FACULTY OF INFORMATION TECHNOLOGY AND ELECTRICAL ENGINEERING

DEGREE PROGRAMME IN ELECTRONICS (MASTER'S)

Course Name: 521304A Filters – Simulation Exercise

Firstname Lastname: Arafat Miah

Study right number: 2512200

Table of Contents

Abstract and AI usage .... **Error! Bookmark not defined.**
1. Multiple-Feedback filter demos 4
   1.1. After first simulation 4
   1.2. Circuit A 4
   1.3. Circuit B 5
   1.4. Circuit C 7
   1.5. Distortion 8
2. A Third-order Active-RC All-pole Filter 10
3. Circuit A - a balanced version 13
4. Ladder filter with Transfer function D 15
5. All-pass equalizer (APE) for Transfer function D 17
Feedback 20
Appendices 21
   Appendix 1 21
   Appendix 2 24
   Appendix 3 27
   Appendix 4 30

Abstract

This work presents the design and LTspice simulation of multiple analog filter circuits based on given transfer functions and Chebyshev prototype tables. The tasks include implementing active-RC filter sections, building a 3rd-order all-pole filter, converting a low-pass ladder prototype into a band-pass ladder (LP→BP), and applying an all-pass equalizer concept to improve group-delay behavior while keeping the magnitude response essentially unchanged. Simulation results (magnitude, phase, and group delay) were generated and compared to the target responses, and a MATLAB script was used to visualize the pole–zero map of the optimized all-pass equalizer.

AI usage statement

AI was used only for writing support and clarification (e.g., improving wording/structure, explaining task requirements, and interpreting simulation plots). All circuit design decisions, LTspice implementation, simulations, parameter selection, group-delay measurements, and MATLAB code creation were done by me. AI was used as a guideline when something was unclear, but it did not produce the final technical work.

1. Multiple-Feedback filter demos

1.1. After first simulation

My parameter ddmmyy:151299

Simulate and press control-L to get the circuit element parameters. Document them below.

R1 = 1512.99 Ω
R2 = 1071.1152 Ω
R3 = 1512.99 Ω
C1 = 164.7186 nF
C2 = 2.3116 μF

1.2. Circuit A

(i) Which prototype filter function does Circuit A implement?
Circuit A implements a **Chebyshev 3 dB low-pass prototype (2nd-order biquad)** rather than Butterworth. Butterworth is maximally flat in the passband (monotonic, no ripple/shape variation), while Chebyshev uses a controlled ripple/peaking behavior to achieve a faster transition to the stopband. The parameter set used in Circuit A (w01, Q, K) matches the standard Chebyshev 3 dB prototype values for a **2nd-order section**, and the simulated magnitude response is consistent with a Chebyshev-type behavior.

(ii) Filter order
Circuit A is a **2nd-order** active filter (one biquad section → one complex pole pair). This is visible from the single resonant tendency and the final roll-off behavior typical of a 2nd-order low-pass section.

Simulation evidence
The simulated **frequency response of Circuit A** is included in Fig.1 , showing the expected low-pass behavior of the designed 2nd-order Chebyshev section.

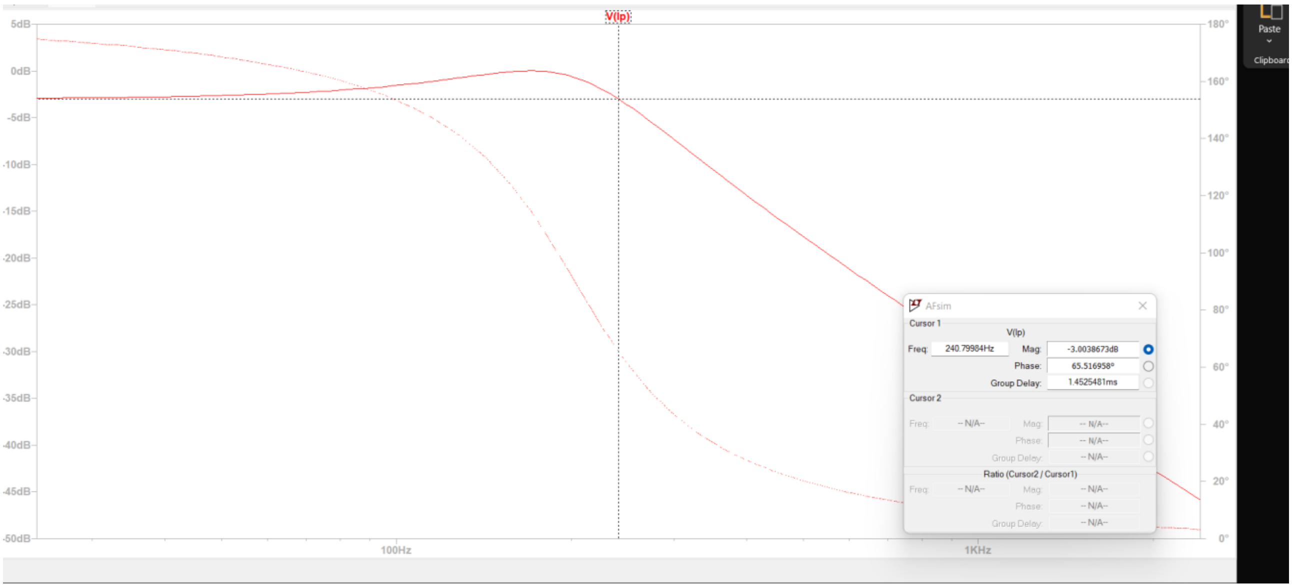

Figure 1: Frequency response of Circuit A.

1.3. Circuit B

Objective

Circuit B topology is already a Multiple-Feedback (MFB) high-pass structure.
However, its parameter values were placeholders. The goal of this task is to redesign the parameter values of Circuit B so that its cutoff frequency matches the cutoff frequency of Circuit A.

Method Used

The low-pass to high-pass transformation was performed using the standard RC→CR substitution rule:

$$R \to \frac{1}{\omega_p C} \qquad C \to \frac{1}{\omega_p R}$$

where the actual pole frequency of Circuit A is:

$$\omega_p = w01 \cdot w0$$

This ensures that both circuits share the same cutoff frequency.

The following parameter substitutions were implemented in Circuit B:

```
.param C3 = 1/(w0*R1)
.param C4 = 1/(w0*R3)
.param C5 = 1/(w0*R2)
.param R4 = 1/(w0*C2)
.param R5 = 1/(w0*C1)
```

Thus, each resistor in Circuit A was converted to a capacitor in Circuit B and each capacitor in Circuit A was converted to a resistor while preserving the cutoff frequency.

Result – Circuit Diagram

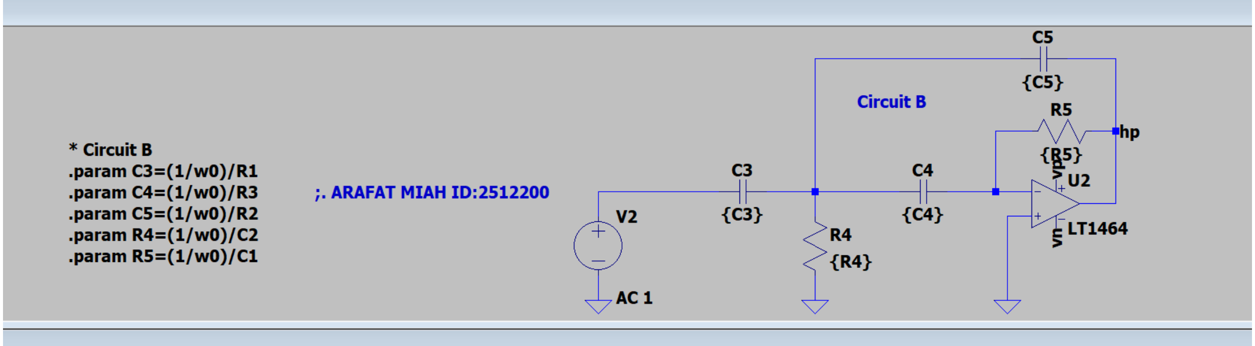

Figure 2: Frequency response of Circuit B.

The topology remains unchanged. Only the `.param` definitions were modified to match the cutoff of Circuit A.

Frequency Response Verification

To verify correct matching:

- The magnitude response of Circuit A (V(lp)) and Circuit B (V(hp)) were plotted on the same Bode diagram.
- The cutoff frequency was determined at the −3 dB point.

From the cursor measurement:

$$f_c \approx 240.8 \text{ Hz}$$

At this frequency:

- Circuit A shows approximately −3 dB (low-pass cutoff)
- Circuit B shows approximately −3 dB relative to its passband (high-pass cutoff)

This confirms that both filters share the same cutoff frequency.

Result – Frequency Response

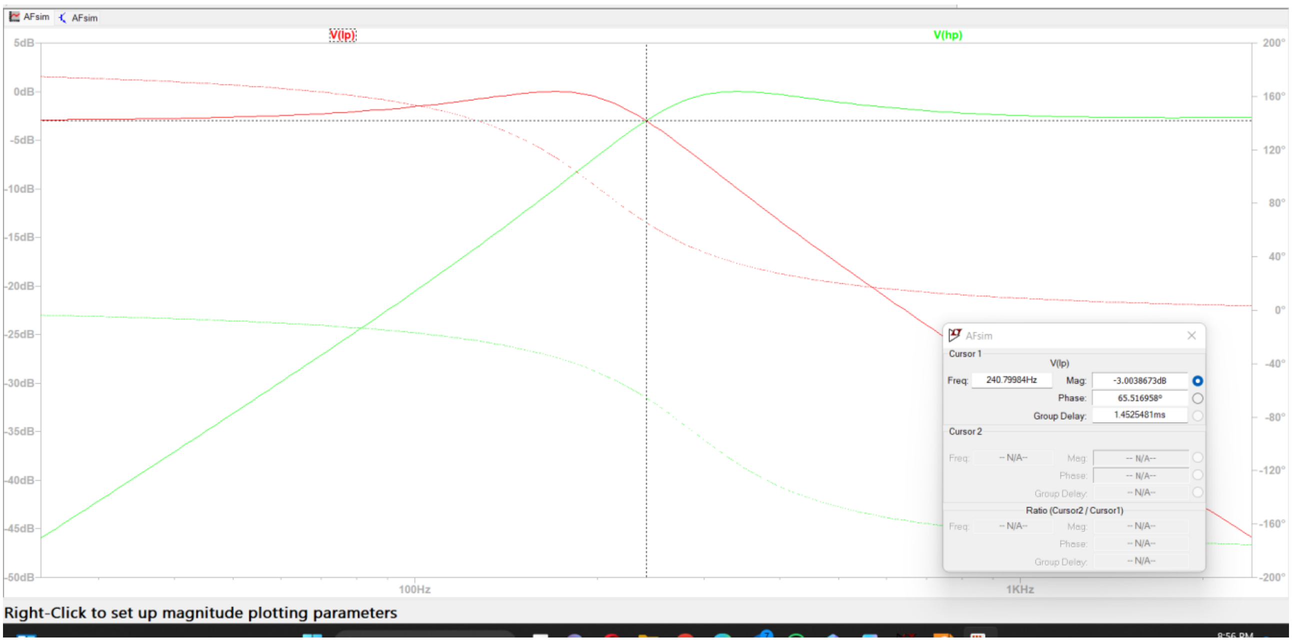

Figure 3: Bode Plot of Circuit A (LP) and Circuit B (HP) – Cutoff Matching

Observations:

- Circuit A exhibits low-pass behavior.
- Circuit B exhibits high-pass behavior.
- The cutoff frequencies coincide.
- The responses are complementary around the same transition frequency.

