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.

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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.

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 [4] (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 make 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.

Double feedback with only one inductor at input transistor is used to have wideband input impedance matching. This simple impedance matching network could improve the power consumption and noise figure compare to the other UWB impedance matching topologies.

The π-section and T-section improve the power gain in cascode structure. The cascode topology is used to widen the bandwidth and provides good isolation of output from input. The power gain of this amplifier at higher frequencies is also degraded due to the capacitive effect of large size $M_1$ and $M_2$. To counterbalance this gain degradation, a series-peaking inductor $L_2$ as shown in Fig. 4 is added to make the
power gain improves at upper edge of UWB. The inductor L2 could also resonate with Cgs2. The Cgs2 is parasitic capacitor at drain of M2. Cd1 is parallel combination of gate-drain capacitor (Cgd1) and drain-bulk capacitor (Cdb1) 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, Cfb2) are used for wide band input impedance matching and noise matching of the circuit. Rd1 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 L4 resonate with Cgd1 and Cdb1 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 Rf2 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).

\[
Z_o \approx \frac{1}{g_{m4} + j\omega (C_{gs4} + C_{gsb4}) + \frac{1}{Z_{bias}}} \quad (1)
\]

The \(g_{m4}\), Cgs4 and Cgsb4 are the transconductance, gate-source capacitor and gate-bulk capacitor of transistor M4, respectively. Also Zbias is impedance of Lbias. Lbias is made of a single transistor (M4), so Zbias is equal to \((1/j\omega C_{gsb4})(|r_{ds4}|)\). Cgsb4 and rds4 are gate-drain capacitor and drain-source resistor of transistor M4, respectively. We could choose appropriate M4 dimension to have output impedance matching. The buffer voltage gain can be written as (2):

\[
\frac{V_{o4}}{V_{g4}} = \frac{Z_L(g_{m4} + j\omega (C_{gs4} + C_{gsb4}))}{Z_L(g_{m4} + j\omega (C_{gs4} + C_{gsb4})) + 1} \quad (2)
\]

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 M4 is shown in (3).

\[
\frac{v_{g3}}{v_{g2}} = \frac{R_{d2}}{R_{dd} + Z_L + j(\omega L_4 - \frac{1}{\omega (C_{gs4} + C_{gsb4})})} \quad (3)
\]

In (3), \(g_{m3}\) is the transconductance of transistor M3. Series peaking is used to improve the bandwidth. Inductor L4 resonates with capacitor (Cgsb4+Cgb4)/(1+\(r_{ds4}Z_{bias}\)).

The next gain is \(v_{g2}/v_{g1}\), that could be derived as (4). In (4), \(Z_{g0}\) is input impedance of gain-stage (M4) and is about to \(1/(j\omega C_{gs4})\times\|\{1/oC_{gd3}\}\). Cgs4 and Cgd3 are total capacitor at gate and capacitor of gate-drain of transistor M3. The A is voltage gain between drain to gate of transistor M3.

Equation (4) shows a shunt peaking technique. The gain roll-off is compensated by \(R_{d1}\) and \(L_1\). Moreover, it shows double series peaking technique that Cgd3 makes two spurious resonances with inductors L1 and L2+L3, respectively. \(L_{eff}\) is \((L_1L_2+L_2L_3+L_1L_3)/(L_1+L_2)\).

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 \(i_{g4}/i_{g3}\) we must see the parasitic capacitor at the drain of M1 (Cds1) and source of M2(Cds2). \(i_{g2}\) and \(i_{g4}\) are source current of transistor M2 and drain current of transistor M1, respectively. Parasitic capacitor Cgs2 is parallel combination of Cgs2 and Cgb2. Cgs2 and Cgb2 are source-gate and source-bulk capacitor of transistor M2, respectively. Also, Cds1 is parallel combination of Cds1 and Cds1. Cgb2 and Cgb1 are gate-drain and drain-bulk capacitor of transistor M1, respectively. Cds1 and Cds2 provides additional path for current signal to the ground and degrade the broadband performance of the LNA. Lds1, Cds1 and Cds2 form a broadband π-section LC network as Fig.5.

