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Pseudo-impulse tail current shaping for phase noise reduction in CMOS LC oscillators

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ABSTRACT

In this paper, a low phase noise oscillator using tail current shaping method is presented. The current shaping is achieved using two paths for *current disconnection* and *current injection*, as a result of which, the total tail current is shaped to a sharp and sawtooth waveform, close to an impulse. Each switching transistor is ON only in 22% of an oscillation period, and tail current is mostly supplied to these transistors near the outputs peak points. In those moments, the oscillator sensitivity to noise sources is minimum. The proposed oscillator is designed and simulated in 0.18 μm RF CMOS technology with 1.8 V supply, and using the inductor model offered by the process, with quality factor of 11. Post layout simulations predict an oscillation frequency of 1.65 GHz, and phase noise of −127.7 dBc/Hz at 1 MHz offset, which is 6.3 dB better than that of simple cross coupled oscillator with the same core oscillator power consumption of 2.2 mW. The proposed circuit, however, consumes an extra power of about 1.9 mW for the added current shaping circuits. Compared to conventional tail current shaping technique, the proposed oscillator offers better tail current shaping, and a much higher start-up current and gain, which is desirable.

1. Introduction

Local oscillators (LOs) have an important role in RF systems. The LO block down-converts RF signal in the receiver and up-converts baseband signal in the transmitter. As a result, the LO parameters directly affect the RF and baseband signals, in a transceiver. If the LO circuit is not properly designed, overall performance and reliability of the receiver and transmitter is degraded [1]. From different types of oscillators, such as ring, Colpitts and LC cross coupled, the cross coupled oscillator is more popular and useful, due to several factors, including easiness of fully integrated implementation, inherent differential operation mode, inherent low power consumption, good phase noise performance, relaxed start-up condition, and easily expandable to QVCO structure [2]. In this paper, the proposed method is applied to this type of oscillator. The oscillator phase noise is one of the main performance destructive parameters. Hence, in recent decades many attempts have been performed to reduce power consumption and phase noise, and increase tuning range of fully integrated oscillators [3–9].

The simple cross coupled oscillator, shown in Fig. 1, cannot satisfy most wireless communication standards, such as GSM, WiFi and Bluetooth, in terms of phase noise. Therefore, effective circuit techniques are needed to reduce the phase noise of this oscillator. This weakness in the phase noise results from many mechanisms, such as: (1) Low quality factor of on-chip inductors; (2) Conversion of thermal and flicker noise power of the tail transistor to phase noise; (3) High currents of the switching transistors, at times when the oscillator output is sensitive to noise; and (4) Reduction in the quality factor of the tank circuit caused by the switching transistors in the triode region. In the following, some famous and effective methods to reduce phase noise in $1/f^2$ and $1/f^3$ regions are discussed.

In Refs. [4,5], by applying low pass and notch filter networks in between tail current and common-source node of the switching transistors in the cross coupled oscillator, the second harmonic noise power of the tail current is strongly suppressed. Therefore, the tail transistor second harmonic noise is not down-converted to the oscillation frequency, and as a result, the phase noise is highly reduced. However, those techniques suffer from increased chip area, due to the use of extra inductors.

In a cross coupled oscillator, the tail current source would prevent modulation of the quality factor of the tank circuit with the channel resistance of transistors, which occurs as the switching transistors enter into triode region [4]. Therefore, existence of the tail current source leads to lower phase noise. On the other hand, the thermal and flicker noises of

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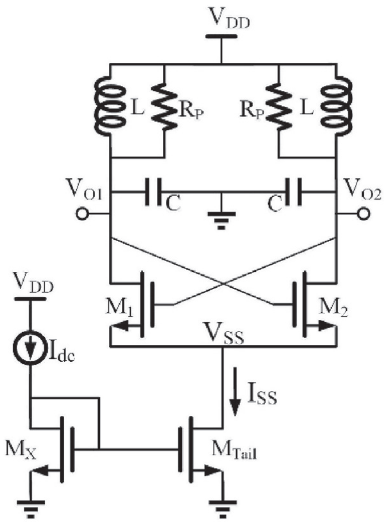

Fig. 1. Circuit schematic of the simple cross coupled oscillator with tail current source.

the tail transistor increase the overall oscillator noise power and can strongly destroy the $\frac{1}{f^2}$ and $\frac{1}{f^3}$ phase noise performances, respectively.

Thermal noise down-conversion and flicker noise up-conversion of the tail transistor for the cross coupled oscillator with complementary structure (i.e., with both NMOS and PMOS transistors) is worse than non-complementary (Only-NMOS/PMOS) structures, because there are two transfer mechanisms of tail transistors noises to phase noise for this oscillator. These mechanisms are AM to FM and Common Mode Modulation (CMM) to FM conversions, while, there is only AM to FM conversion mechanism for non-complementary structures, and this is a significant difference [10]. Outputs common mode voltage in the non-complementary structures (such as Fig. 1 oscillator) are forced by V_{DD} or ground, and therefore, there would be no CMM. Simple and easy to implement techniques for tail current flicker noise up-conversion suppression are presented in Ref. [7–9], which strongly reduce complementary oscillator close-in phase noise. However, in general, it seems that use of the tail current source in complementary structure, unlike the other, is not suitable.

