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Low-voltage low-power CMOS RF low noise amplifier

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Abstract

In this paper, a 1 V, 2 GHz CMOS low-noise amplifier (LNA) was developed intended for use in the front-end receiver. The circuit is simulated in standard 0.25 μm CMOS MOSIS. The LNA gain is 25.675 dB, noise figure (NF) is 4 dB, reverse isolation (S_{12}) is −134.3 dB, input return loss (S_{11}) is −14.6 dB, output return loss (S_{22}) is −13.34 dB, and the power consumption is 5.13 mA from a single 1 V power supply. One of the features of the proposed design is using a three-component cascode limitation, one of it is a transistor, to reduce the supply voltage.

Keywords: Low-noise amplifier; RF front-end; Global system for mobile communication (GSM); Global positioning system (GPS); Wireless local area network (WLAN)

1. Introduction

As wireless product such as cellular phones, global system for mobile communication (GSM), global positioning satellite (GPS), wireless local area network (WLAN), etc. became an everyday part of people's lives, the need for higher performance at low costs and low-power consumption became even more important in addition to the size of the wireless device. One of the important blocks in the receiver is the low-noise amplifier (LNA). Today the present goal is to reduce the power consumption, which leads to an increase of the battery-use time and of cost as well [1]; one of the ways of achieving this is to reduce the supply voltage [2].

In this paper, a modified cascode LNA is presented. Noise figure (NF) is an important parameter for RF LNA design; NF is a measure of how much the signal-to-noise ratio (SNR) degrades as the signal passes through a system [3]. The NF simulation is presented in Section 2.4. Recent research in the design of LNAs has focused on the NF analysis and noise optimization in addition to impedance matching as presented in detail in [3,5–17,19–21].

2. LNA design

LNA is the first block in wireless receivers. It is responsible for providing reasonable power gain and linearity, while not degrading the SNR. In the design of LNAs, there are several common goals; these include minimizing the NF of the amplifier, providing gain with sufficient linearity, and providing a stable 50 Ω input impedance to terminate an unknown length of transmission line, which delivers signal from the antenna to the amplifier [4].

Fig. 1 is the most popular narrow-band LNA. It is narrow-band because impedance matching is only established within a very narrow frequency range due to the resonant nature of the reactive matching network. Impedance matching is established by inductive degeneration. Around the operation frequency $\omega_o = 1/\sqrt{C_{gs}(L_g + L_s)}$, the input impedance only presents a real part $Z_{in} = g_m/C_{gs}L_s$; detailed analysis

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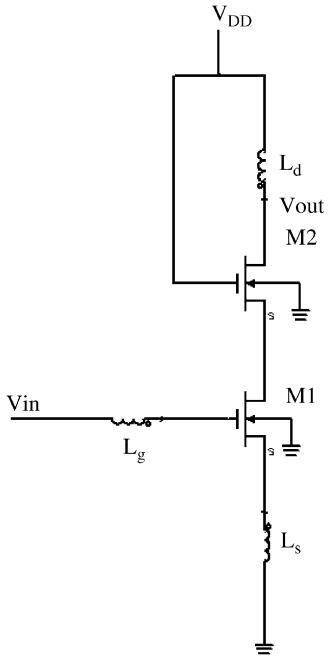

Fig. 1. Shaeffer and Lee low noise amplifier [5].

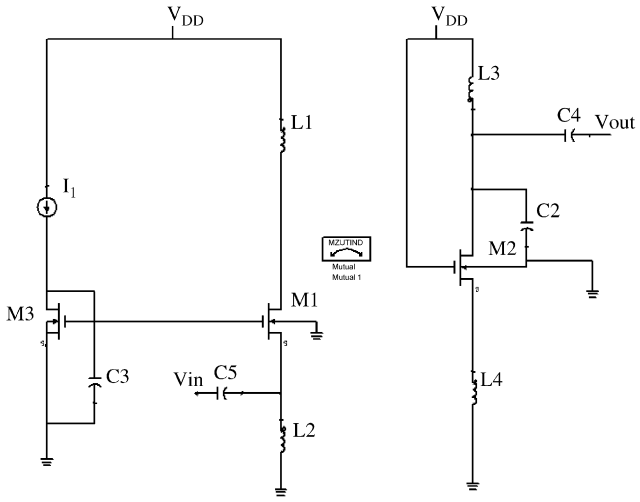

Fig. 2. Modified cascade low-noise amplifier.

