Design and analysis of fully differential folded cascode single-stage opamp

by,

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Contents

1 EXPERIMENTS

Analysis and design of fully differential folded telescopic OP-AMP circuit

2 OBJECTIVE

To find W/L, gain-bandwidth product, output swing, ICMR, and compare the practical and theoretical results

3 Design Specifications:

- VDD= 1.8V
- Differential output swing= 1.8V
- Power dissipation¡=0.12mW
- Voltage Gain=2000 V/V
- Technology=180 nm
- CL=10pF

4 Theory

4.1 Introduction

Op-amp is a common abbreviation for an operational amplifier. It's a high gain DC-coupled differential input voltage device. Op-amps typically create outputs that are millions of times bigger than the voltage difference between their two input terminals. A negative feedback circuit is employed to manage the huge voltage gain. If negative feedback is not employed, the op-amp works as a comparator and provides positive feedback for regeneration in specific applications.

The practical structure of op-amp consists of 3 main block as shown in the above figure

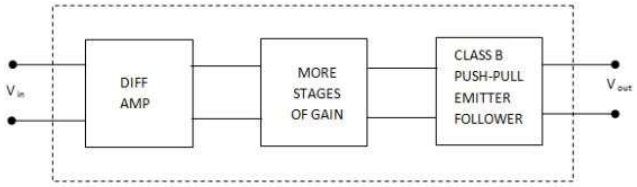

Figure 1: Block diagram of an op-amp

- The first block op-amp is an input differential amplifier that offers high input impedance, big CMRR and PSRR, low offset voltage, low noise, and high gain. The output should be single-ended to avoid symmetrical differential stages in the op-amp circuit. The input transistor should function in the saturation zone, resulting in a significant difference between the input and output signals of the input stages.

- Level shifting compensates for DC voltage changes in the input stage and ensures proper DC bias for subsequent stages.The gain offered by the input stage is insufficient; therefore, extra amplification is required. In differential-to-single-ended conversion, the input stage produces a differential output, followed by a conversion to single-ended signals.

- There is a third block called the output buffer. It provides the low impedance and high output current required to operate the opamp's load. It typically does not add to the increase. If the op-amp is an internal component of a switched-capacitor filter, the output load is a capacitor, therefore the buffer does not need to offer a high current or low output impedance. If the op-amp is at the filter output, it must drive a big capacitor or resistive load. To achieve high current driving capabilities and low output impedance, use big output devices with significant DC bias current.

4.2 Types of OP-Amps

There are various architecture available for op-amp. A few popular topologies are discussed below:

4.2.1 Two stage Op-Amp

The below figure depicts a two-stage op-amp block diagram that includes two differential inputs and a common-source stage. The differential input gives an initial gain, which is then increased in the second stage to maximize output swing. The first stage of a two-stage amplifier has differential inputs that transform the input voltage to the current. The second stage is basically

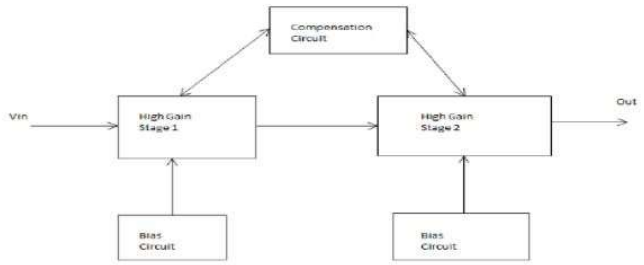

Figure 2: Block diagram of an two stage op-amp

a CS amplifier whose work is to convert current to voltage. The total DC gain of this two-stage structure can be expressed as,

$$A_{\mathrm{v}} = A_{\mathrm{v1}} * A_{\mathrm{v2}} \tag{1}$$

where,
A_{v} : Total gain of two stage Op-Amp
A_{v1} : Gain of first stage
A_{v2} : Gain of second stage

Advantages:
1) It has high output voltage swing.
Disadvantages:
1. It has compromised frequency response.
2. High power consumption due to two stages in its design.
3. It has poor negative supply PSRR at higher frequency.

4.2.2 Telescopic OP-Amp

The telescopic architecture is a simplified version of a single stage OTA. The input differential pair injects signal current into common gate stages, and the circuit converts differential to signal ended using a cascoded current mirror. The transistors are stacked on top of each other to form a telescopic composition, with MOSFETs on each branch connected in a straight line. The

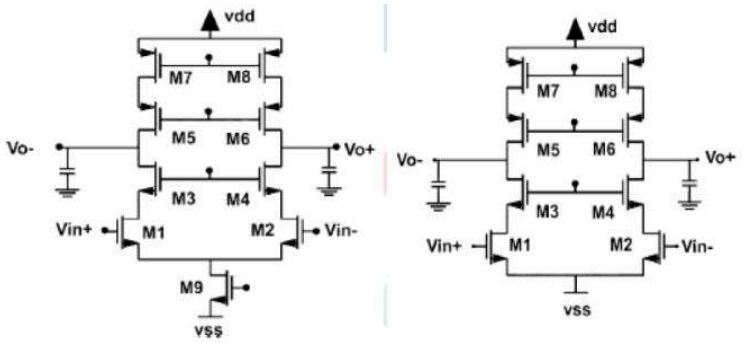

Figure 3: Block diagram of an telescopic op-amp

Telescopic operational amplifier shown in left circuit, all transistors should be operated in saturation region. Transistors M1- M2, M7-M8, and tail current source M9 must have at least Vdsat to offer good common-mode rejection, better frequency response and gain.

