1-Ghz CMOS Analog Signal Squaring Circuit

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1-GHZ CMOS ANALOG SIGNAL SQUARING CIRCUIT

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Engineering

By

Lizhong He

B.S., Taiyuan University of Technology, China, 2011

2016

WRIGHT STATE UNIVERSITY
I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY Lizhong He ENTITLED "1-GHZ CMOS ANALOG SIGNAL SQUARING CIRCUIT" BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF Master of Science in Electrical Engineering.

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Abstract

He, Lizhong, M.S.Egr; Department of Electrical Engineering, Wright State University, 2016. “1-Ghz CMOS Analog Signal Squaring Circuit”

In analog signal processing the squaring circuit represents the core for implementing an analog signal having a value representing the square of the input signal. For example, calculating the square of input signal is necessary in adaptive processing of an input signal based on its instantaneous root mean square value. In this thesis, a new 1-Ghz analog signal squaring circuit (squarer) designed in 180 nanometer CMOS process is presented. It is implemented by CMOS components including current source, current mirror, differential amplifier, low-pass filter, and voltage output buffer. A gain control amplifier and a 10-bit ADC are set up to evaluate the dynamic performance of the CMOS signal squarer. The measured results show a wide sweep capability of analog signal frequency up to 1 GHz with good linearity and spurious-free dynamic range.
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1 INTRODUCTION

1.1 Background

With the increased requirements for the performance of signal preprocessor, such as stability, amplitude, frequency range and others, signal preprocessor becomes more important than it was before. The performance of signal preprocessor directly impacts the result of the following signal analysis and process, such as the working time and results of ADC or DAC\textsuperscript{[1]}. Signal preprocessor can be divided into different types, including the charge / voltage converter, current / voltage converter, frequency / voltage converter, impedance converter, frequency converter, and others. This complementary metal-oxide-semiconductor (CMOS) signal squarer is an application circuit in signal preprocessor.

Complementary referred to the typical CMOS design approach is to use complementary symmetry of p-type and n-type metal oxide semiconductor field effect transistor (MOSFET) component circuits. In circuit design, CMOS circuit technology is usually used for static RAM, microcontrollers, microprocessors, and other digital logic circuit.\textsuperscript{[2]} In some situations, this technology is used in CMOS analog circuits design, such as a data processor, a picture sensor and highly integrated transceivers for communication.

The CMOS devices has two important characteristics, one is high noise and another one is low static power consumption. CMOS devices only produce power when transistor is turned on. Therefore, CMOS devices don’t engender excess heat generated by other forms of CMOS devices. High-density logic functions can be allowed on a chip for CMOS, so CMOS circuit becomes the most commonly used design technique in IC chips.\textsuperscript{[3]} CMOS device power
consumption is a major concern in chip design. In CMOS circuits, power consumption is divided to two parts:

1. Static power dissipation

Gate-source threshold voltage is a property for NMOS and PMOS transistors. When the threshold voltage is bigger than $V_{GS}$, the threshold current of transistor is considered small. The main constitute material of CMOS transistors is silicon dioxide, which is a good insulator. The electrons can pass through the insulation layer to cause a tunnel current, which becomes important especially for 130 nanometer or thinner gate oxide transistors. In modern circuit, the leakage circuit is very small in comparison with the threshold current and the tunnel current.\[^5\]

2. Dynamic power dissipation

Dynamic power dissipation is divided into two types: 1) charging/discharging power, and 2) short-circuit power.

(1) Charging/discharging power

In a complete cycle of CMOS logic gate, CMOS circuit power consumption occurs at various load control switch when the capacitor is charged or discharged.

(2) Short-circuit power

There is a transition period where both PMOS and NMOS transistors are turned on, which induces a short-circuit power. The short-circuit power is dependent on the input signal rise and fall times, the transistor size and the load capacitance.\[^6\]

1.2 Research Motivation

In the electronic apparatus, frequency squarer is typically used in communication and signal processing circuits. Frequency squarer produces an analog signal having a value representing the square of the input signal. It’s a nonlinear circuit and the input
signal is modulated to produce harmonics. A band-pass filter is designed to filter out the harmonics as well as unwanted harmonics from the output.

