EE517 ANALOG IC DESIGN LAB
Experiment 7

Analysis, and design of fully differential telescopic OP-AMP circuits.

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Contents

1 Experiment

Analysis, and design of fully differential telescopic OP-AMP circuits.

2 Objective

2.1 Design Specifications

- Process Technology: 0.18µm CMOS
- Power Supply:
- VDD = 1.8V
- VSS = 0V
- Load Capacitance: 1pF
- Phase Margin: Greater than or equal to 60°
- DC Gain: At least 1000 V/V (60 dB)
- Common Mode Gain: At most 0.1 V/V (-20 dB)
- Unity Gain Frequency: Greater than 100 MHz
- Slew Rate: Greater than or equal to 20 V/µs
- Output Voltage Swing (Differential Peak-to-Peak): At least 600 m Vpp
- Power Consumption: 10mW

2.2 Observations

Verify all the parameters and remaining parameters such as 3-dB bandwidth, Input swing, and output Swing in the cadence tool and perform a comparative detailed analysis with other kind of amplifiers.

3 Parameters

3.1 Transconductance(g_m)

It shows the amount of current changed at output due to change of input voltage at gate terminal.It is he ratio of the change in drain current to the change in gate voltage over a defined, arbitrarily small interval on the drain current-versus-gate-voltage curve.

$$g_m = \frac{dI_{ds}}{dV_{gs}} \tag{1}$$

3.2 voltage Gain A_v:

The voltage gain (AV) is the ratio of change in small signal output voltage to change in the small signal input voltage. It shows the how much the input voltage is amplified at output

$$A_v = \frac{v_{out}}{v_{in}} \tag{2}$$

3.3 Cut off frequency f_c:

It is a frequency at which gain is 3db less than the maximum gain it shows that at this frequency circuit is utilizing atleast half power to amplify.

$$Bandwidth = \frac{1}{2\pi R_{out} C_{OUT}} \tag{3}$$

3.4 Source Drain resistance(R_{ds})

In a MOSFET,output resistance is a crucial parameter that influences circuit gain and plays a key role in designing current sources. It can be determined using the channel length modulation parameter (λ) and the drain current (Id) at VGS-Vth

$$r_{ds} = \frac{V_A}{I_{ds}} \tag{4}$$

3.5 Output Resistance resistance($\mathbf{R_{out}}$)

Output impedance is used to measure the how much current is reached to the load it is measured by connecting the test voltage at output terminal and making all other voltage sources to short. measure the current flowing through it

$$R_{out} = \frac{v_{test}}{I_{test}} \tag{5}$$

3.6 Slew Rate

The slew rate represents the highest rate at which the output can change per microsecond. In differential amplifiers, the maximum output is achieved when the entire tail current flows through one side.

$$SR = \max\left(\frac{dV_{\text{out}}}{dt}\right) \tag{6}$$

3.7 ICMR

The Input Common Mode Range (ICMR) refers to the range of common-mode input voltage that can be applied to a circuit while ensuring all transistors remain in saturation. The maximum ICMR indicates the highest common-mode input voltage that the circuit can handle while maintaining proper operation.

3.8 GBW

The Gain Bandwidth Product (GBWP) of an amplifier is defined as the product of its open-loop gain and the frequency at which the gain drops to -20 dB. It represents the frequency range over which the amplifier maintains a consistent gain.

3.9 CMRR

The Common Mode Rejection Ratio (CMRR) is a critical parameter in amplifier design, indicating how effectively an amplifier can suppress common mode signals while amplifying differential signals. Essentially, it measures

the difference in gain between the differential mode and common mode signals. A high CMRR is desirable because it signifies that the amplifier can maintain a strong differential gain while minimizing the common mode gain. This means that the amplifier can efficiently reject unwanted common mode noise, which is crucial for maintaining signal integrity and accuracy in various applications. In ideal cases, the CMRR should be as high as possible to ensure that the amplifier primarily amplifies the desired differential signals while rejecting common mode interference

$$\text{CMRR} = \frac{A_{diff}}{A_{comm}} \tag{7}$$

4 Theory

About Fully differential telescopic OP-AMP

A telescopic operational amplifier (op-amp) is a specific type of fully differential amplifier that is commonly used in high-speed, low-power, and high-gain applications. It belongs to the class of single-stage op-amps and is called "telescopic" because its internal structure resembles a stacked or telescoping configuration of transistors.

