EE517: ANALOG VLSI LAB
Experiment 7

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

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EEE - VLSI & Nanoelectronics

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1 AIM

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

2 OBJECTIVE

maximum output swing, maximum gain, higher bandwidth, and lower power consumption with a suitable aspect ratio.

3 Provided

Supply of 1.8V

4 Design Specifications

- The target design gain is 60 dB.
- The design should have a GBW 200 MHz.
- Power dissipation 10m W
- Slew rate 50 V/µS

5 THEORY

5.1 TERMS

5.1.1 Transconductance($\mathbf{g_m}$)

In FET, transconductance is the 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, given by

$$g_m = \frac{dI_D}{dV_{GS}} \tag{1}$$

5.1.2 voltage gain $\mathbf{A_v}$

The voltage gain (AV) is the ratio of input voltage and output voltage. This depends on the bias point of the circuit, genrally considered dc gain gain as A_v

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

5.1.3 Cut off frequency $\mathbf{f_c}$

The cutoff frequency of a circuit is the frequency from which it attenuates the output signal. Specifically, it is the frequency at which the power of the output signal is one-half of the input signal. At this frequency, the output voltage drops by a factor of 70.7 percent of input voltage.

$$f_c = \frac{1}{2R\pi(C)} \tag{3}$$

5.1.4 Drain resistance $\mathbf{R_{DS}}$

When the FET's gate-to-source voltage (V_{GS}) exceeds the threshold voltage (V_{th}), it is in the "saturation" and the drain and source are connected by a channel length decreases to accomodate that effect we consider resistance equal to R_{DS}(on).

5.1.5 SLEW RATE

The slew rate aids in determining the maximum input frequency and amplitude that an operational amplifier (op-amp) may accept while maintaining minimally distorted output. In essence, it indicates the op-amp's response time to abrupt input changes.
in this experiment the slew rate is given by

$$slewrate = \frac{I_L}{C_L} \tag{4}$$

5.1.6 ICMR

The range of common-mode voltages that a differential amplifier may function correctly over is known as the input common mode range, or ICMR. It is the range of common-mode signal voltages where the differential voltage gain is constant, to be more precise.

5.1.7 GBWP

The gain at which the bandwidth is measured is multiplied by the amplifier's bandwidth to determine GBWP.
It frequently remains almost constant regardless of the gain at which it is measured for operational amplifiers, or op-amps.

5.1.8 CMRR

The common-mode rejection ratio (CMRR) measures how well a differential amplifier suppresses signals that come simultaneously and in phase on both inputs.
To put it simply, GBWP is the trade-off between bandwidth and gain.

$$CMRR_{dB} = 20\log(\frac{|A_d|}{|A_{cm}|})) \tag{5}$$

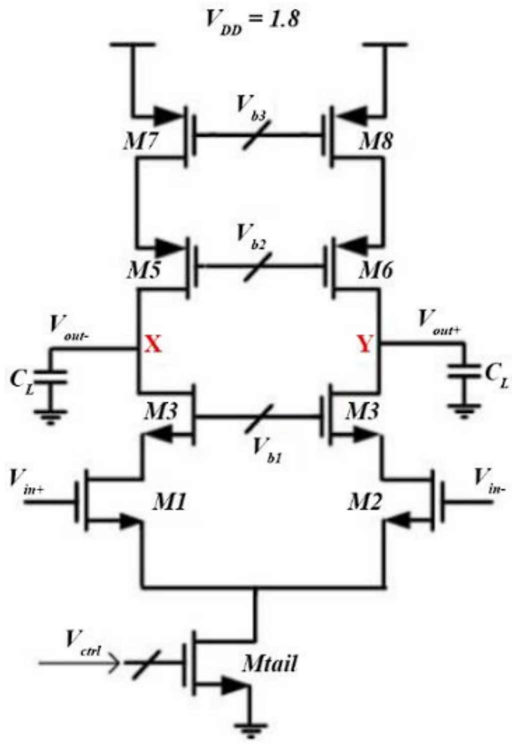
5.1.9 PSRR

The term PSRR refers to an amplifier's or circuit's capacity to prevent changes in the power supply voltage from impacting the output signal.
It measures how successfully the amplifier adjusts the output voltage in response to variations in the DC power source voltage.
An op-amp with infinite PSRR would ideally not be affected by variations in the power supply voltage on the output voltage.

5.2 Fully differential telescopic OP-AMP

In analog integrated circuits, a completely differential telescopic operational amplifier, or op-amp, is a fundamental component. Now let's examine its features and design:

Fully differential op-amps feature a differential input and a differential output, in contrast to traditional single-ended op-amps.
Because of their benefits, they are often utilized in contemporary CMOS integrated circuits.



the circuit diagram is as shown in the figure A high-gain differential amplifier is the most basic type of operational amplifier (Op-Amp). For Op-Amp applications, the gain in the range of 10–100,000 is adequate.

The open-loop gain, short and large signal bandwidths, output swing, linearity, noise, offset, and supply rejection are the performance parameters of an op-amp. These characteristics are communicated with one another through the design of an Op-Amp.

Gain may be produced very little by single cascode differential amplifiers with integrated components. The load capacitance dictates the bandwidth. Differential cascodes are employed to obtain the high gain. The load current sources and power supplies are connected via these cascode connectors.

Each branch's MOSFETs line up with one another to form a structure like a telescoping pole. As a result, this kind of arrangement is called telescoping Op-Amp.

With each of the output loads produced by the cascade current source, the final circuit is symmetric. In source follower applications, for example, a short-circuit issue at one of the inputs to the output limits the output swings as well.
Power consumption is an additional issue. Many designs have been attempted in an attempt to achieve high swing with low power consumption; nevertheless, the power consumption figure has not been disclosed.
The completely differential telescopic Op-Amp is displayed in Figure 1. The output of the completely differential designs, which can be a circuit pair to enhance gain and cover a wider frequency range, is comprised of the first and second switched current mirrors.
However, this may result in an increase in power consumption. Additionally, biasing can reduce dissipation in an Op-amp and boost gain; but, it cannot raise input or output voltage. High gain is not necessary in the design of some applications, such as Fully Differential Difference Transconductance Amplifiers (FDDTA), because these applications need minimal output.

due to the fact that they serve as a low pass filter. One benefit of the completely differential architecture is that only the n-channel MOSFETs are included in the differential mode signal route.
PMOS transistors transmit a constant current, but only NMOS transistors conduct time-varying currents. Because of the increased Op-Amp speed, the n-channel MOSFET has more mobility than the p-channel MOSFET. The telescoping Op-Amp of Figure 1 is used in my design. Due to the double load of the current source, the Common Gate-Common Source (CS-CG) combination produces a larger gain.