1.4. Circuit C

(1) What is this structure known as?

Circuit C is a **Delyiannis–Friend (Multiple-Feedback, MFB) active band-pass biquad**. This is confirmed by the topology (op-amp with two capacitors and two resistors in a multiple-feedback band-pass configuration) and by the band-pass magnitude response with a single resonance peak.

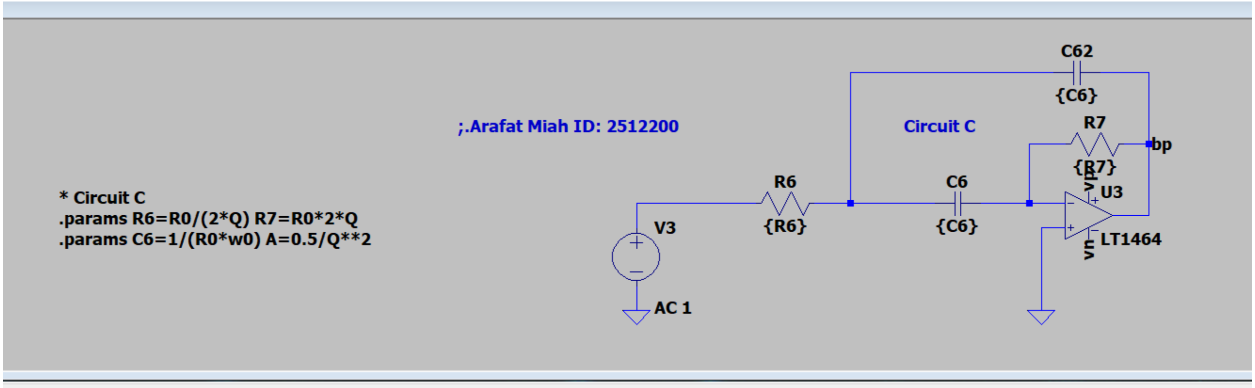

Figure 4. LTspice schematic for Circuit C with 0dB at passband.

---

(2) What is the order of Circuit C?

Circuit C is a **2nd-order** filter because its transfer function denominator is a **2nd-degree polynomial in** s(one biquad section → one complex pole pair).

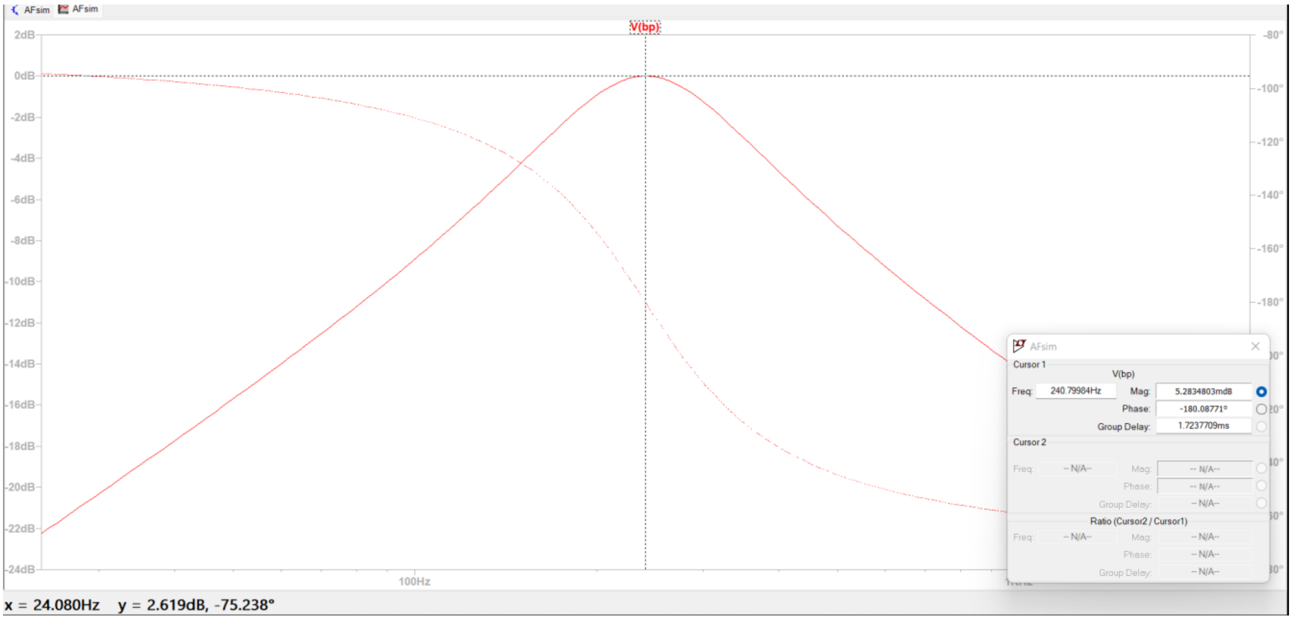

Figure 5. Frequency response for Bandpass Circuit C with 0dB at passband.

1.5. Distortion

To test the effect of non-ideal op-amp behavior, the frequency-scaling parameter was increased by a factor of 10^4:

$$w0_{new} = 10000 \cdot w0$$

After running the AC simulation again, the responses of **V(lp)**, **V(hp)** and **V(bp)** no longer match the original ideal filter shapes. The curves show noticeable gain/shape deviations ("distortion") because the LT1464 is not an ideal op-amp: it has **finite open-loop gain and limited gain-bandwidth**, so at very high frequencies the required feedback action cannot be maintained. Therefore, the active RC filter coefficients effectively change and the magnitude/phase responses deviate from the designed prototype.

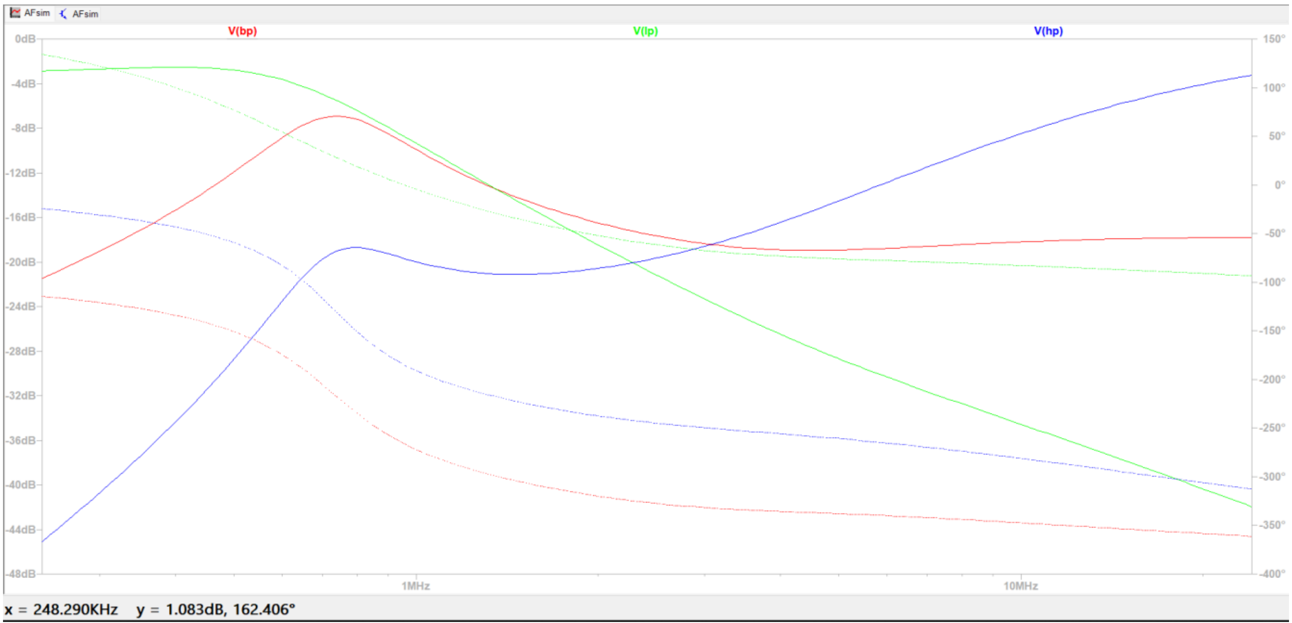

Figure 6: *AC frequency responses after setting* $w0 = 10000\times$*original value (non-ideal LT1464 causes deviation from ideal filter responses).*

2. A Third-order Active-RC All-pole Filter

Objective

The aim of this task is to design and simulate a **3rd-order active-RC all-pole low-pass filter** using the same prototype family as Circuit A (**Chebyshev 3 dB**). Circuit A is kept unchanged in the same LTspice file as a reference, and the frequency responses are compared.

Target transfer function

A 3rd-order all-pole low-pass response can be realized by cascading:

- one **2nd-order pole-pair section**, and
- one **1st-order real-pole section**.

So the intended factored form is:

$$H_3(s) = K \cdot \frac{\omega_{02}^2}{s^2 + \frac{\omega_{02}}{Q_2}s + \omega_{02}^2} \cdot \frac{\omega_{03}}{s + \omega_{03}}$$

This explains why two different normalized ωvalues appear in the table: one belongs to the quadratic (2nd-order) term and the other to the single real pole.

Parameter selection from Table 5.5 (Chebyshev 3 dB, N=3)

From **Table 5.5** for **N = 3**, the denominator is given as one real pole and one 2nd-order term:

- Real pole: $(s{+}0.2986){\rightarrow}\ \omega_{03} = 0.2986$
- Pole pair: $(s^2{+}0.2986s{+}0.839){\rightarrow}\ \omega_{02} = 0.9161,\ Q_2 = 3.068$

The LTspice normalized values used were:

- `w03 = 0.29862`
- `w02 = 0.916064`
- `Q2 = 3.06766`

All frequencies are then scaled by the course parameter `w0`.