To increase the gain, boosting the output resistance is essential. One method to achieve this is by using a cascode structure. However, if only a standard cascode is used, the gain increase is minimal. To overcome this limitation, a stack of two PMOS transistors can be employed as an active load. But when combining this with NMOS transistors, the output resistance decreases because both resistances are in parallel. Therefore, to maintain high output resistance, a structure consisting of two PMOS and two NMOS transistors is used, known as the telescope op-amp.

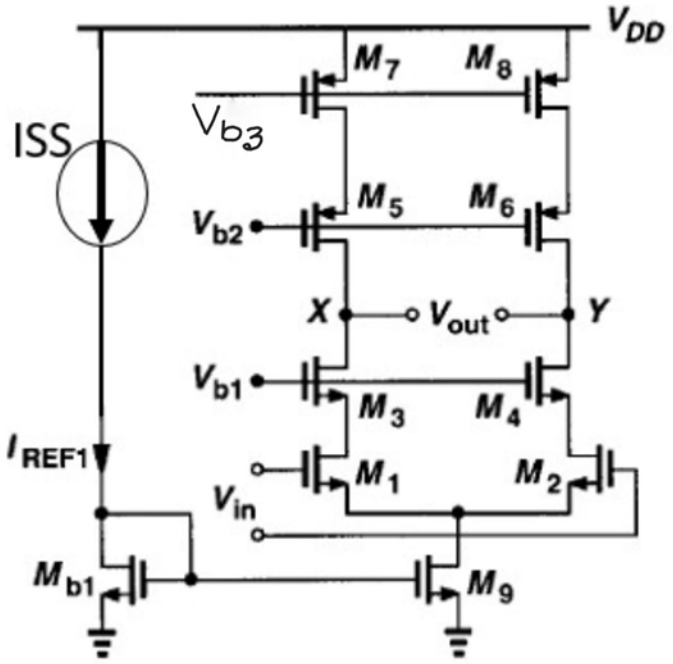

Figure 1: Fully differential telescopic opamp

In this experiment, a single reference source was utilized for biasing the circuit. This source, an NMOS transistor acting as a current mirror, provided the necessary current for the tail current source, which is also an NMOS transistor. Assuming all PMOS and NMOS transistors are identical, the gain can be calculated based on their characteristics.

5 Design procedure of fully differential telescopic opamp

step1
From above circuit diagram we know that:

$$2(V_{DD} - (V_{od7} + V_{od7} + V_{od5} + V_{od3} + V_{od1} + V_{od9})) = 1.8 \tag{8}$$

$$V_{od7} + V_{od5} + V_{od3} + V_{od1} + V_{od9} = 0.9 \tag{9}$$

Since M_9 holds more current, we assign it a higher overdrive voltage of 0.3V.

For the remaining voltages, we note that PMOS transistors have lower mobility but hold the same current as NMOS transistors. Thus, PMOS requires a higher overdrive voltage.

$$V_{od9} = 0.3 \tag{10}$$
$$V_{od7} = 0.2 \tag{11}$$
$$V_{od5} = 0.2 \tag{12}$$
$$V_{od3} = 0.1 \tag{13}$$
$$V_{od1} = 0.1 \tag{14}$$

step2

Given that the gain-bandwidth product (GBW) is:

$$\text{GBW} = 100 \text{ MHz} \tag{15}$$

We know that:

$$\text{GBW} = \frac{g_m}{2\pi C_L} \tag{16}$$

where

$$C_L = 1 \text{ pF} \tag{17}$$

Solving for g_m:

$$g_m = 2\pi \times 10^{-6} \times 100 \tag{18}$$

$$g_m = 628.3185\ \mu A/V^2 \tag{19}$$

We also know that:

$$g_m = \frac{2I_D}{V_{ov}} \tag{20}$$

Substituting $V_{ov} = 0.1V$:

