

# A NEW CMOS OPERATIONAL AMPLIFIER IMMUNE TO EMI

Franco Fiori    Paolo S. Crovetto

Politecnico di Torino – Dipartimento di Elettronica,  
C.so Duca degli Abruzzi, 24 – 10129 Torino - ITALY  
e-mail: fiori@polito.it

**Abstract** - In this paper the high immunity to electromagnetic interference (EMI) of complementary differential pairs is highlighted. Furthermore, a new complementary differential pair with a particularly high immunity to radio frequency interference (RFI) is presented. The operation principle of this new structure is described and design criteria are provided. Such a structure has been designed and employed as an input stage of a folded cascode operational amplifier and its reduced susceptibility to RF interference has been verified by computer simulation.

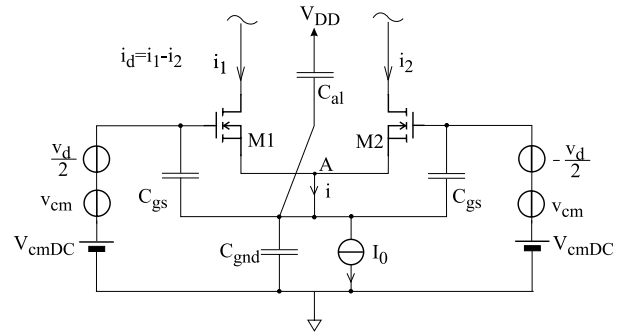


Figure 1. Single nMOS differential pair

## 1. INTRODUCTION

Analog integrated circuits (ICs), because of their high susceptibility to the RF interference which is collected by wires and traces in printed circuit boards, can strongly impact the reliability of any electronic system which operates in an electromagnetic polluted environment. For this reason, the immunity to RFI has become a primary demand in contemporary analog integrated circuit (IC) design.

Among analog ICs, operational amplifiers (opamps) are very important as they are employed as elementary building blocks in most analog and mixed-signal circuits. In these circuits, continuous wave (CW) RFI superimposed onto the input terminals induces a shift in the DC output voltage.

The RFI-induced DC output voltage shift in opamps has been previously investigated developing adequate device models [1,2] and computer simulation-oriented time-domain [3] and frequency-domain [4] (Harmonic Balance) macromodels. Furthermore, recent works have shown the causes of this behaviour, relating it to the nonlinear operation of the differential pair [5].

In this paper, the intrinsic high immunity to RFI of complementary differential pair is highlighted. Then, a new complementary differential pair with a high immunity to RFI is presented and its high immunity features are discussed on the basis of the model which has been presented in [5]. The proposed differential pair has been employed as the input stage of a folded cascode operational amplifier and the very low susceptibility to RFI of the designed circuit compared with a traditional folded cascode operational amplifier has been proven by time-domain computer simulations.

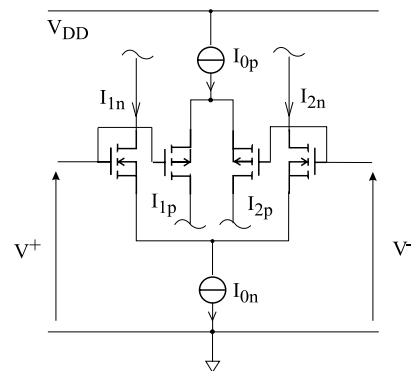


Figure 2. Complementary differential pair

## 2. RFI INDUCED DC OFFSET SHIFT IN OPERATIONAL AMPLIFIERS

Considerations on RF disturbance propagation through opamps let to derive that the RFI induced DC offset shift in opamps is essentially originated by the nonlinear behaviour of the input differential pair (Fig.1).

The mechanism responsible of the DC offset shift is essentially a mixer effect caused by the fluctuations in the effective bias current of a differential pair induced by the common mode component of RF interference superimposed on the input terminals. These fluctuations occur because of the finite admittance of the bias current source, which has a relevant capacitive component due to the reverse junction well-to-isolation capacitance  $C_{al}$  and to the source-to-body capacitance  $C_{gnd}$  in a twin-tub CMOS process.