is found in [5].The high-output impedance is an important property of the cascode structure [19]. To reduce the cascode number of elements, the mutual inductance properties between two inductors were used as shown in Fig. 2, L_1 is connected to the drain of M_1 and L_4 to the source of M_2 in Fig. 1 and the signal is transferred from the drain of M_1 to the source of M_2 through the mutual inductance between L_1 and L_4. As shown in Fig. 2, the LNA differs by one additional capacitor C_2 compared to the typical cascode LNA. The insertion of this capacitance adds a degree of freedom to play with the noise performance in addition to the gain at low-power consumption.

Also the input is applied on the M_1 source instead of the M_1 gate, which makes the body effect increase the equivalent transconductance of the stage [19], as shown in the next subsection.

2.1. Amplifier's gain analysis

The voltage transfer function of the proposed circuit can be written as follows:

$$A_v = (1 + r_{o1}(g_{m1} + g_{mb1}))(1 + r_{o2}(g_{m2} + g_{mb2})) * \frac{S^3 M_1 L_1 L_2}{\sum_{n=0}^{n=8} \delta_n s^n} \quad (1)$$

where

$$\delta_n = L_2\beta_{n-1} - R_1\alpha_n - r_{o2}\beta_n - R_1 L_2 C_2 \alpha_{n-2} - r_{o2} L_2 C_2 \beta_{n-2} \quad (2)$$

for $n = 0$–8,

$$\alpha_6 = \alpha_7 = \alpha_8 = 0,$$

$$\beta_7 = \beta_8 = 0,$$

$$\alpha_t = 0 \text{ and } \beta_t = 0 \quad \text{for } t < 0$$

g_{m1} and g_{m2} are the transconductance of M_1 and M_2, respectively, and g_{mb1}, g_{mb2} are the body-effect transconductance of M_1 and M_2, respectively. C_{gs1} and C_{gs2}, are the gate-source capacitance of M_1 and M_2, respectively. C_{db1} and C_{db2} are the drain-body depletion capacitance of M_1 and M_2, respectively. C_{gd1} and C_{gd2} are the gate-drain capacitance of M_1 and M_2, respectively. C_{sb1} and C_{sb2} are the source-body depletion capacitance of M_1 and M_2 [18]. R_1, R_2, R_3, and R_4 are the loss resistance in series with the inductance L_1, L_2, L_3, and L_4, respectively. β_t and α_t are the functions of M_1 and M_2 device parameters as shown in Appendix A. As seen from Eq. (1), the mutual inductance M_1 between L_1 and L_4 helps in giving extra freedom for controlling the conversion gain taking into account the layout fabrication limitation. Also the body effect affects positively the LNA conversion gain.

Eq. (2) shows that the insertion of the capacitor C_2 gives another degree of freedom to control the LNA conversion gain.

2.2. *S*-parameters simulation result

The circuit of Fig. 2 is simulated with ADS simulation tools. Fig. 3 shows the input return loss simulation result (−14.6 dB at resonance frequency 2 GHz).

The reverse isolation result of the LNA is −134.3 dB at 2 GHz. The LNA gain and the output return loss are presented in Fig. 3. The gain of the LNA at the operating frequency is 25.675 dB and the S_{22} is −13.34 dB.

