İhsan Doğramacı Bilkent University

ELECTRICAL and ELECTRONICS ENGINEERING

Bilkent University

Department of Electrical and Electronics Engineering

EE-313 ELECTRONIC CIRCUIT DESIGN

LAB-4 FINAL REPORT

Wide-Band Amplifier with Feedback

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1 Introduction

This lab, EE313 Laboratory 4, requires a design a two-stage amplifier that uses feedback. The main goals for the amplifier are to achieve a low output impedance and maintain a flat gain across a specific frequency range.

There are 8 specifications that must be specified:

1. Source impedance: 730Ω (50Ω (already present) +680Ω)
2. Load impedance: 47Ω
3. Mid band voltage Gain: 18 dB ± 0.5 dB
4. Bandwidth (−3 dB): at least 40 KHz to 4 MHz (by CNTL-Click in AC analysis)
5. Supply voltage: 12V (single supply)
6. Maximum current consumption: 70mA from the supply voltage
7. Undistorted peak-to-peak output voltage: $1.6V_{pp}$ at 400 KHz.
8. Distortion at the output: Harmonics less than −30 dBc at 100 KHz $1.6V_{pp}$ output voltage (the difference between the fundamental and the highest harmonic in FFT window)

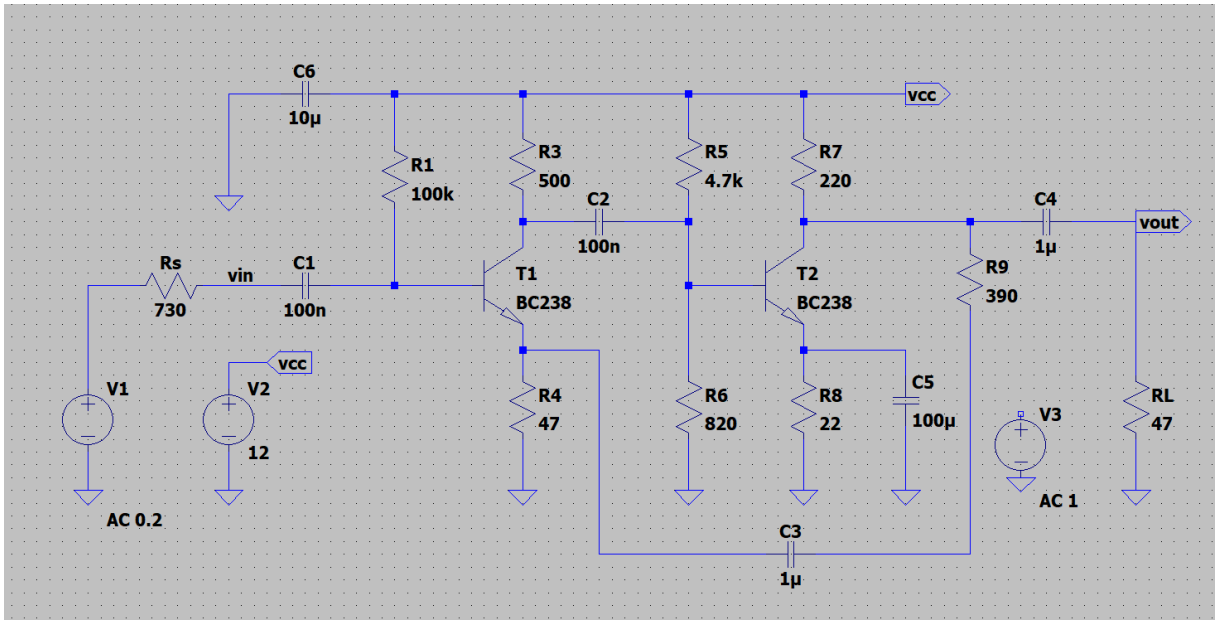

Figure 1: Wide-Band Amplifier with Feedback Circuit Design

2 Component Value Calculation Methodology

The component values for the amplifier were determined based on standard BJT amplifier design principles, targeting the specified DC operating points and AC performance characteristics (gain, bandwidth, output swing, current consumption).

Resistors

Resistor values were calculated to satisfy the following criteria:

- **AC Gain:** Collector resistors (R_3, R_7) were selected to achieve high open-loop gain while respecting DC bias constraints and output voltage swing requirements.
- **Feedback Network:** The feedback resistors (R_9, R_4) were determined based on the target closed-loop voltage gain (A_{CL}), using the approximate relationship for voltage-series feedback: $A_{CL} \approx R_9/R_4$. R_9 was adjusted to meet the specific gain requirement of 18 dB.

Standard resistor values were used throughout the design.

Capacitors

Capacitor values were chosen based on their function and the target frequency response:

- **Coupling/Blocking Capacitors (C_1, C_2, C_3, C_4):** Selected to present low impedance (X_C) at the lowest frequency of interest ($f_L = 40\,\text{kHz}$) compared to the equivalent resistance (R_{equiv}) seen by the capacitor, ensuring minimal impact on the lower -3dB frequency. The condition $X_C \ll R_{equiv}$ or $C \geq 1/(2\pi f_L R_{equiv})$ was used.
- **Bypass Capacitors (C_5, C_6):** Chosen to provide a low impedance path to ground at AC frequencies. C_5 bypasses the emitter resistor R_8, with its value determined by $X_{C5} \ll (R_8 || 1/g_{m2})$ at f_L. C_6 provides power supply decoupling, selected such that X_{C6} is significantly smaller than the effective power supply source impedance at f_L.

Standard capacitor values were selected.

3 PRELIMANARY WORK

1st Specification

Source impedance: 730Ω (50Ω **(already present)** +680Ω)

As shown in Figure 1, I used 730Ω as a source impedance.

2nd Specification

Load impedance: 47Ω

As shown in Figure 1, I used 47Ω as a load impedance.

5th Specification

Supply voltage: 12 V (single supply)

As shown in Figure 1, I used 12V (single supply) as a supply voltage.

6th Specification

Maximum current consumption: 70mA from the supply voltage

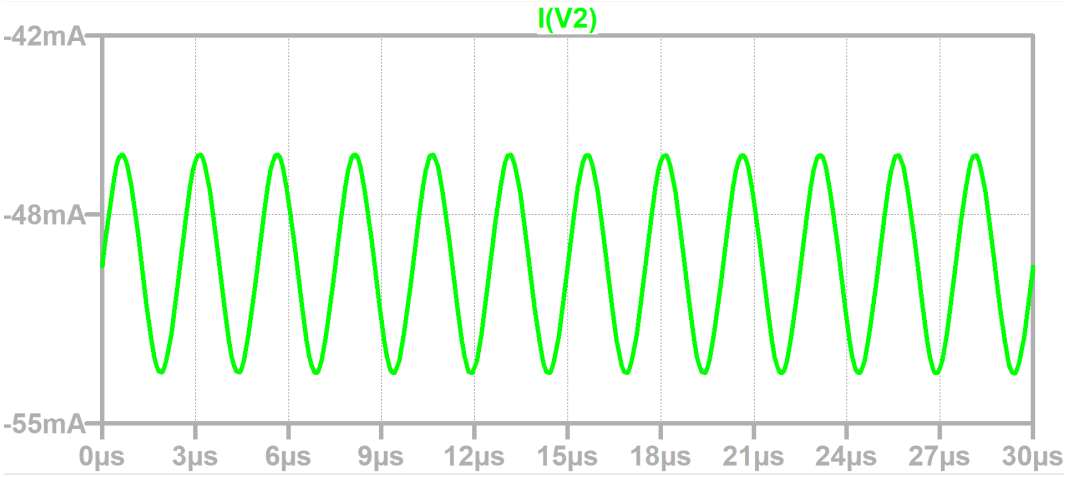

Figure 2: 6th Specification

As shown in Figure 2 maximum current consumption is less than 70mA.

3rd Specification

Mid band voltage Gain: 18 **dB** $\pm$ 0.5 **dB**

For this specification, we should look at gain graph of the circuit.