A prediction of the DC shift induced in the differential current ( $\Delta I_D$ ) by this mechanism can be obtained by a second order circuit analysis.

For the MOS differential pair shown in Fig. 2 the following simplified  $i_D(v_D, i)$  nonlinear static expression is assumed

$$i_D = \begin{cases} -i & v_D < -\sqrt{\frac{i}{\beta}} \\ v_D \sqrt{2\beta i} \sqrt{1 - \frac{\beta v_D^2}{2i}} & |v_D| < \sqrt{\frac{i}{\beta}} \\ i & v_D > \sqrt{\frac{i}{\beta}} \end{cases} \quad (1)$$

where  $i$  is the bias current of the differential pair,  $v_D$  is the input differential voltage and

$$\beta = \frac{\mu C_{ox} W}{2L},$$

where  $\mu$  is the mobility of electrons (holes) in nMOS (pMOS) devices,  $C_{ox}$  is the capacitance of the gate oxide per unit of area and  $W$  and  $L$  are respectively the width and the length of the gate area of the MOS devices of the pair.

By a series expansion of Eqn. (1) in the quiescent point  $(v_d, i) = (0, I_0)$  a second-order expression for  $i_D$  can be obtained

$$i_d = g_m v_d + g_p v_d^2, \quad (2)$$

where  $g_m = \sqrt{2\beta I_0}$  and  $g_p = \sqrt{\frac{\beta}{2I_0}}$ .

Finally, substituting in Eqn. (2) the expressions of the differential mode RFI input voltage and for the effective bias current fluctuations induced by RFI because of the finite shunt admittance of the bias current source and taking the DC component an expression for  $\Delta I_D$  is derived [5]

$$\Delta I_D = \frac{g_p V_{d,pk} V_{cm,pk} |Y(j\omega)|}{2} \cos(\varphi_{cm} + \angle Y(j\omega)). \quad (3)$$

In Expr. (3)  $V_{d,pk}$  and  $V_{cm,pk}$  are respectively the peak amplitudes of the differential and of the common mode component of the input voltage of the pair and the term  $\varphi_{cm}$  is the phase shift between the differential and the common mode signals.

The expression for  $Y(j\omega)$  in Eqn. (3) is

$$Y(j\omega) = \frac{2g_m j\omega C_T}{j\omega(C_T + 2C_{gs}) + 2g_m}, \quad (4)$$

where

$$C_T = C_{al} + C_{gnd}$$

and  $C_{al}$ ,  $C_{gnd}$  and  $C_{gs}$  are shown in Fig. 2.

As the RFI induced input offset voltage shift  $\Delta V_{off}$  in an operational amplifier is almost only due to the input differential pair nonlinearity, it can be derived from  $\Delta I_D$  as

$$\Delta V_{off} = \frac{\Delta I_D}{g_m}. \quad (5)$$

Expr. (5) is similar to the expression usually employed to evaluate the input offset voltage due to transistor mismatches.

### 3. HIGH IMMUNITY COMPLEMENTARY DIFFERENTIAL PAIR

The high immunity features of the complementary differential pair reported in Fig. 2 are now discussed.

This structure is made up of an nMOS differential pair and of a pMOS differential pair with the input terminals connected together. The output of this structure is the overall differential current, i.e. the sum of the differential currents of the two stages

$$i_D = i_{Dn} + i_{Dp} \quad (6)$$

Complementary differential pairs are widely employed in rail-to-rail operational amplifiers: referring to these circuits, anyway, it has to be pointed out that the distortion compensation discussed in the following requires both the differential pairs to be working.

