Accurate Analysis of RF Noise Characteristics in Active MOSFET Mixers in 90 nm Technology

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***Abstract*— In this paper an accurate noise analysis for active mixers in 90 nm technology, based on the variations of the two parameters *W/L* (transistor size) and f_{LO} (local oscillator frequency) is presented. The contribution of the gate resistance noise to the gate and drain total current noises is considered, whereas this noise is usually assumed to be an independent source in the literature. It is shown that the variations of the noise generated by the switching pair in a mixer due to *W/L* variations in a wide range of local oscillator frequency, is less than the variations of the noise generated by the transconductor section of the mixer, which this matter shows the importance of the transconductor. Also it is shown that for the gate-source voltage values near to the threshold voltage value, the variations of the noise generated by the switching pair and the transconductor due to *W/L* variations, is reduced. In this middle, the reduction of the noise generated by the switching pair is more.**

Index Terms—**Noise, Active mixers, Correlation factor, Local oscillator, Transistor size.**

I. INTRODUCTION

The active MOSFET mixer is one of the most important stages specially in the input of the communication systems. Thus the analysis of its output noise, has a great importance [1]-[9]. In this respect, two main techniques, the mathematical [3], [5], [6] and the physical [4] approaches are used. The first technique gives more accurate results for the influence of various parameters on the noise generated in the mixer output.

With the technology progress, the need to increase the velocity and complexity of the integrated circuits, design of transistors with the size of less than 100 nm has been noticed by researchers. In this middle, the transistor BSIM4.6.0 which has been designed at Berkeley university in 90 nm technology, has been used in this research for the noise analysis in a mixer [7]. For this purpose, the transconductor and the switching pair in a mixer have special importance [3]-[6]. The noise variations of these two sections depend on various parameters such as the local oscillator amplitude and frequency, the bias current, etc. [3], [4], [6]. The effect of *W/L* (the ratio of the channel width to the channel length that indicates the transistor size) on the mixer output noise is analyzed and noticed in this paper, whereas has been less noticed in the other studied references.

In Fig. 1, a simple active mixer has been shown. For analyzing the noise generated in the mixer output, it is required to study noises due to its various parts and obtain influence and share of each part on the output total noise. Of course in this paper, the transconductor (TM_3) and the switching pair (TM_1, TM_2) have been noticed.

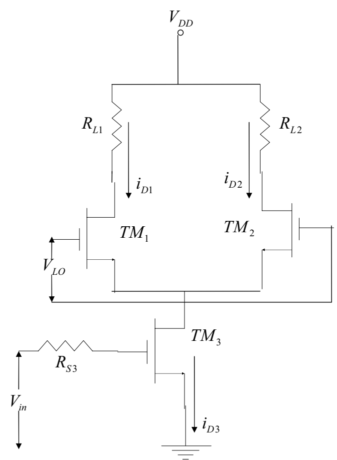

Fig. 1. A single balanced mixer.

II. NOISE SOURCES IN MOSFETS

The most important noise sources in a MOSFET are as follows:

A. The drain current noise

The drain current noise is composed of two terms as follows

$$\overline{i_d^2} = 4kT(\gamma g_m)\Delta f + K\frac{I_D^{\alpha}}{f}\Delta f \cdot \qquad (1)$$

The first term is the thermal noise which has constant PSD (power spectral density) versus the frequency, and the second term is the flicker or *1/f* noise with PSD proportional to the reciprocal of the frequency. The numerical value of α is between 0.5 and 2 [1]. Also γ is assumed to be 2/3 for the long channel and 2.5 for the short channel cases. Moreover I_D and

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g_m are the bias current and the transconductance, which for the short channel MOSFET are expressed as follows [3], [4]

$$I_D = W v_{sat} C_{ox} \frac{(V_{GS}-V_{TH})^2}{V_{GS}-V_{TH}+LE_{sat}}, \qquad (2)$$

$$g_m = \frac{2I_D}{V_{GS}-V_{TH}}\left(\frac{(V_{GS}-V_{TH})/2+LE_{sat}}{V_{GS}-V_{TH}+LE_{sat}}\right) \qquad (3)$$

where W, L, v_{sat}, E_{sat} and C_{ox} are the channel width, the channel length, the saturation velocity of carriers, the saturation electrical field, and the oxide capacitance per unit area. Also V_{GS} and V_{TH} are the gate-source voltage and the threshold voltage, respectively.