Most signal squaring circuit can’t work properly at high frequency in Ghz. Two signal squaring circuit techniques, “A 5Mb/s UWB-IR transceiver front-end for wireless sensor networks in 0.13 mm CMOS” [6] and “A Low-Power and Flexible Energy Detection IR-UWB Receiver for RFID and Wireless Sensor Networks” [7] can work in GHz, however SFDR is in general not high enough. In this paper, a new analog signal squaring circuit is proposed and designated to work for analog input signal frequency in 1-Ghz range while keep SFDR of the squared signal output high. For low frequency input signal it can be 50 db and for high frequency input signal it can be 40 db.

1.3 Thesis Organization:

My thesis organization is depicted in Fig. 1.1.
CMOS Current Sink Source and Current Mirror analog Signal Frequency Square Generator

Introduction

Introduction of each Element of Circuit Design

Current Source, Current Mirror, Differential Amplifier, Low Pass Filter, Output Buffer

High Frequency analog Frequency Square Generator

Circuit work, Simulation Results

Compare the results

Conclusion and Future Work

Figure 1.1 Thesis organization


2 CMOS Signal Squaring Circuit

2.1 Current Source Principle

Current source is an electronic circuit providing current independent of voltage. Ideal current source can be formulated by mathematical model. Independent current source is defined as if the current source can independently designate current without considering any other variables in the circuit.\textsuperscript{8} Conversely, controlled current source is defined as if a current source is depended on values of other voltage or current in the circuit. The resistance of an ideal current source is infinity.\textsuperscript{9} The circuit can determine the voltage for current source completely. If a short circuit connect to current source, the current source’s voltage is zero and thus it delivers zero power. When a load resistor is connected to current source, if the load resistor approaches infinity, the voltage across the circuit close to infinity (open circuit). Therefore, in reality an ideal current source can provide unlimited energy. Ideal physical current source does not exist. A real current source is defined by two characteristics: 1) its internal resistance and 2) its compliance voltage.\textsuperscript{10} Compliance voltage current source can be provided to the maximum load voltage.

At a given load current range, some types of the actual current sources exhibit virtually unlimited internal resistance. However, when these current sources reached the compliance voltage, it will suddenly stop as a current source state.

Current source resistance is much bigger than load impedance, so change the load impedance will not change the current source circuit. Series resistance is meaningless in the current source circuit, because it does not change the current source load, and it will not change the voltage across the load. Current source has
three characteristics: 1) constant current output, 2) infinite DC resistance and 3) infinity AC resistance.\[11]\]

2.1.1 Current source

In the CMOS circuit design, a MOS diode resistor is often used in designing a current source. The schematic is shown in Fig. 2.1 in which the MOS diode operates in saturation.

![Figure 2.1 Current source](image)

The current through the current source is:

\[i_d = \frac{K}{2} \left( \frac{W}{L} \right) (V_{GS} - V_T)^2 (1 + \lambda V_{DS})\]

The relationship between the current \(i_d\) and the voltage \(V_{DS}\) and \(V_{GS}\) is shown in Fig. 2.2:

![Figure 2.2 \(i_d\) vs. \(V_{DS}\) and \(V_{GS}\)](image)
2.1.2 Current sink source

Current sink source design principle is similar to the current source except replacing the NMOS transistors with PMOS transistor and the PMOS operates in saturation.

2.2 Current Mirror

A current mirror is defined as a circuit designed to copy a current through one active device by controlling the current in another active device of a circuit, keeping the output current constant regardless of loading. Conceptually, an ideal current mirror is an ideal inverting current amplifier. Current mirror has three main parameters. 1) the transfer rate (transfer ratio), also called the current amplification factor, 2) the AC output resistance, determined by the output current and voltage, and 3) the lowest working voltage, i.e., the minimum voltage to make the current mirror work.

2.2.1 NMOS Current Mirror

A NMOS current mirror is shown in Fig. 2.3:

![NMOS Current Mirror Diagram](image)

Figure 2.3 NMOS Current mirror

In NMOS current mirror, the current $I_2$ can be calculated as follows:
\[ I_2 = I_1 \cdot \frac{\frac{W_2}{L_2}}{\frac{W_1}{L_1}} \]

where \( I_1 \) is the current source.

\( W_2 \) and \( L_2 \) is the width and length of the transistor M2, and \( W_1 \) and \( L_1 \) is the length and width of the transistor M1. By controlling \( \frac{W_2}{W_1} \), a desirable \( I_2 \) is obtained when \( L_1 = L_2 \).

