Characterization of LO leakage behavior in Transconductance Mixers

V. H. Le, Q.K Tran, S.K Han and S. G. Lee

Abstract –**This paper presents the analysis of LO leakage behavior in transconductance mixers. LO leakage in double balanced active mixer is analyzed by simplified theoretical study and simulation. The theoretical mismatch analysis is carried out instead of a complex mixer nonlinearity analysis; this provides information about the relations of differential imbalances to actual performance. The analysis uses a number of simplifying assumptions, but without losing generality. The analysis and simulation show that the LO leakage behavior is sensitive to the mismatches in the base-band signal and any differential devices of the mixers except for the LO signal mismatch in term of duty circle time. The theoretical model result of LO leakage behavior quite agrees with the simulation result.**

I. INTRODUCTION

The direct conversion transceiver (DCT) has attracted wide-spread attention recently for its simple architecture and easy integration with the base-band circuit, as well as for its low power consumption and potentially low manufacturing costs [1]. However, DCT has some disadvantages such as DC-offset, even-order distortion, flicker noise, I/Q mismatch, LO leakage etc [2], [3]. While those disadvantages are very critical in receiver, the situation is not as bad as in the transmitter except for LO leakage. High LO leakage apparently is the source of interference to other channels in ISM band which is already very crowded with many applications.

Double balanced Gilbert-type mixer has been widely used in wireless transceivers. Due to the fully differential structure, double balanced mixer has many advantages such as high port-to-port isolation, high noise common mode rejection… However maintaining perfect differential signals is almost impossible, the mismatches in double balanced mixer lead to LO leakage to the RF output which could come to seriously block the adjacent channels. Therefore proper evaluation this LO leakage behavior is certainly necessary, which provides the designers the intuitively deep look inside. The LO leakage behavior in double balanced mixer over the mismatches and nonlinearity of devices and signal is analyzed in this paper. The LO leakage model is proved by simulation as its behavior quite compromises with the simulation results.

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II. MODEL ANALYSIS

The LO leakage in mixer can be seen as the mixing product of fundamental harmonic of LO signal with dc current of input transconductance transistors. In double balanced mixer, the LO leakage as well as second-order components are canceled out when taking the output signal differentially. However because of the imbalances of two branches of the mixer the cancellation is not perfect leading to high LO signal presents at the RF output which could be as large as saturating the amplifier and blocking adjacent channels.

To start with the analysis, the transconductance stage is simply modeled with voltage-controlled current source (VCCS) and the mixing transistor function is rectangular switches.

In general the nonlinear VCCS is expressed by Taylor series:

$$i_{BB}(t) = I_{dc} + g_m v_{in}(t) + \beta_2 g_m' v_{in}^2(t) + \beta_3 g_m'' v_{in}^3(t) + \Lambda$$

To reduce the complexity the current is rewritten as:

$$i_{BB}(t) = I_{dc} + g_m\left[v_{in}(t) + \alpha_2 v_{in}^2(t) + \alpha_3 v_{in}^3(t) + \Lambda\right]$$

In (1) the mismatches therefore are presented in dc bias current I_{dc} transconductance g_m and controlled input voltage $v_{in}(t)$, while the nonlinearity factor α_2 and α_3 are assumed to be constant.

The transconductance of input V-I converters when there is mismatch in two branches can be expressed as:

$$g_{mP} = g_m\left(1 + \frac{\Delta g_m}{2}\right) \text{ and } g_{mN} = g_m\left(1 - \frac{\Delta g_m}{2}\right)$$

And also the mismatch in dc bias current in two branches can be described as:

$$I_{dcN} = I_{dc}\left(1 - \frac{\Delta I}{2}\right) \text{ and } I_{dcP} = I_{dc}\left(1 + \frac{\Delta I}{2}\right)$$