B. The gate current noise

The gate current noise is composed of the following parts:

1) The gate shot noise

This gate shot noise is expressed as $\overline{i^2_g}=2qI_G\Delta f$. Since the gate current I_G is usually less than $10^{-15}A$, we often neglect this noise. Also the gate shot noise and the drain current noise are independent [1].

2) The induced gate noise

This noise is generated from the drain current thermal noise, due to the capacitive coupling between the channel and the gate, and is expressed as $S_{I_G}=\overline{i_g^2}/\Delta f = 4kTg_g\beta$. The value of β is assumed to be 3 for the short channel transistor [3]. Also g_g is the real part of the gate-source admittance and is expressed as $g_g=\omega^2C^2_{gs}/(5g_m)$ [2], [3] where C_{gs} is the gate-source capacitance and is expressed as $C_{gs}=2/3C_{ox}WL$ in the saturation region [1]. The induced gate noise is correlated with the drain current thermal noise. Because of uncertainty in accurate determination of the correlation factor, we assume its value to be j 0.395 for the short channel transistor, as the same for the long channel transistor [2], [3].

3) The gate resistance noise

This noise is a thermal voltage noise, due to the gate resistance, and is defined as $\overline{v^2_{nrg}}=4kTR_g=4kTR_{gate}/3$ [3]. The gate resistance noise is amplified and produces an additional noise on the drain current, which can be expressed as $S_{I_D}=4kTR_g g_m^2$ [2]. Also this noise produces an additional noise on the gate current, which can be expressed as $S_{I_G}=4kTR_g\omega^2C^2_{gs}$ [2]. These two additional noises are correlated with each other with the correlation factor 1.0 j [2].

4) The induced flicker noise

Through the same mechanism as generating the induced gate noise, the drain current flicker noise induces an additional noise on the gate current, due to the coupling between the channel and the gate. This additional noise is called the induced flicker noise, which is correlated with the drain current flicker noise, with the correlation factor –j 0.45. Of course, the induced flicker noise is important at the frequency 3GHz, which causes a few percent increase in the gate current noise [2].

III. The Noise in the mixer output

For the noise analysis in the mixer output, two sections are considered: the transconductor which has been indicated as TM_3 in Fig. 1, and the switching (differential) pair which have been indicated as TM_1 and TM_2 in Fig. 1.

A. The Transconductor noise

The equivalent circuit of the transconductor has been shown in Fig. 2

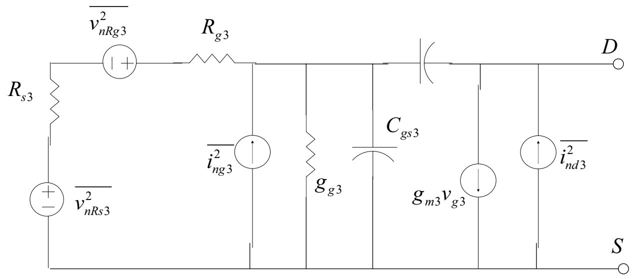

Fig. 2. The transconductor equivalent circuit.

The noise generated by the transconductor is composed of the following parts

1) The induced gate noise

The average power related to PSD of the correlated drain and gate current noises is expressed as follows [3]

$$S^c_{n3}(\omega)=4kT\gamma g_{m3}\left[\left(\frac{\omega_{p3}^2}{\omega_{z3}^2}\right)+\left(1-\left(\frac{\omega_{p3}^2}{\omega_{z3}^2}\right)\right)\left(\frac{\omega_{p3}}{\omega_{LO}}\right)\tan^{-1}\left(\frac{\omega_{LO}}{\omega_{p3}}\right)\right], \qquad (4)$$

$$\omega_{z3}=\left[(k_c+1)^2+k_c^2\left(\frac{1}{|c|^2}-1\right)\right]^{-\frac{1}{2}}\omega_{p3} \quad ; \quad k_c=|c|\sqrt{\frac{\beta\zeta}{\gamma}} \qquad (5)$$

where $R_{sg3}=R_{s3}+R_{g3}$ and $\omega_{p3}=(R_{sg3}\,C_{gs3})^{-1}$. Also R_{g3} and R_{s3} are the equivalent gate resistance and the output source resistance.

