CMOS Mixer Linearization by the Low-Frequency Signal Injection Method

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Abstract - **This paper presents, for the first time, the application of low-frequency signal injection technique to the linearization of a doubly balanced dual gate mixer. The down-conversion mixer is fabricated using 0.35 μm CMOS technology and is designed to operate at 900 MHz RF input frequency with good port-to-port isolation, low LO power and current consumption. Reduction of third-order intermodulation distortion (IMD) level of almost 20 dB is achieved by the proposed scheme.**

I. INTRODUCTION

Linearity is an essential requirement in modern wireless communication systems due to the small channel spacing. Various linearization schemes have been studied extensively for power amplifiers, but much less attention has been paid to mixers [1-2]. The dynamic range of a RF transceiver is often limited by the linearity performance of the first down-conversion mixer. In addition, a highly integrated RF mixer is desired that allows transceiver miniaturization and cost reduction. As a result, the design of mixers (particularly a CMOS version) forces many compromises between conversion gain, LO power, linearity, port-to-port isolation and power consumption. In this paper, the design and measured performance of a high linearity doubly balanced dual-gate mixer, fabricated using 0.35μm CMOS process, is presented. The circuit is designed to operate at a supply voltage of 2V, with an input RF frequency of 900MHz and an output IF frequency of 100 MHz. For linearity improvement, novel low-frequency signal injection technique is introduced and experimentally verified.

II. THEORY

A. Doubly Balanced Dual-Gate CMOS Mixer

Doubly balanced dual-gate mixer has many advantages including high port-to-port isolation and rejection of even-order spurious responses [3]. The dual-gate device can be implemented by using two cascade-connected single-gate FET devices [3] with equal widths.

For optimal performance, the dual-gate mixer (Fig. 1) is selectively biased in such a way that the lower FET (M_2) is operating as a transconductor while the upper FET (M_1) is acting like a switch. For mixing purposes, LO and RF signals are applied to the gate inputs of M_1 and M_2, respectively. To a first approximation, the branch current, i_d, can be expressed by equation (1),

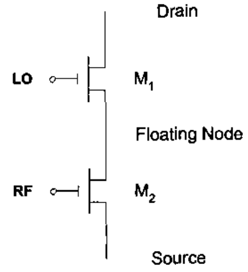

Fig. 1 Dual-gate FET mixer

$$i_d = g_m v_{RF} \cos\omega_{RF} t \times \left\{ \frac{1}{2} + \frac{2}{\pi} \sum_{n=0}^{\infty} \frac{(-1)^n}{2n+1} \cos(2n+1)\omega_{LO} t \right\} \quad (1)$$

where g_m is the transconductance value of the FET (M_2).