\[
\frac{v_{o4}}{v_{g4}} = \frac{R_{d2} + j\omega L_4}{R_{d2} + j\omega L_4 + j\omega L_5 + j\omega L_6 + j\omega L_7 + L_8 + L_9} \quad (4)
\]

In another word, for improvement in power gain and bandwidth, inductor Lg is added between the drain of M1 and source of M2. With precise design, Lds1, Cgs2 and Cds1 will resonate in lower edge frequency of desire band [18]. Equation (5) shows the relation between \(i_{g2}\) and \(i_{g1}\):
\[ i_{d2} \]
\[ i_{d1} = (j\omega C_{d2} + g_{m2})/(C_{d1} + C_{d2}) \]  
\[ = j\omega \left[ 1 - \omega^2 L_{ds}(C_{d1}||C_{d2}) + g_{m2} \right]/(c_{d1} + c_{d2}) \]  
\[ \times \left[ 1 - \omega^2 L_{ds}(C_{d1}||C_{d2}) \right] \]  
\[ \text{In (5), } g_{m2} \text{ is the transconductance of transistor M}_2. \]

To derive the transconductance of the first stage, \((i_{in}/V_{gs1})\), we must notice that the input network impedance is about to \( R_s \) over the wide bandwidth.

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

\[ S_{in} = 4kT\delta \frac{\omega^2 C_{gs}}{g_{d0}} \]  
\[ S_{ind} = 4kT\gamma g_{d0} \]  
\[ S_{inr} = 4kT/R_F \]  

Where \( \delta, \gamma \) are technology dependent and \( g_{d0} \) 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 shown in Fig.8(b):
\[ i_n = \frac{RF(g_m + j\omega C_{gs})}{g_mRF - 1}i_{nF} \]
\[ + \frac{1 + jRF\omega C_{gs}}{g_mRF - 1}i_{nd} \]
\[ e_n = \frac{1}{g_m}i_{nF} + \frac{1}{g_m}i_{nd} \]  

(13)  

(14)  

\[ \frac{S_{e_n}}{4kT} \approx \left( \frac{1}{\alpha g_m} \right) \left( \frac{\alpha}{RFg_m} + \gamma \right) \]  

(18)  

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):

\[ Z_c = \frac{e_{nc}}{i_n} = \frac{e_{nc}}{i_n} = \frac{e_{nc} + e_{nu}}{i_n} = \frac{S_{e_{nc}}}{S_{i_n}} \]
\[ = R_c + jX_c \]
\[ R_c = \frac{G_F/g_m}{G_F + \frac{\omega C_{gs}}{g_m(1 + \alpha^2\alpha^2 + 2|c|\alpha\chi)} \} g_m(1 + \chi^2a^2 + 2|c|\alpha\chi) \]
\[ X_c = -\frac{\omega C_{gs}}{g_m(1 + \chi^2a^2 + 2|c|\alpha\chi)} \]
\[ G_F = \frac{1}{2g_m(1 + \chi^2a^2 + 2|c|\alpha\chi)} \]
\[ RF = \frac{1}{2g_m(1 + \chi^2a^2 + 2|c|\alpha\chi)} \]
\[ X_c = \frac{1}{2g_m(1 + \chi^2a^2 + 2|c|\alpha\chi)} \]
\[ G_F = \frac{1}{2g_m(1 + \chi^2a^2 + 2|c|\alpha\chi)} \]
\[ X_c = \frac{1}{2g_m(1 + \chi^2a^2 + 2|c|\alpha\chi)} \]

By using the introduced parameters, the NF can be expressed as follows [13]

\[ NF = 1 + \frac{R_u + G_n|Z_c| + Z_0^2}{R_s} \]
\[ = 1 + \frac{R_u + G_n(R_s + R_c)^2 + (X_s + X_c)^2}{R_s} \]  

(25)  

Here \(Z_s = R_s+jX_s\) is the source impedance. Classic noise optimization theory shows that the minimum noise figure is achieved if the source impedance \(Z_s = Z_{opt} = R_{opt} + jX_{opt}\) could be chosen such as it is in [7].

\[ R_{opt} = \frac{R_u + R_c}{G_n} \quad \text{and} \quad X_{opt} = -X_c \]  

(26)  

(27)  

With the notification of equations (23) to (27) the noise figure can be rewritten as (28):

\[ NF_{min} = 1 + 2\left[Re(S_{\epsilon_{i,n}}) + \sqrt{S_{\epsilon_{i,n}}S_{i,n} - \left(Im(S_{\epsilon_{i,n}})\right)^2}\right] \]  

(28)  

Fig. 8. (a) Three main noise source (b) Classic input referred noise as \(e_n\) and \(i_n\).

