A Broadband Low Power CMOS LNA for 3.1–10.6 GHz UWB Receivers

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Abstract:
A new approach for designing an ultra wideband (UWB) CMOS low noise amplifier (LNA) is presented. The aim of this design is to achieve a low noise figure, reasonable power gain and low power consumption in 3.1-10.6 GHz. Also, the figure of merit (FOM) is significantly improved at 180nm technology compared to the other state-of-the-art designs. Improved π-network and T-network are used to obtain a high and smooth power gain for the whole frequency band. Impedance matching and noise matching are designed with double feedback and only one inductor that are used at the input of the LNA. Post layout simulation is done for design validation. In this design post layout simulations show the low noise figure of 3.85±0.25 dB, reasonable power gain (18.08dB) and input return loss less than -9.1dB in full band of UWB. The power consumption of the circuit is only 11.3mW from 1.8V voltage supply. The LNA has the group delay about 111±43ps. An input third-order intermodulation point (IIP3) of -9.2 dBm is achieved at 4 GHz. The layout area is 1.056 × 0.658 mm2.

Keywords: Ultra wideband, UWB, Low Noise Amplifier, LNA, CMOS.

Submission date: 30, April, 2015
Conditionally accepted date: 5, Sep., 2015
Acceptance date: 19, Sep., 2016
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1. Introduction

Applications of UWB communication in short-range and high-speed mobile systems have been popular in academic and industry due to commercialization of the frequency band of 3.1GHz to 10.6GHz by Federal Communications Commission (FCC) in 2002 [1]. Since, then there have been many researches on UWB.

Two methods have been introduced to use the UWB spectrum, i.e. Frequency hopping (FH) scheme [2] and impulse radio (IR)[3]. In frequency hopping scheme, the UWB band (3.1-10.6 GHz) is divided to fourteen 528 MHz sub bands with OFDM modulation. In impulse radio, transmission of very short pulses is used with pulse position or polarity modulation.

It is possible to have data rates up to 480Mbps in the lower band of UWB (3.1-4.8GHz). Higher data rates can be obtained by using upper band of the UWB. Fig. 1 shows the lower band and upper band of UWB which consists of band group 1 and 3-5 respectively.

![Fig.1. Band group and frequency limit of UWB](image_url)

An ultra wideband (UWB) low noise amplifier (LNA) for a wireless front-end is crucial in a wide range of receiver architectures. The amplifier must meet several stringent requirements, such as broadband input matching to minimize the return loss, sufficient gain to suppress the noise of a mixer, noise match to achieve low noise figure (NF) and enhance receiver sensitivity, low power consumption to increase battery life, high linearity to have high dynamic range and low output intermodulation distortion in high power input and small die area to reduce the cost.

The paper is organized as follows. Section 2 describes the recent design of common ultra wideband LNA topologies, namely, common-gate, resistive shunt feedback, distributed amplifier and current reuse. Section 3 introduces the widening technique and noise-canceling followed by the proposed circuit topology. In Section 4, analytical equations are derived to show the gain performance. In Section 5, the noise analysis, considering the NF at all frequencies is coming. Circuit design and post layout simulation results for proposed ultra wideband LNA are reported in Section 6. Finally, Section 7 presents the conclusion.

2. Recent Research

Different topology of ultra wideband (UWB) CMOS low noise amplifiers (LNAs) have been proposed in literatures in the last decade: e.g. distributed amplifiers (DAs) provide good impedance matching, flat gain and good group delay over a wide range of frequency and excellent IIP3. However distributed amplifiers tend to consume large dc current due to the distribution of multiple amplifying stages, which makes them less attractive for low power application. Also, their demand for high quality transmission lines makes them unsuitable for low cost application due to the large silicon area they need. Another topology is resistive shunt feedback architecture proposed by [5] and [6] that provides good wideband matching, higher stability, sufficient linearity and flat gain but tend to suffer from poor noise figure, large power dissipation and insufficient power gain. Alternatively, a reactive feedback implementation provides better noise performance. The common gate configuration [6] uses the resistive part looking into the source of the transistor to match the input to well-defined source impedance (e.g. 50Ω). This topology has the benefit of wide bandwidth, good input-output isolation and linearity, generally independent NF from angular frequency over the bandwidth and wideband input matching. However, for an input of 50Ω, the required input transconductance must be 20mS, which translates into high power consumption. The common gate with the input matching filter topology can solve this problem and achieve better wideband property. The other structure is inductor source degenerated [7] that employs inductor at source terminal to generate a real term for the input impedance and often works with cascode transistor. This method due to its good noise performance, high gain and high reverse isolation, it is usually used in narrowband scheme. Wide band input matching is reported with adapting a band pass LC filter at the input of the inductor source degenerated LNA [8]. The band pass filter incorporates the input impedance of the cascode as a part of the filter and shows good performance while dissipating small amount of dc power. However, the LC filter mandates a number of reactive elements, which could lead to a larger chip area and NF degradation due to low Quality factor of inductors of LC filter. In this method on-chip transformer matching could save some area [9]. Differential amplifiers show excellent treatment toward second order harmonics. These LNAs, however consume extra power likely about two times of their single-ended counterpart [10]. Current reuse technique has been used in many recent LNA topologies to reduce power dissipation especially in mobile devices [11]. This topology composed of two common source configuration stages under common current structure. This method effectively save power but its chip area is large due to using several inductors. Another solution for UWB LNA is to use forward body biasing for reducing threshold voltage of CMOS transistor [12]. This technique needs low voltage supply; its power consumption is very low and is very suitable for low power application. However, using resistor in body terminal for limiting the current makes poor noise performance and the linearity of this method is slightly worse than that of the other designs.
In this work, we propose a figure of merit (FOM) which takes into account power consumption, noise figure, power gain and bandwidth. Due to the input inductor and the double feedback at input, reasonable input impedance and noise matching could be achieved at all over the UWB frequencies. Middle stage could be used for bandwidth gain improvement. Output impedance matching is done with buffer stage. It matches the circuit with standard 50 Ω resistor. Moreover, the high frequency noise can be effectively suppressed by the good noise match at input transistor with size of transistor, input inductor and double feedback network. This leads to proper noise figure. The cascode topology results in good isolation of output from input and has a wideband behavior.