Substituting the given values for the parameters, we obtain

$k_c=0.079\sqrt{6}$, $|c|=0.395 \rightarrow \omega_{z3}=0.784\omega_{p3}$,

$$S^c_{n3}(\omega)=4kT\gamma g_{m3}\left(1.627-0.627\left(\frac{\omega_{p3}}{\omega_{LO}}\right)\tan^{-1}\left(\frac{\omega_{LO}}{\omega_{p3}}\right)\right). \qquad (6)$$

2) The output source resistance noise

The average power related to PSD of the noise source $\overline{v^2_{nRs3}}$ in the output of TM_3 is expressed as follows [3]

$$S^u_{n3}(\omega)=4kT\,g^2_{m3}R_{s3}\left(\frac{\omega_{p3}}{\omega_{LO}}\right)\tan^{-1}\left(\frac{\omega_{LO}}{\omega_{p3}}\right). \qquad (7)$$

3) The gate resistance noise

In [3], the thermal noise source of the gate resistance ($\overline{v^2_{nRg3}}$) has been considered as an independent source, and a formulation similar to that obtained for the noise of the output source resistance ($S^u_{n3}(\omega)$) has been expressed. But as mentioned in section II.B, the voltage noise source $\overline{v^2_{nRg3}}$ causes additional noises on the drain and gate currents, which are correlated with each other with the correlation factor j 1.0. Thus we should consider this issue for computing the noise due to the gate resistance in the mixer output, related to the

transconductor. So for computing the average power of the noise due to the source $\overline{v_{nRg3}^2}$ in the transconductor output, we define the parameters γ', β', ω'_{z3}, k'_c, and c' instead of γ, β, ω_{z3}, k_c, and c in Eqs. (4) and (5) as follows

$$S_{I_D} = 4kTR_g g_m^2 \rightarrow \gamma' = R_g g_m, \tag{8}$$

$$S_{I_G} = 4kTR_g \omega^2 C_{gs}^2 = 4kT\frac{\zeta\omega^2 C_{gs}^2}{g_m}\left(\frac{R_g g_m}{\zeta}\right) \rightarrow \beta' = \frac{R_g g_m}{\zeta}, \tag{9}$$

$$\omega'_{z3} = \left[(k'_c+1)^2 + k'^2_c\left(\frac{1}{|c'|^2}-1\right)\right]^{-\frac{1}{2}} \omega_{p3} \tag{10}$$

where $k'_c = |c'|\sqrt{\beta'\zeta/\gamma'}$, $c' = j\ 1.0$ and $\zeta = 0.2$. Thus we can express the average power of the gate resistance noise as

$$S_{n3}^c(\omega)_{Rg3} = 4kT\gamma' g_{m3}\left[\left(\frac{\omega_{p3}^2}{\omega'^2_{z3}}\right) + \left(1 - \left(\frac{\omega_{p3}^2}{\omega'^2_{z3}}\right)\right)\left(\frac{\omega_{p3}}{\omega_{LO}}\right)\tan^{-1}\left(\frac{\omega_{LO}}{\omega_{p3}}\right)\right]. \tag{11}$$

Substituting the parameters values, we have

$k'_c = 1$, $|c'| = 1 \rightarrow \omega'_{z3} = \omega_{p3}/2$,

$$S_{n3}^c(\omega)_{Rg3} = 4kTR_{g3} g_{m3}^2\left(4 - 3\left(\frac{\omega_{p3}}{\omega_{LO}}\right)\tan^{-1}\left(\frac{\omega_{LO}}{\omega_{p3}}\right)\right). \tag{12}$$

The total noise power in the output of TM_3 will be

$$S_{n3}(\omega) = S_{n3}^c(\omega) + S_{n3}^c(\omega)_{Rg3} + S_{n3}^u(\omega)$$

$$= 4kTg_{m3}\left[\begin{pmatrix}1.627\gamma \\ +4R_{g3}g_{m3}\end{pmatrix} + \begin{pmatrix}R_{s3}g_{m3} \\ -0.627\gamma \\ -3R_{g3}g_{m3}\end{pmatrix}\left(\frac{\omega_{p3}}{\omega_{LO}}\right)\tan^{-1}\left(\frac{\omega_{LO}}{\omega_{p3}}\right)\right]. \tag{13}$$