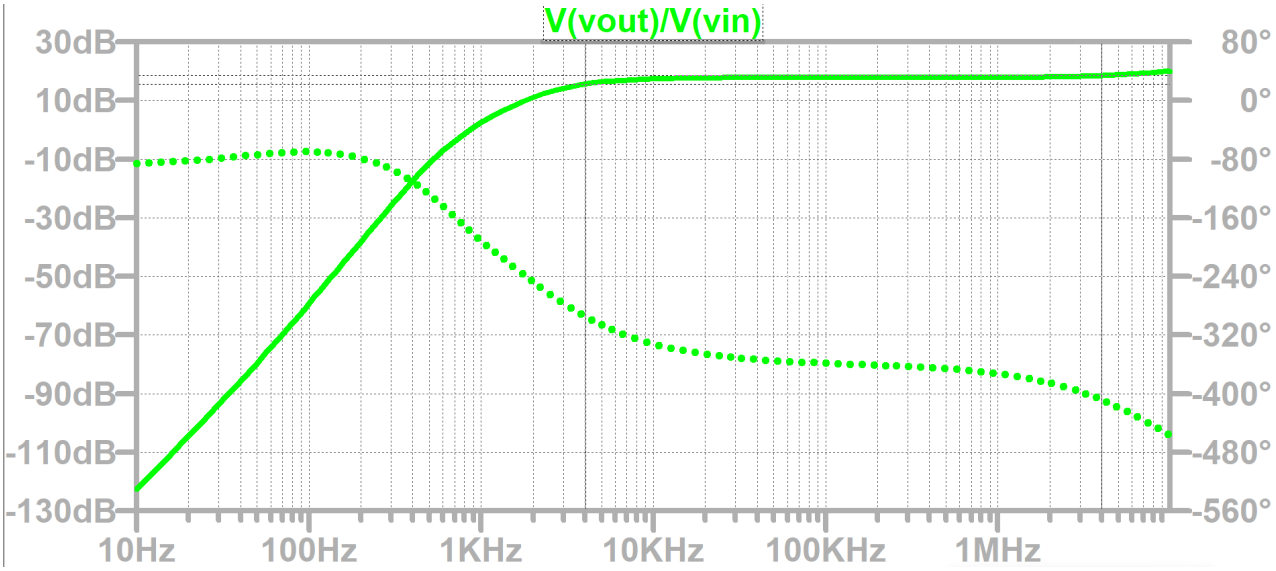

Figure 3: Gain Graph of the Circuit

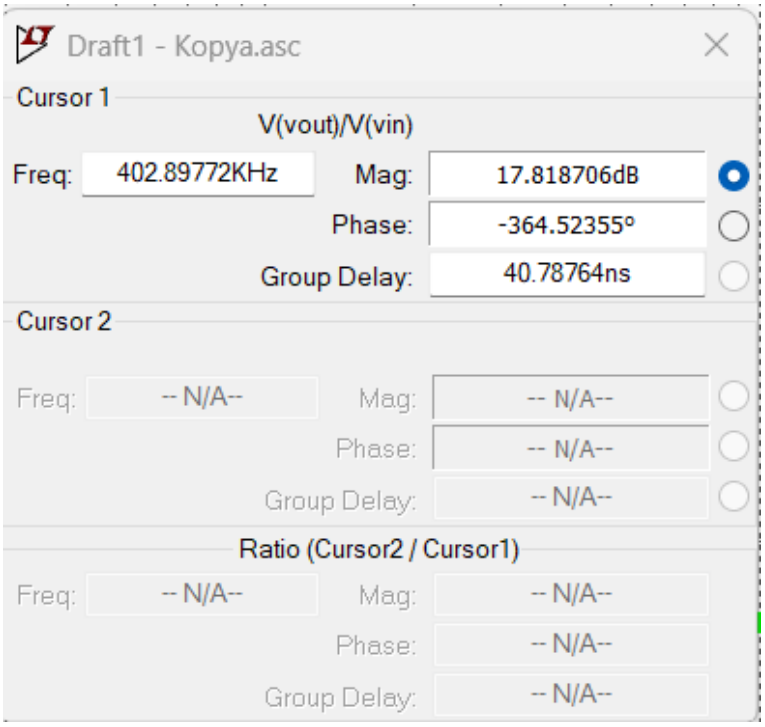

Figure 4: Bandwidth Specification

As shown in Figure 4, at 400KHz we have a gain of 17.8 dB

4th Specification

Bandwidth (−3 dB): at least 40 KHz to 4 MHz (by CNTL-Click in AC analysis)
For this specification, we should look at gain graph from previous specification.

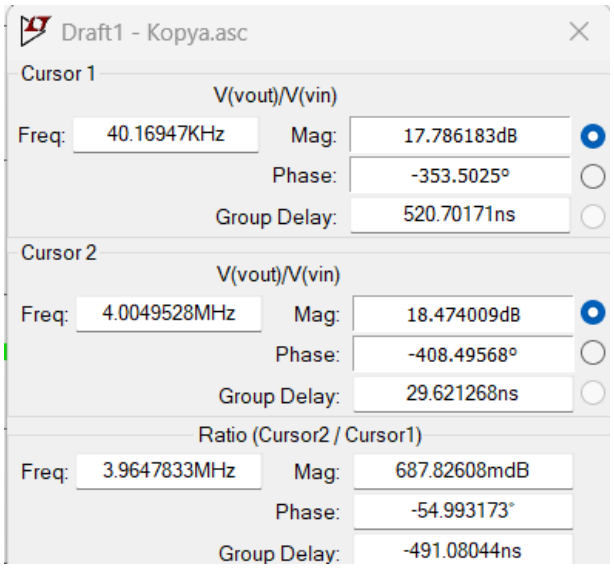

Figure 5: Bandwidth Specification

As shown in the figures, the bandwidth covers 40 KHz to 4 MHz interval.

7th Specification

Undistorted peak-to-peak output voltage: $1.6V_{pp}$ **at 400 KHz.**

For this specification, we should look at the gain graphic.

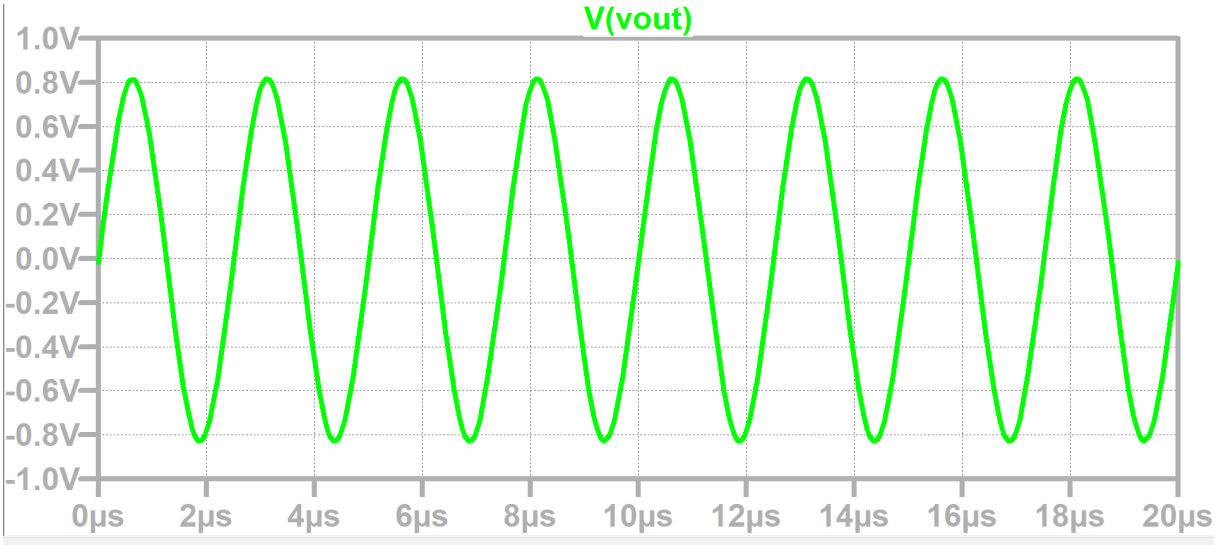

Figure 6: $1.6V_{pp}$ at 400 KHz

8th Specification

Distortion at the output: Harmonics less than -30 dBc at 100 KHz $1.6V_{pp}$ output voltage (the difference between the fundamental and the highest harmonic in FFT window)

For this specification, we should look at the gain graphic.