LTspice implementation (task2.asc)

- Circuit A remains unchanged and its output is **V(lp)**.
- The 3rd-order filter is implemented as a cascade:

- **2nd-order active biquad stage** → intermediate node **2lp**
- **1st-order active pole stage** → final output node **3lp**

The following parameter block was used in LTspice:

```
; --- Task 2 parameters (3rd-order all-pole: 2nd-order + 1st-order pole) ---
.params w02=0.916064 w03=0.29862 Q2=3.06766
.params R4=1*R0 R6=1*R0 R7=R4 R8=R7
.param  R5=R1
.param  C4=Q2*(R6*R5+R6*R4+R5*R4)/(R4*R5*R6*w02*w0)
.param  C3=1/(R5*R6*C4*w02**2*w0**2)
.param  C5=1/(R8*w03*w0)
```

Personal Observation — why an op-amp stage is used instead of adding only a passive RC

A 3rd-order all-pole response can be obtained by cascading the 2nd-order active section with a **simple passive RC pole**, which would still produce a 3rd-order transfer function. However, placing a passive RC network directly after the 2nd-order active stage can **load** the previous stage (finite output impedance / finite input impedance), which may **shift the effective** $\omega_0$and **change** Q. As a result, the measured response may deviate from the intended Chebyshev prototype.
To avoid this interaction, the extra pole is implemented as an **active 1st-order stage using an op-amp**, which provides buffering (isolation) so the overall response matches the theoretical cascade more closely:

$$H_3(s) = H_2(s) \cdot H_1(s)$$

Simulation and comparison

AC analysis was executed and both outputs were plotted on the same graph:

- **V(lp)** → 2nd-order Circuit A reference
- **V(3lp)** → 3rd-order all-pole filter output

The 3rd-order response shows a steeper stopband roll-off than the 2nd-order response, which is consistent with an increased filter order.

Figures

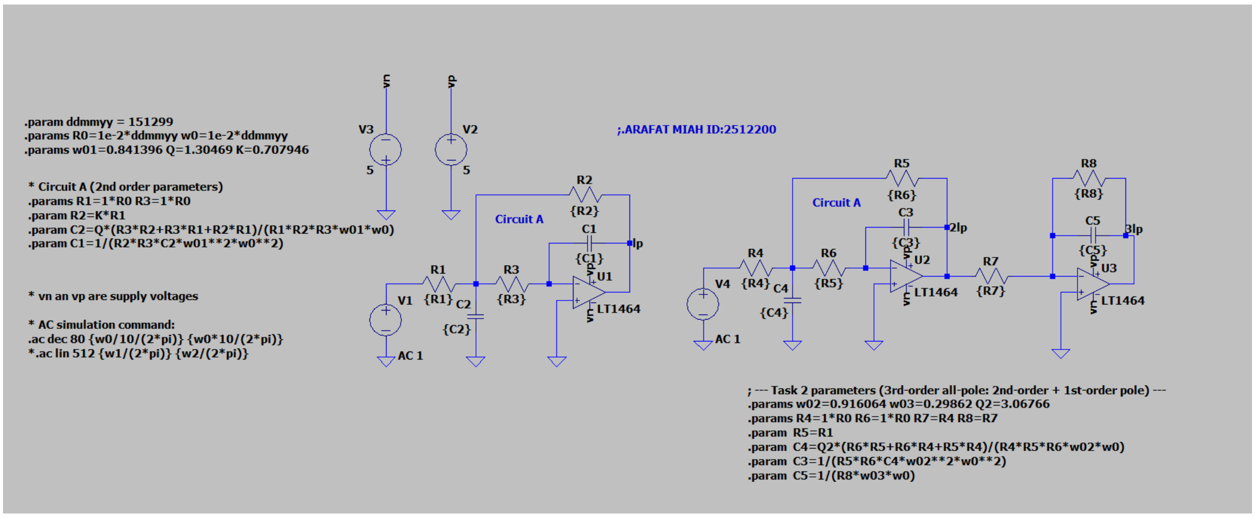

Figure 7: LTspice schematic for the third-order active-RC all-pole Filter.

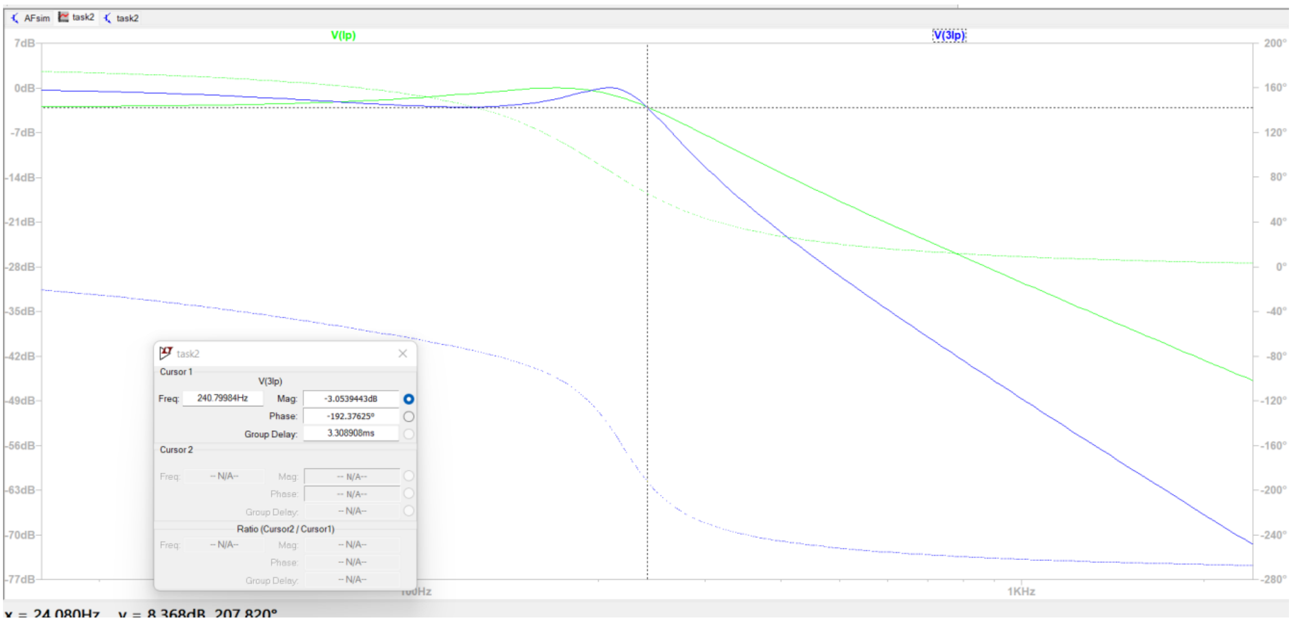

Figure 8: Frequency response of Circuit A and the 3rd order filter.

3. Circuit A - a balanced version

To implement the **balanced (differential) version of Circuit A**, the reference **balanced biquad (LT1994)** example was studied first to understand the correct way to drive and measure a fully differential filter. Using the same idea, Circuit A (single-ended MFB 2nd-order section) was converted into a **balanced structure** by creating two symmetric signal paths and measuring the output **differentially**.

In the balanced design, the single-ended op-amp **LT1464** is replaced by the **LT1994 fully-differential amplifier**, so the circuit can generate **two outputs**: `bp_p` and `bp_m`. The key output for comparison is the differential response:

$$V_{out,diff} = V(bp_p) - V(bp_m)$$

Also, the grounded capacitor from the single-ended version was implemented in the balanced form using the equivalent split value (**C2/2**) to keep the response consistent with the original design.

Finally, the magnitude response of **Circuit A (V(lp))** was plotted together with the balanced differential output **V(bp_p)−V(bp_m)**. The curves match closely, confirming that the balanced implementation reproduces the original filter response.

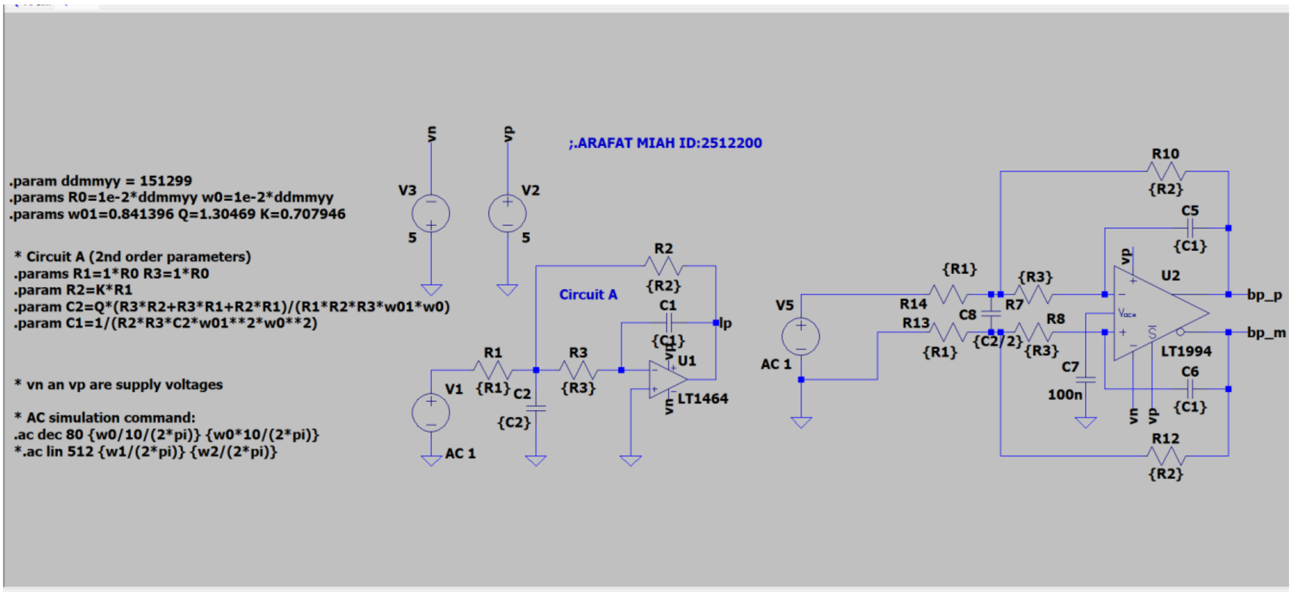

Figure 9: LTspice schematic for the balanced version of Circuit A.

