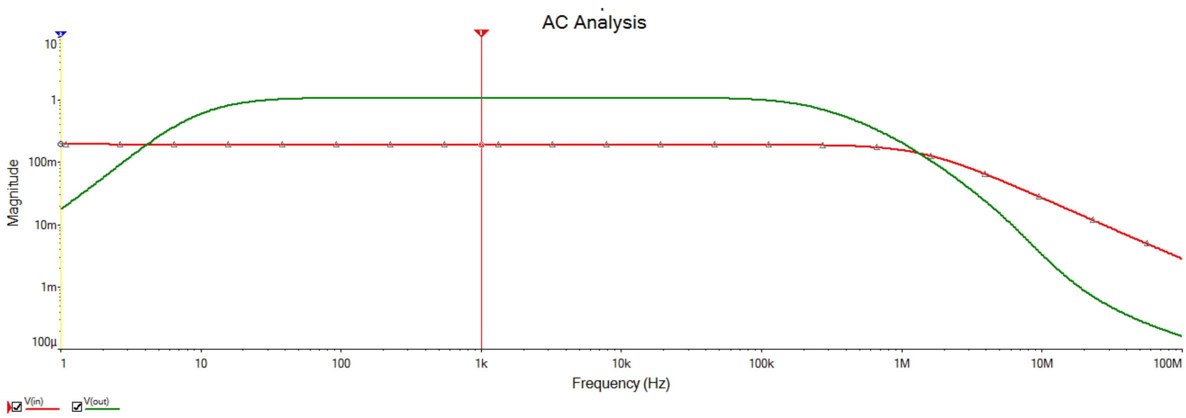
Next,We set x value of cursor 2 to 1K and find that the output magnitude for that point is 1.0645V ie. 0dB is 1.0645V.

According bandwidth definition, the magnitude of bandwidth limitation is -3dB. So

$$V_{-3dB} = \frac{V_{0dB}}{\sqrt{2}} = \frac{1.0645V}{\sqrt{2}} = 0.752715V \approxeq 752mV$$

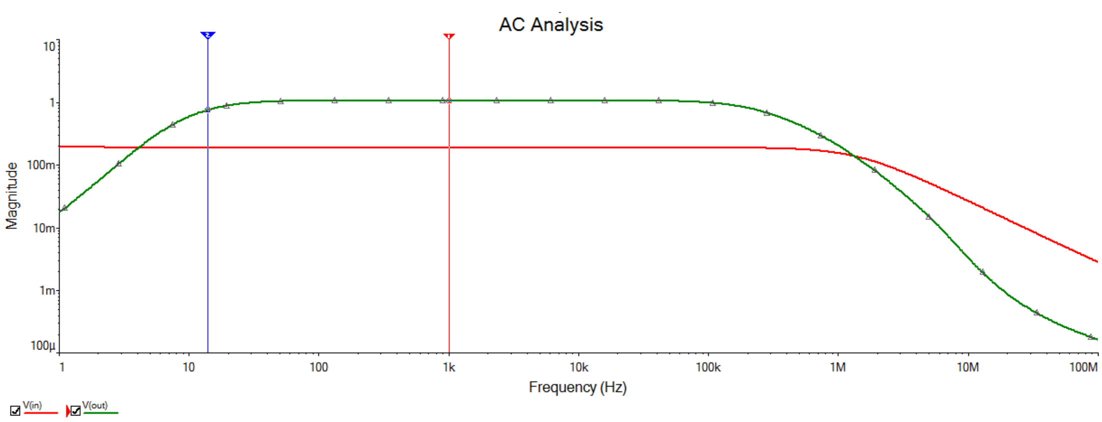
Then we set the cursor 1 to the position which magnitude of output signal is 752mV and the result is shown in Figure 7.3.From the cursor data, we know $x2 = 14Hz$ when $y2 = 752mV$ ie. the lower bandwidth limitation is 14 Hz.

