

REVIEW OF FOLDED CASCODE & TELESCOPIC OP-AMP

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Abstract- This paper presents the detailed design of a single stage telescopic op-amp and single ended folded cascade op-amp by using design equations. The concept of telescopic & folded cascode op-amp topology, its design methodology in terms of procedure, criteria and equations has been presented. The performance characterizing parameter & operations of their proposed structure are discussed in fundamental form. The proposed telescopic structure yields medium gain while the folded cascode provides comparatively high gain than the telescopic op-amp.

Index Terms: Op-amp (operational amplifier), Telescopic op-amp, Folded cascode op-amp (FCOA), Unity Gain Bandwidth (UGB), Gain, Phase margin, Input Common-Mode Range (ICMR), Power Supply Rejection Ratio (PSRR), Slew Rate (SR).

I. INTRODUCTION

1.1 INTRODUCTION:

An operational amplifier is often called an op-amp. It is rather a high gain DC-coupled differential input voltage device. Usually an op-amp produce very large output i.e. million times larger than the voltage difference across its two input terminal where a negative feedback circuit is used to control the large voltage gain. If negative feedback doesn't used then the op-amp acts as a comparator, and also acts as positive feedback for regeneration in certain application[15].

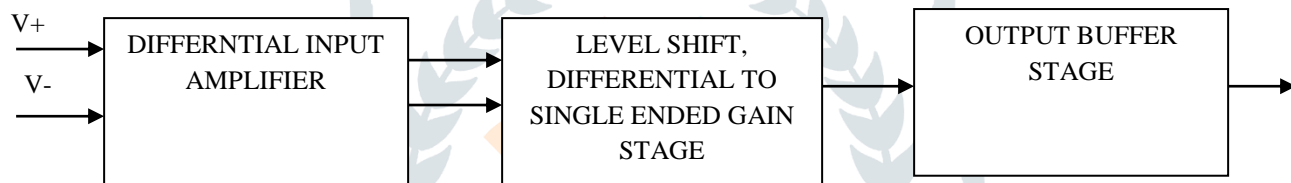


Fig.1-General structure of op-amp

The practical structure of op-amp consists of 3 main block as shown in fig 1:

- The first block op-amp is input differential amplifier, which is designed so that it provide very high input impedance, a large CMRR and PSRR, a low offset voltage, low noise and high gain. Its output should preferably be single ended, so that the rest of the op-amp need not contain symmetrical differential stages. Since the transistor in the input region should operate in saturation region so that there is appreciable difference in the input and output signal of the input stages[6].
- The second stage performs one or more of the following[6]:
 - Level shifting:** This is needed to compensate for the DC voltage change occurring in the input stage, and this to assure the appropriate DC bias for the following stage.
 - Added gain:** The gain that is provided by input stage is not sufficient and this the additional amplification is required.
 - Differential to single ended conversion:** The input stage which has a differential output, and the conversion to single ended signals is performed in a subsequent stage.
- There is a third block called output buffer. It provides the lower impedance and larger output current needed to drive the load of the op-amp. It normally does not contribute to the gain. If the op-amp is an internal component of a switched-capacitor filter, then the output load is a capacitor, and the buffer need not provide very large current or very lower output impedance. However if the op-amp is at the filter output, then it have to drive a large capacitor and/or resistive load. This requires large current drive capability and very low output impedance which can only be attained by using large output devices with appreciable DC bias current[6].

1.2 TYPES OF OP-AMPS:

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

TELESCOPIC:

The design that is shown in fig 2 although has smaller voltage swing, this is offset somewhat by the lower noise factor. Due to the fact that above mentioned the telescopic op-amp is better candidate for low power, low noise OTA [1].