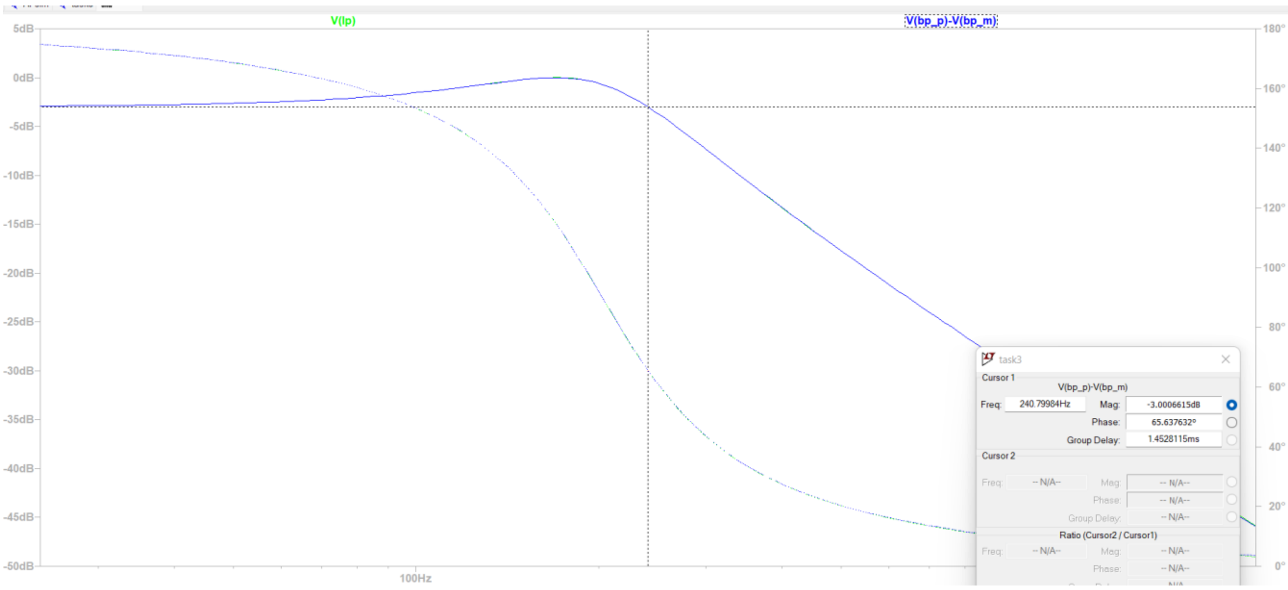

Figure 10: Frequency responses of Circuit A and the balanced version.

4. Ladder filter with Transfer function D

Design idea (what was done)

Transfer function D is a **band-pass (BP)** response obtained from a **low-pass (LP)** prototype using the **LP→BP transformation**.
The **LP→BP transform doubles the order**, so a **2nd-order LP ladder** becomes a **4th-order BP ladder** (because each LP reactive element becomes an LC resonator).
The normalized ladder coefficients were taken from **Table 11.5 for Chebyshev 3 dB ripple** with $r = \frac{R_S}{R_L} = \frac{1}{8}$. In this design, the selected prototype values are:

- $C_n = 6.1219$
- $L_n = 0.2596$

Scaling steps used

1. **Set impedance level** to avoid unrealistic component sizes:
   - Chose $R_0 = 1000\,\Omega$
   - $R_S = \frac{R_0}{8} = 125\,\Omega$
   - $R_L = R_0 = 1000\,\Omega$
2. **Impedance scaling** (LP prototype → real LP values):
   - $C_{LP} = \frac{C_n}{R_0}$
   - $L_{LP} = L_n \cdot R_0$
3. **Frequency transform to band-pass**:
   - $w_0 = 10^{-2} \cdot ddmmyy(\text{rad/s})$
   - $BW = 0.5 \cdot w_0$
4. **Transform elements**:
   - **Shunt capacitor → parallel resonator**:
     $$C_1 = \frac{C_{LP}}{BW}, L_1 = \frac{BW}{w_0^2 C_{LP}}$$
   - **Series inductor → series resonator**:
     $$L_2 = \frac{L_{LP}}{BW}, C_2 = \frac{BW}{w_0^2 L_{LP}}$$

Circuit Representation and Simulation

The LTspice circuit schematic is shown in **Figure 11**, where:

- **Transfer Function D** is implemented with a **Laplace behavioral source (B1)** to compare with the ladder filter.
- The ladder network uses the scaled L_1, C_1, L_2, C_2 values from the LP-to-BP transformation.

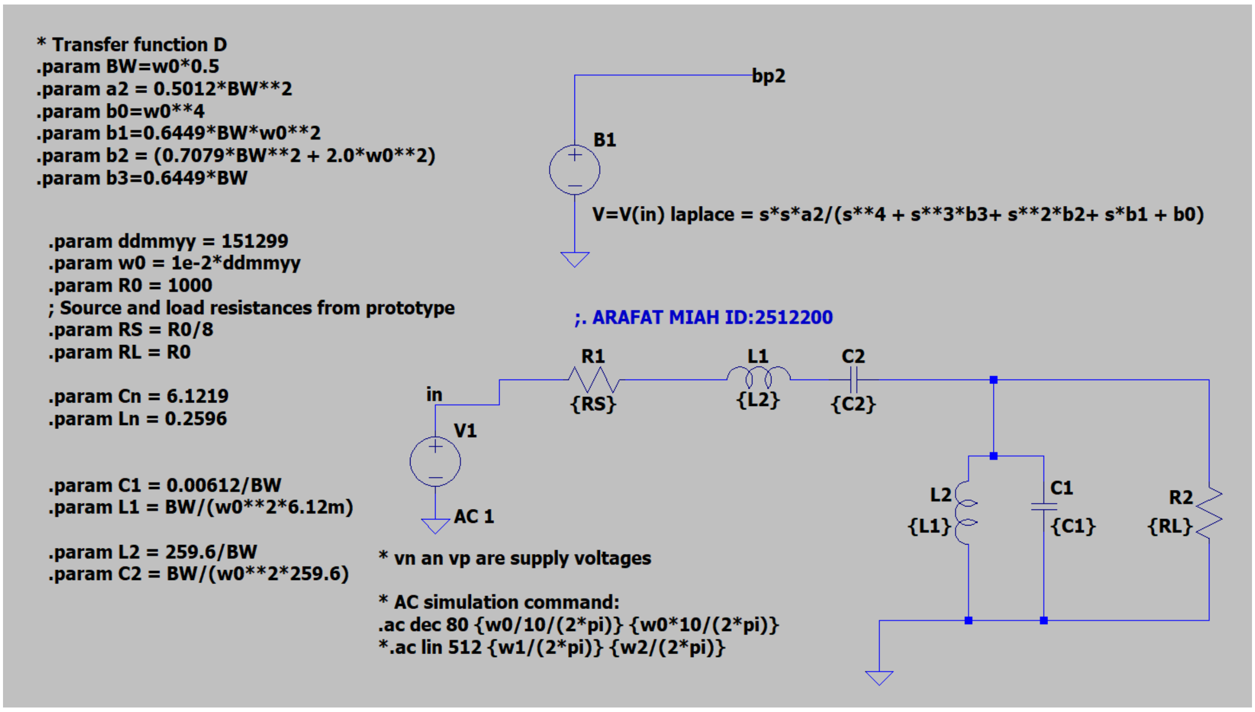

Figure 11: LTspice schematic for the bandpass ladder filter.

Simulation Result:

The frequency response (shown in **Figure 12**) successfully matches the desired bandpass filter characteristics with the calculated components. The ladder filter is compared with the Laplace output from **B1** to validate the design.

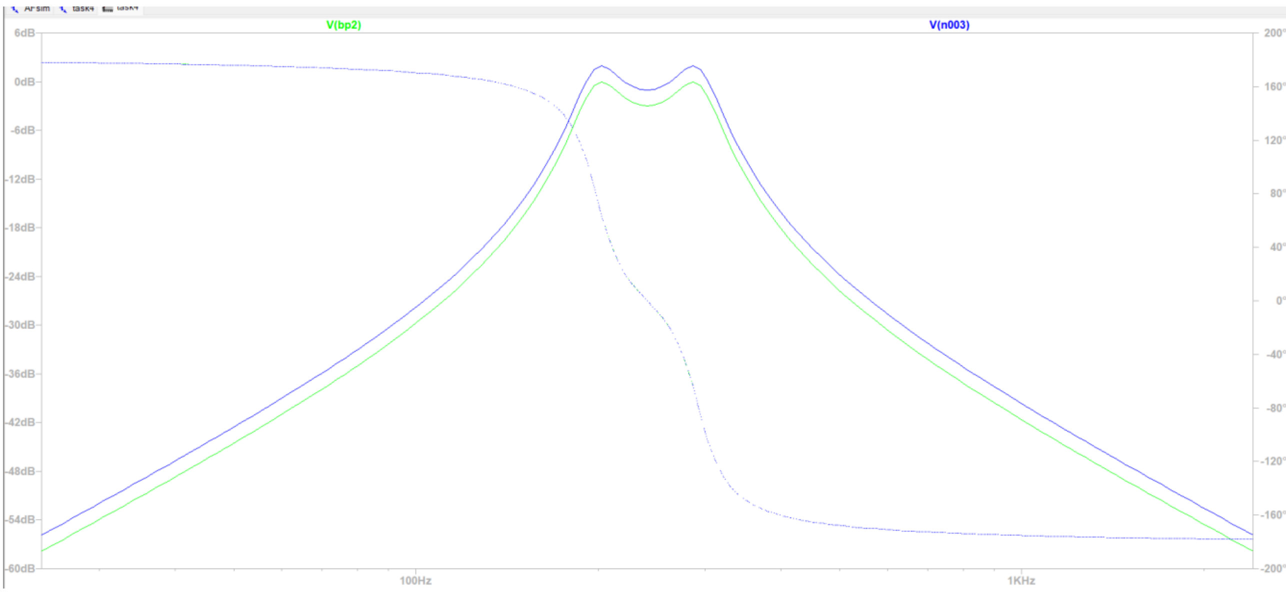

Figure 12: Frequency response of function D and the ladder filter.