### 2.2.2 PMOS Current Mirror

A PMOS current mirror is shown in Fig. 2.4:

![Diagram of PMOS current mirror](image)

PMOS current mirror principle is basically same with the NMOS current mirror, except that the current source in the bottom portion, and for current magnitude PMOS current mirror through the PMOS transistor transformation instead of NMOS transistors. In the circuit design, designers need to choose NMOS current mirror or PMOS current mirror based on different situations.

### 2.3 Differential Amplifier

The differential amplifier is commonly used in many CMOS circuit designs. It
amplifies the difference of two input voltage $v_1$ and $v_2$ when operating in the differential mode signal state\textsuperscript{[15]} or zoom in two input voltage average value when operating in the common mode signal state\textsuperscript{[16]}. The differential amplifier is shown in Fig. 2.5. It has two operations:

(1) Common signal mode

When the differential amplifier operates in common mode, its input voltage $v_{IC}$ $v_{IC}$ equals to the average of $v_1$ and $v_2$ as shown in Fig. 2.5.

In this case the two input signals are amplified.

(2) Differential signal mode

For differential signal mode, the input signal equal to the difference of $v_1$ and $v_2$. $v_{ID}$ represents the input signal as shown in Fig. 2.5. In this case, differential amp amplified the difference between two input signals.

The performance of the differential amplifier is evaluated by two important parameters\textsuperscript{[17]}. 

![Figure 2.5 Differential Amp](image-url)
(1) Common mode rejection ratio (CMRR)

The common mode rejection ratio is defined as how well: 1) the differential amplifier rejects the common mode input voltage and 2) the differential amplifier amplifies the differential-input voltage. It is calculated as $\text{CMRR} = \frac{A_{VD}}{A_{VC}}$ where $A_{VD}$ is the differential signal gain and the $A_{VC}$ is the common mode signal gain.

A higher value of CMRR will lead to a better performance of differential amplifier.

(2) Input common mode range (ICMR)

Input common mode range is defined as the scope of common-mode voltages in which the differential amp can touch and enlarge the input signal difference with the same gain. Usually, ICMR is a range for all MOS transistors operate in saturation.[18]

### 2.4 Low-Pass Filter

Low-pass filter is a filter that passes input signal whose frequency is below the cut-off frequency and attenuates input signal whose frequency is above the cut-off frequency.

#### 2.4.1 RC Low-Pass Filter

A simple low-pass filter is RC filter, which connects a resistor in serial with an output capacitor. The output capacitor exhibits reactance and blocks high-frequency signals as it functions like a short circuit. The interrupt frequency, also called the turn over frequency or cut off frequency, is formulated as follows:
\[ f_c = \frac{1}{2\pi \tau} = \frac{1}{2\pi RC} \]

where R and C are resistance and capacitance values. The cut off frequency is a reciprocal of the time constant \( \tau \).

\[ w_c = \frac{1}{\tau} = \frac{1}{RC} \]

Low pass filter behavior can be interpreted as the time for capacitor charge or discharge through the resistor. At low frequencies, it has enough charging time to charge the capacitor before the input signal switches its polarity; the output voltage is same as the input voltage. At high frequencies, it only has little time to charge the capacitor before the input signal switches its polarity; the output voltage is small enough to be neglected. \[19\]

### 2.4.2 RLC Low Pass Filter

A RLC low-pass filter is comprised of resistor, inductor and capacitor connected in series or parallel connection. The main difference between the RLC low-pass filter and RC low-pass filter is that RLC low pass filter has minimum impedance when it’s at the resonance frequency, but the RC low pass filter has smaller impedance with higher frequency.

### 2.5 Output Buffer Circuit

An output buffer provides impedance transformation, which is mainly classified to two designs: 1) voltage output buffer and 2) current output buffer. \[20\]

#### 2.5.1 Voltage Output Buffer

An ideal voltage output buffer has infinity input resistance and zero output resistance. However, a real voltage output buffer has high input impedance and low
output impedance. A good linearity and fast output response is critical to the voltage output buffer performance[21]. If the voltage amplification factor is unity, the voltage output buffer is called the unity gain amplifier buffer and its output tracks the input voltage. [22]

2.5.2 Current Output Buffer

An ideal current output buffer has zero input resistance and infinity output resistance. However, a real current output buffer has low input impedance and high output impedance.[23] A good linearity and fast output response is critical to the current output buffer performance. If the current amplification factor is unity, the current output buffer is called the unity gain current amplifier buffer and its output tracks the input current.[24]
3 1-Ghz CMOS Signal Frequency Squarer

3.1 Introduction:

The proposed 1-Ghz CMOS signal frequency squarer is designed by a current source, a PMOS current mirror, a differential amplifier, a low-pass filter, and a voltage output buffer. A gain control amplifier and a 10-bit ADC are used to evaluate the dynamic performance of signal frequency.

