Analytical Method for Gain Analysis of a Double Balanced Gilbert Cell Mixer

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ABSTRACT

A novel analytical approach for gain analysis of a double balanced Gilbert Cell Mixer is presented on this paper. An initial design of a gilbert cell mixer with differential transistor pair for the core mixer and low noise amplifier for the RF input is evaluated. The method aims on showing how the gate width and length have an effect on the mixer conversion gain, and further an evaluation of how tuning resistive loads could maximize the gain by almost +200% is demonstrated. This paper is not focused on demonstrating the design of Gilbert cell mixer but the gain analysis of an initial ready-made design. The testing is carried out on Advance design system simulation software.

KEYWORDS

Conversion gain, Double Balanced, Gilbert Cell Mixer

1. Introduction

Mixers play an important role in wide band communication systems, which use heterodyne system architectures at millimeter wave carrier frequencies [1]. Most of the Radio Frequency (RF) systems require mixers so as it can act as a translating device [2]. Example in receivers a mixer is used to convert the RF input frequency to an Intermediate frequency (IF) or baseband signal for easy signal processing, also a mixer is used in transmission systems to convert the frequency to a higher RF or higher IF frequency for transmission, hence in receivers it is down conversion and in transmitters it is up conversion [3]. During the conversion process a mixer will produce gain or loss; this will depend on the type of the mixer used. Normally active mixer produce conversion gain and hence they are good in many RF system application since they will have no or negligible noise and intermodulation distortions, however active mixers are affected by linearity and will require further improvements like adding degeneration resistors or inductors which will tradeoff gain for linearity [4]. Figure 1 shows RF three port mixer.

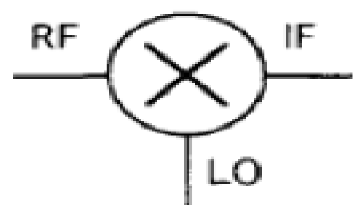

Figure 1. RF three port mixer

Passive mixers provide loss hence they have higher noise figures, but they provide good linearity and utilize less DC power [1]. For the mixers like double balanced Gilbert Cell linearity could be improved by degeneration resistors as mentioned above, however the mixer must have enough gain to do so. Hence forth methods for gain optimization are demonstrated on further stages of this paper. By definition conversion gain is the ratio of the desired IF output to the RF input signal value in which for both of them can be (voltage or power) [2]. Therefore conversion gain is dependent upon the ratio of the input and output voltages, apart from this the gain can be affected by other factors like trans conductance, local oscillator LO power, channel size etc.

2. Related Work

Due to change of technologies especially in the use radio communication equipment's which uses high frequencies components, devices such as mixer, which will be able to translate the frequencies to proper IF output to the receiver are highly demanded. On a research article done by I.Kallfass et al (2008) [1], states that due to an increase of high-speed semiconductors technologies a gradual increase cutoff frequency has been seen. Therefore the mixers and multipliers which act as translating circuits can be realized using the same semiconductor technologies, example of the technologies used includes INP based pseudomorphic or GaAs base metamorphic which are high electron mobility transistors. Kallfass, Massler & Leuther, (2007) [1], suggested a dual gate FET mixer of sub harmonic type achieved a conversion loss of 8.5 dB on down conversion. The mixer is operated by a 10 dBm sub harmonic LO signal power, the mixer also achieves a 3 dB RF bandwidth. The sub harmonic design of a dual gate FET mixer is applicable to applications that involve imagining systems that operate at a frequency environment of 220 GHz; therefore the mixer is more applicable to active radar frontend sensors. A.Tessman et al. (2008) [5], evaluated and analyzed the mixer using wafer measurements, the tested mixer achieved a conversion maximum gain of -4.7 dB at 214 GHz, the full measured bandwidth was from 165 to 220 GHz, from the results the gain maintained a threshold of -10 dB and above. The mixer was operated by a LO power of 10dBm and consumed a total dc power of 36 mW. The down conversion sub harmonic pumped dual gate FET mixer is used in applications of active and passive high resolution imagining systems. By comparing the results of the three dual gate FET mixers, it's found that the fundamental dual gate FET mixers performs better than other by providing a good conversion gain of a positive value, on comparing the two sub harmonics, the pumped sub harmonic improves the conversion gain by 1.1 dB. Due to the development of millimeter wave wireless communication systems, the sub harmonics mixers (SHM) or the harmonics mixers of second order or higher becomes a better choice in wireless communication applications. However the in which these mixers are facing is the continuous reduced supply voltage for each technology generation; hence the sub harmonics mixer that uses a low voltage supply becomes a better option for millimeter wave communication systems. On a research done by Hu Zijie & Koen Mouthaan (2012) [6], the researcher presents a sub harmonic cascode FET mixer that uses low voltage for operation. The proposed cascode FET uses a biasing method that requires a low supply voltage and effectively facilitating the generation of the second harmonic of the LO signal for sub harmonic mixing. J.S.Moon et al. (2013) [7] demonstrates a zero bias linear resistive FET mixer, which uses graphene FET with state-of-art-mixer mixer linearity. The graphene gate pumped resistive FET mixer tested achieved excellent mixer linearity at low LO power. The mixer is tested with no applied drain bias, hence there is no DC power dissipation consumed. The local oscillator signal is applied to the gate while the RF signals passes through the drain, in the channel resistance the modulation of FET with LO occurs and this provides a required linear RF mixer performance.