5. All-pass equalizer (APE) for Transfer function D

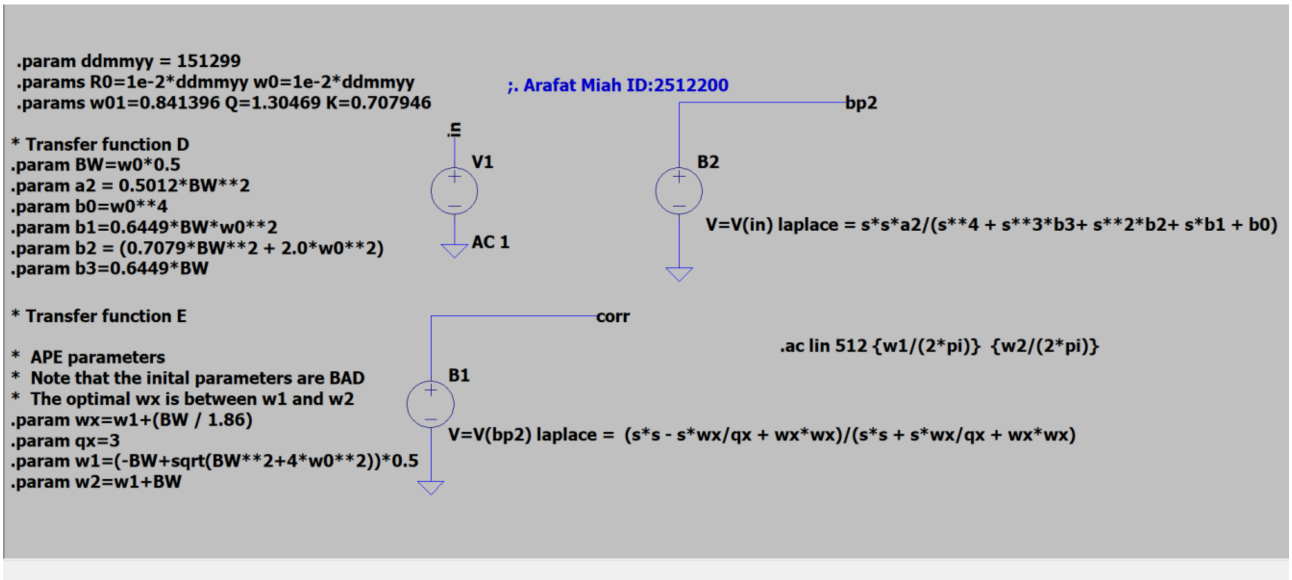

Figure 13: *LTspice schematic of Transfer functions D and E*

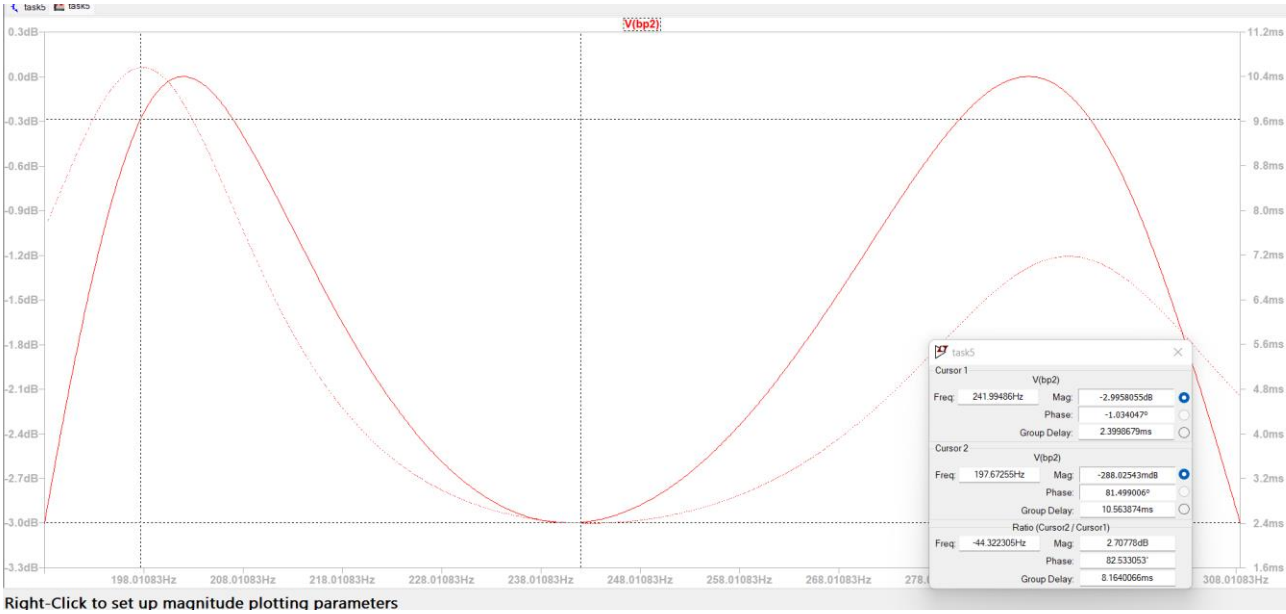

Figure 14: Magnitude and Group delay for function D.

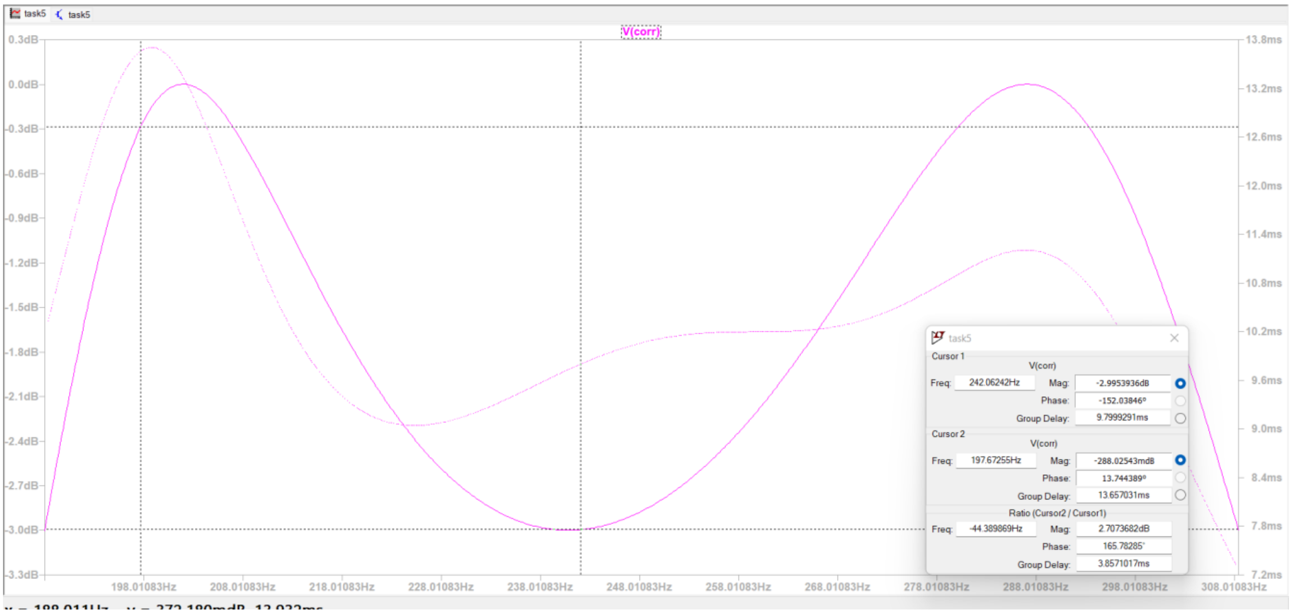

Figure 15: Magnitude and Group delay for function D with optimized All-pass equalizer.

```
% Task 5 matlab code — Pole-Zero map of the optimized All-Pass
Equalizer (APE)

ddmmyy = 151299;

% From my LTspice params
w0 = 1e-2 * ddmmyy;       % rad/s
BW = 0.5 * w0;            % rad/s

w1 = 0.5 * (-BW + sqrt(BW^2 + 4*w0^2));   % rad/s
w2 = w1 + BW;                             % rad/s

% Optimized APE parameters
qx = 3;
wx = w1 + (BW/1.86);

% APE transfer function: H(s) = (s^2 - (wx/qx)s + wx^2) / (s^2 +
(wx/qx)s + wx^2)
num = [1, -wx/qx, wx^2];
den = [1,  wx/qx, wx^2];

z = roots(num);
p = roots(den);

% Plot pole-zero map
figure;
```

```
plot(real(z), imag(z), 'bo', 'MarkerSize', 10, 'LineWidth', 2);
hold on;
plot(real(p), imag(p), 'rx', 'MarkerSize', 10, 'LineWidth', 2);
grid on; axis equal;
xline(0); yline(0);
xlabel('Real Axis'); ylabel('Imag Axis');
title('Pole-Zero Map of Optimized APE');
legend('Zeros','Poles','Location','best');
text(0.98, 0.02, 'Arafat Miah (ID:2512200)', ...
    'Units','normalized', ...
    'HorizontalAlignment','right', ...
    'VerticalAlignment','bottom', ...
    'FontWeight','bold');

hold off;
```

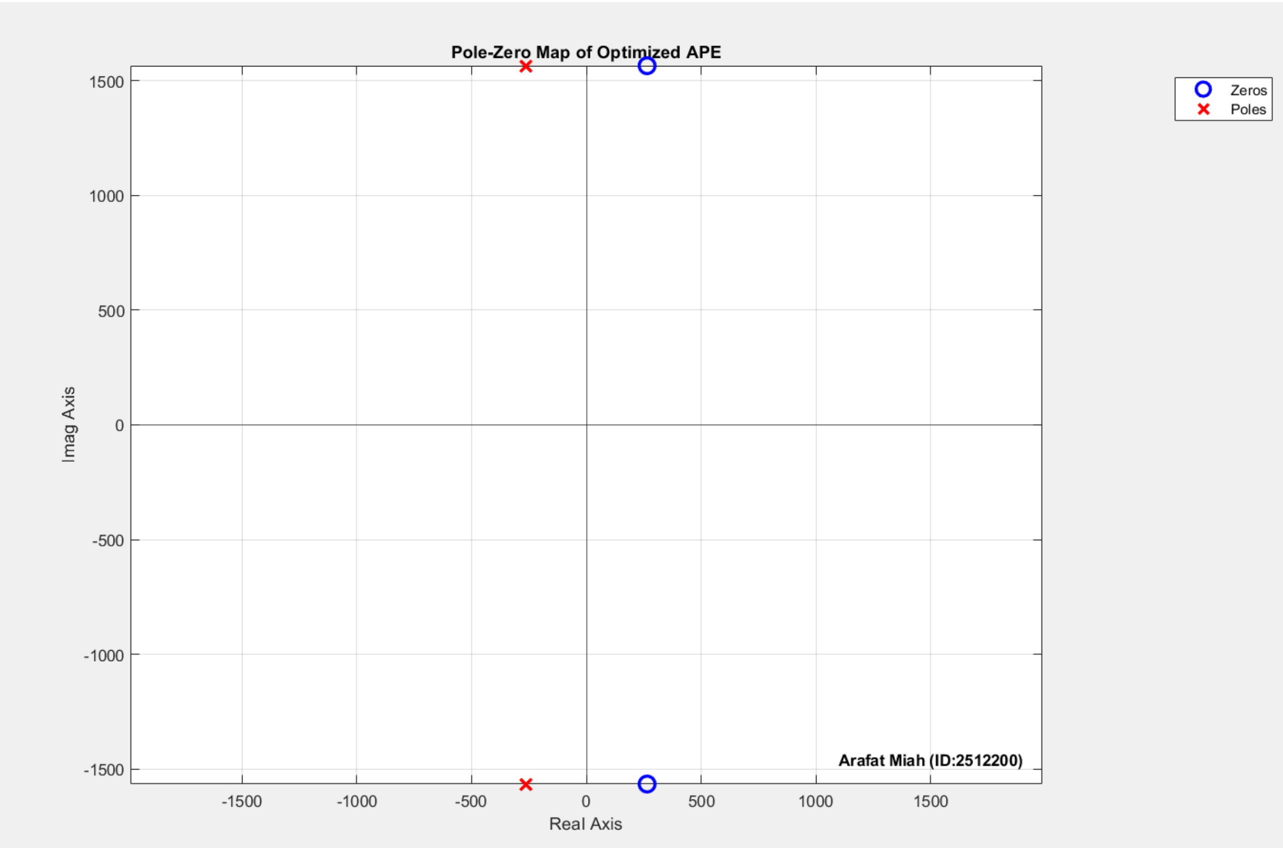

Figure 16: Pole-Zero Map for the optimized All-pass equalizer.