3. Circuit Analysis

Fig. 2 shows a typical narrowband cascode LNA topology with inductive source degeneration. In this topology, the inductors $L_s$ and $L_g$ are added for simultaneous noise matching and input impedance matching. [13].

Widening the bandwidth and wideband impedance and noise matching with the source-degenerated UWB CMOS LNA topology can be done in several ways. Fig. 3 shows the multi-section LC network and feedback solution.

In LC network, overall imaginary input reactance resonates over the bandwidth. In [7] two section on-chip LC chebyshev filter for ultra wideband impedance matching is used. In [14] and [8] a three and two section LC filter is used as input reactive network, respectively. A drawback of this approach for UWB LNA is the large group delay variation that the signal can experience, due to several resonances in the input matching network. Moreover, it requires moderate to large silicon area and introduces high insertion loss at input network due to limited quality factor of inductors and degrades the amplifier noise figure (NF). Reference [23] shows improvement the operation of UWB receiver by compensation method and using pre-filter, significantly. Also, we have restriction in using additional filter.

Another method for increasing the bandwidth of a narrow band amplifier for UWB application is feedback solution. The feedback network could be inductive [15], resistive [16] or parallel resistive-capacitive [17]. The feedback could widen the bandwidth of LNA and improves the stability especially at high frequency. Furthermore, the precise design with double feedback network could give advantage of matching circuit with less inductor at the input. We must mention that the on-chip inductor has low quality factor that could degrades the noise figure of LNA.

The proposed UWB CMOS LNA used from two feedback network, resistive and capacitive–resistive, as shown in Fig. 4. The main advantage in our circuit is the low power consumption that makes it suitable for portable devices. The low noise figure of the circuit at all UWB could be done without high current in first stage.
power gain improves at upper edge of UWB. The inductor L2 could also resonate with Cds. The Cds is parasitic capacitor at drain of M2. Cds is parallel combination of gate-drain capacitor (Cgds) and drain-bulk capacitor (Cgbs) of M2.

The LNA consists of two transistors as cascode (M1, M2), a gain stage (M3) and a buffer stage (M4). The inductor, Lg, beside gate-source capacitor of M1 (Cgs1) and double feedback (RF1, Cf2RF2) are used for wide band input impedance matching and noise matching of the circuit. Rbal and L1 make shunt peaking technique in drain of transistor M2 that improves the bandwidth of LNA. The T-section inductor, L1, L2 and L3 makes double series peaking technique to improve the gain and bandwidth. Also Lg, beside parasitic capacitor at drain of M1 and source of M2 makes a π-section that improves the bandwidth of LNA. The common source transistor (M3) is used for improve the gain. The inductor L3 resonate with Cgd2 (gate-source capacitor of M2) and Cgbs to improve the bandwidth. Finally, the transistor M4 is used to make a buffer stage for output impedance match up to 50Ω, standard resistor. In addition to the point of self-biasing of RF1, the feedback resistors RF1 and CF2RF2 are also beneficial for the input impedance matching. Also, the feedback resistors RF1 and RF2 are used to have better input impedance matching over wide band and more stability.

4. Gain Analysis

In the output, the transistor M4 is used as a buffer that also brings us output matching over ultra wideband frequency. The output impedance of the circuit could be written as (1).

\[ Z_o \approx \frac{1}{g_{m4} + j\omega (C_{gs4} + C_{gbs}) + \frac{1}{Z_{bias}}} \]  

(1)

The \( g_{m4}, C_{gs4} \) and \( C_{gbs} \) are the transconductance, gate-source capacitor and gate-bulk capacitor of transistor M4, respectively. Also \( Z_{bias} \) is impedance of \( \text{I}_{bias}. \) \( Z_{bias} \) is made of a single transistor (M5), so \( Z_{bias} \) is equal to \((1/\omega C_{gs1})/(\text{I}_{bias}). C_{gds} \) and \( \text{I}_{ds} \) are gate-drain capacitor and drain-source resistor of transistor M3 respectively. We could choose appropriate \( M_4 \) dimension to have output impedance matching. The buffer voltage gain can be written as (2):

\[ \frac{v_{o4}}{v_{g4}} = \frac{Z_L(g_{m4} + j\omega (C_{gs4} + C_{gbs}))}{Z_L(g_{m4} + j\omega (C_{gs4} + C_{gbs})) + 1} \]  

