

An Ultra-Wideband Low-Noise Amplifier for 3–5-GHz Wireless Systems

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Abstract— In this paper, an ultra-wideband low-noise amplifier is designed and simulated in a 0.13- μm CMOS technology for a 3–5-GHz UWB system. For ultra-wideband operation, shunt-series feedback topology is used. To improve noise performance, the amplifier employs inductive load. Biasing point variation which occurs due to the resistive feedback is fixed by adding a capacitor in series with feedback. Thus, the desirable gain is achieved with a lower power consumption. Simulations show a -3-dB gain bandwidth of 6 GHz between 2 GHz and 8 GHz, a minimum noise figure of 1.9 dB in the 3–5-GHz band, a power gain of 11.5 dB while consuming 13.9 mW.

I. INTRODUCTION

Ultra-wideband (UWB) technology uses narrow pulses to transmit information over a wide frequency band. As approved by the Federal Communication Commission (FCC) in 2002 [1], a UWB system must occupy at least 500 MHz of bandwidth between 3.1 GHz and 10.6 GHz and transmit maximum equivalent isotropic radiated power (EIRP) spectral density of -41.3 dBm/MHz . Owing to the low power of UWB signals it can coexist with other systems that use the same frequency band. This technology has many applications such as wireless personal area networks (WPANs) which is currently developing by the IEEE standard group, sensor networks, and localizers [2].

Unique advantages of UWB systems such as high data rate, low-power consumption, immunity to multipath environments, and coexistence with narrow band systems are due to the very narrow pulses and low power of the transmitted signals. However, these characteristics, in turn, introduce new challenges in the design of UWB receivers. Since a UWB system employs very narrow pulse, its equivalent spectrum will spread over a wide frequency band with extremely low power. One of the most critical component in the analog front-end, the LNA, requires to amplify the received signal with sufficient gain and as little additional noise as possible. Design of a broadband LNA with matched input impedance, flat gain, and good noise performance over the entire frequency spectrum is a very difficult task.

In this paper, a low-noise amplifier for use in ultra-wideband systems is designed and analyzed. The LNA employs shunt-series feedback topology to enjoy its broad band behavior and good input and output characteristics [3]. To further increase the gain and bandwidth, cascode common source architecture

is employed. A capacitor is used in series with feedback to avoid the effect of the output voltage on the optimum biasing point. Therefore, the desirable gain is achieved with a low power consumption. To improve the output noise performance, an inductive load which also overcomes the gain degradation at higher frequencies is employed. Another inductor is added in series with feedback to give additional gain at higher frequencies.

Simulation of the LNA in a 0.13- μm CMOS technology illustrates a power gain of 11.5 dB in the -3-dB gain bandwidth of 2–8 GHz, a minimum noise figure of 1.9 dB in the 3–5-GHz band, and a power consumption less than 14 mW.

The remainder of the paper is organized as follows. Section II discusses the LNA design. Section III describes more accurate considerations in the design of ultra-wideband LNAs. Section IV presents the results of the simulations, and Section V concludes the paper.

II. LNA DESIGN

The inductive degeneration topology is often used for the design of narrow band LNAs [3], [4]. The most important advantage of this topology is low noise figure due to the existence of inductor in the drain and source of the transistor. However, the inductor in the source of the transistor causes the LNA to show narrow band characteristics. Hence, this topology cannot satisfy the wideband requirements needed for ultra-wideband LNAs.

Shunt-series feedback topology can match the input impedance in a broad bandwidth. Also, it presents a good noise performance. However, due to the presence of the resistive feedback, the biasing point of the LNA is fixed with the output voltage. Therefore, the biasing cannot be set to the optimal point. Consequently, to achieve the desired gain, the system consumes more power than the case of having optimal biasing point. Moreover, the architecture has the stability problem due to feedback. Motivated by some good characteristics of this topology such as low-noise performance and wideband behavior, we have chosen this architecture and in the subsequent sections, after analyzing a simplified circuit, we propose a new architecture based on the shunt-series feedback topology which overcomes the above problems.

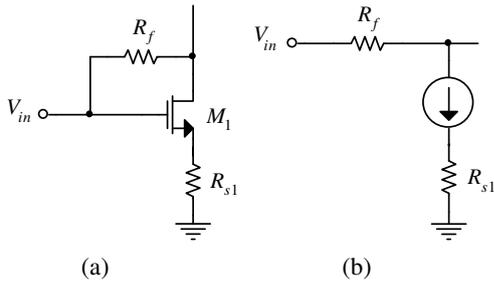


Fig. 1. Shunt-series feedback amplifier. (a) LNA circuit, (b) small signal equivalent circuit.