Figure 3.1 CMOS Frequency Squarer

The part of differential Amp (Fig. 3.2) is used to square the input signal frequency.

We can get the small signal model for this part like Fig. 3.3.
In the small signal model, the $V_{ID}=V_{GN}+(v_{in+}+v_{in-})/2$ and $r_{out}$ is the equivalent output resistance. Then, from Figure 3.1.2 the following current equations are derived.

$$I_{D1} = 0.5k_n(V_{GN} + v_{in+} - V_s - V_{THN})^2 + I_6$$

$$I_{D2} = 0.5k_n(V_{GN} + v_{in-} - V_s - V_{THN})^2 + I_6$$
\[ I_{D3} = 0.5k_p (V_{GN} + v_{in+} - V_S - |V_{THp}|)^2 + i6 \]

\[ I_{D4} = 0.5k_p (V_{GP} + v_{in-} - V_S - |V_{THp}|)^2 + i6 \]

\[ I_{D1} + I_{D2} = I_{D3} + I_{D4} = I_{D5} \]

\[ k_n = u_n c_{ox} \left( \frac{W}{L} \right) k_p = u_p c_{ox} \left( \frac{W}{L} \right) \]

So, \( \text{Vout1} = Vcc - (I_{D1} + I_{D2}) \ast Zn \)

\[ = [Vcc - k_n (V_{GN} - V_S - V_{THN})^2 \ast Zn - k_n \ast v_{in+}^2 \ast Zn - 2I_6 \ast Zn] \]

\[ \text{Vout2} = (I_{D3} + I_{D4}) \ast Zp \]

\[ = k_p (V_{GP} - V_S - V_{THN})^2 \ast Zp + k_p \ast v_{in+}^2 \ast Zp + 2I_6 \ast Zn \]

In Fig. 3.4 the output Vout2 includes input AC signal square, without using the proposed current sink source and current mirror. From the output waveform, the dynamic range of Vout2 is about 7 mV, which is too weak for the 10-b ADC and next stage use. So, in order to increase the dynamic range of Vout2, a current sink source and a current mirror are designed and used before the differential amp. Form Fig. 3.5 the dynamic range of Vout2 is increased to the 839 mV, which is about 120 times of the original dynamic range of 7 mV.
Figure 3.4 The Vout2 before using the proposed current sink source and current mirror

Figure 3.5 The Vout2 after using the proposed current sink source and current mirror
The transistor sizes of the differential amp are given in Table 3.1.

Table 3.1 The transistor sizes of the differential amp

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>30u/180n</td>
</tr>
<tr>
<td>M2</td>
<td>30u/180n</td>
</tr>
<tr>
<td>M3</td>
<td>10u/180n</td>
</tr>
<tr>
<td>M4</td>
<td>10u/180n</td>
</tr>
</tbody>
</table>

Table 3.2 The transistor sizes of the current source and current mirror

<p>| | |</p>
<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>M6</td>
<td>15u/180n</td>
</tr>
<tr>
<td>M7</td>
<td>10u/180n</td>
</tr>
<tr>
<td>M8</td>
<td>10u/180n</td>
</tr>
</tbody>
</table>

Table 3.3 The capacitance values

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>1pf</td>
</tr>
<tr>
<td>C2</td>
<td>1pf</td>
</tr>
<tr>
<td>C3</td>
<td>1pf</td>
</tr>
<tr>
<td>C4</td>
<td>1pf</td>
</tr>
</tbody>
</table>

Table 3.4 The resistance values

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>100Ω</td>
</tr>
<tr>
<td>R2</td>
<td>100Ω</td>
</tr>
</tbody>
</table>

In order to evaluate dynamic performance of the signal squarer, a test bed is set up in Fig. 3.6. The square output of the frequency squarer is fed to a gain control amp, which adjust the square output dynamic range and the DC offset voltage to meet the 10-bit ADC specifications.
3.2 ADC Design