(2)

In (2), \( Z_L \) is the standard impedance (50Ω) parallel with \( r_{ds4} \) and \( Z_{bias}. \) The value of \( r_{ds4} \) and \( Z_{bias} \) is much greater than \( Z_L. \) Also the capacitor of gate-source (Cgs4) is in femtofarad range, so in UWB frequencies the buffer voltage gain is about 0.5.

Middle stage with transistor M3 is used for gain and bandwidth improvement and its effect on the gain of the circuit is very crucial. Voltage gain from gate of transistor M3 to gate of transistor M1 is shown in (3).

\[ \frac{v_{o4}}{v_{g4}} = \frac{-g_{m2} (Z_L + j \omega (C_{gs1} + C_{gbs}))}{Z_L + j \omega L_4 + 1} \]  

(3)

In (3), \( g_{m2} \) is the transconductance of transistor M1. Series peaking is used to improve the bandwidth. Inductor \( L_4 \) resonates with capacitor \((C_{gs4}+C_{gbs})/(1+g_{m2}Z_L)\).

The next gain is \( v_{o3}/v_{g3} \) that could be derived as (4). In (4), \( Z_{bias} \) is input impedance of gain-stage (M3) and is about to \( 1/(\text{I}_{bias} C_{gs1})=1/(\text{I}_{bias} (C_{gs1}+C_{gbs}+1+A)C_{gs3}) \). \( C_{gs3} \) and \( C_{gbs} \) are total capacitor at gate and capacitor of gate-drain of transistor M3. The A is voltage gain between drain to gate of transistor M4.

Equation (4) shows a shunt peaking technique. The gain roll-off is compensated by \( R_{bal} \) and L1. Moreover, it shows double series peaking technique that \( C_{g3} \) makes two spurious resonances with inductors \( L_{ds} \) and \( L_{ds}+L_3 \), respectively. \( L_{ds} \) is \((L_1+L_2+L_3+L_4)/(L_1+L_2+L_3+L_4)\). In the other word we use triple series peaking technique to increase the bandwidth of the amplifier and improve the power gain.

The current that flows from the M1 should transfer to output. For calculation the \( i_s/i_{ds} \) we must see the parasitic capacitor at the drain of M1 (Cds) and source of M2(Cgb2). \( i_s \) and \( i_{ds} \) are source current of transistor M2 and drain current of transistor M1, respectively. Parasitic capacitor Cgb2 is parallel combination of Cgd3 and Cdb2. Cgs4 and Cgb3 are source-gate and source-bulk capacitor of transistor M2, respectively. Also, CD1 is parallel combination of Cgd4 and Cdb4. Cgd3 and Cdb3 are gate-drain and drain-bulk capacitor of transistor M1, respectively. Cgb2 and Cgb4 provides additional path for current signal to the ground and degrade the broadband performance of the LNA. Lds, Cds, and Cdb2 form a broadband π-section LC network as Fig.5.

\[ \frac{i_s}{i_{ds}} = \frac{Z_{bias} + j \omega L_{bias}}{Z_{bias} + j \omega C_{gds}} + l \]  

(4)

In another word, for improvement in power gain and bandwidth, inductance \( L_{ds} \) is added between the drain of M1 and source of M2. With precise design, \( L_{ds} \), Cdb2 and L4 will resonate in lower edge frequency of desire band [18]. Equation (5) shows the relation between \( i_s \) and \( i_{ds}: \)
In (5), $g_{m2}$ is the transconductance of transistor M2. To derive the transconductance of the first stage, ($\delta_m/V_{gs1}$), we must notice that the input network impedance is about to $R_s$ over the wide bandwidth. Feedback resistors ($R_{F1}$ and $R_{F2}$) bring us more frequencies of 3.1GHz to 10.6GHz. Bandwidth and wideband matching against the gain between gate of M1 and drain of M2. After some calculation we would have:

$$\frac{i_{d1}}{i_{m1}} \approx g_{m1} \frac{(Z_x)}{(Z_{F2})} + sL_{dy1} + R_s$$

(6)

In (6) $Z_x$ is the input impedance form gate of M1. $Z_x$ could be written as (7):

$$Z_x = \frac{1}{j\omega} \left[ C_{gs1} + C_{gr1} \right] \left| \frac{1}{g_{m2}R_{F1}} \left| g_{m2}L_{ds} \right| \right| \frac{1}{g_{m1}R_{F1} + g_{m2}}$$

(7)

From (6) and (7) we could write the input impedance of the circuit as (8):

$$Z_{in} = \frac{j\omega L_g + Z_{F2}}{1 + g_{m1}R_{F1}} \frac{1}{j\omega C_{gs1}}$$

(8)