The gain of the amplifier can be calculated by using half part as .

$$GAIN = g_{mn}[(g_{mn}ron^2)||(g_{mp}rop^2)] \tag{6}$$

Where $\mathrm{g_m}$ is the transconductance and ro is the drain resistors in the MOSFETs. So, the gain of the telescopic cascode Op-Amp increases.
The output swing is as:

$$V_cmo = 2[v_{dd} + (V_{od1} + V_{od3} + V_{odtail} + |V_{od5}| + |V_{od7}|)] \tag{7}$$

Where, the $\mathrm{V_{od}}$ is overdrive voltage of the MOSFETs, and $\mathrm{V_{obtail}}$ reduce through the Mtail MOSFET present-day supply. This circuit's output voltage is substantially lower than that of a straight forward completely differential Op-Amp.

6 SIMULATION RESULTS

6.1 DC ANALYSIS

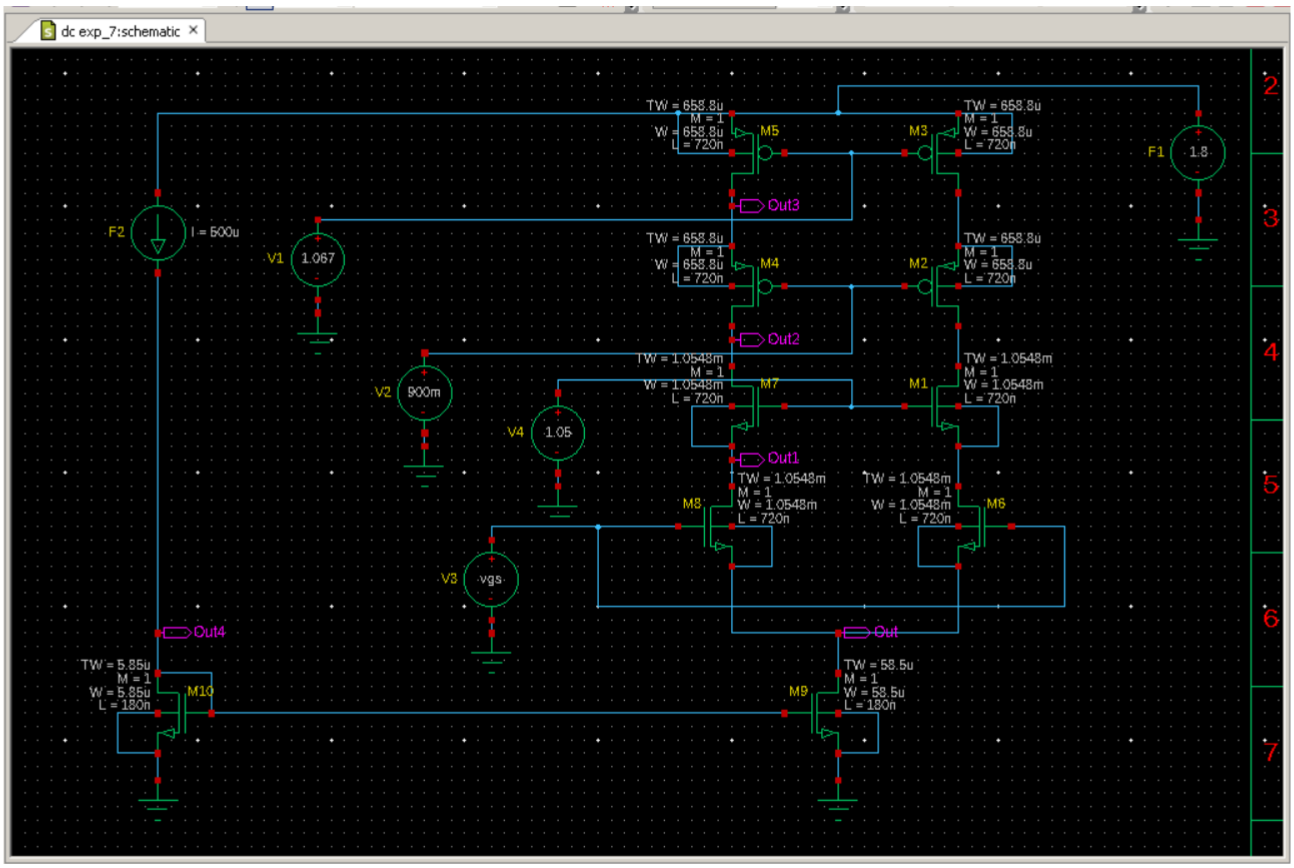


Figure 1: DC ANALYSIS schematic of fully differential telescopic OP-AMP circuits

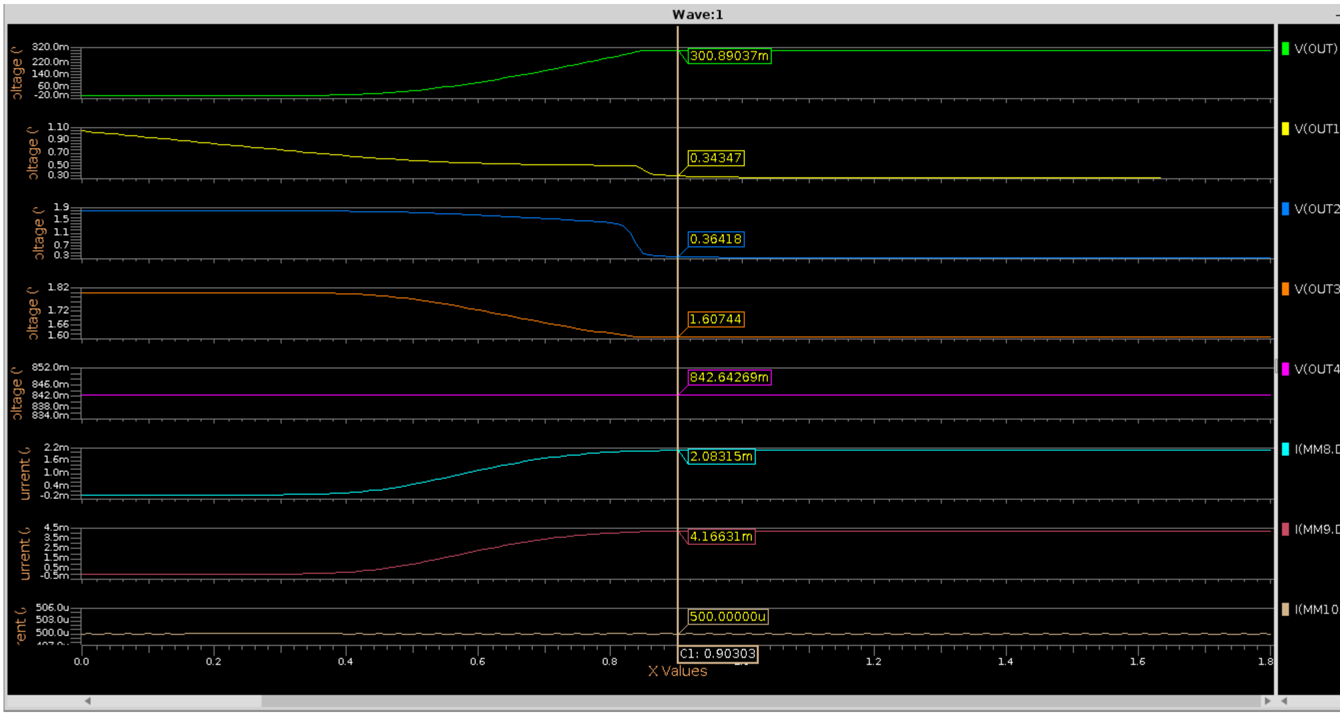


Figure 2: DC ANALYSIS graph of fully differential telescopic OP-AMP circuits

we mainly check whether all the MOSFETS are in saturation are not

for M5,M3 and V_{gs} = -0.733v and V_{DS} = -0.193v thus $|(V_{gs}\text{-}V_{th})| < V_{DS}$

$for M2, M4 and V_{\mathrm{gs}} = -0.707 v and V_{\mathrm{DS}} = -1.042 v thus |(V_{\mathrm{gs}} - V_{th})| < V_{DS}$

$for M1, M7 and V_{\mathrm{gs}} = 0.70653 v and V_{\mathrm{DS}} = 0.15801 v thus (V_{\mathrm{gs}} - V_{th}) < V_{DS}$

$for M6, M8 and V_{\mathrm{gs}} = 0.60303 v and V_{\mathrm{DS}} = 0.05403 v thus (V_{\mathrm{gs}} - V_{th}) < V_{DS}$

$for M9 and V_{\mathrm{gs}} = 0.842 v and V_{\mathrm{DS}} = 0.300 v thus (V_{\mathrm{gs}} - V_{th}) < V_{DS}$
thus all the transistors are in saturation

