Design of a Low Current Leakage Integrator for Non-Coherent Ultra-WideBand Receiver

By

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Abstract

Non-coherent receiver architecture is preferred more than coherent receiver architecture in many applications due to its lower complexity (hence lower cost) and lower energy consumption even though it may have shorter communication range. Even it has a lower complexity, it is still problem to utilize energy without sacrificing performance of the system. Integrator is a key block of non-coherent receiver architecture, needs to be designed for minimum power consumption and minimum distortion. Current leakage is one of the most important distortion type of integrator, needs to be taken under control.

In this thesis work, three different Gm-C based integrator has been designed to identify effects of different performance parameters of OTA on the current leakage. Three different cascode/telescopic based OTA are implemented in circuit level using a 90nm CMOS technology and Cadence tools. Furthermore, both system level and circuit level simulations are given and compared.

Improved Telescopic OTA and Regulated Cascode OTA are implemented which have 15.71MHz and 2.23MHz cutoff frequencies respectively, against the Conventional Telescopic OTA that has 3.166 MHz cut off frequency. Both Improved and Regulated OTA has lower current leakage %4.38 and %6.93 at 150MHz input signal than Conventional Telescopic OTA that has %7.70 current leakage during discharging.
Acknowledgement

This thesis project has been done at Ipack VINN Excellence Design Center at KTH. I appreciate this opportunity to work with real project. During this period, I have learned a lot not only in terms of specific knowledge and technical skills of doing research but also the way that research activities are conducted in the international environment.

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<th>Description</th>
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</thead>
<tbody>
<tr>
<td>BER</td>
<td>Bit Error Rate</td>
</tr>
<tr>
<td>UWB</td>
<td>Ultra Wideband</td>
</tr>
<tr>
<td>IR</td>
<td>Impulse Radio</td>
</tr>
<tr>
<td>RX</td>
<td>Receiver</td>
</tr>
<tr>
<td>WSN</td>
<td>Wireless Sensor Networks</td>
</tr>
<tr>
<td>MB-OFDM</td>
<td>Multi-Band Orthogonal Frequency Division Multiplexing</td>
</tr>
<tr>
<td>WLAN</td>
<td>Wireless Local Area Network</td>
</tr>
<tr>
<td>OOK</td>
<td>On-Off Keying</td>
</tr>
<tr>
<td>PPM</td>
<td>Pulse Position Modulation</td>
</tr>
<tr>
<td>IC</td>
<td>Integrated Circuit</td>
</tr>
<tr>
<td>WPAN</td>
<td>Wireless Personal Area Network</td>
</tr>
<tr>
<td>BER</td>
<td>Bit Error Rate</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal to Noise Ratio</td>
</tr>
<tr>
<td>LNA</td>
<td>Low Noise Amplifier</td>
</tr>
<tr>
<td>VGA</td>
<td>Voltage Gain Amplifier</td>
</tr>
<tr>
<td>BPF</td>
<td>Band Pass Filter</td>
</tr>
<tr>
<td>S-H</td>
<td>Sample and Hold</td>
</tr>
<tr>
<td>ADC</td>
<td>Analog to Digital Converter</td>
</tr>
<tr>
<td>BW</td>
<td>Bandwidth</td>
</tr>
<tr>
<td>OTA</td>
<td>Operational Transconductance Amplifier</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>Opamp</td>
<td>Operational Amplifier</td>
</tr>
<tr>
<td>CMFB</td>
<td>Common Mode Feedback</td>
</tr>
<tr>
<td>GBW</td>
<td>Gain Bandwidth Product</td>
</tr>
<tr>
<td>$A_{OL}$</td>
<td>Open Loop Gain</td>
</tr>
<tr>
<td>SR</td>
<td>Slew Rate</td>
</tr>
<tr>
<td>$f_c$</td>
<td>Cutoff Frequency</td>
</tr>
<tr>
<td>$R_{OUT}$</td>
<td>Output Resistance</td>
</tr>
<tr>
<td>$C_L$</td>
<td>Load Capacitance</td>
</tr>
<tr>
<td>$G_m$</td>
<td>Transconductance</td>
</tr>
<tr>
<td>$V_{in_p}$</td>
<td>Positive Input Voltage</td>
</tr>
<tr>
<td>$V_{in_n}$</td>
<td>Negative Input Voltage</td>
</tr>
<tr>
<td>$V_{GS}$</td>
<td>Gate to Source Voltage</td>
</tr>
<tr>
<td>$V_{T}$</td>
<td>Threshold Voltage</td>
</tr>
<tr>
<td>$L$</td>
<td>Channel Length</td>
</tr>
<tr>
<td>$I_{DS}$</td>
<td>Drain to Source Current</td>
</tr>
<tr>
<td>RGC</td>
<td>Regulated Cascode</td>
</tr>
<tr>
<td>FBC</td>
<td>Fixed Biased Cascode</td>
</tr>
<tr>
<td>OBC</td>
<td>Optimally Biased Cascode</td>
</tr>
</tbody>
</table>
CHAPTER 1

INTRODUCTION

1.1 Background

The concept of Ultra-Wideband (UWB) was formulated in the early 1960s through research in time-domain electromagnetics and receiver design. Through this work, the first UWB communications patent was awarded for the short-pulse receiver [23]. After that time, UWB was referred in broad terms as “carrierless” or impulse technology. Even though the knowledge has been in existence for over thirty years, Ultra Wideband-Impulse Radio (UWB-IR) is an emerging technology that has been introduced in wireless sensor networks design to reduce the power consumption and improve the communication capabilities [1]. Nowadays, UWB receiver is mostly used with coherent or non-coherent structure. Coherent based receiver offer long range and better Bit Error Rate performance in noisy channel conditions. But these types of receivers have higher complexity which causes higher cost and higher power consumption. In many applications where cost and energy consumption are critical, non-coherent receivers are desirable even though they may have shorter communication range and inferior performance under certain channel conditions [24]. In this project, non-coherent energy receiver is used because it allows simple circuit architecture that does not require a frequency synthesizer and a signal template for integration. In non-coherent differential architecture based receiver, the integrator is the one of the important analog block. Due to high frequency requirement, integrator is implemented using Gm-C structure. In this structure, operational transconductance amplifier is used for Gm. The operational amplifier is the block with the highest power consumption in analog integrated circuits in many applications. Thanks to the low power consumption, telescopic operational transconductance amplifier is chosen instead of two stage and folded-cascode OTA. During integration, discharging (current leakage) is occurring on the Sample-Hold capacitors. These current leakages can be higher or lower according to the OTA performance. This thesis project targets to identify effects of OTA parameters on the current leakage. The most important OTA parameters which have a contribution on the current leakage are defined in system level analysis.
According to this system level feedback, different Telescopic (Cascode) OTA circuits are implement and their current leakage and parameters are compared.

1.1 Thesis Outline

This thesis project covers the theoretical analysis, system level and circuit level design of Gm-C Integrator and OTA design for non-coherent ultra-wideband receiver.

Chapter 2 gives overview of the ultra-wideband impulse radio (UWB-IR) receiver technology including fundamental theories and architectures for receiver.

Chapter 3 presents different type of integrators and effect of various parameter of OTA are analyzed and the corresponding solutions for current leakage are discussed.

Chapter 4 presents the details of circuit level design of different implemented Gm-C Integrator. Conventional Telescopic OTA, Improved Telescopic OTA and Regulated Telescopic OTA are implemented at transistor level. Furthermore, their signal analyses are given in this chapter.

Chapter 5 offers the transistor level simulation results for both AC and Transient Analysis. Current leakage calculations for all implemented OTA are given. Also, hand calculation and simulation results are compared. Finally, some suggestions about chosen of OTA parameters to decrease current leakage (discharging) are given according to the results.
CHAPTER 2

OVERVIEW OF THE ULTRA-WIDEBAND IMPULSE RADIO (UWB-IR) RECEIVER TECHNOLOGY

This chapter gives an overview of the ultra-wideband impulse radio receiver technology. Firstly, it begins with an introduction of the ultra-wideband technology. Secondly, due to importance and relations with integrator, both UWB receiver modes and modulation techniques are discussed. Thirdly, UWB-IR RX Architecture is described.