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.

\[ i_n = i_{nF} + j\left(\frac{\omega}{\omega_\alpha}\right)\]  

(15)  

Where \(\omega_\alpha = g_m/C_{gs}\) 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 represented as \(S_{vns} = 4kTR_s\), the noise figure (NF) of first stage is given by (16):

\[ NF = 1 + \frac{S_{e_n} + S_{i_n}}{S_{vns}} \]  

(16)  

In (16), \(S_{e_n}\) and \(S_{i_n}\) 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:

\[ \frac{S_{i_n}}{4kT} = G_F + \frac{\omega}{\omega_\alpha} \]  

(17)  

Where \(\chi = \sqrt{\delta/(5\gamma)}\), and \(c = S_{i_{n,ind}}^2/S_{i_{nd},i_{nd}}^2\) is the correlation coefficient between the gate noise and the drain noise for MOS device, \(c \approx 0.395\) [19]. We must notice that there is no correlation between the noise of resistor \(R_S\) and gate noise and drain noise. The parameter \(\alpha = g_m/g_{0h}\) accounts for short channel effect. It describes the transconductance reduction due to velocity saturation and mobility decrease due to vertical fields [13].

Calculations of the input referred noise voltage power spectral density (PSD) are carried out as (18):
Where Re() and Im() means real and imaginary parts of equation. In this situation that $S_{nin}$ just have imaginary part we can rewrite the (28) as (29).

$$NF_{min} = 1 + 2\sqrt{\operatorname{Re}(S_{c})S_{in} - \operatorname{Im}(S_{c})^2}$$

(29)

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

$$NF = 1 + 2\sqrt{\operatorname{Re}(B_1(\omega)) + B_2(\omega)}$$

(30)

$$B_1(\omega) = \frac{Y}{a g_m} \left\{ 1 + \left( \frac{\omega}{\omega_T} \right)^2 (1 + \alpha^2 \omega^2) \right\}$$

(31)

$$B_2(\omega) = \left( \frac{\omega}{\omega_T} \right)^2 \gamma^2 \omega^2 (1 - |c|^2)$$

(32)

At first glance at (30), shunt feedback will degrade the minimum noise figure (NF$_{min}$), 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$_{min}$) and other parameters [13] as (33):

$$NF = NF_{min} + 1 + \frac{G_m}{R_g} \left[ (r_s - r_{opt}) \right]^2 + (X_s - X_{opt})^2$$

(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 $1.058 \times 0.658 \text{ mm}^2$ excluding the test pads.

The design, simulation, post layout simulation and trimming of the proposed CMOS UWB LNA, are based on the TSMC 0.18μm RFCMOS process. For better performance at high frequencies and lower parasitic, a minimum channel length of 180nm 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 (192μm) 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 to resonate with capacitor $C_{c2}$ and parasitic capacitor at gate of $M_4(C_{gs4})$ to improve the bandwidth of the circuit.

The total noise figure (NF) can be written by 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 pH. The value of $L_2$ is chosen to be 582pH for resonating and peaking with parasitic capacitor at drain of $M_2$ ($C_{d2}$) at the frequency of 10GHz as mentioned before.

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The inductor $L_3$ at T-section makes series peaking with input capacitor from $M_1$ transistor ($C_{gs1}$) has the value 1.96nH to smooth the gain at lower frequencies.

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 1870Ω and 411Ω, 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 $L_1 = 4.04nH$.

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 pH.

The value of $L_1$ is chosen to be 582pH 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 1.96nH to smooth the gain at high frequency.