Assuming that the noise of the transconductor current (i_{D3}) is white, its total average power in the mixer output will be [3], [6]

$$\overline{S_{n3}^o}(\omega) = S_{n3}(\omega)\sum_{n=-\infty}^{\infty}|p_{1,n}|^2. \tag{14}$$

For the large values of the local oscillator amplitude, $\sum_{n=-\infty}^{\infty}|p_{1,n}|^2$ is almost unity [3], [6], thus we have

$$\overline{S_{n3}^o}(\omega) \approx S_{n3}(\omega)$$

$$= 4kTg_{m3}\left[\begin{pmatrix}1.627\gamma \\ +4R_{g3}g_{m3}\end{pmatrix} + \begin{pmatrix}R_{s3}g_{m3} \\ -0.627\gamma \\ -3R_{g3}g_{m3}\end{pmatrix}\left(\frac{\omega_{p3}}{\omega_{LO}}\right)\tan^{-1}\left(\frac{\omega_{LO}}{\omega_{p3}}\right)\right]. \tag{15}$$

B. The switching noise

Similar to that discussed for the transconductor noise, we have the following relation for the total output noise of the switching pair

$$S_{n12}(\omega) = S_{n12}^c(\omega) + S_{n12}^c(\omega)_{R_{g12}} + S_{n12}^u(\omega). \tag{16}$$

For each term in the above relation, we have

1) The induced gate noise

For the correlated gate and drain current noises, we have [3]

$$S_{n12}^c(\omega) = 4kT\gamma g_{m12}\left[\left(\frac{\omega_{p12}^2}{\omega_{z12}^2}\right) + \left(1 - \left(\frac{\omega_{p12}^2}{\omega_{z12}^2}\right)\right)\left(\frac{\omega_{p12}}{\omega_{LO}}\right)\tan^{-1}\left(\frac{\omega_{LO}}{\omega_{p12}}\right)\right], \tag{17}$$

$$\omega_{z12} = \left[(k_c+1)^2 + k_c^2\left(\frac{1}{|c|^2}-1\right)\right]^{-\frac{1}{2}} \omega_{p12} \tag{18}$$

where $\omega_{p12} = (R_{sg12}\ C_{gs12})^{-1}$ and $g_{m12}(t) = 2g_{m1}\ g_{m2}\ /(g_{m1}+g_{m2})$. by considering the parameters values mentioned in the section III. A, we will have

$$S_{n12}^c(\omega) = 4kT\gamma g_{m12}\left[1.627 - 0.627\left(\frac{\omega_{p12}}{\omega_{LO}}\right)\tan^{-1}\left(\frac{\omega_{LO}}{\omega_{p12}}\right)\right]. \tag{19}$$

2) The output source resistance noise

Similar to that obtained in the section III. A, we will have

$$S_{n12}^u(\omega) = 4kTR_{s12}g_{m12}^2\left(\frac{\omega_{p12}}{\omega_{LO}}\right)\tan^{-1}\left(\frac{\omega_{LO}}{\omega_{p12}}\right). \tag{20}$$

3) The gate resistance noise

Similar to that discussed for the transconductor noise in the section III. A, by defining the parameters γ', β', k'_c, and ω'_{z12}, the noise power due to the gate resistance for the switching pair can be expressed as follows

$$S_{n12}^c(\omega)_{R_{g12}} = 4kT\gamma' g_{m12}\left[\left(\frac{\omega_{p12}^2}{\omega'^2_{z12}}\right) + \left(1 - \left(\frac{\omega_{p12}^2}{\omega'^2_{z12}}\right)\right)\left(\frac{\omega_{p12}}{\omega_{LO}}\right)\tan^{-1}\left(\frac{\omega_{LO}}{\omega_{p12}}\right)\right], \tag{21}$$

$$\omega'_{z12} = \left[(k'_c+1)^2 + k'^2_c\left(\frac{1}{|c'|^2}-1\right)\right]^{-\frac{1}{2}} \omega_{p12} \tag{22}$$

where $\gamma' = R_{g12}\ g_{m12}$ and $\beta' = R_{g12}\ g_{m12}/\zeta$. Thus we will have

$$S_{n12}^c(\omega)_{R_{g12}} = 4kTR_{g12}g_{m12}^2\left[4 - 3\left(\frac{\omega_{p12}}{\omega_{LO}}\right)\tan^{-1}\left(\frac{\omega_{LO}}{\omega_{p12}}\right)\right]. \tag{23}$$

