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Current Mode Current Injection Technique for Gain and Bandwidth Enhancement for Novel CFOA

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Abstract: *In this work we have compared the voltage-mode and current-mode amplifier using IC LM675 and IC AD844 respectively for gain and bandwidth relationship. Further we have presented a new CFOA based on CCCII and AD844. We have used translinear loop and current mirrors with low supply voltage. This circuit is operated at low supply voltage of 1V with bandwidth (-3dB) of 106 MHz at value of Rx as 50. This CFOA is verified as Inverting amplifier. We have introduced a DC current injection technique at node X which reduces Rx further, which increases gain and bandwidth(-3dB) up to 24.12 dB and 169 MHz respectively with the injection current of 600 A. Hspice simulation for TSMC 0.18 m CMOS technology is presented.*

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I. Introduction

Various literatures has already proved that the current-mode approach in analog circuits has various advantages as compared to the voltage-mode approach .In current-mode approach the data is represented in terms of the branch current of the circuit instead of the node voltages as in voltage-mode circuits. The advantages of CM are simple circuit structure, gain bandwidth in-dependency, reduced input impedance, better linearity etc [1]-[11]. The biggest advantage of as we are working with currents the supply requirement is lesser which reduces the power requirement.

The original concept of current conveying and current mirrors were invented by sedra [12] is motivating to reuse the same. We propose a new CFOA based on the CCII and AD844 design for low-voltage, low-power circuit de-signs in particular with reduced value of Rx to improve the gain and -3dB bandwidth independently. Remaining paper organization is as follows. In section II we compared the voltage mode and current mode using IC LM675 and IC AD844 respectively for gain bandwidth independence, we describe the new CFOA architecture based on AD844 and its working in section III. In section IV the simulation results for the inverting amplifier using new CFOA is presented. Section V introduces a current biasing technique which reduces Rx and increases bandwidth as well as gain with simulation results and mathematical model. Finally we conclude this research in section VI.

II. The Comparison of VM and CM

Comparison of Voltage Mode and Current Mode for the Gain and Bandwidth Dependency is discussed in the section with IC's. We have verified that in Voltage Mode if gain increases the bandwidth decreases and vice verse. But in case of current mode they can be controlled independently [13]. In current mode amplifier, the resistance Rf controls the Bandwidth and Rg controls the gain. It is verified using IC LM 675 in voltage mode and IC AD 844 in current mode.

An inverting amplifier is implemented using IC LM 675 as shown in Fig. 1. The Rf value is kept constant at 100K and the value of Rg is varied from 1 to 25 K. The plot of gain and bandwidth is shown in Fig. 2 which shows that when gain increases the bandwidth decreases and vice versa.