Advantages

1. The design under consideration combines the low power, high speed advantage of the of the Telescopic architecture with the high swing capability.
2. It achieves high performance while maintaining high common mode and supply rejection and ensuring constant performance parameters.

4.2.3 Folded Telescopic OP-Amp

To overcome the disadvantages of prior topologies, folded cascade op-amps are used. The folded structure offers greater flexibility in voltage levels as it eliminates the need to stack the cascade transistor on top of the input device. Folded cascode op-amps exhibit single-pole settling behaviour at high unity gain frequencies.

Telescopic architecture is ideal for systems requiring moderate gain from op-amps when big supply voltages are applied. However, as the supply voltage dropped, the folded cascode had to be reconsidered. A telescoping op-amp without a tail current source (shown on the right side) improves differential swing by 2Vdsat+2Vmargin, but its commonmode and power-supply rejection are severely impaired. In addition, the performance of op-amps with or without tail transistors in the linear area is affected by input common-mode and supply voltage variations, which is undesirable in most analogue applications.

Two-stage cascode op-amp circuits are commonly used for circuits with high gain and output impedance, but folded cascode can improve performance even further. The input signal of a common-gate (CG) stage is current, and the transistor in the common-source (CS) stage converts voltage into current. This topology is known as the "cascode" topology.A simple cascode circuit is shown below,

Here, transistor M1 generates a small signal drain current proportional to

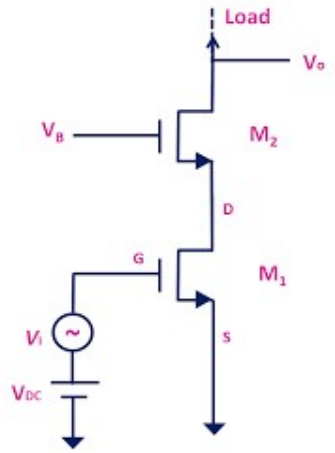

Figure 4: Circuit diagram of an cascode stage

Vin, and transistor M2 connects or routes this current to resistance RD. The transistor M1 is known as an input device, and they both carry the same current.

Folded cascode op-amp enhances the ICMR and PSRR to a reasonable level. The FCOA achieves good ICMR by cascading at the output stage and using a differential amplifier. The folded cascode op-amp has a higher output

swing than traditional telescopic amplifiers, but requires twice as much current. The big output swing shortens the input and output, making it easy to select the common-mode level. The foldable cascode i6 s more commonly utilised than telescoping op-amps.

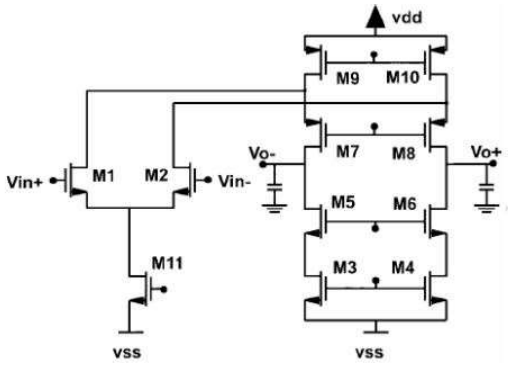

Figure 5: Circuit diagram of an folded telescopic op-amp stage

Advantages
1. It has comparatively superior frequency response then two stage op-amp.
2. Better PSRR then two stage op-amp.
3. Power consumption nearly equals to two stage op-amp.

4.3 Parameter Definitions

4.4 Trans conductance (g_m)

Trans conductance indicates sensitivity of circuit to its input voltage

$$g_m = \frac{dI_{ds}}{dV_{gs}} \tag{2}$$

4.5 Threshold Voltage(V_{th})

The minimum gate source voltage for which the MOSFET goes into inversion and turned on.

$$V_{th} = V_{gs} \ at \ which \ \frac{d^2 I_D}{dV_{GS}^2} \ is \ maximum \tag{3}$$

4.6 Early Voltage(V_A)

Since the drain and substrate PN diode becomes more reverse biased, the space change region increases at drain.since the drain current is more, there will be significant voltage drop across the space charge region. which is called *Early voltage*

$$V_A = \frac{1}{r_o I_{D_{sat}}} \tag{4}$$

4.7 Channel length modulation parameter(λ)

As we increase Vds, the pinch off point moves towards source which reduces effective channel length which is called channel length modulation. since there will be high electric field in space charge region it pulls electrons into drain. now the dependence of magnitude of current on Vds arises. the parameter that signifies the channel length modulation is λ

$$\lambda = \frac{1}{V_A} \tag{5}$$

5 AC analysis

By fixing all the DC values we make sure that the transistor is in saturation such that the we obtain significant AC parameters. now we apply small signal, make changes in circuit accordingly and observe the following parameters called AC Parameters.