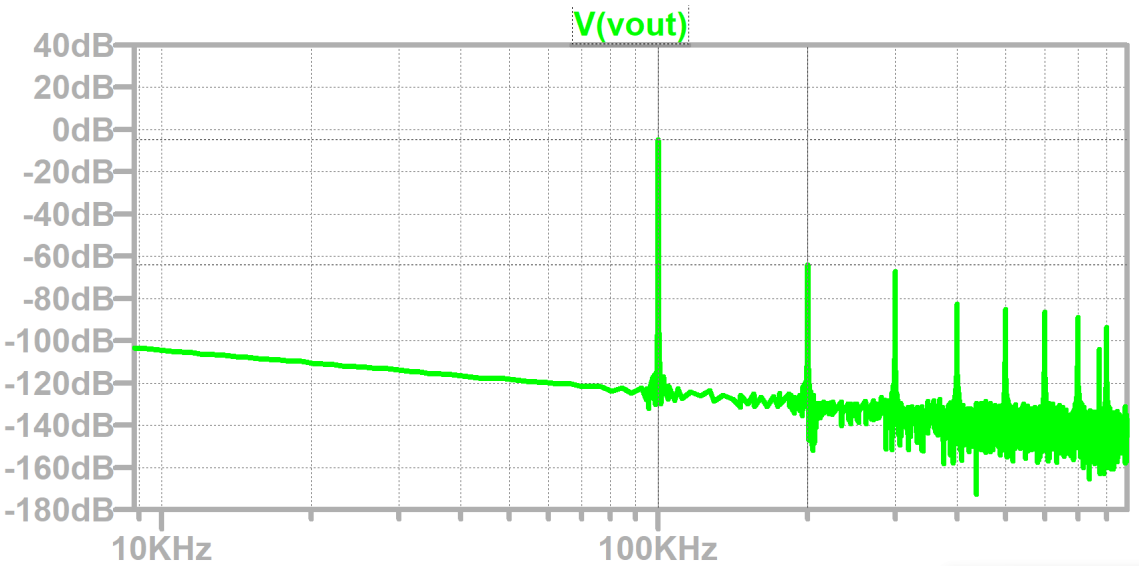

Figure 7: FFT graph

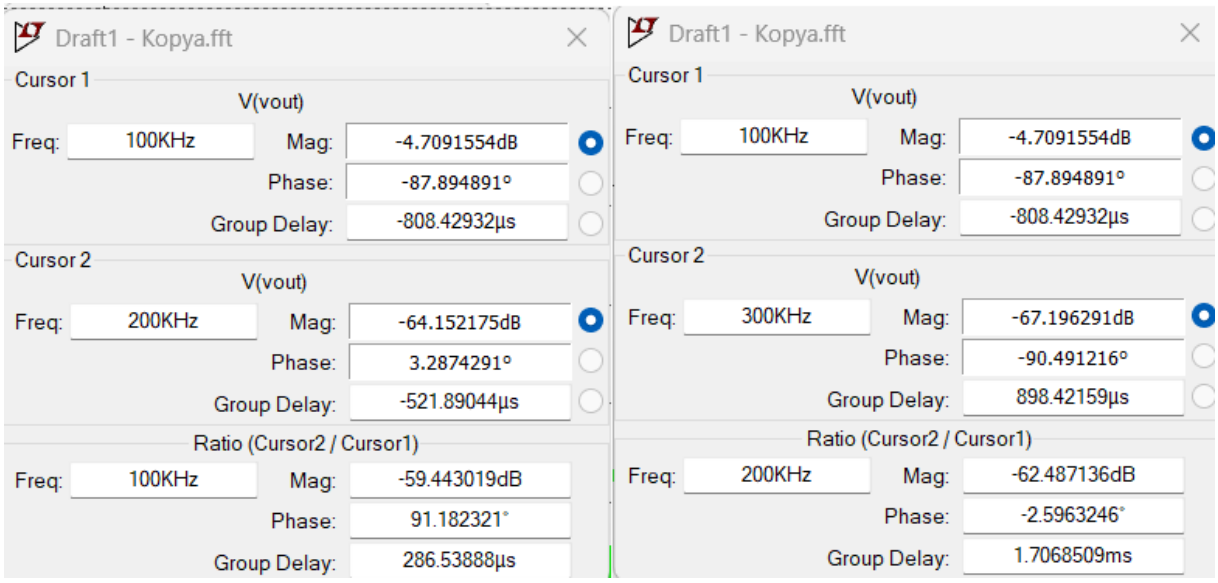

Figure 8: dBc difference

As shown in the graph, there is at least 30 dBc difference between fundamental harmonic and other harmonics.

4 Tables

Average Current

We see the average current in Figure 2

I_c (mA)	49 mA

Table 1: Average Current

Small-signal Bandwidth

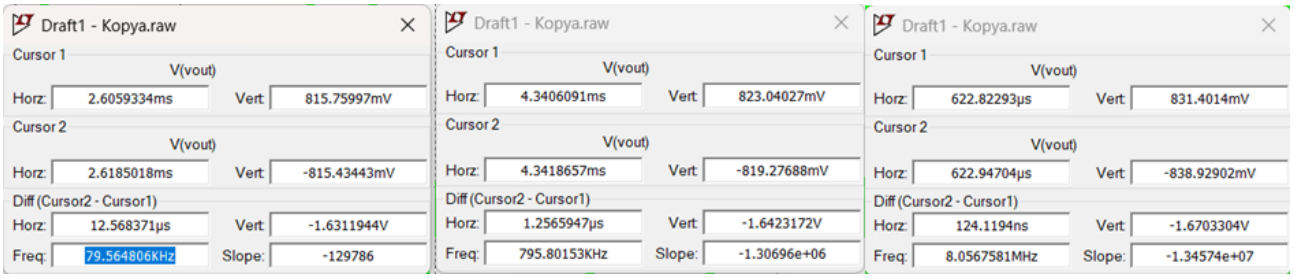

Figure 9: $V_{out(pp)}$ values for different inputs

f (kHz)	$V_{in(pp)}$ (mV)	$V_{out(pp)}$ (V)	V_{out}/V_{in} (dB)
40	200	1.63 V	18.22 dB
400	200	1.64 V	18.27 dB
4000	200	1.67 V	18.43 dB

Table 2: The small-signal bandwidth

Harmonics

We see harmonics in Figure 7 and Figure 8

f (kHz)	V_{out} (dB)
100	-4.7 dB
200 (2nd harmonic)	-64.15 dB
300 (3rd harmonic)	- 67.19 dB

Table 3: The harmonic content of the output voltage

R_{in} Calculation

R_L	V_{out}/V_{in} at 100 kHz
50 Ω	8.2
10 kΩ	7.55
R_{in}	$115.5k\Omega$

Table 4: The small-signal input impedance

The formula is:

$$R_{in} = \frac{R_{S2} - \left(\frac{A_{v1}}{A_{v2}}\right) R_{S1}}{\left(\frac{A_{v1}}{A_{v2}}\right) - 1}$$

Calculation:

$$\frac{A_{v1}}{A_{v2}} = \frac{8.2}{7.55} \approx 1.0861$$

$$R_{in} = \frac{10\,000\,\Omega - (1.0861) \times 50\,\Omega}{1.0861 - 1} = \frac{10\,000\,\Omega - 54.305\,\Omega}{0.0861} = \frac{9945.695\,\Omega}{0.0861} \approx 115\,513\,\Omega$$

Thus, the calculated input impedance is $R_{in} \approx 115.5\,\text{k}\Omega$.

R_{out} Calculation

R_L	V_{out}/V_{in} at 100 kHz
(open circuit)	8.95
10 Ω	4.85
R_{out}	8.45 Ω

Table 5: The small-signal output impedance

$$A_{vL} = A_{voc} \times \frac{R_L}{R_L + R_{out}}$$

Now, substitute the given values:

$$R_{out} = 10\,\Omega \times \frac{8.95 - 4.85}{4.85}$$

$$R_{out} = 10\,\Omega \times \frac{4.10}{4.85}$$

$$R_{out} \approx 10\,\Omega \times 0.8454$$

$$R_{out} \approx 8.45\,\Omega$$

Therefore, the small-signal output impedance of the amplifier at 100 kHz is approximately $8.45\,\Omega$.