A 10-b ADC is created in Verilog-A code. The code is blow:

```verbatim
// Verilog A for reseach_va, adc10bits, Verilog-a
`include "constants.vams"
`include "disciplines.vams"
module adc10bits(vd9, vd8, vd7, vd6, vd5, vd4, vd3, vd2, vd1, vd0, vdec, vin, vclk);
electrical vd9, vd8, vd7, vd6, vd5, vd4, vd3, vd2, vd1, vd0, vdec, vin, vclk;
parameter real trise = 0 from [0:inf);
parameter real tfall = 0 from [0:inf);
parameter real tdel = 0 from [0:inf);
parameter real vlogic_high = 5;
parameter real vlogic_low  = 0;
parameter real vtrans_clk     = 2.5;
parameter real vref        = 1.0;
`define NUM_ADC_BITS 10
real unconverted;
real halfref;
real decb;
real vd[0:`NUM_ADC_BITS-1];
real co[0:`NUM_ADC_BITS-1];
```
integer i;

analog begin

@ ( initial_step ) begin

halfref = vref / 2;

end

@ (cross(V(vclk) - vtrans_clk, 1)) begin

unconverted = V(vin);

for (i = (`NUM_ADC_BITS - 1); i>= 0 ;i = i - 1) begin

vd[i] = 0;

co[i] = 0;

if (unconverted > halfref) begin

vd[i] = vlogic_high;

co[i] = 1;

unconverted = unconverted - halfref;

end else begin

vd[i] = vlogic_low;

co[i] = 0;

end

unconverted = unconverted * 2;

end
end


//

// assign the outputs

//

V(vd9) <+ transition( vd[9], tdel, trise, tfall );
V(vd8) <+ transition( vd[8], tdel, trise, tfall );
V(vd7) <+ transition( vd[7], tdel, trise, tfall );
V(vd6) <+ transition( vd[6], tdel, trise, tfall );
V(vd5) <+ transition( vd[5], tdel, trise, tfall );
V(vd4) <+ transition( vd[4], tdel, trise, tfall );
V(vd3) <+ transition( vd[3], tdel, trise, tfall );
V(vd2) <+ transition( vd[2], tdel, trise, tfall );
V(vd1) <+ transition( vd[1], tdel, trise, tfall );
V(vd0) <+ transition( vd[0], tdel, trise, tfall );
V(vdec) <+ decb/1023;
`undef NUM_ADC_BITS
end
endmodule

3.3 Gain Control Amplifier

A gain control amp is created in Verilog-A code. The code is blow:

`include "constants.vams"
`include "disciplines.vams"
module amp(sigin, sigout);
input sigin;
output sigout;
electrical sigin, sigout;
//parameter real gain = 0.5/(vin_high - vin_offset);
real vin_high,vin_offset;
real gain;
analog begin
    // peak input voltage so far
vin_high=max(V(sigin),vin_high);

// average mid-point so far (in effect)
vin_offset=idt(V(sigin),0)/$realtime;

// max is to ensure that you don't end up with divide by zero
// and massive gain at start of simulation (adjust 0.1 to a reasonable
// value)

gain=0.5/max(vin_high-vin_offset,0.1);
V(sigout) <+ gain*V(sigin) + 0.5*gain - gain*vin_offset;

end
endmodule

In order to test my circuit output, I use a 10 bit ideal ADC to test the circuit, but for
the ideal ADC, the input signal range should be 0 to 1V, the offset DC voltage should
be 0.5V, and the amplitude should be 0.5V. In case of 100Mhz analog input signal, the
Fig. 3.7 is the square output wave form before the gain control, the DC offset voltage is
1.1995V, and the dynamic range is 14.25mv. It’s far away for the ideal ADC dynamic
range. The Fig.3.8 is the square output wave form after the gain control amplifier for
100Mhz analog input signal, the dc offset voltage from 1.1995V move to the 0.5V, and
the dynamic range is increased from 14.25mv to 1V, so it’s ready for 10bit ADC to do
the FFT analysis.
Figure 3.7 The square output waveform before the gain control amplifier for 100Mhz analog input signal

Figure 3.8 The square output waveform after the gain control amplifier for 100Mhz analog
input signal

Based on the different input signal frequency, the gain control amplifier is used to make the square output’s offset voltage is 0.5V, and the dynamic range is 1V. The amplification coefficient is different for different input frequency. The summary of amplification coefficient based on the simulation results is shown in table 3.5.