5.1 AC parameters

5.1.1 voltage Gain A_v:

After applying a significant DC input, we provide AC input such that there will be a significant voltage obtained at output. In order to compare the input and output obtained we make use of a parameter called AC Gain which is the ration of both.

$$A_v = \frac{v_{out}}{v_{in}} \tag{6}$$

5.1.2 Cut off frequency f_c:

Any AC circuit will have a significant AC Gain till some frequency, after some frequency the gain of the circuit falls significantly. which we usually call roll off. cut off frequency is nothing but the value of frequency at which the gain will be 3dB less than that of maximum gain

$$\text{cut off frequency} = \text{frequency}_{\text{at 3db less than maximum gain}}$$

5.2 Output resistance R_o

In practical circuits, we connect multiple blocks of analog circuits in cascade where one circuit loads another circuit with a resistance. Output of preceding circuit loads succeeding circuits with preceding circuits output resistance. Hence it is an important AC parameters.

$$Rout = \frac{V_{test}}{I_{test}} \tag{7}$$

5.3 Slew rate

Maximum rate of change of output is known as slew rate

$$Slewrate = \frac{dV_{out}}{dt}_{max} \tag{8}$$

5.4 CMRR

Usually in differential amplifiers, the common signal is considered as noise will be rejected and output will be free from noise. in order to quantify the ability to reject the noise we use CMRR

$$CMRR = \frac{A_{diff}}{A_{comm}} = infinite|_{ideal} \tag{9}$$

5.5 PSRR

A differential amplifier rejects common mode signal and amplifies differential signal. Hence to quantify the ability of differential circuit to amplify differential signal and suppress common mode signal we use PSRR

$$PSRR = \frac{\delta V_{cc}}{\delta V_{out}} = infinite|_{ideal} \tag{10}$$

5.6 ICMR

The range of common mode input we can apply so that all the transistors are in saturation

6 Design approach

Lets design all the parameters for the given specifications,

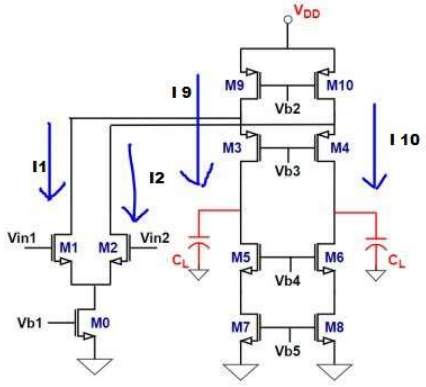

Figure 6: Design circuit of folded telescopic op-amp

Power constraint:
$P_{dissipation} = V_{dd} * (I2 + I1 + I9 + I10)$
$V_{dd} = 1.8v$
Given, $P_{dissipation} = 0.12mW$.
hence,$(I2 + I1 + I9 + I10) = 66.67$ uA.
$I9 = I10 = 30$ uA.
$I0 = I3 = I7 = I4 = I6 = I8 = I5 = 15$ uA
so, $I1 = I2 = 15$ uA
Let's design in such a way that I1 + I2 greater than I9 + I10 for maximizing gain.

Voltage swing constraint:
We know that half circuit is going to have 0.9v of swing in telescopic structure.

V9 + V3 + V5 + V7 = V10 + V4 + V6 + V8 = 0.9v

ICMR Constraint:
ICMR = Vgs1 = Vov0 = o.5 *(0.3+1.2) = 0.75
therefore, Vod1 = 0.05v.
Vod0 = 0.15v.

Widths and Lengths:
since we have current and overdrive voltages of every MOSFET, from the basic saturation current equation of NMOS and PMOS we obtain below W/L values,

transistor	aspect ration	width	length
M0	5.84	1440nm	8176 nm
M1	11.690	1800nm	21042 nm
M2	11.690	1800nm	21042 nm
M3	3.644	1440nm	5241 nm
M4	3.644	1440nm	5241 nm
M5	1.461	1440um	2103nm
M6	1.461	1440um	2103nm
M7	1.461	1440um	2103nm
M8	1.461	1440um	2103nm
M9	4.859	1800 nm	8745 nm
M10	4.859	1800 nm	8745 nm
M11	4.859	1800 nm	8745 nm