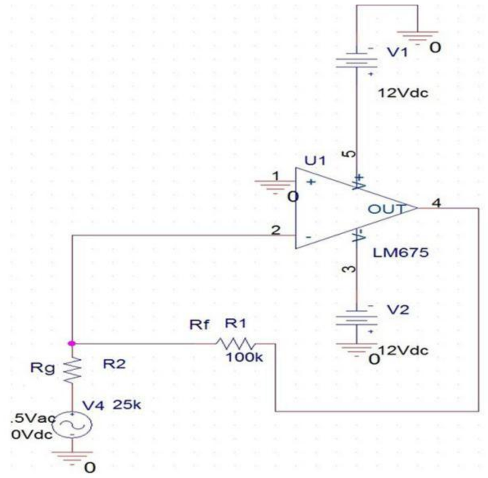

Fig. 1 Voltage Mode INV AMPLIFIER using LM675

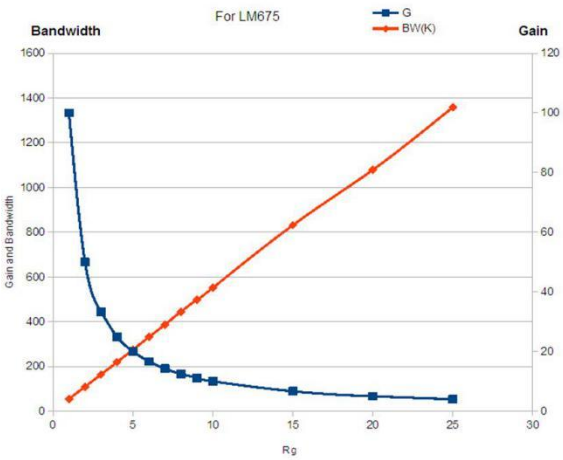

Fig. 2 Gain Vs Bandwidth in Voltage Mode with Rf constant

Now the inverting amplifier is implemented using AD844 in current mode logic as shown in Fig. 3 using adjoint principle and it was found as shown in Fig. 4 that the Bandwidth remains constant and gain reduces as Rg increases.

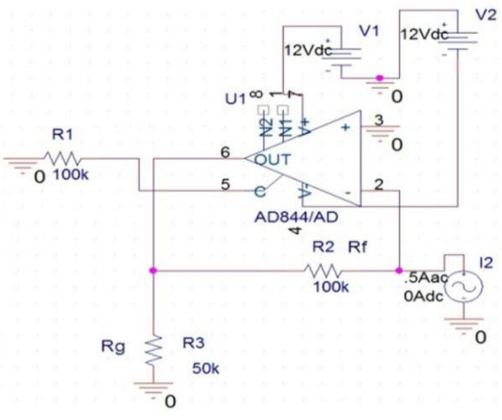

Fig. 3 Current Mode INV AMPLIFIER using AD844

Similarly now the other condition is checked. The voltage mode circuit of LM675 was verified by keeping Rg constant at 25K and Rf is varied from 5K to 550K. The plot of gain Vs bandwidth is as shown in Fig. 5 which shows that there is a wide variation in the gain and the bandwidth.

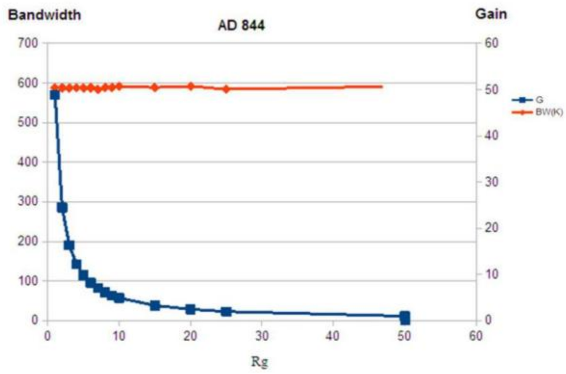

Fig. 4 Gain Vs Bandwidth in Current Mode with Rf constant

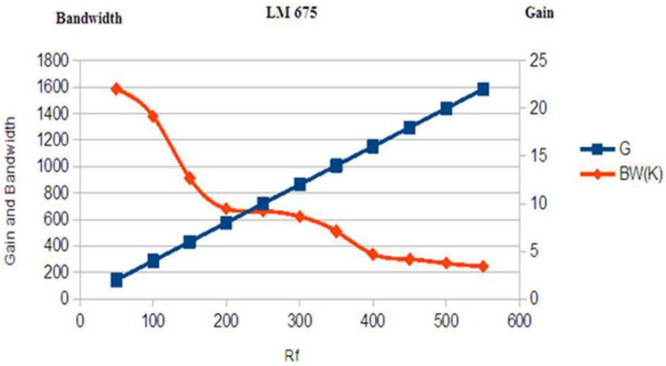

Fig. 5 Gain Vs Bandwidth for Voltage Mode with Rg Constant

If now we see current mode circuit of AD844 by keeping Rg constant at 25K and Rf is varied from 5K to 550K. The plot of gain Vs bandwidth in Fig. 6 shows very less variation in the gain bandwidth as compared to the voltage mode circuit