$$\frac{2I_D}{0.1} = 628.3185\ \mu A/V^2 \tag{21}$$

$$2I_D = 62.83185\ \mu A \approx 62\ \mu A \tag{22}$$

step3
For the M_9 transistor, the drain current is given as:

$$I_D = 62\ \mu A = 50\ \mu A \tag{23}$$

For the transistor to be in the saturation region, the drain current equation is:

$$I_D = \frac{1}{2}\mu_n C_{ox} \left(\frac{W}{L}\right) (V_{ov})^2 \tag{24}$$

where

$$\mu_n C_{ox} = 320\ \mu A/V^2 \tag{25}$$

$$V_{ov} = 0.3V \tag{26}$$

Substituting the values:

$$50 \times 10^{-6} = \frac{1}{2} \times (320 \times 10^{-6}) \times \left(\frac{W}{L}\right) \times (0.3)^2 \tag{27}$$

Solving for $(W/L)_9$:

$$\left(\frac{W}{L}\right)_9 = 3.472 \tag{28}$$

step4
For the M_1 transistor, the drain current is given as:

$$I_D = 25\ \mu A \tag{29}$$

For the transistor to be in the saturation region, the drain current equation is:

$$I_D = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)(V_{ov})^2 \tag{30}$$

where

$$\mu_n C_{ox} = 320\ \mu A/V^2 \tag{31}$$
$$V_{ov} = 0.1V \tag{32}$$

Substituting the values:

$$25 \times 10^{-6} = \frac{1}{2} \times (320 \times 10^{-6}) \times \left(\frac{W}{L}\right) \times (0.1)^2 \tag{33}$$

Solving for $(W/L)_1$:

$$\left(\frac{W}{L}\right)_1 = 15.625 \tag{34}$$

$$\left(\frac{W}{L}\right)_1 = \left(\frac{W}{L}\right)_2 = \left(\frac{W}{L}\right)_3 = \left(\frac{W}{L}\right)_4 = 15.625 \tag{35}$$

step5
For the M_5 transistor, the drain current is given as:

$$I_D = 25\ \mu A \tag{36}$$

For the transistor to be in the saturation region, the drain current equation is:

$$I_D = \frac{1}{2}\mu_p C_{ox}\left(\frac{W}{L}\right)(V_{ov})^2 \tag{37}$$

where

$$\mu_n C_{ox} = 200\ \mu A/V^2 \tag{38}$$
$$V_{ov} = 0.2V \tag{39}$$

Substituting the values:

$$25 \times 10^{-6} = \frac{1}{2} \times (200 \times 10^{-6}) \times \left(\frac{W}{L}\right) \times (0.2)^2 \tag{40}$$

Solving for $(W/L)_1$:

$$\left(\frac{W}{L}\right)_5 = 6.25 \tag{41}$$
$$\left(\frac{W}{L}\right)_5 = \left(\frac{W}{L}\right)_6 = \left(\frac{W}{L}\right)_7 = \left(\frac{W}{L}\right)_8 = 6.25 \tag{42}$$

step6

for M1 and M2:

We know that the source voltage of M_1 is nothing but the drain voltage of M_9, which is:

$$V_{S1} = 0.3V \tag{43}$$

The overdrive voltage is given as:

$$V_{OD1} = 0.1V \tag{44}$$

From the MOSFET equation:

$$V_{GS1} - V_{th1} = 0.1 \tag{45}$$

$$V_{G1} - V_{S1} - V_{th1} = 0.1 \tag{46}$$

Substituting known values:

$$V_{G1} - 0.3 - 0.55 = 0.1 \tag{47}$$

Solving for V_{G1}:

$$V_{G1} = V_{G2} = 0.95V \tag{48}$$

step7
for M3 and M4:
We know that the source voltage of M_3 is nothing but the drain voltage of M_1, which is:

$$V_{S3} = 0.4V \tag{49}$$

The overdrive voltage is given as:

$$V_{OD3} = 0.1V \tag{50}$$

From the MOSFET equation:

$$V_{GS3} - V_{th3} = 0.1 \tag{51}$$

$$V_{G3} - V_{S3} - V_{th3} = 0.1 \tag{52}$$

Substituting known values:

$$V_{G3} - 0.4 - 0.55 = 0.1 \tag{53}$$

Solving for V_{G1}:

$$V_{G3} = V_{G4} = 1.05V \tag{54}$$

step8
for M7 and M8:
We know that the overdrive voltage is $V_{od7} = 0.2$:

$$V_{od7} = 0.2\,\mathrm{V} \tag{55}$$

The overdrive voltage equation is given by:

$$V_{sg7} - V_{th7} = 0.2 \tag{56}$$

This simplifies to:

$$V_{s7} - V_{g7} - V_{th7} = 0.2 \tag{57}$$

Substituting the given values:

$$1.8 - V_{g7} - 0.55 = 0.2 \tag{58}$$

Simplifying the equation:

$$V_{g7} = V_{g8} = 1.05\,\mathrm{V} \tag{59}$$

step9
for M5 and M6:
We know that the source voltage of M5 is equal to the drain voltage of M7, which is 1.6V. Additionally, the overdrive voltage is 0.2V:

$$V_{od5} = 0.2\,\mathrm{V} \tag{60}$$

The overdrive voltage equation is:

$$V_{sg5} - V_{th5} = 0.2 \tag{61}$$

This simplifies to:

$$V_{s5} - V_{g5} - V_{th5} = 0.2 \tag{62}$$

Substituting the given values:

$$1.6 - V_{g5} - 0.55 = 0.2 \tag{63}$$

Simplifying the equation:

$$V_{g5} = V_{g6} = 0.85\,\mathrm{V} \tag{64}$$

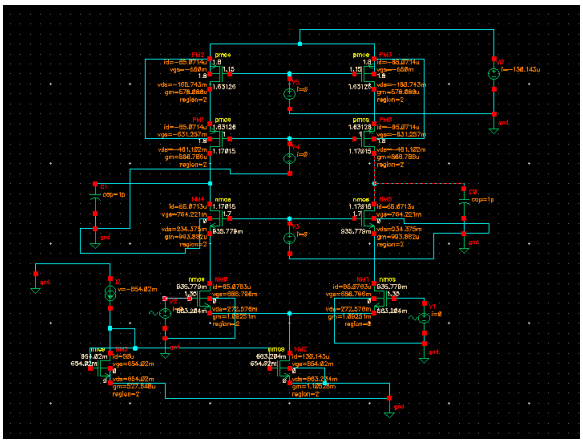

Figure 2: Schematic of fully differential telescopic opamp

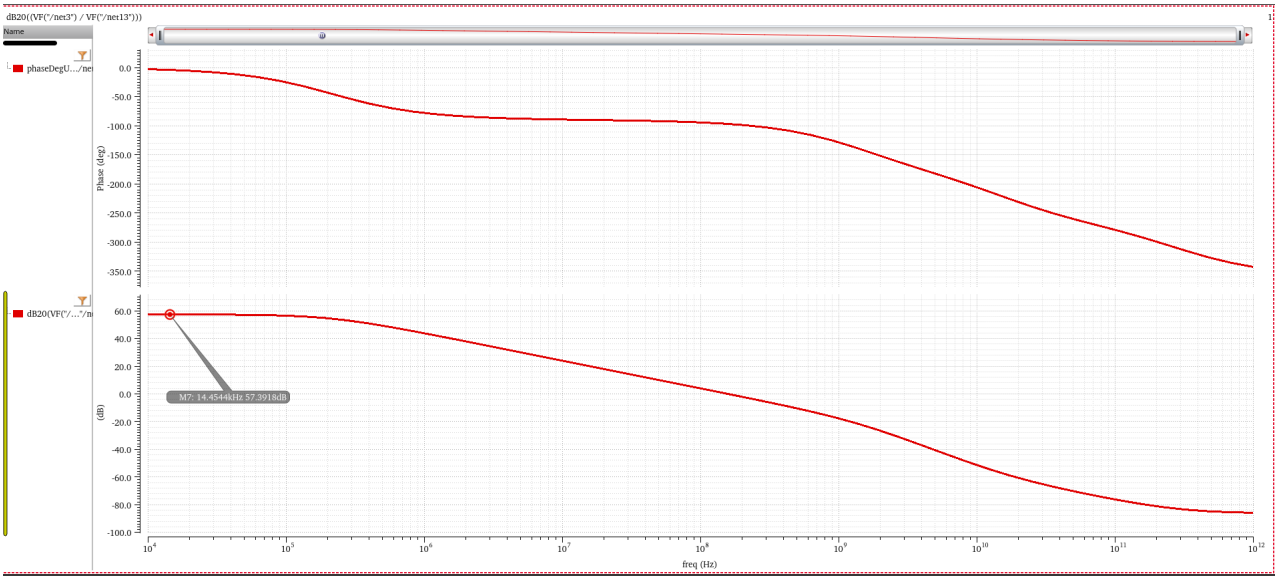

Figure 3: Gain of fully differential telescopic opamp

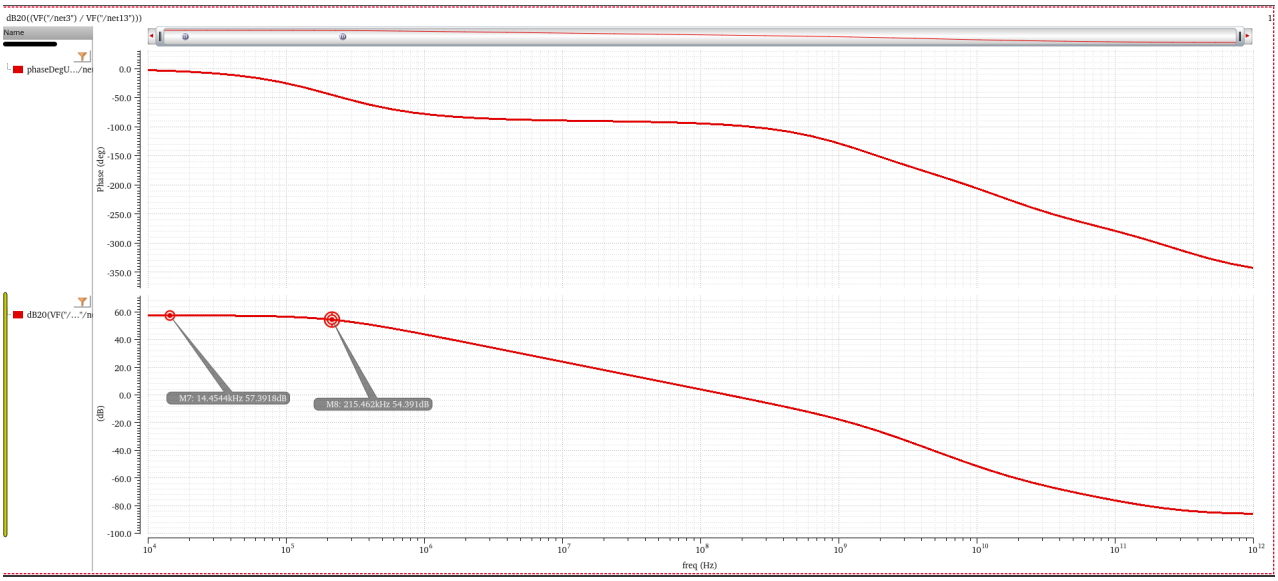

Figure 4: cutoff frequency of fully differential telescopic opamp

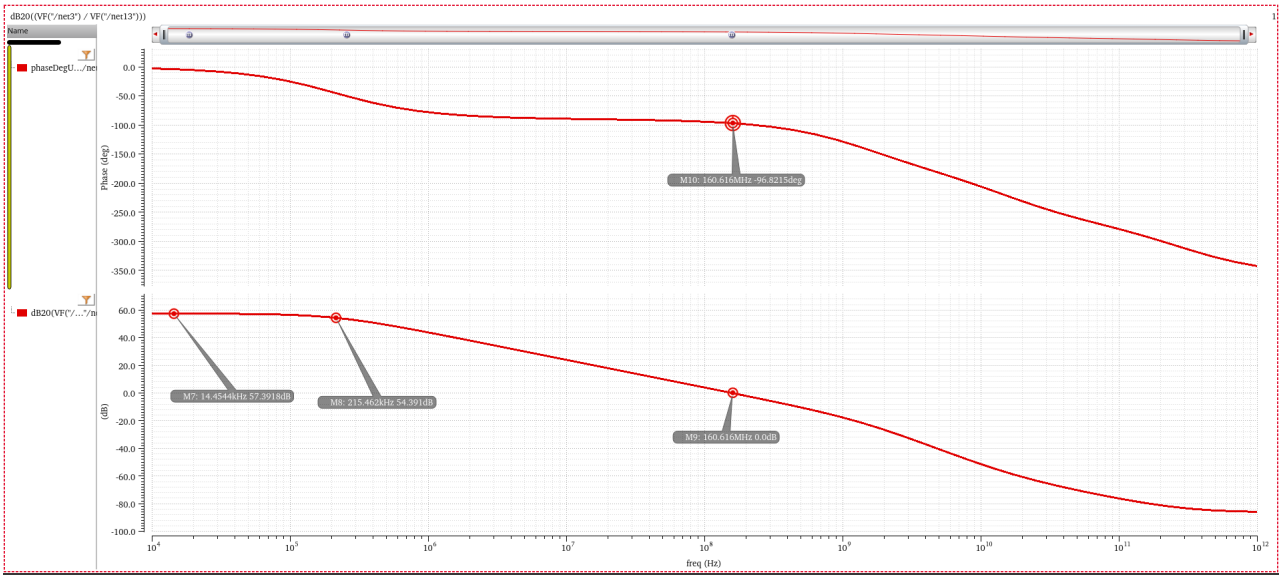

Figure 5: Phase margin of fully differential telescopic opamp

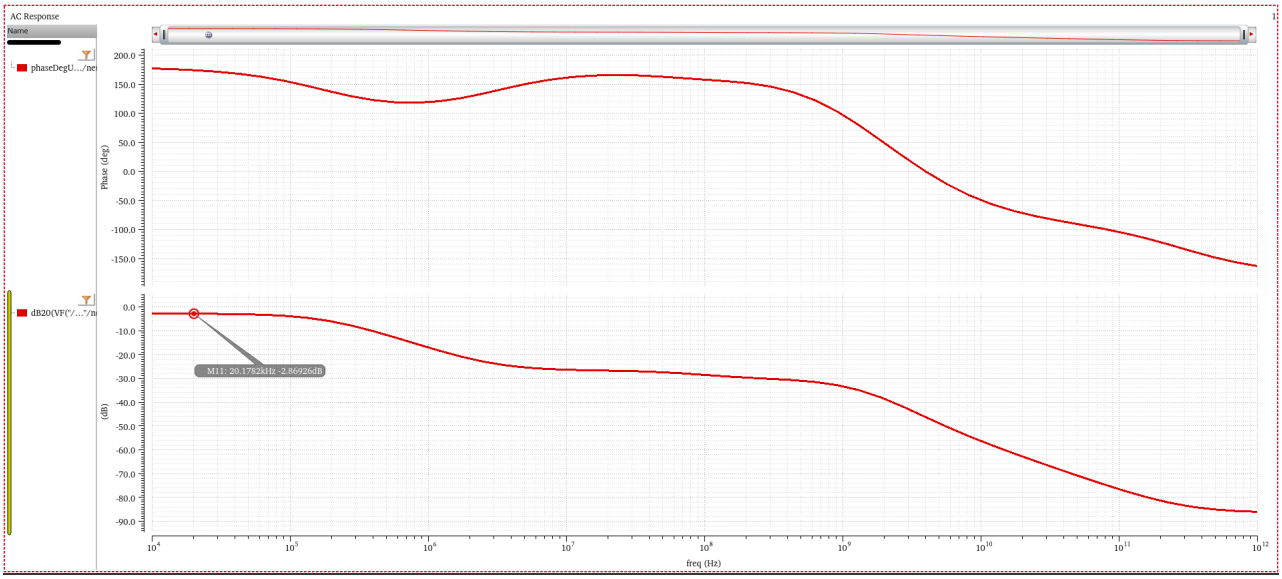

Figure 6: CMRR of fully differential telescopic opamp

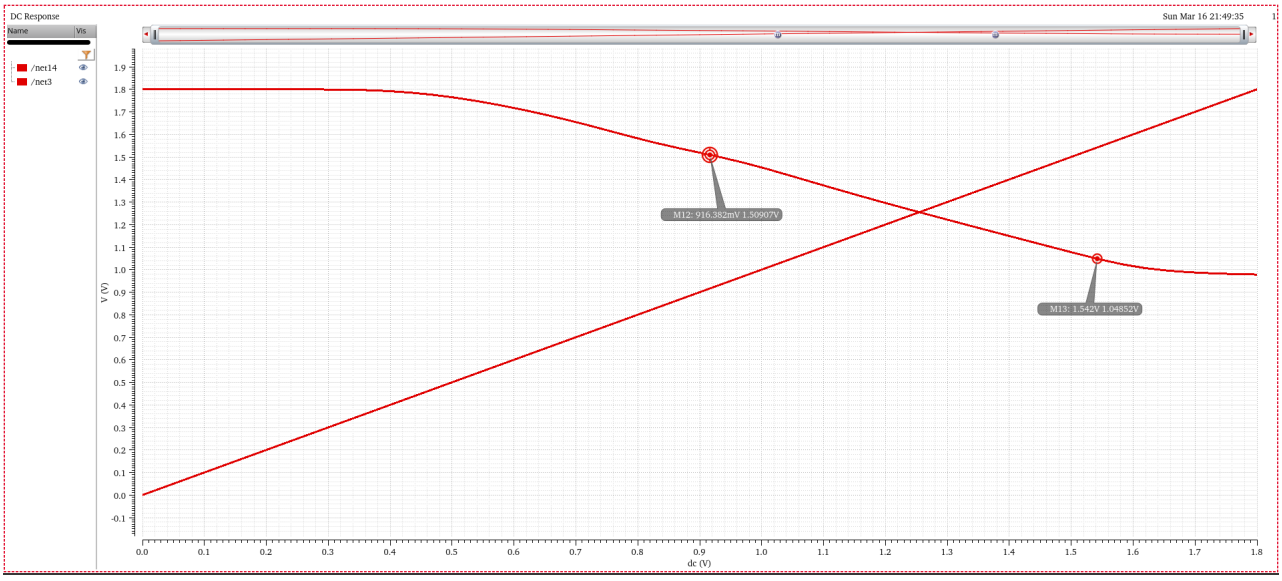

Figure 7: voltage swing of fully differential telescopic opamp

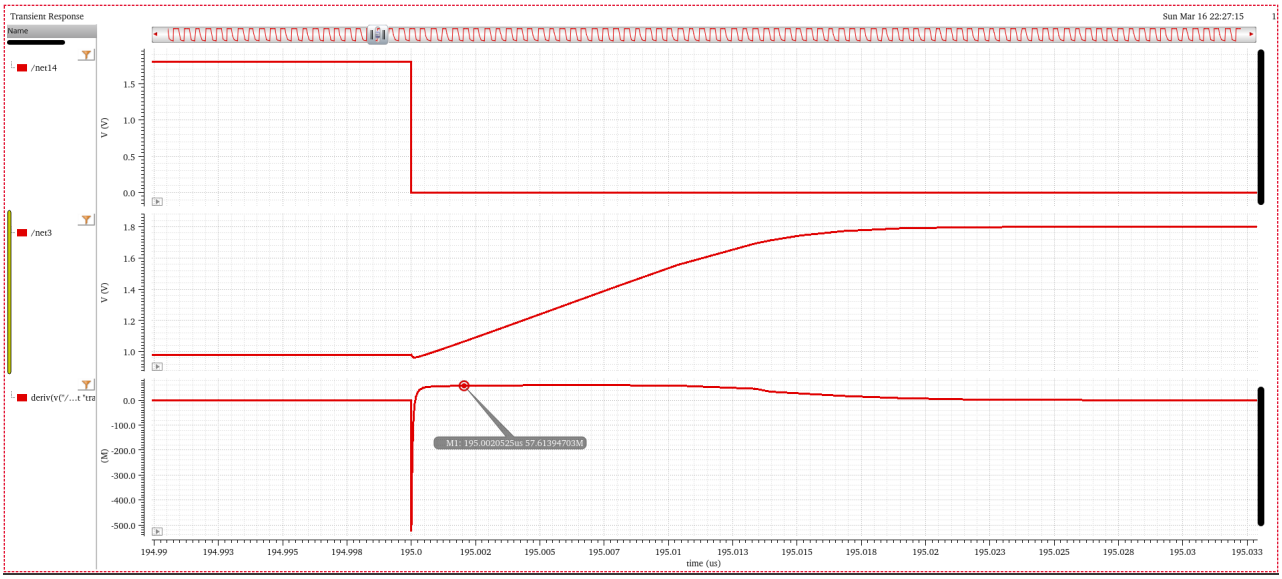

Figure 8: Slew Rate of fully differential telescopic opamp

6 Observations

The gain of the designed telescope amplifier is:

$$A_V = 57.3977\,\text{dB} \tag{65}$$

The 3 dB frequency bandwidth is:

$$\text{Bandwidth} = 215.462\,\text{kHz} \tag{66}$$

The gain-bandwidth product is:

$$\text{GBW} = 160.616\,\text{MHz} \tag{67}$$

The phase margin is:

$$\text{PM} = 83.1785 \tag{68}$$

The common-mode gain is slightly high because of less tail current resistance, and we are passing milliampere current through 180nm:

$$A_{CM} = -2.869\,\text{dB} \tag{69}$$

$$\text{Slew Rate} = 57.613\,\text{V/µs} \tag{70}$$

7 Results

Transistor	**(W/L)**	**Width (W)**	**Length (L)**
M1	51.52	27.825 um	540 nm
M2	51.52	27.825 um	540nm
M3	36.4	21.84um	600 nm
M4	36.4	21.84um	600 nm
M7	58.44	15.78µm	270 nm
M8	58.44	15.78µm	270 nm
M9	14.83	49.98µm	3.37 um
M10	11.11	2µm	180 nm
M5	116.6	35µm	300 nm
M6	116.6	35µm	300 nm

Table 1: Transistor parameters

Transistor	$\mathbf{V_G}$	$\mathbf{V_{GS}}$	$\mathbf{V_{DS}}$	$\mathbf{I_D}$
M1	1.35 V	0.686 V	0.273 V	25uA
M2	1.35 V	0.686 V	0.273 V	25uA
M3	1.7 V	0.763 V	0.248 V	25uA
M4	1.7 V	0.763 V	0.248 V	25uA
M7	1.15 V	-0.650 V	-0.168 V	-25uA
M8	1.15 V	-0.650 V	-0.168 V	-25 uA
M9	0.654 V	0.654 V	0.663 V	50uA
M10	0.654 V	0.654 V	0.654 V	50uA
M5	1 V	-0.631 V	-0.446 V	25uA
M6	1 V	-0.631 V	-0.446 V	25uA

Table 2: Bias voltages of transistors

Variable	Theoretical Value	Practical Value
Gain	60 dB	57.3977 dB
Bandwidth	-	215.462 kHz
GBW	$\geq$ 100 MHz	160.616 MHz
PM (Phase Margin)	$\geq$ 60	83.1785
CMRR	-20dB	-2.8692 dB
slewrate	-	57.613 V/us

Table 3: Theoretical and Practical Values

8 Conclusion

- The fully differential telescopic op-amp was designed to achieve high gain and wide output swing, making it suitable for applications requiring both high performance and stability under varying load conditions.
- Slew rate limitations were considered, and the amplifier was optimized to achieve a sufficient slew rate for high-frequency applications while maintaining low distortion and noise.
- The phase margin (PM) and gain-bandwidth product (GBW) were carefully designed to ensure that the op-amp has sufficient stability and bandwidth, making it suitable for high-speed applications.
- The common-mode rejection ratio (CMRR) was observed to be lower than expected due to the high tail current in the input differential pair, which caused the resistance at the tail current MOSFET to be reduced. However, this trade-off was made to achieve higher speed and gain.
- All the results obtained practically and theoretically closely matched