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Thus the VCCSs presented two separated branches are:

$$i_{BBP}(t)=I_{dcP}+g_{mP}\left[v_{inP}(t)+\alpha_2 v_{inP}^2(t)+\alpha_3 v_{inP}^3(t)+\Lambda\right]$$
$$i_{BBN}(t)=I_{dcN}+g_{mN}\left[v_{inN}(t)+\alpha_2 v_{inN}^2(t)+\alpha_3 v_{inN}^3(t)+\Lambda\right] \quad (1)$$

The LO signal is square-wave approximation, in which the duty circle is used as a mismatch parameter. The Fourier series presenting LO gate functions (Fig.1) are given separately as:

$$g_{LOP}(t)=\eta_P-\left(\frac{2}{\pi}\right)\Big[\sin(\eta_P\pi)\cos(\omega_{LO}t)$$
$$-\left(\frac{1}{2}\right)\sin(2\eta_P\pi)\cos(2\omega_{LO}t)$$
$$+\left(\frac{1}{3}\right)\sin(3\eta_P\pi)\cos(3\omega_{LO}t)-\Lambda\Big]$$
$$g_{LON}(t)=\eta_N+\left(\frac{2}{\pi}\right)\Big[\sin((1-\eta_N)\pi)\cos(\omega_{LO}t)$$
$$-\left(\frac{1}{2}\right)\sin(2(1-\eta_N)\pi)\cos(2\omega_{LO}t) \quad (2)$$
$$+\left(\frac{1}{3}\right)\sin(3(1-\eta_N)\pi)\cos(3\omega_{LO}t)-\Lambda\Big]$$

The different duty circles of the positive and negative gate functions are modeled by unequal conduction time (in percentages) $\eta_P=\eta\left(1+\frac{\Delta\eta}{2}\right)$ and $\eta_N=\eta\left(1-\frac{\Delta\eta}{2}\right)$ respectively.

Therefore as can be seen in Fig.2 the currents in two output branches of mixer can be calculated:

$$i_{oP}(t)=i_{BBP}(t)\cdot g_{LON}(t)+i_{BBN}(t)\cdot g_{LOP}(t)$$
$$i_{oN}(t)=i_{BBN}(t)\cdot g_{LON}(t)+i_{BBP}(t)\cdot g_{LOP}(t) \quad (3)$$

At the input, the base-band signal considering amplitudes and phases imbalances can be modeled

$$v_{inP}(t)=+A_{BBP}\cos(\omega_{BB}t+\Delta\varphi)$$
$$v_{inN}(t)=-A_{BBN}\cos(\omega_{BB}t)$$

In these the amplitudes of two branches can be written:

$$A_{BBP}=A_{BB}\left(1+\frac{\Delta A_{BB}}{2}\right) \text{and } A_{BBN}=A_{BB}\left(1-\frac{\Delta A_{BB}}{2}\right)$$

And the phase mismatch is modeled by $\Delta\varphi$.

At the RF output the positive and negative branches loads of mixer can be expressed as $R_P=R\left(1+\frac{\Delta R}{2}\right)$ and $R_N=R\left(1-\frac{\Delta R}{2}\right)$.

The output voltages of two branches then are:

$$v_{oP}(t)=i_{oP}(t)\cdot R_P$$

$$v_{oN}(t)=i_{oN}(t)\cdot R_N$$

Finally the differential output voltage is

$$v_{oN}(t)=v_{oP}(t)-v_{oN}(t)=i_{oP}(t)\cdot R_P-i_{oN}(t)\cdot R_N \quad (4)$$

Thus substituting (1), (2) and (3) into (4), neglecting the high order nonlinearity components of base-band signal (the third and higher order components are neglected) we have interested LO component:

$$LO\_leakage=\frac{2}{\pi}\cos(\omega_{LO}t)\cdot R\cdot$$
$$\left[(a\cdot c-b\cdot d)\left(1+\frac{\Delta R}{2}\right)-(b\cdot c-a\cdot d)\left(1-\frac{\Delta R}{2}\right)\right]$$