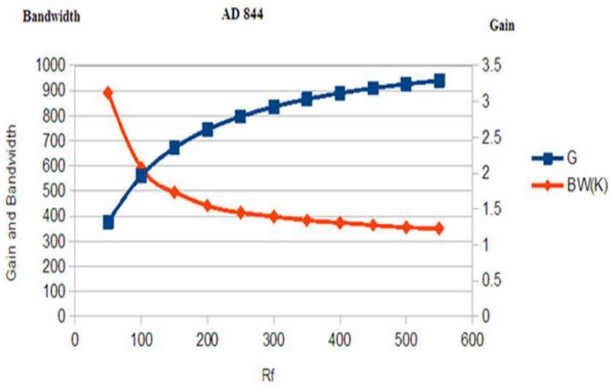

Fig. 6 Gain Vs Bandwidth for Current Mode with Rg Constant

From Fig. 5 and Fig. 6 we can conclude that as compared to the voltage mode the variation in gain Vs bandwidth is very less in the current mode circuit.

III. CFOA at Device Level

The AD844 schematic using BJT is as shown in Fig. 7 which has the combination of different current mirrors and buffer circuit [14]. We have replaced the existing AD844 BJT's by MOSFET's and obtained the new CFOA configuration as shown in Fig. 8.

The IC AD 844 is very popular as it can be used as CCII+ as well as CCII-.It can replace the conventional OP AMP with its Z terminal open. In AD 844 the input resistance is approximately 50, for ideal CFOA it is zero. The current applied at X input is copied to a complementary symmetry pair of unity-gain current mirrors with the same current at node Z.

The very common current mode blocks in analog circuits are the second generation current conveyors [15]-[20]. The main idea to increase the bandwidth and gain independently by reducing the parasitic resistance Rx at node x. Here we consider a simpler topology with minimum sizing of the transistors inspired from AD 844 configuration with buffer voltage output at node W. There are two current mirrors (M5, M6) and (M7, M8), MOSFETs (M1, M2, M3 and M4) forms a trans-linear loop works with lower voltages giving very small input impedance. MWP1, MWN2 are used for biasing purpose and MWP2 and MWN1 acts as complementary symmetry pair. Finally we have MWN2 and MWP2 forming a voltage follower with output node W.

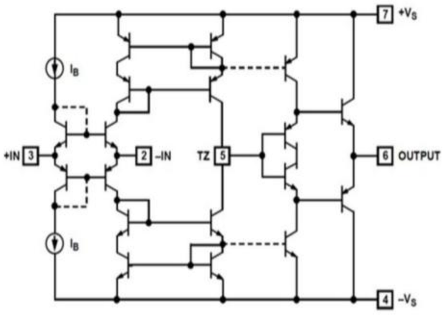

Fig. 7 AD 844 schematic

The new proposed CFOA is shown in Fig. 8 with W/L ratios.

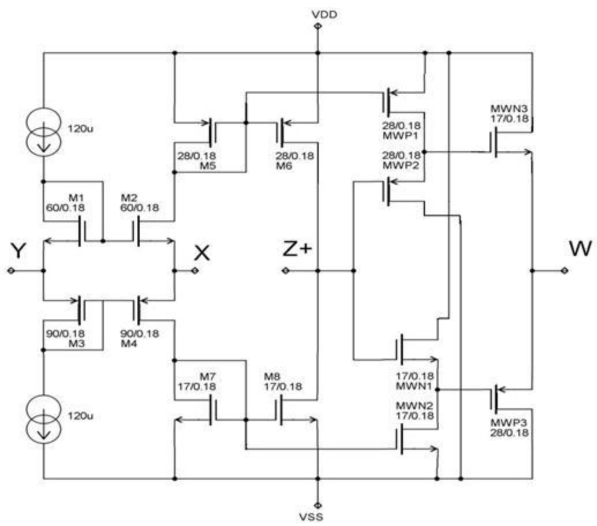

Fig. 8 New Proposed CFOA

This four terminals CFOA is characterized by the following relationship
Iy = 0, Vx = Vy, Ix = Iz, Vw = Vz

Where Vx, Vy, Vz and Vw and Ix, Iy and Iz are the voltages and currents of terminals x, y, z, w respectively.

To satisfy the Ideal equations of the CFOA, it should be have low impedance on terminal X and high impedance on terminals Y and Z [23]-[28]. The W/L ratios are shown in table I.