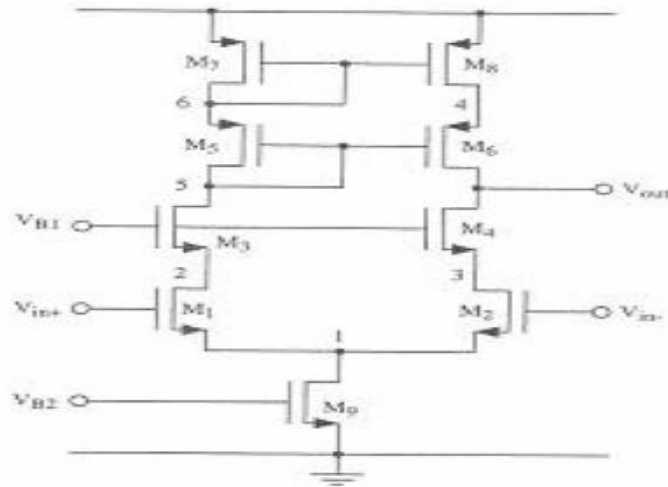


Fig.2 Telescopic Cascode single stage amplifier

Advantage:

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.

FOLDED CASCODE:

In order to alleviate the drawback of previous topologies folded cascade op-amp are used. The primary advantage of the folded structure lies in the choice of the voltage levels because if doesn't stack the cascode transistor on the top of the input device. Folded cascode op-amp have the important property of single pole settling behavior with large unity gain frequency [1].

Advantage:

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.

TWO-STAGE OP-AMP:

Two-stage op-amp block diagram shown in fig 3 consist of two differential inputs and the second stage is a common-source stage. The given differential input provides initial gain and gain is increased by second stage and hence maximizes the output swing. The first stage of two-stage amplifier having differential inputs whose function is to convert given input voltage to current [5].

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

$$A_v = A_{v1} * A_{v2} \tag{1}$$

where,

A_{v1} : gain of first stage.

A_{v2} : gain of source follower i.e. second stage.

The DC gain can be expressed as :

$$A_v = G_m * R_{out} \tag{2}$$

where

G_m : transconductance of input network

R_{out} : effective output resistance

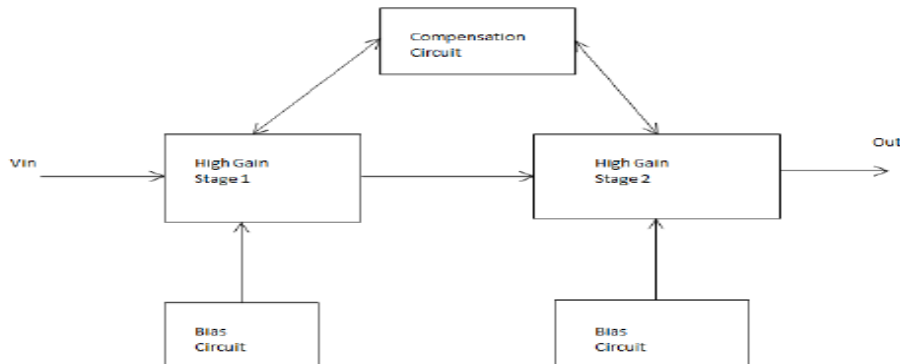


Fig 3:Block diagram of two stage op-amp

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.

II. TELESCOPIC OP-AMP

The telescopic architecture is the simplest version of a single stage OTA shown in fig2, the input differential pair injects the signal current into common gate stages. Then, the circuit achieves the differential to signal ended conversion with cascoded current mirror. The transistor are placed one on the top of the other to create a sort of Telescopic composition. This results in the structure in which MOSFETs on each branches are connected along a straight line like the lenses of refracting telescope. Hence, this configuration is also known as telescopic configuration[1].

The Telescopic operational amplifier shown in fig:4(a), all transistors should be operated in saturation region. Transistors M1- M2, M7-M8, and tail current source M9 must have at least V_{dsat} to offer good common-mode rejection, better frequency response and gain[1].

When we have to apply large supply voltages, telescopic architecture becomes the better choice for the systems requiring moderate gain for the op-amp. However, when the supply voltage reduced, it forced reconsideration in favor of the folded cascode[1].

Although a telescopic op-amp without the tail current source fig:4(b) improves the differential swing by $2V_{dsat}+2V$ margin, the common-mode rejection and power-supply rejection of such a circuit is greatly compromised. Moreover, the performance parameters(such as unity gain frequency) of the op-amp with no tail or with a tail transistors in the linear region is sensitive to input common-mode and supply voltage variation which is undesired in most analog cases[7].

