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A Review Paper on Frequency Compensation of Transconductance Operational Amplifier (OTA)

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Abstract: *In this brief, types of frequency compensation for operation transconductance amplifier are explained in detail. Compensation which is used to enhance frequency stability of the OTA, and to make gain and phase linear for required frequency range. As we know capacitor inside the OTA causes output to lag behind by 90° with each pole they create, If the addition of these phase lags add-up to 360°, the output signal will be in phase with the input signal. Feeding output signal back in proportion to input when the gain of the amplifier is sufficient will cause the amplifier to oscillate. To avoid such undesirable condition frequency compensation is required in OTA, the frequency compensation is used to make a particular pole dominant on other poles to make the transfer function 2nd order.*

KEY WORDS: CMOS technology, operational amplifier, operational trans-conductance amplifier (OTA), Gain Bandwidth Product (GBW), Phase margin, positive feedback, gain enhancement.

1. INTRODUCTION

In electronics industry operational amplifier are the basic building blocks to develop analog environment for analog circuits. Generally amplifiers use negative feedback for its frequency stability, to avoid unwanted creation of positive feedback which causes amplifier to oscillate. The negative feedback controls the overshoot ringing of amplifier and it's bandwidth. Gain bandwidth product is very crucial parameter which shows the stability of the amplifier over the desired frequency range. Frequency compensation is a technique which uses pole splitting method to make the transfer function of single order to 2nd order with a dominant pole. Wide band amplifiers are most widely used for pulse and video amplification in communication systems and video display units. Some of the present non-feedback bandwidth-enhancing techniques are: cascoding [11], Cc-cancellation [2], [3] and “parasitic capacitance compensation” [4] techniques. Cascode and Cc-cancellation techniques prevent bandwidth reduction caused by “Miller effect,” but as mentioned in later part better frequency responses are achievable in an amplifier. “Parasitic capacitance compensation” is a technique for cancelling undesired capacitors of an amplifier. However, frequency limitation of active compensating network does not permit an exact cancellation. Circuits described which are also mainly applicable to low-gain amplifiers. A new technique is introduced in this paper based on an effect similar to the one occurring in the resistive feedback amplifiers.

2. DOMINANT-POLE COMPENSATION

Dominant pole compensation is the most widely used method for frequency compensation. It is a form of lag compensation, in this compensation a low frequency pole will be made dominant by adjustment of low frequency pole in a manner that other higher poles are to be made very far from the dominant pole, so that the transfer function (gain vs frequency curve) crosses the 0db line in between the dominant pole and other poles. Generally the lowest frequency is set to be dominant, so that it dominates the effect of higher frequency poles which reduces phase margin. It will make the difference between "open loop output phase and closed loop phase response of feedback network, not to falls below -180^0 with maintaining gain constant.

General purpose operational trans conductance amplifier uses dominant pole compensation by adding capacitor in between the gain stages of OTA. Adding capacitor introduces pole which is adjusted at low frequency so that gain vs frequency curve cross 0db just after the low frequency which is considered as dominant, this result, phase margin of

45°approximately depending upon the location of other or next higher poles. This phase margin is sufficient to control the oscillation, in commonly used feedback system. The dominant pole compensation has other advantage such as, it controls the overshoot and ringing of the OTA when we apply to step input. It is the most demanding requirement in terms of stability of OTA.

This type of frequency compensation passes through two drawbacks:

2.1 At high frequency the bandwidth of the OTA reduces thereby reducing open loop gain, this will affect in amount of feedback which causes distortion at such high frequency.

2.2 Dominant pole compensation technique reduces the slew rate of the OTA. This is caused by current driving stage which charge and discharge the compensated capacitor, this limits the fast-changing output of the OTA.

Pole splitting technique is used in dominant pole compensation. This will move the lower frequency of uncompensated amplifier towards origin to make it dominant and other higher frequency poles were move to a higher frequency.

3. MILLER COMPENSATION TECHNIQUE:

Miller compensated two stage OTA which is compensated by C_M capacitor to enhance the frequency response is shown in figure 1 and figure 2 shows its small signal model for frequency analysis.