By considering that $\overline{g_{m12}} = 2I_S/(\pi V_{LO})$ [6] and $\overline{g_{m12}^2(t)} = 2.32I_S^2/(\pi^2 V_{LO}V_x)$ [3], the total average power of the output noise for the switching pair will be

$$\overline{S_{n12}^o(\omega)} \approx 4kT\left(\frac{2I_S}{\pi V_{LO}}\right)\left[\begin{pmatrix}1.627\gamma \\ +\dfrac{4.64I_S}{\pi V_x}R_{g12}\end{pmatrix} + \begin{pmatrix}\left(\dfrac{1.16I_S}{\pi V_x}\right)(R_{s12}-3R_{g12}) \\ -0.627\gamma\end{pmatrix}\left(\frac{\omega_{p12}}{\omega_{LO}}\right)\tan^{-1}\left(\frac{\omega_{LO}}{\omega_{p12}}\right)\right] \tag{24}$$

where $\theta V_x = J_S/2 + \sqrt{J_S^2/4 + J_S}$, $J_S = (\theta^2/K)I_S$, $\theta = 1/(LE_{sat})$, and $K = Wv_{sat}C_{ox}/(LE_{sat})$. Also I_S is the bias current.

IV. SIMULATION USING 90 NM TECHNOLOGY

In this section, the output noise relations, which were discussed and obtained in the sections II and III for the transconductor and the switching pair, are plotted using MATLAB and compared with each other. We have used the N1 NMOS Level 14 of the transistor BSIM4.6.0, which has 90 nm channel length [7]. Two important parameters in this study have been considered

- *W/L* ratio that is defined as the transistor size,
- The local oscillator frequency (f_{LO}).

By considering the relations mentioned for g_m, I_D, C_{gs} in the section II, the transition frequency can be expressed as

$$f_T \approx \frac{g_m}{2\pi C_{gs}} = \frac{3v_{sat}}{2\pi L}\frac{V_{eff}(V_{eff}/2 + LE_{sat})}{(V_{eff}+LE_{sat})^2} \tag{25}$$

where $V_{eff} = V_{GS} - V_{TH}$ is the effective voltage. With the parameters values of the transistor BSIM4.6.0 [7] and

assuming V_{eff} =0.4V, f_T is obtained equal to 269.6 GHz, and also $f_p=\omega_{p3}/(2\pi)$ will be equal to 29.76 GHz. Despite of the high value for the transition frequency, because of the variations in the behavior of resistances and connections and also the secondary effects as the radiation, at the high frequencies, the curves for the total noises generated by the transconductor and the switching pair have been plotted up to 30 GHz, which is approximately equal to f_p.

A. The transconductor noise variations

In Figs. 3 and 4, the mixer output noise variations due to the transconductor, versus *W/L* for f_{LO} ranges 0.1-3 GHz and 3-30 GHz have been plotted. Fig. 3 shows that for the small values of f_{LO} ($f_{LO}<f_p/10$), the output noise generated by the transconductor is not sensitive to f_{LO} variations and this frequency will not be appeared in the noise formulation. From Eq. (15), we have

$$\frac{\omega_{LO}}{\omega_{p3}} << 1 \rightarrow \left(\frac{\omega_{p3}}{\omega_{LO}}\right)\tan^{-1}\left(\frac{\omega_{LO}}{\omega_{p3}}\right) \approx 1,$$

$$\overline{S^o_{n3}(\omega)} \approx 4kTg_{m3}\left[\gamma + (R_{s3}+R_{g3})g_{m3}\right]. \qquad (26)$$

As shown in Fig. 4, with increasing f_{LO}, the effect of this frequency will be appeared in the output noise generated by the transconductor.