2.1 SCHEMATIC DIAGRAM:

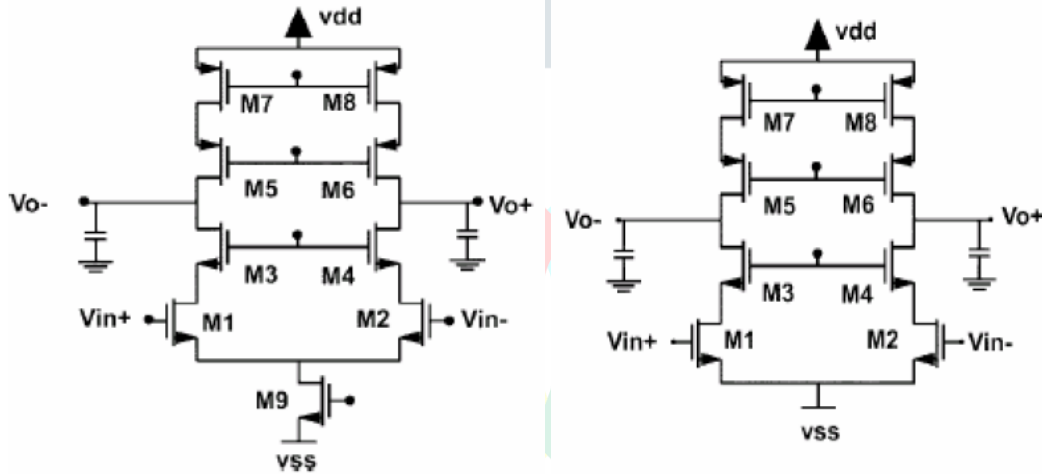


Fig:4(a) Telescopic amplifier

Fig:4(b) No-tail telescopic amplifier

2.2 PROPOSED STRUCTURE OF TELESCOPIC OP-AMP:

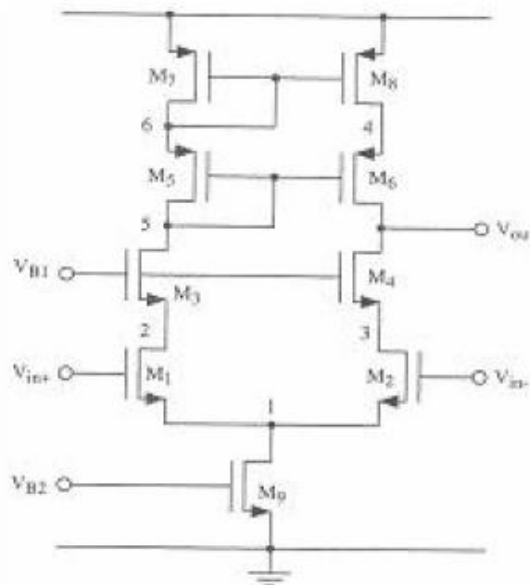


Fig:5 Single-ended Telescopic Cascode

2.3 DESIGN PROCEDURE:

SPECIFICATIONS [1]

- . Gain at dc (Av)
- . Unity gain bandwidth (GB)
- . Load capacitance (CL)
- . Slew rate (SR)
- . Power Dissipation (P_{diss})

DESIGN STEPS [1]:

STEP1: The first step of the design gives the estimation of the bias current assuming the GBW established by the dominant node, we have

$$2\pi f_T = \frac{2I_{ss}}{(V_{GS} - V_{TH})} \frac{1}{C_L} \tag{3}$$

where I_{ss} is the tail current.