Phase and Phase Margin

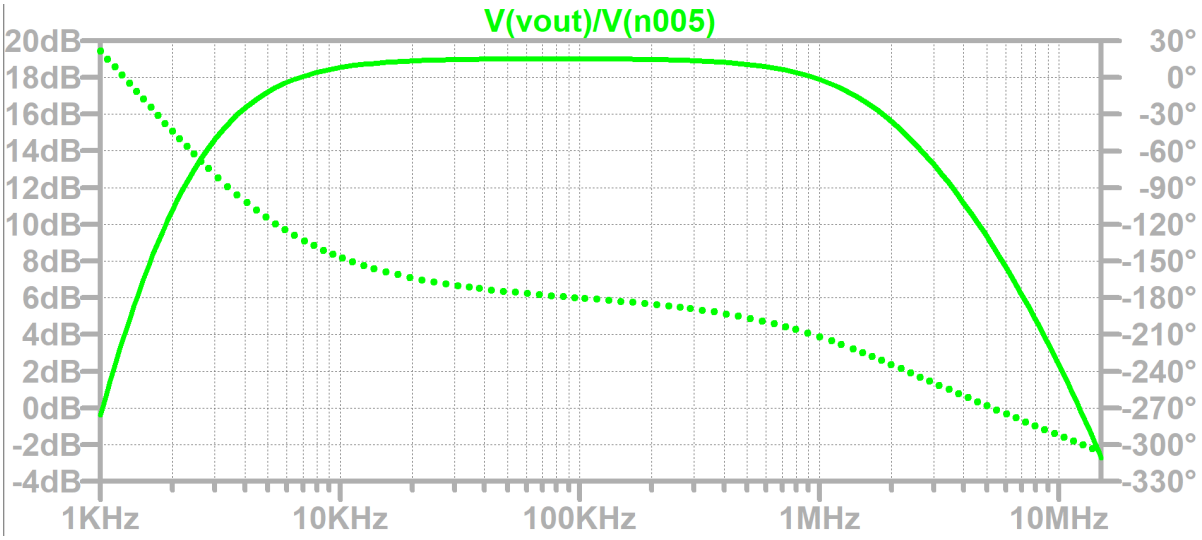

Figure 10: Open loop voltage gain

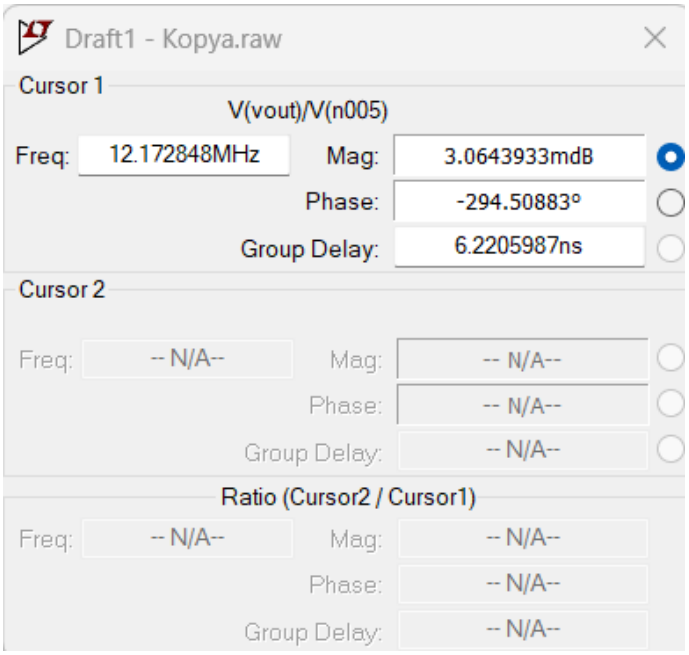

Figure 11: Phase and Phase Margin

f (MHz)	Phase (degrees)	PM (degrees)
12.17	-294	64

Table 6: phase margin (PM) of the open-loop system

5 EXPERIMENTAL WORK

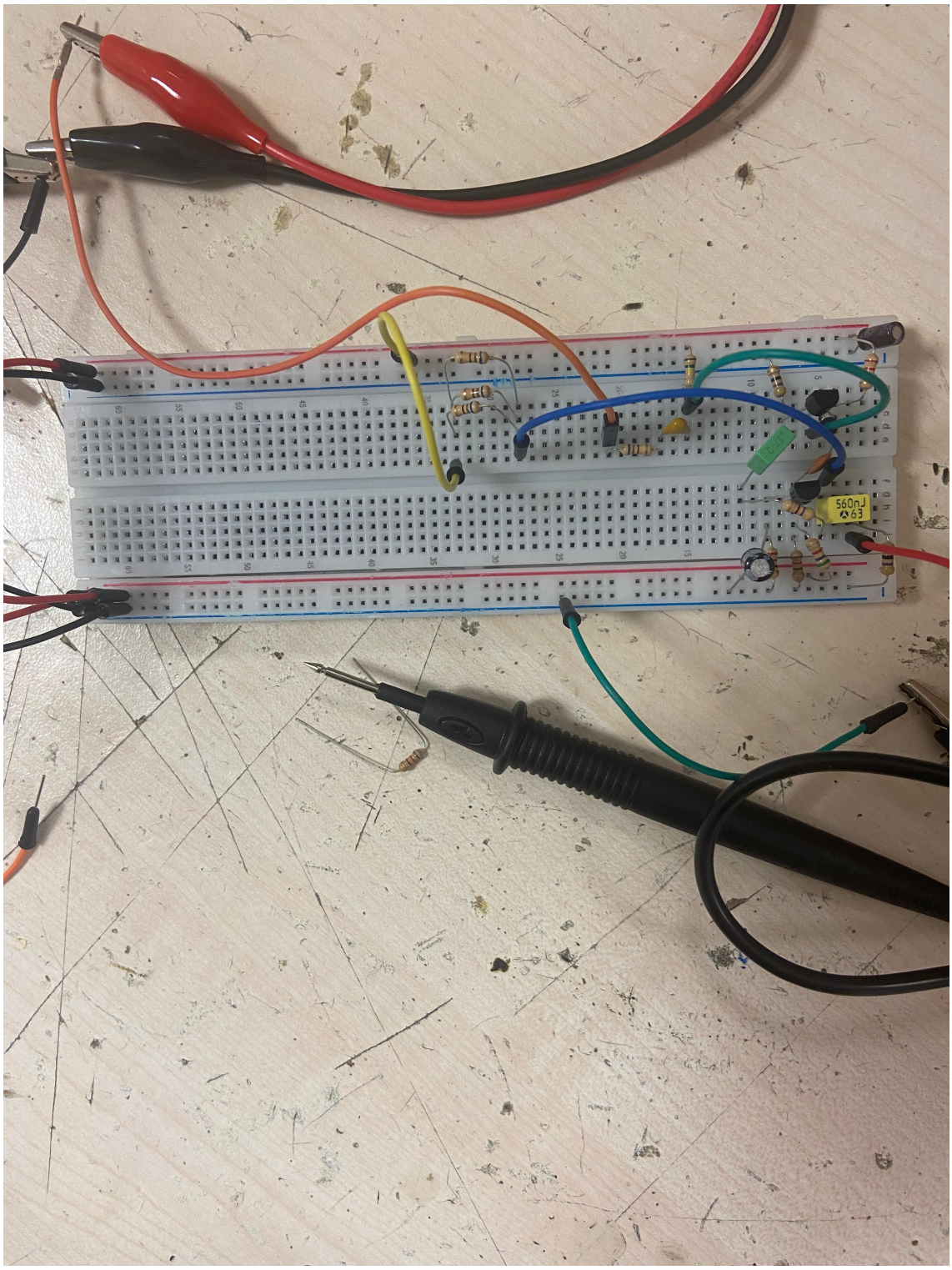

Figure 12: Wide-Band Amplifier with Feedback Circuit Design

Average Current

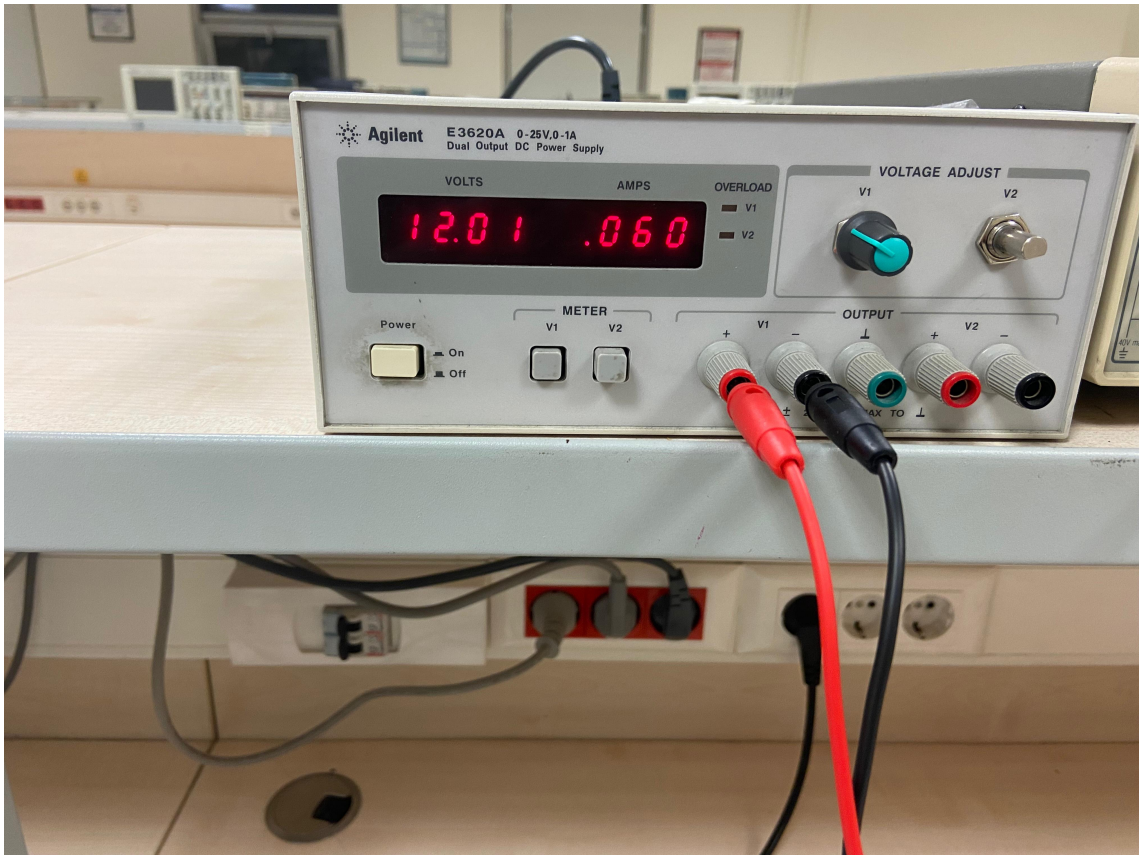

Figure 13: Average Current

As we can see in Figure 13, the average current consumption is less than 70 mA.