Table 3.5 Amplification coefficient of the gain control amp

<table>
<thead>
<tr>
<th>Input Frequency (Mhz)</th>
<th>Gain coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>70</td>
</tr>
<tr>
<td>200</td>
<td>116</td>
</tr>
<tr>
<td>300</td>
<td>177</td>
</tr>
<tr>
<td>400</td>
<td>250</td>
</tr>
<tr>
<td>500</td>
<td>339</td>
</tr>
<tr>
<td>600</td>
<td>447</td>
</tr>
<tr>
<td>700</td>
<td>565</td>
</tr>
<tr>
<td>800</td>
<td>695</td>
</tr>
<tr>
<td>900</td>
<td>848</td>
</tr>
<tr>
<td>1000</td>
<td>925</td>
</tr>
</tbody>
</table>

3.4 Experimental Results

3.4.1 100-Mhz input analog signal simulation results

Applying 100 Mhz input signal, the differential amplifier input and the square output waveforms are shown in Fig. 3.9 where the yellow, green, light blue and blue waveforms are the four input signals $V_{GN+\text{in}^+}$, $V_{GN+\text{in}-}$, $V_{GP+\text{in}^+}$, $V_{GP+\text{in}}$; the purple waveform is the square output waveform. The square signal waveform (200Mhz) shown in Fig. 3.10 is after the square signal output after the low-pass filter, the voltage buffer amplifier and the gain control amplifier.
Figure 3.9 The differential amplifier four input signals $V_{GN+}v_{in+}$, $V_{GN+}v_{in-}$, $V_{GP+}v_{in+}$, $V_{GP+}v_{in-}$ and the square output waveform for 100Mhz analog input signal

Figure 3.10 The test bed output square signal waveform (200Mhz)
The FFT spectrum of the test bed output square signal waveform (200Mhz) after the 10-b ADC is shown in Fig. 3.11. The SFDR is 50.96db.

### 3.4.2 500-Mhz input analog signal simulation results

Applying 500 Mhz input signal, the differential amplifier input and the square output waveforms are shown in Fig. 3.12 where the yellow, green, light blue and blue waveforms are the four input signals $V_{GN}+V_{in+}$, $V_{GN}+V_{in-}$, $V_{GP}+V_{in+}$, $V_{GP}+V_{in}$; the purple waveform is the square output waveform. The square signal waveform (1Ghz) shown in Fig. 3.13 is after the square signal output after the low-pass filter, the voltage buffer amplifier and the gain control amplifier.
Figure 3.12 The differential amplifier four input signals $V_{GN}+V_{in+}$, $V_{GN}+V_{in-}$, $V_{GP}+V_{in+}$, $V_{GP}+V_{in-}$ and the square output waveform for 500Mhz analog input signal.

Figure 3.13 The test bed output square signal waveform (1Ghz)
The FFT spectrum of the test bed output square signal waveform (1Ghz) after the 10-b ADC is shown in Fig. 3.14. The SFDR is 44.88db. Compare with the SFDR value for 200Mhz in Fig. 3.9, the value has 6.08db damping from 50.96db. It means the output for 500Mhz input signal is less stability and more noise than the output for 100Mhz input signal.

### 3.4.3 1-Ghz input analog signal simulation results

Applying 1 Ghz input signal, the differential amplifier input and the square output waveforms are shown in Fig. 3.15 where the yellow, green, light blue and blue waveforms are the four input signals $V_{GN+V_{in+}}$, $V_{GN+V_{in-}}$, $V_{GP+V_{in-}}$, $V_{GP+V_{in}}$; the purple waveform is the square output waveform. The square signal waveform (1Ghz) shown in Fig. 3.16 is after the square signal output after the low-pass filter, the
voltage buffer amplifier and the gain control amplifier.

Figure 3.15 The differential amplifier four input signals $V_{GN+}v_{in+}$, $V_{GN+v}v_{in-}$, $V_{GP+v}v_{in+}$, $V_{GP+v}v_{in}$ and the square output waveform for 1GMHz analog input signal
Figure 3.16 The test bed output square signal waveform (2Ghz)

Figure 3.17 FFT spectrum of the test bed output square signal waveform (2Ghz) after the 10-b ADC
The FFT spectrum of the test bed output square signal waveform (2Ghz) after the 10-b ADC is shown in Fig. 3.17. The SFDR is 38.15db. The output waveform is clear and stable.