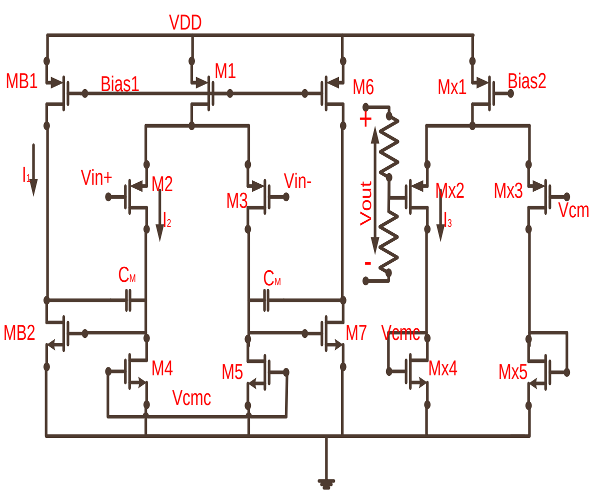

Fig.1 Compensated two-stage OTA

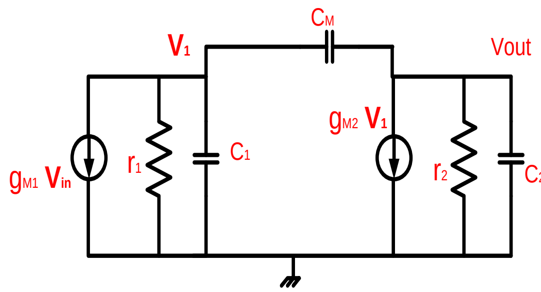

Fig.2 Small signal model of compensated two-stage OTA

we use $\frac{V_1}{V_{in}} \times \frac{V_o}{V_1} = \frac{V_0}{V_i}$

$$\frac{V_1}{1/sc_1} + \frac{V_1}{R_1} + \frac{V_1 - V_0}{1/sc_c} + g_m V_{in} = 0$$

$$V_1 = \left(sc_1 + \frac{1}{R_1} + sc_c\right) + g_{m1}V_{in} - V_0 sc_c = 0$$

$$V_1 = \frac{V_0 sc_c R_1 - g_{m1}V_{in}R_1}{1 + sR_1(c_1 + c_c)} \qquad \text{........(1)}$$

$$\frac{V_0}{1/sc_2} + \frac{V_0}{R_2} + \frac{V_0 - V_1}{1/sc_c} + g_{m2}V_1 = 0$$

$$V_0\left[s(c_2 + c_c) + \frac{1}{R_2}\right] = V_1[sc_c - g_{m2}] \qquad \text{...................(2)}$$

from equation (1) & (2)

$$V_0\left[s(c_2 + c_c) + \frac{1}{R_2}\right] = \frac{(V_0 sc_c R_1 - g_{m1}V_{in}R_1)(sc_c - g_{m2})}{1 + sR_1(c_1 + c_c)}$$

$$\frac{V_0}{V_{in}} = \frac{g_{m1}g_{m2}R_1R_2(1 - sc_c/g_{m2})}{s^2[(R_2R_1(c_1c_2 + c_1c_c + c_2c_c))]\, s[R_2(c_2+c_c) + R_1(c_1+c_c) + c_c g_{m2}R_1R_2] + 1}$$

$$T(s) = \frac{A_{DC}\left(1 - \frac{S}{Z}\right)}{\left(1 + \frac{S}{P_1}\right) + \left(1 + \frac{S}{P_2}\right)} = \frac{A_{DC}\left(1 - \frac{S}{Z}\right)}{1 + S\left(\frac{1}{P_1} + \frac{1}{P_2}\right) + S^2\left(\frac{1}{P_1}\frac{1}{P_2}\right)}$$

$$s\left(\frac{1}{P_1} + \frac{1}{P_2}\right) \approx \frac{S}{P_2} \quad \text{as } P_2 \text{ is large enough}$$

$$\frac{1}{P_1} = coefficents\ of\ \text{"}s\text{"} \ \& \ \frac{1}{P_1}\frac{1}{P_2} = coefficents\ of\ \text{"}s^2\text{"}$$

$$P_1 = \frac{1}{R_2(c_2+c_c) + R_1(c_1+c_c) + c_c g_{m2}R_1R_2}$$

$$P_1 \approx \frac{1}{c_c g_{m2}R_1R_2}$$

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$$P_1P_2 = \frac{1}{R_1R_2(c_1c_2 + c_1c_c + c_2c_c)}$$

$$P_2 = \frac{c_c g_{m2} R_1 R_2}{R_1R_2(c_1c_2 + c_1c_c + c_2c_c)} \approx P_2 = \frac{c_c g_{m2}}{(c_c c_2)} \approx \frac{g_{m2}}{(c_2)}$$