6.2 AC ANALYSIS

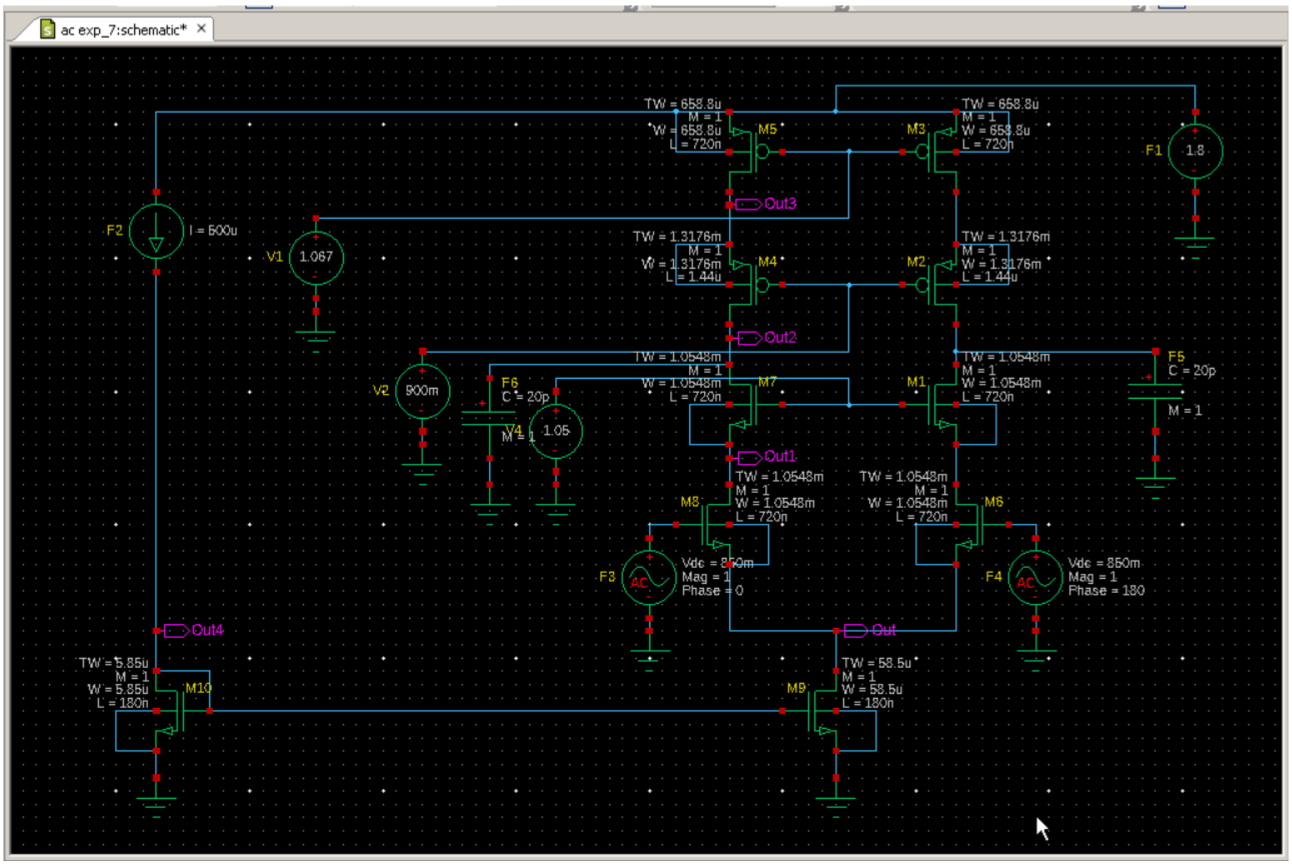


Figure 3: AC ANALYSIS schematic of fully differential telescopic OP-AMP circuits

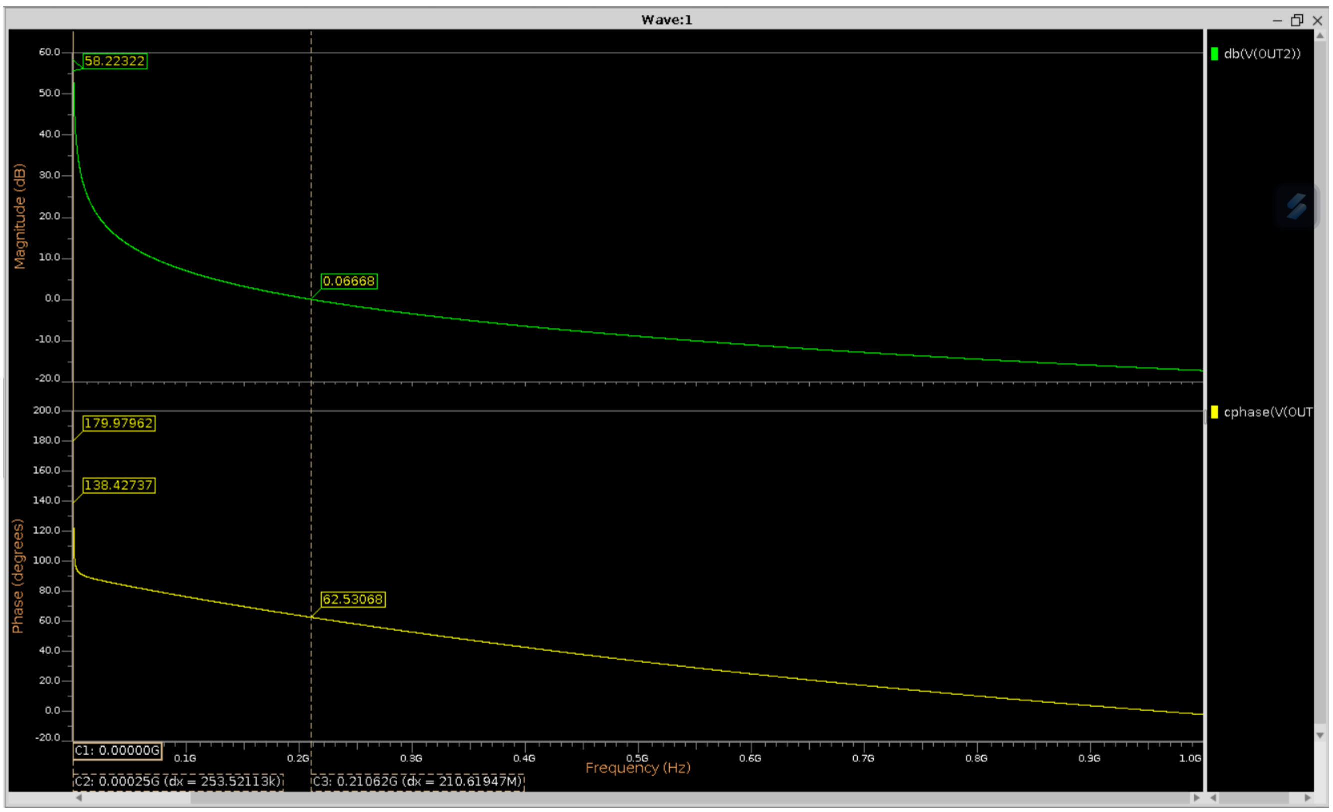


Figure 4: AC ANALYSIS graph of fully differential telescopic OP-AMP circuits

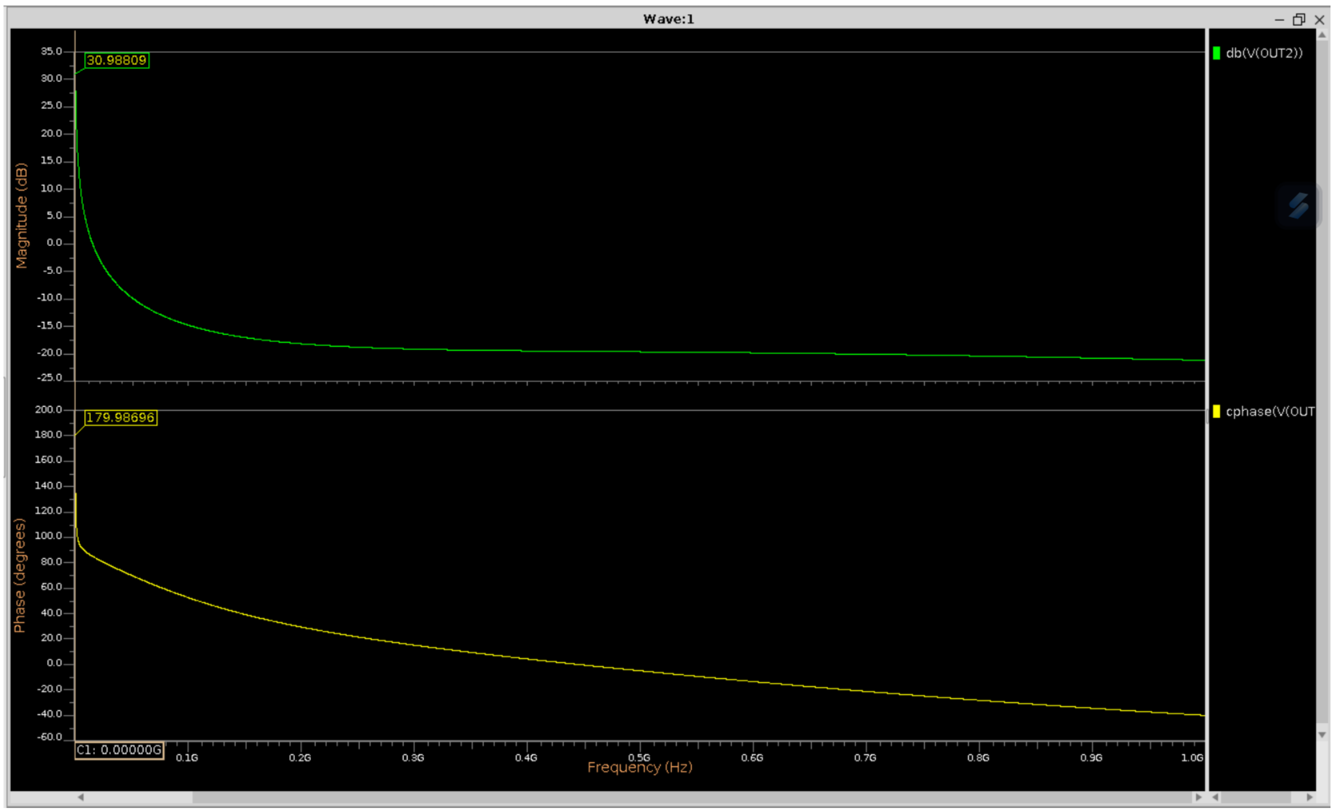


Figure 5: COMMAN mode gain graph of fully differential telescopic OP-AMP circuits

6.3 PSRR

We used the unity feed back and the inverting terminal to compute the PSRR.
The dc bias voltage was applied to the non-inverting terminal.which turns on the NMOS.
The AC source should be applied at the VDD and output taken will provide the PSRR.