2.1 Ultra-Wideband Impulse Radio Technology Overview

Ultra-wideband communication (UWB) is an emerging technology and research topic; however the knowledge of UWB has been existence for over forty years. It has been introduced in Wireless Sensor Networks (WSN) design as a way to reduce the power consumption and improve the communication capabilities with respect to narrow band systems [1] and Multi-Band (MB-OFDM) [2][3]. The UWB systems can be classified into Impulse Radio (IR) and Orthogonal Frequency Division Multiplexing (OFDM) based system. Whereas the OFDM based UWB system is suitable to high data rate communication, the UWB-IR is appropriate solution for low rate and low power applications. [4] Unlike classical radio systems, the UWB-IR receiver does not require a down conversion stage. This means that a local oscillator in the receiver can be omitted and as a result UWB-IR receiver can be implemented in low cost complementary metal oxide-semiconductor (CMOS) [5][6]. The important features and their benefits of UWB technology can be seen in table 2-1 [7]. Furthermore, the available frequency band of UWB is allocated as shown in Figure. 2-1[4].
As seen from Figure. 2-1, 3.1~10.6 GHz band can be used except 5-6 GHz ISM band assigned for WLAN applications. Therefore, overall bands are composed of 3.1~5 GHz lower band and 6~10.6 GHz higher band.

**Table 2-1: Features and Benefits of UWB Technology**

<table>
<thead>
<tr>
<th>Features</th>
<th>Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Speed Throughput in short range</td>
<td>Fast, High Quality Transfer</td>
</tr>
<tr>
<td>Low Power Consumption</td>
<td>Long Battery Life for Portable Devices</td>
</tr>
<tr>
<td>CMOS Technology</td>
<td>Low Cost</td>
</tr>
<tr>
<td>Low Complexity</td>
<td>Low Design Time</td>
</tr>
<tr>
<td>Wired Connectivity Options</td>
<td>Convenience and Flexibility</td>
</tr>
</tbody>
</table>
2.2 UWB Receiver Architectures/Modes and Modulation Techniques

In the previous researches and literature, it is easy to find different receiver architecture such as super regenerative architecture, coherent, semi coherent and non-coherent architectures. It is important to decide which receiver architecture more appropriate for investigated application. Moreover, it is needed to decide carefully which modulation techniques will be used with the chosen receiver architecture. There is numerous modulation techniques can be used with UWB-IR, On-Off Keying (OOK) and Pulse Position Modulation (PPM) are two of them. OOK and PPM are popular UWB modulation techniques due to their simplicity and flexibility towards duty cycle pulsed communication system [8]. In this project a 0.66nJ/bit non-coherent energy receiver that works with PPM and OOK modulation a data rate up to 33Mb/s has been designed. For more details, please check reference [3] which is written by IPack Vinn Excellence Center researches. In the below sections, more details and explanations can be found about different receiver modes and modulation techniques.

2.2.1 Receiver Architectures/Modes

**Super-Regenerative** architectures using OOK modulation use a self-oscillation induced by the incoming signal and proportional to its power and frequency [9]. This architecture can achieve low energy per bit but has low immunity to external interferences. **Coherent** architecture shows a better sensitivity and performance but the synchronization usually requires higher circuit complexity that can increase the power consumption [3]. The template signal generation is a kind a disadvantage of coherent architecture. The template signal generation requires a channel estimation which is highly complex to predict due to energy dispersion over multiple delayed paths [3] [10]. **Non-Coherent** architecture allows simple circuit architecture that does not require a frequency synthesizer and a signal template for integration. Furthermore, it can be operated with smaller current consumption [11] [12].
### 2.2.2 Modulation Techniques

**On Off Keying (OOK)** is the most simple modulation technique where a pulse is transmitted to represent/determine a binary ‘1’ and where no pulse is transmitted represent/determined a binary ‘0’. Simplicity of physical implementation of OOK is the biggest advantage which it has. However, there are some system drawbacks. Synchronization can be easily lost if the data contains a steady stream of “0’s.” Also, Bit Error Rate (BER) performance of OOK is worse than PPM. OOK can be used both for non-coherent, semi-coherent and coherent receive mode. OOK timing in different receive modes can be seen in figure 2-2.

![Figure 2-2: OOK timing in different receive modes](image)

In non-coherent mode using OOK modulation, energy is integrated over several pulses. Integrator is not closed between pulses, giving relaxed timing requirements. On the other hand, non-coherent detection requires a good estimation of the integrator threshold. Non-coherent detection can be achieved by setting the pulse clock equal to the symbol clock using a long integration window. In semi-coherent mode using OOK modulation, energy is integrated over one or several pulses. Integrator is only active over a small window around the time where the pulse is expected to arrive. This gives a better signal to noise ratio (SNR) compared to non-coherent detection and allow more accurate positioning, however requires a more accurate timing circuit [13].

**Pulse Position Modulation** is a modulation technique where timing of the each pulse is changed to transmit data instead of varying the amplitude. In PPM, the information in the transmitted signal is determined by position of pulses. Figure 2-3 shows the timing for semi coherent reception of a PPM modulated signal. In this example a logical ‘0’ is represented by one pulse position (black curve) and logical ‘1’ is represented by another position (gray curve).
In this project for PPM modulation, two interleaved integrators are used. Depending on which pulse position contains the most energy, one of the integrators will have a higher final output value. The advantage of the pulse position modulation compared to on-off keying is that no threshold level is needed to distinguish between one and zero.

### 2.3 UWB-IR Receiver Architecture Description

In this project, the receiver (RX) is based on a non-coherent differential architecture. In the receiver, the signal is amplified by the Low Noise Amplifier (LNA) and Voltage Gain Amplifier (VGA), squared by the four quadrant multiplier and then integrated by a bank of 4 integrators. Figure 2-4 shows the RX architecture.
The receiver has been designed to work with UWB-IR passive sensor tags introduced in [14], inside the 3.1-4.8 GHz band. The incoming signal is received by antenna and a Band Pass Filter (BPF) which is working for 3.1-4.8GHz, is used to remove out of band interferences. The resulting signal is amplified, rectified and integrated respectively. This signal amplified by LNA and VGA. LNA and VGA provide the required gain that compensates the analog multiplier attenuation based on the incoming signal strength. Then, it is rectified by multiplier/square circuit which drives the integrator. After that, signal which is an output of the multiplier integrated by integrator. Two independent multiplier circuits have been used for each integrator to avoid circuit over-loading which significantly reduces the bandwidth (BW) and increases the signal attenuation. Using Sample and Hold (S-H) capacitor the final analog voltage is stored. This voltage is then amplified and sampled by a differential Analog to Digital Converter (ADC) for bit evaluation.
CHAPTER 3

OVERVIEW OF THE INTEGRATOR AND SYSTEM LEVEL DESIGN OF INTEGRATOR

This chapter will explain integrator which is the important building block for UWB Receiver. Firstly, the simplest passive RC integrator will be described. Secondly, Active Opamp-C integrator will be explained. Thirdly, Gm (OTA) - C integrator which is used in this project will be given, with brief explanation why it is more suitable for UWB applications. Finally, the important parameters of OTA which cause a current leakage (discharging) and their affects will be discussed.

3.1.1 Passive RC Integrator

The simplest integrator passive RC integrator is shown in figure 3-1. Passive RC Integrator is made up of passive components such as resistors, capacitors so have no amplifying elements such as transistors or opamp so have no signal gain, therefore its output level is always less than the input. This circuit can be used both low pass filter and integrator. To identify when this circuit works as an integrator, it is needed to look its transfer function.

![RC Integrator Diagram](image)

Figure 3-1: RC Integrator
The corresponding transfer function relating the output voltage to the input voltage is given by Eq. (3.1).

\[
\frac{V_o(s)}{V_i(s)} = \frac{1}{1+RCs}
\]  

(3.1)

The circuits acts as an integrator if RCs \(\gg 1\) or equivalently for Eq. (3.2) [15]

\[
W = 2\pi f \gg \frac{1}{RC} \text{ rad/s}
\]  

(3.2)

In other words, passive RC circuit acts as integrator only for signals with frequency 10 times higher than cutoff frequency of passive RC circuit (low pass filter). To understand when exactly this circuit works as an integrator, frequency response curve (bode plot) of RC is given in figure 3-2. After the cut off frequency point, there is a slope of -20 dB/decade where the circuit works as an integrator.

