Correspondence

Comments on "Design Issues in CMOS Differential LC Oscillators"

HongMo Wang

***Abstract*—The phase noise difference reported in the above paper appears to have a topological cause, and a simple analysis shows that the difference is 6 dB under otherwise identical conditions.**

I. Introduction

In the above paper,[1] the authors show the phase noise difference observed experimentally between the complementary cross-coupled differential LC oscillator and its NMOS-only counterpart and offer a number of reasons for the superiority of the former in terms of phase noise. This correspondence points out another important consideration in this comparison. The analysis below assumes that the two topologies are compared with the same tank circuits, as well as equal bias currents and transconductances.

II. Carrier Power and Phase Noise of the Two Topologies

The above paper has shown that the differential voltage amplitude is $4\pi^{-1}I_{\rm tail}R_{\rm eq}$. Using the same approach and assuming the same tank circuit and tail current, the NMOS-only oscillator and its equivalent circuit can be shown as in Fig. 1. Since the equivalent circuit is linear, superposition can be used to find the differential voltage amplitude due to each current source one at a time. In each half of the oscillating period, a part of the tail current is shunt through one half of the inductor and thus does not pass through the $R_{\rm eq}$ to generate the signal power. A simple derivation, using basic network analysis and the relation $\omega^{-2} = LC$, shows that each current source contributes a differential voltage amplitude of $\pi^{-1}I_{\rm tail}R_{\rm eq}$. Since the two voltages add in-phase, the overall differential amplitude in this case is $2\pi^{-1}I_{\rm tail}R_{\rm eq}$.

Comparing the two cases shows that the complementary topology yields four times or 6 dB more power in the carrier signal level than its counterpart. Since phase noise is inversely proportional to the signal power, the former will thus have a 6-dB improvement in phase noise over the latter simply due to the topological difference even if one topology has no "faster switching" than the other, as the above paper has suggested.

Moreover, the paper concludes that the "smaller $1/f^3$ noise corner" observed is mainly caused by the "better rise- and fall-time symmetry." Since $1/f$ noise in MOS devices can be reduced by increasing oscillation amplitude [1], [2], however, does the reduction in the noise corner stem partly from a difference in the oscillation amplitudes of the two cases considered?

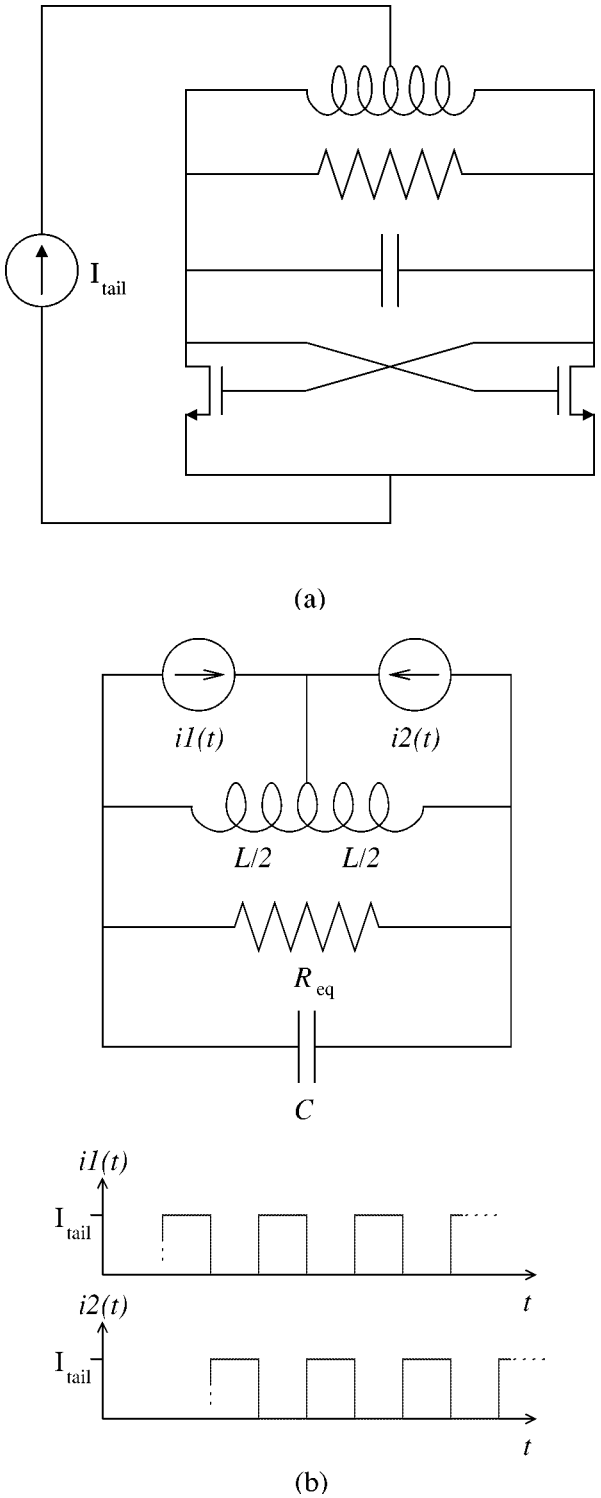

Fig. 1. (a) NMOS-only oscillator. (b) Equivalent circuit when the oscillator is in oscillation and the transistors are switched on and off at the oscillating frequency.