7 waveforms

7.1 DC analysis

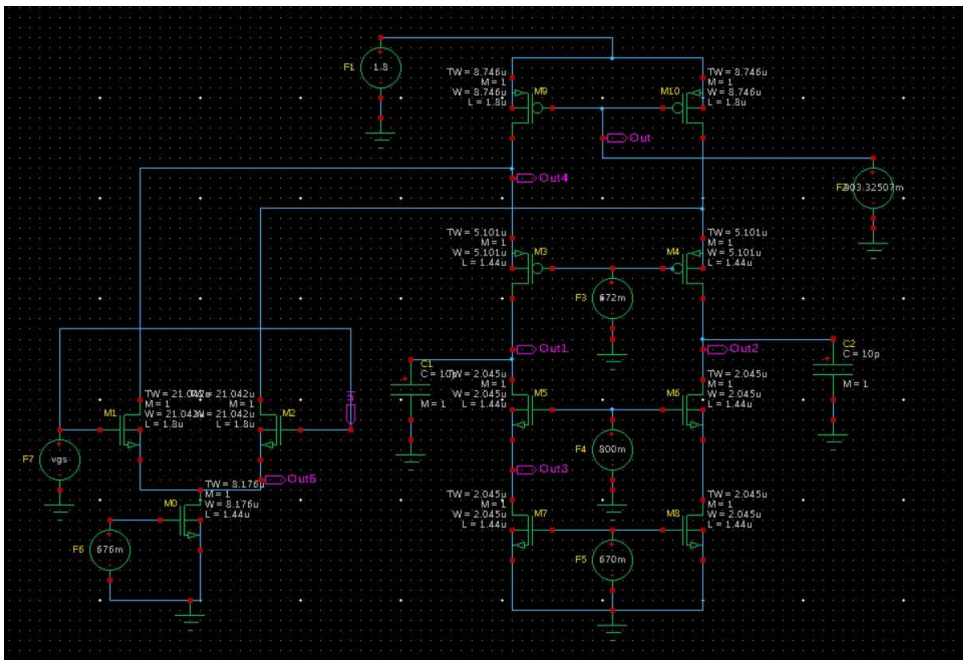

Figure 7: circuit diagram for DC analysis of Telescope amplifier

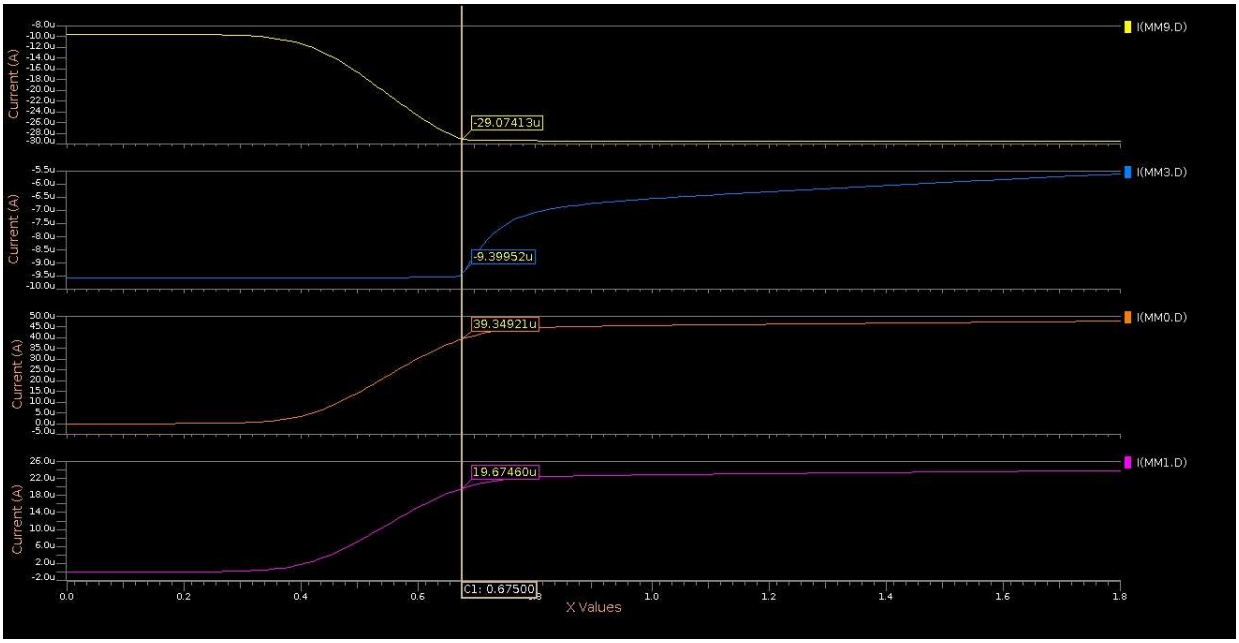

Figure 8: DC analysis of Telescope amplifier

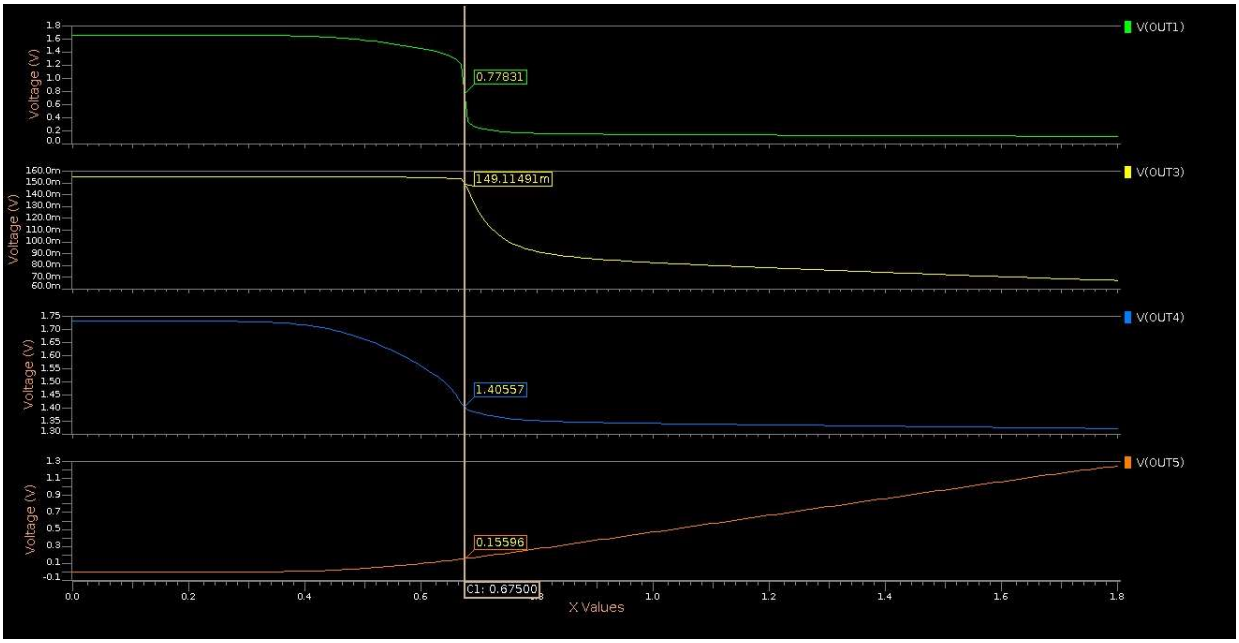

Figure 9: DC analysis of Telescope amplifier

7.2 AC analysis

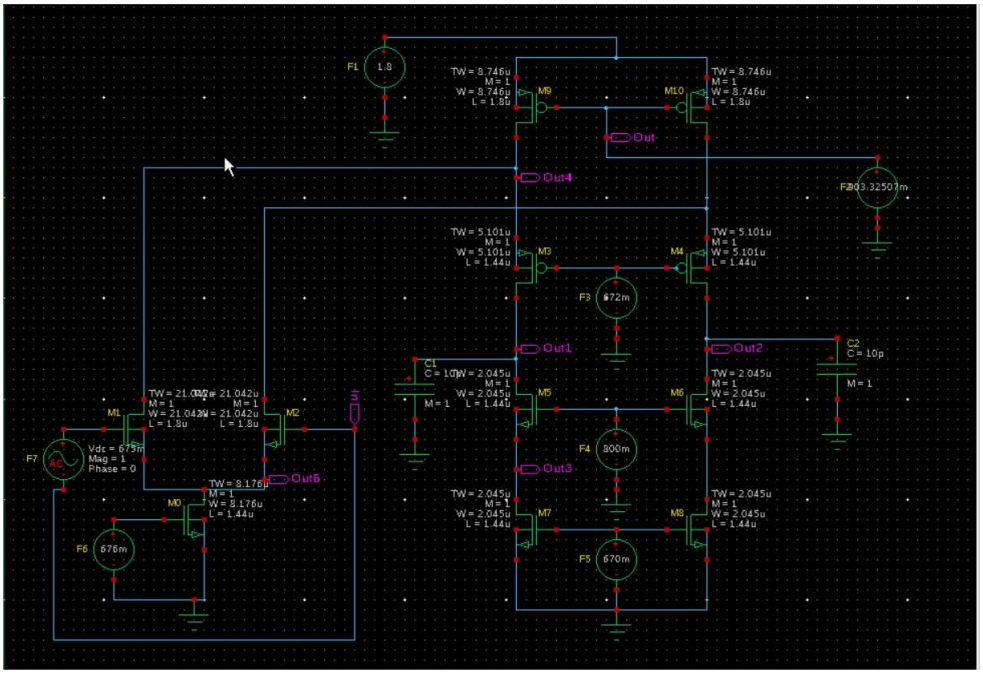

Figure 10: circuit diagram for AC analysis of Telescope amplifier