Or:

$$LO\_leakage=\frac{2}{\pi}\cos(\omega_{LO}t)\cdot R\cdot$$
$$\left[(a-b)(c+d)+\frac{\Delta R}{2}(a+b)(c-d)\right]$$

While:

$$a=I_{dcP}+\frac{1}{2}g_{mP}\cdot\alpha_2 A_{BBP}^2\cos^2\Delta\varphi$$
$$b=I_{dcN}+\frac{1}{2}g_{mN}\cdot\alpha_2 A_{BBN}^2$$
$$c=\sin[(1-\eta_N)\pi]$$
$$d=\sin(\eta_P\pi)$$

$$LO\_leakage=\frac{2}{\pi}\cos(\omega_{LO}t)\cdot R\cdot$$
$$\Big\{\Big[I\Delta I+g_m\alpha_2 A_{BB}^2\bullet$$
$$\Big(\cos^2\Delta\varphi-1+$$
$$\Delta A(\cos^2\Delta\varphi+1)+$$
$$\frac{\Delta g_m\Delta A}{2}(\cos^2\Delta\varphi+1)\Big)\Big]\left[\sin\left(\frac{\pi}{2}\eta\Delta\eta\right)\cos(\pi\eta)\right]$$
$$+\Delta R\Big[2I+\frac{1}{2}g_m\alpha_2 A_{BB}^2\bullet$$
$$\Big(\cos^2\Delta\varphi+1+$$
$$\Delta A(\cos^2\Delta\varphi-1)+$$
$$\frac{\Delta g_m\Delta A}{2}(\cos^2\Delta\varphi-1)\Big)\Big]\left[\cos\left(\frac{\pi}{2}\eta\Delta\eta\right)\sin(\pi\eta)\right]\Big\}$$
$$(5)$$

It has been shown in (5) that LO leakage depends on the mismatches of output load, bias current, transconductance of input devices and the imbalance in amplitude and phase of base-band input signal. Also in (5) we can find that the mismatches in LO signals presented by duty circle does not contribute to the leakage of LO signal to the output when assuming that there is no mismatch in other parameters, we mention that because the mismatch in LO signals does not affect in other devices' or signals' parameters or their effects are symmetrical in two branches. In (5) we see that the mismatch in output load does not directly contribute to the LO leakage (when there is no mismatch in other parameters, the output load mismatch ΔR does not show up in equation (5)). However when there is mismatch in output load, leading to mismatch in output voltage swings then to mismatch in the switching transistors, as the result the output load mismatch ΔR shows up in the equation (5), in another word this mismatch then contributes to the LO leakage.

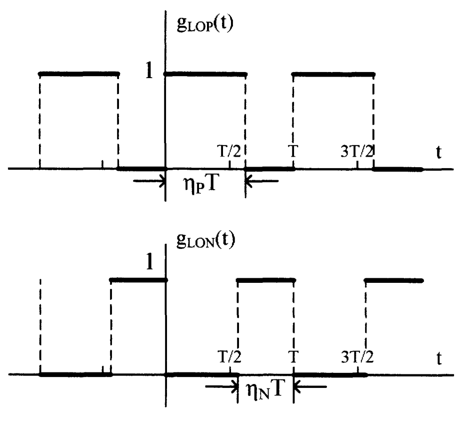

Fig. 1. LO square signals: $g_{LOP}(t)$ and $g_{LOP}(t)$ functions.

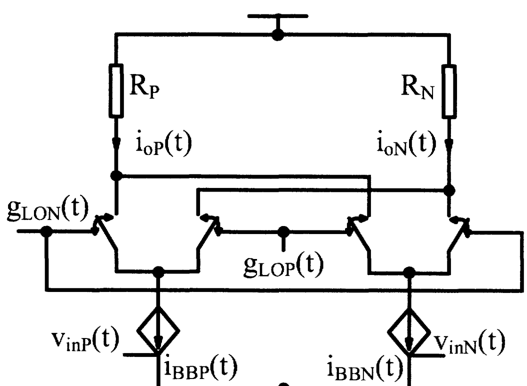

Fig. 2. Model for double-balanced switching mixer.