I_c (mA)	60 mA

Table 7: Average Current

Small-signal Bandwidth

40 kHz input

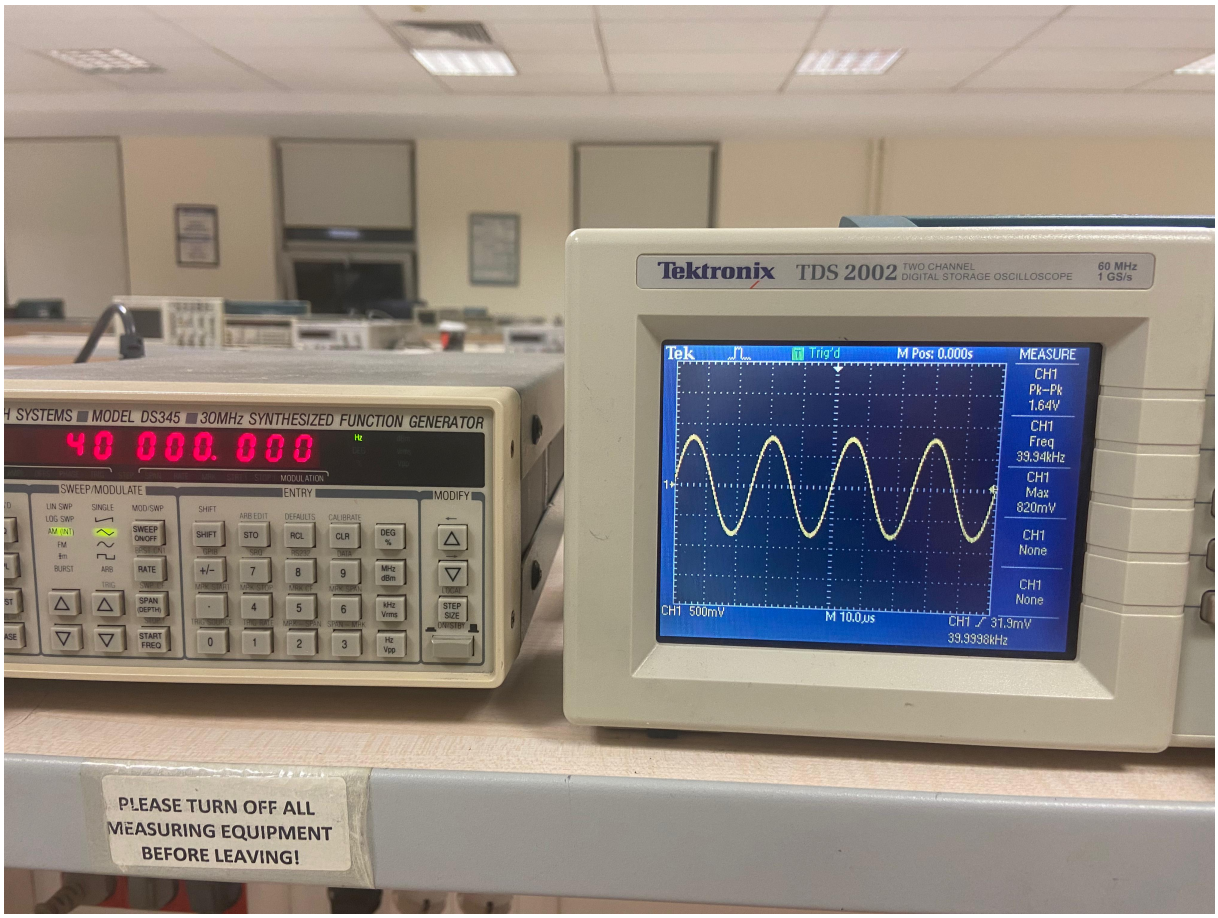

Figure 14: $V_{out(pp)} = 1.64V$ when 40 kHZ input signal

400 kHz input

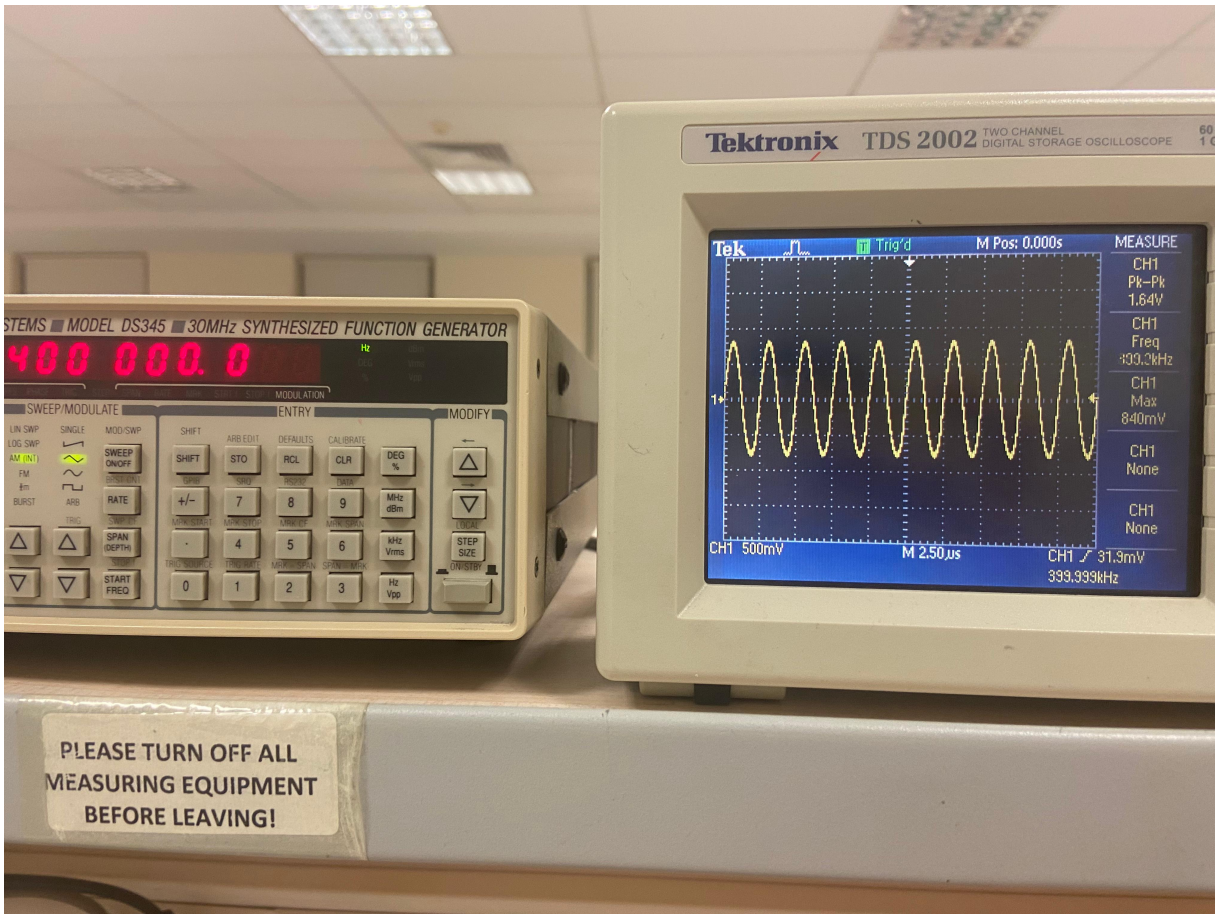

Figure 15: $V_{out(pp)} = 1.64V$ when 400 kHZ input signal

4 MHz input

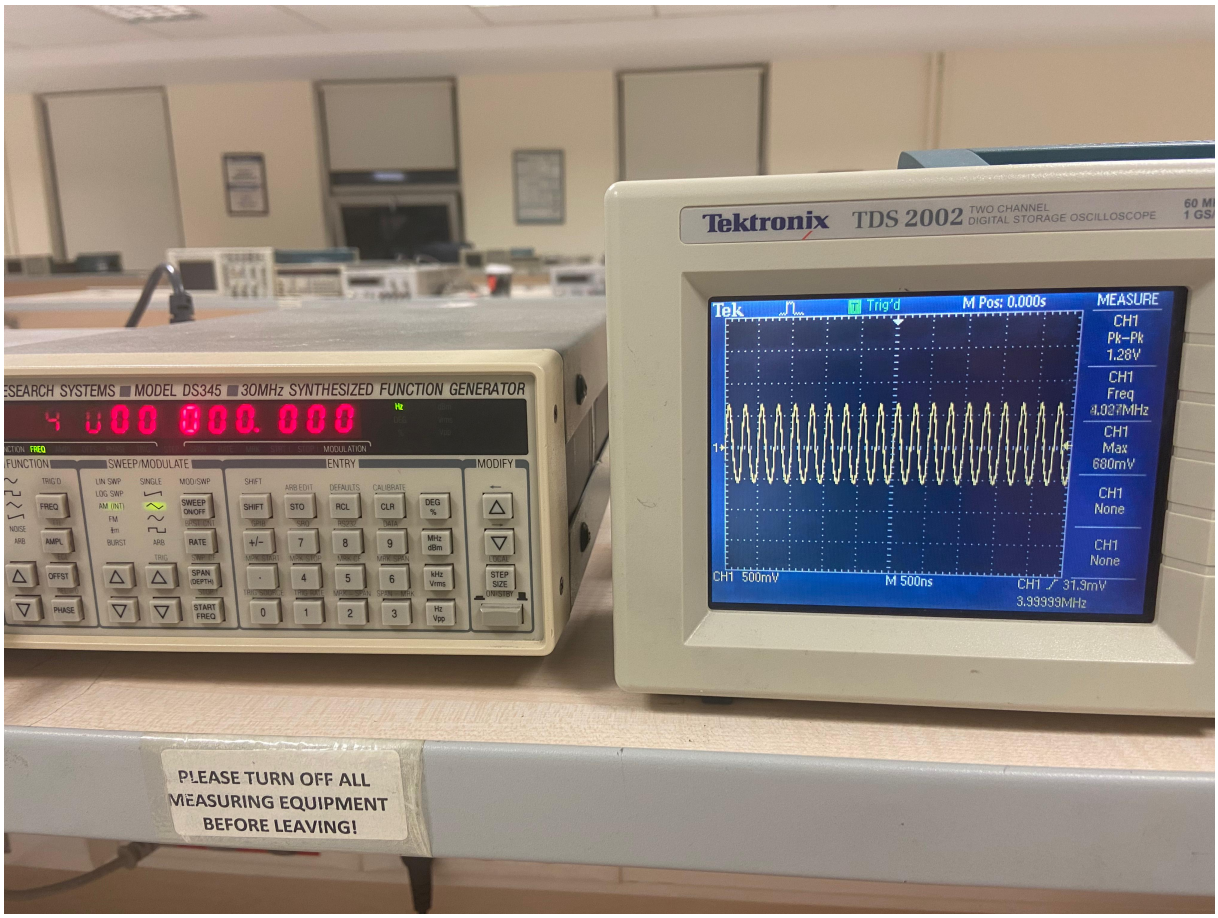

Figure 16: $V_{out(pp)} = 1.28V$ when 4 MHZ input signal

f (kHz)	$V_{in(pp)}$ (mV)	$V_{out(pp)}$ (V)	V_{out}/V_{in} (dB)
40	200	1.64 V	18.27 dB
400	200	1.64 V	18.27 dB
4000	200	1.28 V	16.12 dB

Table 8: The small-signal bandwidth

As we can see in Figure 14, Figure 15 and Figure 16, 3dB bandwidth is at least 40 KHz-4 MHz while the mid-band (400KHz) gain is 18.27 dB.