A. Shunt-Series Feedback LNA Analysis

A simplified architecture of a shunt-series feedback LNA is shown in Fig 1(a). H-parameters can be calculated from the small-signal model shown in Fig. 1(b) as

$$[H] = \begin{bmatrix} R_f & 1 \\ \frac{g_m R_f}{1 + g_m R_{s1}} & \frac{g_m}{1 + g_m R_{s1}} \end{bmatrix} \quad (1)$$

Using the standard equations, H-parameters can be converted to S-parameters as follows

$$[S] = \frac{1}{\Delta} \begin{bmatrix} \frac{R_f}{Z_0} - \frac{g_m Z_0}{1 + g_m R_{s1}} & 2 \\ 2 \left(1 - \frac{g_m R_f}{1 + g_m R_{s1}} \right) & \frac{R_f}{Z_0} - \frac{g_m Z_0}{1 + g_m R_{s1}} \end{bmatrix} \quad (2)$$

Where $\Delta = S_{11}S_{22} - S_{12}S_{21}$ and Z_0 is the characteristic impedance of the system. In ideal matching condition, i.e., $S_{11} = S_{22} = 0$, R_{s1} can be calculated as

$$R_{s1} = \frac{Z_0^2}{R_f} - \frac{1}{g_m} \quad (3)$$

Substituting (3) onto (2) gives S-parameters with the assumption of ideal matching:

$$[S] = \begin{bmatrix} 0 & \frac{Z_0}{R_f + Z_0} \\ 1 - \frac{R_f}{Z_0} & 0 \end{bmatrix} \quad (4)$$

As shown in (4), by choosing appropriate value for R_{s1} and R_f , flat gain, S_{21} can be achieved. Since the value of R_{s1} cannot be negative, (3) limits g_m by the following equation

$$g_m \geq \frac{R_f}{Z_0^2} = \frac{1 - S_{21}}{Z_0} \quad (5)$$

Thus, the desirable gain determines the minimum value of g_m . If (5) does not satisfy, the system will oscillate. Due to parasitic capacitance and inductance that cannot be neglected at higher frequencies, the gain is degraded. Also, because the biasing point is not adjusted to the optimum voltage, the LNA requires higher power consumption to achieve the desired gain. Therefore, this simple architecture of shunt-series feedback topology needs some modifications to overcome the mentioned problems.

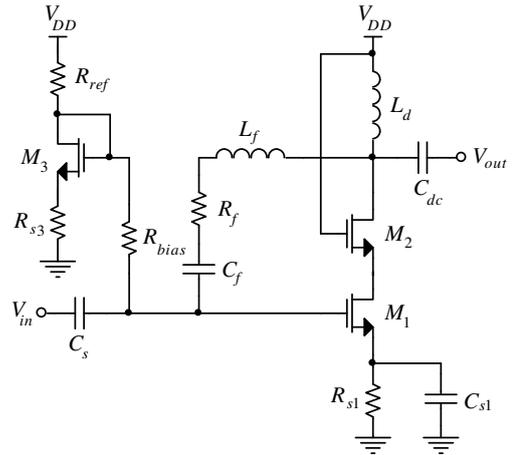


Fig. 2. Modified shunt-series feedback ultra-wideband low-noise amplifier with cascode topology.

B. The Proposed LNA Architecture

Fig. 2 shows the modified architecture of the shunt-series feedback LNA. Cascode topology is used instead of simple common source to increase the gain and the bandwidth, and to improve the stability of the system [3], [4]. Also, the frequency compensated matching network technique, described in Section III-B, is applied to improve the gain flatness of the system in the desired frequency band [5].

In Fig. 2, the inductor, L_d , replaces the resistive load. This inductor decreases the output noise and also compensates for the gain degradation of the LNA at higher frequencies. This compensation occurs, because the magnitude of the inductor's impedance increases as frequency increases. Regarding to the manufacturing limitations, L_d cannot be large enough to achieve the wideband response. Therefore, to achieve a higher gain and bandwidth, an inductor, L_f , is added. Although, by increasing R_f the LNA gain increases, (5) limits the value of R_f , whereas increasing the inductor, L_f , has not any effect on (5).

As mentioned before, feedback causes the biasing point to vary by the output voltage. Due to this nonoptimal biasing point, the LNA has to consume a higher power to achieve the desirable gain. Because of this, the capacitor, C_f , is added to separate the output and the input voltage levels. Therefore, the optimal biasing point can be achieved. To bias the circuit, transistor, M_3 , is employed. This transistor and transistor M_1 form a current mirror source and its channel width is some fractions of M_1 's channel width to minimize the power overhead of the bias circuit [3].

