CHAPTER 5

High Power Gain UWB LNA

5.1 Introduction

FCC allows use of 3.1-10.6 GHz UWB frequency spectrum, for commercial wireless communication since 2002. Due to wideband of UWB technology, opens new frontier in wireless communications and provide high data rate and less multi path fading. UWB technology is widely used in high data rate wireless communication, penetration imaging and high accuracy locating applications. Various IEEE standards adopt this technology to improve performance of wireless system.

5.1.1 Ultra Wide Band (UWB) Technology

Defense department of United State was using this technology since early 1960’s, but it was not popular as UWB, but different nomenclature was used. Patent awarded to UWB communication system in 1973. Before 1980’s this technology was referred as impulse, carried free, or based band communication. After 1989 this technology is popularly known as Ultra Wideband (UWB). Most of technological advance has been classified before 1994.

To utilize UWB technology for commercial wireless communication, Federal Communications Commission (FCC) has given permission with restrict to transmit low power.
5.1.2 Bandwidth and Guidelines of UWB Technology

Fig. 2.1 graphically shows the Equivalent Isotropic Radiated Power (EIRP) spectral transmission limits set by the FCC for the commercial use UWB communication. Vehicular RADAR system uses 1.61 – 3.1 GHz band. The FCC has put strict restriction on outdoor transmission limit to avoid interference with exciting system in 1.61-3.1 GHz band.

![Graph showing EIRP Emission](image)

**FIGURE 5.1:** EIRP Emission specified by the FCC.

UWB signal is defined in terms of spectral occupancy. FCC defined UWB signal should have a spectral more than 500 MHz or more than 20% of fractional bandwidth. Fractional bandwidth is defined by the (5.1)

\[ F_{bw} = \frac{\text{Bandwidth(BW)}}{\text{Center Frequency}} = \frac{f_{\text{Upper}} - f_{\text{Lower}}}{(f_{\text{Upper}} + f_{\text{Lower}})/2} \]  \hspace{1cm} (5.1)

In (5.1) \( f_{\text{Upper}} \) and \( f_{\text{Lower}} \) are the upper and lower -10 dB radiation frequencies.

5.1.3 Features and Applications of UWB Technology

Extremely wide bandwidth of UWB, opens new frontier for wireless communication users. Bandwidth is the main limitation to improve performance of wireless communication. UWB have wide bandwidth, which improve communication channel capacity, quality and data rate of wireless communication. It’s easily illustrating using shannon’s Channel Information Capacity theorem. The shannon’s theorem is state that
maximum channel capacity depend on bandwidth and signal to noise ratio as shown in (5.2).

\[ C = B \log_2 \left( 1 + \frac{S}{N} \right) \]  

Where, \( C \) is maximum theoretical capacity, \( B \) is channel bandwidth, \( S \) is signal power and \( N \) is noise power.

In narrowband system due to restricted bandwidth data rate is controlled by the transmitted power (S). UWB system has a very large channel bandwidth, which reduce need of high power transmission to establish adequate data rate. According to FCC regulations, UWB can reach data rate speed greater than 110 MB/s over 10-15 meters [88].

Due to low transmission power and high data rate in UWB technology, opens new frontier in wireless communications. UWB is widely used in high data rate short distance wireless communication, personal area networks, sensor networks, RADAR, image penetrating, medical applications and RFID. Due to low power consumption and very large bandwidth, it is used in wireless real time signal transmitting and observing of the human body [89]. Similarly various biomedical applications take advantages of UWB technology.

### 5.1.4 UWB System Standards

IEEE is developing several IEEE standards that adventure the UWB bandwidth specified by FCC and integrates it with the existing IEEE standards to insure good quality of service to users.

IEEE define IEEE 802.15 standard for Wireless Person Area Network (WPAN) which use UWB technology. Within this standard sub standards IEEE 802.15a is defined for high data rate communication. IEEE 802.15a is implemented using UWB system. IEEE standards improve performance by incorporate UWB technology.

### 5.1.5 UWB System Architectures

UWB system use two main system level approaches, Impulse type Impulse Radio UWB (IR UWB) and carrier based Orthogonal Frequency Division Multiplexing UWB (OFDM
UWB) to utilize frequency spectrum of UWB. The Multi-band OFDM Alliance supports a type of OFDM architecture referred to as Multi Band OFDM specified in www.multibandofdm.org. UWBforum propose another forum, direct sequence UWB based on IR UWB. IR UWB is included in IEEE 802.15.4a standards due to its simplicity and localization capability compared to OFDM UWB system.

