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Study and Performance Analysis of Two Stage High Speed Operational Amplifier Using Indirect Compensation

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Abstract- **The performance analysis of the two-stage CMOS operational amplifiers employing Miller capacitor in conjunction with the common-gate current buffer is presented. Unlike the previously reported design strategy of the opamp of this type, which results in the opamp with a lower power supply requirements, better phase margin and better speed. The Opamp is designed to exhibit a unity gain frequency of 1.46GHz and exhibits a gain of 115dB with a 117˚ phase margin. As compared to the conventional approach, the indirect compensation method results in a higher unity gain frequency under the same load condition. Simulation has been carried out in LT-SPICE.**

*Keywords- **Current Buffer, Miller Compensation, Indirect Compensation, Phase Margin ,Unity Gain Frequency***

I. INTRODUCTION

To avoid closed-loop instability, frequency compensation is necessary in opamp design [1]–[7]. For two-stage CMOS opamp, the simplest compensation technique is to connect a capacitor across the high gain stage. This results in the pole splitting phenomena which improves the closed-loop stability significantly. However, due to the feed-forward path through the Miller capacitor, a right-half-plane (RHP) zero is also created. In theory, such a zero can be nullified if the compensation capacitor is connected in conjunction with a nullifying resistor. The value Compensation capacitor required in above case in the order of pf which is not acceptable as capacitor acquires largest area in an IC fabrication. Large value of capacitance also results in low bandwidth and slow speed. In this paper performance of a indirectly compensated current buffer Opamp has been studied and compared with conventional Opamp(Miller Compensated).The current buffer compensated opamp requires a small value of Miller capacitance(fF) which results in much faster Opamp. Unlike conventional Compensation strategy, the indirect compensation using current buffer introduced a left-half-plane (LHP) zero which increases the phase margin hence stability. The performance of two opamp strategies has been compared using various performance parameters like Unity gain frequency, Step response and D.C analysis.

II. CONVENTIONAL OPAMP

Two stage op-amps have been the dominant amplifier topologies used in analog system design due their simple frequency compensation and relaxed stability criterions. The two-stage op-amps have conventionally been compensated using Miller compensation or Direct Compensation technique. Figure 1 shows circuit diagram of a two stage op-amp with a feedback capacitance C_C (Miller capacitance) used to ensure closed loop stability by pole splitting. Before compensation, the poles of the two-stage cascade are given as $P_1 = \frac{1}{R_1C_1}$ and $p_2 = \frac{1}{R_2C_2}$ where R_1, C_1, R_2, C_2 are the resistances and capacitances respectively at input and output nodes respectively. In order to achieve dominant pole stabilization of the opamp. Miller compensation has been employed to achieve pole splitting. In this technique, the compensation capacitor (Cc) is connected between the output of the first and second stages as shown in figure 1.