3. Proposed Design

The active Gilbert cell mixer tested is shown on figure 2. Mosfet 5-6 represents the transistor differential pair which its main purpose is switching the signal and the output is taken at v_{out} 1 and v_{out} 2, the switching at these transistors happens very fast, when Mosfet 1 & 3 are conducting the other pair is off and the process is reversed, this function multiplies (mixes) the signal coming from the transistors beneath. Mosfet 1-2 is the trans conductance (gm) stage, this should calculated theoretically through mathematical equation on how gm can affect the conversion gain. The transistors at the gm stage are connected to degeneration inductors at the source terminal to share the gain for linearity and to efficiently handle the power from the low noise amplifier (LNA) and to provide optimal noise matching; hence these inductors help the Gilbert mixer achieve a better linearity compared to other active mixers.

At the top of the differential pairs through drain terminals, the transistors are connected to the tuning resistive loads (RL) these loads are very important for the mixer and they play a major role for the conversion gain of the mixer. The rest of the remaining transistors are current mirrors responsible for reflection and circulation of current in the mixer.

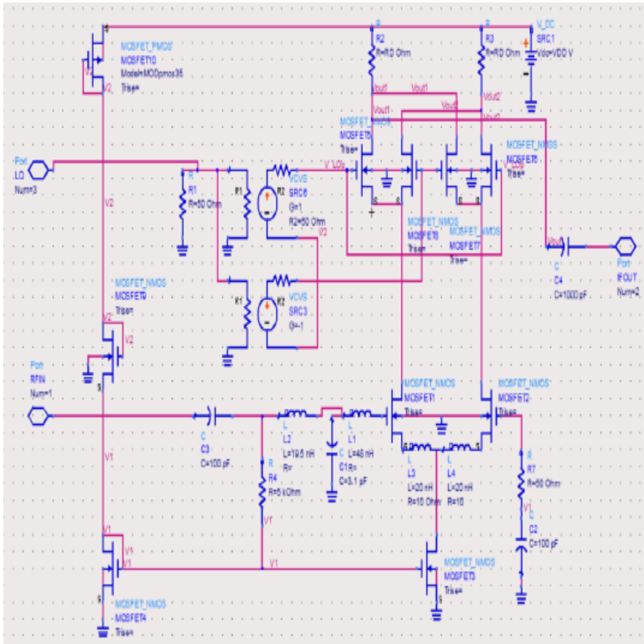

Figure 2. Double balanced Gilbert Cell Mixer Analyzed

4. Mathematical Analysis

The mathematical analysis for gain derivation on a double balanced Gilbert cell mixer is represented in Figure 3[8].

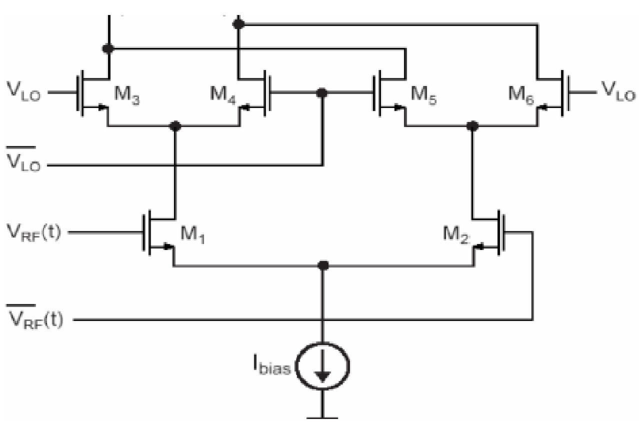

Figure 3. Gilbert Cell Topology

Notation:

I_1= Current passing through M3
I_2= Current passing through M4
I_3= Current passing through M5
I_4= Current passing through M6
Iod= Differential output current
I_{DC}= Biasing current
S(t)= Switching function of the mixer

$$I_1 - I_2 = (I_{DC} + I_1 \cos\omega_{RF}t)S(t) \qquad (1)$$

$$I_4 - I_3 = (I_{DC} - I_{RF} \cos\omega_{RF}t)S(t) \qquad (2)$$

$$I_{01} = I_1 + I_3 \qquad (3)$$

$$I_{02} = I_2 + I_4 \qquad (4)$$

$$I_{od} = I_{01} - I_{02} = (I_1 + I_3) - (I_2 + I_4) \qquad (5)$$

$$= (I_1 - I_2) + (I_4 - I_3)$$

$$= (I_{DC} + I_1 \cos\omega_{RF}t)S(t) + (I_{DC} - I_{RF} \cos\omega_{RF}t)S(t)$$

$$= (2I_{RF} \cos\omega_{RF}t)S(t) \qquad (6)$$

S(t) is the switching function of the mixer and is given by $\frac{2}{\pi}$, by expanding equation 6 we get,

$$\frac{4I_{RF}}{\pi}\Big\{\sin(\omega_{LO} - \omega_{RF})t + \sin(\omega_{LO} + \omega_{RF})t + \frac{1}{3}\sin(3\omega_{LO} - \omega_{RF})t + \frac{1}{3}\sin(3\omega_{LO} + \omega_{RF})t + \ldots\Big\} \qquad (7)$$

By taking the amplitude of equation 7 we get the conversion gain of the mixer to be,

$$G_C = \frac{\frac{4I_{RF}}{\pi}(RL)}{2V_{RF}} = gmRL\left(\frac{2}{\pi}\right) = \frac{Vo(t)}{Vrf(t)}$$

$$\therefore G_C = \frac{Vo(t)}{Vrf(t)} = gmRL\left(\frac{2}{\pi}\right) \qquad (8)$$

For a gilbert cell mixer with degeneration resistor or inductors the formula is given as,

$$\frac{Vo(t)}{Vrf(t)} = \left(\frac{2}{\pi}\right)\left(\frac{R_L}{Rs + \frac{1}{gm}}\right) \qquad (9)$$

From both gain equations 8 & 9, the mixer is proportional and depends on the trans-conductance value (gm) and the tuning resistive load (RL) in a sense that any of these two variables are increased the gain of the mixer will increase and vice versa.

Other important equation for analyzing gain of the mixer are shown below

$$I_{DS} = \frac{1}{2}U_n C_{ox}\frac{W}{L}(V_{GS} - V_T)^2\left(1 + \lambda(V_{DS} - V_{DS,SAT})\right)$$

$$= \frac{1}{2}U_n C_{ox}\frac{W}{L}(V_{GS} - V_T)^2 \qquad (10)$$

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Equation 10 is the current equation for the transistors operating in saturation since the MOSFET will be drived in saturation region so that the changing voltage will have no effect on the current. Equation 10 is the simplified version of the equation by neglecting the channel modulation of the transistor device [4]. Another important formula for trans-conductance relating it to channel size is shown in equation 11.

$$gm = U_n C_{ox} \frac{W}{L} (V_{GS} - V_T)^2 \tag{11}$$

Hence one can see that the trans conductance of the mixer depends on the width to length ratio of the transistor, by increasing the channel width while keeping the channel length minimum, it will increase the trans conductance of the mixer and hence the gain of the mixer will increase. Trans-conductance is also given as a change in drain current divided by the small change in gate to source voltage, in our case the transistors are operated in saturation region hence the ratio will be drain current divided by the voltage over drive.

$$gm = \frac{2I_D}{(V_{GS} - V_T)} \tag{12}$$

5. Simulation analysis and results

The Gilbert cell mixer is initially designed on BSIM3V3 model of MOSFET transistor CMOS 0.25-micrometer technology. The BSIM model is for deep submicron chip fabrication, and the models are designed by university of California, Berkeley, Department of electrical and electronics engineering. The parameter values for the models used are in Table 1 [4].