As same as step before, we move the cursor 1 to the higher frequency part and makesure its magnitude equals 752mV.This time we get the higher bandwidth



	V(in)	V(out)
x1	1.0088k	1.0088k
y1	187.6935m	1.0645
x2	1.0000	1.0000
y2	192.9429m	17.5552m
dx	-1.0078k	-1.0078k
dy	5.2494m	-1.0469
dy/dx	-5.2088µ	1.0389m
1/dx	-992.2762µ	-992.2762µ

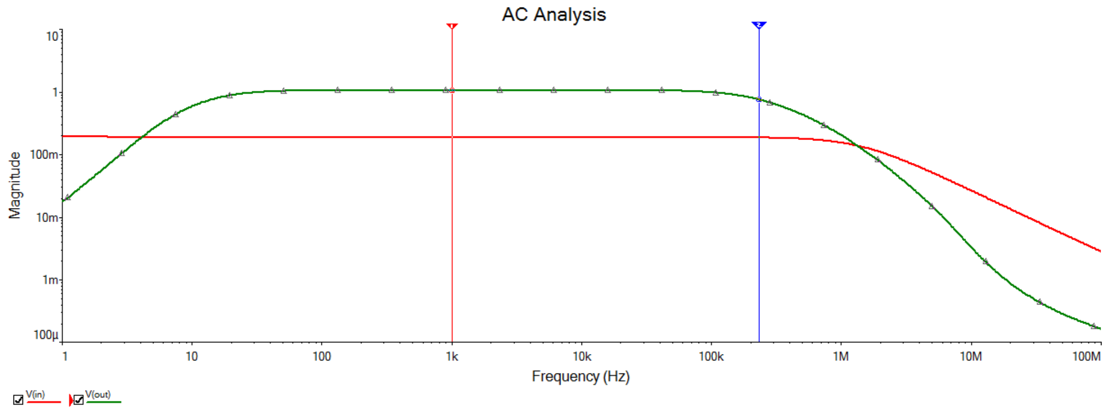
Figure 7.2: find the maximum magnitude



	V(in)	V(out)
x1	1.0088k	1.0088k
y1	187.6935m	1.0645
x2	14.0116	14.0116
y2	187.8570m	752.7261m
dx	-994.7724	-994.7724
dy	163.4344µ	-311.7666m
dy/dx	-164.2933n	313.4050µ
1/dx	-1.0053m	-1.0053m

Figure 7.3: find the lower bandwidth limitation

limitation is $232KHz$ from cursors data table.



	V(in)	V(out)
x1	1.0088k	1.0088k
y1	187.6935m	1.0645
x2	232.0869k	232.0869k
y2	185.2844m	752.6881m
dx	231.0781k	231.0781k
dy	-2.4091m	-311.8046m
dy/dx	-10.4256n	-1.3493µ
1/dx	4.3275µ	4.3275µ

Figure 7.4: find the higher bandwidth limitation

Now from these simulation results, we can estimate the output bandwidth of our circuit is between $14Hz$ to $232KHZ$.

7.2 Bandwidth practical circuit test

Now we can do bandwidth test on our practical circuit.We connect signal generator to input port.In the meawhile, the speaker and ocilliscope connect to the output port.

As the same test steps as simulation, we measure the output magnitude of 1KHz input signal and the result is shown in Figure 7.6.We can read the output magitude from ocilliscoe is 984mV which is very close our simulation result ie. 1.0645V.

Then we need calculate the -3dB magnitude again.

$$V_{-3dB} = \frac{V_{0dB}}{\sqrt{2}} = \frac{984mV}{\sqrt{2}} approxeq 700mV$$

Therefore, I decrease the input signal frequency until the output signal magnitude equal 700mV.And the result is shown as Figure 7.7.We can read input signal