Implementation of RF frontend for both the types of system architecture either IR UWB or OFDM UWB require wideband, high power gain, low noise figure and linear 3.1-10.6 GHz wideband LNA.

IMPULSE RADION UWB: IR-UWB communication use baseband pulses of very short duration as signalling and either On-Off keying (OOK), pulse-position modulation (PPM), or pulse amplitude modulation (PAM) as modulation schemes. IR UWB is used in ZigBee technology for IEEE 802.15.4 (WPAN) standard due to high data rate, low complexity and very low power.

Fig. 5.2 shows IR-UWB receiver architecture. The optimum match filter functionality is achieved using analog correlator (∫) and template generator. The optimum match filter maximized signal to noise ratio with presence of noise. At narrowband lower frequency this matched filtering function is performed using digital hardware but for RF UWB receiver to implement matched filtering in digital domain is practically impossible using current technology. ADC designing for UWB signal to operate at Nyquist rate using current technology is impossible task.

![IR UWB Receiver architecture](image)

FIGURE 5.2: IR UWB Receiver architecture.

To relax ADC performance requirements, need to down convert RF signals and improve signal to noise ratio. Mixer down convert RF signals to IF band and LNA improve signal
High Power Gain UWB LNA

to noise ratio of RF signals. An LNA design for an IR UWB receiver should to operate 3.1–10.6 GHz wideband with adequate power gain, input matching, low noise figure and linearity.

**MULTI BAND OFDM UWB:** Due to increasing demand of wireless communications recently made OFDM techniques are popular. OFDM is widely used in modern wireless communication products, to take advantage of existing design, OFDM proposed for UWB system.

The MB-OFDM systems use multiple orthogonal bands to achieve Ultra-Wideband communication as shown in Fig. 5.3.

![Multi band proposed for the IEEE 802.15.3a standard.](image)

**FIGURE 5.3:** Multi band proposed for the IEEE 802.15.3a standard.

![MB OFDM UWB receiver architecture.](image)

**FIGURE 5.4:** MB OFDM UWB receiver architecture.

Fig. 5.4 shows MB OFDM UWB receiver architecture proposed by the Multiband Alliance for IEEE 802.15.3a standards. Fig. 5.4 shows MB OFDM UWB receiver architecture is more complex compare to IR UWB receiver. The MB OFDM has higher
power consumption it makes MB OFDM not suitable for low power receiver. MB OFDM has potential to provide high data rate and it is use entire 3.1–10.6 GHz frequency spectrum of UWB.

Both the IR UWB and OFDM UWB systems achieved very high data rates but having complex receiver architecture and consuming high power.

LNA used in RF front end of UWB receiver implement using three different approaches; 1) Multiple LNAs for each band, 2) an LNA with tunable capabilities to cover entire 3.1-10.6 GHz spectrum, 3) single 3.1-10.6 GHz UWB LNA. In this thesis design 3.1-10.6 GHz UWB high power gain LNA to support both IR UWB and OFDM UWB systems.

5.2 Proposed High Power Gain UWB LNA

Proposed design for UWB LNA has CG input stage with multi cascaded CS stages. Resistive load provide wideband output matching in most of literature survey design use resistive load. Drawback of using resistance in design is adding thermal noise. In our design we have used low quality factor inductor as load. To extend bandwidth we have resonant each stage at different frequency. Our design forms cascaded three active band pass filter structure. In last stage we have used common drain to drive high capacitive load of next stage. Complete schematics of our design shown in figure this UWB LNA is design using 0.18 μm RFCMOS technology.

MULTISTAGE LNA DESIGN: The proposed UWB LNA has multi amplifier stages as shown in Fig. 5.5.

![Diagram](image)

**FIGURE 5.5:** Different stages of proposed design.
5.2.1 Circuit Analysis of Proposed Design

The schematic of the proposed LNA is demonstrated in Fig. 5.6. The LNA consists of four stages with separate biasing circuits. The input stage of the LNA is a common gate, which gives high bandwidth input matching. The inductor connected between the source of the M1 and ground provides the LC resonator with Cgs1. It also gives the input impedance matching to 50Ω. The second stage is the cascode stage to increase gain. The third stage is a cascode amplifier with series RC feedback to increase gain and bandwidth enhancement, and the last stage is a common drain amplifier for driving the input capacitive load for a mixer [90].

In proposed LNA, width of M1 is chosen to get the better transconductance with the source inductor. The large value capacitor is between the M1 gate and ground ensures better AC grounding. It is also bypasses the biasing circuit noise.

