An Ultra-Wideband Resistive-Feedback Low-Noise Amplifier with Noise Cancellation in $0.18\mu\text{m}$ Digital CMOS

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Abstract— We present a wideband resistive feedback CMOS low-noise amplifier (LNA) with noise cancellation technique for ultra-wideband applications. The LNA achieves a 3-dB bandwidth of 0.7 - 6.5GHz, power gain of 12.5dB, and noise figure of 3.5 - 4.2dB within the 3-dB bandwidth. The input matching is better than -11dB from 0.7 to 12GHz. The IIP3 is measured -5dBm at 5GHz. It is implemented in a $0.18\mu\text{m}$ standard digital CMOS technology, occupies an area of $0.78\text{mm} \times 0.68\text{mm}$, and consumes 11.1mW from a 1.8V supply.

I. INTRODUCTION

Ultra-wideband (UWB) communications has become the one of the main research focus for both academia and industry with the approval of UWB technology for commercial applications in the 3.1 - 10.6GHz band by FCC [1]. With such a large bandwidth, UWB technologies promise to offer low-power, high data rate wireless connectivity for future short-range communication systems. UWB receivers (particularly UWB impulse radios) have relatively simple structures compare to their narrow-band counterpart. However, the large bandwidth presents new challenges for the front-end circuits such as low-noise amplifiers (LNA), correlators, and filters. Wideband front-ends are also needed for emerging multi-band, multi-standard radio systems because of their lower cost, lower power, and better reconfigurability than conventional multi radio solutions [2].

There are many possible solutions for wideband LNAs [3], [4], [5], [6], as shown in Fig. 1. Distributed amplifiers [3] can provide very large bandwidth because of their unique gain-bandwidth trade-off. However, large power consumption and chip area make them unsuitable for typical low-power, low-cost UWB applications. Common-gate amplifiers [4], [7] exhibit excellent wideband input matching, but suffers from a relatively large noise figure (NF). Narrow-band LNAs like an inductively degenerated common-source amplifier can also be converted into a wideband one by adding a wideband input matching network [5]. However, the insertion loss of the passive input matching degrades the NF rapidly with frequency. Resistive-feedback amplifiers [6], [8], [9], [10] have very good wideband input matching characterisitc. However, low NF and low power consumption can be hardly achieved simultaneously across a large frequency range. In [11], noise cancellation technique is used to relax this trade-off in resistive-feedback amplifiers. In this paper, the bandwidth of a resistive-feedback amplifier with noise cancellation is further extended by using the inductive shunt peaking and series peaking techniques. Therefore, good input matching, low power consumption,

Fig. 1. Possible wideband LNA topologies: (a) Distributed amplifier; (b) Common-gate amplifier; (c) Passive input matching; and (d) Resistive feedback.

and low NF can be achieved simultaneously over a wide bandwidth.

II. CIRCUIT ANALYSIS AND DESIGN

The wideband resistive feedback noise canceling LNA is shown in Fig. 2. The first stage is based on resistive feedback LNA. The L_{load} and L_g are added for inductive shunt peaking and series peaking, respectively, which will be discussed later. The second stage (M_3 and M_4 , where M_3 acts as a source follower and M_4 acts as common-source amplifier) is added for wideband output matching and partially noise cancellation by connecting gate of M_4 with the gate of M_1 .

Assume the main noise contribution of the LNA is from M_1 , and its noise current is modeled by i_n^2 . The noise current flows into the drain of M_2 (node X) through M_2 and part of it flows into input node (node Y) through R_f and C_f . The noise voltage at node X and Y are fully correlated and have the same phases. These two noise voltages at node X and Y will appear

Fig. 2. Schematic of the wideband resistive-feedback noise-canceling LNA.

at output node through M_3 and M_4 , respectively. The noise voltage at the source of M_3 keeps the same phase as node X, while the noise voltage at the drain of M_4 has the opposite phase from node Y. Therefore, the two noise voltages at output node are still correlated but with opposite phases. The noise current of M_1 can be partially or completely cancelled at the output node. It can be proved [11] that the noise current of M_1 can be completely cancelled if

$$\frac{g_{m4}}{g_{m3}} = 1 + \frac{R_f}{R_s} \quad (1)$$

where g_{m4} and g_{m3} are the transconductance of M_4 and M_3 , respectively, and assumes source follower M_3 has a voltage gain of one.

