An Analog Front End Based on Chopped Signals Highly Immune to RFI

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Abstract—Amplifiers used in analog signal conditioning circuits are usually protected against electromagnetic interference (EMI) by means of filters placed at the PCB level. The literature is plenty of solutions aimed at keeping filters’ attenuation as high as possible in the widest possible frequency range, but actually such filters are less effective than expected because of the parasitic elements introduced by interconnects, therefore EMI can be propagated into ICs causing temporary or definitive operation failures. This can be avoided inserting EMI filters at the IC level and/or using circuit topologies intrinsically immune to EMI. This paper shows that the immunity to RFI of analog circuits based on feedback opamps is significantly improved if input signals are chopped before being amplified.

I. INTRODUCTION

Most of mechanical, chemical and safety systems used in automotive, industrial and telecom applications base their operation on signals picked up from the field by means of sensors and transducers, which convert physical signals into their electrical counterpart. The output swing of such signals is much much smaller than the input range of common ADC therefore, aiming to avoid an excessive reduction of the SNR, i.e., excessive ENOB penalty, they must be properly amplified and filtered before being converted into their digital counterparts. Furthermore, such signals are corrupted by electromagnetic interference (EMI) that are usually rejected referring to differential gain stages rather than single-ended, and/or using passive filters placed in the signal conditioning chain and, if possible, placing the amplifier (sometimes even the analog-to-digital converter) into the sensor package, as close as possible to the transducer to keep the antenna efficiency of interconnects as low as possible. However, such solutions are usually effective only in some frequency bands and not in some others where the interference is allowed to propagate into the ICs causing operation failures.

The abnormal behaviour of analog ICs when concerned by EMI is usually explained referring to the combined action of active nonlinear devices (e.g., transistors) and capacitors (wanted or parasitic) that causes the EMI rectification, hence its demodulation [1,2,3]. This unwanted effect is an issue whenever demodulated EMI drops into the amplifier bandwidth, because in such the interference cannot be removed from the wanted signal to be amplified. To prevent the EMI demodulation from taking place, EMI filters are inserted at the integrated circuit level [4,5] or wideband highly linear circuits are used or self-cancellation techniques are implemented [6,7,8].

The solution proposed in this paper to avoid the amplifier output signal from being affected by RFI demodulated disturbances is not based neither on EMI filtering solutions nor on self-cancellation techniques.

The basis of RFI rectification in basic circuits and in feedback opamps are reviewed in Section II, the proposed solution to increase the immunity to RFI and some experimental results are presented in Section III and concluding remarks are drawn in Section IV.

II. RFI RECTIFICATION

The basic concept behind the demodulation of RFI carried out by analog circuits can be easily explained referring to the ideal circuit shown in Fig. 1 that comprises a MOS transistor biased in the saturation region by two DC voltage sources $V_{GS}$ and $V_{DS}$, with the input port affected by a modulated RF interference ($v_{RF}$). Being the drain current a nonlinear function of the gate-source voltage, the current waveform is distorted, hence its spectrum is composed of the fundamental, several harmonics and intermodulation products. Among these, the most harmful contribution to the output is surely that given by the intermodulation products, because the base-band information (modulation signal) carried by the radio frequency signal appears demodulated in the MOS drain current just superimposed onto the baseband nominal output signal. In the particular case of continuous wave (CW) interference the average current flowing in the transistor is affected by a DC offset [1]. Indeed, if the drain current is expressed as

$$i_D = \beta_n (v_{DS} - V_{TH-n})^2$$

Fig.1: Setup used to analyse MOS transistor RFI rectification.
where $V_{GS}$ is the gate-source voltage, $V_{TH-n}$ is the transistor threshold and $\beta_n$ is defined as

$$\beta_n = \frac{\mu_n C_{ox}}{2} \left( \frac{W}{L} \right)^2$$

where $\mu_n$ is the electron mobility, $C_{ox}$ is the gate-oxide capacitance, $W$ is the channel width and $L$ is the channel length. The gate-source voltage can be expressed as

$$V_{GS} = V_{GS}^{DC} + v_{gs}(t),$$

where $V_{GS}^{DC}$ is the DC component and $v_{gs}(t)$ is the time-varying component, which represents the interference. As far as periodic disturbances are concerned, the average value of the nMOS drain current can be expressed as

$$\bar{i}_D = \frac{1}{T} \int_0^T i_D(t) \, dt,$$

where $T$ is the period of $v_{gs}(t)$. Substituting (1) and (3) in (4), the average drain current can be expressed as

$$\bar{i}_D = \beta_n (V_{GS} - V_{TH-n})^2 + \beta_n v_{gs}^2$$

hence, the output offset current is given by

$$\Delta i_D = \beta_n \frac{v_p^2}{2}$$

where $v_p$ is the RFI peak amplitude.

Fig. 2 shows the large-signal input/output characteristic of an nMOS transistor without RFI (continuous line) and with CW RFI (magnitude and frequency are constants) applied at the input port (dashed line). The offset induced by RFI in the drain current is highlighted by the time domain waveform sketched in the same figure.

