Design of Ultra-Wideband LNA with 3.6±0.4 dB NF and 15.9±1.1 dB Gain

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Abstract: This paper presents an ultra-wideband (UWB) low noise amplifier (LNA) with low and flat noise figure (NF) as well as high and flat gain using 0.18 \( \mu \)m CMOS technology. Frequency range for both NF and gain is expanded by using current-reuse and weak shunt resistor feedback. The LNA consumes 8.4 mW under 1.8 V. High performances are achieved with the gain of 15.9±1.1 dB, NF of 3.6±0.4 dB within 2.9-10.8 GHz band. The input 1 dB compression point \( (P_{1dB}) \) is -17.1 dBm at 7 GHz. The area of the LNA is 0.63 mm\(^2\), with pads included.

Keywords: Ultra-wideband (UWB), low noise amplifier (LNA), noise figure (NF), gain

Classification: Integrated circuits (memory, logic, analog, RF, sensor)

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1 Introduction

Comparing to widely used IEEE 802.11, Bluetooth and others, ultra-wideband (UWB) technology (3.1-10.6 GHz) has the advantages of high bandwidth, high-data rate, low power, and high security so that it has great potential for short-range wireless communications [1, 2]. As a core device, UWB low noise amplifier (LNA) design is the key point in radio frequency (RF) front-end. The design requirements for UWB LNA are good matching, flat power gain, low noise figure, and low power consumption within the very wide frequency range. Recently, current-reuse has been reported to be very useful design technique for low power LNAs and it was widely used to reduce the overall power consumption and improve the current efficiency. Using this methods, the dc current is shared among transistors, while each contributes to the overall gain of the LNA [3, 4, 5].

Moreover, Some CMOS-based UWB LNA, which utilize the current-reused technique, were reported [6, 7, 8, 9]. For the current-reused UWB LNA in [6], the minimum NF and flat power gain were achieved, while the gain is 7.92 dB which is not enough. For the UWB LNA in [7], it presented power gain of 23 dB. Though the NF of 3-7 dB was not satisfactory. For [8], though the NF of 3.9-5.8, the bandwidth did not reach 3.1-10.6 GHz. For the UWB LNA in [9], a dual-resonance network was proposed to achieve bandwidth more than 3.1-10.6 GHz. However, the S21 of 13.5±1.5 and NF of 4-4.6 is still not satisfactory.

In this work, an UWB LNA with current-reuse technique is proposed. With effective design, a LNA is designed and fabricated using commercial 0.18 μm CMOS technology. The measurements results demonstrate a good input impedance matching, high and flat power gain, high linearity, and low and flat NF within the whole UWB band, while only 8.64mW is consumed.

2 UWB LNA analysis and design

The proposed LNA with current-reused technique is shown in Fig. 1, which consists of an input stage, a current-reused stage and an output stage. To optimize the noise figure (NF) the common source (CS) topology is used in the input stage with a $g_{m}$-transistor $M_1$, an RC shunt-shunt feedback $R_F$. 
(420 Ω) and $C_F$ (724 fF), a source degenerated inductor $L_S$ (199 pH) and series inductor $L_{G1}$ (1.27 nH). The common gate (CG) topology is applied in the current-reused stage with a transistor $M_2$, a series inductor $L_{G2}$ (1.25 nH), a peaking inductor $L_M$ (6.44 nH), a capacitor $C_D$ (3.58 pF) and a parallel capacitor $C_M$ (9 pF). In addition, the load inductor $L_D$ (1.38 nH) is utilized in the output stage to achieve high gain.

2.1 Input matching and NF

The small-signal equivalent circuit of the input stage is shown in Fig. 2. The input impedance is approximately considered as:

$$Z_{IN} = \frac{V_X}{I_X} \approx Z_{IN1} || Z_F. \quad (1)$$

Where $Z_F = R_F + \frac{1}{C_F s}$ and $Z_{IN1} = V_X/I_{X1}$.

According to the theory in [10], $Z_{IN1}$ is derived by

$$Z_{IN1} = \frac{(R_D + \frac{1}{C_{GD1}s})(L_S C_{GS1}s^2 + g_m L_S + 1)}{L_S C_{GS1}s^2 + (R_D C_{GS1} + g_m L_S)s + g_m R_D + C_{CGS1}/C_{GD1} + 1} + L_{G1}s. \quad (2)$$

Where $g_m$, $C_{GS1}$, $C_{GD1}$ are the transconductance, the parasitic capacitance between gate and source and gate and drain of $M_1$, respectively. Source degenerated inductor $L_S$ and weak shunt resistor feedback ($R_F$ and $C_F$) are used to extend the bandwidth. In addition, the stability of amplifier can be improved by an RC negative feedback network as well. From Fig. 1, according to Miller effect approximation, the feedback resistance can be replaced by equivalent impedance in the input port, the total output noise is expressed as

$$\overline{V^2_{n, out}} = 4kT(R_S || R_F)(g_m R_D)^2 + 4kT\gamma R_D^2 + kT\gamma g^2_m \quad (3)$$

Fig. 1. Proposed UWB LNA.
So that the NF is described as

\[
NF = \frac{V_{n,\text{out}}^2}{A^2V R T R_S} + 1 = 1 + \frac{R_S}{R_F} + \frac{1}{g_m R - S} \gamma \left( 1 + \frac{R_S}{R_F^2} \right) + \frac{R_F}{R_F + R_S} g_m R S \gamma \left( \frac{\omega_0}{\omega_T} \right)^2
\]

(4)

Where \( R_S, \gamma \) and \( \omega_T \) are the source impedance, the body effect coefficient and the characteristic frequency, respectively.