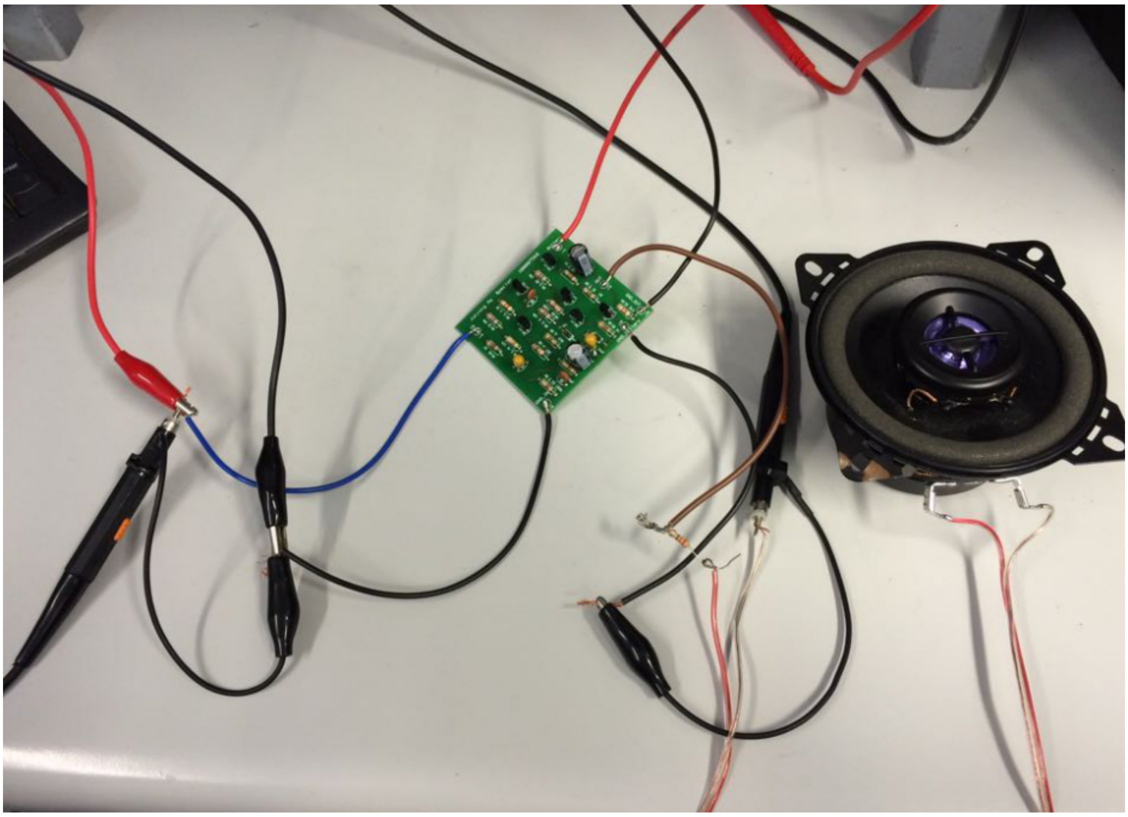


Figure 7.5: Bandwidth practical circuit for test

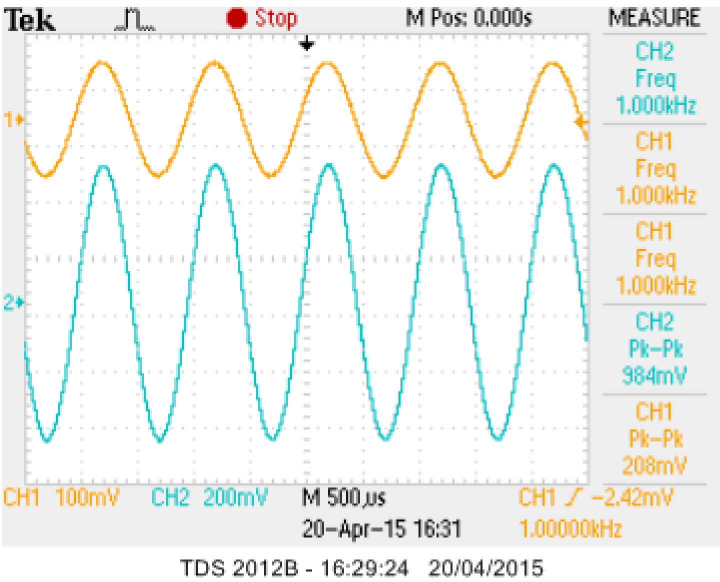


Figure 7.6: 1K sine wave input signal test

frequency at this moment is 22Hz ie. the practical lower bandwidth limitation is 22Hz.

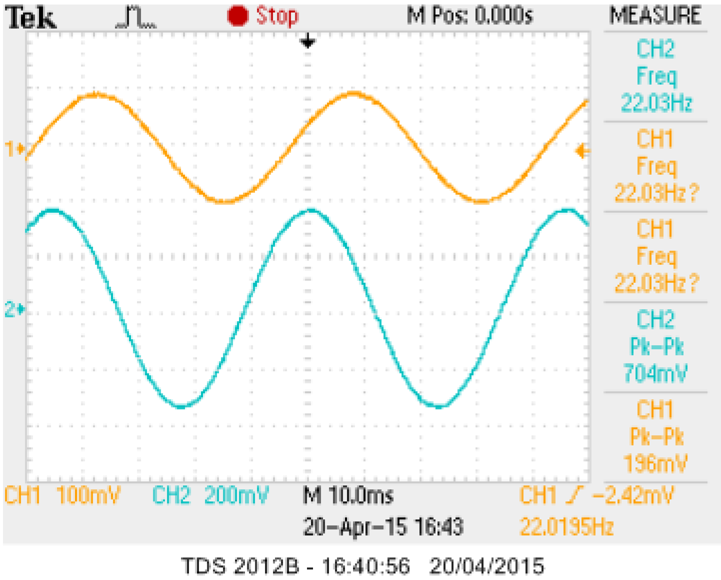


Figure 7.7: find the practical lower bandwidth limitation

Next,I increase the input signal frequency untial the output siganl magnitude euqal 700mv.And the result is shown as Figure 7.8.We can read input signal frequency at this moment is 220kHz ie. the practical lower bandwidth limitation is 220kHz.