Table 1, BSIM3 Parameter Model

K =UnCox/2	171.4uA/V^2
Vt	0.7V
V_{th0}	.0.51 volts
Ids	3mA
Iout (Iss)	6mA

The simulation was run for different five output samples of different width to length ratio and the last two results for different increment in resistive loads, the results show that for the same RF power of -30 dbm the mixer provided an improvement in gain for each increment of W/L and RL without requiring much power. Table 2. Shows the exact values used to achieve the results portrayed in the next figures,

Table 2. Parameter used to analyze the gain

RF power (dbm)	Channel Length (um)	Channel Width ($10^{-4}m$)	Resistive Load (ohm)	RF voltage (V)	Maximum Conversion gain (dB)
-30	0.4	8	200	0016/12590	1.4
-30	0.3	9	200	0016/129062	2.133
-30	0.3	10	200	0016/12933	2.607
-30	0.3	10	360	0016/12962	4.412
-30	0.3	10	560	0016/12970	4.949

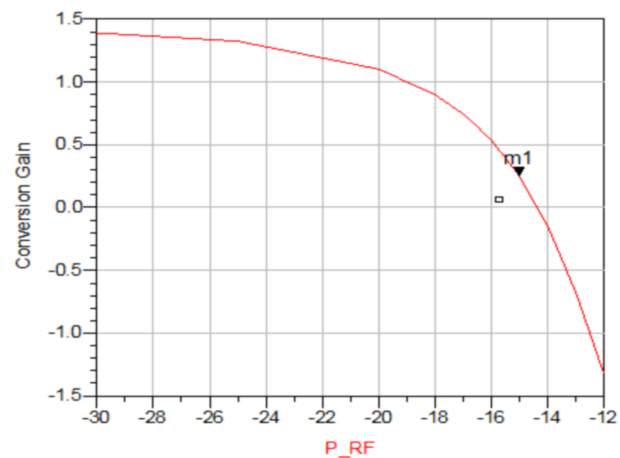

Figure 4. Conversion gain vs RF input power sample 1

Table 3. RF input power vs Conversion Gain tabulation for sample 1

RF power (dbm)	RF voltage	Conversion gain, dB
-30	0016/12590	1.390
-25	0028/12607	1.323
-20	0050/12765	1.101
-18	0063/13078	0.897
-17	0071/13353	0.744
-16	0080/13729	0.538
-15	0091/14573	0.252
-14	0103/15586	-0.144
-13	0117/16842	-0.672
-12	0134/18361	-1.321

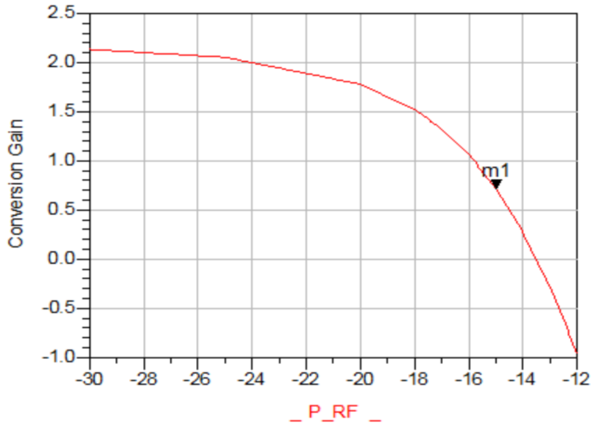

Figure 5. Conversion gain vs RF input power sample 2

Table 4. RF input power vs Conversion Gain tabulation for sample 2

RF power, dBm	RF voltage	Conversion gain, dB
-30	0016/19062	2.133
-25	0028/19169	2.053
-20	0050/19587	1.778
-18	0063/20027	1.519
-17	0071/20368	1.323
-16	0080/20822	1.063
-15	0090/21407	0.719
-14	0102/22133	0.272