III. MORE ACCURATE CONSIDERATIONS IN THE UWB LNA DESIGN

The analysis presented in the previous section is based on low-frequency models. However, at higher frequencies, the effects of parasitic capacitors and inductors should be taken into consideration. For a more accurate design, some important

issues such as stability, constant gain, and noise figure should be exactly investigated.

A. LNA Stability

Stability factor of a system can be defined with S-parameters as [4]

$$k = \frac{1 + |\Delta|^2 - |S_{11}|^2 - |S_{22}|^2}{2|S_{12}||S_{21}|} \quad (6)$$

To have an unconditional stable system, the following equations must be simultaneously satisfied

$$k > 1, \quad \Delta < 1 \quad (7)$$

To put the system in the unconditionally stable region, one can add a series resistor or a shunt conductance to the input or output port [6]. Adding a series resistor will increase the output noise, due to the thermal noise of the resistor in the signal path. Therefore, it is better to add a shunt conductance to the port. This conductance should be small enough to produce a little equal current noise while stabilizes the LNA.

B. Constant Gain

Transduced gain is usually used in RF design as defined below [3]

$$G_T = \frac{\text{Power delivered to the load}}{\text{Available power from the source}} \quad (8)$$

The above definition can be described with S-parameters and the reflection coefficients of the source and the load of the LNA as

$$G_T = \frac{|S_{21}|^2 (1 - |\Gamma_S|^2) (1 - |\Gamma_L|^2)}{|(1 - S_{11}\Gamma_S)(1 - S_{22}\Gamma_L) - S_{12}S_{21}\Gamma_L\Gamma_S|^2} \quad (9)$$

where Γ_S and Γ_L are the source and the load reflection coefficients, respectively. In UWB LNA design, having a flat gain is more important than maximum gain achievement which is exactly unlike the narrow band design that is required to achieve maximum gain. To maximize the gain, Γ_S and Γ_L should be zero. However, in UWB systems, reflection coefficients are designed to fix G_T in a broad frequency band. In other word, at some frequencies G_T is reduced to keep the gain flatness. This method is called frequency-compensated matching or selective mismatching [5].

Frequency-compensated matching method is a simple way to decrease the gain by not perfectly matching the transistor to its load. In other word, there is no perfectly impedance matching in the bandwidth of the system. To use this method, constant gain circles should be plotted on a Smith chart. For a UWB LNA, the constant gain circles must be plotted on a single chart at some frequencies over the bandwidth of the system. By changing the feedback elements, such as R_f , L_f , and C_f , constant gain circles can be moved to overlap at somewhere near the centre of the Smith chart. In this case, the gain of the UWB LNA is flat over the operational frequency range. Fig. 3 shows constant gain circles of the proposed LNA over the 3–5-GHz band. The circles are plotted at the frequencies of 3, 4, and 5 GHz. As can be seen, the circles overlaps near the centre of the chart and the resulting gain in Fig. 4 shows only 0.5 dB variation in the 3–5-GHz band.

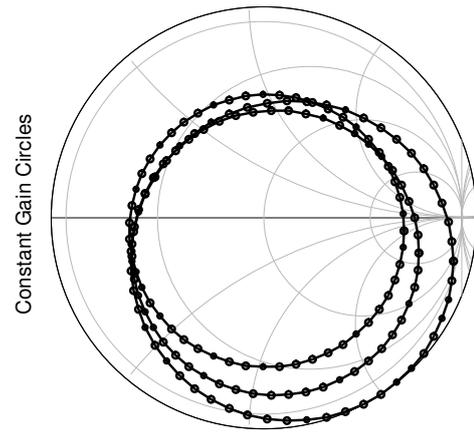


Fig. 3. Constant gain circles at 11.5 dB over the 3–5-GHz band.

C. Noise Considerations

One of the most important noise sources is the input resistor of the power supply. Since, in a UWB system there is no perfectly impedance matching, reflected signals generate noise. The other important noise sources are thermal noises which are generated by the feedback resistor and transistor. The two major noise types in transistor are Flicker noise and thermal noise. Since, a UWB system has a wide frequency range, Flicker noise is neglected. There are two thermal noise sources in the transistor. First, the drain noise generated in the channel and second, the thermal noise generated by the gate resistor which can be decreased with proper layout technique.