Proper choice of inductor $L_{d4}$ 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 $M_1$, ($C_{d1}$|$C_{d2}$) to show a broadband property. It is chosen in this design as 582pH.

Second stage with 2.5mA current usage is designed to improve the overall gain of the circuit. The width of transistor $M_1$ is chosen to 80μm. Drain resistor ($R_{d2}$) is chosen 200Ω to make reasonable gain for LNA. The inductor $L_4$ has the value of 1.15nH 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 (R_F1, R_F2) on noise figure of the circuit. As could be seen in Fig. 10 and 11 resistors feedback (R_F1, R_F2) directly improve the noise figure at all frequencies, as could be seen in (30).

Also Fig. 12 shows effects of R_F2 on input return loss. Feedback resistor (R_F2) has inversely improved the S_{11}, as shown in Fig. 12. Equation (8) shows the same result.

Fig. 13 shows the power gain for three value of inductor L_1. We could see the inverse and direct relation between the value of inductor L_1 and power gain and bandwidth, respectively.

Equation (4) shows the same relations. Inductor L_1 in numerator of equation (4) has direct relation with power gain (S_{21}). On the other hand the inductor L_1 beside 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 bandwidth. So the optimum value of inductor L_1 could be chosen.

Fig. 14 shows the power gain for different value of inductor L_2. We could see the inverse relation between the value of inductor L_2 and bandwidth of the LNA. Equation (4) shows the same relation. The inductor L_2 resonates with C_{d2} to at edge of bandwidth to improve it, so choosing smaller value for L_1 makes higher
resonance frequency and it could improve the bandwidth.

Fig. 15. Effect of variation of L3 on S21 of the LNA

Fig. 15 shows the power gain (S21) for three value of inductor L3. We could see the inverse relation between the value of inductor L1 and bandwidth. Equation (4) shows the same relation. Inductor L3 resonates with Cgs3 to improve the bandwidth, so choosing smaller value for L1 makes higher resonance frequency and it improves the bandwidth.

Fig. 16. Effect of variation of Rd1 on S21 of the LNA

Fig. 16 shows the effect of Rd1 on power gain (S21) and could show the correctness of shunt peaking technique that is used by Rd1 and L1 at equation (4). Smaller Rd1 makes roll-off factor is happen at smaller frequency. It could be seen at Fig. 16 that the power gain is falling for Rd1=88Ω, but it will rise at about 3.5 GHz due to shunt peaking. Shunt peaking is happen for Rd1=88Ω sooner, so its rising point is happen sooner compare with bigger Rd1. The rising point for bigger Rd1 is happen later, at higher frequency, so for higher Rd1 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, 19, 20, 21, and 22 show the comparison between hand calculations and simulations of voltage gain (VO/VG4), (VG4/VG3), (VG3/Vd2), (VD2/VIN) and NF (noise figure). We could see in Fig. 18 the same result of hand calculation and simulation result for voltage gain (VO/VG4). There are some differences between hand calculation and simulation in Fig. 19 and 20 in voltage gain (VG4/VG3) and (VG3/Vd2). The reason for these differences is ignoring the parasitic resistance and capacitance of inductors in hand calculation, L4 for Fig. 19 and L1, L2 and L3 for Fig. 20, respectively. Hand calculation and simulation result are close to each other in Fig. 21 for voltage gain (Vd2/VIN). Also, there are some differences especially at high frequencies due to ignoring parasitic resistance and capacitance of inductors Lds and Lg in hand calculation. Also neglecting the gate-drain capacitance of M1 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.

Fig. 18. Hand Calculation and Simulation of Voltage Gain VO/VG4

Fig. 23 and 24 show the power gain and noise figure of CMOS UWB LNA over 3.1-10.6GHz, respectively. Noise figure (NF) is 3.6dB to 4.1dB and has ±0.25dB variations. Power gain is 15.6dB to 18.08dB was achieved over the 3.1-10.6GHz band of interest. Fig. 25 shows the post layout simulation of S12 against...
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. 26. Post Layout Simulation of Scattering Parameters $S_{11}$ and $S_{22}$