The Quality factor of the circuit shown in Fig. 7 can be approximately given by (9):

$$Q \approx \frac{\omega L_g}{R_s + \left[ \left| \left( R_{F1} \right) \frac{s}{\omega C_{gs1}} + \frac{1}{\omega L_g} \right] \left| \left( \left( R_{F2} \right) \frac{s}{\omega C_{gs1}} + \frac{1}{\omega L_g} \right) \right|^2 \right] + 1}$$

(9)

From (9), and considering the inversely linear relation between the bandwidth and the quality factor, the narrowband LNA can be converted into a ultra wideband amplifier by the proper selection of feedback network. The feedback resistors also provide its conventional roles of flattening the gain over a wider bandwidth with much smaller noise figure degradation. Depending on the required bandwidth and noise contribution, the feedback resistor is chosen. Also smaller feedback resistor makes smaller quality factor and more bandwidth and better input impedance matching as (8). Although noise calculations will show us inverse relation between noise figure and the value of feedback resistors, we need compromise between noise and gain with input return loss and bandwidth.

![Fig. 6. Equivalent circuit at input stage](image)

5. Noise Analysis

The main source of noise that increases the noise figure of a circuit is the first stage. So, to have a glance at noise figure of a circuit, we could analysis the noise of the first stage. In this section we analyze the noise figure of resistive shunt feedback in the first stage of CS LNA (Fig. 4) for three main sources of noise in this structure. To simplify the calculations, transistor is assumed to have infinite output impedance. Beside the thermal noise of $R_{F1}$, $R_{F2}$ (shunt feedback resistors), the drain noise current, due to the carrier thermal agitation in the channel and the induced gate noise, because of the coupling of the fluctuating channel charge into the gate terminal are taken into account.

The induced gate noise, drain noise and resistor noise power spectral densities are formulated as follows, respectively [13].

$$S_{i_{ng}} = 4kT\delta \omega^2 C_{gs}$$

(10)

$$S_{i_{nd}} = 4kTg_{do}$$

(11)

$$S_{i_{nr}} = 4kTR$$

(12)

Where $\delta$ and $\gamma$ are technology dependent and $g_{do}$ is the channel conductance at $V_{DS}=0$. Also, $T$ and $K$ are temperature and Boltzmann constant, respectively.

Three noise sources, shown in Fig.8(a), are input referred in a conventional way and replaced by two correlated noise generators, as are shown in Fig.8(b):

![Fig. 7. Equivalent circuit for Q-factor calculation](image)
where \( \omega = \frac{v(t)}{C_{gs}} \) is the unity gain frequency. We can model the noise due to thermal noise of input voltage source resistor \( R_s \) as \( v_{ns}(t) \). So if the noise power spectral density (PSD) due to \( v_{ns}(t) \) be expressed as follows [13]

\[
S_{in} = \frac{1}{4K\tau} \left( \frac{\alpha}{\alpha + \gamma} \right) \frac{g_m(1 + \chi^2a^2 + 2|c|\chi)}{g_m(1 + \chi^2a^2 + 2|c|\chi)}
\]

(17)

In (16), \( S_{en} \) and \( S_{in} \) are the input referred noise PSDs due to the internal noise source of \( M_1 \) and resistor \( R_s \). A simple expression for the input referred noise current power spectral density (PSD) is given by:

\[
S_{in} = \frac{S_{en} + S_{in}}{S_{en}}
\]

(16)

By the notification of the operation frequency (UWB) and small amount of gate-source capacitor and pretty big \( R_s \), we can rewrite \( i_n \) as (15). Pretty large feedback resistor helps us reduce the noise effect of it on the noise figure of circuit as we would see in forward equations of noise calculations.

\[
i_n = i_{nF} + J(\omega) \dot{v}_{ns} + i_{ng}
\]

(15)

where \( \omega = \frac{g_m}{g_mR_F} \) is the unity gain frequency. We can model the noise due to thermal noise of input voltage source resistor \( R_s \) as \( v_{ns}(t) \). So if the noise power spectral density (PSD) due to \( v_{ns}(t) \) be expressed as \( S_{vns} = 4KTR_s \), the noise figure (NF) of first stage is given by (16):

\[
NF = 1 + \frac{S_{en} + S_{in}}{S_{en}}
\]

(16)

The noise voltage can be expressed as the sum of two components, one fully correlated, \( e_{nc} \), and the other, \( e_{nu} \), uncorrelated to the noise current as (19):

\[
e_n = e_{nc} + e_{nu}
\]

(19)

Carrying out the calculations, the correlation impedance \( Z_c \) is written as (20):

\[
Z_c = \frac{e_{nc}}{i_n} = \frac{(e_{nc} + e_{nu})i_n}{i_n} = \frac{S_{en}}{S_{in}}
\]

(20)

\[
R_c = \frac{G_F/g_m}{G_F + J(\omega) \dot{v}_{ns} + j2 \frac{2}{\alpha}|\alpha+1|}
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\]

(20)
Where Re() and Im() means real and imaginary parts of equation. In this situation that \( S_{enm} \) just have imaginary part we can rewrite the (28) as (29).