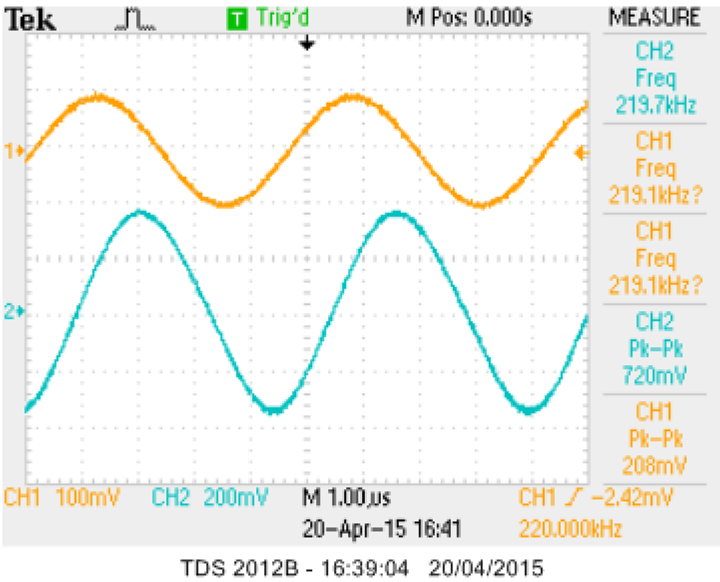


Figure 7.8: find the practical higher bandwidth limitation

Now we get the result which we want to know is that our practical bandwidth region is 22Hz to 220KHz and this is very close to our simulation result in previous section.

7.3 Other practical test

We also input square wave to check whether its stable in hign frequency region and it's obvious that there is no overshoot in transition edge of output signal.There this result is satisfied.

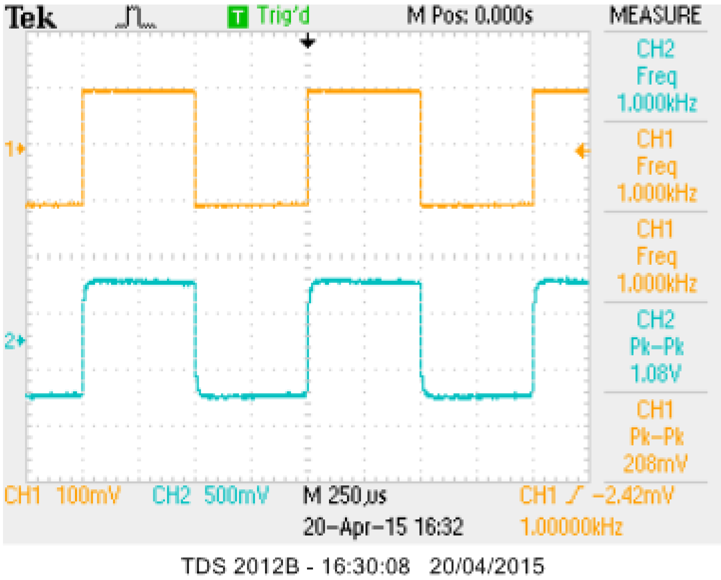


Figure 7.9: Input sqaure wave

Next we input the triangle wav to check the linearity of out circuit and the result in Figure 7.10 shows the output signal follows input signal very well.

