Design and Analysis of UWB Down-Conversion Mixer with Linearization Techniques

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Abstract: - Frequency translation which converts the original signal to a much lower baseband frequency signal is a vital role in the RF receiver design. In this work, a high linear down-conversion Gilbert cell mixer at 100MHz is designed using TSMC 0.18µm RF CMOS process. Linearity is an important performance measure in RF circuits particularly in mixer design. In this paper, the two types of linearization techniques called Cross Coupled Post Distortion (CCPD) and Multiple Gated Transistor (MGTR) are performed on wideband CMOS mixer and their performances are analysed. The mixer covers the frequency band of 3.1-9.5 GHz. The mixer with CCPD provides the conversion gain of 7.96dB with a noise figure of 14.66dB at 100MHz IF. The mixer with MGTR provides the conversion gain of 6.12dB with a noise figure of 14dB. The third order intercept point for these techniques is 3.33dBm and -1.365 dBm respectively. From this analysis, CCPD technique gives the high gain and high linearity for this UWB mixer. The circuit operates at the supply voltage of 1.8 V and the power consumption is 6.93mW.

Key-Words: - CCPD, down-conversion mixer, Linearization techniques, MGTR, UWB mixer.

1 Introduction

Federal Communication Commission introduced Ultra Wide-Band technology in the frequency range of 3.1-10.6 GHz for unlicensed use [1]. UWB technology (IEEE 802.15.3a) is suitable for high-rate data communication for short range. Its bandwidth of 7.5 GHz is divided into 14 channels with a bandwidth of 528 MHz. The down conversion mixer is an important component in RF receiver front-end which is shown in Fig.1. The mixer is used as a frequency translation device which down converts the Radio Frequency (RF) signal passing through Low Noise Amplifier (LNA) into Intermediate Frequency (IF) signal.

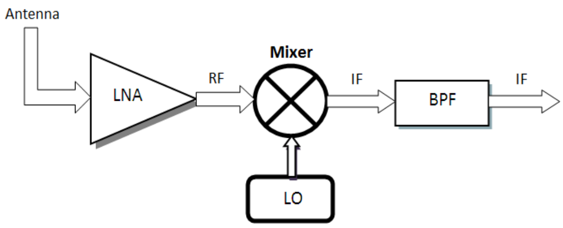

Figure 1: RF Receiver Frontend

The RF parameters such as linearity, conversion gain, noise figure, power consumption and port-to-port isolation are important for mixer design. Several papers were presented for UWB down-conversion mixer. High gain mixers suffer from low linearity [2, 3]. The linearity of the down-converter needs to be increased to meet the system linearity specifications. To improve the linearity of the mixer design, several linearization techniques were implemented [4, 5, 6]. The linearity of these techniques was improved, but they made the circuits more complex with high power dissipation and cost. Using Differential Multiple Gated Transistors (DMGTR) [7], the linearity of the mixer was highly improved. Thereby the linearity of the RF front-end improved. But it consumed high DC power. The current-reuse bleeding technique [8] was implemented with upconverison mixer. It achieved high IIP3 but it consumed more power and the mixer has a complicated structure. The linearity of the mixer was improved by Cross Coupled Post Distortion (CCPD) technique [9]. But the drawbacks of this mixer were less conversion gain and high noise figure. In order to achieve wide bandwidth, some papers presented with new techniques. The feedback amplifier was introduced in [10] to get the wide bandwidth. The common-gate RF transconductance stage [11] exhibited the flat conversion gain over the wide RF and IF band and good input/output matching. In this paper, the three stage UWB mixer is designed using CMOS technology and its performances are analysed.

In section 2, the wideband mixer design is analysed. The UWB mixer design with linearization techniques is presented in section 3. In section 4, the simulation results are illustrated and also comparison with other mixers is given. The conclusion is provided in section 5.

2 Wideband Mixer Design

The conventional Gilbert cell mixer shown in Fig.2 consists of three stages such as Transconductance stage, Mixing stage and Load stage. The RF input signal is given to transconductance stage acting in saturation region where the RF voltage is converted into RF current. The mixing stage is acting in triode region that performs switching by LO signal.