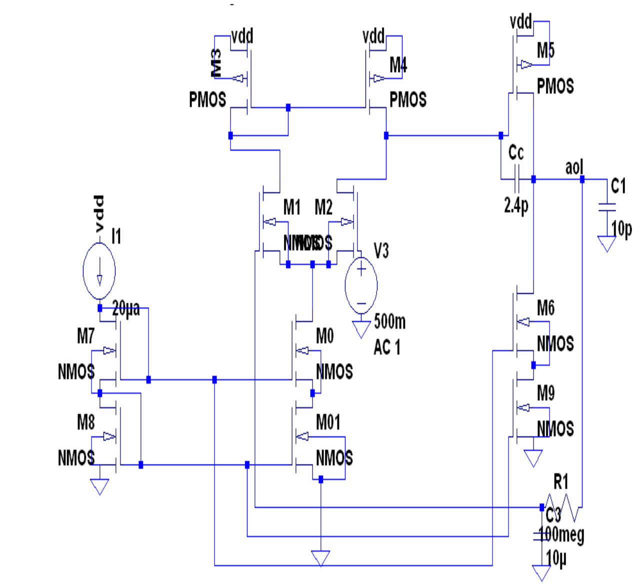

Figure 1. Conventional Opamp

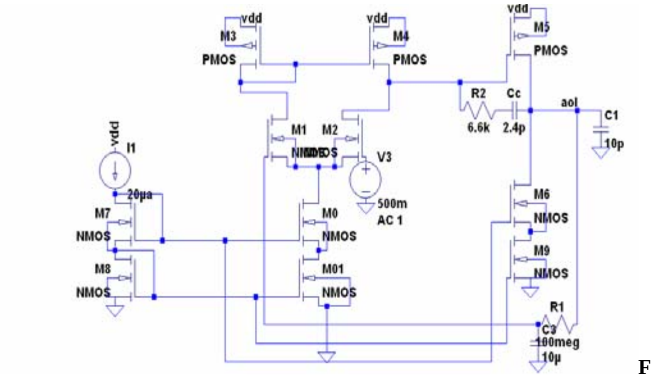

Figure 2. Conventional Opamp with nullifying resistor

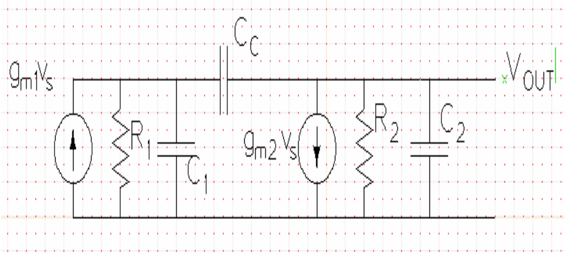

Figure 3. Small signal model for Conventional opamp

The small signal transfer function for a Miller compensation two-stage opamp is given as[1]

$$\frac{V_{OUT}}{V_S} = g_{m1} g_{m2} R_1 R_2 \frac{\left(1-\frac{S}{Z_1}\right)}{\left(1-\frac{S}{P_1}\right)\left(1-\frac{S}{P_2}\right)} \qquad (1)$$

The RHP zero is located at

$$Z_1 = \frac{g_{m2}}{c_c} \qquad (2)$$

The dominant pole is located at

$$P_1 = -\frac{1}{g_{m2} R_1 R_2 C_C} \qquad (3)$$

The non dominant pole is located at

$$P_2 = -\frac{g_{m2}}{c_1 + c_2} \qquad (4)$$

The open loop gain is given by

$$A_V = g_{m1} R_1 g_{m2} R_2 \qquad (5)$$

The compensation capacitor splits the input and output poles apart thus obtaining the dominant and non-dominant poles which are spaced far away from each other. However, Miller compensation also introduces a right-half-plane (RHP) zero due to the feed-forward current from the output of the first stage to the op-amp's output. This zero eliminated by using a nullifying resistor [3] in conjunction with Miller capacitance as shown in figure 2. Nullifying resistor introduces zero in left half of plane cancelling the effect of RHP zero. Resistor in series with the capacitor, is used to Fig. 2, to attenuate the higher frequency signals (where the zero occurs) and push the zero out to a higher frequency. Adding the resistor moves the zero to a frequency see equation (6) and (7)
Equation (6) represents frequency response without a nullifying resistor

$$f_z = \frac{1}{2\pi c_c \frac{1}{g_{m2}}} \qquad (6)$$

Equation (7) represents frequency response without a nullifying resistor

$$f_z = \frac{1}{2\pi c_c \left(\frac{1}{g_{m2}} - R_Z\right)} \qquad (7)$$

If $R_Z = \frac{1}{g_{m2}}$, the zero disappears (is pushed to an infinite frequency). If, $R_Z > \frac{1}{g_{m2}}$ the zero is pushed back into the LHP (phase shift is opposite from the poles)

III. CURRENT BUFFER INDIRECT COMPENSATION

Notice, in Fig. 1 that the current fed back through *Cc* is

$$i_{c_c} = \frac{V_{OUT} - \frac{V_{OUT}}{A_2}}{\frac{1}{j\omega C_C}} \quad (8)$$

If the second-stage gain, A_2 *is* reasonably large, then equation (8) can be approximated using

$$i_{c_c} \approx \frac{V_{OUT}}{j\omega C_C}$$

If we can feed back this current indirectly to the output of the diff-amp, we can still compensate the op-amp (and have pole-splitting). Further, if we do it correctly, we avoid connecting the compensation capacitor directly to the output of the diff-amp and thus avoid the RHP zero. Towards this goal, consider the modified op-amp schematic seen in Fig 3.