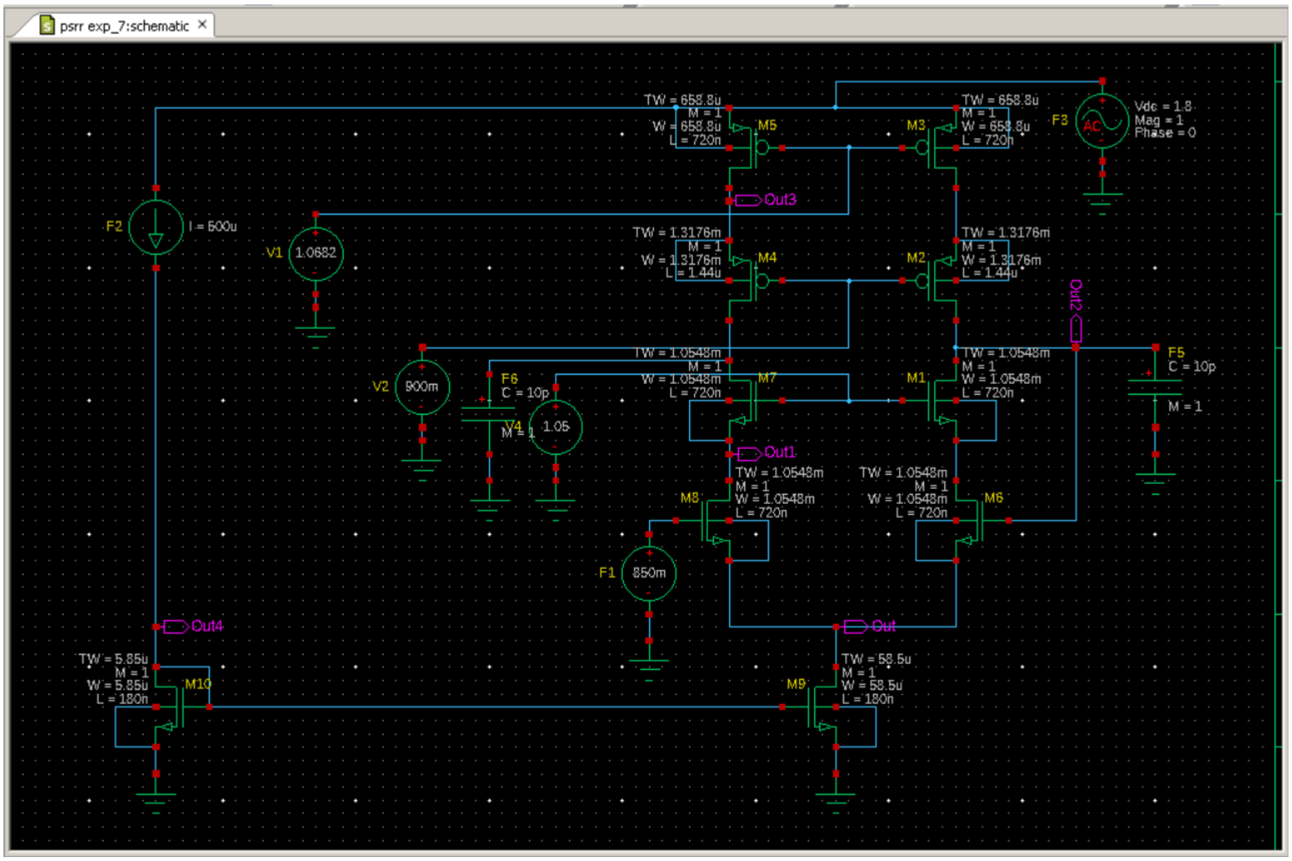


Figure 6: PSRR schematic of fully differential telescopic OP-AMP circuits

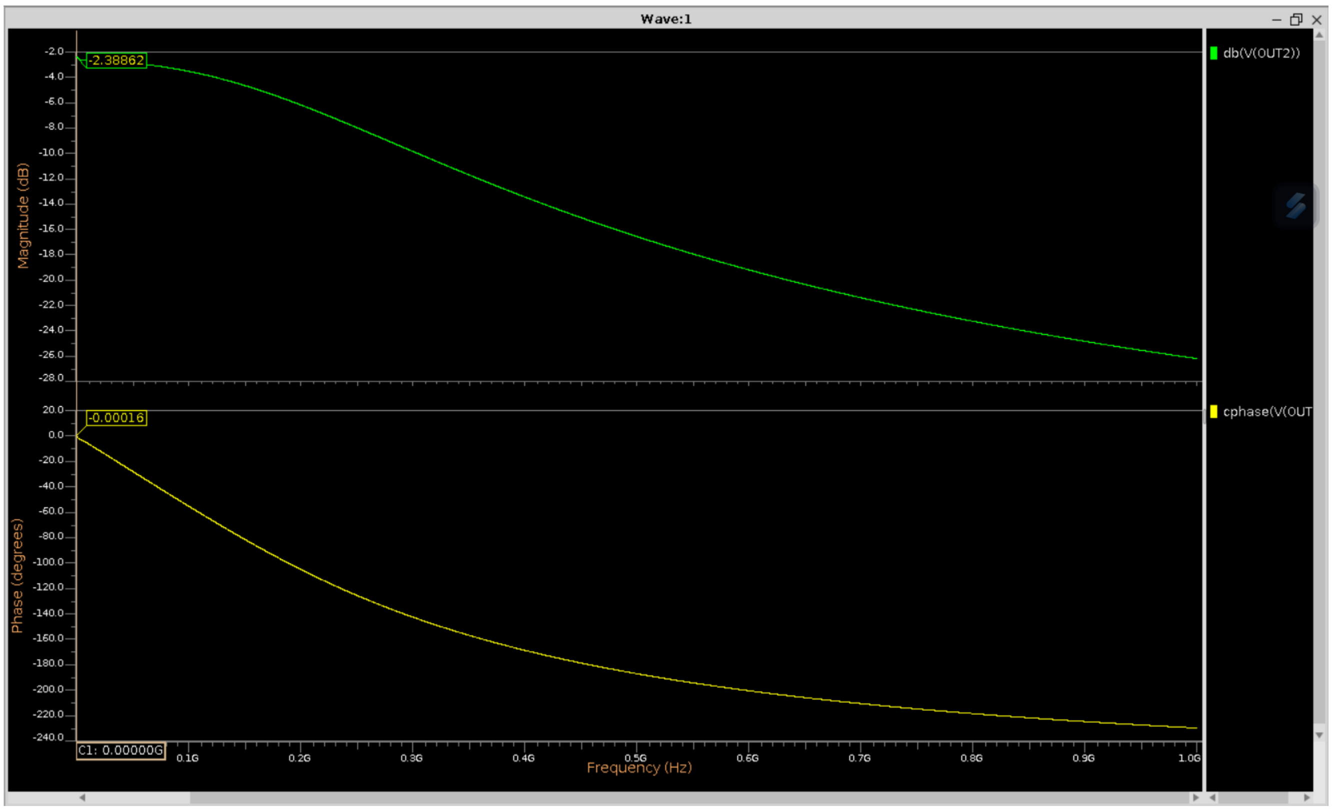


Figure 7: PSRR graph of fully differential telescopic OP-AMP circuits

6.4 SLEW RATE

generally slew rate corresponds to maximum current flowing through the load capacitor.
for that we have given input to only one of the transistors and then obtained the transient analysis