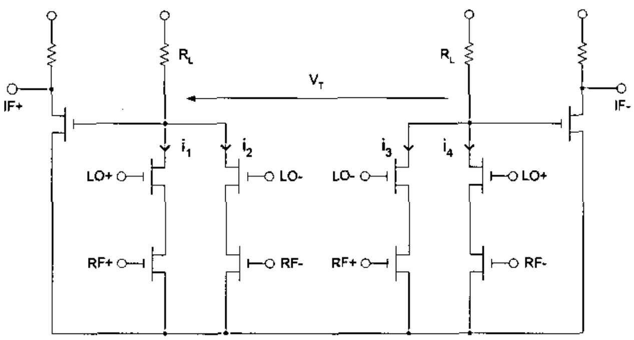

Fig. 2 Schematic diagram of doubly balanced dual-gate mixer

$$
\begin{aligned}
v_T &= \left(i_1 + i_2 - i_3 - i_4\right)R_L \\
&= \left\{
\begin{array}{l}
g_m\, v_{RF} \cos\omega_{RF}t \times \left[\dfrac{1}{2} + \dfrac{2}{\pi}\sum_{n=0}^{\infty} \dfrac{(-1)^n}{2n+1}\cos(2n+1)\omega_{LO}t \right] \\
-\; g_m\, v_{RF} \cos\omega_{RF}t \times \left[\dfrac{1}{2} - \dfrac{2}{\pi}\sum_{n=0}^{\infty} \dfrac{(-1)^n}{2n+1}\cos(2n+1)\omega_{LO}t \right] \\
-\; g_m\, v_{RF} \cos\omega_{RF}t \times \left[\dfrac{1}{2} - \dfrac{2}{\pi}\sum_{n=0}^{\infty} \dfrac{(-1)^n}{2n+1}\cos(2n+1)\omega_{LO}t \right] \\
+\; g_m\, v_{RF} \cos\omega_{RF}t \times \left[\dfrac{1}{2} + \dfrac{2}{\pi}\sum_{n=0}^{\infty} \dfrac{(-1)^n}{2n+1}\cos(2n+1)\omega_{LO}t \right]
\end{array}
\right\} R_L \\
&= \frac{8}{\pi} v_{RF}\, g_m R_L \cos\omega_{RF}t \times \left\{ \cos\omega_{LO}t - \frac{1}{3}\cos 3\omega_{LO}t + \frac{1}{5}\cos 5\omega_{LO}t + \dots \right\} \qquad (2)
\end{aligned}
$$

$$v_{IF} = \frac{4}{\pi} v_{RF}\, g_m R_L \cos\left(\omega_{LO} - \omega_{RF}\right)t \qquad (3)$$

Fig. 2 shows the schematic diagram of a doubly balanced dual-gate mixer with common-source output buffers. Expressions for the output voltage (v_T) and the corresponding IF signal (v_{IF}) are given in equation (2) & (3). In practice, due to the device's nonlinearity, the transconductance value is a function of the input voltage that can be approximated as:

$$g_m = g_{m1} + g_{m2} v_{gs}(t) + g_{m3} v_{gs}{}^2(t) \qquad (4)$$

where g_{m1}, g_{m2} and g_{m3} are bias-dependent coefficients.

And in the presence of two-tone input signals, third-order IMD components will appear at the IF spectrum, as illustrated in Fig. 3. Mathematically, the output IF signal may be shown as:

$$
\begin{aligned}
v_{IF} &= \frac{4}{\pi} v_{RF}\, g_{m1} R_L \cos\left(\omega_{IF} + \frac{\Delta\omega}{2}\right)t \\
&+ \frac{4}{\pi} v_{RF}\, g_{m1} R_L \cos\left(\omega_{IF} - \frac{\Delta\omega}{2}\right)t \\
&+ \frac{3}{\pi} v_{RF}{}^3\, g_{m3} R_L \cos\left(\omega_{IF} + \frac{3\Delta\omega}{2}\right)t \\
&+ \frac{3}{\pi} v_{RF}{}^3\, g_{m3} R_L \cos\left(\omega_{IF} - \frac{3\Delta\omega}{2}\right)t
\end{aligned} \qquad (5)
$$

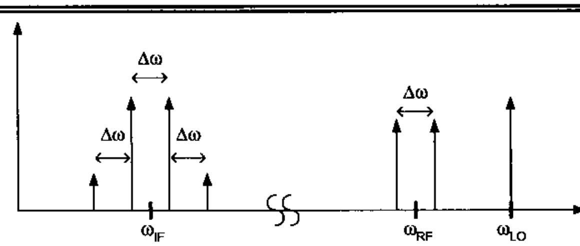

Fig. 3 Simplified output Spectrum

B. Low-Frequency Signal Injection Method

Fig. 4 shows the variation of transconductance as a function of drain voltage for a typical FET device operating close to the linear region.

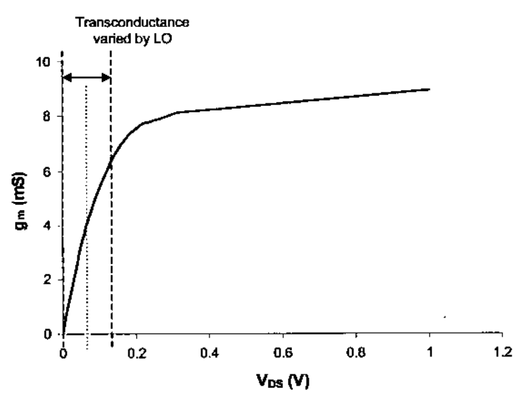

Fig. 4 Variation of g_m as a function of V_{DS}

For IMD suppression [4], a low-frequency signal (Δf) is injected into the mixer via the drain circuitry, which leads to the modulation of the device's transconductance:

$$g_m(\text{mod}) = g_m \left(1 + G\, v_{RF}^{\ 2} \cos \Delta\omega t\right) \qquad (6)$$