Feedback

This simulation work was very useful for connecting theory (transfer functions, Chebyshev tables, and transformations) with practical implementation in LTspice. It improved understanding of staging/loading effects, order changes in LP→BP transformations, and why an all-pass equalizer can reduce group-delay variation without changing magnitude. The most challenging part was correctly measuring and comparing group delay and tuning the equalizer parameters, but the final results made the objective clear and meaningful.

Appendices

Appendix 1

```
r1 n001 n003 1512.99
r2 lp n001 1071.11521854
r3 n002 n001 1512.99
c1 lp n002 1.64718581031167e-07
c2 0 n001 2.3115971953193e-06
v1 n003 0 ac 1
v2 n006 0 ac 1
r4 n004 0 1
r5 hp n005 1
c3 n004 n006 4.36845518571022e-07
c4 n005 n004 1
c5 hp n004 1
v3 n009 0 ac 1
r7 bp n008 3947.9658462
c6 n008 n007 4.36845518571022e-07
c62 bp n007 4.36845518571022e-07
r6 n007 n009 579.827391947513
a:u1:1 n002 0 0 0 0 0 0 0 ota g=0 in=.4f
c:u1:2 n002 0 1p
b:u1:1 0 u1:n004 i=10u*dnlim(uplim(v(0),v(vp)+.5,.1), v(vn)+1.5, .1)+1n*v(0)
b:u1:2 u1:n004 0 i=10u*dnlim(uplim(v(n002),v(vp)+.51,.1), v(vn)+1.49, .1)+1n*v(n002)
c:u1:9 vp n002 1.5p
c:u1:10 u1:n004 0 .5f rpar=100k noiseless
m:u1:1 vp u1:n005 lp lp u1:n temp=27
m:u1:2 vn u1:n005 lp lp u1:p temp=27
c:u1:3 vp lp .1p
d:u1:5 u1:n005 lp u1:y
d:u1:6 lp u1:n005 u1:y
r:u1:2 vp u1:n006 100g noiseless
r:u1:3 u1:n006 vn 100g noiseless
c:u1:4 lp vn .1p
c:u1:1 n002 vn 1.5p
c:u1:6 vp 0 1.5p
c:u1:7 0 vn 1.5p
a:u1:6 0 u1:n004 0 0 0 0 u1:n007 0 ota g=1.25u linear cout=58f en=24n enk=9 rout=1meg vhigh=1e308 vlow=-
1e308
d:u1:2 n002 vn u1:dbias
d:u1:4 0 vn u1:dbias
a:u1:3 0 u1:n007 0 0 0 0 u1:n006 0 ota g=20u iout=3.75u cout=3.97p vlow=-1e308 vhigh=1e308
g:u1:1 0 u1:n005 u1:n006 0 1µ
c:u1:8 0 u1:n005 11f rpar=1meg noiseless
d:u1:3 vp vn u1:dc
c:u1:11 u1:n006 lp 3p rser=300k noiseless
g:u1:2 u1:n006 0 u1:n006 vp 100m dir=1 vto=-1.1
g:u1:3 0 u1:n006 vn u1:n006 100m dir=1 vto=-1.1
a:u2:1 n005 0 0 0 0 0 0 0 ota g=0 in=.4f
c:u2:2 n005 0 1p
b:u2:1 0 u2:n004 i=10u*dnlim(uplim(v(0),v(vp)+.5,.1), v(vn)+1.5, .1)+1n*v(0)
b:u2:2 u2:n004 0 i=10u*dnlim(uplim(v(n005),v(vp)+.51,.1), v(vn)+1.49, .1)+1n*v(n005)
c:u2:9 vp n005 1.5p
c:u2:10 u2:n004 0 .5f rpar=100k noiseless
m:u2:1 vp u2:n005 hp hp u2:n temp=27
```

```
m:u2:2 vn u2:n005 hp hp u2:p temp=27
c:u2:3 vp hp .1p
d:u2:5 u2:n005 hp u2:y
d:u2:6 hp u2:n005 u2:y
r:u2:2 vp u2:n006 100g noiseless
r:u2:3 u2:n006 vn 100g noiseless
c:u2:4 hp vn .1p
c:u2:1 n005 vn 1.5p
c:u2:6 vp 0 1.5p
c:u2:7 0 vn 1.5p
a:u2:6 0 u2:n004 0 0 0 0 u2:n007 0 ota g=1.25u linear cout=58f en=24n enk=9 rout=1meg vhigh=1e308 vlow=-
1e308
d:u2:2 n005 vn u2:dbias
d:u2:4 0 vn u2:dbias
a:u2:3 0 u2:n007 0 0 0 0 u2:n006 0 ota g=20u iout=3.75u cout=3.97p vlow=-1e308 vhigh=1e308
g:u2:1 0 u2:n005 u2:n006 0 1µ
c:u2:8 0 u2:n005 11f rpar=1meg noiseless
d:u2:3 vp vn u2:dc
c:u2:11 u2:n006 hp 3p rser=300k noiseless
g:u2:2 u2:n006 0 u2:n006 vp 100m dir=1 vto=-1.1
g:u2:3 0 u2:n006 vn u2:n006 100m dir=1 vto=-1.1
a:u3:1 n008 0 0 0 0 0 0 0 ota g=0 in=.4f
c:u3:2 n008 0 1p
b:u3:1 0 u3:n004 i=10u*dnlim(uplim(v(0),v(vp)+.5,.1), v(vn)+1.5, .1)+1n*v(0)
b:u3:2 u3:n004 0 i=10u*dnlim(uplim(v(n008),v(vp)+.51,.1), v(vn)+1.49, .1)+1n*v(n008)
c:u3:9 vp n008 1.5p
c:u3:10 u3:n004 0 .5f rpar=100k noiseless
m:u3:1 vp u3:n005 bp bp u3:n temp=27
m:u3:2 vn u3:n005 bp bp u3:p temp=27
c:u3:3 vp bp .1p
d:u3:5 u3:n005 bp u3:y
d:u3:6 bp u3:n005 u3:y
r:u3:2 vp u3:n006 100g noiseless
r:u3:3 u3:n006 vn 100g noiseless
c:u3:4 bp vn .1p
c:u3:1 n008 vn 1.5p
c:u3:6 vp 0 1.5p
c:u3:7 0 vn 1.5p
a:u3:6 0 u3:n004 0 0 0 0 u3:n007 0 ota g=1.25u linear cout=58f en=24n enk=9 rout=1meg vhigh=1e308 vlow=-
1e308
d:u3:2 n008 vn u3:dbias
d:u3:4 0 vn u3:dbias
a:u3:3 0 u3:n007 0 0 0 0 u3:n006 0 ota g=20u iout=3.75u cout=3.97p vlow=-1e308 vhigh=1e308
g:u3:1 0 u3:n005 u3:n006 0 1µ
c:u3:8 0 u3:n005 11f rpar=1meg noiseless
d:u3:3 vp vn u3:dc
c:u3:11 u3:n006 bp 3p rser=300k noiseless
g:u3:2 u3:n006 0 u3:n006 vp 100m dir=1 vto=-1.1
g:u3:3 0 u3:n006 vn u3:n006 100m dir=1 vto=-1.1
v5 vp 0 5
v6 0 vn 5
b2 corr 0 v=v(bp2) laplace=(s*s-s* 1181.30689512582 / 2 + 1181.30689512582 * 1181.30689512582)/(s*s+s*
1181.30689512582 / 2 + 1181.30689512582 * 1181.30689512582)
b1 bp2 0 v=v(in) laplace=s*s* 286829.08413453 /(s**4+s**3* 487.8636255 +s**2* 4983397.8087292 +s*
1116787525.01769 + 5240156171426.62)
v4 in 0 ac 1
.model u3:dc d(ron=2k roff=1g vfwd=1 epsilon=.1 ilimit=130u noiseless)
```

```
.model u3:dbias d(ron=1t roff=1t ilimit=.4p noiseless)
.model u3:p vdmos(vto=10m kp=100m pchan)
.model u3:n vdmos(vto=-10m kp=100m)
.model u3:y d(ron=100 roff=1t vfwd=1.2 epsilon=.1 noiseless)
.model u2:dc d(ron=2k roff=1g vfwd=1 epsilon=.1 ilimit=130u noiseless)
.model u2:dbias d(ron=1t roff=1t ilimit=.4p noiseless)
.model u2:p vdmos(vto=10m kp=100m pchan)
.model u2:n vdmos(vto=-10m kp=100m)
.model u2:y d(ron=100 roff=1t vfwd=1.2 epsilon=.1 noiseless)
.model u1:dc d(ron=2k roff=1g vfwd=1 epsilon=.1 ilimit=130u noiseless)
.model u1:dbias d(ron=1t roff=1t ilimit=.4p noiseless)
.model u1:p vdmos(vto=10m kp=100m pchan)
.model u1:n vdmos(vto=-10m kp=100m)
.model u1:y d(ron=100 roff=1t vfwd=1.2 epsilon=.1 noiseless)
.ac dec 80 24.0799837348607 2407.99837348607
.end

solver = Normal
Maximum thread count: 8
tnom = 27
temp = 27
method = trap
WARNING: Less than two connections to node corr.  This node is used by b2.
Direct Newton iteration failed to find .op point.  (Use ".option noopiter" to skip.)
Starting Gmin stepping
Gmin = 10
Gmin = 1.07374
vernier = 0.5
vernier = 0.25
vernier = 0.125
vernier = 0.0625
vernier = 0.03125
Gmin = 1.0412
vernier = 0.015625
vernier = 0.0078125
Gmin = 1.0132
vernier = 0.00390625
vernier = 0.00195312
Gmin = 1.00827
vernier = 0.00260417
vernier = 0.00130208
Gmin = 1.00515
vernier = 0.000651042
vernier = 0.000868055
vernier = 0.000434028
Gmin = 1.00434
vernier = 0.000578703
vernier = 0.000434027
Gmin = 1.00339
Gmin = 0
Gmin stepping failed

Starting source stepping with srcstepmethod=0
Source Step = 3.0303%
Source Step = 33.3333%
Source Step = 63.6364%
Source Step = 93.9394%
```

Source stepping succeeded in finding the operating point.

Total elapsed time: 0.503 seconds.