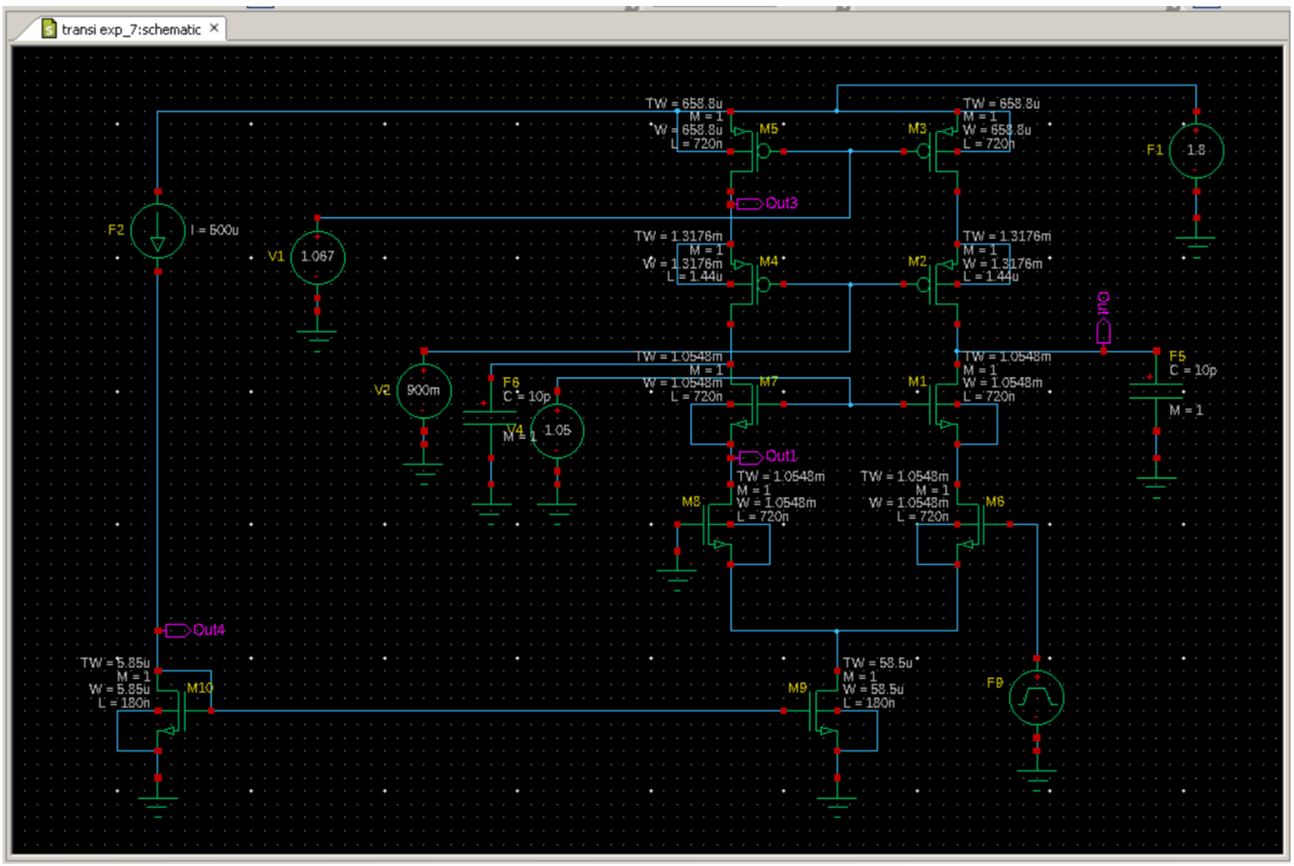


Figure 8: PSRR schematic of fully differential telescopic OP-AMP circuits

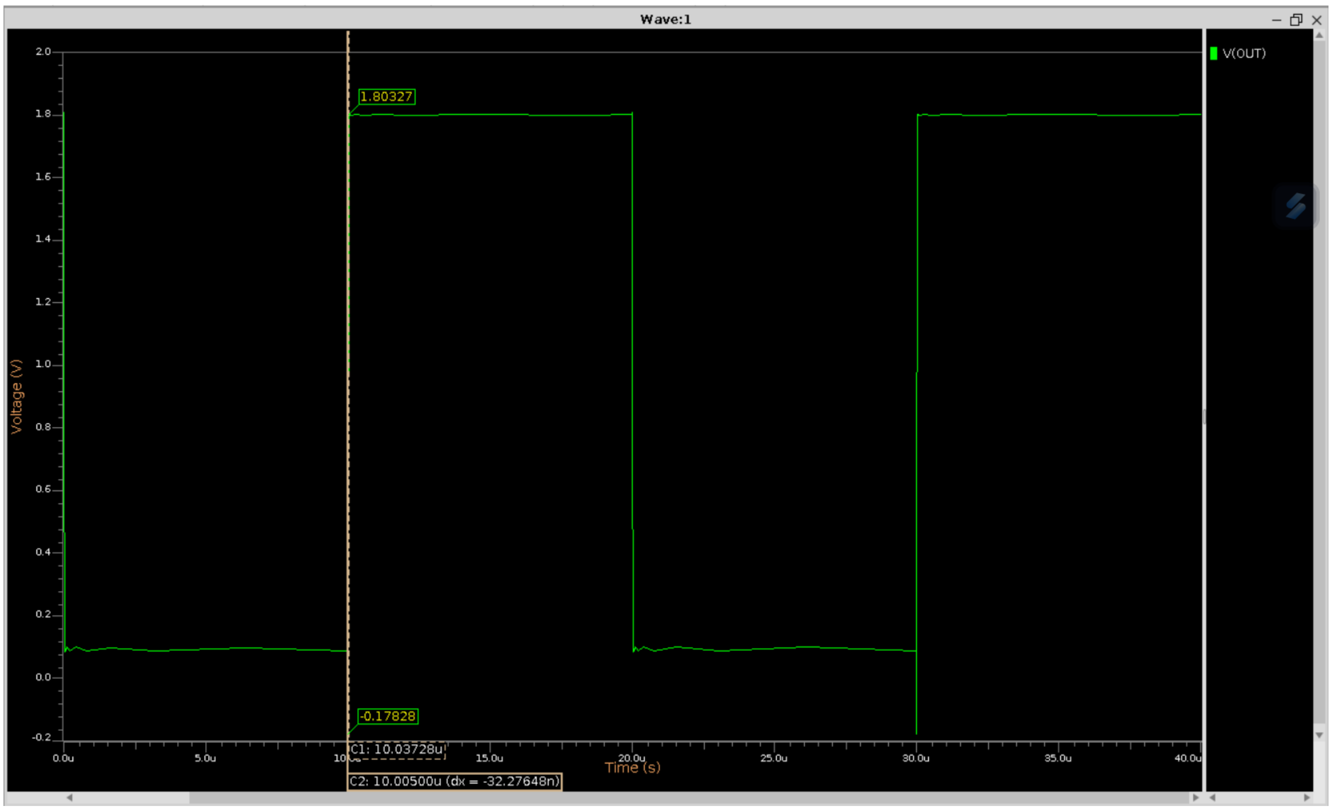


Figure 9: PSRR graph of fully differential telescopic OP-AMP circuits

6.5 ICMR OCMR

we have taken the unity gain model to evaluate the ICMR and OCMR, we can get the ICMR and OCMR in the same graph.
we have taken the negative feedback type with input given at the inverting terminal and we sweep the DC voltage and the resultant graph is as shown:

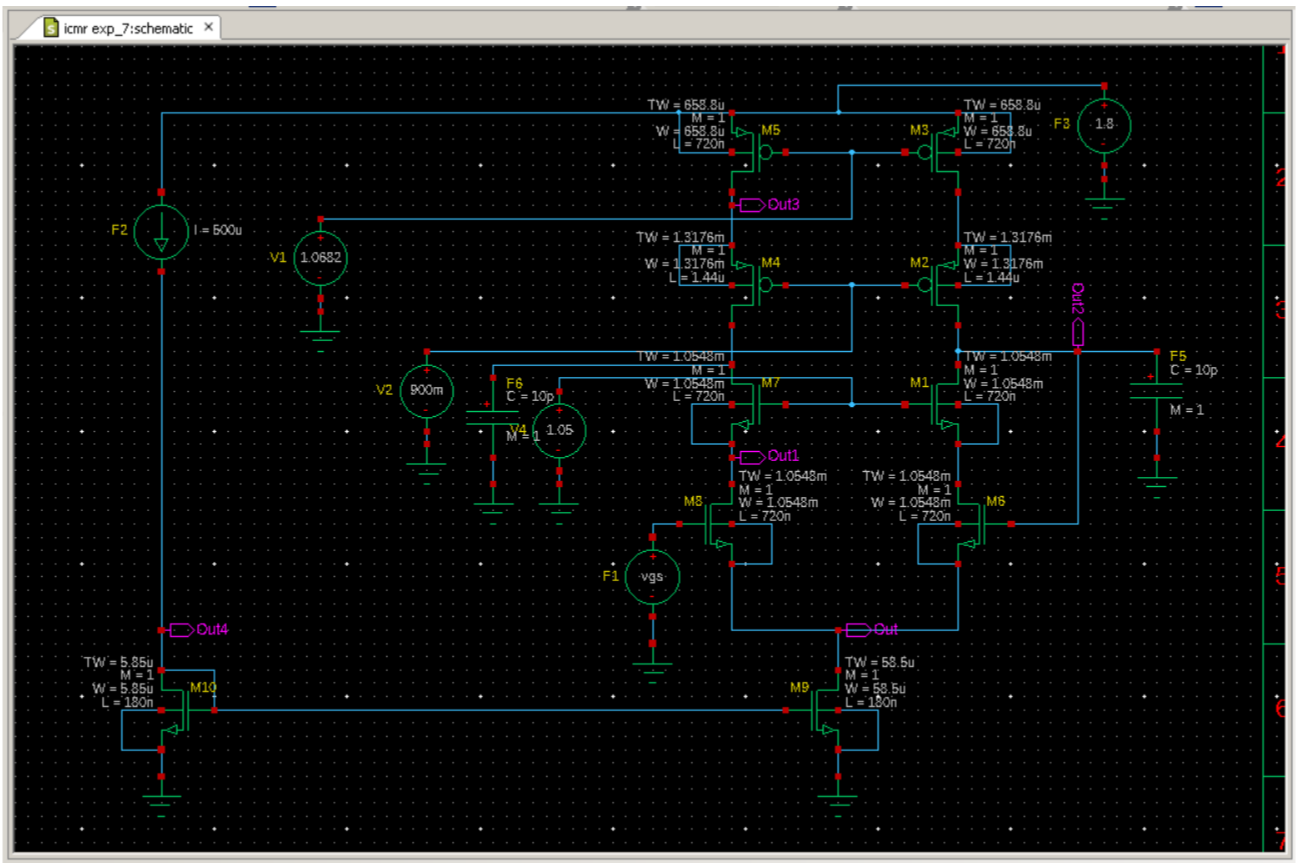


Figure 10: ICMR,OCMR schematic of fully differential telescopic OP-AMP circuits

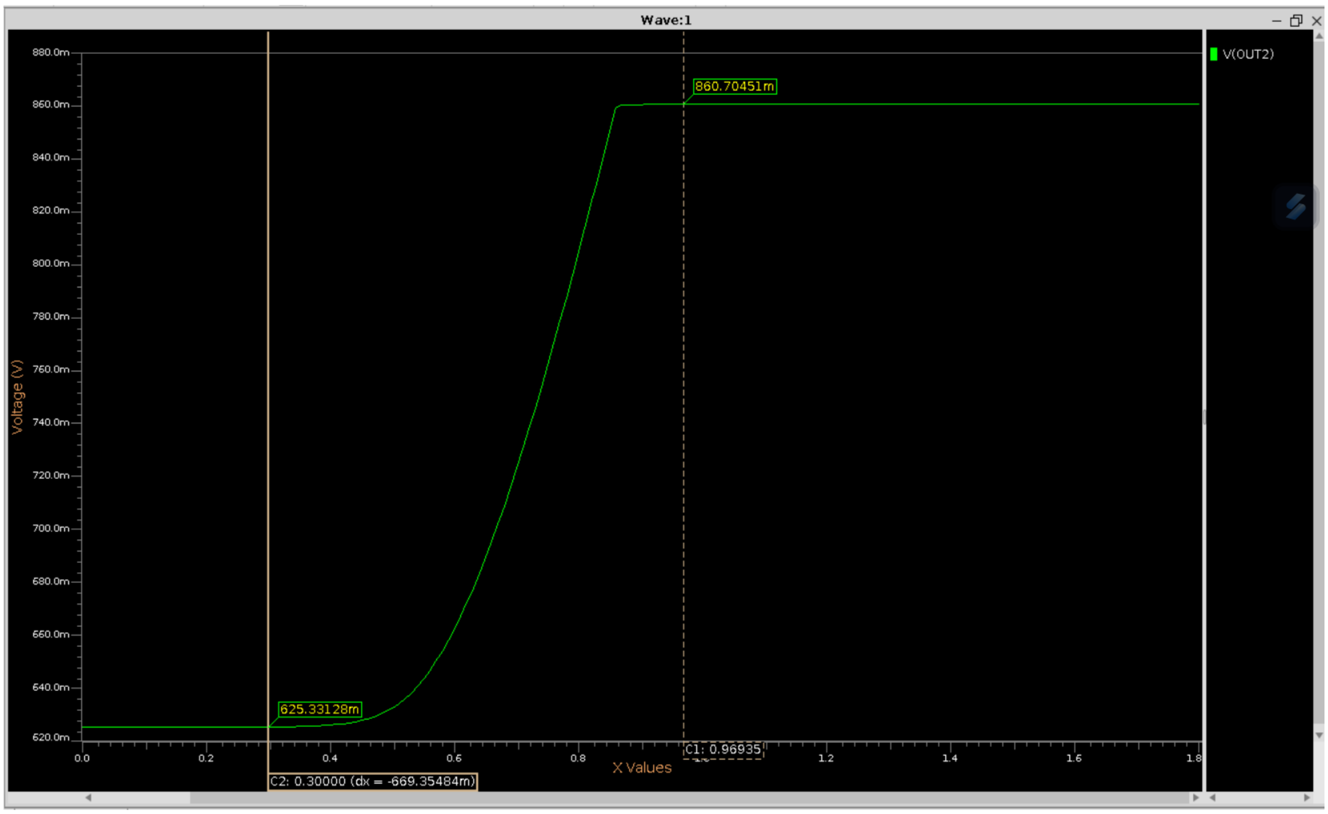


Figure 11: ICMR,OCMR graph of fully differential telescopic OP-AMP circuits

6.6 observation

gain of the telescope amplifier is.

$$A_V = 58.22dB \tag{8}$$

gain bandwidth product

$$GBW = 210Mhz \tag{9}$$

phase margin

$$PM = 117.5 \tag{10}$$

obtained common mode gain little bit high ,

$$A_CM = 30.58dB \tag{11}$$

PSRR

$$PSRR = -2.388dB \tag{12}$$

slew rate

$$SR = 61.12V/\mu s \tag{13}$$

input comman mode range

$$ICMR = 0.669v \tag{14}$$

output comman mode range

$$OCMR = 0.235 \tag{15}$$

7 CALCULATION

1. We first proceed with the power limit given in the question
2. we are given with power limit of 10mw. hence we can get a maximum current of 5.55mA
3. so we consider current flowing through the telescope amplifier as 5mA and current flowing through the current mirror as 5uA.
4. we are given with the golden current as 5uA, so we can directly the current mirror with 5uA.
5. to obtain the design parameter such as WIDTH and LENGTH of all the transistors we need to find the current flowing through the transistor and the overdrive voltage of the corresponding transistor.
6. we already know the current flowing through the telescope amplifier then current flowing through the each transistor are as follows:
    - TRANSISTORS M1,2,3,4,5,6,7,8 = 2.5mA
    - TRANSISTOR M9 = 5mA
    - TRANSISTOR M10 = 500uA.
7. from the output swing equation as shown below :

$$V_{cmo} = 2[v_{dd} + (V_{od1} + V_{od3} + V_{odtail} + |V_{od5}| + |V_{od7}|)] \tag{16}$$

    for a output swing of 1.8v we get remain voltage as 0.9v for all the transistors.

8. remain voltage is assigned to all the transistors to get optimum size design as follows:
    - M9 = 0.3V
    - M2,3,4,5 = 0.2V
    - M1,7,6,8 = 0.1V

9. now we are given the slew rate hence we can get the load capacitance (C_L) as follows:

$$slewrate = \frac{I_L}{C_L} \tag{17}$$

here we are taking the current through the tail transistor as 5mA hence we take (C_L) as 10pF.

10. we know the current flowing through the each transistor hence we are able to calculate the width and length of all the transistors with the help of current equation here we have considered μ_n as 320u

    - M1,6,7,8 = 1462.19

    we approximate it to 1465.
    for remaining pmos we have considered μ_p 137u

