Available online at www.sciencedirect.com
ScienceDirect
Int. J. Electron. Commun. (AEÜ) 64 (2010) 795–805
International Journal of Electronics and Communications
www.elsevier.de/aeue

Minimum phase noise of an *LC* oscillator: Determination of the optimal operating point of the active part

David Cordeau*, Jean-Marie Paillot

Laboratoire d'Automatique et d'Informatique Industrielle - ESIP, EA 1219, 4 avenue de varsovie, 16021 Angoulême, France

Received 26 February 2009; accepted 8 June 2009

Abstract

In this paper, we describe an original method for determining the optimal operating point of the active part (transistor) of an *LC* oscillator leading to the minimum phase noise for given specifications in terms of power consumption, oscillation frequency and for given devices (i.e., transistor and resonator). The key point of the proposed method is based on the use of a proper *LC* oscillator architecture providing a fixed loaded quality factor for different operating points of the active part within the oscillator. The feedback network of this architecture is made of an *LC* resonator with coupling transformers. In these conditions, we show that it is possible to easily change the operating point of the amplifier, through the determination of the turns ratio of those transformers, and observe its effect on phase noise without modifying the loaded quality factor of the resonator. The optimal operating point for minimum phase noise is then extracted from nonlinear simulations. Once this optimal behavior of the active part is known and by associating the previous *LC* resonator, a design of an *LC* oscillator or VCO with an optimal phase noise becomes possible. The conclusions of the presented simulation results have been widely used to design and implement a fully integrated *LC* differential VCO on a 0.35 μm BiCMOS SiGe process.

Keywords: Class-C; Cyclostationary noise; Operating point; Power added; Oscillators

1. Introduction

Mobile communication system evolution demands continuous efforts toward the improvement of radio-frequency (RF) circuit performances. Concerning the oscillators and voltage-controlled oscillators (VCOs), the phase noise requirements are even more stringent. Indeed, the carrier rejection and the transmission quality of any systems depend on the phase noise of the signals applied to the modulator. Furthermore, from the designer point of view, pressure is growing as design time is getting shorter and shorter. In this context, it seems to be very interesting to know rapidly if the specification required in terms of phase noise and consumption is consistent with the technology provided. Due to these considerations, this paper describes a method for determining the optimal operating point of the active part of an *LC* oscillator leading to the minimum phase noise for given specifications in terms of power consumption, oscillation frequency and for given devices.

Section 2 is a brief review of some of the existing phase noise models giving important key points for phase noise minimization. Section 3 presents the theoretical analysis of the chosen *LC* oscillator topology and concludes with the sequence to be carried out to obtain the oscillation at a frequency f_0 for a given operating point of the amplifier. Section 4 describes the simulations leading to the optimal operating point of a SiGe HBT *LC* oscillator. Finally, Section 5 presents the design and implementation of a fully integrated differential VCO optimized in phase noise using the conclusions of the previous section.

* Corresponding author. Tel.: +33 5 45673228; fax: +33 5 45673229.
E-mail address: david.cordeau@univ-poitiers.fr (D. Cordeau).

1434-8411/$ - see front matter © 2009 Elsevier GmbH. All rights reserved.
doi:10.1016/j.aeue.2009.06.005

2. Brief review of phase noise existing models

The model proposed in [1], known as the Leeson–Cutler phase noise model, predicts a phase noise spectral density in the $1/f^2$ region of the spectrum of

$$S_{\Phi}(\Delta f) = 10 \times \log\left[\frac{2FkT}{g_S}\left(\frac{f_0}{2Q\Delta f}\right)^2\right] \quad (1)$$

where F is the noise factor, k is Boltzmann's constant, T is the absolute temperature, P_S is the average power dissipated in the resistive part of the resonator, f_0 is the oscillation frequency, Q is the loaded quality factor of the resonator and Δf is the frequency offset from the carrier.

Although the result of simplifying assumptions, this model offers important key points for the reduction of phase noise in the oscillators. Indeed, it can be concluded, from (1), that the loaded quality factor of the resonator needs to be maximized in order to reduce phase noise in the $1/f^2$ region of the spectrum. Furthermore, for a given loaded quality factor Q, the phase noise will be significantly reduced if the resonator dissipated power P_S is increased. However, the dissipated power in the resonator corresponds to the difference between the output and the input powers of the active part under oscillation conditions. This difference represents, in fact, the added power of the oscillator amplifier.