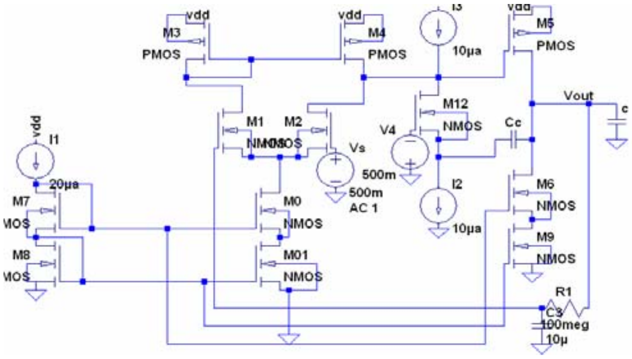

Figure 4. Current buffer Compensated opamp

The added MOSFET M12 form a current buffer. The current is fed back i_{c_c} through the current buffer MOSFET, to the output of the diff-amp.

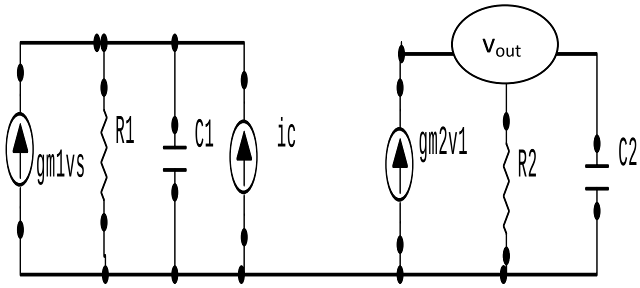

Figure 5. Equivalent circuit of Current buffer Compensated opamp

The transfer function of above opamp is given by[1]

$$\frac{v_{out}}{v_s} = \frac{-g_{m2}g_{m1}R_1R_2\left(1+s\frac{C_c}{g_{m12}}\right)}{s^2(R_1C_1)(R_2C_2)+s(R_1C_1+R_2C_2+R_1g_{m2}R_2C_C)+1} \quad (9)$$

Notice there is LHP zero at

$$f_z = \frac{g_{m12}}{2\pi C_C} \quad (10)$$

Since this zero is in the LHP, it will add to the phase response and enhance the speed of the op-amp. Intuitively, we can think that at high speeds the phase shift through *Cc* will cause the output signal to feed back and add to the signal at node 1. This positive feedback enhances the speed of the op-amp. To determine the location of the second pole, let's assume

$$R_1g_{m2}R_2C_C \gg R_1C_1 \text{ or} R_2C_2 \text{or} R_1C_1R_2C_2$$

So,

$$s_1, 2 = \frac{-R_1g_{m2}R_2C_C \pm R_1g_{m2}R_2C_C}{2(R_1C_1R_2C_2)} \quad (11)$$

Our approximation tell us the location of the lower frequency pole it's given by [7]

$$f_2 \approx \frac{g_{m2}C_c}{2\pi c_1 c_2} \approx \frac{g_{m2}C_c}{2\pi c_1(C_L+C_C)} \quad (12)$$

From Equation (2) the second pole, when using indirect compensation, is located at $-\frac{g_{m2}C_c}{C_L C_1}$ while the second pole for Miller (or direct) compensation was located at $-\frac{g_{m2}}{C_1+C_L}$. By comparing the two expressions, we can observe that the second pole, p2, has moved further away from the dominant pole by a factor of approximately C_c/C_1. This implies that we can achieve pole splitting with a much lower value of compensation capacitor (Cc) and lower value of second stage transconductance (g_{m2}). Lower value of g_{m2} translates into low power design as the bias current in second stage can be much lower. Alternatively, we can set higher value of unity-gain frequency for the op-amp without affecting stability and hence achieving higher bandwidth and speed. Moreover, the load capacitor can be allowed to be much larger for a given phase margin.

Also, unity gain frequency is given by [3]

$$f_{un} \approx \frac{g_{m1}}{2\pi c_c}$$

The indirect feedback of the current through the compensation capacitor results in faster op-amp circuits and less layout area (the compensation capacitor generally dominates the layout area of an op-amp).

