A New Linearization Technique for CMOS Low Noise Amplifiers with Balun Circuitry

Mahdi Barati, Babak MazhabJafari, and Mohammad Yavari

Integrated Circuit Design Laboratory, Department of Electrical Engineering,
Amirkabir University of Technology, Tehran, Iran

Emails: m.barati@aut.ac.ir, babak.mazhabjafari@aut.ac.ir, myavari@aut.ac.ir

Abstract: *In this paper, a new linearization technique for differential low noise amplifiers (LNAs) is introduced. It removes the common-mode current at all frequencies. One of its main advantages is that it allows the receiver to have a single-ended input and a differential output LNA which attenuates even-order inter-modulations. Also, this technique improves the LNA linearity in three ways. Firstly, it removes the common-mode current of all inter-modulations. Secondly, it attenuates even-order inter-modulations because of its balun circuitry operation. Finally, it improves the third input intercept point (IIP3) due to the possibility of different bias currents for input transistors. Simulation results using a 0.18µm RF-CMOS technology with HSPICE-RF show that the IIP3 improves about 13 dBm at the expense of increasing the noise figure about 0.7 dB in constant voltage gain and equal DC-power respected to the conventional differential LNA.*

Keywords: LNA, inter-modulation, IM2, IM3, IIP2, IIP3, transconductance.

1. Introduction

Due to the growth of personal communication devices over the last few years, the design of high performance RF integrated circuits and systems has become more important. During the last years, the development of wireless communication systems and the extension of the usage of wireless devices make the frequency band very noisy and the interference of each band increases due to congestion of the frequency band. So, designers are forced to use more sensitive and highly linear transceivers. In this situation, equipments which work under the same communication standard may suffer from the interference from each other. For example, in the IEEE 802.11 b/g standard, which is for implementing wireless local area network (WLAN) in the 2.4 GHz frequency band, equipment may suffer the interference from microwave ovens, cordless phones and Bluetooth devices. Each IEEE 802.11 b and g has a maximum raw data rate of 11 Mbit/s and 54 Mbit/s over a 20 MHz bandwidth and is very suitable for high speed communication applications.

Since the low noise amplifier (LNA) is the first block of the receiver chain, it must be designed with low noise and high linearity so as to increase the sensitivity and linearity of the receiver. There are several linearization methods for LNAs to attenuate the most important nonlinearity components of MOSFETs such as g_m and g_{ds} [1].

Differential circuits are common in wireless applications as they can reduce the even-order distortion and the susceptibility to the common-mode (CM) noise [2]. So, differential LNAs are more linear than the single-ended ones and have robust outputs against the process variations. The main concern in this type of LNAs is the need for a balun to provide the differential input signal form the antenna. Passive baluns (also known as transformers) are lossy, bulky and very noisy resulting in a higher noise figure (NF) in the receiver [3].

In this paper, a differential LNA with a balun circuitry and a new technique to enhance the linearity by removing the CM current and attenuating the output second and third order inter-modulation components (IM2 and IM3) is proposed.

The paper is organized as follows. Section 2 describes the proposed LNA structure and technique, and provides the noise and linearity analysis. Simulation results of the proposed LNA using a 0.18 µm CMOS process are reported in Sect. 3. Finally, Sect. 4 presents the conclusions.

2. Proposed LNA Structure

For any differential-pair LNA such as the one shown in Fig. 1(a), the drain currents I_1 and I_2 in the left and right branches can be written as [3]:

$$I_1 = I_{CM} + I_{Diff} \quad (1)$$

$$I_2 = I_{CM} - I_{Diff} \quad (2)$$

where I_{CM} is the common-mode current and I_{Diff} is the differential-mode current in a differential-pair amplifier.

The idea in this paper is to design an LNA to remove I_{CM} at all frequencies except for DC. As is seen in Fig.