Thus, for a given loaded quality factor, the transistor must be operated under oscillation conditions as close as possible to its maximum added power state [2]. However, Eq. (1) predicts the phase noise in the $1/f^2$ region mainly due to the tank parallel resistor of the resonator. The Leeson model additionally introduces the factor F as a multiplicative factor, to take into account for the phase noise due to the active part, but without knowing precisely what it depends on and how to reduce it. Unfortunately, the noise generated by the transistor is usually the main phase noise contributor in oscillators and VCOs. Thus, the simplifying assumptions of this model have been revised particularly by Hajimiri and Lee [3,4], who explicitly showed the time-varying nature of phase noise generation.

The key concept in their linear, time-varying (LTV) phase noise theory is the impulse sensitivity function (ISF), whose calculation leads to a very accurate prediction of phase noise due to stationary and cyclostationary noise sources in the oscillator. Thus, according to the ISF theory, the total single sideband phase noise spectral density in the $1/f^2$ region of the spectrum due to one current noise source on one node of the circuit at an offset frequency $\Delta\omega$ is given by [3]

$$L(\Delta\omega) = 10 \times \log\left(\frac{\overline{i_n^2}/\Delta f \cdot \Gamma_{rms}^2}{2 \cdot q_{max}^2 \cdot \Delta\omega^2}\right) \quad (2)$$

where $\overline{i_n^2}/\Delta f$ is the power spectral density of the current noise source in question, Γ_{rms}^2 is the rms value of the impulse sensitivity function (ISF) associated with the noise source considered previously, and q_{max} is the maximum charge swing across the current noise source.

As mentioned earlier, the transistor mainly contributes to the overall phase noise in an oscillator and the dominant noise sources of the transistor are often cyclostationary. For instance, the collector current shot noise of a bipolar transistor and the channel noise of a MOS device are cyclostationary [5,6]. Fortunately, the LTV model developed by Hajimiri and Lee is able to accommodate a cyclostationary noise source with ease. Indeed, considering that a white cyclostationary noise current can be written as the product of a white stationary process and a deterministic periodic function $\alpha(x)$, also called the noise-modulating function (NMF) [4,7,8], strongly correlated with current waveforms of the oscillator, the cyclostationary noise can be treated as a stationary noise by introducing the effective ISF given by [3]

$$\Gamma_{eff}(x) = \Gamma(x) \cdot \alpha(x) \quad (3)$$

Thus, the phase noise due to the cyclostationary current noise source is expressed by (2) replacing Γ_{rms}^2 by $\Gamma_{eff,\ rms}^2$. Consequently, $\Gamma_{eff,\ rms}$ needs to be minimized in order to reduce phase noise significantly. In other words, the transistor would remain off almost all of the time, waking up periodically to deliver an impulse of current at the signal peak of the oscillator, where the ISF ($\Gamma(x)$) has its minimum value, i.e., when the noise to phase noise conversion is at a minimum [5,9]. Thus, the transistor must be operated in class-C under oscillation conditions in order to reduce significantly the phase noise due to the cyclostationary noise sources.

As a conclusion, the Leeson–Cutler phase noise model states that the phase noise spectral density will be all the more low that the resonator dissipated power (P_S) will be high and thus that the transistor must be operated under oscillation conditions as close as possible to its maximum added power state [2] for a given loaded quality factor, whereas, according to the phase noise model of Hajimiri and Lee [3], the transistor must be operated in class-C under oscillation conditions in order to reduce significantly the phase noise due to the cyclostationary noise sources.

Consequently, from the designer point of view, a critical choice, depending partly on the technology used, between those two operating points needs to be done in order to reduce phase noise. Thus, to easily determine this optimal operating point of the active part for given specifications in terms of power consumption, oscillation frequency and for given devices (i.e., transistor and resonator) and loaded quality factor, the right LC oscillator topology must be chosen. Indeed, the latter must provide a fixed loaded quality factor for different operating point of the active part within the oscillator. Such a topology is analyzed in detail in the next section.