Width of M1 selection is a tricky task, because value of inductor L2 is restricted by the RFIC. L2 must be chosen as it will resonate with $C_{d1} + C_{gs2}$ around the center frequency of the interested band. With the help of iteration the L1 value is chosen for the best noise performance. The chosen value of Ls is much greater than value of L1. Here the two LC
tank circuit formed, one is \( \text{L1 with } C_{gs2} + C_{gd1} \) and another is \( \text{Ls with } C_{gs1} \). These both circuits resonate around the center frequency of the interested band \([91]\).

Miller effect creates problem in the selection of the peaking frequency, to reduce miller effect the cascode transistor added to the common source stage which cause increases the higher frequency cutoff. Cascode stage also provides contribution to improve the gain and the reverse isolation, without consuming more power.

### 5.2.2 Input Impedance Analysis

Literature survey shows Common Gate have inherently wideband impedance matching characteristics. In this design we have used CG with inductive source (Ls) input stage for wideband matching. CG suffers from low gain in our design we have used two common source (CS) stage to improve gain and bandwidth.

![Common Gate input stage](image)

**FIGURE 5.7:** Common Gate input stage.

AC equivalent circuit of CG first stage is shown in Fig. 5.8.

![CG AC equivalent circuit](image)

**FIGURE 5.8:** CG AC equivalent circuit.

The input impedance is calculated by

\[
Z_{in} = \frac{-V_{gs}}{I_{in}}
\]  

(5.3)
Value of $R_0$ is very large compared to $Z_0(\omega)$. By applying KCL at input source node of MOSFET:

$$I_{in} = \frac{-V_{gs}}{Z_s(\omega)} - g_{m1}V_{gs} - \frac{(V_{gs} - g_{m1}V_{gs}Z_0(\omega))}{R_o} \quad (5.4)$$

Where, $Z_s(\omega) = j\omega L_s/\left(\frac{1}{j\omega C_{gs}}\right)$ and $Z_0(\omega) = \frac{1}{j\omega C_{gd}}//\frac{j\omega L_d}{Z_{in2}}$

$$Z_{in} = \frac{-V_{gs}}{I_{in}} = \frac{1}{\frac{1}{g_{m1}Z_s(\omega)} + \frac{1}{Z_0(\omega)}} \quad (5.5)$$

For good input matching over the wideband $L_s$ and $C_{gs}$ should be selected such that they resonate at the center frequency leaving only 50Ω real impedance.

### 5.2.3 Noise Analysis and Optimization

As per friss formula first stage noise figure contribute major in overall noise figure of the multistage amplifier. Noise analysis of the first common gate stage of the proposed topology is analyzed in detail.

First stage has two sources of noise, source resistor $R_s$ and channel noise of MOSFET. Noise figure of the CG first stage can be modeled as (5.6).

$$NF1 = 1 + \frac{V_{n,d1}^2}{\alpha^2 A_{p}^2} X \frac{1}{4kT R_s} \quad (5.6)$$

Where $\alpha = \frac{Z_{in}}{R_s + Z_{in}}$, $Z_{in} = S\frac{L_s}{(\frac{1}{S C_{gs}})}$, $V_{n,d1}^2 = \frac{4kTY}{g_m}$ and $A_v = g_{m1}Z_{out}$

Substituting above values in (5.6) NF1 simplify as

$$NF1 = 1 + \frac{\gamma}{g_m} \left[\frac{(S^2 L_s C_{gs1} + 1)^2}{L_s} \frac{R_s}{L_s} + \frac{2(S^2 L_s C_{gs1} + 1)}{L_s} \frac{1}{R_s}\right] \quad (5.7)$$

From the (5.7) shows first stage NF (NF1) is inversely proposal to transconduactance ($g_m$) of M1, input and output impedance and directly proposal to $C_{gs1}$. NF1 can be optimized using two approaches.

- Value of $L_s$ and $C_{gs1}$ select such that it resonant at center of selected band.
- NF1 is inversely proposal to transconductance of the first stage ($g_{m1}$). Increase $g_{m1}$ will improve NF1 but it degrades input impedance matching of the design. Here is tradeoff between input impedance and NF. Reducing $C_{gs1}$ by reducing $W$ of M1.
will result reduction of noise figure. On the other hand, scaling down the width of means more current is consumed to maintain the same transconductance. The \( W_1 \) should be chosen such that it will improve noise performance at given power budget.