1(b), another differential pair is utilized besides of the primary diff pair. Its drain currents like Equation (1) can be decomposed into I_{CM} and I_{Diff}. If the v_{GS} of M_3 and M_4 are chosen equal to the $-v_{GS}$ of M_1 and M_2 transistors, respectively, according to the current equation in MOSFET transistors we have:

$$I_{CM\,1} = -I_{CM\,4}\,, \quad I_{CM\,2} = -I_{CM\,3} \tag{3}$$

$$I_{Diff\,1} = I_{Diff\,4}\,, \quad I_{Diff\,2} = I_{Diff\,3} \tag{4}$$

$$I_{out+} = 2I_{Diff} \tag{5}$$

$$I_{out-} = -2I_{Diff} \tag{6}$$

It is seen that in the output current of the proposed LNA, I_{CM} is removed. This has some advantages in LNA design that it will be clarified in the later discussion.

2.1 Balun circuitry

Because the LNA is the first block in an RF receiver and its input signal comes most often from the antenna, it has to be a single-ended input or we need to use a bulky and noisy balun to convert the single-ended input to a differential one. By removing the CM current in the fundamental frequency of the introduced circuit, the need for a balun is eliminated making possible the use of a differential LNA structure for a single-ended input coming from the antenna.

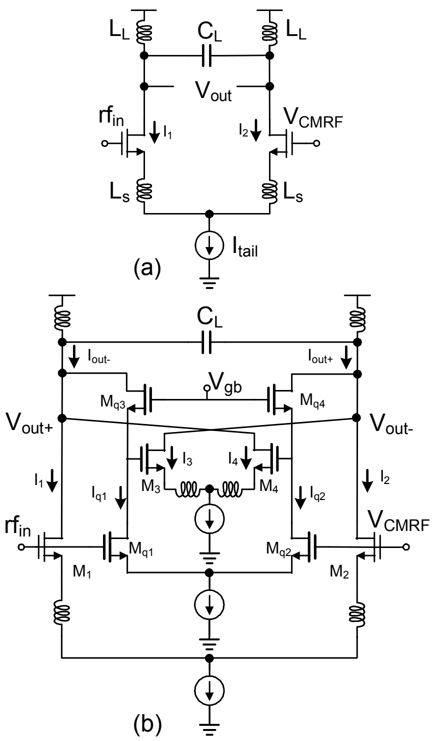


Fig. 1: (a) Conventional differential LNA and (b) proposed LNA

2.2 Inter-modulation attenuation

Different orders of current inter-modulations of the proposed LNA circuit shown in Fig. 1(b) can be decomposed into the CM and Diff currents. For all of them, the CM current is removed and so the linearity is improved. For the second-order inter-modulation (IM2), the CM part of the IM2 is the dominant part [4], so this circuit has a very good linearity performance in wide-band applications. Because the IM3 is often the largest in-band inter-modulation, removing its CM part has more effect on the LNA linearity performance. In this circuit, the IM3 component is attenuated in two ways. Firstly, the CM part of the current is removed. Secondly, since the coefficient of the third-order nonlinearity is the second-order derivative of the device transconductance, g_m, of the transistors which is derived from the Taylor expansion as [5]:

$$i_{ds} = I_{DC} + g_m v_{gs} + \frac{g_m^{'}}{2!} v_{gs}^2 + \frac{g_m^{''}}{3!} v_{gs}^3 + \ldots \tag{7}$$

Plot of the g''_m with respect to the v_{GS} shows that at some values of v_{GS}, the g''_m is negative and at some values of v_{GS} it is positive. So, by biasing $M_{1,2}$ which is the input pair and $M_{q1,q2}$ and also $M_{3,4}$ at different biasing voltages makes the IM3 component to be attenuated since their output current is summed and the g''_m becomes small. This improves the IIP3 [6]. Thus, at an optimum bias point of $M_{1,2}$, $M_{q1,q2}$ and $M_{3,4}$, the g''_m can be canceled at the output current, and hence, the linearity is improved.