Appendix 2

```
LTspice 24.0.12 for Windows
Start Time: Mon Feb 16 17:04:28 2026

   --- Expanded Deck Component Count ---
A's 9
B's 6
C's 35
D's 15
G's 9
M's 6
R's 14
V's 4
tot: 98


    --- Expanded Netlist ---
* E:\Study Oulu\3. Third Period\Filters\Design Exercise\task2.asc
r1 n003 n007 1512.99
r2 lp n003 1071.11521854
r3 n005 n003 1512.99
c1 lp n005 1.64718581031167e-07
c2 0 n003 2.3115971953193e-06
v1 n007 0 ac 1
a:u1:1 n005 0 0 0 0 0 0 0 ota g=0 in=.4f
c:u1:2 n005 0 1p
b:u1:1 0 u1:n004 i=10u*dnlim(uplim(v(0),v(vp)+.5,.1), v(vn)+1.5, .1)+1n*v(0)
b:u1:2 u1:n004 0 i=10u*dnlim(uplim(v(n005),v(vp)+.51,.1), v(vn)+1.49,
.1)+1n*v(n005)
c:u1:9 vp n005 1.5p
c:u1:10 u1:n004 0 .5f rpar=100k noiseless
m:u1:1 vp u1:n005 lp lp u1:n temp=27
m:u1:2 vn u1:n005 lp lp u1:p temp=27
c:u1:3 vp lp .1p
d:u1:5 u1:n005 lp u1:y
d:u1:6 lp u1:n005 u1:y
r:u1:2 vp u1:n006 100g noiseless
r:u1:3 u1:n006 vn 100g noiseless
c:u1:4 lp vn .1p
c:u1:1 n005 vn 1.5p
c:u1:6 vp 0 1.5p
c:u1:7 0 vn 1.5p
a:u1:6 0 u1:n004 0 0 0 0 u1:n007 0 ota g=1.25u linear cout=58f en=24n enk=9
rout=1meg vhigh=1e308 vlow=-1e308
d:u1:2 n005 vn u1:dbias
d:u1:4 0 vn u1:dbias
a:u1:3 0 u1:n007 0 0 0 0 u1:n006 0 ota g=20u iout=3.75u cout=3.97p vlow=-1e308
vhigh=1e308
g:u1:1 0 u1:n005 u1:n006 0 1µ
c:u1:8 0 u1:n005 11f rpar=1meg noiseless
d:u1:3 vp vn u1:dc
c:u1:11 u1:n006 lp 3p rser=300k noiseless
g:u1:2 u1:n006 0 u1:n006 vp 100m dir=1 vto=-1.1
g:u1:3 0 u1:n006 vn u1:n006 100m dir=1 vto=-1.1
```

```
v2 vp 0 5
v3 0 vn 5
r4 n001 n006 1512.99
r5 21p n001 1512.99
r6 n004 n001 1512.99
c3 21p n004 5.18171580697909e-08
c4 0 n001 4.38864595759548e-06
v4 n006 0 ac 1
a:u2:1 n004 0 0 0 0 0 0 0 ota g=0 in=.4f
c:u2:2 n004 0 1p
b:u2:1 0 u2:n004 i=10u*dnlim(uplim(v(0),v(vp)+.5,.1), v(vn)+1.5, .1)+1n*v(0)
b:u2:2 u2:n004 0 i=10u*dnlim(uplim(v(n004),v(vp)+.51,.1), v(vn)+1.49,
.1)+1n*v(n004)
c:u2:9 vp n004 1.5p
c:u2:10 u2:n004 0 .5f rpar=100k noiseless
m:u2:1 vp u2:n005 21p 21p u2:n temp=27
m:u2:2 vn u2:n005 21p 21p u2:p temp=27
c:u2:3 vp 21p .1p
d:u2:5 u2:n005 21p u2:y
d:u2:6 21p u2:n005 u2:y
r:u2:2 vp u2:n006 100g noiseless
r:u2:3 u2:n006 vn 100g noiseless
c:u2:4 21p vn .1p
c:u2:1 n004 vn 1.5p
c:u2:6 vp 0 1.5p
c:u2:7 0 vn 1.5p
a:u2:6 0 u2:n004 0 0 0 0 u2:n007 0 ota g=1.25u linear cout=58f en=24n enk=9
rout=1meg vhigh=1e308 vlow=-1e308
d:u2:2 n004 vn u2:dbias
d:u2:4 0 vn u2:dbias
a:u2:3 0 u2:n007 0 0 0 0 u2:n006 0 ota g=20u iout=3.75u cout=3.97p vlow=-1e308
vhigh=1e308
g:u2:1 0 u2:n005 u2:n006 0 1µ
c:u2:8 0 u2:n005 11f rpar=1meg noiseless
d:u2:3 vp vn u2:dc
c:u2:11 u2:n006 21p 3p rser=300k noiseless
g:u2:2 u2:n006 0 u2:n006 vp 100m dir=1 vto=-1.1
g:u2:3 0 u2:n006 vn u2:n006 100m dir=1 vto=-1.1
c5 31p n002 1.46288098108305e-06
a:u3:1 n002 0 0 0 0 0 0 0 ota g=0 in=.4f
c:u3:2 n002 0 1p
b:u3:1 0 u3:n004 i=10u*dnlim(uplim(v(0),v(vp)+.5,.1), v(vn)+1.5, .1)+1n*v(0)
b:u3:2 u3:n004 0 i=10u*dnlim(uplim(v(n002),v(vp)+.51,.1), v(vn)+1.49,
.1)+1n*v(n002)
c:u3:9 vp n002 1.5p
c:u3:10 u3:n004 0 .5f rpar=100k noiseless
m:u3:1 vp u3:n005 31p 31p u3:n temp=27
m:u3:2 vn u3:n005 31p 31p u3:p temp=27
c:u3:3 vp 31p .1p
d:u3:5 u3:n005 31p u3:y
d:u3:6 31p u3:n005 u3:y
r:u3:2 vp u3:n006 100g noiseless
r:u3:3 u3:n006 vn 100g noiseless
c:u3:4 31p vn .1p
c:u3:1 n002 vn 1.5p
c:u3:6 vp 0 1.5p
c:u3:7 0 vn 1.5p
a:u3:6 0 u3:n004 0 0 0 0 u3:n007 0 ota g=1.25u linear cout=58f en=24n enk=9
rout=1meg vhigh=1e308 vlow=-1e308
d:u3:2 n002 vn u3:dbias
d:u3:4 0 vn u3:dbias
```

```
a:u3:3 0 u3:n007 0 0 0 0 u3:n006 0 ota g=20u iout=3.75u cout=3.97p vlow=-1e308
vhigh=1e308
g:u3:1 0 u3:n005 u3:n006 0 1µ
c:u3:8 0 u3:n005 11f rpar=1meg noiseless
d:u3:3 vp vn u3:dc
c:u3:11 u3:n006 31p 3p rser=300k noiseless
g:u3:2 u3:n006 0 u3:n006 vp 100m dir=1 vto=-1.1
g:u3:3 0 u3:n006 vn u3:n006 100m dir=1 vto=-1.1
r7 n002 21p 1512.99
r8 31p n002 1512.99
.model u3:dc d(ron=2k roff=1g vfwd=1 epsilon=.1 ilimit=130u noiseless)
.model u3:dbias d(ron=1t roff=1t ilimit=.4p noiseless)
.model u3:p vdmos(vto=10m kp=100m pchan)
.model u3:n vdmos(vto=-10m kp=100m)
.model u3:y d(ron=100 roff=1t vfwd=1.2 epsilon=.1 noiseless)
.model u2:dc d(ron=2k roff=1g vfwd=1 epsilon=.1 ilimit=130u noiseless)
.model u2:dbias d(ron=1t roff=1t ilimit=.4p noiseless)
.model u2:p vdmos(vto=10m kp=100m pchan)
.model u2:n vdmos(vto=-10m kp=100m)
.model u2:y d(ron=100 roff=1t vfwd=1.2 epsilon=.1 noiseless)
.model u1:dc d(ron=2k roff=1g vfwd=1 epsilon=.1 ilimit=130u noiseless)
.model u1:dbias d(ron=1t roff=1t ilimit=.4p noiseless)
.model u1:p vdmos(vto=10m kp=100m pchan)
.model u1:n vdmos(vto=-10m kp=100m)
.model u1:y d(ron=100 roff=1t vfwd=1.2 epsilon=.1 noiseless)
.ac dec 80 24.0799837348607 2407.99837348607
.end

solver = Normal
Maximum thread count: 8
tnom = 27
temp = 27
method = trap
Direct Newton iteration failed to find .op point.  (Use ".option noopiter" to
skip.)
Starting Gmin stepping
Gmin = 10
Gmin = 1.07374
vernier = 0.5
vernier = 0.25
vernier = 0.125
vernier = 0.0625
vernier = 0.03125
Gmin = 1.0412
vernier = 0.015625
vernier = 0.0078125
Gmin = 1.0132
vernier = 0.00390625
vernier = 0.00195312
Gmin = 1.00827
vernier = 0.00260417
vernier = 0.00130208
Gmin = 1.00515
vernier = 0.000651042
vernier = 0.000868055
vernier = 0.000434028
Gmin = 1.00434
vernier = 0.000578703
vernier = 0.000434027
Gmin = 1.00339
Gmin = 0
```

```
Gmin stepping failed

Starting source stepping with srcstepmethod=0
Source Step = 3.0303%
Source Step = 33.3333%
Source Step = 63.6364%
Source Step = 93.9394%
Source stepping succeeded in finding the operating point.

Total elapsed time: 0.260 seconds.
```