and zero location $Z = \frac{g_{m2}}{(c_c)}$

& Dc gain $\boldsymbol{A_{DC} = g_{m1} g_{m2} R_1 R_2}$

Figure 3 shows the frequency response of compensated and Uncompensated of OTA

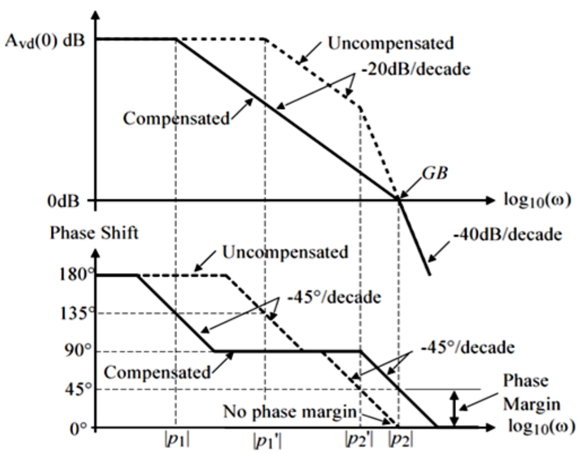

Fig 3. Uncompensated & compensated OTA, gain and phase response

4. MILLER COMPENSATION WITH NESTED RESISTANCE :

Miller compensated nested resistance OTA is shown in figure 4 and its small signal model is shown in figure 5.

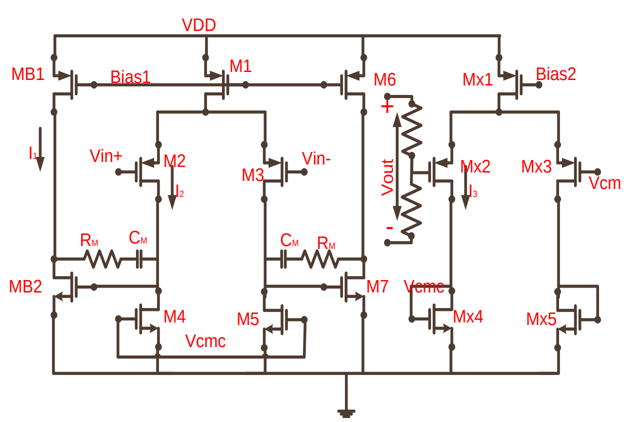

Fig.4 compensated two-stage OTA with nested resistance

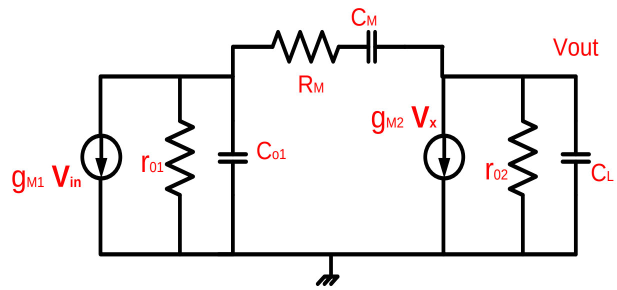

Fig.5 Small signal model of Compensated two-stage OTA with nested resistance OTA

C_{01} &r_{01} is the capacitance and resistance of first stage of OTA and g_{m1} is the transconductance of first stage.C_{02} &r_{02} is the capacitance and resistance of second stage of OTA with g_{m1} is its transconductance ,$C_L + C_2 \approx C_L$ as C_2 is very large. The approximate expression for pole and zero are shown below from equation [2]. Due to nested miller resistance the transfer function is of third order,

$$Z_1 \approx \left((g_{m2}^{-1} - R_M)C_M\right)^{-1}$$

$$P_1 \approx (-g_{m2} r_{02} r_{01} C_M)^{-1}$$

$$P_2 \approx -g_{m2}(C_L)^{-1} \& P_3 \approx (C_M R_M)^{-1}$$

The first pole P1 is at low frequency which set the GBW of the OTA, the zero Z1 cancel out P2 with small and fixed load C_L and P2 & P3 are very far away from P1, so P1 will be the dominant pole to stabilize the frequency, there is limitation on achievable phase margin since increasing Rm not only tunes Z1 to cancel out P2 but it also reduces the third pole when C_L is not fixed, or very large then the phase margin we get is not up to the required level this will create worst condition, as to achieve the required phase margin we have to increase the compensation capacitor, [12]. Use of large capacitive load unfortunately reduces the GBW and other drawback of such compensation is the process variation.