Harmonics

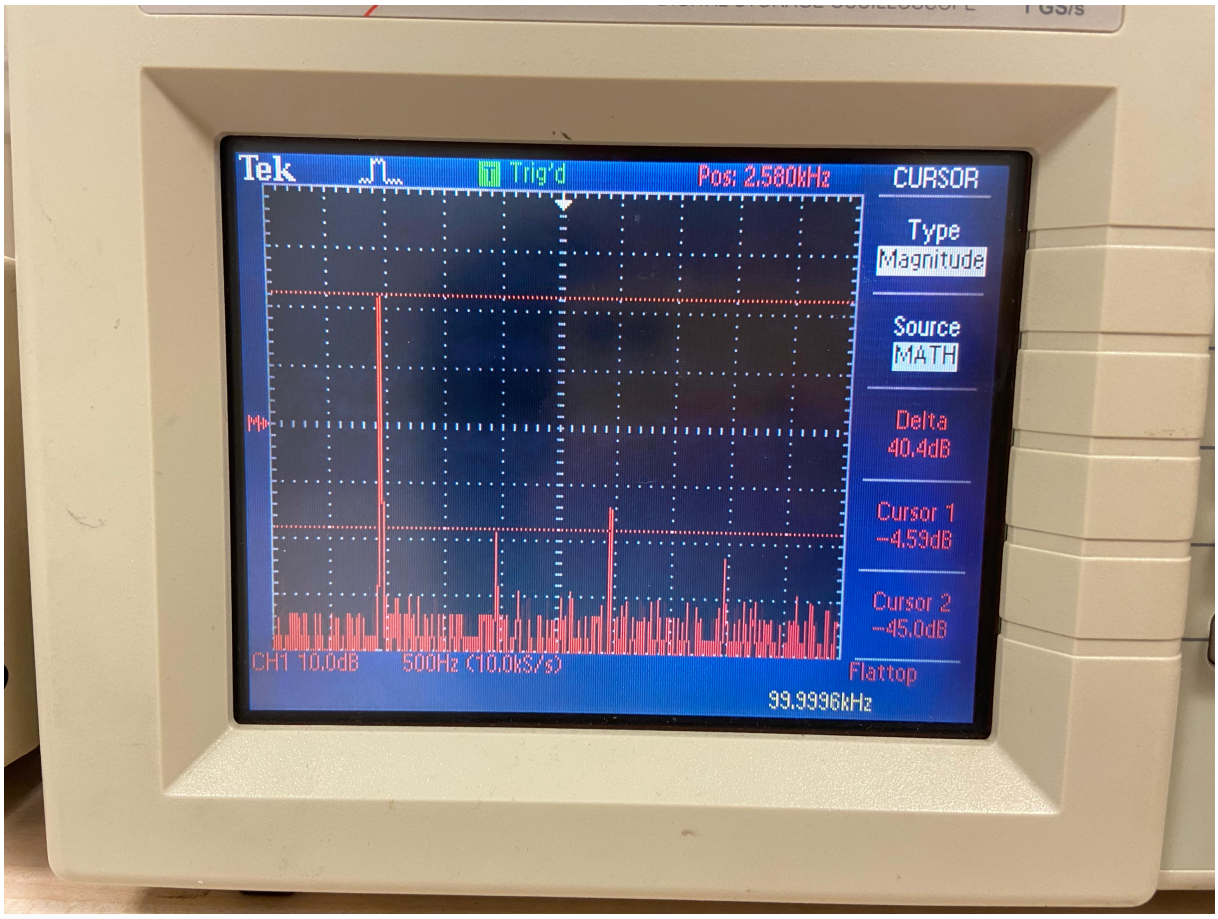

Figure 17: First and second harmonics

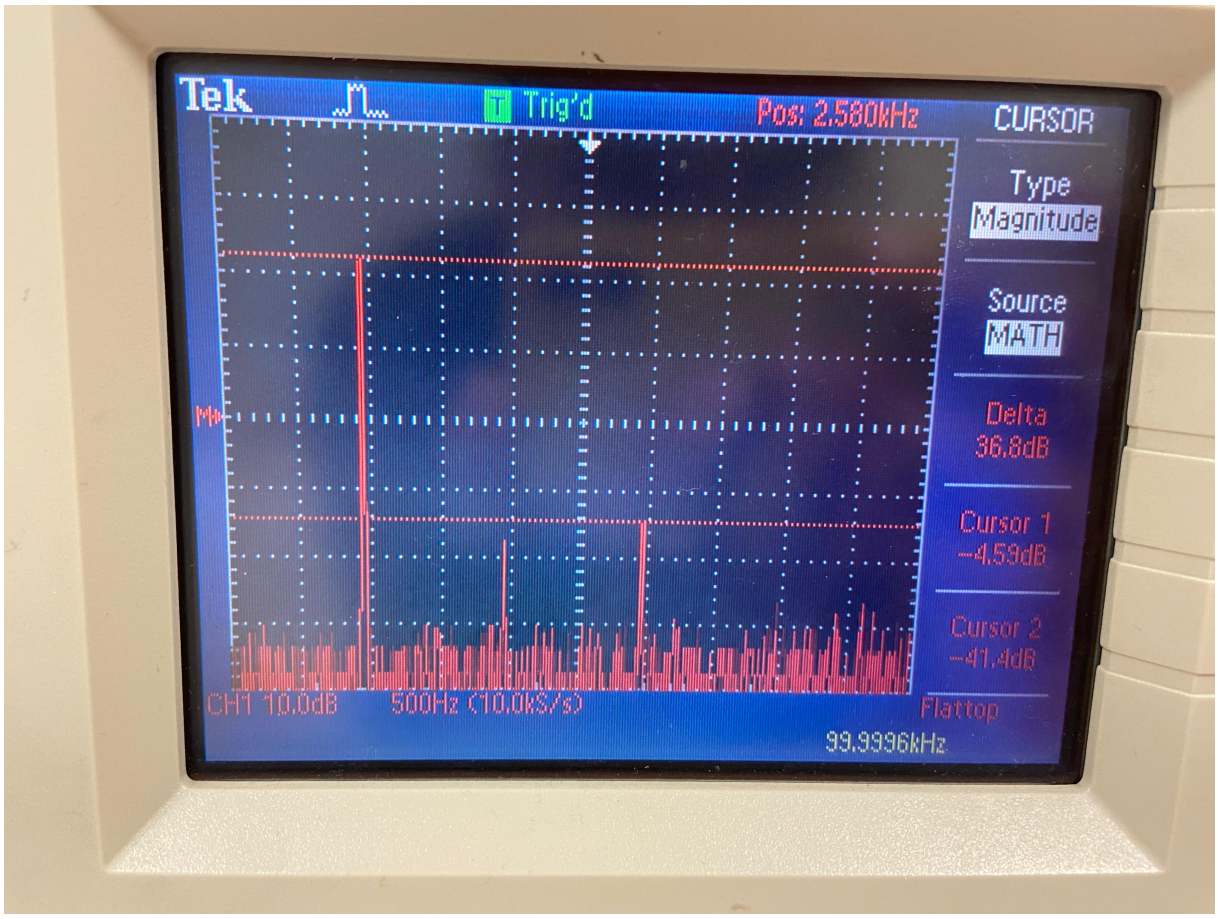

Figure 18: First and third harmonics

f (kHz)	V_{out} (dB)
100	-4.59 dB
200 (2nd harmonic)	-45.0 dB
300 (3rd harmonic)	-41.48 dB

Table 9: The harmonic content of the output voltage

We see harmonics in Figure 17 and Figure 18. The harmonic content of the output voltage is better than 30dBc at 100 KHz.

R_{in} Calculation

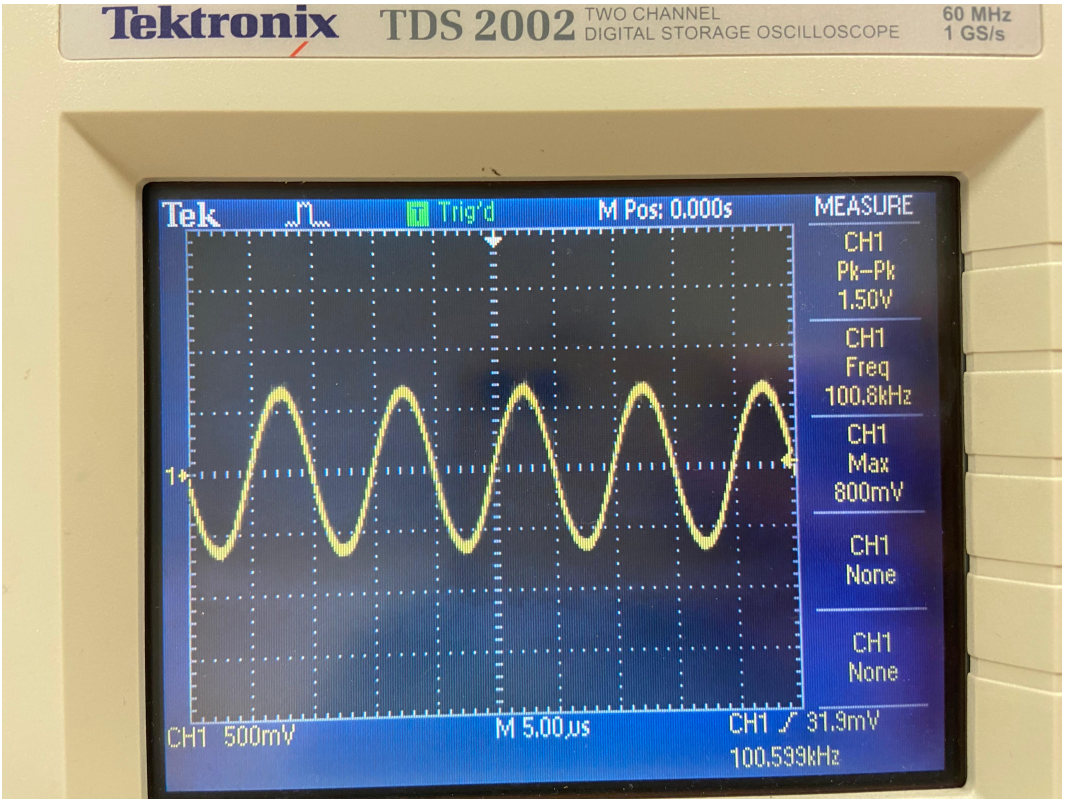

Figure 19: $V_{out} = 1.50$ when $R_L = 50\ \Omega$

$$R_{in} = \frac{R_{S2} - \left(\frac{A_{v1}}{A_{v2}}\right) R_{S1}}{\left(\frac{A_{v1}}{A_{v2}}\right) - 1}$$

- $A_{v1} = 7.5$ (for $R_L = 50\,\Omega$)
- $A_{v2} = 7.0$ (for $R_L = 10\,\text{k}\Omega$)
- $R_{S1} = 50\,\Omega$
- $R_{S2} = 10\,\text{k}\Omega = 10\,000\,\Omega$