\[
NF_{\text{min}} = 1 + 2 \sqrt{S_{g_m}S_{i_n} - |S_{g_m}C_{s3}C_{g2}|^2}
\]

(29)

The minimum noise figure (\( NF_{\text{min}} \)) can be written by (30) Where the \( B_1(\omega) \) and \( B_2(\omega) \) are as (31) and (32).

\[
NF = 1 + 2 \sqrt{G_{RF}B_1(\omega) + B_2(\omega)}
\]

(30)

\[
B_1(\omega) = \frac{\gamma}{\alpha g_m} \left\{ 1 + \left( \frac{\omega}{\omega_r} \right)^2 (1 + \chi^2 \alpha^2) + 2\alpha \sqrt{\chi^2 \left( \frac{\omega}{\omega_r} \right)^2 - |\chi|^2} \right\}
\]

(31)

\[
B_2(\omega) = \left( \frac{\omega}{\omega_r} \right)^2 \gamma^2 \chi^2 (1 - 2\alpha |\chi|^2)
\]

(32)

At first glance at (30), shunt feedback will degrade the minimum noise figure (\( NF_{\text{min}} \)), but if \( R_f \) be pretty large, it has not very bad effect on noise figure, especially it is divided on \( g_m \) of transistor.

The total noise figure (\( NF \)) can be written by minimum noise figure (\( NF_{\text{min}} \)) and other parameters [13] as (33):

\[
NF = NF_{\text{min}} + 1 + \frac{G_{RF}}{R_{F}} \left\{ \left( R_s - R_{\text{opt}} \right)^2 + \left( X_s - X_{\text{opt}} \right)^2 \right\}
\]

(33)

The total noise figure (\( NF \)) will be more than (33) due to finite quality factor of the inductors that are used at the input of the transistors, the channel and gate noise of transistor \( M_2 \) and \( M_3 \) and resistor \( R_{d1} \) and \( R_{d2} \). The contribution of transistor \( M_2 \), \( M_3 \) and \( M_4 \) in noise is much smaller than \( M_1 \). For reducing the noise of the input inductor we must use inductor with high quality factor.

6. Circuit Design and Simulation

The layout of the finished circuit is shown in Fig. 9. The layout area is 1.058 \( \times \) 0.658 mm\(^2\) excluding the test pads.

The design, simulation, post layout simulation and trimming of the proposed CMOS UWB LNA, are based on the TSMC 0.18\( \mu \)m RFCMOS process. For better performance at high frequencies and lower parasitic, a minimum channel length of 180\( \mu \)m is chosen for all the transistors in the circuit.

The power budget of the circuit for low power designing is chosen about 10mW. So the current budget is about 6mA from 1.8V voltage supply. The width of \( M_1 \) transistor (192\( \mu \)m) is optimized for noise. The \( M_1 \) width is sized, for 4mA current, so that the contributions of thermal and induced gate noise and impedance matching are balanced.

Fig. 9. Photograph of the Layout of proposed LNA

- The width of \( M_2 \) transistor (288\( \mu \)m) is decided considering a trade-off between gain and bandwidth. Although the feedback resistor \( R_{F1} = 1700\Omega \) and \( R_{F2} = 500\Omega \) are optimal from the simulation results due to the respectable noise performance. The value of \( R_{F1} \) and \( R_{F2} \) are adjusted as 1870\( \Omega \) and 411\( \Omega \) respectively in order to guarantee reasonable wideband input matching.

- The \( R_{d1} \) and \( L_1 \) are designed to achieve flat gain over the whole bandwidth and make a roll-off factor at appropriate frequency. The value of \( L_1 \) is designed by two opposite requirements. It must be sizable to have large gain and it must be small so that it resonates with \( L_3 \) and \( C_{gs3} \), out-of-band, as well. \( R_{d1} \) is chosen to place the zero frequency as close as possible to the lower edge of the band to improve the gain at lower frequencies. An upper limit to \( R_{d1} \) is set by the voltage headroom. The values for the components of the load are: \( R_{d1} = 134\Omega \) and \( L_1 = 4.04\mu\text{H} \).

- The narrowband LNA is designed at 7 GHz. By the proper selection of the values for \( L_g \), with feedback resistors, \( R_{F1} \) and \( R_{F2} \), the bandwidth extends to cover 3.1–10.6GHz. \( L_g \) for in band matching is selected as 595\( \mu \)H.

- The value of \( L_2 \) is chosen to be 582\( \mu \)H for resonating and peaking with parasitic capacitor at drain of \( M_2 \) (\( C_{d2} \)) at the frequency of 10GHz as mentioned before.

- The inductor \( L_3 \) at T-section makes series peaking with input capacitor from \( M_1 \) transistor (\( C_{gs1} \)) has the value 1.96\( \mu \)H to smooth the gain at high frequency.

- Proper choice of inductor \( L_a \) can resonate with the parasitic capacitor at drain of \( M_1 \) (\( C_{d1} \)) and resonates out of band in series with capacitor at source of \( M_2 \) and drain of \( M_2 \), (\( C_{d1} || C_{d2} \)) to show a broadband property. It is chosen in this design as 582\( \mu \)H.