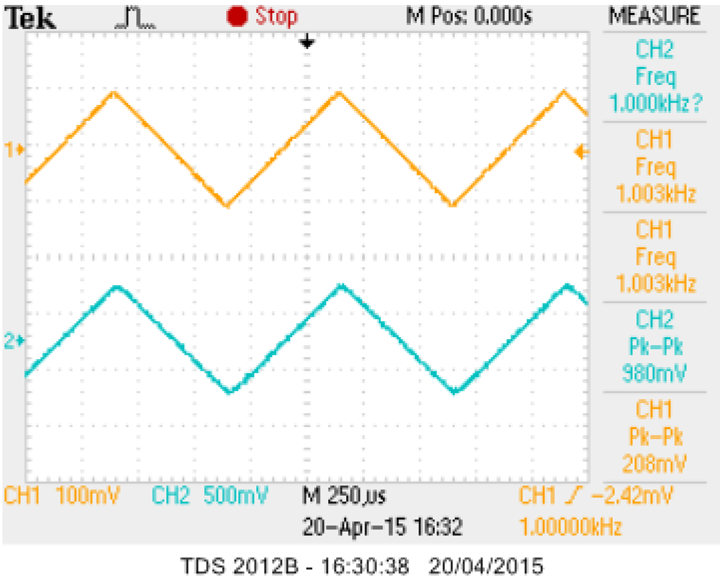


Figure 7.10: Input triangle wave

Chapter 8

Conclusion

From doing this project, I learned how to use NPN transistor to amplify signal, using negative feedback control output gain and eliminate internal distortion, using transistor and diades make currrent source, distinguish different type of output stage, drawing PCB board ,soldering PCB board and test it.

Also, I connect my headphone amplifier with my classmate's microphone amplifier which can amplify the microphone signal and output to the speaker.The system is shown in Figure 8.1.

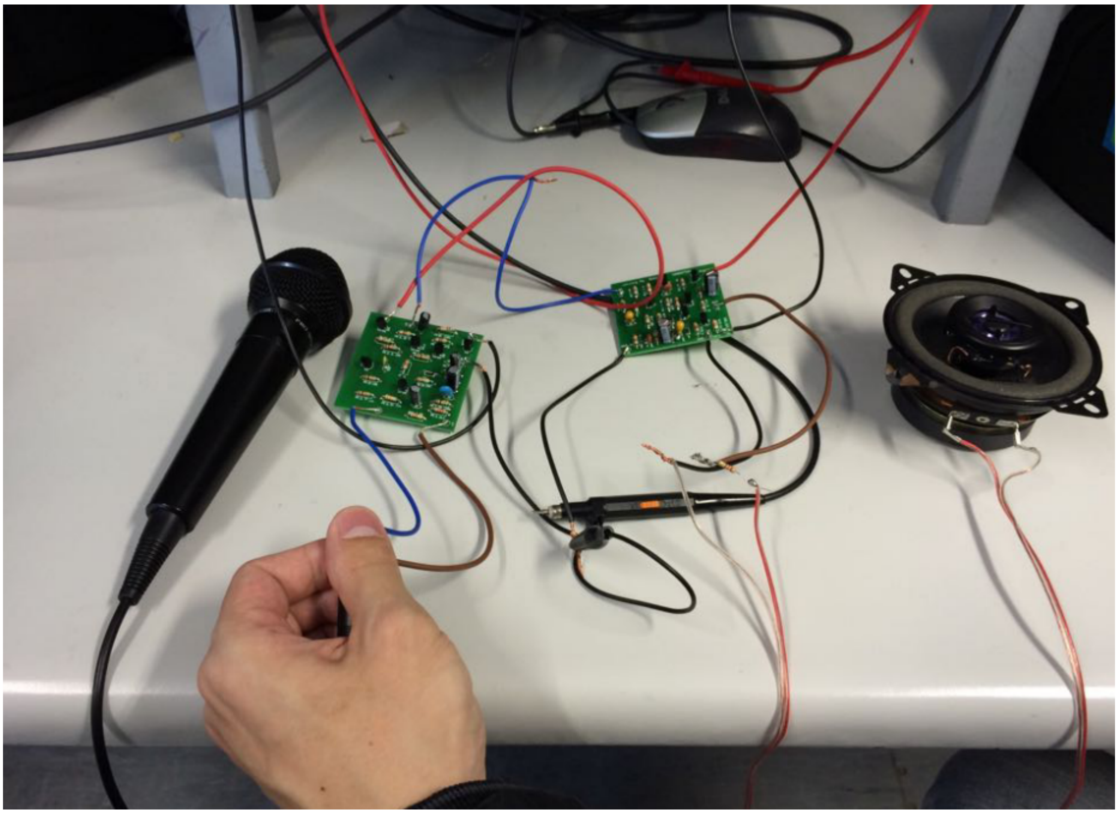


Figure 8.1: micophone amplifier and headphone amplifier system

And last,thanks our supervisor Declan for teaching us all this theory and guide us using equipments to test ourboards.Whithout his patient teaching, I couldn't this high performance headphone amplifier.