2.3 Input matching

The LNA performance is characterized by gain, NF, power consumption, reverse isolation, stability, linearity, and input impedance matching relative to the 50 Ω source impedance. In both proposed and conventional differential LNAs, the input stage has the common-source topology. Therefore, to achieve the input impedance matching relative to the 50 Ω, the typical inductive source degeneration topology [7] as shown in Fig. 2 is used in both circuits. Due to the inductive input impedance of the proposed LNA, the T input matching network is proposed as shown in Fig. 3. Equations (8), (9), and (10) describe the input impedance ($Z_{in}(s)$) seen from the gate of the input transistor for the conventional and proposed LNAs, respectively. An inductor L_B is used in series with R_S to set the resonance frequency at 2.4 GHz in the conventional LNA. For simplicity, all other parasitics and the body effect are ignored.

$$Z_{in-conv}(s) = j\omega L_s + \frac{1}{j\omega C_{gs}} + \frac{g_m L_s}{C_{gs}} \tag{8}$$

$$Z_{in-prop}(s) = j\omega L_S \,\|\, Z_{eq-in}(s) \tag{9}$$

$$Z_{eq-in}(s) = \left[\begin{array}{l} \left(\dfrac{g_m}{g_m{}^2 + 4\left(\omega C_{gs}\right)^2} + \dfrac{(\omega L_S)^2 R_S}{(\omega L_S)^2 + R_S{}^2} \right) \\ + j\omega \left(\dfrac{L_S R_S{}^2}{(\omega L_S)^2 + R_S{}^2} - \dfrac{2C_{gs}}{g_m{}^2 + 4\left(\omega C_{gs}\right)^2} \right) \end{array} \right] \tag{10}$$

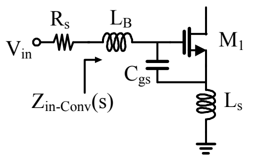


Fig. 2: Typical inductive source degeneration topology

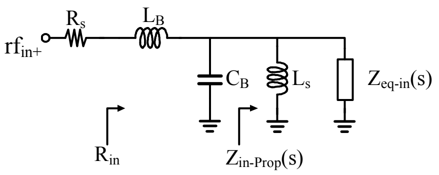


Fig. 3: T input matching network used in the proposed LNA

2.4 Gain comparison

By assuming $i_{1\text{-}4}$ and $i_{q1\text{-}q2}$ to be the small-signal currents of $M_{1\text{-}4}$, $M_{q1,q2}$ in Fig. 1(b), the small-signal output current is obtained as:

$$\begin{aligned} i_{out} &= i_{out+} - i_{out-} \\ &= (i_2 + i_3 + i_{q2}) - (i_1 + i_4 + i_{q1}) = 2g_m v_{in} \end{aligned} \quad (11)$$

$$g_m = g_{m1} + g_{m4} + g_{mq1} \quad (12)$$

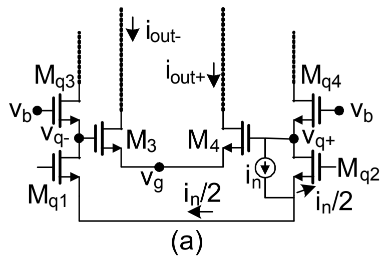
where $g_{m1\text{-}4}$, $g_{mq1\text{-}q2}$ are transconductance of the $M_{1\text{-}4}$, $M_{q1,q2}$ transistors, respectively.

In comparison with the conventional differential LNA where its small-signal output current is $i_{out} = 2g_m v_{in}$, it is seen that the overall form of current does not change.

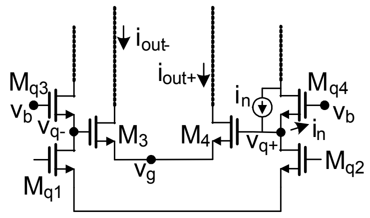
2.5 Noise analysis

This part is considered to estimate the added noise in the designed new circuit compared with conventional differential LNAs.