#### 3.1 RFI-induced DC differential current shift in complementary differential pairs

The RFI-induced differential current shift  $\Delta I_D$ , on which, referring to Eqn.(5),  $\Delta V_{off}$  depends, in a complementary differential pair can be derived from the expressions of the RFI-induced differential current shift in each differential pair and in particular it is given by

$$\Delta I_D = \Delta I_{Dn} + \Delta I_{Dp}. \quad (7)$$

Substituting the expression for  $\Delta I_D$  presented in Eqn. (3), Expr. (7) becomes

$$\Delta I_D = \frac{V_{d,pk} V_{cm,pk}}{2} (F_n + F_p), \quad (8)$$

where

$$F_n = g_{p,n} |Y_n(j\omega)| \cos(\varphi_{cm,n} + \angle Y_n(j\omega)) \quad (9)$$

and

$$F_p = g_{p,p} |Y_p(j\omega)| \cos(\varphi_{cm,p} + \angle Y_p(j\omega)). \quad (10)$$

Furthermore, for topological reasons, using for the common mode voltage a sign convention consistent with the proposed model for the RFI induced DC current shift,

$$\varphi_{cm,p} = \varphi_{cm,n} + \pi$$

and so Expr. (10) can be rewritten in the form

$$F_p = -g_{p,p} |Y_p(j\omega)| \cos(\varphi_{cm,n} + \angle Y_p(j\omega)), \quad (11)$$

which will be useful in the following.

### 3.2 Design of High Immunity Complementary Differential Pairs

Based on Eqn. (8) and considering the expression for  $F_p$  reported in Eqn. (11) it can be noticed how the overall current offset is given by the algebraic sum of two opposite terms, which compensate each other and in particular that

$$F_n = -F_p \longrightarrow \Delta I_D = 0. \quad (12)$$

This nonlinearity compensation mechanism makes complementary differential pairs intrinsically harder to RFI than single differential pairs. Their higher immunity can be further enhanced by a proper sizing of the stage intended to meet condition (12).

Condition (12) can be met for

$$g_{p,n} = g_{p,p} \text{ and } Y_n(j\omega) = Y_p(j\omega). \quad (13)$$

Conditions (13) can be met respecting proper design constrains, in particular the first of conditions (13) is met choosing

$$I_n = I_p \text{ and } \beta_n = \beta_p. \quad (14)$$

The latter requires

$$\frac{\left| \frac{W}{L} \right|_n}{\left| \frac{W}{L} \right|_p} = \frac{\mu_p}{\mu_n}.$$

Supposing conditions (14) to be met, the second of conditions (13) is respected for all frequencies if

$$C_{T,n} = C_{T,p} \text{ and } C_{gs,n} = C_{gs,p}. \quad (15)$$

Conditions (15) can be respected adding shunt capacitors in order to compensate the differences in the values of parasitics.

For example, [4] if  $C_{T,p} > C_{T,n}$ , the first of conditions (15) can be met adding a shunt capacitor  $\Delta C_{T,n}$  to  $C_{T,n}$  of capacitance

$$\Delta C_{T,n} = C_{T,p} - C_{T,n}.$$

The values of parasitics required can be estimated with a very good accuracy from process parameters either analytically or by computer simulation (back annotation). Furthermore, it can be proven that for high frequency CW RFI, the sensitivity of the offset voltage shift to the value of these capacitances is very low.

In fact, for angular frequencies

$$\omega \gg \frac{2g_m}{C_T + 2C_{gs}},$$

equation (4) can be simplified in the form

$$Y(j\omega) \cong \frac{2g_m C_T}{C_T + 2C_{gs}} \quad (16)$$

and the sensitivity of  $\Delta V_{off}$  to  $C_T$  and to  $C_{gs}$  is

$$\frac{\delta \Delta V_{off}}{\Delta V_{off}} = -\frac{2C_{gs}}{2C_{gs} + C_T} \frac{\delta C_{gs}}{C_{gs}} + \frac{2C_{gs}}{2C_{gs} + C_T} \frac{\delta C_T}{C_T}. \quad (17)$$

For instance, assuming  $C_{gs} = 0.1 C_T$  Expr.(17) gives

$$\frac{\delta \Delta V_{off}}{\Delta V_{off}} = -0.1 \frac{\delta C_{gs}}{C_{gs}} + 0.1 \frac{\delta C_T}{C_T}. \quad (18)$$

For this reason, differential pair nonlinear effects can be effectively compensated even though conditions (15) are not exactly met and still a high immunity to RFI can be achieved even without adding any shunt capacitor to the circuit. The latter consideration grants that the proposed approach to improve operational amplifier immunity to EMI is robust to inaccuracies in device sizing due to technology process.