2.3. Amplifier stability

Another important consideration in the LNA design is the amplifier stability. The conditions for unconditionally stable in terms of *S*-parameters [21] are:

$$|\Delta| = |S_{11}S_{22} - S_{12}S_{21}| > 1 \tag{3}$$

and

$$K = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |S_{11}S_{22} - S_{12}S_{21}|^2}{2|S_{12}S_{21}|} < 1 \tag{4}$$

From the above equation, the presented LNA is stable at the frequency of interest 2 GHz as presented in Fig. 4. The presented LNA is stable over a wide frequency range (unconditionally stable). A wide frequency range (0.5–4 GHz) was considered an order to make sure that none of the out-of-the-band frequencies can cause the LNA to oscillate.

2.4. Noise performance simulation result

The NF of the presented LNA is 4 dB at frequency 2 GHz as presented in Fig. 5. NF is affected negatively by the degeneration inductor loss resistance in the transistor M_1 source.

2.5. Power consumption

Today the present goal is to reduce the power consumption, which leads to the increase in the battery-use time and

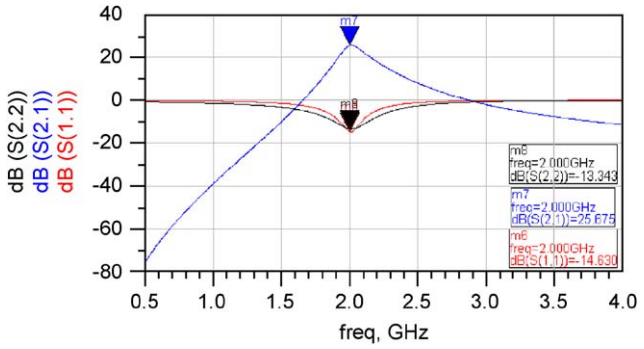

Fig. 3. Input return loss, gain, and output return loss of the LNA.

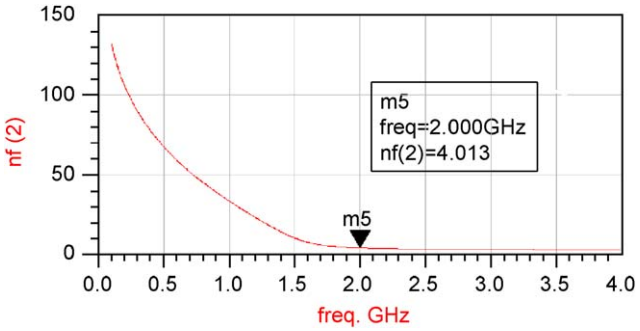

Fig. 5. Noise figure.

of the cost as well. The power consumption reduction is one of the requirements today; one of the ways achieving this is to reduce the supply voltage. In the presented design, the three element limitation including one transistor per stage is used to reduce the supply voltage to 1 V or less, which leads to reducing the power consumption and using a battery for a long time. The power consumption of the presented LNA is 5.13 mA from a 1 V single supply.

3. Conclusion

A low-voltage CMOS LNA based on a modification done to the traditional cascode LNA was presented. Using cascode elements of the reduction technique based on the two transistors limitation to reduce the supply voltage that leads to reduce the power consumption, which is essential today to increase the battery life time on most applications. The input signal is inserted in the M_1 source to take the advantage of the body effect to help increase the conversion gain. The insertion of the capacitor C_2 gives another degree of freedom to control the LNA gain. The LNA is simulated in standard 0.25 μm. The LNA presented here is useful in RF signal-processing applications, in the front-end transceiver, WLAN, and ISM.

The circuit presented here is compared with other circuits in terms of performance and the results are summarized in Table 1.