5. ENHANCEMENT PHASE COMPENSATION

It is clear that Miller compensation improves the phase margin by reducing gain bandwidth, try to increase the gain reduces the phase margin and made the pole complex [3],[4].A positive feedback at the output gain stage increases the gain& bandwidth, based on this approach enhanced phase compensation work as shown in figure 6.

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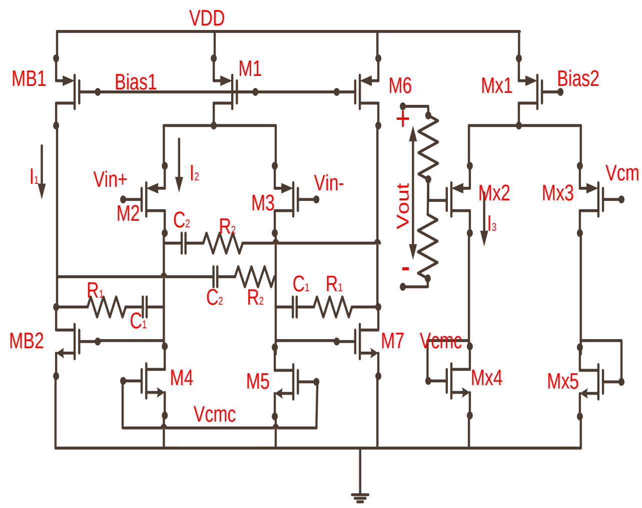

Fig.6 Phase enhanced compensated two-stage OTA

Where two zero are introduced by positive feedback using register and capacitor, this will increase a pole also, to make the transfer functionof fourth order, but due to Miller dominant pole condition two zero cancel out two poles to make it second order transfer function. Small signal model is shown in figure 7.

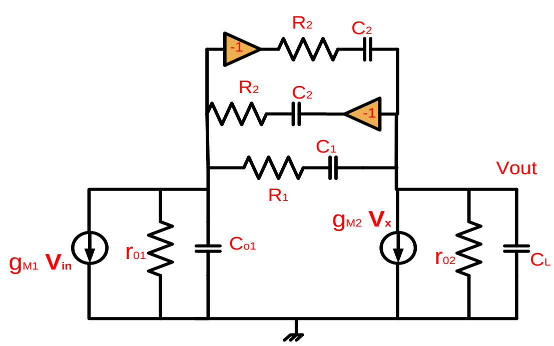

Fig.7 Small signal model of Phase enhanced Compensated two-stage OTA

The positive feedback RC cross-linked couple is made to increase the gain of the OTA and to stabilize it the transfer function. Transfer function is given by the following equations given below [1], and pole and zero approximated from the transfer function, as it is seen that the DC gain of the OTA is unchanged as RC link present an open circuit. Using KCL and KVL.

$$\frac{V_{out}}{V_{in}} = g_{m1}g_{m2}r_{01}r_{02} \times$$

$$\frac{(g_{m2}^{-1}(C_1C_2R_1 - C_1C_2R_2) + R_1R_2C_1C_2)S^2 + (g_{m2}^{-1}(C_2 - C_1) + C_1R_1 + C_2R_2)S + 1}{(C_{01}C_LC_1C_2r_{01}r_{02}R_1R_2)S^4 + D_1S^3 + D_2S^2 + D_3S + 1}$$

$$\begin{aligned} D_1 = {} & C_{01}C_LC_1r_{01}r_{02}R_1 + C_{01}C_LC_2r_{01}r_{02}R_2 \\ & + C_{01}C_1C_2r_{01}r_{02}R_1 + C_LC_1C_2r_{01}r_{02}R_1 \\ & + C_{01}C_1C_2r_{01}r_{02}R_2 + C_LC_1C_2r_{01}r_{02}R_2 \\ & + C_{01}C_1C_2r_{02}R_1R_2 + C_LC_1C_2r_{01}r_{02}R_1 \end{aligned}$$

$$\begin{aligned} D_2 = {} & C_{01}C_Lr_{01}r_{02} + C_{01}C_2r_{01}r_{02} + C_LC_1r_{01}r_{02} + C_{01}C_2r_{01}r_{02} \\ & + C_LC_2r_{01}r_{02} + C_{01}C_1r_{01}R_1 + C_LC_1r_{02}R_1 \\ & + 4C_1C_2r_{01}r_{02} + C_{01}C_2r_{01}R_2 + C_LC_2r_{02}R_2 \\ & + C_1C_2r_{01}R_1 + C_1C_2r_{02}R_1 + C_1C_2r_{01}R_2 \\ & + C_1C_2r_{02}R_2 + C_1C_2R_1R_2 \\ & + C_{01}C_LC_1C_2r_{01}r_{02}R_2g_{m2} \\ & - C_{01}C_LC_1C_2r_{01}r_{02}R_1g_{m2} \end{aligned}$$