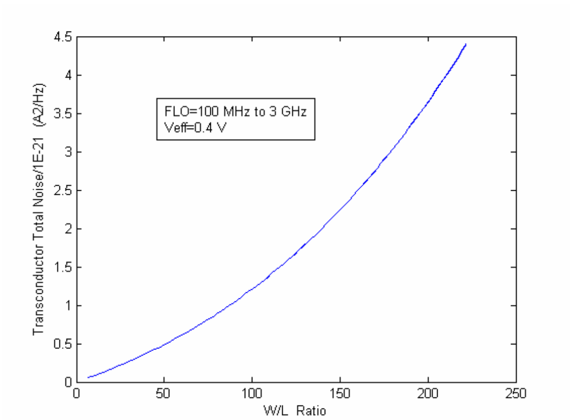

Fig. 3. The transconductor noise versus *W/L* for f_{LO} range 0.1 - 3 GHz and V_{eff} = 0.4 V.

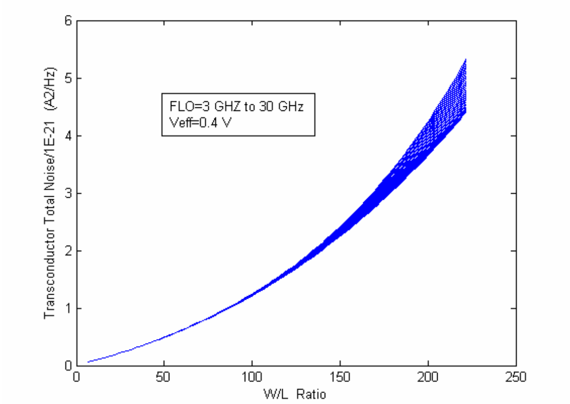

Fig. 4. The transconductor noise versus *W/L* for f_{LO} range 3 - 30 GHz and V_{eff} = 0.4 V.

B. The switching pair noise variations

From Eq. (24), we have

$$\frac{\omega_{LO}}{\omega_{p12}} << 1 \rightarrow \left(\frac{\omega_{p12}}{\omega_{LO}}\right)\tan^{-1}\left(\frac{\omega_{LO}}{\omega_{p12}}\right) \approx 1,$$

$$\overline{S^o_{n12}(\omega)} \approx 4kT\left(\frac{2I_S}{\pi V_{LO}}\right)\left[\gamma + \frac{1.16 I_S}{\pi V_x}(R_{s12}+R_{g12})\right]. \qquad (27)$$

The above equation shows that for the small values of the local oscillator frequency, the switching pair noise is not sensitive to the variations of this frequency. The switching pair noise is clearly dependent on the bias current (I_S) and the reciprocal of the local oscillator amplitude (V_{LO}). The Eq. (27) also shows that for the small values of I_S/V_x ratio, the sensitivity of the switching pair noise to the variations of the important parameter *W/L*, that is applied through R_{g12}, is reduced.

C. The comparison of noise

In Figs. 5-7, the noise variations related to the switching pair and the transconductor have been plotted versus *W/L* for f_{LO} range 3-30 GHz and three effective voltages 0.2, 0.1, and 0.05 V.

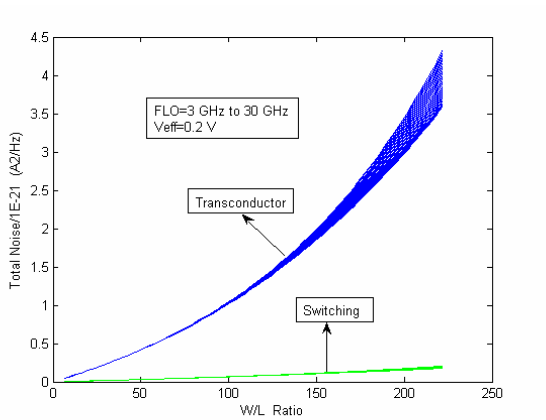

Fig. 5. The comparison of the transconductor & the switching pair noises versus *W/L* for f_{LO} range 3 - 30 GHz and V_{eff} = 0.2 V.