III. SIMULATIONS

A double-balanced mixer (Fig.3) is simulated in TSMC CMOS 0.18μm process using Cadence. The simulated mixer is configured for direct conversion transmitter for IEEE 802.15.4 standard with LO of 910 MHz. The simulation result quite agrees with the analysis. It shows that the LO power leakage to the RF output much depend on the mismatches in the input devices and the output loads while the mismatches in LO signals have no effect on the LO leakage behavior. The simulation results are shown in Fig.4.

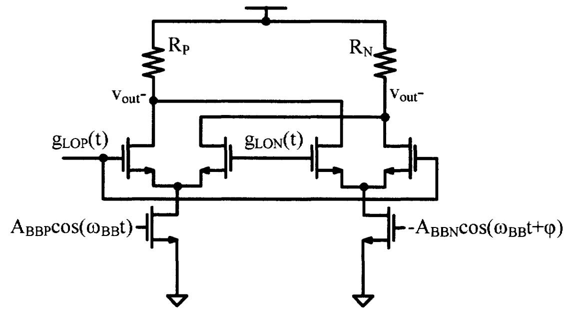

Fig. 3. Double balanced mixer for simulation.

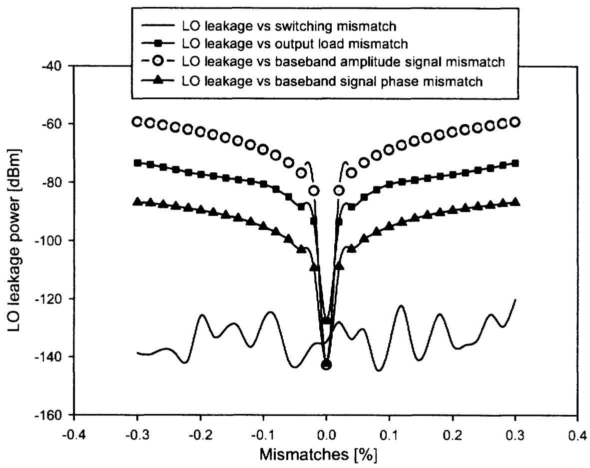

Fig. 4. LO leakage behavior over the mismatches in devices and signal.

III. CONCLUSION

A simple theoretical model of LO leakage behavior in double-balanced mixers has been presented in this paper. The work focuses on mismatch analysis rather than nonlinearity analysis. This analysis shows a good intuitive example of the LO leakage behavior of transconductance mixers and is a basis to be extended into other topologies also. It has been shown that the LO leakage at the RF output is sensitive with any mismatches except for the mismatch of LO signals. In conclusion to suppress the LO leakage at the RF output it is very important to maintain the symmetry of the input devices, differential base-band input signals and the output loads. Mismatch in switching stage almost has no effects on the LO leakage performance.

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REFERENCES

[1] Jose A. Gutierrez, and E. H. Callaway, Low-Rate Wireless Personal Area Netwroks, IEEE Press 2004.

[2] A. A. Abidi, "Direct Conversion Radio Transceivers for Digital Communications", IEEE Journal of Solid-State Circuits, vol.30, no.12, pg.1399 -1410, Dec.1995.

[3] B. Razavi, "Design Considerations for Direct Conversion Receivers", IEEE Transactions on Circuits and Systems-II: Analog and Digital Signal Processing, vol.44, pp. .428-435, June 1997.

[4] Keng Leong Fong; Meyer, R.G., "Monolithic RF active mixer design"; Circuits and Systems II: Analog and Digital Signal Processing, IEEE Transactions on [see also Circuits and Systems II: Express Briefs, IEEE Transactions on] Volume 46, Issue 3, March 1999 Page(s):231 – 239.