Fig. 27. Post Layout Simulation of Scattering Parameters $S_{11}$ and $S_{22}$

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:

$$FOM\ I = \frac{S_{21}BW(\text{GHz})}{(NF(abs.,\min) - 1)P_{D}(\text{mW})} \quad (34)$$
\[ FOM \ II = \frac{S_{21}BW(GHz)}{(NF(abs.min) - 1)P_d(mW)V_{DD}} \] (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 Lg and Lds are symmetric spiral inductor. The simulation shows 40 GHz self resonance frequency for inductor Lg. The quality factor of Lg is shown as Fig. 27 against frequency. The other inductors (L1, L2, L3 and L4) 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 Lg (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>
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<tbody>
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<td>Tech(nm)</td>
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<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>1-12.2</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>4.6</td>
<td>8.6</td>
<td>10.1±1.1</td>
<td>14±1</td>
<td>10</td>
<td>13±0.5</td>
<td>5±1.5</td>
<td>9.5±1.2</td>
<td>14.8±1.2</td>
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<tr>
<td>S11(dB)</td>
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<td>11.9</td>
<td>2.5-4.7</td>
<td>-10.4</td>
<td>-8.1</td>
<td>-8.9</td>
<td>3-4</td>
<td>-10</td>
<td>3-10</td>
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<tr>
<td>Lg</td>
<td>0.595</td>
<td>11.7</td>
<td>17</td>
<td>0.9</td>
<td>9.5±1</td>
<td>4.2</td>
<td>-9</td>
<td>2.8</td>
<td>-9.9</td>
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<tr>
<td>L3</td>
<td>.512</td>
<td>17.9</td>
<td>17</td>
<td>0.9</td>
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<td>4.2</td>
<td>-9</td>
<td>2.8</td>
<td>-9.9</td>
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Table 2. Device Value and Type of the proposed LNA

<table>
<thead>
<tr>
<th>Transistor(W/L)</th>
<th>Type</th>
<th>Resistor(Ω)</th>
<th>Type</th>
<th>Capacitor(F)</th>
<th>Type</th>
<th>Inductor(nH)</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>M4=24×8/0.18 μm/μm</td>
<td>rf2v</td>
<td>R1 = 3830</td>
<td>rphpoly_rf</td>
<td>C3 = 1.74</td>
<td>MIMcap_rf</td>
<td>L1 = 4.04</td>
<td>Standard</td>
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<tr>
<td>M3=36×8/0.18 μm/μm</td>
<td>rf2v</td>
<td>R2 = 4740</td>
<td>rphpoly_rf</td>
<td>C4 = 1.84</td>
<td>MIMcap_rf</td>
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<td>R3 = 1870</td>
<td>rphpoly_rf</td>
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<td>M1=20×8/0.18 μm/μm</td>
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<td>R4 = 200</td>
<td>rphpoly_rf</td>
<td>-</td>
<td>-</td>
<td>L1 = 4.04</td>
<td>Standard</td>
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Table 3. LNA's Performance on Extreme Corner Cases

<table>
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<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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<td>16.4</td>
<td>-9</td>
<td>-11.3</td>
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<td>SS , -40</td>
<td>3.1</td>
<td>17.9</td>
<td>-8.3</td>
<td>-9.9</td>
</tr>
<tr>
<td>SF , 90</td>
<td>4.4</td>
<td>17</td>
<td>-10.5</td>
<td>-11</td>
</tr>
<tr>
<td>SF , -40</td>
<td>3.8</td>
<td>17</td>
<td>-9</td>
<td>-8.5</td>
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<tr>
<td>FS , 90</td>
<td>4.3</td>
<td>19.4</td>
<td>-9.6</td>
<td>-8.1</td>
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<tr>
<td>FS , -40</td>
<td>2.8</td>
<td>19.8</td>
<td>-9.1</td>
<td>-12.5</td>
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<tr>
<td>FF , 90</td>
<td>4</td>
<td>19</td>
<td>-10.4</td>
<td>-8.5</td>
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<tr>
<td>FF , -40</td>
<td>3</td>
<td>19.5</td>
<td>-8.7</td>
<td>-10.3</td>
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</tbody>
</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 the gain 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