IV. SIMULATION RESULTS

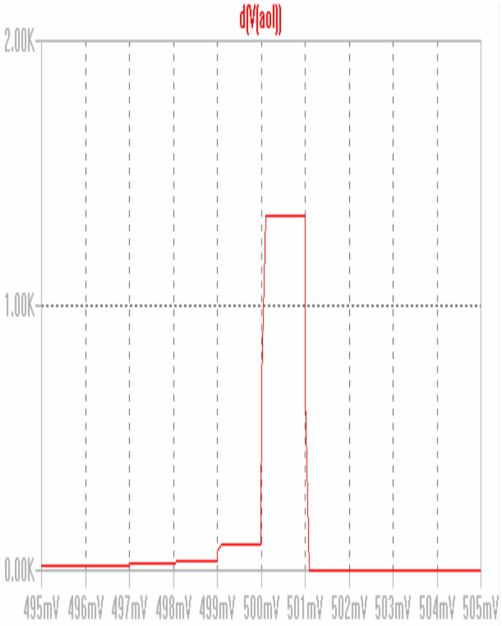

Figure 6. D.C gain curve of conventional opamp

The Simulation of CMOS OPAMP with and without compensation is carried out at 180nm CMOS technology parameters transistors only using LT-SPICE. Dc analysis is done to get D.C gain, ICMR and A.C analysis has been done to A.C gain, Phase margin, UGB. Transient analysis has also been done to see step response of various CMOS OPAMPs.

Figure 6 shows D.C gain curve of conventional Operational Amplifier. D.C gain of about **1.3k** is obtained from this configuration.

Figure7 shows D.C gain curve of Current Buffer Compensated Operational Amplifier. D.C gain of about **720** is obtained from this configuration.

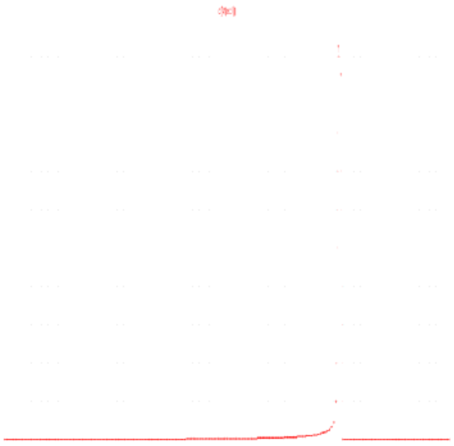

Figure 7. D.C gain curve of current buffer compensated opamp

For the frequency response plot, an ac signal of 1V is swept with 100 points per decade from a frequency of 100Hz to 10GHz. Fig.6,7 illustrates the frequency response which shows a dc gain in dB versus frequency in Hz(in log scale) and phase margin of OPAMP in open loop. The gain is found to be 96 dB and phase margin 92˚ for conventional operational amplifier and for current buffer compensated 115 dB and 117˚respectively.A unity gain frequency of 2.58MHz for conventional operational amplifier and 1.46GHz for current buffer compensated operational amplifier is found.

Figure8 shows frequency response curve of conventional Operational Amplifier.

Figure9 shows frequency response curve of Current Buffer Compensated Operational Amplifier.