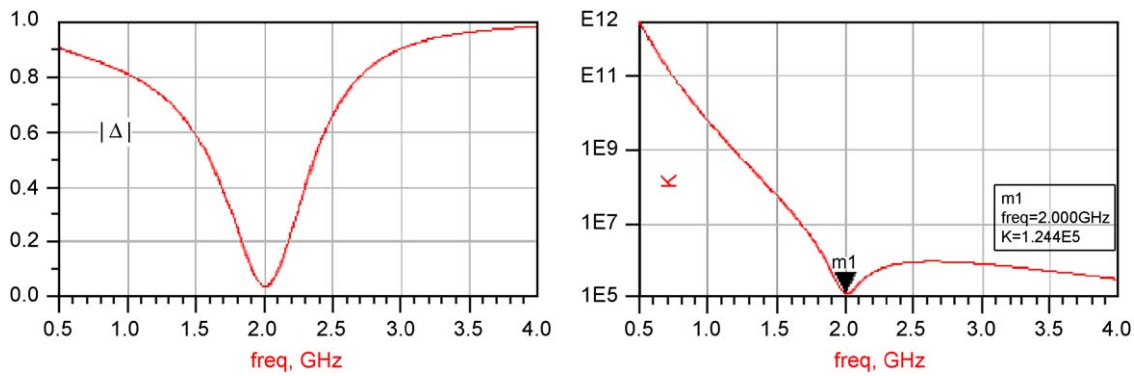

Fig. 4. Stability condition (5) and stability factor *K*.

Table 1. Comparison of LNA performances

Ref.	S_{11} (dB)	Gain (dB)	NF (dB)	Freq. (MHz)	Supply voltage (V)	Tech. (CMOS) (μm)
[5]	–	22	3.5	1000	1.5	0.6
[4]	–	19.7	2.37	1900	2.25	0.2
[12]	−14	12.74	2.5	2100	3.5	0.5
[22]	–	14.9	3	2200	1.2	0.25
[23]	−19.7	18	1.6	2000	1.6	0.13
[24]	−11.5	11	2.95	900	2.5	0.35
[25]	−8	14.5	2.6	2000	1.5	0.13
This design	−14.6	25.67	4	2000	1	0.25

Appendix A

$$A_v = (1 + r_{o1}(g_{m1} + g_{mb1}))(1 + r_{o2}(g_{m2} + g_{mb2})) * \frac{S^3 M_1 L_1 L_2}{\sum_{n=0}^{n=8} \delta_n s^n}$$

where

$$\delta_n = L_2\beta_{n-1} - R_1\alpha_n - r_{o2}\beta_n - R_1 L_2 C_2 \alpha_{n-2} - r_{o2} L_2 C_2 \beta_{n-2}$$

for $n = 0$–8

$$\alpha_t = 0 \text{ and } \beta_t = 0 \quad \text{for } t < 0$$

$$\alpha_t = F_1(r_{o1}, r_{o2}, R_3, R_4, R_s, L_1, L_2, L_3, L_4, M_1, C_1, C_{gs1}, C_{db1}, C_{gd1}, g_{m1}, g_{mb1}, g_{m2}, g_{mb2})$$

where

$$\alpha_0 = R_4(R_3 + r_{o1})$$

$$\alpha_1 = R_3 L_1 A_1 + \frac{L_1}{R_s}(r_{o_1} R_4 + R_3 R_4) + r_{o1}(L_4 + R_3 R_4(C_{db1} + C_{gd1})) + R_3 L_4 + R_4 L_3$$

$$\alpha_2 = L_1 A_1 (L_4 + R_3 R_4 (C_{db1} + C_{gd1})) + (r_{o_1} R_4 + R_3 R_4) L_1 C_1 + r_{o1}(R_3 L_4 + R_4 L_3)(C_{db1} + C_{gd1}) + (L_3 L_4 - M_1^2) + \frac{L_1}{R_s}(r_{o_1}(L_4 + R_3 R_4 (C_{db1} + C_{gd1}) + R_3 L_4 + R_4 L_3)$$

$$\alpha_3 = L_1 A_1 (C_{db1} + C_{gd1})(R_3 R_4 + R_4(L_3 - M_1)) + r_{o_1}(C_{db1} + C_{gd1})(L_3 L_4 - M_1^2) + \frac{L_1}{R_s}(r_{o1}(R_3 L_4 + R_4 L_3)(C_{db1} + C_{gd1}) + (L_3 L_4 - M_1^2)) + L_1 C_1 (r_{o1}(L_4 + R_3 R_4 (C_{db1} + C_{gd1})) + R_3 L_4 + R_4 L_3)$$