    - M2,3,4,5 = 911.215

    we approximate it to 915.
    for M9=325,M10 = 32.5 .

11. we need to find the voltage applied at the each transistor gate to obtain the baising point.
    we have taken the voltage V_{DS} equal to the overdrive voltage. which means V_{GS} as sum of overdrive voltage and the threshold voltage , and then according to the source and the gate source voltage of the each transistor we obtained the gate voltage, as follows:

    - for M5, M3 = 1.064v
    - for M2, M4 = 0.900v
    - for M1, M7 = 1.050v

12. for 180nm technology we have early voltage as 0.9v we get rds as 360kohms

13. $$g_{mn} = \frac{2I_D}{(V_{gs} - V_{th})^2} \tag{18}$$

we get g_{mn} = 51m(A/V) for current of 2.5mA.

$$g_{mp} = \frac{2I_D}{(V_{gs} - V_{th})^2} \tag{19}$$

we get g_{mp} = 25.5m(A/V) for current of 2.5mA.

14. we get gain from below equation as

$$GAIN = g_{mn}[(g_{mn}ron^2)||(g_{mp}rop^2)] \tag{20}$$

approximately 110

15. for further increase in gain ,we can tweek the value of rds, in order to increase rds we increase the length from 180nm to 720nm.
then rds will be 1440.
AV = 1345.

8 RESULTS

8.1 TRANSISTORS

transistor	aspect ratio	width	length
M1	1465	1.0548mm	720nm
M2	915	658.8um	720nm
M3	915	658.8um	720nm
M4	915	658.8um	720nm
M5	915	658.8um	720nm
M6	1465	1.0548mm	720nm
M7	1465	1.0548mm	720nm
M8	1465	1.0548mm	720nm
M9	325	58.5um	180nm
M10	32.5	5.85um	180nm

8.2 DC analysis

transistor	V_G	V_{GS}	V_{DS}	I_D
M1	1.050	0.706	0.159	2.08m
M2	0.900	-0.707	-1.242	2.08m
M3	1.067	-0.733	-0.193	2.08m
M4	0.900	-0.707	-1.242	2.08m
M5	1.067	-0.733	-0.193	2.08m
M6	0.862	0.603	0.057	2.08m
M7	1.050	0.706	0.159	2.08m
M8	0.862	0.603	0.057	2.08m
M9	0.842	0.842	0.300	4.16m
M10	0.842	0.842	0.842	500u

8.3 AC ANALYSIS

Variable	theoretical value	practical value
gain	60db	58.22db
bandwidth		0.289Mhz
GBW	200Mhz	210Mhz
PM	–	62.8^o
CMRR	–	30.58db
PSRR	–	-2.388db

8.4 Transient results

variable	theoretical	practical
slew rate	50 V/μs	61.12 V/μs
ICMR	–	0.669v
OCMR	-	0.235v

9 CONCLUSION

- as given in the question Telescope amplifier is constructed for high swing and high gain.
- Because we are passing milliampere currents in 180 node technology with low over drive voltage, we obtained high width and length values.
- because We have very little resistance at the tail current mosfet because of the high current, which results in lower CMRR.
- Every outcome, both theoretically and practically, matched