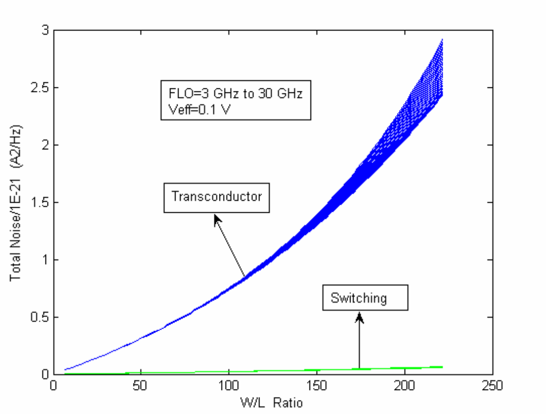

Fig. 6. The comparison of the transconductor & the switching pair noises versus *W/L* for f_{LO} range 3 - 30 GHz and V_{eff} = 0.1 V.

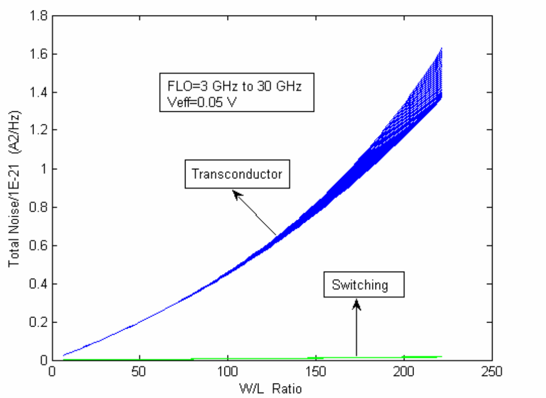

Fig. 7. The comparison of the transconductor & the switching pair noises versus W/L for f_{LO} range 3 - 30 GHz and $V_{eff} = 0.05$ V.

Figs. 5-7 show that the sensitivity of the noise generated by the switching pair in the mixer output, versus W/L variations for various local oscillator frequencies, is less than the sensitivity of the noise generated by the transconductor. This subject reveals the importance of the transconductor in the mixer output total noise. Also it is found that with reducing the effective voltage V_{eff}, the variations of the noises generated by the transconductor and the switching pair versus W/L, is reduced. In this middle, the reduction of the noise generated by the switching pair, is more, which this issue reveals much dependence of the switching pair noise on the effective voltage variations. As shown in Fig. 7, when V_{eff} approaches to zero, the variations of the noise generated by the switching pair versus W/L goes near to zero. This means that the output noise generated by the switching pair, is independent from the transistor size for the small values of the effective voltage.

In [4], it is claimed that the density of the output noise generated by the switching pair, only depends on the local oscillator amplitude and the bias current, and doesn't depend on the transistor size (using the approximate physical model). The dependence of the noise generated by the switching pair on the local oscillator amplitude and the bias current, which were discussed in section III, is clear in Eqs. (24) and (27).

V. Conclusion

In this paper, we have discussed the noise generated by the transconductor and the switching pair in a single balanced active mixer. The obtained relations have been simulated using the parameters related to the N1 NMOS level 14 model of the transistor BSIM4.6.0, which has 90 nm channel length.

The simulation results show that the output noise of the switching pair and the transconductor in a wide range of frequencies 0.1 to 30 GHz, increases with increasing W/L. Moreover, at very small values of the local oscillator frequency, the sensitivity of the noise generated by the transconductor and switching pair to the variations of this frequency, is reduced. Also the noise generated by the switching pair is clearly dependent on the local oscillator amplitude and the bias current. It has been found that the variations of the noise generated by the switching pair due to W/L variations, for various values of the local oscillator frequency, is less than the variations of the noise generated by the transconductor. This issue reveals the importance of the transconductor in the noise generation.

Also it has been shown that with reducing the effective voltage value, the variations of the noise generated by the switching pair and the transconductor due to W/L variations, is reduced. In this middle, the reduction of the noise generated by the switching pair is more, which this subject clears more dependence of the switching pair on the effective voltage variations. In this respect, with approaching this voltage to zero, the noise generated by the switching pair will not be sensitive to the W/L variations .

It is necessary to point that in extracting the noise relations, the contribution of the gate resistance noise to the gate and drain total current noises has been considered, whereas this noise is usually assumed to be an independent source in the literature.

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