While the noise can be partially or completely cancelled, the wanted signal can be added at the output node. The signal voltages at node Y and X have opposite phases. Therefore, after M_3 and M_4 , the signal voltages at output node have same phases and will not be cancelled. Assuming source follower M_3 has unit voltage gain, then the overall voltage gain of the LNA is

$$A_v = \frac{V_{out}}{V_{in}} = \frac{V_X A_{M3} + V_Y A_{M4}}{V_Y} \quad (2)$$

$$= \frac{1 - g_{M1} R_f}{1 + \frac{R_f}{R_{load}}} - \frac{g_{m4}}{g_{m3}} \quad (3)$$

In the case of complete noise cancellation, the overall voltage gain of the LNA is

$$A_{v,nc} = \frac{1 - g_{M1} R_f}{1 + \frac{R_f}{R_{load}}} - 1 - \frac{R_f}{R_s} \quad (4)$$

Assuming complete noise cancellation and neglecting noise contribution of the cascade device M_2 and series inductor L_g , the noise factor after first stage is mainly determined by R_s , R_f and R_{load} . Here the noise contribution by L_{load} can be

Fig. 3. Power gain versus frequency with different L_g .

Fig. 4. Chip photo of the prototype LNA.

included in that by R_{load} . The noise factors of first stage can be derived [4]

$$F_1 = 1 + \frac{R_f(1 + g_{M1} R_s)^2}{R_s(1 - g_{M1} R_f)^2} + \frac{(R_s + R_f)^2}{R_s R_{load}(1 - g_{M1} R_f)} \quad (5)$$

where the second and third term are the noise contribution by R_f and R_{load} , respectively. The noise factors at the output node can be derived as

$$F_t = 1 + \frac{R_s \left(\frac{R_s + R_f}{R_{load}} + 1 + g_{M1} R_s \right)^2}{R_f \left(\frac{R_s + R_f}{R_{load}} - 1 - g_{M1} R_s \right)^2} \quad (6)$$

where the second term is the noise contribution by R_f . The noise contribution by M_3 and M_4 are ignored here, since they are very small compared to that by R_f . As is shown in (6), in addition to the noise contribution from M_1 , the noise contribution from R_{load} can also be cancelled at the output node, which can further lower the total noise factor.

The inductor L_{load} of the LNA is used for shunt peaking purpose at high frequency. The inductive load can provide a resonant peaking at the output when the amplifier starts to roll off at high frequencies and equalize the power gain of the LNA to a constant value across the bandwidth by compensating the decreasing impedance of capacitance with the increase

Fig. 5. Measured power gain.

Fig. 6. Measured return loss and reverse isolation.

of frequency [12]. The series inductor L_g is used to further boost the gain at high frequencies and extend the bandwidth by resonating with the parasitic gate to source capacitance of M_1 and parasitic capacitance formed by bottom plate of C_f to substrate[13][14]. Fig. 3 shows the simulated power gain with different value of L_g . As is shown in the Fig. 3, a higher gain and larger bandwidth can be achieved with an optimized L_g . In addition to the gain boost and bandwidth extension, the resonance between L_g and the parasitic gate to source capacitance of M_1 and parasitic capacitance formed by bottom plate of C_f to substrate can benefit the input matching, high gain and low noise. As is shown in [4][5], resistive feedback LNA suffers from the tradeoff between input matching, gain and noise figure. The use of the L_g to resonate with the parasitic capacitance at input node relaxes of the tradeoff and can achieve the good input matching, high gain and low noise simultaneously.

III. MEASUREMENT RESULTS

The wideband resistive feedback LNA is designed and implemented in a standard $0.18\mu\text{m}$ digital CMOS process. The microphotograph of this LNA is shown in Fig. 4. The chip occupies an area of $0.78\text{mm} \times 0.68\text{mm}$. The LNA consumes 11.1mW at a voltage supply of 1.8V.