Table 1 W/L Ratios of MOSFETs

MOSFETs	W/L ratios
M1,M2	60/0.18
M3,M4	90/0.18
M5,M6	28/0.18
M7,M8	17/0.18
MWP1,MWP2,MWP3	28/0.18
MWN1,MWN2,MWN3	17/0.18

We are presenting the derivation for the currents and the voltages in the CFOA
VXY = (VGSp)Y −(VGSp)X = (VGSn)Y −(VGSn)X
Call it equation (1)

With : (VGS)n = $\sqrt{\frac{(Id)n}{\frac{1}{2}u_n C_{0x}\left(\frac{w}{L}\right)n}} + (V_{th})n$

and : (VGS)p = $\sqrt{\frac{(Id)p}{\frac{1}{2}\mu p\, C_{0x}\left(\frac{w}{2}\right)p}} + (v_{th})_p$

The current through transistors M1 and M3 is equal to I0. In this case, the potential difference VXY is equal to

(VXY) = (VGS1)n – (VGS2)n = $\sqrt{\frac{(I_0)}{\frac{1}{2}\mu n\, C_{0x}\left(\frac{w}{L}\right)n}}$ - $\sqrt{\frac{(Id)n}{\frac{1}{2}u_n C_{0x}\left(\frac{w}{L}\right)n}}$ ……….. (2)

(VXY) = (VGS3)p – (VGS4)p = $\sqrt{\frac{(I_0)}{\frac{1}{2}\mu p\, C_{0x}\left(\frac{w}{L}\right)p}}$ - $\sqrt{\frac{(Id)p}{\frac{1}{2}\mu p\, C_{0x}\left(\frac{w}{2}\right)p}}$ …………..(3)

By determining relationships (Id2)n and (Id4)p according to I0 and VXY form (2) and (3) and applying the relationship IX = (Id2)n− (Id4)p and taking everything into account we find :

VX ≈ VY + $\frac{Ix}{\sqrt{2I_0 Cox}\left(\sqrt{\mu p\left(\frac{w}{L}\right)p}+\sqrt{\mu_P\left(\frac{w}{L}\right)n}\right)}$ ……………………………………………(4)

By identifying the characteristic equations of CFOA circuit , we have :

Rx = $\frac{1}{\sqrt{2I_0 Cox}\left(\sqrt{\mu p\left(\frac{w}{L}\right)p}+\sqrt{\mu_P\left(\frac{w}{L}\right)n}\right)}$

If $\mu p\left(\frac{w}{L}\right)p = \mu_P\left(\frac{w}{L}\right)n$

The expression of input resistance becomes:

Rx = $\frac{1}{\sqrt{8Cox\mu\left(\frac{w}{L}\right)I_0}}$

After substituting all the variables the value of Rx is approximately 50Ω.

IV. CFOA As Inverting Amplifier

The CFOA which we have design is checked as an inverting amplifier at device level as shown in Fig. 9. The adjoint principle is used from the theory of voltage mode to current mode transformation.