The tail current shaping method is a phase noise reduction method that greatly reduces the phase noise in both $1/f^2$ and $1/f^3$ regions. This method is based on the results of the Hajimiri's phase noise model [11]. In this method, the conduction angle of the switching transistors decreases. Also, the amplitude of the tail current is reduced at outputs zero crossing points, where the oscillator is more sensitive to the noise sources. As a result, the conversion factor of the noise sources to the phase noise decreases. This technique is further discussed in Section 2.

In this paper, according to the results of Hajimiri's phase noise model that is a strong theory for phase noise analysis, a new tail current shaping structure for phase noise reduction is presented. The rest of this paper is structured as follows. In Section 2, the tail current shaping technique is described and analyzed. In Section 3, the proposed circuit is presented and its operation principles are explained. The simulation results and theoretical validation of the noise reduction mechanism for the proposed oscillator is demonstrated in Section 4. Finally, Section 5 concludes the paper.

2. Tail current shaping technique

In Hajimiri's theory, where the oscillator is assumed as a linear time variant (LTV) system, a closed formula for phase noise performance reduction is introduced, as

$$\begin{aligned} L(\Delta\omega) &= 10log\left(\frac{\overline{i_n^2}/\Delta f}{4q_{max}^2\Delta\omega^2}\sum_{n=0}^{\infty}C_n^2\right) \\ &= 10log\left(\frac{\overline{i_n^2}/\Delta f}{2q_{max}^2\Delta\omega^2}\Gamma_{rms}^2\right) \end{aligned} \tag{1}$$

in which, $L(\Delta\omega)$, $\overline{i_n^2}/\Delta f$, Γ_{rms}, $\Delta\omega$, q_{max} and C_n are phase noise at $\Delta\omega$ from the carrier frequency, noise power spectral density, ISF root mean square, offset frequency, maximum charge of tank capacitance defined as $q_{max} = CV_{max}$, and Fourier coefficients of ISF, respectively.

In this theory, it is proved that the oscillator has time variant sensitivity to the noise source. This expression of phase noise has good agreement with measurement results. Also, this model suggests some effective phase noise reduction techniques [11]. The Impulse Sensitivity Function (ISF) demonstrates the oscillator sensitivity to the noise source, and it is shown that ISF is directly proportional to the output voltage derivative. In the case of an ideal LC oscillator, the ISF is a sine wave with swing range of ±1 and 90° phase shift, with respect to the oscillator outputs. Therefore, the ISF is minimum, when the outputs are near their peaks, and maximum, in zero crossing points.

In Colpitts and cross coupled oscillators, the main transistors are in cut off, in part of the oscillation period, and as a result, the thermal noise of those transistors have a cyclostationary behavior. In other words, their noise power is modulated by their drain current, and therefore, the root mean square (RMS) of thermal noise power spectral density (PSD) is reduced. To apply the effect of this behavior in the phase noise equation, the effective ISF is defined as (2) for substitution in (1),

$$\Gamma_{eff}(\omega_0 t) = \Gamma(\omega_0 t)\,\alpha(\omega_0 t) \tag{2}$$

in which, $\alpha(\omega_0 t)$ is the noise modulation function (NMF) and it is directly proportional to drain current of the switching transistors. NMF is normalized to the maximum value of 1. In Colpitts oscillator, the switching transistors, unlike cross coupled, is off more than half the oscillation period, and thus this oscillator has a good cyclostationary behavior (i.e., with less noise power). Therefore, the ISF_{eff} value for Colpitts is less than that of cross coupled oscillator, and thereby, it has a lower phase noise [12]. However, Colpitts oscillator is less popular in integrated circuit design, as it is a single ended oscillator. Also, it has a difficult oscillation start condition, which requires higher bias current, and therefore, higher power consumption.

From the above discussion, it is concluded that phase noise is directly proportional to $ISF_{eff,rms.}$ Therefore, any technique that could reduce this value, would improve the phase noise, significantly. This can be done by reducing the time duration of conduction of the switching transistors. In other words, the average of NMF is decreased by reducing transistors drain currents, and thus, $ISF_{eff,rms}$ is also reduced. It should be noted here that the current reduction must be applied to the oscillator, at outputs zero crossing points, when the oscillator sensitivity to noise source is maximum, so that ISF is shaped in a desirable form. Otherwise, this conduction angle reduction will not necessarily result in lowering output phase noise. The only way to obtain such conditions is shaping the tail transistor current. The main method for implementing this idea is providing a feedback path from oscillator outputs to the tail current source. This technique is called tail current shaping (TCS).

In Ref. [13], tail current shaping technique is analyzed and formulated. For the conduction angle 2φ of switching transistors, Fig. 2 diagram is presented in this reference, for calculation of the phase noise improvement. This figure is presented here for validation of the proposed tail current shaping method in phase noise reduction, which is discussed in the next section.

Assuming ideal switching transistors for Fig. 1 oscillator, which is fed by a constant tail current source, the drain current of those transistors are square waves with conduction time of half the oscillation period. Therefore, the duty cycle is 50% and the conduction angle is π radians. In this case, the single ended output amplitude is obtained by multiplying