![Bode Plot of RC Integrator](image)

**Figure 3-2: Bode Plot of RC Integrator** [16]
Now, it is time to see bode plot of ideal integrator so it can easily identified when the circuits work as an integrator or filter. Bode plot of ideal integrator is given figure 3-3. According to this figure, ideal integrator works perfectly where the circuit response is decreasing a slope of -20 dB/decade or – 6dB/octave and has a -90° phase.

![Bode Plot of Ideal Integrator](image)

**Figure 3-3: Bode Plot of Ideal Integrator [17]**

### 3.1.2 Active Opamp-C Integrator

The main disadvantage of passive RC circuit is that the amplitude of the output signal is less than that of the input signal, so the gain is never greater than unity. To get higher gain, opamp-C integrator can be used. Its principle of operation and frequency response is exactly the same as those for the previously seen passive RC circuit; the only difference this time is that it uses an op-amp for amplification and gain control. The simplest form of an opamp-c integrator is to connect an inverting or non-inverting amplifier with resistance and capacitance. As an example non-inverting Opamp-C Integrator can be seen in figure 3-4.
Opamp-C Integrator has same frequency response with passive RC integrator which is given in figure 3-2 with higher gain. One of the drawbacks of this integrator is that it does not have a good response at higher frequencies. Due to that reason, Gm-C Integrator is preferred in high frequency applications.

### 3.1.3 Gm-C Integrator

Gm-C integrator can be realized with Operational Transconduction Amplifier (OTA) and capacitor or capacitor banks. Gm-C integrator is based on an open-loop integrator structure. Gm-C integrator can be seen in figure 3-5.
In this integrator structure, a transconductor produces a current proportional to the differential input voltage and the output is taken across the integrating capacitors. If the transconductor is ideal with a transconductance equal to $G_m$, the transfer function of integrator can be given as in the eq. (3.3).

$$H(s) = \frac{G_m}{sC} \quad (3.3)$$

Since the Gm-C integrator is an open-loop integrator, it has the potential for very high speeds. Furthermore, the transconductor has to drive only capacitive loads; however, the integrator unity gain frequency is sensitive to parasitic capacitances. Tradeoff between different integrator configurations related with linearity, power and frequency can be seen in the table 3.1.

**Table 3-1: Integrator Topologies with Tradeoff [19]**

<table>
<thead>
<tr>
<th>Topologies</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Frequency</td>
</tr>
<tr>
<td>Opamp-C</td>
<td>Low</td>
</tr>
<tr>
<td>Gm-C</td>
<td>High</td>
</tr>
<tr>
<td>Gm-Opamp-C</td>
<td>Low</td>
</tr>
</tbody>
</table>

It can be easily seen, among different architectures or topologies, Gm-C is more suitable for energy detection receivers because high frequency response with lower power consumption.

The DC gain, linearity and the high frequency performance of the integrator is heavily dependent on the particular transconductor used in the design. That’s why, it is important to choose proper Gm topology for Gm-C Integrator. There are many Gm (transconductance) topologies can be found in the literature. The most important ones are Telescopic, Folded Cascode and 2-Stage OTA. For different parameters, tradeoff between the important Gm topologies can be seen in table 3-2.
### Table 3-2: Gm (Transconductance) Topologies for Different Parameters

<table>
<thead>
<tr>
<th>Topologies</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gain</td>
</tr>
<tr>
<td>Simple 2-Stage</td>
<td>Medium</td>
</tr>
<tr>
<td>Folded Cascode</td>
<td>High</td>
</tr>
<tr>
<td>Telescopic</td>
<td>High</td>
</tr>
</tbody>
</table>

The other important parameter for OTA is power consumption. There is a tradeoff between speed, power and gain too for OTA design and these parameters are usually contradicting parameters. The telescopic amplifier consumes the least power compared with the other two OTA. In this project, Gm-cell is implemented with telescopic/cascode OTA to get higher speed. Also, a Common Mode Feedback (CMFB) based on a differential continuous time topology is added to Gm-Cell to provide enough common mode gain and maintain a steady DC operating point. Brief explanation about OTA and CMFB design for this project is given in the chapter 4.

### 3.2 System Level Design of Integrator

System level analyze has been done in this project to identify which parameters of circuit has an effect on the current leakage (discharging) in the integrator. This current leakage is occurring during S-H capacitors are discharging. This leakage decreases the performance of the receiver. The most important circuit parameters which create leakage and limit overall all performance of the receiver are investigated. These parameters are Open Loop Gain ($A_{OL}$), Cutoff Frequency ($f_c$), Gain Bandwidth Product (GBW), Output Resistance ($R_{OUT}$), and Slew Rate (SR). In the below section, how these parameters affect leakage is explained. Furthermore, to decrease leakage, appropriate way to choose parameters is given for optimum circuit level design. Before looking effect of these parameters, it is necessary to know ideal and practical (non-ideal) integrator transient and frequency responses. Frequency and phase response plots of ideal and practical integrator are given in figure 3-6.
In reality, the response deviates from the ideal case at low frequencies due to finite DC gain and at high frequencies due to parasitic poles and zeros which creates finite bandwidth. A transistor-based integrator cannot produce an output voltage from $-\infty$ to $+\infty$. In reality, integrator can only produce output voltages within a finite range, typically from ground to a source voltage depending on type of topology like Gm-C. In non-ideal case, phase can differ too. Even, it can works as integrator below or above 90° phase, but it decrease efficiency and can affect circuit stability. The step response of Ideal Integrator with finite dc gain which is 1 is given in figure 3-7-a. Transient response of the non-leakage practical integrator where square input pulse is used is also given in figure 3.7-b.

Figure 3-6: Bode plot of ideal and practical (non-ideal) Integrator [17]
Figure 3-7-a: Transient Response of Ideal Integrator

Figure 3-7-b: Transient Response of non-leakage practical (non-ideal) Integrator

In the figure 3-7-b, it can be seen that: the signal is integrated during period of integration, after that it saturates. In the below section, it will be understood more clearly, how integrator transient response will change, if there is a leakage.

3.2.1 Open Loop Gain, Cutoff Frequency and Gain Bandwidth Product

Open loop gain, Cutoff frequency and Gain bandwidth product are common characterization parameters which are used to classify the functionality of the OTA structures. These performance measurement parameters will be used to analyze designed OTA circuits/structures via theoretical calculations and simulations in chapter 4, briefly. Now, it is good to know general formula of each parameter for OTA structure. Open loop gain, cutoff frequency and gain bandwidth product equations are given in the eq. (3.4), (3.5) and (3.6) respectively.

\[ \text{AOL} = g_{m1} \cdot R_{\text{OUT}} \tag{3.4} \]

\[ f_c = \frac{1}{2\pi R_{\text{OUT}} C_L} \tag{3.5} \]

\[ \text{GBW} = \frac{g_{m1}}{2\pi C_L} \tag{3.6} \]
It is obvious; GBW is product of open loop gain and cutoff frequency. It is called unity gain bandwidth too. Now, open loop gain response is investigated to identify its effect on leakage by assuming each integrator has same unity gain bandwidth with variable DC gain. Both AC and Transient response plots are given in the figure 3-8.

Figure 3-8: Bode and Transient Response Plots of Integrators with different gains

In the figure 3-8, one can see that, when DC gain is increased while GBW is kept constant, it has a better transient response which is more closed to ideal one. As a result, having more gain will decrease leakage (discharging). Now, cutoff frequency response is investigated to identify its effect on leakage by tuning center frequency and keeping the DC gain constant, the unity gain bandwidth will vary as shown in the figure 3-9.

Figure 3-9: Bode and Transient Response Plots of Integrators with different cutoff frequency
In the figure 3-9, one can see that, when cutoff frequency is decreased while gain is kept constant, it has a better transient response which is more closed to ideal one. As a result, having lower cutoff frequency will decrease leakage (discharging).