To estimate the added noise, firstly, it should be noticed that at the output of the LNA, the thermal noise is only important and so the flicker noise (1/f noise) is neglected. After that, in the proposed LNA, the tail current, compared with conventional differential LNA, is divided into three branches. The thermal noise of a transistor is proportional to its g_m which changes with square root of the drain current. So, it affects the output current noise. Also, for $M_{q1\text{-}q4}$ as it is seen in Fig. 4, their noise is transferred to the output from the path of $M_{3\text{-}4}$.



(a)



(b)

Fig. 4: Proposed schematic for calculating: (a) M_{q2}'s noise and (b) M_{q4}'s noise

To calculate the added noise in Fig. 1(b), the noise of M_{q1} and M_{q3} are calculated like those of M_{q2} and M_{q4}, so just the noise calculation of M_{q2} and M_{q4} are considered here. To calculate the noise of M_{q2}, consider Fig. 4(a). Here is the noise effect of M_{q2} on the output current of the input transistors:

$$\begin{aligned} i_{out} &= i_{out+} - i_{out-} \\ &= g_{m3}(v_{q+} - v_{q-}) = -\frac{g_{m3}}{g_{mq4}} i_n \end{aligned} \quad (13)$$

where g_{m3} is the transconductance of M_3.

According to Fig. 4(b), it is seen that all noise current of M_{q4} will pass through itself because $1/g_{mq4} << r_{dsq2}$, and it has no effect on the output noise.

In equations (13), i_n^2 is the thermal noise power of M_{q2}. It is concluded that:

$$\left(\frac{g_{m3}}{g_{mq4}} i_n\right)^2 = \left(\frac{g_{m3}}{g_{mq4}}\right)^2 4kT\gamma g_{mq4} = \frac{g_{m3}^2}{g_{mq4}} 4kT\gamma \quad (14)$$

From the above equation, it can be concluded that if $g_{mq4} = g_{m3}$, then the noise effect of M_{q2} is equal to that of M_3. So, the noise effect of $M_{q1\text{-}4}$ is equal to double the output noise of the quasi differential pair or multiply the output noise of the input transistors by 1.5. It means that at the worst case the g_m of $M_{1\text{-}4}$ and $M_{q1\text{-}q4}$ are equal, and the output noise can be increased up to 1.7 dB.

The thermal noise of $M_{3\text{-}4}$ transistors appears at the output like that of the conventional differential LNA.

3. Simulation Results

The proposed technique was applied to a conventional differential LNA as shown in Fig. 1(b) and it was simulated by HSPICE-RF and the results are compared with those of the conventional differential LNA shown in Fig. 1(a). To calculate the IIP3, different levels of RF input signal are applied to the circuit and the fundamental frequency and the third-order inter-modulation component are plotted at the output as shown in Fig. 5. Table I shows the comparison results. According this Table, the IIP3 of the proposed LNA has been improved about 12.9 dBm compared with the conventional differential LNA.

To have a fair comparison in the linearity, in conventional differential and proposed LNAs, the gain and input DC power were kept constant. Also, it is seen in Fig. 6, the noise figure of the proposed LNA is increased about 0.7 dB as was foreseen by the theory in Sect. 2.5. S_{11} which represents the input impedance matching relative to the 50 Ω is shown in Fig. 7. It is seen that the proposed LNA has a good input matching.

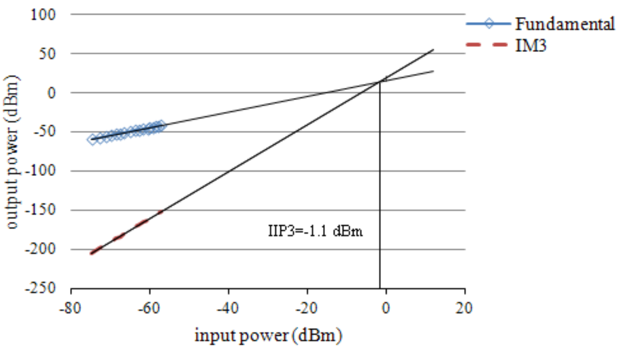


Fig. 5: Simulated IIP3 of the proposed LNA

TABLE I: Simulation results comparison.