Hence, from equation (5) & (6), the resulting IMD signal can be derived as:

$$\begin{aligned} v_{IMD3} &= \frac{2}{\pi} v_{RF}^{\ 3} G\, g_{m1} R_L \cos\left(\omega_{IF} + \frac{3\Delta\omega}{2}\right)t \\ &+ \frac{2}{\pi} v_{RF}^{\ 3} G\, g_{m1} R_L \cos\left(\omega_{IF} - \frac{3\Delta\omega}{2}\right)t \\ &+ \frac{3}{\pi} v_{RF}^{\ 3} g_{m3} R_L \cos\left(\omega_{IF} + \frac{3\Delta\omega}{2}\right)t \\ &+ \frac{3}{\pi} v_{RF}^{\ 3} g_{m3} R_L \cos\left(\omega_{IF} - \frac{3\Delta\omega}{2}\right)t \end{aligned} \qquad (7)$$

where G is a gain constant. The above expression indicates that by properly controlling the strength of the injected signal (both the magnitude and phase of G), total suppression of IMD may be achieved.

III. Experimental Results

Fig. 5 shows the microphotograph of the mixer fabricated using 0.35μm CMOS process. The circuit had an active area of less than 300 × 250 μm^2. The RF, IF and LO signals were fed differentially from off-chip passive 3dB hybrids. At a supply voltage of 2V, an optimum LO power of –7dBm is required. Measured conversion gain and port-to-port isolation for the range of RF frequencies from 850 to 950 MHz is given in Fig. 6. More than 30 dB of port-to-port isolation is achieved by using the doubly balanced structure. The entire mixer and buffer combination consumed a total current of 3.6mA. Overall performance of the mixer operating at an RF frequency of 900 MHz is summarized in Table I.

Fig. 7 shows the experimental setup for CMOS mixer linearization. Low-frequency signal, generated externally by a nonlinear element (FET), was injected into the mixer through the drain biasing circuitry. Two-tone measurement was conducted using signals centered at 900 MHz with a frequency separation of 100 kHz. The IF IM3 level of the mixer was found to be reduced by almost 20 dB (Fig. 8) upon adjusting the magnitude of the injected signal. Fig. 9 shows the measured IMD performance of the mixer as the RF input power level is varied.

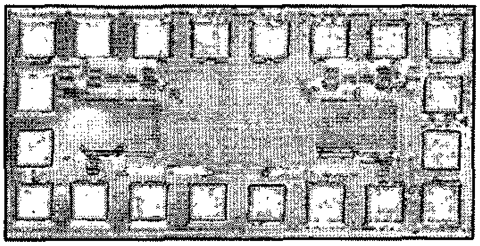

Fig. 5 Microphotograph of CMOS mixer chip

LO power	-7 dBm
Conversion Gain	1.1 dB
Output P1dB	-14.3 dBm
Output IP3	-2.2 dBm
LO-IF isolation	33.3 dB
RF-IF isolation	32.4 dB
Mixer Current	1.4 mA
Output Buffer Current	2.2 mA

Table I Summary of mixer's performance at 900 MHz

IV. Conclusion

The design and implementation of a doubly balanced dual-gate CMOS mixer has been described. Good RF-IF and LO-IF isolation were demonstrated. More than 15dB reduction in third-order IMD level was observed over a wide input power range. The proposed method requires no complex RF circuitry and is amendable to monolithic integration.