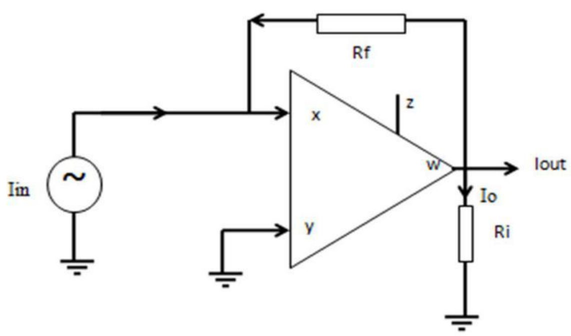

Fig. 9 CFOA as inverter

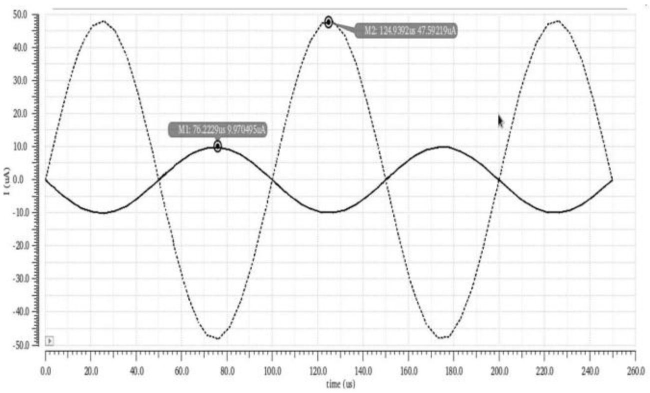

Fig. 10 CFOA as inverter with gain of 5

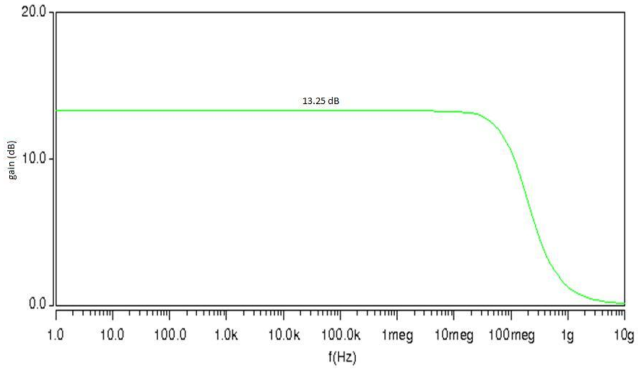

Fig. 11 Frequency response of inverting amplifier

The inverting amplifier is implemented using this CFOA with value of Rf as 250, value of Ri as 50.The input and output waveform is shown in Fig. 10 with the amplification factor of 5 as shown in Fig. 11. The practical gain was found to be 13.25 dB against the theoretical value of 13.97 dB. The (-3dB) bandwidth was found to be 106.2 MHz which is higher than that of AD 844(65MHz).

The similar results were obtained for different values of gain by varying Rf at 100 , 250 ,300 ohms keeping Ri as 50 constant, the frequency response are as shown in Fig. 12.

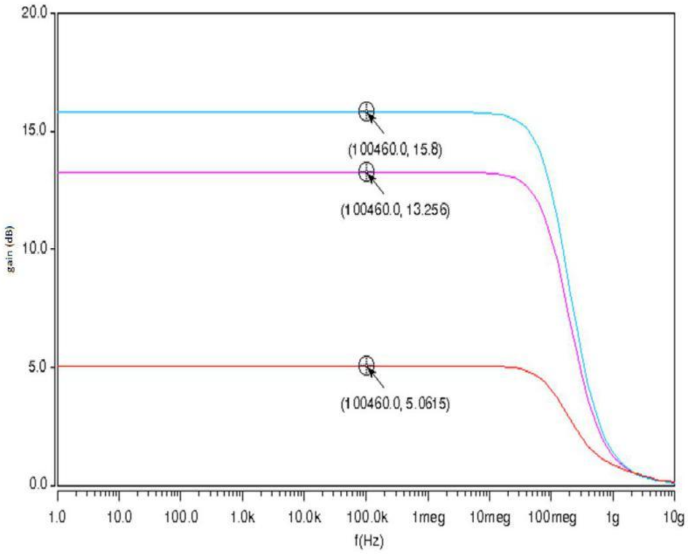

Fig. 12 Gain of 5, 13.25 and 15.8

V. Current Injection Technique

By introducing an external dc current source at node x, we can increase the gain and bandwidth which implies that it reduces the value of Rx. By selecting the component values Ri = 50 ohm, Rf = 250 ohm the CFOA at device level as inverting amplifier is implemented with current injection technique as shown in Fig. 13.