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[1]A. Hajimiri and T. Lee, *IEEE J. Solid-State Circuits*, vol. 34, pp. 717–724, May 1999.

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Authors' Reply

Ali Hajimiri and Thomas H. Lee

We have read the comments by Wang with interest and have split our reply into two parts to address each of his main points separately.

I. PHASE NOISE DIFFERENCE FROM TOPOLOGY

We agree that tank-voltage amplitude for the complementary oscillator can be twice as large as the NMOS-only topology for the same tail current. This conclusion holds if both oscillators operate in the current-limited regime.

Furthermore, if the devices are scaled to keep the overall transconductance of the cross-coupled pair constant, the improvement in phase noise would be 6 dB when both NMOS and PMOS pairs have identical excess noise factors γ. In practice, the amount of improvement depends on the relative noise contributions of the NMOS, PMOS, and tail current source as well as the passive elements.

In our paper,[1] however, we studied the two topologies with equal-sized NMOS transistors. Therefore, the transconductance was not constant. In this case, the 6-dB increase in the signal power cannot improve phase noise by this full amount because the PMOS transistors are not noiseless. Assuming that the NMOS and PMOS transistors have roughly equal transconductances and noise and that the noise in the $1/f^2$ region is dominated by the noise of the differential pair, the improvement in the phase noise will be around 3 dB. Nevertheless, the topological difference between the two oscillators is the dominant source of the observed phase noise difference in the $1/f^2$ region. Generally speaking, the amount of improvement depends on the relative noise contributions of the NMOS transistors, PMOS transistors, and tail current source as well as the passive elements.

II. $1/f^3$ CORNER FREQUENCY

Although the switching of the MOS transistors due to a higher amplitude of oscillation results in a reduction in the effective $1/f$ noise of the transistors as observed in [1] and [2], this characteristic cannot account for the large improvement in the $1/f^3$ corner of the complementary topology for three reasons. First, $1/f$-corner comparisons between the topologies were performed with the same tank amplitude, and hence, we expect similar reductions in the $1/f$ noise due to switching. Second, for most practical oscillators, the $1/f$ noise of the tail current source is the dominant source of $1/f^3$ phase noise. This dominance is due to the large dc value of the impulse sensitivity function for the tail current source shown in Fig. 8 of the original paper. This effect can be intuitively understood by noting that the small changes in the tail current due to $1/f$ noise directly modulate the transconductance and nonlinear capacitors of the differential-pair transistors. The $1/f$ noise of the tail current source, however, is not significantly affected by the trap-site-resetting phenomena observed in [3] and [4] and therefore will be approximately the same for both oscillators. Third, the relationship between the $1/f^3$ corner in the phase-noise spectrum and the $1/f$ noise corner of the device is independent of the oscillation amplitude because the noise in both regions are affected by the changes in $q_{\max}$ by the same amount [2]. This independence is to be expected because to first order, increasing the signal power should uniformly translate the phase-noise curve downward, leaving the $1/f^3$ corner unchanged.

Since the tank amplitudes of the two cases in our experiments were equal, the tail bias current of the NMOS-only oscillator was twice that of the complementary oscillator. The $1/f$ noise corner of the drain current can be easily calculated to be [5]

$$f_{\text{corner}} = \frac{K}{C_{\text{ox}} W L} \frac{1}{4kT\gamma} \frac{g_m^2}{g_{d0}} \tag{1}$$

where K is a constant, C_{ox} is the gate oxide capacitance per unit area, W and L are the width and length of the transistor, g_m is the transconductance, and g_{d0} is the zero drain voltage channel conductance of the transistor. For a short-channel transistor operating in velocity saturation, g_m is independent of the drain current and g_{d0} is proportional to it. Based on this simplified analysis, the $1/f$ noise current is inversely proportional to the drain current. As a result, for equal tank amplitudes, the NMOS-only topology has a $1/f$ noise corner frequency that is approximately half of the complementary one. In spite of this initial advantage, the measured $1/f$ noise corner frequency of the NMOS-only topology is significantly higher than that of the complementary one. This observation further verifies the reduction of the $1/f$ noise upconversion due to symmetry as argued in the original manuscript.

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