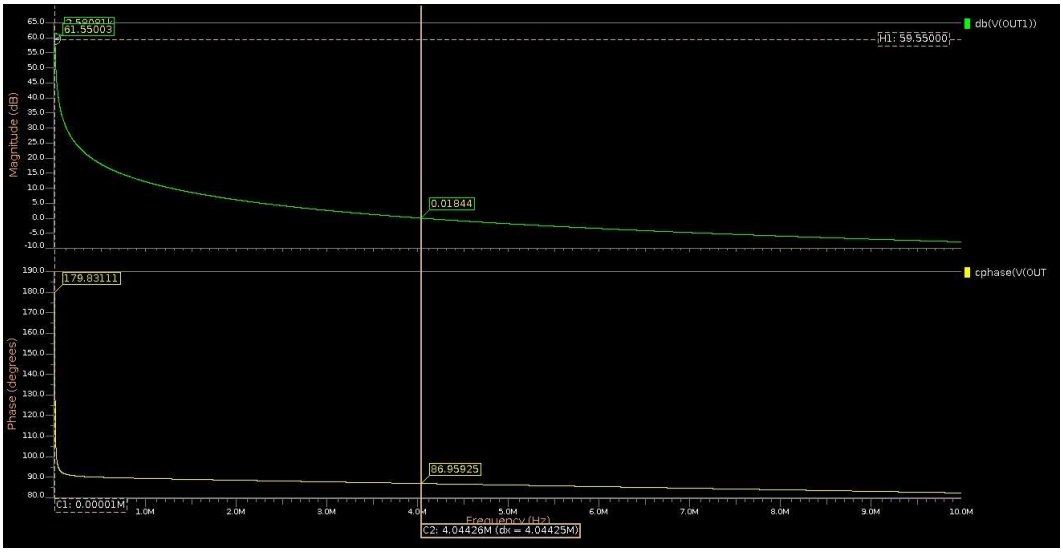

Figure 11: AC analysis of Telescope amplifier

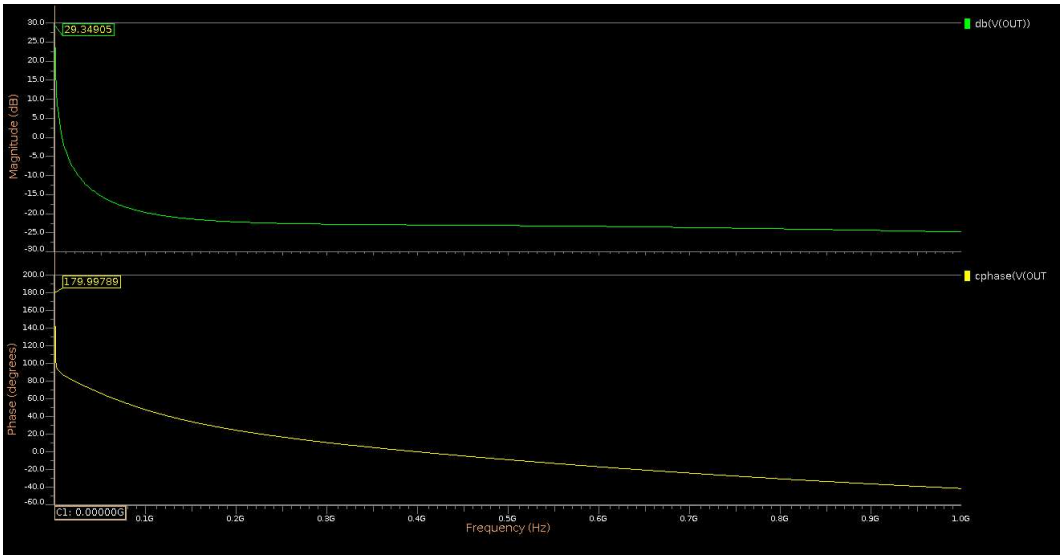

Figure 12: Common Mode gain of Telescope amplifier

7.3 PSRR

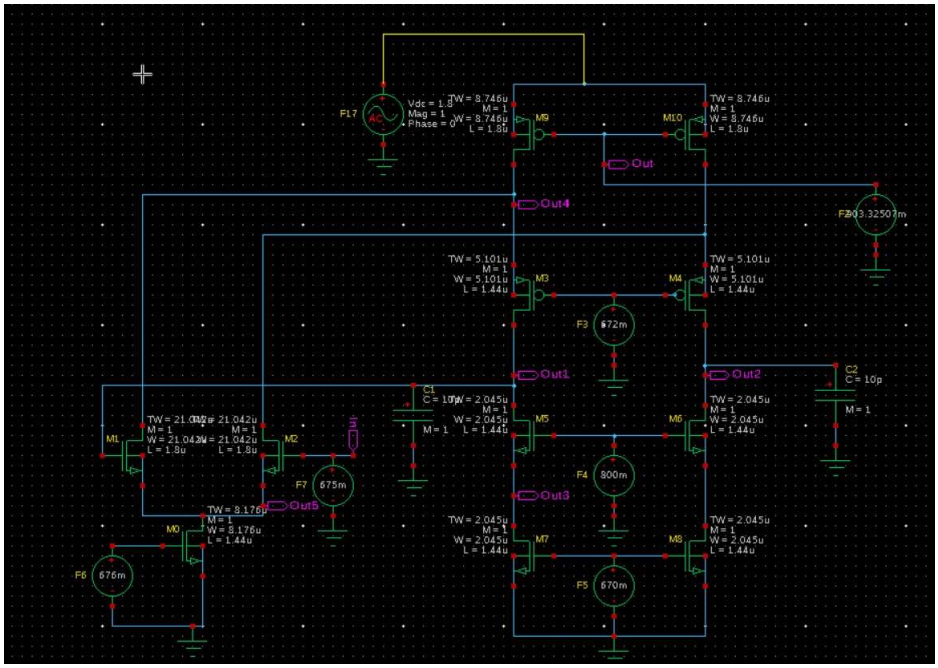

Figure 13: circuit diagram for PSRR analysis of Telescope amplifier

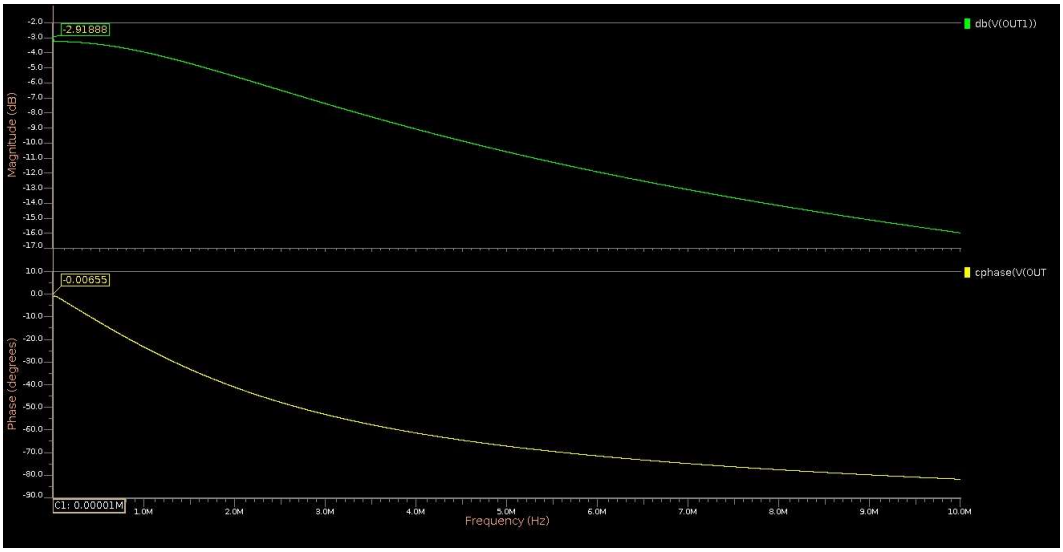

Figure 14: PSRR analysis of Telescope amplifier

7.4 ICMR and OCMR

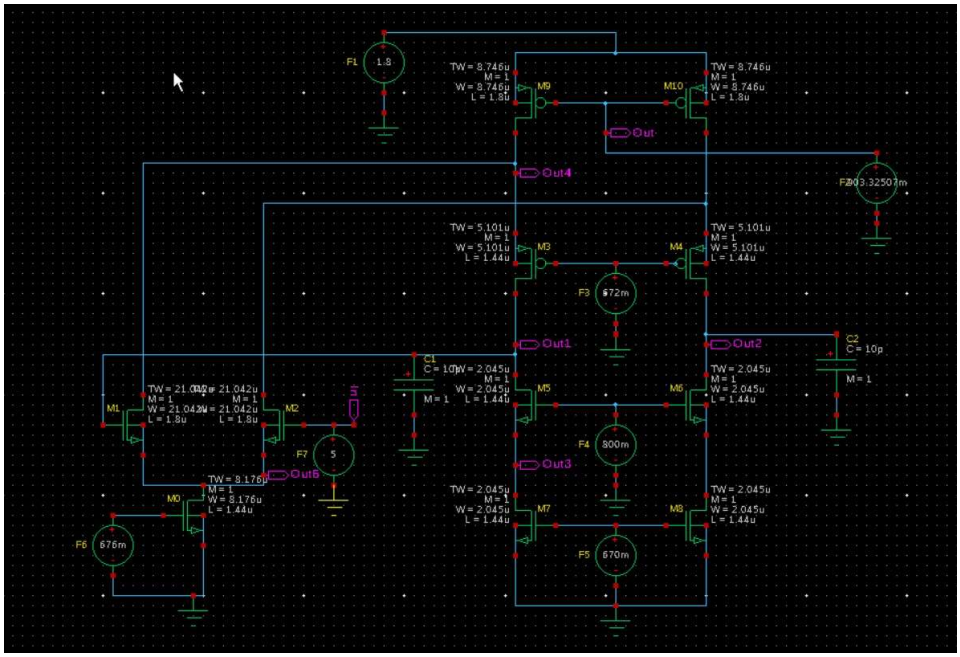