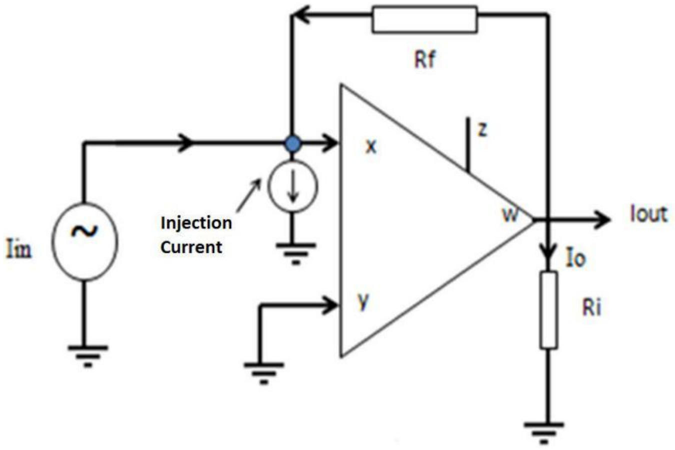

Fig. 13 Current Injection technique

Fig. 14 shows the waveform with and without current injection technique. It can be seen that without the current injection technique the gain is 13.25dB and the (-3dB) bandwidth is 106.2 MHz, wherein with -600uA dc injection current at node x increases the gain up to 24 and the (-3dB) bandwidth is also increased to 169 MHz.

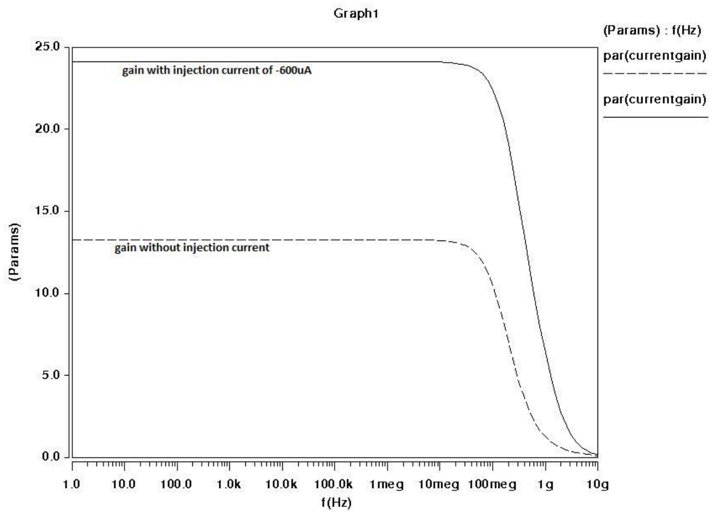

Fig. 14 Comparison with and without Injection Current

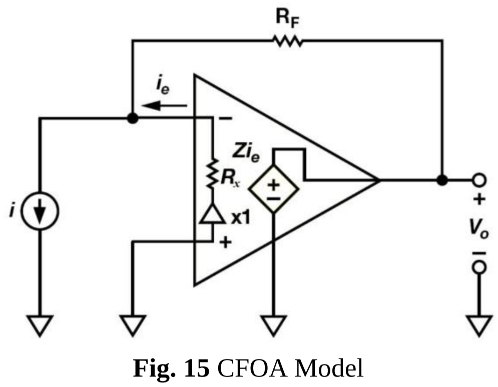

Fig. 15 CFOA Model

The practical CFOA model is as shown in Fig. 15, which has unity gain buffer across their inputs. A current mirror reflects the error current is converted to a voltage and fed to the output.

The mathematical model for the proposed CFOA is as given. From Fig. 8 we can derive the relation between Ix and Vx as given

$\mathrm{I}_x = \mathrm{I}_{p1} - \mathrm{I}_{n1}$………………… (5)

where I_{p1} is current through transistor M_4 and M_7. I_{n1} is current through transistor M_2 and M_5.

Using equation (5) we get

$\mathrm{I}_x = \frac{1}{2}K'_p\left(\frac{90}{0.18}\right)(V_x - V_{GP} - V_{T_p})^2 - \frac{1}{2}K'_n\left(\frac{60}{0.18}\right)(V_{G_n} - V_x - V_{T_n})^2$……………(6)

Now,

$$\mathrm{I}_Z = \mathrm{I}_{n0} - \mathrm{I}_{p0}$$

Where In0 is current through transistor Mwn3 and Ip0 is current through transistor Mwp3.