$$\begin{aligned} D_3 = {} & C_{01}r_{01} + C_Lr_{02} + C_1r_{01} + C_1r_{02} + C_2r_{01} + C_2r_{02} + C_1R_1 \\ & + C_2R_2 + g_{m2}C_1r_{01}r_{02} - g_{m2}C_2r_{01}r_{02} \end{aligned}$$

$$Z_1 \approx -\frac{1}{C(R_1 + R_2)}$$

$$Z_2 \approx -\frac{R_1 + R_2}{C(R_1R_2)}$$

$$P_1 \approx -\frac{1}{(C_L + 2C)r_{02} + 2Cr_{01}}$$

$$P_2 \approx -\frac{(C_L + 2C)r_{02} + 2Cr_{01}}{2C_Lr_{02}r_{01} + 4r_{02}r_{01}C^2}$$

$$P_3 \approx -\frac{2C_L + 4C}{CC_L(R_1 + R_2)} \& P_4 \approx -\frac{R_1 + R_2}{C_{01}(R_1R_2)}$$

$$R_1 + R_2 \approx \frac{2C_Lr_{02}r_{01} + 4Cr_{02}r_{01}}{C_Lr_{02} + 2C(r_{02} + r_{01})}$$

$$\alpha/(1+\alpha)^2 \approx \frac{C_L}{2C_L + 4C}$$

$$BW_{RATIO} \approx \frac{(C_L + C_M)r_{02} + g_{m2}r_{02}r_{01}C_M}{(C_L + 2C)r_{02} + 2Cr_{01} + C(R_1 + R_2)}$$

$$GBP_{RATIO} \approx \frac{(R_1 + R_2)C_L}{C_{01}R_1R_2g_{m2}}$$

Figure 8 shows frequency response for the Miller compensation and the Phase enhanced compensation.

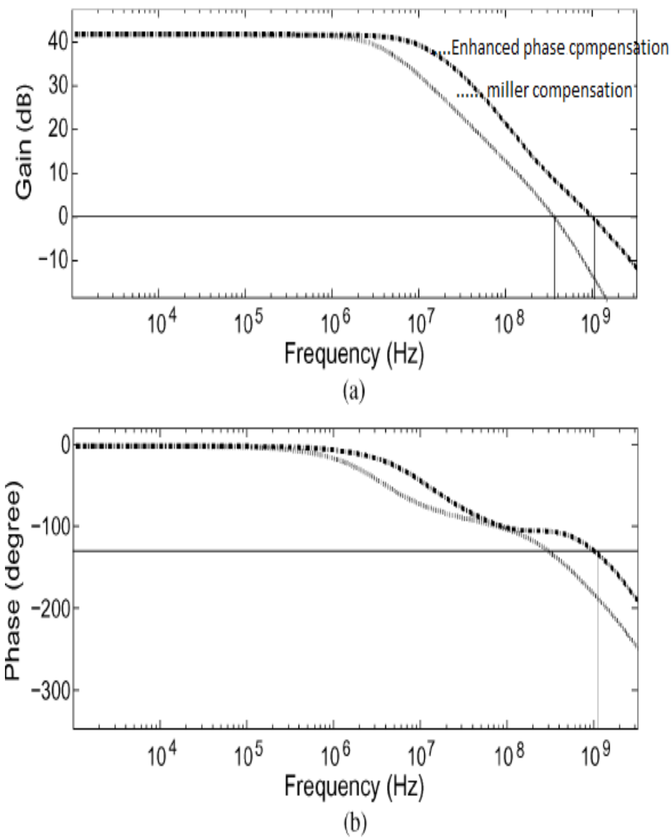

Fig.8 Frequency response for miller and phase enhanced compensation in terms of Gain and Phase

6. CONCLUSION

Three types of compensation technique is discussed in this paper and it shows that the phase enhance compensation is better than miller compensated technique in respect to phase enhance. The compensation technique provides improved bandwidth and gain bandwidth in caparison to uncompensated OTA.

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