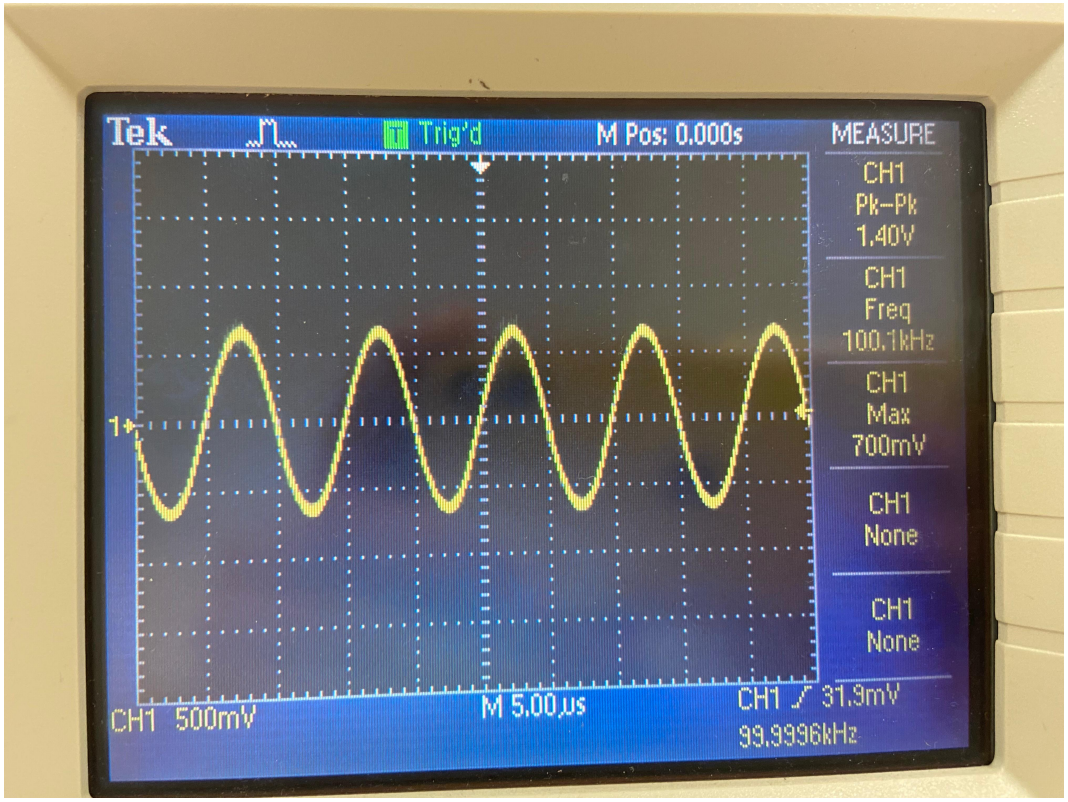

Figure 20: $V_{out} = 1.40$ when $R_L = 10\ k\Omega$

$$\frac{A_{v1}}{A_{v2}} = \frac{7.5}{7.0} = \frac{75}{70} = \frac{15}{14} \approx 1.0714$$

$$R_{in} = \frac{10\,000\,\Omega - \left(\frac{15}{14}\right) \times 50\,\Omega}{\left(\frac{15}{14}\right) - 1}$$

$$R_{in} = \frac{10\,000\,\Omega - \frac{750}{14}\,\Omega}{\frac{1}{14}}$$

$$R_{in} \approx 139\,291.74\,\Omega$$

The calculated input impedance is:

$$R_{in} \approx 139.29\,\text{k}\Omega$$

R_L	V_{out}	V_{out}/V_{in} at 100 kHz
50 Ω	1.50 V	7.5
10 kΩ	1.40 V	7.0
R_{in}		$139k\Omega$

Table 10: The small-signal input impedance

R_{out} Calculation

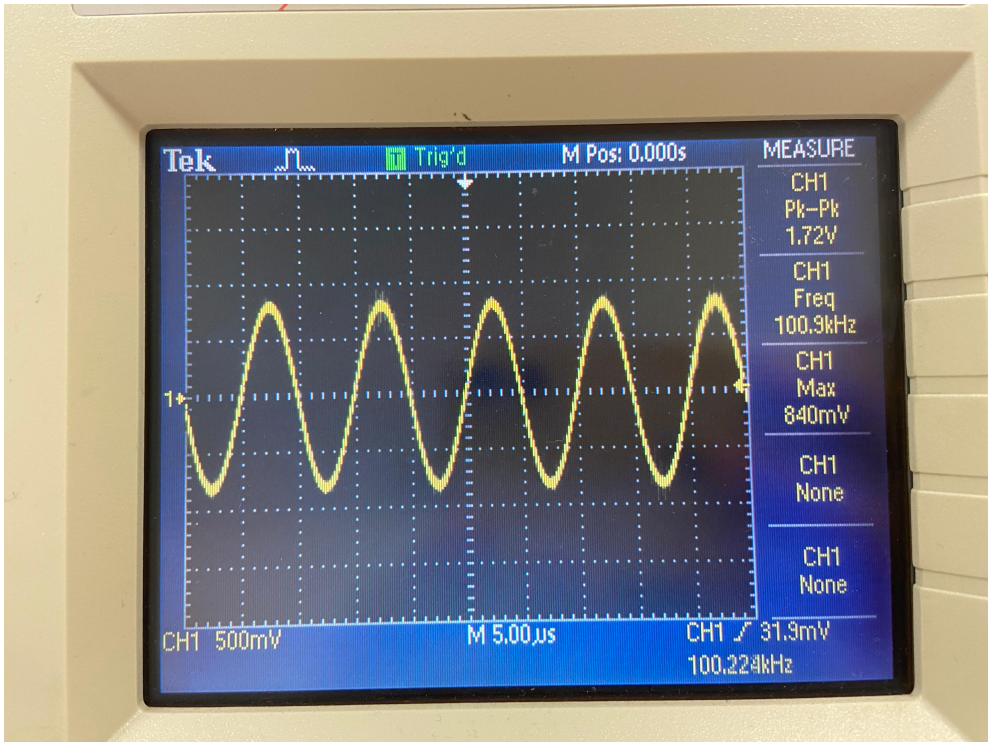

Figure 21: $V_{out} = 1.7$ when $R_L = \infty$

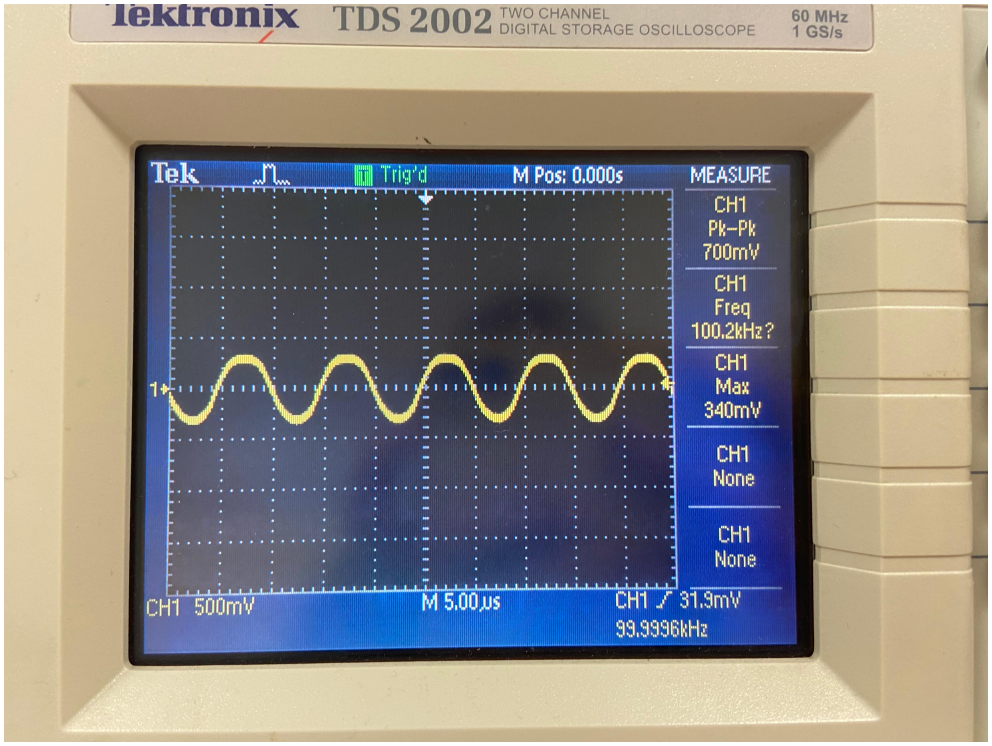

Figure 22: $V_{out} = 0.7$ when $R_L = 10\ \Omega$

R_L	V_{out}	V_{out}/V_{in} at 100 kHz
(open circuit)	1.70 V	8.5
10 Ω	0.7 V	3.5
R_{out}		14.29 Ω

Table 11: The small-signal output impedance

$$A_{vL} = A_{voc} \times \frac{R_L}{R_L + R_{out}}$$

Now, substitute the given values:

$$\begin{aligned} R_{out} &= 10\,\Omega \times \frac{1.7\,\text{V} - 0.7\,\text{V}}{0.7\,\text{V}} \\ R_{out} &= 10\,\Omega \times \frac{1.0\,\text{V}}{0.7\,\text{V}} \\ R_{out} &\approx 10\,\Omega \times 1.4286 \\ R_{out} &\approx 14.29\,\Omega \end{aligned}$$

Therefore, based on these values, the small-signal output impedance of the amplifier at 100 kHz would be approximately 14.29 Ω.

6 Conclusion

In this preliminary lab, we designed and simulated a wide-band feedback amplifier to meet specific performance goals. We calculated component values for desired DC and AC characteristics, using BJT principles and feedback for gain control. Simulation results confirmed the circuit met specifications, and we analyzed impedance and phase margin for stability. The experimental phase involved component adjustments to achieve these specifications. Bandwidth proved challenging but was optimized for a balanced circuit, supported by experimental data. This lab provided valuable practical insights into amplifier design and component selection for performance targets.