Iz ≈ K.Ix

At node X by KCL,

$\mathrm{I}_{in} + \mathrm{I}_{Rf} = \mathrm{I}_x + \mathrm{I}_{bias}$

$\mathrm{I}_{in} + \frac{V_0 - V_{x0}}{Rf} = \mathrm{I}_x + \mathrm{I}_{bias}$

$\mathrm{I}_{in} + \mathrm{I}_o\frac{RL}{Rf} - \frac{Vx}{Rf} = \mathrm{I}_x + \mathrm{I}_{bias}$…………………….. (7)

Taking derivatives w.r.t Iin

$1 + \frac{RL}{Rf}\frac{\partial I_0}{\partial \mathrm{I}_{in}} - \frac{1}{Rf}\frac{\partial V_x}{\partial \mathrm{I}_{in}} = \frac{\partial I_x}{\partial \mathrm{I}_{in}}$

On simplifying we get,

$\mathrm{A_I} = \frac{RL}{Rf}\left[\frac{\partial I_x}{\partial \mathrm{I}_{in}}\left(1 + \frac{1}{Rf}\frac{\partial V_x}{\partial \mathrm{I}_{in}}\right) - 1\right]$………………… (8)

Differentiating equation (6) we will have relation of δV/δIx which is substituted in equation (8) to further simplify the expression for current gain. If we apply KCL at node z we have $\mathrm{I}_Z = \mathrm{I}_0 + \mathrm{I}_{RF}$

$$\mathrm{K\,I}_x = \mathrm{I}_0 + (\mathrm{Ibias} + \mathrm{I}_x - \mathrm{I}_{in})$$

$$(\mathrm{K}-1)\,\mathrm{I}_x = \mathrm{I}_0 + \mathrm{Ibias} - \mathrm{I}_{in}$$

$$(\mathrm{K}-1)\frac{\partial I_x}{\partial \mathrm{I}_{in}} = \frac{\partial I_0}{\partial \mathrm{I}_n} - 1$$

$\frac{\partial I_x}{\partial \mathrm{I}_{in}} = \frac{(\mathrm{AI}-1)}{(\mathrm{K}-1)}$……………………………………………… (9)

substituting (9) in (8) we get the final expression of current gain in terms of Rx

$\mathrm{A_I} = -\frac{\frac{RF}{RL} - \frac{1}{(k-1)}\frac{(Rf+Rx)}{R_L}}{1 - \frac{(Rf+R_L)}{(k-1)RL}}$

Simplifying we get, $\mathrm{A_I} = -\frac{\frac{Rf}{RL}}{1 - \frac{(Rf+R_x)}{(k-1)RL}}$ …………………(10)

Equation (10) satisfies the gain and Ibias for the value of K as 8.72 by which the W/L ratios of the transistors M6 and M8 should be multiple of that of transistors M5 and M7.

The CFOA conventional model is also shown in fig.16 which gives the relation of bandwidth and resistance r_n which in the above mathematical modeling is referred as Rx.