## 4. A HIGH IMMUNITY OPERATIONAL AMPLIFIER

An operational amplifier based on the high immunity complementary differential pair discussed above has been designed and simulated by ELDO [6], a SPICE-like circuit simulator, using the models of the devices available in a standard CMOS process.

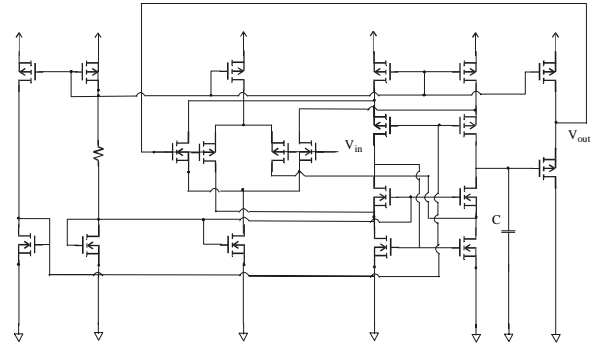


Figure 3. High Immunity Folded Cascode opamp.

The proposed structure, which is shown in Fig. 3 is a standard folded cascode operational amplifier in which the input differential pair has been replaced by the proposed complementary differential pair.

In order to verify the immunity of this structure to RFI superimposed on the input terminals, time-domain computer simulations have been performed. In particular, the RFI induced DC offset voltage shift of the operational amplifier with the proposed input stage, connected in a voltage follower feedback configuration, has been compared with the RFI induced DC offset voltage shift of standard nMOS-input and pMOS-input folded cascode operational amplifiers in the same feedback configuration and under identical test conditions.

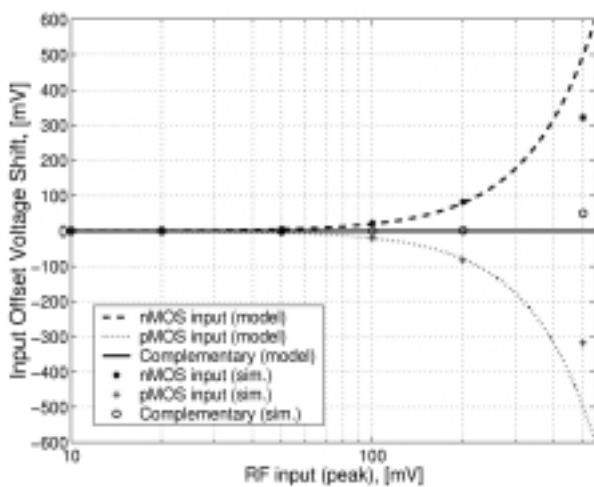


Figure 4.  $\Delta V_{off}$  in nMOS input, pMOS input and High Immunity Complementary opamp

The simulated RFI induced DC offset voltage shift in these three structures is reported in Fig. 4 as a function of the amplitude of a sinusoidal CW interference with a frequency of 100MHz superimposed on the input terminals. In this figure the marks represent simulation results while the solid, dashed and dotted lines represent the prediction obtained by the model proposed in [5], on which the considerations carried about in the previous section are based.

From Fig. 4 it can be noticed how effectively the proposed circuit shows particular high immunity features. The residual RFI induced DC offset voltage shift can be ascribed to higher order nonlinear effects neglected in the proposed model.

This model, in particular, is based on the assumption that each transistor is working in the saturation region. If the peak amplitude of the RF interference is high enough, the previous condition is no longer respected and the offset compensation proposed in this work is no longer effective. It should be noted, anyway, that also in these conditions the behaviour of the high immunity

structure proposed is much better than conventional structures.

## 5. CONCLUSION

In this paper, a new opamp input stage which is particularly immune to EMI has been proposed. The insight in the nonlinear mechanisms responsible of the RFI-induced DC offset voltage shift in operational amplifiers gained by previous work is employed in order to achieve a cancellation of the second-order nonlinear effects in the differential pair.

The effectiveness of the proposed solution is confirmed by computer simulation results, which also show that the proposed circuit has an improved behaviour even beyond the validity limits of the model on which it is based.

## 6. ACKNOWLEDGEMENTS

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## 7. REFERENCES

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