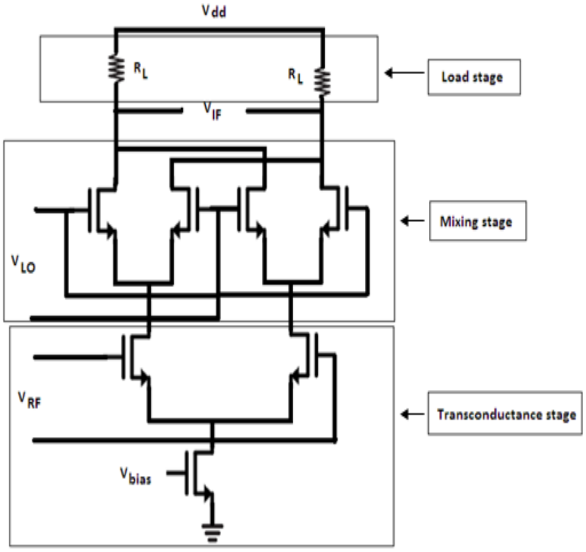

Figure 2: Structure of the conventional mixer

The proposed mixer design shown in Fig.3 is the combination of Common-Gate transconductance stage (M_1, M_2), multiplying stage (M_3,M_4,M_5,M_6) and load stage (M_7,M_8) with feedback amplifier (M_9, M_{10}, M_{11}). To obtain the flat conversion gain over the wide bandwidth, the feedback amplifier is used at the load stage. The conversion gain (A_V) expressed in Equation (1) is proportional to the transconductance of the transistors (M_1, M_2).

$$A_V = G_m R_L \frac{2}{\Pi} \qquad (1)$$

The relationship between the transconductance and gate width of the transistors is defined as Equation (2).

$$g_m = \sqrt{2\mu_n C_{ox} \frac{W}{L} I_D} \qquad (2)$$

where μ_n,C_{ox},W,L and I_D are the electron mobility, gate oxide capacitance, gate width of the core transistors, gate length of the core transistors and drain current, respectively.

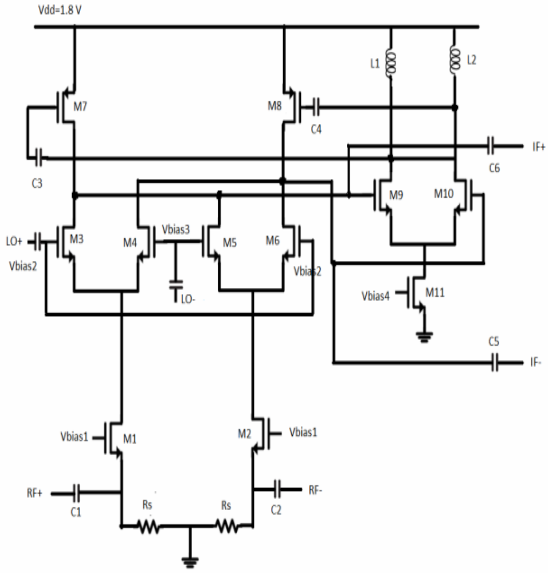

Figure 3: Wideband mixer design

The RF input signal is given to the CG transconductance stage where the RF voltage (V_{RF}) is converted into AC input RF current (I_{RF}). The RF current for differential mixer is expressed as Equations (3) & (4).

$$I_{RF+} = g_{m1} \frac{V_{RF}}{2} \sin \omega_{RF} t \qquad (3)$$

$$I_{RF-} = -g_{m2} \frac{V_{RF}}{2} \sin \omega_{RF} t \qquad (4)$$

where g_{m1},g_{m2} are the transconductance of transistor M_1 and M_2 respectively. In mixing stage, the square wave (LO signal) is multiplied with the signal from transconductance stage. So the differential mixer output current is derived as the following Equations.

$$I_{IF} = (I_{A1} - I_{A2}).\sin(\omega_{LO} t)$$
$$= g_{m1}.g_{m2}.V_{RF}.\sin \omega_{RF} t.\sin(\omega_{LO} t)$$
$$= g_{m1}.g_{m2}.V_{RF}.\frac{1}{2}[\underbrace{\cos(\omega_{RF} - \omega_{LO})t}_{Difference} - \underbrace{\cos(\omega_{RF} + \omega_{LO})t}_{Sum}] \qquad (5)$$

The difference frequency and sum frequency denoted in Equation (5) are the output frequency (IF) and undesired frequency which will be removed by the filtering. The PMOS transistors (M_7,M_8) are used as load that are driven by feedback amplifier. The feedback amplifier consists of a differential pair (M_9, M_{10}) and inductive loads (L_1, L_2). It can be switched ON or OFF by using the bias voltage of the tail transistor (M_{11}). The inductors are used for tuning at lower and higher frequency. Thereby, the conversion gain can be obtained for wideband.