STEP 2: Design Tail transistor M9 and calculate W and L of this transistor by using the transistor in saturation .The equation used is

$$I_{ss} = \frac{\mu C_{OX}}{2} \left(\frac{W}{L}\right)_9 (V_{GS} - V_{TH})^2 \tag{4}$$

STEP 3: Calculate the bias V_{B2} of transistor M9 using the equation

$$V_{B2} = V_{GS9} - V_{TH} \tag{5}$$

STEP 4: Design the differential pair of the circuit, by assuming both of them to be working in saturation mode. Their aspect ratios could be calculated using bias current I_{ss}. The equation used is

$$I_{ss} = \frac{\mu C_{OX}}{2} \left(\frac{W}{L}\right)_1 (V_{GS} - V_{TH})^2 \tag{6}$$

STEP 5: Calculate the common mode voltage that allows M9 to be in Saturation

$$V_{in, cm} \geq V_{sat, 9} + V_{GS1} \tag{7}$$

STEP 6: Design the High Compliance Current mirror and calculate the Bias voltage that is applied to both the gates by the following equation

$$V_{B1} - V_2 - V_{TH, n} = V_{sat, 3} \tag{8}$$

where V_{B1} is the bias voltage that is applied to High Compliance current mirror, V₂ is the voltage at node 2 and V_{TH, n} is the threshold voltage. The aspect ratios of transistors M3 and M4 can be calculated by assuming both the transistors in saturation and both are matching. The current equation is

$$I_{ss} = \frac{\mu C_{OX}}{2} \left(\frac{W}{L}\right)_{3,4} (V_{GS} - V_{TH})^2 \tag{9}$$

where

$$V_{GS} = V_{B1} - V_{sat, 2} - V_{TH, n} \tag{10}$$

STEP 7: Design the Cascode Current Mirror stage where there are four PMOS transistors, which are identical, and the current passing through them is same as the drain and gate are tied to each other. They all are in saturation mode. The current flowing is same that was in High Compliance Current Mirror stage. The aspect ratios can be calculated by the following current equation

$$I_{ss} = \frac{\mu C_{OX}}{2} \left(\frac{W}{L}\right)_{5,6,7,8} (V_{GS} - V_{TH})^2 \tag{11}$$

where

$$V_{GS} = V_{DD} - 3V_{TH, P} \tag{12}$$

III. FOLDED CASCODE OP-AMP (FCOA)

Basically two-stage cascode op-amp circuits are mostly used in designing of circuits where there is a requirement of high gain & high output impedance. But the performance can be even better if folded cascode is used.

Furthermore we know that the input signal of a common-gate(CG) stage is current and transistor in common-source(CS) stage converts voltage into current. Thus, the topology in which the CS stage is cascaded with CG stage, it is referred as “cascode” topology[11]. A simple cascode stage is drawn below [11] :

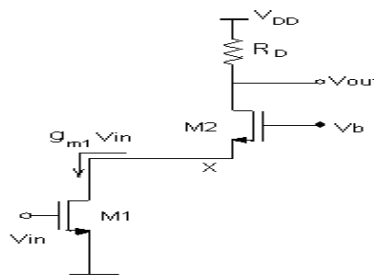


Fig.6 : Schematic of Cascode stage

Here transistor M1 generates small signal drain current proportional to V_{in} and transistor M2 links or routes this current to resistance R_D . The transistor M1 is known as input device and both of them carry equal current[11].

Folded cascode op-amp provides improves the ICMR and PSRR to a decent level. The FCOA uses cascading at the output stage combined with differential amplifier ,that results in achieving good ICMR. Folded cascode op-amp provides larger output swing than the ordinary conventional telescopic amplifier but it consumes twice the current than the telescopic. Because of large output swing, the input and output are shorted so that it becomes much convenient & easier for selection of input common-mode level. The folded cascode is more widely used than the telescopic op-amp[17].

Folded cascode op-amp possess a very important property i.e. it allows the input common-mode level close or nearer to supply voltage. With PMOS input, the input common-mode level can be lower to 0V while one with NMOS input it can reach to supply voltage V_{DD} . As compared to ordinary op-amp, folded cascode provides high gain with large output swing and is a single-pole op-amp. The major advantage of single-pole op-amp is that it provides great stability and large phase margin [16].