Fig. 7. Measured and simulated noise figure.

Fig. 5 shows the measured power gain of the LNA. The measured power gain achieves a maximum of 12.5dB and the 3-dB bandwidth is 0.7 - 6.5GHz. The LNA remains 1-dB flatness from 0.7 to 4.5GHz.

The measured input, output return loss and the measured reverse isolation are presented in Fig. 6. The input return loss is better than -11dB in the 3-dB bandwidth and remains the performance up to 12GHz. The output return loss is below -8dB up to 12GHz and remains a value of less than -10dB across the most of the band. As is shown in Fig. 6, the measured reverse isolation is below -30dB across the band of interest.

The measured and simulated noise figures are illustrated in Fig. 7. The measured noise figure is from 3.5 to 4.2dB across the 3-dB bandwidth, which is slightly higher than the simulated noise figure. This is mainly due to the lack of very accurate noise model of deep submicron CMOS. The measured and simulated noise figures show the good effect of the wideband noise cancellation on the LNA.

The measured IIP3 with two-tone test is shown in Fig. 8 and Fig. 9. The measurement is performed at 1GHz, 3GHz and 5GHz. As is shown in Fig. 8 and Fig. 9. The measured IIP3 is -5.8dBm, -5.9dBm and -5dBm at 1GHz, 3GHz and 5GHz, respectively.

Performance is summarized in Table I. Comparisons with the previously reported LNAs are also listed in Table I. Compared to the previously published LNAs, especially the wideband resistive feedback LNAs, this work achieves good input matching, low noise figure and low dc current consumption across a wide range of frequencies simultaneously.

A figure of merit (FOM) is used here to compare the performance of different LNAs with similar function. The FOM here evaluates the maximum power gain, 3-dB bandwidth, excess noise factor and the power consumption of the LNA and it is defined as

$$FOM = \frac{|S21|BW[GHz]}{|F - 1|Power[mW]} \quad (7)$$

Based on the calculated FOM in Table I, this work has a

Table I. Performance Summary

Ref.	CMOS Tech.	Bandwidth (GHz)	S21 _{max} (dB)	S11 _{max} (dB)	NF (dB)	IIP3 (dBm)	Supply (V)	Power (mW)	FOM
[6]	0.13- μ m	5.9	16	-9	4.7 – 5.7	-	2	38*	3.2
[8]	0.18- μ m	2 – 4.6	9.8	-9	2.3 – 5.2	-7@4GHz	1.8	12.6	2.8
[9]	0.13- μ m	1-7	17	-10	2.4@3GHz	-4.1	1.4	25*	16.3
[10]	90-nm	0.4 – 1	16	-10	3.5-5.3	-17@0.9GHz	1.2	16.8	1.1
[11]	0.25- μ m	0.002 – 1.6	13.7	-8	1.9 – 2.4	0@0.9GHz	2.5	35	1.9
[7]	0.13- μ m	0.8 – 2.1	14.5	-8.5	2.6	16@0.9,2GHz	1.5	11.6	3.9
This Work	0.18- μ m	0.7 – 6.5	12.5	-11	3.5 – 4.2	-5@5GHz	1.8	11.1	7.5

*Differential outputs.

Fig. 8. Measured IIP3 at 3GHz.

Fig. 9. Measured IIP3 at different frequencies.

good performance and is better than all the other works expect for [9].

IV. CONCLUSION

A wideband resistive feedback CMOS LNA with noise cancellation for multi-band, multi-standard receivers is implemented in 0.18 μ m standard digital CMOS process. By using the design technique for wideband LNA, the proposed LNA achieves a power gain of 12.5dB, a noise figure from 3.5 to 4.2dB across the 3-dB bandwidth from 0.7 to 6.5GHz. The input return loss is better than -11dB up to 12GHz. The

LNA occupies an area of 0.78mm $\times$ 0.68mm, and consumes 11.1mW from a voltage supply of 1.8V.

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