3 Mixer Design with Linearization Techniques

Linearity of the Gilbert-cell mixer is an important performance measure. It is determined mainly by its transconductance stage. Several linearization techniques have been presented using volterra series [12, 13, 14]. Without considering the memory effect in a weak nonlinear applications, the drain current of a common-source MOSFET can be expressed by Taylor series expansion with respect to the small signal gate-to-source voltage (v_{gs}) is expressed in Equation (6).

$$I_{DS} = I_{DC} + g_m V_{gs} + \frac{g'_m}{2!} V_{gs}^2 + \frac{g''_m}{3!} V_{gs}^3 + ... \quad (6)$$

Where g_m^n denotes the n^{th} order derivatives of the transconductance. The third order intercept point (IP3) of the gate voltage given as [15] is expressed in Equation (7).

$$IP3 = \sqrt{\frac{4g_m}{3g''_m}} \quad (7)$$

The IP3 of the device can be improved by reducing g''_m as small as possible.

3.1 Multiple Gated Transistor Technique

One of the most widely used techniques is the Multiple Gated Transistors (MGTR) technique. The concept of MGTR technique is explained using Fig.4. The input signal from the port is given to the gate of the all transistors. The drains of differential main transistor are connected to the respective drains of the differential auxiliary transistor. The main transistors shown in figure are operating in strong inversion region and the auxiliary transistors are operating in weak inversion region. The MGTR scheme improves the linearity by cancellation of third order derivative due to the introduction of auxiliary transistors.

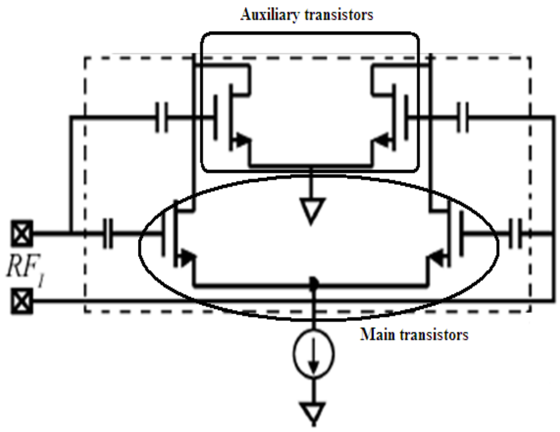

Figure 4: Transconductance stage with MGTR

Fig.5 shows the UWB mixer with MGTR technique. The MGTR consists of M_1,M_{1a},M_2,M_{2a} NMOS transistors. M_1, M_2 are the Main Transistors (MT) providing major gain of the mixer and M_{1a}, M_{2a} are the Auxiliary Transistors (AT) compensating for the nonlinearity.

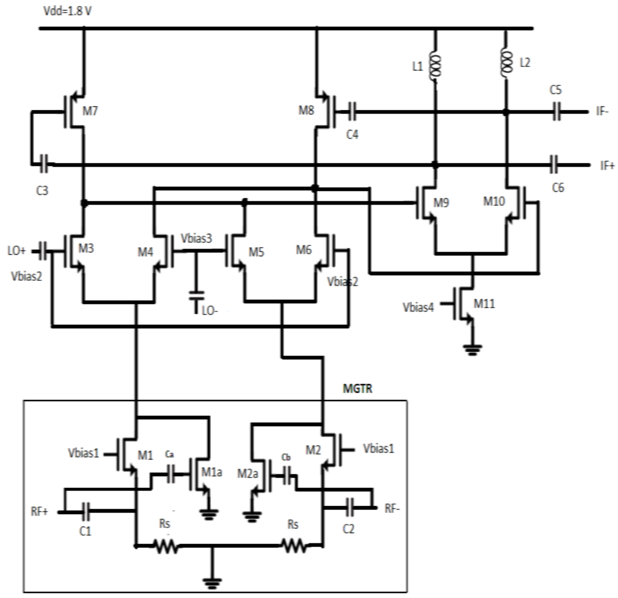

Figure 5: UWB mixer with MGTR

3.2 Cross Coupled Post Distortion Technique

The second technique used in this paper is Cross Coupled Post Distortion (CCPD) technique to improve the linearity of the UWB mixer. It is explained with the Fig.6. In this technique, the AC signal from the drain of MTs is passed through the coupling capacitors (C_a, C_b) to the gate of ATs.