3.1 SCHEMATIC DIAGRAM :

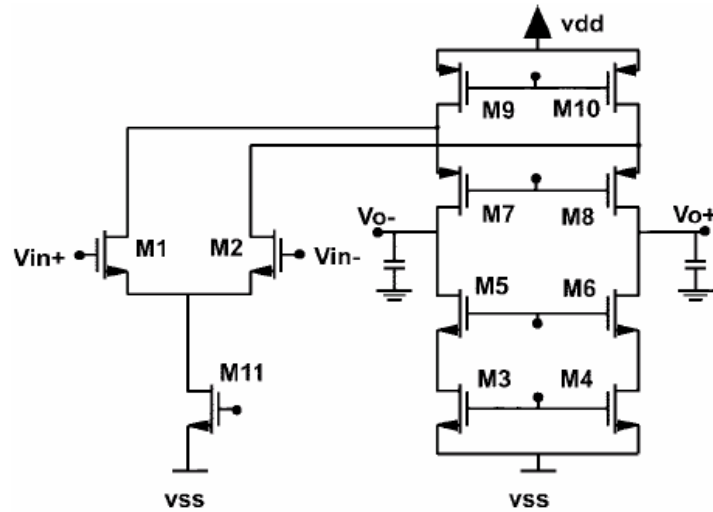


Fig 7 : Folded cascode amplifier

Also, it is more appropriate for negative feedback as it increases the small signal gain. Some of the important advantages are mentioned below:

1. The structure provides much better frequency response than two-stage op-amp.
2. It provides decent high frequency PSRR.
3. The overall power consumption is nearly same as that of two-stage structure.

3.2 PROPOSED STRUCTURE OF FOLDED CASCODE OP-AMP:

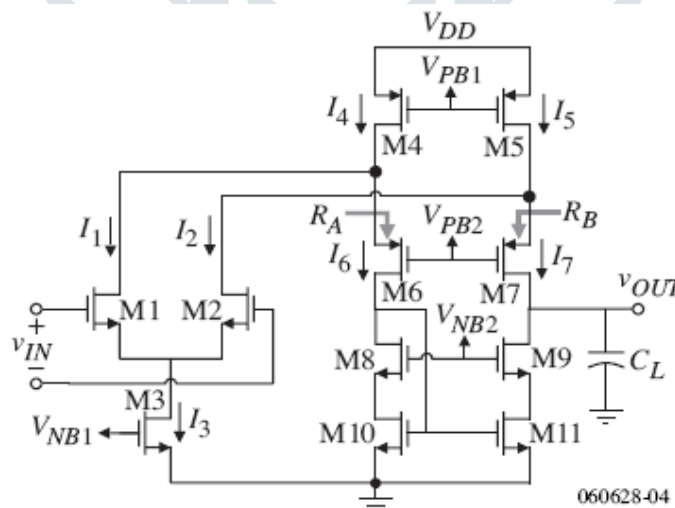


Fig 8 : Single –ended Folded cascode op-amp

3.3 DESIGN PROCEDURE[1]:

SPECIFICATIONS:

- . Gain at dc (A_v)
- . Unity gain bandwidth (GB)
- . Load capacitance (CL)

. Slew rate (SR)

. Power Dissipation (Pdiss)

1. Slew rate :

$$I_3 = SR \cdot C_L \quad (13)$$

2. Bias currents in output cascode, thus avoiding zero currents in cascode :

$$I_4 = I_5 = 1.2I_3 \text{ to } 1.5I_3 \quad (14)$$

3. Using maximum output voltage, $V_{out(max)}$

$$V_{SD5(sat)} = V_{SD7(sat)} = 0.5[V_{DD} - V_{out(max)}] \quad (15)$$

$$S_5 = \frac{2I_5}{K_P V_{SD5}^2}, S_7 = \frac{2I_7}{K_P V_{SD7}^2}, (S_4 = S_5, S_6 = S_7) \quad (16)$$

4. Using minimum output voltage, $V_{out(min)}$:

$$V_{SD9(sat)} = V_{SD11(sat)} = 0.5[V_{out(min)} - V_{SS}] \quad (17)$$

$$S_{11} = \frac{2I_{11}}{K_N V_{SD11}^2}, S_9 = \frac{2I_9}{K_N V_{SD9}^2}, (S_{10} = S_{11}, S_8 = S_9) \quad (18)$$