Appendix 3

```
LTspice 24.0.12 for Windows
Start Time: Mon Feb 16 17:03:28 2026

   --- Expanded Deck Component Count ---
A's 12
B's 6
C's 34
D's 16
G's 7
M's 6
R's 18
S's 9
V's 4
tot: 112


    --- Expanded Netlist ---
* E:\Study Oulu\3. Third Period\Filters\Design Exercise\task3.asc
r1 n003 n009 1512.99
r2 lp n003 1071.11521854
r3 n006 n003 1512.99
c1 lp n006 1.64718581031167e-07
c2 0 n003 2.3115971953193e-06
v1 n009 0 ac 1
a:u1:1 n006 0 0 0 0 0 0 0 ota g=0 in=.4f
c:u1:2 n006 0 1p
b:u1:1 0 u1:n004 i=10u*dnlim(uplim(v(0),v(vp)+.5,.1), v(vn)+1.5, .1)+1n*v(0)
b:u1:2 u1:n004 0 i=10u*dnlim(uplim(v(n006),v(vp)+.51,.1), v(vn)+1.49,
.1)+1n*v(n006)
c:u1:9 vp n006 1.5p
c:u1:10 u1:n004 0 .5f rpar=100k noiseless
m:u1:1 vp u1:n005 lp lp u1:n temp=27
m:u1:2 vn u1:n005 lp lp u1:p temp=27
c:u1:3 vp lp .1p
d:u1:5 u1:n005 lp u1:y
d:u1:6 lp u1:n005 u1:y
r:u1:2 vp u1:n006 100g noiseless
r:u1:3 u1:n006 vn 100g noiseless
c:u1:4 lp vn .1p
c:u1:1 n006 vn 1.5p
c:u1:6 vp 0 1.5p
c:u1:7 0 vn 1.5p
a:u1:6 0 u1:n004 0 0 0 0 u1:n007 0 ota g=1.25u linear cout=58f en=24n enk=9
rout=1meg vhigh=1e308 vlow=-1e308
d:u1:2 n006 vn u1:dbias
d:u1:4 0 vn u1:dbias
```

```
a:u1:3 0 u1:n007 0 0 0 0 u1:n006 0 ota g=20u iout=3.75u cout=3.97p vlow=-1e308
vhigh=1e308
g:u1:1 0 u1:n005 u1:n006 0 1µ
c:u1:8 0 u1:n005 11f rpar=1meg noiseless
d:u1:3 vp vn u1:dc
c:u1:11 u1:n006 lp 3p rser=300k noiseless
g:u1:2 u1:n006 0 u1:n006 vp 100m dir=1 vto=-1.1
g:u1:3 0 u1:n006 vn u1:n006 100m dir=1 vto=-1.1
v2 vp 0 5
v3 0 vn 5
a:u2:1 n002 n008 0 0 0 0 0 0 ota g=0 in=2.5p ink=638
c:u2:5 vp n002 2p rser=1.4meg
c:u2:6 u2:x0 0 1f rpar=100k noiseless
m:u2:1 vp u2:n009 bp_p bp_p u2:n temp=27
m:u2:2 vn u2:n012 bp_p bp_p u2:p temp=27
c:u2:7 u2:n006 0 1.4f
c:u2:8 u2:n015 0 1.4f
m:u2:3 vp u2:n016 bp_m bp_m u2:n temp=27
m:u2:4 vn u2:n020 bp_m bp_m u2:p temp=27
d:u2:4 u2:n016 bp_m u2:y
d:u2:5 bp_m u2:n020 u2:y
d:u2:8 bp_p u2:n012 u2:y
d:u2:9 u2:n009 bp_p u2:y
r:u2:9 bp_p u2:vcm 4k noiseless
r:u2:11 u2:vcm bp_m 4k noiseless
b:u2:1 0 u2:x0 i=10u*dnlim(uplim(v(n008),v(vp)-1.15,.1), v(vn)-.2,
.1)+1n*v(n008)
b:u2:2 u2:x0 0 i=10u*dnlim(uplim(v(n002),v(vp)-1.14,.1), v(vn)-.21,
.1)+1n*v(n002)
c:u2:19 vp bp_p 1p
c:u2:12 bp_p vn 1p
c:u2:16 vp bp_m 1p
c:u2:17 bp_m vn 1p
r:u2:7 vp u2:n006 10meg noiseless
r:u2:10 u2:n006 vn 10meg noiseless
r:u2:13 u2:n015 vn 10meg noiseless
r:u2:6 vp u2:n015 10meg noiseless
d:u2:3 vn n008 u2:dclp
d:u2:2 vn n002 u2:dclp
d:u2:6 n008 vp u2:dclp
d:u2:7 n002 vp u2:dclp
b:u2:5 0 u2:n008 i=10u*dnlim(uplim(v(n005),v(vp)-.7,.1), v(vn)+1, .1)+1n*v(n005)
c:u2:9 u2:n008 0 10f rpar=100k noiseless
b:u2:6 u2:n008 0 i=10u*dnlim(uplim(v(u2:vcm),v(vp)-.69,.1), v(vn)+.99,
.1)+1n*v(u2:vcm)
c:u2:13 u2:n004 0 1f
a:u2:6 vp vp 0 0 0 u2:n007 0 0 schmitt vt=2 vh=10m trise=1u tfall=1u
a:u2:7 u2:n007 0 u2:n006 u2:n006 u2:n006 u2:n006 u2:n009 u2:n006 schmitt vt=.5
vh=10m vhigh=0 vlow=-10 rout=1k cout=4p
a:u2:8 u2:n007 0 u2:n006 u2:n006 u2:n006 u2:n012 u2:n006 u2:n006 schmitt vt=.5
vh=10m vhigh=10 vlow=0 rout=1k cout=4p
a:u2:9 u2:n007 0 u2:n015 u2:n015 u2:n015 u2:n015 u2:n016 u2:n015 schmitt vt=.5
vh=10m vhigh=0 vlow=-10 rout=1k cout=4p
a:u2:10 u2:n007 0 u2:n015 u2:n015 u2:n015 u2:n020 u2:n015 u2:n015 schmitt vt=.5
vh=10m vhigh=10 vlow=0 rout=1k cout=4p
a:u2:11 0 u2:x0 u2:n007 0 0 0 u2:n017 0 ota g=1m linear cout=100f rout=1k en=3n
enk=876 vlow=-1e308 vhigh=1e308
a:u2:5 u2:n017 0 u2:n018 u2:n018 u2:n018 u2:n018 u2:n004 u2:n018 ota g=100u
iout=13.3u vlow=-1e308 vhigh=1e308
c:u2:10 bp_m u2:n018 200f
g:u2:3 0 u2:n015 0 u2:n018 200n
```

```
g:u2:1 0 u2:n006 0 u2:n004 200n
s:u2:6 u2:n004 0 u2:n006 vp u2:swlim
s:u2:1 0 u2:n004 vn u2:n006 u2:swlim
s:u2:5 u2:n018 0 u2:n015 vp u2:swlim
s:u2:4 0 u2:n018 vn u2:n015 u2:swlim
c:u2:15 bp_p u2:n004 200f
d:u2:10 n002 n008 u2:dinp
c:u2:1 n002 vn 2p rser=1.4meg noiseless
c:u2:2 vp n008 2p rser=1.4meg noiseless
c:u2:3 n008 vn 2p rser=1.4meg noiseless
c:u2:4 vp n005 1p rpar=80k noiseless
c:u2:18 n005 vn 1p rpar=80k noiseless
s:u2:2 vp n002 u2:n007 0 u2:swbias
s:u2:3 vp n008 u2:n007 0 u2:swbias
s:u2:7 vp vn u2:n007 0 u2:swpow
d:u2:1 vp vn u2:dpow
d:u2:11 vp vp u2:dshut
r:u2:2 vp vn 17k noiseless
a:u2:4 0 u2:n008 u2:n007 0 0 0 u2:n011 0 ota g=1m linear en=15n enk=10 rout=1k
cout=200p vlow=-40m vhigh=40m
g:u2:2 0 u2:n004 0 u2:n011 5µ
g:u2:4 0 u2:n018 0 u2:n011 5µ
s:u2:8 u2:n004 0 0 u2:n007 u2:swshut
s:u2:9 0 u2:n018 0 u2:n007 u2:swshut
c:u2:14 0 u2:n018 1f
r7 n002 n001 1512.99
r8 n008 n007 1512.99
c5 bp_p n002 1.64718581031167e-07
c6 bp_m n008 1.64718581031167e-07
c7 n005 0 100n
v5 n004 0 ac 1
r10 bp_p n001 1071.11521854
r12 bp_m n007 1071.11521854
r13 n007 0 1512.99
r14 n001 n004 1512.99
c8 n001 n007 1.15579859765965e-06
.model u2:swshut sw(ron=10k roff=500meg vt=-.5 vh=-.1 noiseless)
.model u2:swlim sw(ron=100k roff=1t vt=150m vh=-100m level=2 ilimit=100u oneway
noiseless)
.model u2:swpow sw(level=2 ron=80 roff=1g vt=.5 vh=-100m ilimit=7.35m noiseless)
.model u2:swbias sw(level=2 ron=1k roff=1g vt=.5 vh=-100m ilimit=18u noiseless)
.model u2:dclp d(ron=500 roff=1g vfwd=.8 epsilon=.1 noiseless)
.model u2:dinp d(ron=100 roff=4.5k vfwd=1.1 epsilon=.1 noiseless)
.model u2:dpow d(ron=1k ilimit=20u vfwd=.5 epsilon=.1 noiseless)
.model u2:dshut d(ron=60k roff=300k vfwd=1.5 epsilon=.2 noiseless)
.model u2:y d(ron=50 roff=1t vfwd=.8 epsilon=10m noiseless)
.model u2:p vdmos(vto=200m kp=155m pchan)
.model u2:n vdmos(vto=-200m kp=155m)
.model u1:dc d(ron=2k roff=1g vfwd=1 epsilon=.1 ilimit=130u noiseless)
.model u1:dbias d(ron=1t roff=1t ilimit=.4p noiseless)
.model u1:p vdmos(vto=10m kp=100m pchan)
.model u1:n vdmos(vto=-10m kp=100m)
.model u1:y d(ron=100 roff=1t vfwd=1.2 epsilon=.1 noiseless)
.ac dec 80 24.0799837348607 2407.99837348607
.end

solver = Normal
Maximum thread count: 8
tnom = 27
temp = 27
method = trap
```

```
Direct Newton iteration failed to find .op point.  (Use ".option noopiter" to
skip.)
Starting Gmin stepping
Increasing initial diagonal Gmin to 100
Gmin = 100
Gmin = 10.7374
Gmin = 1.15292
Gmin = 0.123794
Gmin = 0.0132923
Gmin = 0.00142725
Gmin = 0.00015325
Gmin = 1.6455e-05
Gmin = 1.76685e-06
Gmin = 1.89714e-07
Gmin = 2.03704e-08
Gmin = 2.18725e-09
Gmin = 2.34854e-10
Gmin = 2.52173e-11
Gmin = 2.70769e-12
Gmin = 2.90735e-13
Gmin = 0
Gmin stepping succeeded in finding the operating point.

Total elapsed time: 0.170 seconds.
```

Appendix 4

```
LTspice 24.0.12 for Windows
Start Time: Mon Feb 16 19:00:12 2026

   --- Expanded Deck Component Count ---
B's 1
C's 2
L's 2
R's 2
V's 1
tot: 8


    --- Expanded Netlist ---
* E:\Study Oulu\3. Third Period\Filters\Design Exercise\task4.asc
b1 bp2 0 v=v(in) laplace=s*s* 286829.08413453 /(s**4+s**3* 487.8636255 +s**2*
4983397.8087292 +s* 1116787525.01769 + 5240156171426.62)
v1 in 0 ac 1
r1 n001 in 125
r2 0 n003 1000
l1 n001 n002 0.343161554273326
l2 0 n003 0.0539986030345401
c1 n003 0 8.08994110998751e-06
c2 n003 n002 1.2730025060531e-06
.ac dec 80 24.0799837348607 2407.99837348607
.end

solver = Normal
Maximum thread count: 8
tnom = 27
temp = 27
method = trap
WARNING: Less than two connections to node bp2.  This node is used by b1.
```

```
.OP point found by inspection.
Total elapsed time: 0.109 seconds.
```