References

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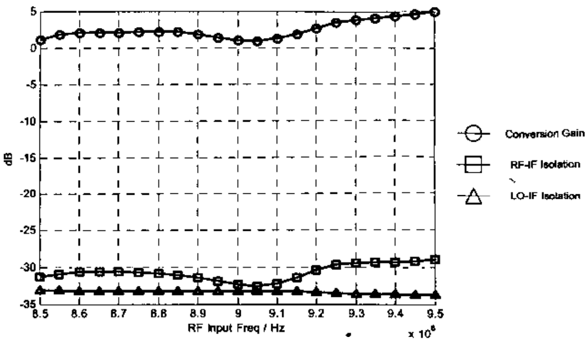


Fig. 6 Mixer's performance versus RF frequency

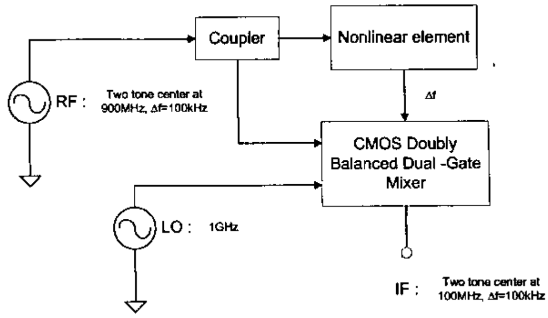
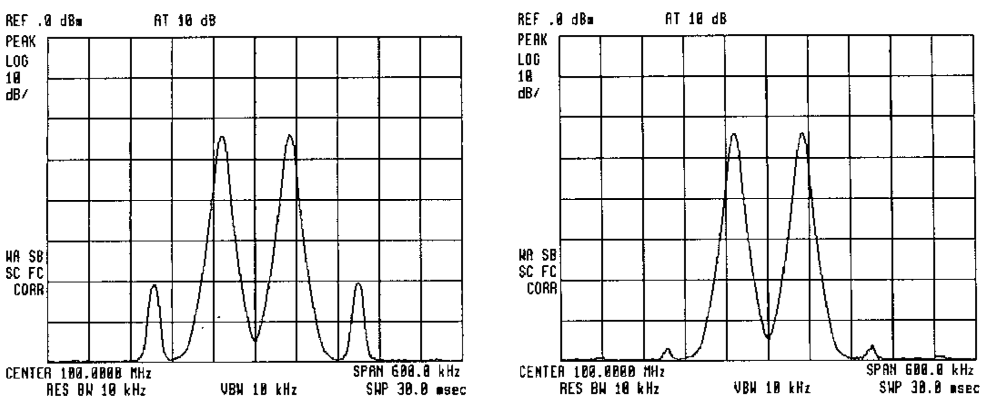
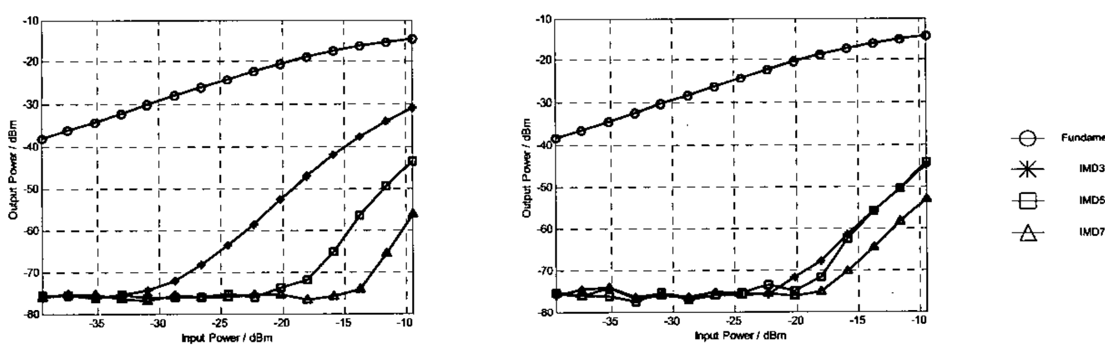


Fig. 7 Experimental linearization system



(a) (b)

Fig. 8 Output IF Spectrum (a) without linearization; (b) with linearization



(a) (b)

Fig. 9 Mixer's IMD performance versus RF input power (a) without linearization; (b) with linearization