### 3.2.2 Slew Rate

Slew rate is other common characterization parameter which is used to classify the functionality of the OTA structures. Help of Simulink, with the same open loop gain and cutoff frequency with different current leakage integrator is realized. Thanks to this architecture, changing of slew rate is understood for different current leakage. Transient response of this integrator is given in the figure 3-10.

![Figure 3-10: Transient Response of Integrator with different current leakage](image)

In the figure 3-10, one can see that, current leakage is getting smaller when slew rate is getting higher and integrator has a better transient response which is more closed to ideal one. As a result, higher slew rate will decrease leakage (discharging).

### 3.2.3 Output Resistance

Output resistance is one of the most important characterization parameter with transconductance for OTA structure. Output resistance affects both gain and cutoff frequency. According to eq. (3.4) and (3.5), if output resistance is increased, gain will increased and cutoff frequency will decrease. These results show that the higher output resistance, lower current leakage. To identify that, Gm-C integrator is modeled in Pspice. Transient response of integrator with different output resistance can be seen in the figure 3-11.
Figure 3-11: Transient Responses of Integrator with different output resistance

In the figure 3-11, one can see that, current leakage is getting smaller when output resistance is getting higher. Even, with 1M ohm output resistance (black curve) which is not practical for OTA, there is no current leakage. Furthermore, it should be noticed, if the output resistance is getting higher, slew rate is increasing too. As a result, higher output resistance will decrease leakage (discharging).

As an overall result, to get lower current leakage, \( A_{\text{OL}} \), SR and \( R_{\text{OUT}} \) should be higher and cutoff frequency (-3dB frequency point) should be lower, which can be shown in table 3-3.
Table 3-3: Getting Lower Current leakage

<table>
<thead>
<tr>
<th>To get Lower Current Leakage (discharging)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Open Loop Gain</td>
<td>High</td>
</tr>
<tr>
<td>Cutoff Frequency</td>
<td>Low</td>
</tr>
<tr>
<td>Slew Rate</td>
<td>High</td>
</tr>
<tr>
<td>Output Resistance</td>
<td>High</td>
</tr>
</tbody>
</table>

It is obvious, increasing output resistance will increase both open loop gain and slew rate and decrease cutoff frequency. So the most important parameter is Output resistance to decrease current leakage. According to this knowledge, the new improved circuit which has a higher \( R_{\text{OUT}} \) is designed and compared with conventional circuit in Chapter 4.
CHAPTER 4

INTEGRATOR CIRCUIT LEVEL DESIGN

This chapter will explain circuit level design of integrator which is the important building block for UWB Receiver. Firstly, integrator circuit structure will be described. But this chapter generally will focus on the most important circuit block OTA design and its signal analysis. There are three different OTA circuit is implemented in this project to compare and identify current leakage in the circuit level. Secondly, first implemented Conventional Telescopic (Cascode) OTA design will be given in details. Thirdly, second implemented Improved Telescopic OTA design will be described. After that, last implemented Regulated Cascode OTA will be explained. Finally, a Common Mode Feedback (CMFB) circuit will be mentioned.

4.1 Integrator Circuit Structure

Integrator structure can be seen in figure 4-1. Integrator is implemented by using a Gm-cell that injects a current into the Sample-Hold capacitors (Cint1 or Cint2) which is proportional to the input voltage. Also, there is a set of switches which controls the capacitor charging and discharging cycles. These cycles are generated by Integration Window and Reset signals.

![Figure 4-1: Integrator Structure](image-url)
There is a switch resistance between Gm-cell and the Sample-Hold capacitor, which can be used to modify integrator RC constant. Common Mode Feedback Circuit is another circuit block which is added to provide enough common-mode gain and maintain a steady DC operating point. The Gm-cell is implemented with three different Operational Transconductance Amplifiers (OTA), each of them is explained in below sections. Same top level circuit diagram of integrator which can be seen in figure 4-2 is used in Cadence to test integrator with different OTAs.

Figure 4-2: Top Level Circuit Diagram of Integrator (Test Bench)
4.2 Conventional Telescopic (Cascode) OTA

A conventional, fully differential Telescopic, Operational Transconductance Amplifier (OTA) configuration is shown in figure 4-3.

![Figure 4-3: Conventional Telescopic OTA](image)

The Telescopic OTA employs differential input pairs (M1 and M2), cascode devices (M3 and M4) and current source loads (M5, M6, M7 and M8). An input device (M1 and M2) generates drain current proportional to input voltages (Vinp and Vinn). The cascode devices simply routes the current to current loads. Furthermore, cascode devices will increase the output resistance. It means larger the output impedance, the larger gain. OTA is loaded with PMOS cascode current sources (M5, M6, M7 and M8) to increase output impedance and reduce the Sample-Hold capacitor current leakage when long integration windows are used [3]. Figure 4-4 shows Conventional Telescopic OTA circuit schematic which is implemented in Cadence.
For UWB Receiver, high speed OTA is necessary. In this project when designing each OTA circuit, overdrive voltage ($V_{GS-V_T}$) of input devices and channel length (L) of transistors values are selected carefully according to the table 4-1.

**Table 4-1: High Speed Design [20]**

<table>
<thead>
<tr>
<th></th>
<th>High Gain</th>
<th>High Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{GS-V_T}$</td>
<td>Low (0.2V)</td>
<td>High (0.5V)</td>
</tr>
<tr>
<td>L</td>
<td>High</td>
<td>Low</td>
</tr>
</tbody>
</table>

It is striking that for high frequency (UWB) design, a large $V_{GS-V_T}$ is required and the lowest possible value of channel length L. This is exactly the opposite of what is required for high gain [20]. It is good to remember that, setting the values of $V_{GS-V_T}$ is the same as setting ratio of $gm/IDS$. Signal analysis of telescopic OTA is given below section. In this signal analysis part, the most important and related parameters of OTA for current leakage are chosen. Hand calculation
of each parameter can be found in Appendix. Furthermore, results are given and compared in simulation and result chapter 5.

4.2.1 Open Loop Gain ($A_{OL}$)

Open loop gain is one of the most important parameter for OTA design. In the OTA circuit, output current is given by equation 4.1.

$$i_{out} = i_{d1} - i_{d2} \quad (4.1)$$

where:

$$i_{d1} = g_{m1}V_i(+) \quad i_{d2} = g_{m2}V_i(-) \quad (4.2)$$

Assuming: $g_{m1} = g_{m2}$, and substituting (4.2) into (4.1):

$$i_{out} = g_{m1}(V_i(+) - V_i(-)) \quad (4.3)$$

The output resistance is given by Eq. 4.4

$$R_{OUT} = \left\{ \left[ 1 + (g_{m3} + g_{mbs3})*ro3\right]*ro1 + ro3 \right\} || \left\{ \left[ 1 + (g_{m5} + g_{mbs5})*ro5\right]*ro7 + ro5 \right\}$$

which is simplified

$$R_{OUT} \approx (g_{m3}*ro3*ro1) || (g_{m5}*ro5*ro7) \quad (4.4)$$

Combining (4.3) and (4.4), the output voltage is then given by:

$$V_{out} = i_{out} R_{out} = g_{m1}(V_i(+) - V_i(-))(g_{m3}*ro3*ro1) || (g_{m5}*ro5*ro7) \quad (4.5)$$

and the open loop gain is:

$$A_{OL} = \frac{V_{out}}{V_{in}} = g_{m1} (g_{m3}*ro3*ro1) || (g_{m5}*ro5*ro7) \quad (4.6)$$
4.2.2 Bandwidth

High frequency of cascode stage is investigated clearly in [21]. Here, critical pole frequency equations are given with output frequency (cutoff frequency). High frequency model of cascode stage can be seen in figure 4-5.