Parameter	Proposed LNA	Conventional diff. LNA
Frequency [GHz]	2.4	2.4
S11 [dB]	< -15	< -15
NF [dB]	2.5	1.8
Gain [dB]	17.14	17.2
IIP3 [dBm]	-1.1	-14
Power [mW]	11.7	11.7
Technology	180 nm	180 nm

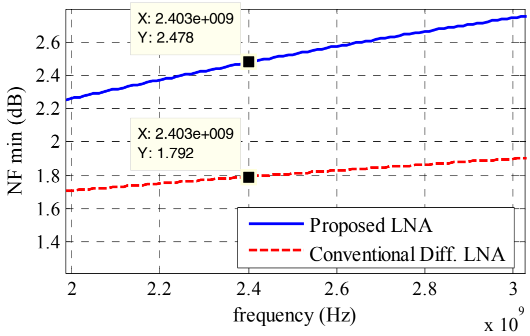


Fig. 6: Simulated NF_{min}

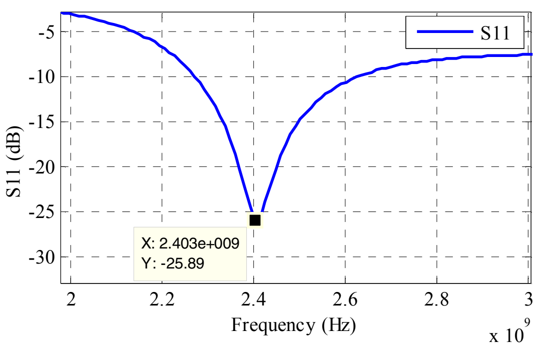


Fig. 7: Simulated input impedance matching, S_{11}

4. Conclusion

In this paper, a new technique was proposed to remove the common-mode currents in CMOS LNAs at all frequencies. By using this technique, the differential LNA has no need to a bulky and noisy balun. In fact, it represents a balun circuitry. Another advantage of this circuit is its higher linearity. This proposed circuit improves the linearity in three ways. To have a fair comparison in the linearity operation with the conventional differential LNAs, the design and simulations were performed with the equal voltage gain and dc-power. Simulation results confirm the improved linearity behaviour at the expense of slightly increased NF and needing two additional inductors.

References

[1] H. Zhang and E. Sanchez-Sinencio, “Linearization Techniques for CMOS Low Noise Amplifiers: A Tutorial,” *IEEE Trans. on Circuits and Systems—I: Regular Papers,* vol. 58, no. 1, pp. 22-36, Jan. 2011.

[2] M. A. Martins, P.-I. Mak, and R. P. Martins, "A Single-to-Differential LNA Topology with Robust Output Gain-Phase Balancing against Balun Imbalance," *IEEE Int. symposium on circuits and systems (ISCAS),* pp. 289-292, May 2011.

[3] M. Barati and M. Yavari, “A highly linear mixer with inherent balun using a new technique to remove common mode currents,” *IEEE Int. symposium on circuits and systems (ISCAS),* pp. 1884-1887, May 2011.

[4] D. Manstretta, M. Brandolini, and F. Svelto, “Second-order intermodulation mechanism in CMOS downconverters,” *IEEE J. Solid- State Circuits*, vol. 38, no. 3, pp. 394-406, Mar. 2003.

[5] W. H. Chen, G. Liu, B. Zdravko, and A. M. Niknejad, "A Highly Linear Broadband CMOS LNA Employing Noise and Distortion Cancellation," *IEEE J. Solid- State Circuits*, vol. 43, no. 5, pp. 1164-1176, May. 2008.

[6] M. Barati and M. Yavari, “A linearization technique for active mixers in zero-IF receivers with inherent balun,” *IEICE Electronics Express*, vol. 8, no. 24, pp. 2080-2086, Dec. 2011.

[7] H. Zhang, Z. Fan, and E. Sanchez-Sinencio, "A low power, Linearized, Ultra-Wideband LNA Design Technique," *IEEE J. Solid- State Circuits*, vol. 44, no. 2, pp. 230-330, Feb. 2009.