As a result, the most important noise sources in the LNA can be summarized as: power supply noise, thermal noise of the feedback resistor and transistor noise which is generated in the channel. A higher feedback resistors decreases its thermal noise. Also, increasing the channel width decreases the channel noise.

IV. SIMULATION RESULTS

The proposed UWB LNA is simulated using Agilent ADS in a 0.13- μm CMOS technology. The supply voltage is $V_{DD} = 1.6$ V. The channel width of the transistors are $W_1 = W_2 = 10W_3 = 550$ μm . The biasing current is set to $I_{D1} = 10I_{D3} = 7$ mA. A 3-nH inductor, L_d , is used as the load of the LNA. Considering the gain flatness, bandwidth and stability, feedback components are chosen as: $R_f = 350$ Ω , $L_f = 2$ nH, and $C_f = 400$ fF. In a 50- Ω system, a 2-k Ω resistor is adequate for R_{bias} which results in a negligible noise current.

Fig. 4 shows the simulated S-parameters of the designed LNA. The maximum power gain of the amplifier is 11.5 dB in a -0.5 -dB gain bandwidth of 3–5 GHz and the -3 -dB gain bandwidth is 6 GHz between 2 GHz and 8 GHz. Noise figure versus frequency variation is shown in Fig. 5 which attains a minimum of 1.9 dB in the 3–5-GHz band. Fig. 5 also shows the stability factor, k , and Δ , versus frequency. As can be seen, (7) is satisfied for the entire bandwidth, Thus, the LNA is unconditionally stable.

TABLE I
COMPARISON OF THE PROPOSED UWB LNA WITH PUBLISHED WORKS

Ref.	BW_{3-dB} (GHz)	G_{max} (dB)	NF_{min} (dB)	DC Supply (V)	Power (mW)	Technology	Year
[7]*	1.5 ~ 7.5	7	8.7	3	216	0.6- μm CMOS	2002
[8]*	1 ~ 7	13.1	3.3	1.8	75	0.18- μm CMOS	2003
[9]*	2 ~ 4.6	9.8	2.3	1.8	12.6	0.18- μm CMOS	2005
[10]*	3 ~ 6	15.91	4.7	1.8	59.4	0.18- μm CMOS	2005
This work**	2 ~ 8	11.5	1.9	1.6	13.9	0.13- μm CMOS	2006

* Experimental. ** Simulation.

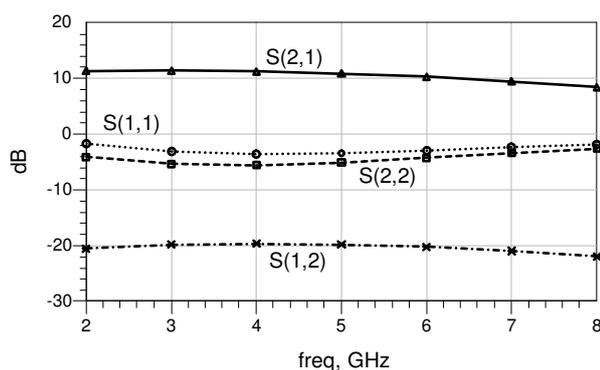


Fig. 4. S-parameters of the proposed LNA.

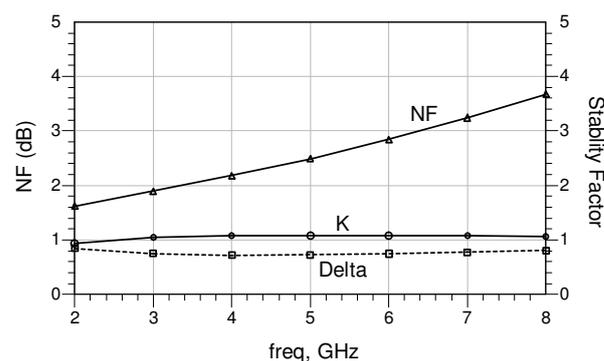


Fig. 5. Noise figure and stability factor of the proposed LNA.

Table I compares the simulation results of this work with some previously reported works. For a better comparison we have chosen references [7]–[10] since the bandwidth of the LNA in these works are near to the bandwidth of the LNA in our work.

V. CONCLUSION

The proposed ultra-wideband LNA architecture is based on the resistive shunt-series feedback topology. To improve noise performance, the amplifier employs inductive load. Simulations using a 0.13- μm CMOS technology show a -3 -dB gain bandwidth of 6 GHz between 2 GHz and 8 GHz, a minimum noise figure of 1.9 dB in the 3–5-GHz band, and a power gain of 11.5 dB with 13.9 mW power consumption.

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