![High Frequency model of Cascode Stage](image)

At node A, the implemented circuit has another input capacitance which is parallel to $C_{GS1}$. So the pole associated with node A is given by Eq. 4.7

$$W_{p,A} = \frac{1}{R_s[(CGS1+\text{Cin})+(1+\frac{g_{m1}}{g_{m2}+g_{mb2}})CD1]}$$ (4.7)

At node X, the pole is calculated with Eq. 4.8

$$W_{p,X} = \frac{g_{m2}+g_{mb2}}{2CD1+CDB1+CSB2+CGS2}$$ (4.8)

Finally output node creates a third pole which is dominant pole/bandwidth of the OTA is given by Eq. 4.9

$$W_{p,\text{out}} = \frac{1}{R_{out}(CDB2+CGD2+CL+CS)}$$ (4.9)
4.2.3 Gain Bandwidth Product (GBW)

GBW is product of open loop gain and bandwidth. Equations (4.6) and (4.9) are combined for the gain bandwidth product (GBW) which is given Eq. 4.10

\[
\text{GBW} = \frac{gm1}{2\pi(CDB2 + CL + CGD2)}
\] (4.10)

4.2.4 Maximum Output Current and Slew Rate

The maximum output current of the conventional Telescopic OTA is limited by the bias current and given by Eq. 4.11.

\[
I_{OUT\ MAX} = \frac{I_{BIAS}}{2}
\] (4.11)

The slew rate (SR) is given by Eq. 4.12

\[
\text{SR} = \frac{I_{OUT\ MAX}}{CL}
\] (4.12)

4.3 Improved Telescopic (Cascode) OTA

An improved, fully differential Telescopic, Operational Transconductance Amplifier (OTA) configuration is shown in figure 4-6.

![Figure 4-6: Schematic of Improved Telescopic Operational Transconductor Amplifier](image-url)
From figure 4-6, one can find that a PMOS differential pair is introduced as compared with the conventional telescopic OTA. The PMOS differential pair injects current into nodes A and B, which helps improve the gain of the amplifier. Furthermore, the PMOS differential does not consume additional power and the power consumption of the improved design is the same as the conventional OTA. Implemented Improve Telescopic OTA can be seen in figure 4-7.

![Figure 4-7: Schematic of Improved Telescopic Operational Transconductor Amplifier in Cadence](image_url)

The transistors M0-M8 use the same architecture as the conventional telescopic OTA. M9-M11 are newly introduced to improve the gain of the amplifier. Results will be discussed in the next chapter. However, it is good to state that in here: Improved telescopic OTA has better gain due to increase of $gm_1$ but output resistance is decreased unfortunately compare to conventional design. To get higher gain and lower cutoff frequency, it is decided to design new OTA which has a higher output resistance. Then regulated cascode OTA which is explained in details in later section is chosen for this purpose.
4.3.1 Open Loop Gain (A_{OL})

Additional PMOS differential pair will contribute to Gm. To identify contribution, it is better to look small signal equivalent of both conventional and improved OTA. Figure 4-8 shows small signal equivalent circuits of the conventional OTA and figure 4-9 shows small signal equivalent circuits of the improved OTA.

![Figure 4-8: Small Signal half- equivalent circuit of the Conventional Telescopic OTA](image1)

![Figure 4-9: Small Signal half- equivalent circuit of the Improved Telescopic OTA](image2)

Compared with Fig. 4-8, there is an additional PMOS transistor whose drain is connected to M3 transistor’s gate. So the new Gm is given by Eq. 4.13

\[
Gm = gm_1 + gm_{10} \tag{4.13}
\]

What’s more, new output resistance is given Eq. 4.14

\[
R_{OUT} \approx (gm_3 * ro_3*(ro_1||ro_{10})) || (gm_5 * ro_5 * ro_7) \tag{4.14}
\]

As a result, open loop gain for new improved circuit is given Eq. 4.15

\[
A_{OL} = GmR_{OUT} = (gm_1 + gm_{10}) (gm_3 * ro_3*(ro_1||ro_{10})) || (gm_5 * ro_5 * ro_7) \tag{4.15}
\]
4.3.2 Bandwidth

A new additional PMOS differential pair will affect only X node which is farther from the other two nodes. Now, X node will be moved a little bit farther from the others too. So, it will not affect frequency response. But due to the change in output resistance, dominant pole/bandwidth of the OTA will change and it moves to the right and get higher cutoff frequency. The new equations for poles are given Eq. 4.16, 4.17 and 4.18 respectively.

\[
W_{p,A} = \frac{1}{R_s[(C_{GS1}+C_{in})+(1+\frac{g_{m1}+g_{m10}}{g_{m3}+g_{mb3}})C_{GD1}]} \tag{4.16}
\]

\[
W_{p,X} = \frac{g_{m3}+g_{m10}+g_{mb3}}{2C_{GD1}+C_{DB1}+C_{SB3}+C_{GS3}} \tag{4.17}
\]

\[
W_{p,\text{out}} = \frac{1}{R_{out}(C_{DB3}+C_{GD3}+C_{L}+C_{S})} \tag{4.18}
\]

4.3.3 Gain Bandwidth Product (GBW)

GBW is product of open loop gain and bandwidth. Equations (4.15) and (4.18) are combined for the gain bandwidth product (GBW) which is given Eq. 4.19

\[
\text{GBW} = \frac{g_{m1}+g_{m10}}{2\pi(C_{DB3}+C_{L}+C_{GD3})} \tag{4.19}
\]

4.3.4 Maximum Output Current and Slew Rate

The maximum output current of the improved Telescopic OTA is limited both the bias current and the current of M9 and given by Eq. 4.20.

\[
I_{\text{OUT MAX}} = (I_{\text{BIAS}} - I_{\text{M9}})/2 \tag{4.20}
\]

The slew rate (SR) is given by Eq. 4.21

\[
\text{SR} = \frac{I_{\text{OUT MAX}}}{C_{L}} \tag{4.21}
\]
4.4 Regulated Telescopic (Cascode) OTA

A Regulated Cascode, fully differential Telescopic, Operational Transconductance Amplifier (OTA) configuration is shown in figure 4-10.

Regulated Cascode OTA is version of simple telescopic circuit with the gate voltage of the cascode transistor being controlled by a feedback amplifier [22]. To obtain more gain, feedback is applied around the cascode transistor. This feedback is actually parallel-series feedback, causing the output impedance to rise by amount of feedback gain. The gain goes up by the same amount [20]. However, that gain boosting adds another gain enhancement at low frequencies. It will not alter the GBW. This phenomenon can be seen in figure 4-11.
In the fig. 4-11, one can see that, all of them (Regulated Cascode, Cascode and Single Trans.) have the same GBW but different gains and bandwidths. Implemented schematic of Regulated Cascode OTA is given in figure 4-12.
4.4.1 Open Loop Gain (A_{OL})

Additional NMOS differential pair will not contribute to Gm. It will only change R_{OUT}. The change in output resistance with respect to output voltage is given in figure 4-13 for both Regulated Cascode (RGC) and Fixed Biased Cascode (FBC) OTA. Optimally Biased Cascode (OBC) OTA is kind of FBC OTA which is technic used in Conventional Telescopic OTA design.

![Output Resistance Comparison](image)

Figure 4-13: Output Resistance as a function of the output voltage for the RGC and The OBC OTA, respectively [22]

The new output resistance equation is given by Eq. 4.22

\[
R_{OUT} \approx ((gm_3+gm_{10})*ro_3*(ro_{10}\|ro_9)*ro_1) \| (gm_5*ro_5*ro_7) \quad (4.22)
\]

As a result, open loop gain for Regulated Cascode OTA circuit is given Eq. 4.23

\[
A_{OL} = GmR_{OUT} = gm_1 ((gm_3+gm_{10})*ro_3*(ro_{10}\|ro_9)*ro_1) \| (gm_5*ro_5*ro_7) \quad (4.23)
\]

4.4.2 Bandwidth

A new additional NMOS differential pair will affect only X node which is farther from the other two nodes. Now, X node will be moved a little bit farther from the others too. So, it will not affect frequency response. But due to the change in output resistance, dominant pole/bandwidth of the OTA will change and it moves to the left and get lower cutoff frequency. The new equations for poles are given Eq. 4.24, 4.25 and 4.26 respectively.
\[
Wp,A = \frac{1}{R_s[(C_{G1}+C_{in})+(1+\frac{g_{m1}}{g_{m3}+g_{m10}+g_{mb3}})C_{GD1}]} \tag{4.24}
\]

\[
Wp,X = \frac{g_{m3}+g_{m10}+g_{mb3}}{2C_{GD1}+C_{DB1}+C_{SB3}+C_{GS3}} \tag{4.25}
\]

\[
Wp,\text{out} = \frac{1}{R_{out}(C_{DB3}+C_{GD3}+C_{L}+C_{S})} \tag{4.26}
\]