- Second stage with 2.5mA current usage is designed to improve the overall gain of the circuit. The width of transistor \( M_3 \) is chosen to 80\( \mu \)m. Drain resistor (\( R_{d2} \)) is chosen 200\( \Omega \) to make reasonable gain for LNA. The inductor \( L_4 \) has the value of 1.15\( \mu \)H to resonate with capacitor \( C_{d2} \) and parasitic capacitor at gate of \( M_4 (C_{gs4}) \) to improve the bandwidth of the circuit.
The buffer must drive a 50Ω external load and is used for measurements and output impedance matching. The buffer is biased by means of a current source made up of one transistor. The bias current for this stage is selected due to has proper output return loss although it reduces the power gain. The current about 2.4mA is chosen for buffer stage.

All design parameters are listed in Table 1. Post layout simulation shows the dc current of first stage is about 3.7mA and 2.5mA for second stage. From the supply voltage of 1.8V, the power consumption of the 3.1-10.6GHz LNA is 11mW, without including the output buffer stage.

Fig. 10 and 11 show the effect of feedback networks (Rf1, Rf2) on noise figure of the circuit. As could be seen in Fig. 10 and 11 resistors feedback (Rf1, Rf2) directly improve the noise figure at all frequencies, as could be seen in (30).

Also Fig. 12 shows effects of Rf2 on input return loss. Feedback resistor (Rf2) has inversely improved the S11, as shown in Fig. 12. Equation (8) shows the same results.

Fig. 13 shows the power gain for three value of inductor L1. We could see the inverse and direct relation between the value of inductor L1 and power gain and bandwidth, respectively.

Equation (4) shows the same relations. Inductor L1 in numerator of equation (4) has direct relation with power gain (S21). On the other hand the inductor L1 beside inductor L3 resonates with Cgs3 to improve the bandwidth, so choosing smaller value for L1 makes higher resonance frequency and it improves bandwidth. So the optimum value of inductor L1 could be chosen.

Fig. 14 shows the power gain for different value of inductor L2. We could see the inverse relation between the value of inductor L2 and bandwidth of the LNA. Equation (4) shows the same relation. The inductor L2 resonates with Cd2 to at edge of bandwidth to improve it, so choosing smaller value for L1 makes higher
resonance frequency and it could improve the bandwidth.

Fig. 15. Effect of variation of \( L_3 \) on \( S_{21} \) of the LNA

Fig. 15 shows the power gain (\( S_{21} \)) for three value of inductor \( L_3 \). We could see the inverse relation between the value of inductor \( L_1 \) and bandwidth. Equation (4) shows the same relation. Inductor \( L_3 \) resonates with \( C_{gs3} \) to improve the bandwidth, so choosing smaller value for \( L_1 \) makes higher resonance frequency and it improves the bandwidth.

Fig. 16. Effect of variation of \( R_{d1} \) on \( S_{21} \) of the LNA

Fig. 16 shows the effect of \( R_{d1} \) on power gain (\( S_{21} \)) and could show the correctness of shunt peaking technique that is used by \( R_{d1} \) and \( L_1 \) at equation (4). Smaller \( R_{d1} \) makes roll-off factor is happen at smaller frequency. It could be seen at Fig. 16 that the power gain is falling for \( R_{d1}=88\Omega \), but it will rise at about 3.5 GHz due to shunt peaking. Shunt peaking is happen for \( R_{d1}=88\Omega \) sooner, so its rising point is happen sooner compare with bigger \( R_{d1} \). The rising point for bigger \( R_{d1} \) is happen later, at higher frequency, so for higher \( R_{d1} \) the power gain is smaller at high frequency.

Fig. 17 shows the effect of direct relation between feedback resistor and power gain. Equation (6) shows the same result. Also the bandwidth has inverse relation with feedback resistor as (9). So to select the feedback resistor we must consider the improvement of input return loss (as Fig.12) and power gain. On the other hand we must mention to noise figure. So the proper value of feedback resistor could be selected.

Fig. 18. Hand Calculation and Simulation of Voltage Gain \( V_O/V_{G4} \)

Fig. 18, 19, 20, 21, and 22 show the comparison between hand calculations and simulations of voltage gain (\( V_O/V_{G4} \), \( V_{G4}/V_{G3} \), \( V_{G3}/V_{D2} \), \( V_{D2}/V_{IN} \) and NF (noise figure). We could see in Fig. 18 the same result of hand calculation and simulation result for voltage gain (\( V_O/V_{G4} \)). There are some differences between hand calculation and simulation in Fig. 19 and 20 in voltage gain (\( V_{G4}/V_{G3} \) and \( V_{G3}/V_{D2} \)). The reason for these differences is ignoring the parasitic resistance and capacitance of inductors in hand calculation, \( L_4 \) for Fig. 19 and \( L_1 \), \( L_2 \) and \( L_3 \) for Fig. 20, respectively. Hand calculation and simulation result are close to each other in Fig. 21 for voltage gain (\( V_{D2}/V_{IN} \)). Also, there are some differences especially at high frequencies due to ignoring parasitic resistance and capacitance of inductors \( L_{ds} \) and \( L_g \) in hand calculation. Also neglecting the gate-drain capacitance of \( M_1 \) has some effects in this different result.