The output impedance of the source follower is calculated as

\[
Z_{\text{out}}(\omega) = \frac{1+j\omega Z_2(\omega) c_{gs6}}{g_m + j\omega c_{gs6}} / \left/ r_{06} / r_{07} \right.
\]  

\[
Z_{\text{out}}(\omega) = \frac{1+j\omega Z_2(\omega) c_{gs6}}{g_m + j\omega c_{gs6}} \quad (5.9)
\]

Where \( r_{06} \) and \( r_{07} \) are drain to source resistor of M6 and M7 respectively, the value these resistors are very large compare to other term so it can be neglected. Optimized design variables value of the proposed high power gain UWB LNA is given in Table 5.1.

<table>
<thead>
<tr>
<th>Components</th>
<th>Value</th>
<th>Components</th>
<th>Value</th>
</tr>
</thead>
<tbody>
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<td>( W_1 )</td>
<td>5.6x64 ( \mu )m</td>
<td>( L_s )</td>
<td>1.48 nH</td>
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<td>( W_2 )</td>
<td>5.3x64 ( \mu )m</td>
<td>( L_{d1} )</td>
<td>0.61 nH</td>
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<td>( W_3 )</td>
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<td>( W_4 )</td>
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<td>( W_5 )</td>
<td>5.3x64 ( \mu )m</td>
<td>( V_{b1} )</td>
<td>0.51 V</td>
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<td>( W_6 )</td>
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<td>( V_{b2} )</td>
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<tr>
<td>( W_7 )</td>
<td>2x30 ( \mu )m</td>
<td>( V_{dd} )</td>
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<td>( R_f )</td>
<td>6.0 k( \Omega )</td>
<td>( C_1 )</td>
<td>1.0 pF</td>
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<tr>
<td>( C_f )</td>
<td>120 fF</td>
<td>( C_2 )</td>
<td>1.0 pF</td>
</tr>
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5.2.4 Layout of UWB LNA Design

![Layout of UWB LNA](image)

FIGURE 5.9: Layout of UWB LNA.
5.2.5 Simulation Results and Discussion

FIGURE 5.11: $S_{21}$ and $S_{11}$ simulation results of UWB LNA.
Proposed High Power Gain UWB LNA

Figure 5.12: Noise Figure Simulation results of UWB LNA.

Figure 5.13: DC simulation result of UWB LNA.

Figure 5.14: Harmonic simulation result of UWB LNA @ 6GHz frequency.
TABLE 5.2: IIP3 value at different frequencies of UWB LNA.

<table>
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<th>Freq.</th>
<th>IIP3 (dBm)</th>
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<td>4</td>
<td>-13.5</td>
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<tr>
<td>5</td>
<td>-8</td>
</tr>
<tr>
<td>6</td>
<td>-3.5</td>
</tr>
<tr>
<td>7</td>
<td>-5</td>
</tr>
<tr>
<td>8</td>
<td>-3.3</td>
</tr>
<tr>
<td>9</td>
<td>-3</td>
</tr>
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</table>

Simulation results of proposed UWB LNA, achieved high power gain greater than 20 dB in interested 3.1-10.6 GHz band with tolerable noise figure 2.8-6 dB. Input and output impedance matching coefficient S\(_{11}\) and S\(_{22}\) are less than -9 dB in interested band which shows good input and output matching and maximum power transfer takes place. Fig. 5.14
Proposed High Power Gain UWB LNA shows harmonic simulation of the design at 6 GHz to find linearity measure IIP3 and it achieved IIP3 is -3.5 dBm. Performed harmonic simulation at different frequencies and achieved IIP3 at different frequencies is shown in Table 5.2. Fig. 5.15 is the plot of frequency versus IIP3 of the design and it shows average IIP3 of the design is -5.5 dBm. The design is achieve good linearity by optimum biasing of each stages. DC simulation result of the design is shown in Fig. 5.13. The proposed design consuming 23 mA total current including bias circuit current from 1.5 V supply. So, total power consumption of the UWB LNA is 34 mW. Fig. 5.16 is the group delay simulation result of the UWB LNA. Group delay variation of the proposed UWB LNA is ±100ps.

Compare proposed design results with published work is given in Table 5.3. It is observed from Table 5.3 that the proposed UWB LNA design having very high power gain, good linearity and wideband impedance matching with tolerable noise figure. Due to high power gain our design is most suitable for low power signal UWB receiver RFIC and it will open new frontier for UWB wireless communication receiver design. Figure 5.17 shows FOM comparison of the proposed UWB LNA design with published UWB LNA design. Proposed UWB LNA design achieved 32.99 FOM.
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<th>Parameter</th>
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<th>Freq. (GHz)</th>
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<th>$S_{11}$ (dB)</th>
<th>NF (dB)</th>
<th>IIP3 (dBm)</th>
<th>Power Consumption (mW)</th>
<th>Area (mm$^2$)</th>
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