### 4.4.3 Gain Bandwidth Product (GBW)

GBW is product of open loop gain and bandwidth. Equations (4.23) and (4.26) are combined for the gain bandwidth product (GBW) which is given Eq. 4.19. Note that, GBW is same for conventional Telescopic OTA and Regulated Cascode OTA due to no change in Gm.

\[
\text{GBW} = \frac{g_{m1}}{2\pi(C_{DB3}+C_{L}+C_{GD3})} \tag{4.27}
\]

### 4.4.4 Maximum Output Current and Slew Rate

The maximum output current of the Regulated Cascode OTA is limited both the bias current and the current of M9 and given by Eq. 4.28.

\[
I_{\text{OUT MAX}} = (I_{\text{BIAS}})/2 \tag{4.28}
\]

The slew rate (SR) is given by Eq. 4.29

\[
\text{SR} = \frac{I_{\text{OUT MAX}}}{C_{L}} \tag{4.29}
\]
CHAPTER 5

SIMULATIONS AND RESULTS

5.1 AC and Transient Analyses of Designed OTAs

Before showing analyses results, it is better to mention about input signal properties. It has 6mV input amplitude. This value assumed to be got at the output of the squarer circuit. Furthermore, Square pulse is used for input signal. In these analyses, 150MHz input frequency which is 10 times higher than highest cutoff frequency (15.71MHz for Improved OTA) is used. Also, to explain importance of input signal frequency for integrator, transient responses of OTAs are given with different input signal frequencies.

5.1.1 AC and Transient Analyses of Conventional Telescopic OTA

Figure 5-1 shows bode plot of the conventional telescopic OTA.

![Bode Plot of the Conventional Telescopic OTA](image)

**Figure 5-1: Bode Plot of the Conventional Telescopic OTA**

Gain Margin = 31.59 dB (@-180) – 0 dB (@unity) = 31.59 dB

Phase Margin = -180° - (-287.1° (@unity gain)) = 107.1°
Frequency @peak= 871 KHz = 32.03 dB
Frequency @-3dB_{high}= 348.2 KHz = 29.03 dB
Frequency @-3dB_{low}= 3.166 MHz = 29.03 dB
Frequency @unity gain= 1.25 GHz = 0 dB
Frequency @2GHz = 2GHz = -4.368 dB

Figure 5-2 shows Transient response of the conventional telescopic OTA

Figure 5-2: Transient Response of the Conventional Telescopic OTA
5.1.2 AC and Transient Analyses of Improved Conventional Telescopic OTA

Bode plot of the improved conventional telescopic OTA can be seen in figure 5-3.

![Bode Plot of the Conventional Telescopic OTA](image)

**Figure 5-3: Bode Plot of the Conventional Telescopic OTA**

- **Gain Margin**: $34.3\, \text{dB (at -180)} - 0\, \text{dB (at unity)} = 34.3\, \text{dB}$
- **Phase Margin**: $-180^\circ - (-302^\circ \, (\text{at unity gain})) = 122.0^\circ$
- **Frequency @peak**: 1.585 MHz = 34.69 dB
- **Frequency @-3dB_high**: 410 KHz = 29.03dB
- **Frequency @-3dB_low**: 15.71 MHz = 29.03dB
- **Frequency @unity gain**: 3.60 GHz = 0 dB
- **Frequency @2GHz**: 2GHz = 5.304 dB

Transient response plot of the improved conventional telescopic OTA can be seen in figure 5-4.
5.1.3 AC and Transient Analyses of Regulated Cascode OTA

Figure 5-5 shows bode plot of the regulated cascode OTA

Gain Margin = 35.61 dB (@-180) – 0 dB (@unity) = 35.61 dB

Phase Margin = -180° - (-295.8° (@unity gain)) = 115.8°
Frequency @peak = 871 KHz = 35.69 dB
Frequency @-3dB_{high} = 304.1 KHz = 29.03dB
Frequency @-3dB_{low} = 2.23 MHz = 32.9dB
Frequency @unity gain = 1.48 GHz = 0 dB
Frequency @2GHz = 2GHz = -2.642 dB

Figure 5-6 shows Transient response of the Regulated Cascode OTA

Figure 5-6: Transient Response of the Regulated Cascode Telescopic OTA
5.2 Overall Results and Current Leakage (Discharging) Calculation

Figure 5-7 shows bode plots of the designed OTA together. Red one represents Regulated OTA, Green represents Improved Telescopic OTA and finally, black curve represent Conventional Telescopic OTA.

Figure 5-7: Bode Plots of the designed OTAs, Conventional Telescopic (Black), Improved Telescopic (Green) and Regulated Cascode (Red) OTA

Transient response plot of the designed OTA together can be seen in figure 5-8. Again, Red one represents Regulated OTA, Green represents Improved Telescopic OTA and finally, black curve represent Conventional Telescopic OTA.
Figure 5-8: Transient Responses of the designed OTAs, Conventional Telescopic (Black), Improved Telescopic (Green) and Regulated Cascode (Red) OTA

**General formula to calculate Current Leakage (Discharging) in percentage**

\[
\text{Current Leakage} = \frac{\text{Discharged Voltage (Energy) at saturated cycle}}{\text{Total Integrated Voltage (Energy) until saturated cycle}} \times 100\%
\]

**Note:** Saturated Cycle is a cycle where total integrated energy is %10 lower than maximum total integrated energy which is calculating at transient response analysis.

**Current Leakage (Discharging) Calculations for Each Circuit where input signal is 150MHz**

**At Saturated Cycle: For Conventional Telescopic OTA (Black Graph)**

Total Integrated voltage = 26.08mV, Discharged Voltage = 26.08mV – 24.07mV = 2.01mV

Current Leakeage = \( \frac{2.01\text{mV}}{26.08\text{mV}} \times 100\% = 7.70\% \)

**At Saturated Cycle: For Regulated Cascode OTA (Red Graph)**

Total Integrated voltage = 36.57 mV, Discharged Voltage = 36.57mV – 34.97mV = 1.6mV

Current Leakeage = \( \frac{1.6\text{mV}}{36.57\text{mV}} \times 100\% = 4.38\% \)
At Saturated Cycle: For Improved OTA (Green Graph)

Total Integrated voltage = 48.34mV, Discharged Voltage = 48.34mV – 44.99mV = 3.35mV

Current Leakeage = (3.35mV/48.34mV) *100% = % 6.93

Both hand calculation and simulation results can be seen in table 5-1 and 5-2, respectively.

Table 5-1: Hand Calculations of OTAs

<table>
<thead>
<tr>
<th>Hand Calculation Results</th>
<th>Regulated OTA</th>
<th>Improved OTA</th>
<th>Conventional OTA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Open loop Gain</strong></td>
<td>29.695 dB</td>
<td>28.82 dB</td>
<td>26.9 dB</td>
</tr>
<tr>
<td><strong>F\text{Y}_{\text{OUT}}</strong></td>
<td>2.961 MHz</td>
<td>26.094 MHz</td>
<td>3.698 MHz</td>
</tr>
<tr>
<td><strong>GBW</strong></td>
<td>269.521 MHz</td>
<td>715.9 MHz</td>
<td>243.52 MHz</td>
</tr>
<tr>
<td><strong>I\text{MAX}_{\text{OUT}}</strong></td>
<td>247.082 uA</td>
<td>762.561 uA</td>
<td>217.793 uA</td>
</tr>
<tr>
<td><strong>Slew Rate</strong></td>
<td>98.832 V/us</td>
<td>305.024 V/us</td>
<td>87.118 V/us</td>
</tr>
<tr>
<td><strong>Settling Time</strong></td>
<td>0.584ns</td>
<td>0.241 ns</td>
<td>0.645 ns</td>
</tr>
</tbody>
</table>