The noise figure of first stage that used in hand calculation has some differences with simulation result due to noise of other transistors and resistors in other stages that was mentioned at the end of section 5.
The frequency of the LNA that has the value less than -39 dB in full desire band. Fig. 26 and 27 show the post layout simulation of scattering parameters $S_{11}$ and $S_{22}$ against frequency of the CMOS UWB LNA, respectively. $S_{11}$ is -9.6 to -13dB and $S_{22}$ is -10.8 to -12.6dB, were achieved over the 3.1-10.6GHz band of interest.

Fig. 28 shows the post layout simulation group delay against frequency characteristics of the CMOS UWB LNA. Simulation shows about 111±43ps of phase linearity for this circuit.

The two-tone test for third-order intermodulation distortion (IP3) is shown in Fig. 29. The test is performed at 4GHz. Tone spacing is 1MHz. The simulated IIP3 is about -9.2dBm.
The IIP3 of the LNA was examined at seven different frequencies with 10 MHz frequency spacing at 4, 5, 6, 7, 8, 9, and 10GHz, respectively. As in Fig. 30 an average IIP3 is about -10dBm.

Simulation results of the proposed LNAs and the prior published state-of-the-art UWB LNAs are summarized in Table 1. For the comparison of different topologies, we include two figures of merit (FOMs) in the table 1, FOM I, which does not include voltage supply, and FOM II, which does:

$$FOM\ I = \frac{S_{21}BW(\text{GHz})}{(NF(abs.m\text{in}) - 1)P_{0}(mW)} \quad (34)$$

Fig. 25. Simulated reverse gain(dB)

Fig. 26. Simulated input return loss(dB)

Fig. 27. Simulated output return loss(dB)

Fig. 28. Simulated Group Delay(ps)

Fig. 29. Simulated IIP3 at 4 GHz

Fig. 30. Simulation IIP3 versus intermodulation frequency

Table 1: Comparison of LNAs

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>S12 (dB)</th>
<th>S11 (dB)</th>
<th>S22 (dB)</th>
<th>IIP3 (dBm)</th>
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Pre-Layout Simulation
Post-Layout Simulation

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>S11 (dB)</th>
<th>S11 (dB)</th>
<th>S22 (dB)</th>
<th>IIP3 (dBm)</th>
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</thead>
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<td>4</td>
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<td></td>
<td>-9.2</td>
</tr>
<tr>
<td>5</td>
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<td></td>
</tr>
<tr>
<td>6</td>
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<td>7</td>
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<tr>
<td>10</td>
<td></td>
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</tr>
</tbody>
</table>

Pre-Layout Simulation
Post-Layout Simulation

590pH Symmetric Inductor with 40 μm radius and 2 turns on M6
\[ FOM_{II} = \frac{S_{21} BW(GHz)}{(NF(abs\_min) - 1)P_d(mW)V_{DD}} \]  

(35)

The table 1 shows one of the best FOM for this design with very good NF and excellent power gain, although the input return loss and power consumption of the proposed circuit are in good situation. The values of elements that are used in the proposed circuit are listed in table 2. The inductors \(L_g\) and \(L_d\) are symmetric spiral inductor. The simulation shows 40 GHz self resonance frequency for inductor \(L_g\). The quality factor of \(L_g\) is shown as Fig. 27 against frequency. The other inductors (\(L_1\), \(L_2\), \(L_3\) and \(L_4\)) are chosen as standard spiral inductors. All of them have 9μm of width on metal 6 in TSMC 0.18 μm RF CMOS process. Types of capacitors that are used in the circuit are MIMCAP_rf capacitor. The type of resistors and transistors that are used in the design are listed in table 2. The post simulation results for extreme corner cases are shown in table 3.

![Fig. 26. Quality factor of \(L_g\) (symmetrical inductor)](image)