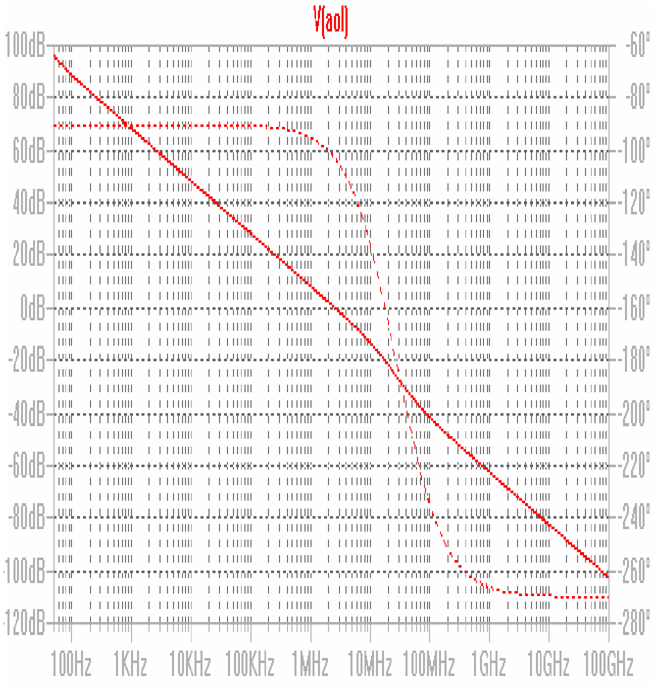

Figure 8. Frequency Response of conventional OPAMP

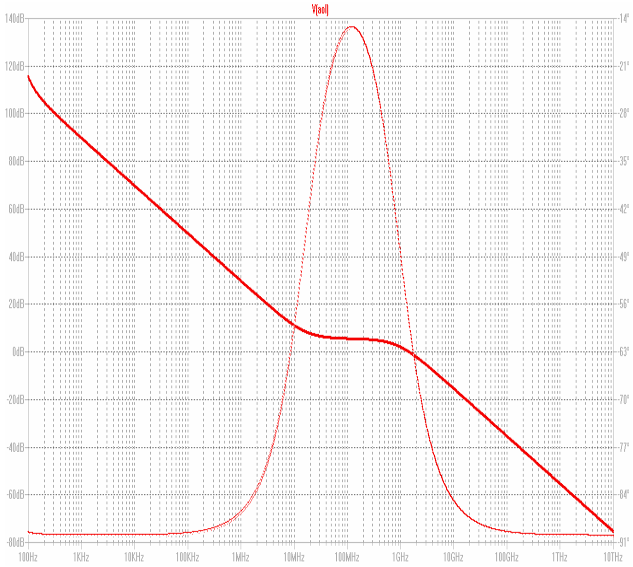

Figure 9. Frequency response of current buffer indirect compensation

The step response simulation is carried out performing a transient analysis using a pulse waveform of 5mV for a pulse period of 0.5µsec. The slew rate (+ve and –ve) are found to be 0.09V/µs and 0.09V/µs for conventional opamp 50V/µs and 4V/µs for current buffer compensated opamp. The slew rate response is as shown in figure 10 and figure 11.

Figure10 and figure11 shows step response curve of conventional and Current Buffer Compensated Operational Amplifier respectively.

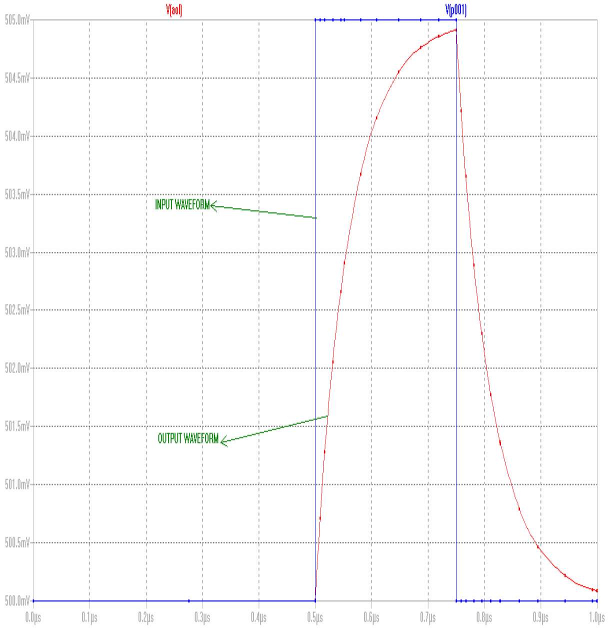

Figure 10. Step Response of conventional opamp

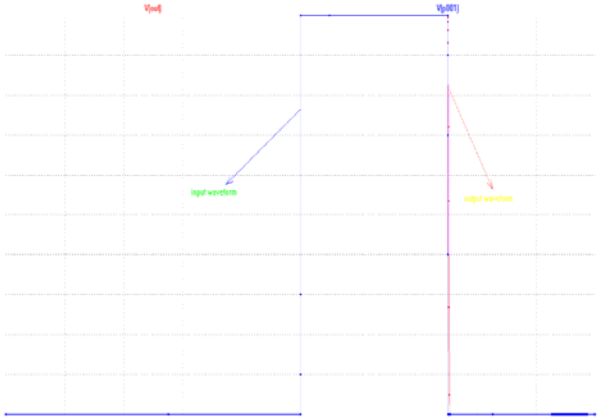

Figure 11. Step Response of current buffer indirect compensation

Figure12 and figure13 shows slew rate curves of conventional and Current Buffer Compensated Operational Amplifier respectively.