Table 5-2: Simulation Results of OTAs

<table>
<thead>
<tr>
<th>Simulations Results</th>
<th>Regulated OTA</th>
<th>Improved OTA</th>
<th>Conventional OTA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Open Loop Gain</strong></td>
<td>35.9 dB</td>
<td>34.69 dB</td>
<td>32.03 dB</td>
</tr>
<tr>
<td><strong>Frequency @peak</strong></td>
<td>871 KHz</td>
<td>1.585 MHz</td>
<td>871 KHz</td>
</tr>
<tr>
<td><strong>Frequency @-3dB_{\text{high}}</strong></td>
<td>304.1 KHz</td>
<td>410 KHz</td>
<td>348.2 KHz</td>
</tr>
<tr>
<td><strong>Frequency @-3dB_{\text{low}}</strong></td>
<td>2.23 MHz</td>
<td>15.71 MHz</td>
<td>3.166 MHz</td>
</tr>
<tr>
<td><strong>Frequency @unity gain/GBW</strong></td>
<td>1.48 GHz</td>
<td>3.60 GHz</td>
<td>1.25GHz</td>
</tr>
<tr>
<td><strong>Gain @2GHz</strong></td>
<td>-2.642 dB</td>
<td>5.304 dB</td>
<td>-4.368dB</td>
</tr>
<tr>
<td><strong>Gain Margin (GM)</strong></td>
<td>35.61 dB</td>
<td>34.3 dB</td>
<td>31.59 dB</td>
</tr>
<tr>
<td><strong>Phase Margin (PM)</strong></td>
<td>115.8°</td>
<td>122°</td>
<td>107.1°</td>
</tr>
<tr>
<td><strong>Current Leakage @150MHz</strong></td>
<td>%4.38</td>
<td>%6.93</td>
<td>%7.70</td>
</tr>
</tbody>
</table>
CHAPTER 6

CONCLUSION

6.1 Summary

In this thesis work, integrator block for UWB-IR Receiver has been proposed. To understand current leakage response which occurs during integration, different Operational Transconductance Amplifier’s characterization parameters such as slew rate, dc gain, cutoff frequency, GBW and output resistance has been investigated both in system level and transistor level. Three different OTAs whose names are Conventional Telescopic OTA, Improved Telescopic OTA and Regulated Telescopic OTA are designed in transistor level with 90 nm CMOS Technology using 1V supply voltage. Consequently, thanks to higher open loop gain 35.9 dB, lower cutoff frequency 2.3MHz and higher output resistance value Regulated OTA has % 56 improved current leakage responses at 150MHz input signal during discharging than Conventional Telescopic OTA which has 32.03 dB open loop gain, 3.2 MHz cutoff frequency and lower output resistance value. Improved Telescopic OTA has % 9 improved current leakage responses than Conventional Telescopic OTA too with its 34.69 dB open loop gain and 15.71 MHz cutoff frequency.

6.2 Future Work

To obtain lower current leakage response, Operational Transconductance Amplifier should be designed with sub-threshold transistors so lower cutoff frequencies with higher output resistance can be gotten with higher dc gain.

Also, transistor level design should be completed for the layout of the entire integrator.

Furthermore, when it is implemented, even two CMOS transistors with the same dimension could not be identical after fabrication. To obtain more realistic performance of integrator, Monte Carlo and process corner simulation needs to be conducted before layout.
Conventional Telescopic OTA

HAND CALCULATION AND SIMULATION RESULTS

Hand Calculation

OPEN LOOP GAIN

\[ |A_V| = G_M \cdot R_{OUT} \text{ where } G_M = gm1 \text{ and} \]

\[ R_{OUT} = \left\{ \left[ 1 + (gm3 + gmbs3) \cdot ro3 \right] \cdot ro1 + ro3 \right\} \parallel \left\{ \left[ 1 + (gm5 + gmbs5) \cdot ro5 \right] \cdot ro7 + ro5 \right\} \]

\[ R_{OUT} \approx (gm3 \cdot ro3 \cdot ro1) \parallel (gm5 \cdot ro5 \cdot ro7) \]

\[ |A_V| = gm1 \cdot [(gm3 \cdot ro3 \cdot ro1) \parallel (gm5 \cdot ro5 \cdot ro7)] \text{ where} \]

Gm1 = 3.87717 m, gm3 = 3.88647m, gm5 = 4.64024m, ro1 = 1.69599K + 50K = 51.69599K,
Ro3 = 390.851, ro5 = 1.26483K, ro7 = 1.04951K,

As a Result \( |A_V| = 22.1428, 20\log |A_V| = 26.9 \text{ dB} \)

AC ANALYSIS (Hand Calculation)

For 1st pole A

\[ W_{p,A} = \frac{1}{R_s \left[ (C_{GS1} + C_{in}) + \left( 1 + \frac{gm1}{gm3 + gmbs3} \right) C_{GD1} \right]} \quad \text{ where} \]

Rs = 50K, gm1 = 3.87717m, gm3 = 3.88647m, gmbs3 = 500.638u,
C_{GS1} = 51.6542f, C_{GD1} = 11.5638f, C_{in} = 5pF

As a result \( f_A = 627.362 \text{ KHz} \)

For 2nd pole X

\[ W_{p,X} = \frac{gm3 + gmbs3}{2C_{GD1} + C_{DB1} + C_{SB3} + C_{GS3}} \quad \text{ where} \]

gm3 = 3.88647m, gmbs3 = 500.638u,
C_{DB1} = 2.37541f, C_{GD1} = 11.5638f, C_{SB3} = 5.30924f, C_{GS3} = 77.4536f

As a result \( f_X = 6.448 \text{ GHz} \)
For 3rd pole Y

\[ W_{p,\text{out}} = \frac{1}{R_{out}(C_{DB3}+C_{GD3}+C_{L}+C_{s})} \]

where

\[ R_{OUT} = (gm3*ro3*ro1) \parallel (gm5*ro5*ro7), \]
\[ C_{DB3} = 4.3121f, C_{GD3} = 29.999f, C_{L} = 2.5p, C_{s} = 5pF \]
\[ Gm5 = 4.64024m, ro5 = 1.26483K, ro7 = 1.04951K, gm3 = 3.88647m, \]
\[ Ro3 = 390.851, ro1 = 1.69599K + 50K = 51.69599K \]

As a result \( f_Y = 3.698 \text{ MHz} \)

GAIN BANDWIDTH PRODUCT

\[ GBW = \frac{gm1}{2\pi(C_{DB3}+C_{L}+C_{GD3})} \]

where

\[ gm1 = 3.87717m \text{ and } C_{L} = 2.5pF, C_{DB3} = 4.3121f, C_{GD3} = 29.999f, \]

As a result \( GBW = 243.52 \text{ MHz} \)

MAXIMUM OUTPUT CURRENT

\[ I_{OUT}^{\text{MAX}} = \frac{I_{\text{BIAS}}}{2} \]

where \( I_{\text{BIAS}} = 435.586u \)

As a result \( I_{\text{OUT}}^{\text{MAX}} = 217.793uA \)

SLEW RATE AND SETTLING TIME

\[ SR = \frac{I_{\text{OUT} \text{ MAX}}}{C_{L}} \]

where

\( I_{\text{MAX} \text{ OUT}} = 217.793uA \text{ and } C_{L} = 2.5pf, \text{ Settling Time} = C_{L}/gm1 \)

As a Result \( SR = 87.118 \text{ V/us} \), Settling Time = 0.645ns
Improved Telescopic OTA

HAND CALCULATION AND SIMULATION RESULTS

Hand Calculation

OPEN LOOP GAIN

\[ |A_V| = G_M R_{OUT} \text{ where } G_M = gm_1 + gm_{10} \text{ and} \]

\[ R_{OUT} \approx (gm_3 ro_3 (ro_1 || ro_{10})) || (gm_5 ro_5 ro_7) \]

\[ |A_V| = (gm_1 + gm_{10})(gm_3 ro_3 (ro_1 || ro_{10})) || (gm_5 ro_5 ro_7) \text{ where} \]

\[ Gm_1 = 10.38m, \ gm_{10} = 965.685u, \ gm_3 = 11.654m, \ gm_5 = 13.5502m, \ ro_1 = 328.438 + 50K = 50.239K, \ Ro_3 = 331.077, \ ro_5 = 293.079, \ ro_7 = 208.349K, \]