Table 1. Performance Compared with the Fabricated Papers*

<table>
<thead>
<tr>
<th>This Work</th>
<th>[4]</th>
<th>[6]</th>
<th>[7]</th>
<th>[8]</th>
<th>[15]</th>
<th>[17]</th>
<th>[20]</th>
<th>[21]</th>
<th>[22]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tech(nm)</td>
<td>180</td>
<td>180</td>
<td>180</td>
<td>180</td>
<td>90</td>
<td>180</td>
<td>180</td>
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<td>180</td>
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<tr>
<td>BW(GHz)</td>
<td>1.122</td>
<td>0.1-11</td>
<td>2.8-10.4</td>
<td>2.2-9.5</td>
<td>2.3-10.5</td>
<td>0-14.5</td>
<td>3-10.6</td>
<td>1-12</td>
<td>3.2-11.5</td>
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<tr>
<td>S11(dB)</td>
<td>18.08</td>
<td>8.1</td>
<td>10.4</td>
<td>10.1±1.1</td>
<td>14±1</td>
<td>10</td>
<td>13±0.5</td>
<td>9.5±1</td>
<td>14.8±1.2</td>
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<td>S10(dB)</td>
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<td>&lt;12</td>
<td>&lt;11</td>
<td>&lt;10</td>
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<td>&lt;10</td>
<td>&lt;9</td>
<td>&lt;12</td>
<td>&lt;8.3</td>
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<td>NF(dB)</td>
<td>3.6-4.1</td>
<td>2.9</td>
<td>4.5-6</td>
<td>3.5-6.6</td>
<td>3-4</td>
<td>5.6-6</td>
<td>2.5-4.7</td>
<td>4.2-5</td>
<td>3.5-8</td>
</tr>
<tr>
<td>Power(mW)</td>
<td>11.3</td>
<td>21</td>
<td>2</td>
<td>8.9</td>
<td>17</td>
<td>30</td>
<td>14.1</td>
<td>20</td>
<td>11.7</td>
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<tr>
<td>IIP3(dBB)</td>
<td>-9.2</td>
<td>-3.4</td>
<td>-5.4</td>
<td>-9</td>
<td>-8</td>
<td>-6.2</td>
<td>-6.5</td>
<td>-7</td>
<td></td>
</tr>
<tr>
<td>FOM1(GHz/mW)</td>
<td>6.3</td>
<td>1.3</td>
<td>4.2</td>
<td>0.9</td>
<td>1.8</td>
<td>0.5</td>
<td>1.3</td>
<td>0.85</td>
<td>1.6</td>
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<tr>
<td>FOM2(GHz/VmW)</td>
<td>3.5</td>
<td>0.7</td>
<td>2.2</td>
<td>0.5</td>
<td>1</td>
<td>0.6</td>
<td>0.7</td>
<td>0.47</td>
<td>0.9</td>
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Table 2. Device Value and Type of the proposed LNA

<table>
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<tr>
<th>Transistor(W/L)</th>
<th>Type</th>
<th>Resistor(Ω)</th>
<th>Type</th>
<th>Capacitor(pF)</th>
<th>Type</th>
<th>Inductor(nH)</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1SF=24×8/0.18 μm/μm</td>
<td>rf2v</td>
<td>R9=3830</td>
<td>rphpoly_rf</td>
<td>C2=1.74</td>
<td>MIMcap_rf</td>
<td>L1=4.04</td>
<td>Standard</td>
</tr>
<tr>
<td>M2SF=36×8/0.18 μm/μm</td>
<td>rf2v</td>
<td>R9=4740</td>
<td>rphpoly_rf</td>
<td>C1=1.84</td>
<td>MIMcap_rf</td>
<td>L1=1.96</td>
<td>Standard</td>
</tr>
<tr>
<td>M3SF=10×8/0.18 μm/μm</td>
<td>rf2v</td>
<td>R1=1870</td>
<td>rphpoly_rf</td>
<td>C2=0.325</td>
<td>MIMcap_rf</td>
<td>L1=0.512</td>
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</tr>
<tr>
<td>M4SF=20×8/0.18 μm/μm</td>
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<td>R1=134</td>
<td>rphpoly_rf</td>
<td>L1=1.15</td>
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<td>RD1=200</td>
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Table 3. LNA’s Performance on Extreme Corner Cases

<table>
<thead>
<tr>
<th>NF(dB)</th>
<th>S21(dB)</th>
<th>S11(dB)</th>
<th>S22(dB)</th>
<th>Pdc(mW)</th>
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<tr>
<td>SS, 90</td>
<td>4.4</td>
<td>16.4</td>
<td>-9</td>
<td>-11.3</td>
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<tr>
<td>SS, -40</td>
<td>3.1</td>
<td>17.9</td>
<td>-8.3</td>
<td>-9.9</td>
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<tr>
<td>SF, 90</td>
<td>4.4</td>
<td>17</td>
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<td>-11</td>
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<td>SF, -40</td>
<td>3.8</td>
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<tr>
<td>FS, -40</td>
<td>2.8</td>
<td>19.8</td>
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<tr>
<td>FF, 90</td>
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</table>

7. Conclusion

This paper presented a new topology for low noise amplifier architecture that is operating in 3.1-10.6 GHz UWB range. The circuit design and post layout simulation were done with TSMC 0.18μm RF CMOS process. By utilizing special inductive peaking technique and its flatness was improved. Using one inductor and double feedback at the input network enhanced the input impedance and noise matching in whole frequency band.

The design base on an optimization over the effective operating frequency band, noise figure and power consumption. The effective additional noise from feedback resistors is negligible due to the pretty large of the resistors. Noise calculation is done through a detailed noise analysis. Improvement in power gain was achieved by a shunt and series peaking technique and mixed π-section and T-section in the circuit. Post layout simulation results show a flat noise figure of 3.85±0.25dB over the full UWB, power gain of 18.08 dB with bandwidth from DC to 12.2GHz. The linearity of the LNA was detected by IIP3 of -9.2dBm, while consuming 11.3mW from a 1.8V voltage supply. The layout area is about 0.696mm² excluding the test pads. The excellent FOM of this work comparing to other works shows the advantage of the circuit for using in front-end of a multi-standard wireless system and portable devices.

References