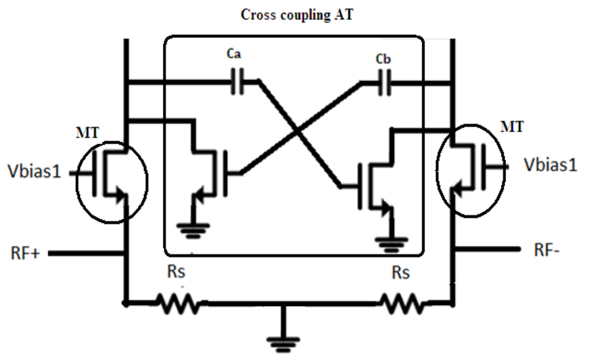

Figure 6: Transconductance stage with CCPD

The differential main transistor pair is biased in strong inversion, which has a negative third-order derivative g3. Therefore, the third-order nonlinearity provided by the cross-coupling post-distortion canceller FET should be positive, which requires biasing ATs in the weak inversion region. Fig.7 shows the UWB mixer with CCPD. The differential pair M_1 and M_2 is operating in strong inversion region, which has a negative 3^{rd} order derivative. The FETs M_{1a} and M_{2a} providing positive transconductance are operating in weak inversion region.

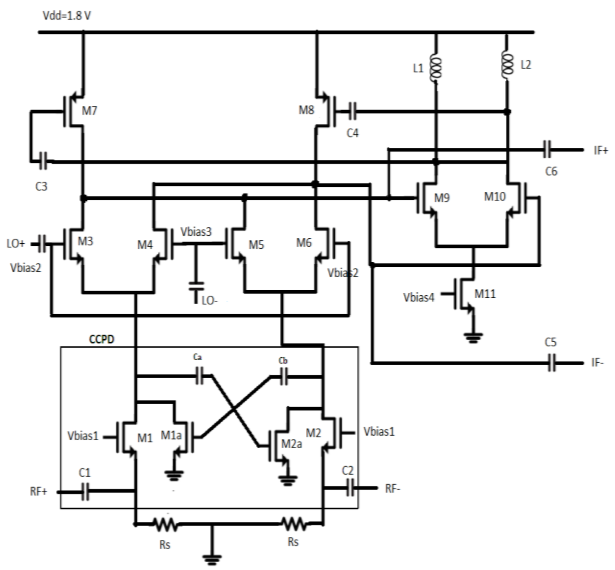

Figure 7: UWB mixer with CCPD

4 Simulation Results

The UWB mixer design is simulated using Advanced Design System software in a 0.18µm RF CMOS process with 1.8V supply voltage. The important measures such as conversion gain, noise figure, port-to-port isolation and 3^{rd} order Input Intercept Point (IIP3) are calculated. Fig.8 shows the simulated conversion gain of mixer with and without linearization techniques. This design is evaluated with RF input power of -30dBm, LO input power of 0dBm, with the LO fixed at 6.4 GHz.

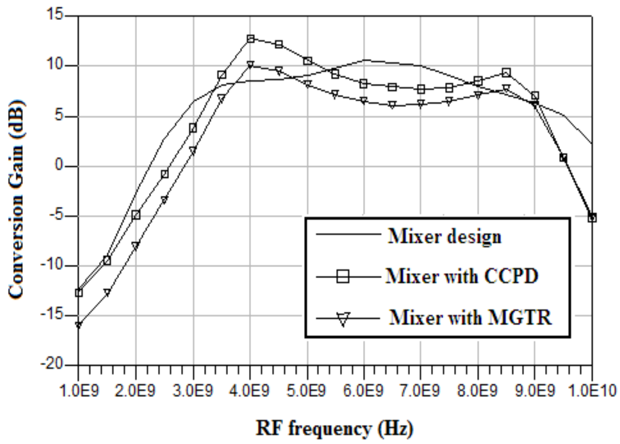

Figure 8: Conversion Gain

Fig.9 shows the DSB noise figure of the mixer with and without linearization techniques. Noise figure is plotted as a function of RF power. The UWB Mixer with linearization techniques gives the DSB NF of 14dB and 14.656dB at 100MHz. Port-to-Port isolation represents the amount of leakage between the mixer ports. The values of the port-to-port isolation are represented in Table 1.