Furthermore, RFI demodulation can be also analysed referring to a MOS transistor biased at the source terminal by a DC current sinker (see Fig. 3) with the gate voltage affected by RFI and the source terminal loaded by the parasitic capacitor $C_p$. In such a case, a part of the RF input voltage drops across the transistor gate-source capacitance causing RFI rectification that results in a reduction of the average gate-source voltage. This effect can be also highlighted referring to the input-output characteristics shown in Fig. 2, because having the average drain current kept constant at $i_D$, the average gate-source voltage is shifted down i.e., a positive DC offset voltage $V_{off}$ is experienced at the circuit output to ground.

### III. RFI Rectification in Feedback OPAMP

RFI rectification in feedback amplifiers can be easily analysed referring to opamps like that shown in Fig. 4 composed of a differential input stage cascaded with a differential to single-ended transresistor ($R_m$), whose output is fed back to the input through a passive network $Z_1, Z_2$ and the input is driven by a nominal signal ($v_{in}$) corrupted by RFI.

In nominal conditions, i.e., without interference, any imbalance of the input differential voltage causes output voltage variations such that the differential input voltage is minimized (feedback error). As a consequence, the differential pair transistors experience the same gate-source voltage,
hence the drain currents $i_{D1}$ and $i_{D2}$ equal each other. If the RF source is on, the transistors M1 and M2 are both concerned by the RFI but the parasitic capacitance $C_p$ loading the tail makes the RF voltage magnitude affecting the M1 gate-source voltage greater than that across M2. By this reasoning the M1 average drain current should be greater than that of M2 but actually it is not because such a potential imbalance is immediately compensated by the feedback that keeps the average differential input voltage at the minimum (average loop error). The drawback of such a compensation is the generation of an output offset voltage whose magnitude depends only on the RFI magnitude and frequency. At this point, it is worth noting that neither the bias current of M1, M2 nor the RF voltages at the transistors’ gate source terminals depend on the baseband input voltage level ($v_{in}$), and this means that the offset induced by the RFI is the same regardless of the baseband signal magnitude. This result is also confirmed by time domain simulations carried out at the transistor level (Spectre simulations) and by susceptibility tests carried out on different opamps, all based on the topology shown in Fig. 4. Such opamps have been characterized referring to the test setup shown in Fig. 5 in which the RFI generated by an RF source ($v_{RF}$) is superimposed onto the nominal input signal through a bias tee and the output voltage is observed using an oscilloscope connected to the output low-pass filter ($R_0, C_0$) [9]. With the RF source off the output signal copies the input (waveforms till $t_0$ in Fig.6) whereas with the RF source switched on the output voltage still copies the input but it is affected by a DC offset voltage ($v_{off}$), as it is sketched in Fig. 6. The output offset voltage ($v_{off}$) versus frequency of the opamp TS-912 induced by a 0dBm CW interference is shown in Fig. 7 while the error induced by the same RFI on the output voltage difference

$$\Delta v_{err} = \Delta v_1 - \Delta v_0,$$

and the offset attenuation defined as

$$Att_{dB} = 20 \log_{10} \left( \frac{V_{off}}{\Delta v_{err}} \right)$$

are shown in Fig. 8 and 9, respectively.

![Fig. 5 DPI test setup](image)

![Fig. 6 Amplifier input and output waveforms with and without RFI.](image)

![Fig. 7 DPI measurement results. – Output offset voltage induced by RFI.](image)

![Fig. 8 DPI measurement results. – Error affecting $\Delta v$ for $\Delta v_0 = 10mV$.](image)
On the basis of these results, it can be concluded that the immunity of analog front-end based on feedback opamps is significantly increased if the baseband input signal to be amplified is chopped first. Therefore, if the input voltage to be amplified is chopped before being corrupted by the RFI, the voltage provided to the amplifier is a square wave corrupted by RFI, thus the output voltage is a square wave of amplitude $v_{\text{ind}}/\beta$ affected by a time invariant offset of magnitude $v_{\text{off}}/\beta$. However, it must be noted that the RFI induced offset can lead the amplifier output to exceed the input range of the stage that follows causing overload errors. This offset as well as the OpAmp technology offset can be cancelled out using the circuit shown in Fig. 10. Here, the output voltage is first chopped, then the resulting square wave is applied to a notch filter (NF) at the chopping frequency. The correction voltage resulting from NF is converted into the correction current by the differential transconductor (3) needed to set the average output voltage to $v_{\text{REF}}$. This additional feedback is effective at very low frequency, hence it does not introduce any stability issue. The proposed circuit has been designed referring to a $0.35 \mu m$ CMOS technology process and its capability to remove the DC offset induced by the RFI has been checked performing time domain analyses with Spectre. An example of waveforms obtained from time domain analysis is given in Fig. 11 where from the top to the bottom, the input voltage affected by CW RFI ($1 V_{pk}$, 50 MHz) and the amplifier output voltage are plotted.

**IV. CONCLUSIONS**

This work has highlighted that the immunity of common feedback opamps based on current biased differential input stages is almost independent from the nominal input signal amplitude. As a consequence, if the input signal is chopped before being amplified, the time-varying component at the amplifier output is not concerned by the demodulated RFI. This result has been proved through time domain simulations and experimental tests carried out on commercial opamps registering improvements greater than 40dB. Furthermore, it has been observed that the DC offset resulting at the opamp output from RFI rectification can lead to overload errors. A circuit based on chopped signals that removes such a DC offset has been proposed.

**REFERENCES**