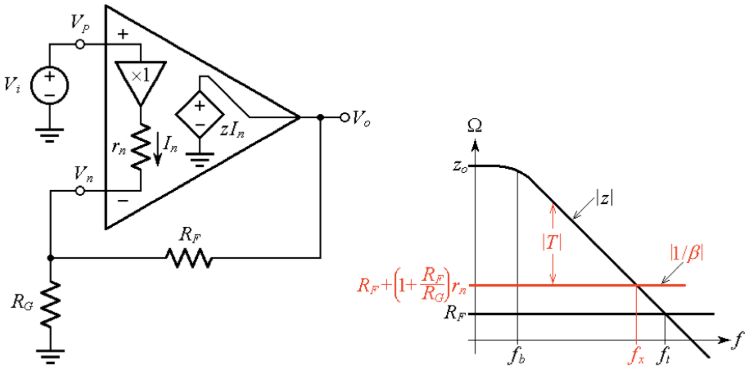

Fig. 16 CFOA Model and frequency response

$V_o = zI_n$ ………………… (11)
$I_n = \frac{V_n}{R_G} + \frac{V_n - V_o}{R_F} = \frac{V_n}{R_G || R_F} - \frac{V_o}{R_F}$ ………….. (12)
$V_n = V_i - r_n I_n$ ………………………………….. (13)
Substitute (13) in (12)
$I_n = \frac{V_i - r_n I_n}{R_G || R_F} - \frac{V_o}{R_F}$ ………………………………. (14)
Substitute (14) in (11)
$\frac{V_o}{V_i} = \left(1 + \frac{R_F}{R_G}\right) \frac{1}{1 + R_F + \left(1 + \frac{R_F}{R_G}\right) r_n} = A$ …………. (15)
$A = A_{ideal} \frac{1}{1 + \frac{1}{T}}$ ……………………………………… (16)
$A_{ideal} = \lim_{T \to \infty} \left(1 + \frac{R_F}{R_G}\right)$ ……………………. (17)
$T = z\beta = \frac{z}{R_F + \left(1 + \frac{R_F}{R_G}\right) r_n}$ ……………………………. (18)
The closed-loop AC response:
$\left[R_F + \left(1 + \frac{R_F}{R_G}\right) r_n\right] \times f_x = R_F \times f_t$
$f_x = \frac{f_t}{1 + \frac{r_n}{R_F}\left(1 + \frac{R_F}{R_G}\right)}$)…………….. (19)

Fig. 16 shows various waveforms where the dc injection current at node x is varied from -100uA to -600uA, with the steps of -100uA and the conclusion is that the gain as well as the bandwidth gradually increases. The theoretical and practical values are verified using equation 10, 11 and simulation results in Fig. 16 respectively. Comparison of the injection current with gain and bandwidth is given in table 2.

Table 2 Gain Bandwidth for different Injection Currents

I_{inject}	$Gain(20log_{10}(\frac{I_o}{I_{in}}))$	Bandwidth (-3db)
0 µA	13.256	106.25 MHz
-100 µA	16.463	111.2 MHz
-200 µA	19. 23.137	117 MHz
-300 µA	21.369	122 MHz
-400 µA	23.137	128.87 MHz
-500 µA	23.918	133 MHz
-600 µA	24.117	169 MHz

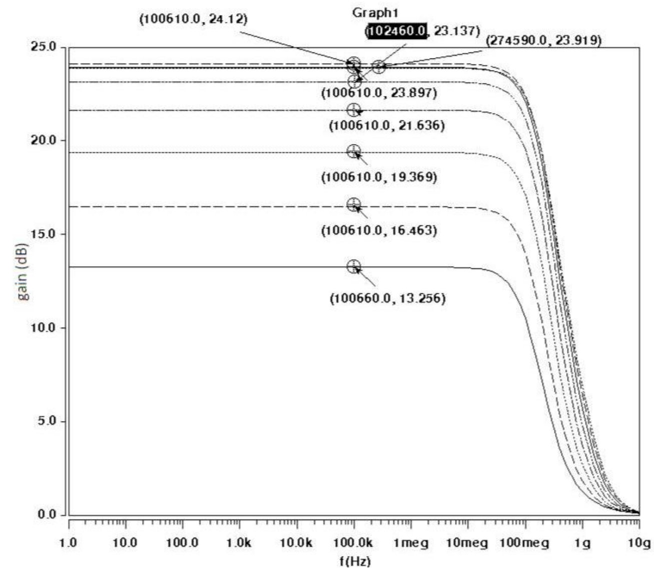

Fig. 17 Varying injection current from 0 to -600uA, with the step of -100Ua

VI. Conclusion

A new CFOA is presented, analyzed and simulated using Hspice for TSMC 0.18 m. This CFOA has been demonstrated to improve the gain as well as bandwidth with the current injection technique at node X. Table 2 gives the summary of simulation results which proves that the reduction of Rx at node X increases the gain and bandwidth further. Also the comparison of VM and CM is done at integrated circuit level for inverting amplifier, which demonstrates the gain bandwidth independency of CM circuits. The CFOA which we have designed using trans-linear loop and current mirrors works at very low supply voltage of 1V.

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