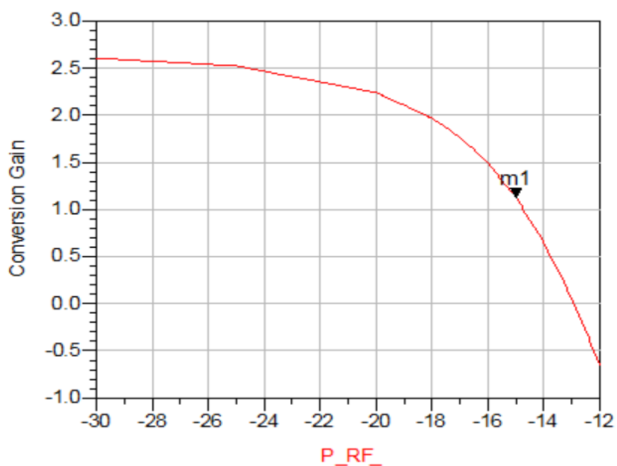

Figure 6. Conversion gain vs RF input power sample 3

Table 5, RF input power vs Conversion Gain tabulation for sample 3

RF power, dBm	RF voltage	Conversion gain, dB
-30	0016/12933	2.607
-25	0028/13080	2.524
-20	0050/13634	2.240
-18	0064/14191	1.971
-17	0072/14610	1.766
-16	0081/15154	1.493
-15	0092/15836	1.128
-14	0104/16660	0.652

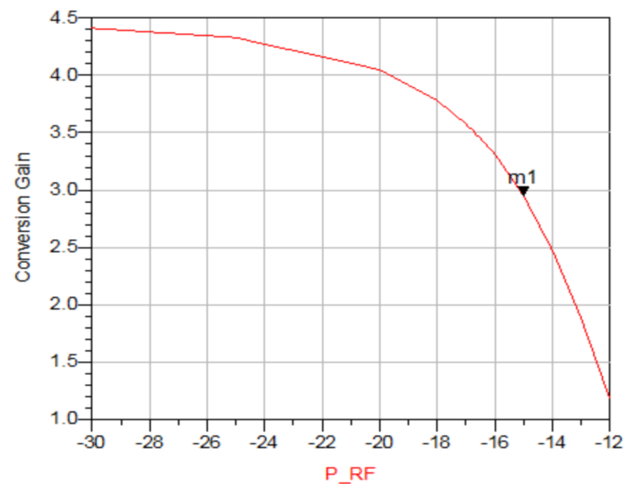

Figure 7, Conversion gain vs RF input power sample 4

Table 6, RF input power vs Conversion Gain tabulation for sample 4

RF power, dBm	RF voltage	Conversion Gain, dB
-30	0016/129620	4.412
-25	0028/13107	4.329
-20	0050/13650	4.049
-18	0063/14196	3.782
-17	0071/14608	3.580
-16	0081/15142	3.310
-15	0091/15815	2.949
-14	0104/16630	2.477

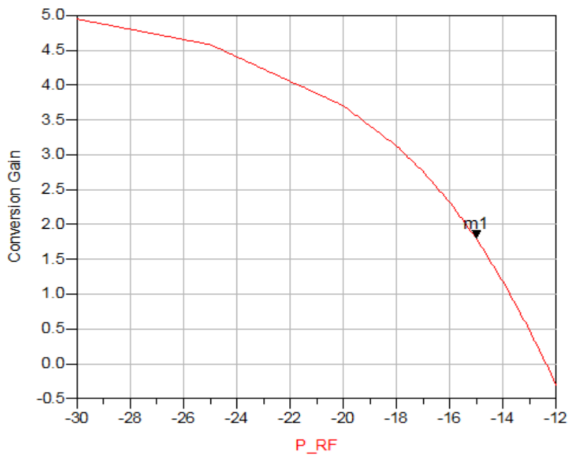

Figure 8. Conversion gain vs RF input power sample 5

Table 7, RF input power vs Conversion Gain tabulation for sample 5

RF power, dBm	RF voltage	Conversion gain, dB
-30	0016/12970	4.949
-25	0028/13160	4.582
-20	0049/13759	3.704
-18	0062/14289	3.125
-17	0070/14677	2.756
-16	0079/15175	2.317
-15	0089/15801	1.795
-14	0101/16560	1.182

The results clearly show and indicate the rise in gain for the same input RF power, due to modification of channel size of the MOSFET and increment of the resistive load. The resistive load can be increased to a certain extent however it is increased to a very large value it will affect the DC biasing of the mixer and hence the performance of the mixer will deteriorate.

Conclusion

This paper has presented two major methods of gain improvement in Gilbert cell mixers, the methods involved increasing the channel width of the MOSFET while keeping the channel length at minimum, this method has proved well by increasing the gain by 200% as seen in the results, increasing the resistive loads also has proved to have a positive results on gain, and together both methods have improved the gain by almost 300% from 1.39 dB to 4.9 dB. Increasing the bias current can do further improvement on gain however it can be limited to power requirements.

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