$$\alpha_4 = \left(L_1 A_1 + \frac{L_1}{R_s} r_{o_1}\right)(C_{db1} + C_{gd1})(L_3 L_4 - M_1^2) + L_1 C_1 (r_{o1}(R_3 L_4 + R_4 L_3)(C_{db1} + C_{gd1}) + (L_3 L_4 - M_1^2))$$

$$\alpha_5 = r_{o1} L_1 C_1 (C_{db1} + C_{gd1})(L_3 L_4 - M_1^2)$$

$$\alpha_6 = \alpha_7 = \alpha_8 = 0$$

and

$$\beta_t = F_2(r_{o1}, r_{o2}, R_3, R_4, R_s, L_1, L_2, L_3, L_4, M_1, C_1, C_{gs1}, C_{gs2}, C_{sb2}, C_{db1}, C_{gd1}, g_{m1}, g_{mb1}, g_{m2}, g_{mb2})$$

where

$$\beta_0 = R_1(R_3 + r_{o1})$$

$$\beta_1 = L_1 R_3 + r_{o_1} R_1 R_3 (C_{db1} + C_{gd1}) + R_1(L_3 + R_3 R_4 (C_{gs2} + C_{sb2})) + A_1 L_1 + r_{o1} L_1 + r_{o1} R_1 R_4 (C_{gs2} + C_{sb2})$$

$$\beta_2 = R_3(L_1 C_1 R_1 + L_1(A_1 + r_{o1})(C_{db1} + C_{gd1}) + (L_3 + R_3 R_4 (C_{gs2} + C_{sb2}))(L_1 + r_{o1} R_1 (C_{db1} + C_{gd1})) + R_1(C_{gs2} + C_{sb2})(R_3 L_4 + R_4 L_3) + r_{o1} R_1 L_1 C_1 + R_4(C_{gs2} + C_{sb2})(A_1 + r_{o1}) L_1 + r_{o1} R_1 R_4 (C_{gs2} + C_{sb2})$$

$$\beta_4 = (L_3 + R_3 R_4 (C_{gs2} + C_{sb2}))(r_{o1} R_1 L_1 C_1 (C_{db1} + C_{gd1})) + (C_{gs2} + C_{sb2})(R_3 L_4 + R_4 L_3)(R_1 L_1 C_1 + (A_1 + r_{o1})(C_{db1} + C_{gd1}) L_1) + (L_3 L_4 - M_1^2)(L_1 + r_{o1} R_1 (C_{db1} + C_{gd1})) + r_{o1} R_1 L_1 L_4 C_1 (C_{gs2} + C_{sb2})$$

$$\beta_3 = R_3(r_{o1} R_1 L_1 C_1 (C_{db1} + C_{gd1}) + (L_3 + R_3 R_4 (C_{gs2} + C_{sb2}))(R_1 L_1 C_1 + (A_1 + r_{o1})(C_{db1} + C_{gd1}) L_1) + (C_{gs2} + C_{sb2})(R_3 L_4 + R_4 L_3)(L_1 + r_{o1} R_1 (C_{db1} + C_{gd1})) + R_1(L_3 L_4 - M_1^2) + r_{o1} R_1 L_1 C_1 R_4 (C_{gs2} + C_{sb2}) + L_4(C_{gs2} + C_{sb2})(A_1 + r_{o1}) L_1$$

$$\beta_5 = (C_{gs2} + C_{sb2})(R_3 L_4 + R_4 L_3)(r_{o1} R_1 L_1 C_1 (C_{db1} + C_{gd1})) + (L_3 L_4 - M_1^2)(R_1 L_1 C_1 + (A_1 + r_{o1}) L_1 (C_{db1} + C_{gd1}))$$

$$\beta_6 = (L_3 L_4 - M_1^2)(r_{o1} R_1 L_1 C_1 (C_{db1} + C_{gd1}))$$

$$\beta_7 = \beta_8 = 0$$

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