As a Result \[ |A_V| = 27.60, \ 20\log |A_V| = 28.82 \text{ dB} \]

AC ANALYSIS (Hand Calculation)

For 1st pole A

\[ W_p,A = \frac{1}{R_s[(c_{GS1} + c_{in}) + \left(1 + \frac{gm_1 + gm_{10}}{gm_3 + g_mbs_3}\right)c_{GD1}]} \]

\[ R_s = 50K, \ gm_1 = 10.38m, \ gm_{10} = 965.685u, \ gm_3 = 11.654m, \ g_mbs_3 = 1.4758m, \]

\[ c_{GS1} = 59.4236f, \ c_{GD1} = 11.8364f, \ c_{in} = 5pF \]

As a result \[ f_A = 626.410 \text{ KHz} \]

For 2nd pole X

\[ W_p,X = \frac{gm_3 + g_mbs_3}{2c_{GD1} + c_{DB1} + c_{SB3} + c_{GS3}} \]

\[ gm_3 = 11.654m, \ g_mbs_3 = 1.4758m, \]

\[ c_{DB1} = 2.78277f, \ c_{GD1} = 11.8364f, \ c_{SB3} = 5.57967f, \ c_{GS3} = 91.9886f \]

As a result \[ f_X = 16.849 \text{ GHz} \]
For 3rd pole Y

\[
W_{p,\text{out}} = \frac{1}{R_{\text{out}}(C_{DB3}+C_{GD3}+C_{L}+C_{S})}
\]

where

\[
R_{\text{out}} \approx (g_{m3}r_{o3}(r_{o1}||r_{o10})) || (g_{m5}r_{o5}r_{o7}),
\]

\[
C_{DB3} = 3.81884f, C_{GD3} = 18.7039f, C_{L} = 2.5p,
\]

\[
C_{S} = 5pF, g_{m5} = 4.64024m, g_{m5} = 13.5502m, r_{o1} = 328.438 + 50K = 50.239K, r_{o3} = 331.077
\]

\[
r_{o5} = 293.079, r_{o7} = 208.349K
\]

As a result \(f_Y = 26.094\) MHz

GAIN BANDWIDTH PRODUCT

\[
\text{GBW} = \frac{g_{m1}+g_{m10}}{2\pi(C_{DB3}+C_{L}+C_{GD3})}
\]

where

\[
g_{m1} = 10.38m, g_{m10} = 965.685u\text{ and } C_{L} = 2.5pF, C_{DB3} = 3.81884f, C_{GD3} = 18.7039f,
\]

As a result \(\text{GBW} = 715.9\) MHz

MAXIMUM OUTPUT CURRENT

\[
I_{\text{OUT}}^{\text{MAX}} = (I_{\text{BIAS}} - I_{M9})/2
\]

where

\[
I_{\text{BIAS}} = 1.608m, I_{M9} = 83.8569u
\]

As a result \(I_{\text{OUT}}^{\text{MAX}} = 762.561uA\)

SLEW RATE AND SETTLING TIME

\[
\text{SR} = \frac{I_{\text{OUT}}^{\text{MAX}}}{C_{L}}
\]

where

\[
I_{\text{OUT}}^{\text{MAX}} = 762.561uA\text{ and } C_{L} = 2.5pf, \text{ Settling Time} = C_{L}/g_{m1}
\]

As a Result \(\text{SR} = 305.024\text{ V}/\mu\text{s} , \text{ Settling Time} = 0.241\text{ns}\)
Regulated Cascode OTA

HAND CALCULATION AND SIMULATION RESULTS

Hand Calculation

OPEN LOOP GAIN

\[ |A_V| = G_M \times R_{OUT} \text{ where } G_M = \text{gm}1 \text{ and} \]

\[ R_{OUT} \approx ((\text{gm}3+\text{gm}10) \times \text{ro}3 \times (\text{ro}10 \parallel \text{ro}9) \times \text{ro}1) \parallel (\text{gm}5 \times \text{ro}5 \times \text{ro}7) \]

\[ |A_V| = \text{gm}1((\text{gm}3+\text{gm}10) \times \text{ro}3 \times (\text{ro}10 \parallel \text{ro}9) \times \text{ro}1) \parallel (\text{gm}5 \times \text{ro}5 \times \text{ro}7) \]

\[ \text{Gm}1 = 4.27427\text{m}, \text{gm}10 = 1.171\text{m}, \text{gm}3 = 4.5512\text{m}, \text{gm}5 = 5.20223\text{m}, \text{ro}1 = 949.328 + 50\text{K} = 50.949\text{K}, \text{Ro}3 = 700.928, \text{ro}5 = 1.68978\text{K}, \text{ro}7 = 587.081, \text{ro}9 = 3.12956\text{K}, \text{ro}10 = 15.055\text{K} \]

As a result \[ |A_V| = 30.53, 20\log |A_V| = 29.695\text{ dB} \]

AC ANALYSIS (Hand Calculation)

For 1st pole A

\[ W_p,A = \frac{1}{R_s[(C_{GS1}+C_{in})+(1+\frac{gm1}{gm3+gm10+gmbs3})C_{GD1}]} \]

\[ R_s = 50\text{K}, \text{gm}1 = 4.27427\text{m}, \text{gm}10 = 1.171\text{m}, \text{gm}3 = 4.5512\text{m}, \text{gmbs}3 = 605.101\text{u}, \]

\[ C_{GS1} = 59.4236\text{f}, C_{GD1} = 11.8364\text{f}, C_{in} = 5\text{pF} \]

As a result \[ f_A = 627.51\text{ KHz} \]

For 2nd pole X

\[ W_p,X = \frac{gm3+gmbs3}{2C_{GD1}+C_{DB1}+C_{SB3}+C_{GS3}} \text{ where} \]

\[ \text{gm}3 = 4.5512\text{m}, \text{gmbs}3 = 605.101\text{u}, \]

\[ C_{DB1} = 2.52967\text{f}, C_{GD1} = 11.8364\text{f}, C_{SB3} = 5.15759\text{f}, C_{GS3} = 81.5152\text{f} \]

As a result \[ f_X = 7.27\text{ GHz} \]
For 3rd pole Y

\[ W_{p,\text{out}} = \frac{1}{R_{\text{out}}(C_{DB3}+C_{GD3}+C_L+C_s)} \]

where

\[ R_{\text{OUT}} \approx ((gm3+gm10)*ro3*(ro10||ro9)*ro1) || (gm5*ro5*ro7), \]
\[ C_{DB3} = 3.61043f, C_{GD3} = 19.8577f, \]
\[ C_L = 2.5p, C_s = 5pF, gm5 = 4.64024m, gm5 = 5.20223m, ro1 = 949.328 + 50K = 50.949K, \]
\[ Ro3 = 700.928, ro5 = 1.68978K, ro7 = 587.081, ro9 = 3.12956K, ro10 = 15.055K \]

As a result \( f_Y = 2.961 \text{ MHz} \)

**GAIN BANDWIDTH PRODUCT**

\[ \text{GBW} = \frac{gm1}{2\pi(C_{DB3}+C_L+C_{GD3})} \]

where

\[ gm1 = gm1 = 4.27427m, C_L = 2.5pF, C_{DB3} = 3.61043f, C_{GD3} = 19.8577f, \]

As a result \( \text{GBW} = 269.521 \text{ MHz} \)

**MAXIMUM OUTPUT CURRENT**

\[ I_{\text{OUT MAX}} = (I_{\text{BIAS}})/2 \]

where

\[ I_{\text{BIAS}} = 494.164u, \]

As a result \( I_{\text{OUT MAX}} = 247.082uA \)

**SLEW RATE AND SETTLING TIME**

\[ SR = \frac{I_{\text{OUT MAX}}}{C_L} \]

where

\[ I_{\text{MAX OUT}}^{\text{MAX}} = 247.082uA \text{ and } C_L = 2.5pf, \text{ Settling Time} = C_L/gm1 \]

As a Result \( SR = 98.832 \text{ V/us} \), Settling Time = 0.584ns
REFERENCES