**Fig. 2.** Small-signal equivalent circuit for input stage.

### 2.2 Analysis of Current-reused

The current-reused stage is composed of components \( M_2, L_{G2}, L_M, C_D \) and \( C_M \). The parasitic capacitors in node A and B limit \( f_T \) of the transistor. The peaking inductor \( L_M \) is used to compensate the parasitic capacitances. \( L_M \) is equal to \((C_A + C_B)/4g_m \), where \( g_m, C_A \) and \( C_B \) are the transconductance of transistor, and the capacitor of parasitic at node A and B. Thereby the frequency characteristics in A and B could be improved and the gain of the LNA is boosted around 2 dB in simulation. In addition, \( L_M \) is large enough to provide the high impedance path to block the signal. The signal goes into the gate of \( M_2 \) through the \( L_{G2} \) and \( C_D \), which perform a series resonant with \( C_{GS} \) of \( M_2 \). As a result, the signal can be amplified twice under con-current structure.

Since \( C_M \) is large enough, the current-reused stage can be regard as a CS stage. The transfer functions for two CS stages of the proposed LNA, \( H_1(s) \) and \( H_2(s) \), can be derived as following:

\[
H_1(s) = -\frac{sL_M g_m}{s^2C_{GS1}(L_S + L_{G1}) + s g_m L_S + 1}
\]

(5)

\[
H_2(s) = -\frac{g_m R_D}{s^2(C_D + C_{GS2})L_{G2} + 1}
\]

(6)

\[
H(s) = \frac{sL_M g_1 g_m R_D}{s^4K_1K_2 + s^3K_3K_2 + s^2(K_1 + K_2) + sK_3 + 1}
\]

(7)
Where \( K_1 = \sqrt{C_{GS1}(L_S + L_G1)} \), \( K_2 = \sqrt{(C_{GS1} + CGS2 + C_D)L_G2} \) and \( K3 = g_mL_S \). Equation (7) helps concluding that current-reuse LNA gain can be enhanced by employing series peaking inductor.

### 2.3 Design of UWB LNA

Enhancing noise performance of UWB LNA is achieved through RC feedback injection of thermal noise and optimized input stage transconductance. In this UWB LNA design, the transistor (\( M_1 \)) bias is set to an optimal \( NF_{\text{min}} \) and a reasonable gain current density. Formula (4) demonstrates that NF can be decreased by increasing \( g_m \), and noise matching is wideband independent of frequency. Considering NF and gain simultaneously with suitable dc power consumption, \( 8 \, \mu m \times 21 \) fingers of the device size are designed for the input stage of the LNA. The details of the transistor sizes and bias conditions of each stage are shown in Fig. 1.

In terms of power consumption, the width of gate and current density are optimized for noise matching and impedance matching. The dimensions and bias voltage for active devices are listed in Fig. 1. For size of transistor \( M_2 \), it required to optimize the \( f_T \) of \( M_2 \), the capacity reactance of source of \( M_2 \) match the capacity resistance of drain of the gm device (\( M_1 \)), the \( f_T \) of \( M_2 \) transistor is maximum. Power matching and noise matching can be optimized simultaneously by adjusting the \( L_S \) value. It is important to note that the source impedance of the amplifier is sensitive to performance of the LNA, so that layout of \( L_S \) is optimized.

The value of \( L_M \) can also be seen as an inter-stage matching, its characteristic impedance is equal to input impedance of \( M_2 \) (\( 1/g_m \)). \( L_G2 \) and \( C_D \) form a low impedance path, which generates the pole for further expansion of the bandwidth, while the impedance of \( L_M \) is large enough to provide high impedance path. The LNA in Fig.1 shows that node B is a high impedance, \( L_M \) and \( C_M \) make up the resonant network and ensures \( C_M \) to connect to the stable ground. It is worth explaining that peaking inductor in current-used stage by using \( L_G2 \) could improve the gain bandwidth characteristics of current-used stage.

### 3 Measurement results

The UWB LNA is fabricated using TSMC 0.18 \( \mu m \) standard CMOS process. Fig. 6 shows the chip micrograph of LNA. The chip occupies a silicon area of 0.88 mm\( \times \)0.72 mm with the pads included. At the gate voltage of 0.65 mV, the LNA draws 4.8 mA from a 1.8 V supply. As expected, the good agreements between measured and simulated results for the UWB LNA are shown in Fig.7. The measurement results demonstrates a good performance that within UWB band the return loss S11 is below-12 dB. An excellent input match of proposed LNA was achieved through the series input resonance network with degeneration inductor.

Power gain maximization and flattening is achieved through peaking inductor
technique and weak shunt resistor feedback as explained in Section 2.2. The high and flat power gain $S_{21}$ is 15.9±1.1 dB, $S_{12}$ is better than -30 dB. Through RC feedback injection of thermal noise and optimized input stage transconductance, an excellent NF of 3.6±0.4 dB is reached in the frequency range of 2-10.8 GHz as shown in Fig. 8. In addition, the input 1-dB compress point $P_{1dB}$ of about -17.1 dBm are achieved within 2-10.8 GHz. It is examined at 7 GHz as shown in Fig. 9. The performances of proposed LNA are compared with those in recent publications in Table I. As we can see, the proposed LNA exhibits the lowest and flattest NF, the highest and flattest power gain, low power consumption.

4 Conclusion
A UWB LNA with current-reused technique has been presented. We propose an efficient design which improves the design accuracy and efficiency and helps the implementation of the high-performance RF system. With inductive
peaking, weak shunt resistor feedback and source degeneration techniques, we designed and implemented a high performance UWB LNA with input wideband matching and current-reused techniques. The measurement results show that it achieves NF ranged from 3.2 to 4 dB, and the peak gain of 17
dB within 3-dB bandwidth of about 8 GHz under a power dissipation of 8.64 mW, which is one of the best results reported among the published UWB LNAs.

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