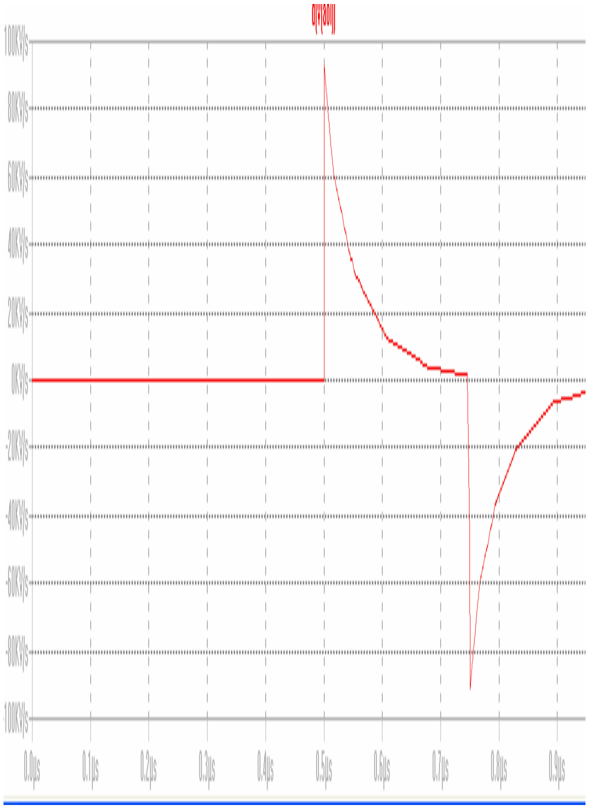

Figure 12. Slew rate of conventional Operational Amplifier

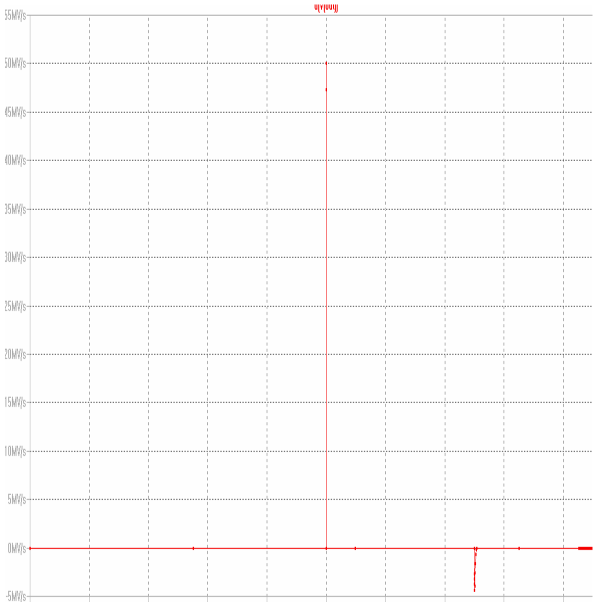

Figure 13. Slew rate of current buffer compensated Operational Amplifier

Table I. PERFORMANCE ANALYSIS COMPARISON OF CONVENTIONAL AND CURRENT BUFFER COMPENSATED OPAMP

S.NO.	***PARAMETER***	***CONVENTIONAL OPAMP***	***CURRENT BUFFER COMPENSATED***
1.	D.C GAIN	1.3K	720
2.	UGB	2.6 MHZ	1.46 GHZ
3.	PHASE MARGIN (IN DEGREES)	92˚	117˚

4.	SLEW RATE	0.1 V/µs	50v/µs

Table 1 shows the Comparison of various parameters of conventional and current buffer compensated Operational Amplifiers.

V. CONCLUSION

In this paper Two stage operational amplifier is successfully implemented using LT-SPICE at 180 nm technology. In this work current buffer compensated operational amplifier is used for increase in stability, increase in UGB and for increase in speed. The current buffer indirect feedback compensation technique, discussed in this paper, is a practical and superior technique as compare to conventional technique for compensation of op-amps, and results in faster and low power op-amp topologies with significantly smaller layout area. The two-stage op-amps employing current buffer for indirect feedback compensation simulated using LT-SPICE demonstrated a ten times enhancement in gain-bandwidth and 500 times faster transient settling when compared to the Miller compensated opamps.

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