5. Using gain bandwidth(GB) :

$$S_1 = S_2 = \frac{g_m^2}{K_N I_3} = \frac{GB^2 \cdot C_L^2}{K_N I_3} \quad (19)$$

6. Using minimum input common mode :

$$S_3 = \frac{2I_3}{K_N \left(V_{in(min)} - V_{SS} - \sqrt{\left(I_3 / K_N S_1 \right) - V_{T1}} \right)^2} \quad (20)$$

7. Using maximum input common mode :

S4 and S5 must meet or should exceed the values in step 3.

$$S_4 = S_5 = \frac{2I_4}{K_P \left(V_{DD} - V_{in(min)} + V_{T1} \right)^2} \quad (21)$$

8. Power dissipation is given by :

$$P_{diss} = (V_{DD} - V_{SS})(I_3 + I_{10} + I_{11}) \quad (22)$$

PARAMETERS TO BE MEASURED:

1. Offset Voltage:

The amplifiers output is supposed to be completely independent of common potentials applied to both inputs and is supposed to be zero when the voltage difference between the inverting and non-inverting inputs is zero. For an ideal op-amp, if $V_a = V_b$ (which is easily obtained by short circuiting the input terminals) then $v_0 = 0$. In real devices, this is not exactly true, and a voltage $V_{0,off} \neq 0$ will occur at the output for shorted inputs. Since $v_{0,off}$ is usually directly proportional to the gain, the effect can be more conveniently described in terms of the input offset voltage $V_{in,off}$, defined as the differential input voltage needed to restore $v_0=0$ in the real devices. For MOS op-amps $V_{in,off}$ is about 5- 15mV.

2. Slew Rate:

For a large input step voltage, some transistors in the op-amp may be driven out of their saturation regions or completely cut-off. As a result the output will follow the input at a slower finite rate. The maximum rate of change dV_0/dt is called slew rate. It is not directly related to the frequency response. For typical MOS op-amps slew-rates of 1~20 V/ μ s can be obtained.

3. Frequency Response:

Because of stray capacitances, finite carrier mobilities and so-on, the gain A decreases at high frequencies. It is usual to describe this effect in terms of the unity gain bandwidth, that is the frequency f_0 at which $|A(f_0)| = 1$. For MOS op-amps, f_0 is usually in the range of 1-10 MHz. It can be measured with the op-amp connected in a voltage-follower configuration.

4. Bandwidth (BW):

An ideal operational amplifier has an infinite Frequency Response and can thus be used to amplify signals of any frequency. However as evident from the frequency response curve below the gain of the amplifier is not constant irrespective of frequency and after the first pole it begins to drop with a slope of 20dB/decade thus the higher the frequency of the first pole the higher the range of freq over which it operates desirably.

5. Gain:

Operational amplifiers are mainly used to amplify the input signal and the higher its open loop gain the better as in many applications they are used with a feedback loop, so ideal op-amps are characterized by a gain of infinity. For practical op-amps, the voltage gain is finite. Typical values for low frequencies and small signals are $A = 10^2 - 10^5$, corresponding to 40-100 dB gain.

CONCLUSION [3]:

1. From the theoretical study of telescopic and folded cascode presented in this paper, it is concluded that the overall voltage swing of a folded-cascode op-amp is only slightly higher than that of a telescope configuration. This advantage comes at the cost of higher power dissipation, lower voltage gain and higher noise.
2. Folded cascode op-amps are used widely, even more than telescopic topologies, because the input and outputs can be shorted together and the choice of the input common-mode level is easier.
3. In telescopic op-amp, three voltage must be defined carefully, the input CM level and the gate bias voltage of the PMOS and NMOS cascode transistors, whereas in folded-cascode configurations only the latter two are critical.
4. In folded-cascode op-amp, the capability of handling input CM levels are close to one of the supply rails.

PERFORMANCE OF VARIOUS OP-AMP TOPOLOGIES [5]:

Topologies	Gain	Output swing	Power dissipation	Noise
Two stage	High	Highest	Medium	Low
Folded cascode	Medium	Medium	Medium	Medium
Telescopic	Medium	Medium	Low	Low

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