Figure 15: circuit of ICMR and OCMR analysis of Telescope amplifier

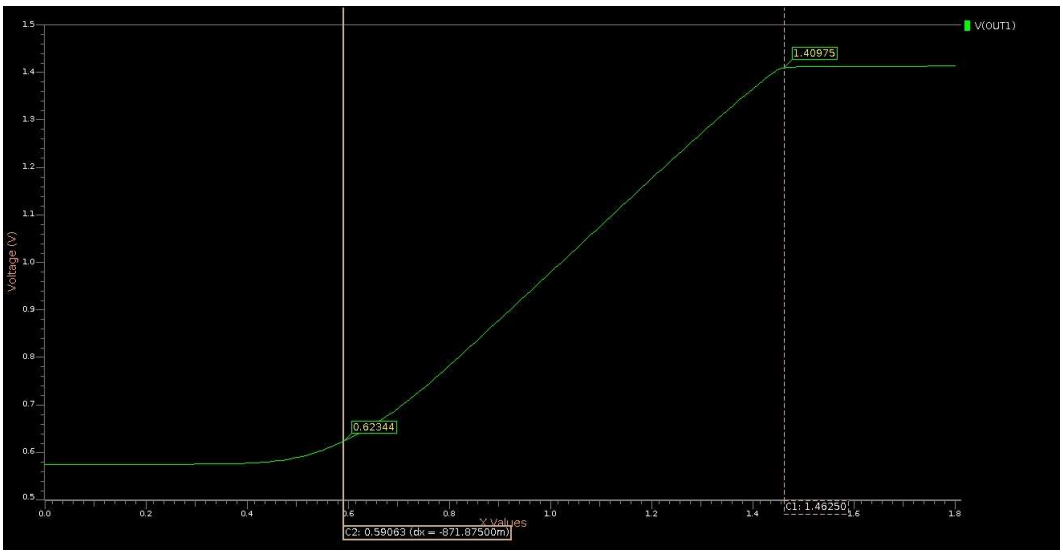

Figure 16: results of ICMR and OCMR analysis of Telescope amplifier

7.5 Slew rate

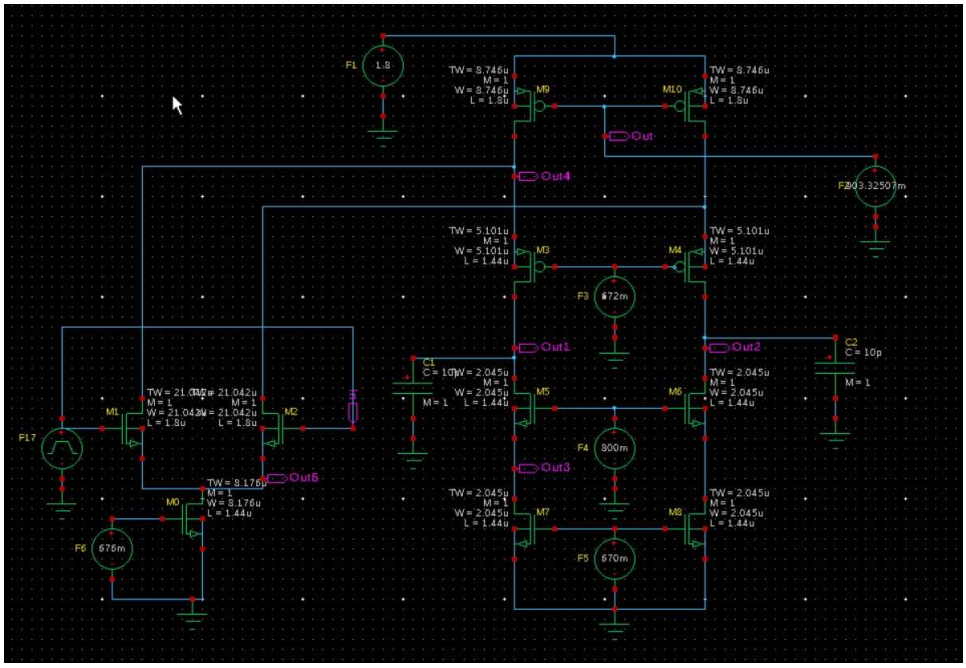

Figure 17: Circuit diagram to find the slew rate

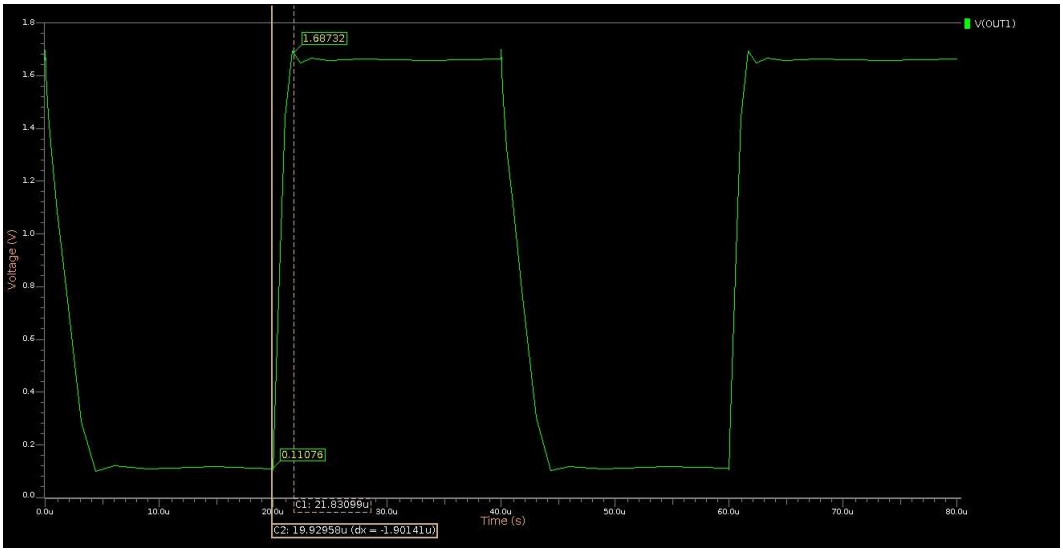

Figure 18: Results of slew rate

8 Comparsion Tables

8.1 Bias voltages of transistors

transistor	V_G	V_{GS}	V_{DS}	I_D
M0	0.676v	0.676v	0.18v	31.349uA
M1	0.675v	0.513v	1.206v	19.674uA
M2	0.675v	0.513v	1.206v	19.674uA
M3	0.672v	-0.714v	-0.479v	-9.399 uA
M4	0.672v	-0.714v	-0.479v	-9.399 uA
M5	0.8v	0.638v	0.745v	9.399 uA
M6	0.8v	0.638v	0.745v	9.399 uA
M7	0.670v	0.670v	0.745v	9.399 uA
M8	0.670v	0.670v	0.745v	9.399 uA
M9	0.903v	-0.897	-0.414	-29.074uA
M10	0.903v	-0.897	-0.414	-29.074uA

8.2 AC results

Variable	practicalvalue
gain	61.55 dB
bandwidth	0.0026 Mhz
GBW	4.27 Mhz
PM	86.95
CMRR	29.3dB
PSRR	-2.91dB

8.3 Transient results

Variable	theoretical value	practical value
slew rate	1	0.829
ICMR/OCMR max	1.409	0.623
ICMR/OCMR min	1.462	0.593

9 Conclusions:-

- we can see there is significant improvement in gain as compared to single stage op-amp.
- All the results have been obtained practically and matching with the theoretical justification. The theoretical calculations have been done.