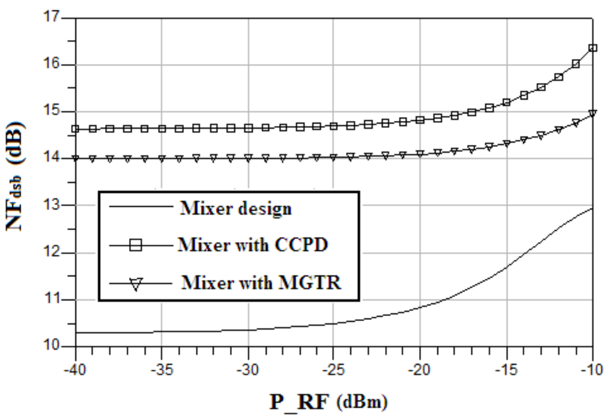

Figure 9: Noise Figure

Table 1: Values of port-to-port isolation

Measures	Mixer design	Mixer with MGTR	Mixer with CCPD
RF to IF (dB)	18.32	38.3	29.18
LO to IF (dB)	29.24	32.7	32.7
LO to RF (dB)	30.6	33.97	38.03

Fig.10 shows the IIP3 values of Mixer with and without linearization techniques. The IIP3 value is noted at 6.5GHz. The Multiple Gated Transistor technique gives the linearity of -1.37 dBm for this UWB mixer design. The Cross Coupled Post distortion technique provides the high linearity of 3.33dBm.

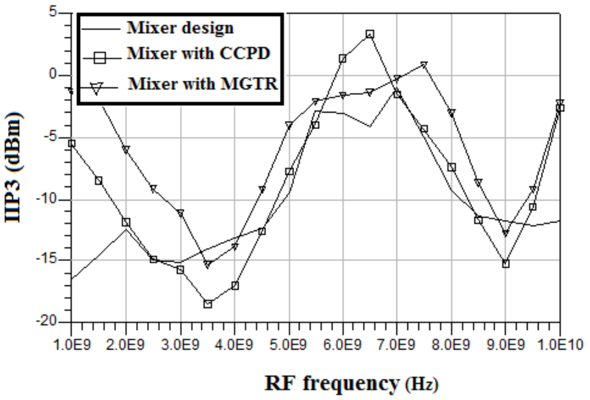

Figure 10: IIP3 values

The performance measures are tabulated in Table 2. The UWB mixer gives the high conversion gain. But its IIP3 value is -4.095 dBm. After including the linearization techniques, UWB mixer with MGTR gives the conversion gain of 6.122dB and IIP3 of -1.365 dBm. UWB mixer with CCPD gives the conversion gain of 7.956dB and IIP3 of 3.326dBm.

Table 2: Performance summary of UWB Mixer and its Linearization Techniques

Measures	Mixer design	Mixer with MGTR	Mixer with CCPD
RF frequency (GHz)	3.5-9.5	3.5-9.5	3.5-9.5
IF frequency (MHz)	100	100	100
Conversion gain (dB)	10.3	6.122	7.956
Noise figure (dB)	10.36	14	14.656
IIP3 (dBm)	-4.095	-1.365	3.326
LO-RF isolation	30.6	33.93	38.03
Power (mW)	6.7	6.93	6.93

From the analysis, the CCPD technique gives high linearity to this UWB mixer. This design is compared with the other UWB mixers, as shown in Table 3.

Table 3: Comparison with other Mixer designs

Reference	Mixer with CCPD	[7]	[10]	[11]
Technology (µm)	0.18	0.18	0.13	0.13
RF (GHz)	3.5-9.5	0.2-2	50-75	1-10
IF (MHz)	100	35	200	100
P_{LO} (dBm)	0	-	2	0
Conversion gain (dB)	7.96	39	5.6	3
NF_{dsb} (dB)	14.66	3.1-6.1	15.2	11.3
IIP3 (dBm)	3.33	-4	-	-7
P_{dc} (mW)	6.93	36	13.78	8.4

From the Table 3, It is inferred that Mixer with CCPD design peformed well than the other existing works.

5 Conclusion

The UWB mixer is designed in TSMC 0.18µm RF CMOS technology. To increase the linearity of the wideband mixer, the MGTR and CCPD techniques are employed. The IIP3 values for MGTR and CCPD techniques were -1.365dBm and 3.326dBm, respectively. Hence the designed UWB mixer with Cross Coupled Post Distortion technique has been provided the high linearity than the designed UWB mixer with Multiple Gated Transistor technique. The conversion gain for this UWB mixer with CCPD was 7.956dB at 6.5GHz and the DSB NF was 14.656dB.

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