3.5 Simulation Results

This chapter first shows the circuit design of signal squarer and explains its operation principle and limitation. Next, Cadence software is used to evaluate the performance. The input signal frequency were varied from 100Mhz to 1Ghz. Table 3.6 shows SFDR for different input signal frequency. SFDR decreases from 50.96db for 100Mhz to 38.15db for 1Ghz input signal. The signal squaring circuit can work properly for a maximum input analog signal frequency up to 1.32Ghz.

<table>
<thead>
<tr>
<th>Input Signal Frequency</th>
<th>Output SFDR</th>
</tr>
</thead>
<tbody>
<tr>
<td>100Mhz</td>
<td>50.96db</td>
</tr>
<tr>
<td>200Mhz</td>
<td>51.44db</td>
</tr>
<tr>
<td>300Mhz</td>
<td>48.68db</td>
</tr>
<tr>
<td>400Mhz</td>
<td>46.83db</td>
</tr>
<tr>
<td>500Mhz</td>
<td>44.88db</td>
</tr>
<tr>
<td>600Mhz</td>
<td>42.65db</td>
</tr>
<tr>
<td>700Mhz</td>
<td>41.94db</td>
</tr>
<tr>
<td>800Mhz</td>
<td>40.77db</td>
</tr>
<tr>
<td>900Mhz</td>
<td>39.07db</td>
</tr>
<tr>
<td>1Ghz</td>
<td>38.15db</td>
</tr>
</tbody>
</table>

The sign squaring circuit of [6,7] is based on differential amplifier design of Fig. 3.18. Table 3.7 shows SFDR comparison with [6,7].

30
Figure 3.18   Differential amplifier based signal quarcing circuit

Table 3.7 SFDR comparison

<table>
<thead>
<tr>
<th></th>
<th>[6]</th>
<th>[7]</th>
<th>This work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency band(Ghz)</td>
<td>3</td>
<td>6</td>
<td>1.3</td>
</tr>
<tr>
<td>CMOS technology(nm)</td>
<td>180</td>
<td>90</td>
<td>180</td>
</tr>
<tr>
<td>Support voltage(V)</td>
<td>1.8</td>
<td>1</td>
<td>1.8</td>
</tr>
<tr>
<td>Average SFDR(db)</td>
<td>35.34</td>
<td>29.65</td>
<td>44.72</td>
</tr>
</tbody>
</table>
4 CONCLUSION

4.1 Conclusion

In this research, the proposed analog signal squaring circuit maintains good linearity and achieves high SFDR for input signal frequency up to 1-GHz. Three design challenges were observed. They are:

(1) The roll of current source and current mirror is important, which provides a stable DC bias voltage at an analog input signal to ensure that the next stage difference amplifier can function properly to square the input signal. If the DC bias voltage of the input signal is not in the correct range, the signal squaring function can not be achieved.

(2) The roll of differential amplifier is important, which achieves squaring function of the analog input signal. The challenge of this part design is to optimize transistor sizes and $V_{\text{bias}}$ values for M5 and M6. Numerical simulation runs were conducted and based on these results the differential amplifier is optimized to generate clear and stable output waveforms.

(3) The roll of low pass filter is important, which reduces noise at the squared output signal. And, through the output buffer a clear and stable output waveform is obtained. In the test bed, a gain control amplifier is used to control the dynamic range of the squared output signal, which is fed to the 10-b ADC. Thereafter, FFT analysis is conducts using Cadence toolset.

4.2 Future work

My future research includes:

(1) Increase input signal frequency range from 1 Ghz to 2 ~ 3 Ghz. Improve my current differential amplifier design to function in a wider bandwidth while keep
linearity and high SFDR for the squared output waveform.

(2) Design new current sink source and current mirror circuit to provide DC bias voltage to the wide bandwidth differential amplifier and reduce the input noise.

(3) Design a new noise reduction filter in a wider bandwidth for the signal squaring output to improve the linearity and SFDR.
5 REFERENCE


R. Srivastava, M. Gupta, and U. Singh, “FGMOS transistor based low voltage and low power fully programmable gaussian function generator,” Analog


