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# A modified multiphase oscillator with improved phase noise performance

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ABSTRACT

This paper investigates the factors that influence the phase noise performance of an oscillator and proposes a modified structure for improved phase noise performance. A single and multiphase oscillator analysis using the harmonic balance method is presented. The modified structure increases the oscillation amplitude without increasing the bias current and leads to improved phase noise performance as well as decreased power consumption. The modification is analyzed and the figure of merit of the oscillator shows a significant improvement of 21 dB. Numerical and analytical solutions are presented to predict the oscillation frequency and phase noise. The analytical solution is used to approximate the first harmonic and can be combined with numerical simulations to extrapolate phase noise performance.

## 1. Introduction

Oscillators are ubiquitous to radio frequency circuits, where frequency translations and channel selection play a central role in the analog communications channel. Oscillators also form part of digital systems as a time reference [1]. Typical heterodyne receivers require an intermediate frequency channel. The associated oscillators and variable filters can only be centered perfectly at a single frequency and degrade performance at the boundaries of the channel. These circuits also require image-rejecting filters and phase-locked loops to enable down-conversion. The penalty for these components is increased circuit area and power consumption [2]. A direct down-conversion circuit will enable the number of components in the system to be reduced. A requirement added by the structural change is a passive sub-harmonic mixer. Quadrature oscillators can be achieved by cross-coupling two nominally identical LC differential voltage-controlled oscillators (VCOs) [3]. Because of the widespread use of VCOs in wireless communication systems, the development of comprehensive nonlinear analysis is of great interest for both theory and applications [4]. A key characteristic that defines the performance of an oscillator is the phase noise measurement and extensive work has been done to quantify phase noise. The VCO is also a key component in phase-locked loops and will contribute to most of the out-of-band phase noise, as well as a significant portion of in-band noise [5]. Current state-of-the-art modulation techniques, implemented at 60 GHz, such as quadrature amplitude modulation and orthogonal frequency domain multiplexing, require phase noise specifications better than 90 dBc/Hz at a 1 MHz offset [6]. It has been shown that owing to the timing of the current injection, the Colpitts oscillator tends to outperform other oscillator structures in terms of phase noise performance [7]. The Colpitts oscillator has a major flaw in that the startup gain must be relatively high when compared to the cross-coupled oscillator. The oscillation amplitude cannot be extended as in the cross-coupled case [8]. The oscillation amplitude is generally limited by the oscillator's bias current and is given as $\frac{2I_P R_{\text{tank}}}{\pi}$ [9]. The phase noise is defined by a stochastic differential equation, which can be used to predict the system's phase noise performance. The characteristics of the oscillator can then be defined using the trajectory. The model projects the noise components of the oscillator onto the trajectory and then translates the noise into the resulting phase and amplitude shift [10]. The phase noise performance of an oscillator can be improved by altering the shape of the trajectory. The trajectory of the oscillator can be separated into slow and fast transients. The phase noise performance can be improved by improving the shape of the slow manifold of the oscillator [11]. Close-in phase noise can be directly improved by improving the loaded quality factor of the tank circuit [12]. The Colpitts and differential Colpitts oscillator are selected as the basis for analyzing performance. The organization and contribution of this paper are as follows: In Section II the factors that influence phase noise are discussed; the results are compared to a system where the non-linear restorative force has been omitted to produce closed form solutions. Several characteristics influencing phase noise are identified. In Section III, a simple single-phased Colpitts oscillator is analyzed. The analysis is based on the harmonic balance technique and is analytically extracted for the first Fourier component, which is simultaneously estimated. This method

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can be extended for higher order harmonics [13]. The approximate frequency–amplitude relationship for a conservative nonlinear oscillatory system in which the restoring force has an exponential form is studied. The solutions are valid for the complete range of oscillation amplitudes, including limiting cases of amplitudes approaching zero and infinity. The analysis used in this paper produces accurate results because of the large number of harmonics that are explained using this technique [13]. Modified nodal analysis is used to determine the differential system describing the oscillator. The set of equations is non-linear and a closed form solution does not exist. The oscillation frequency and amplitude can be fully explained using this technique, and an approximation of the first harmonic component is made. The transistor is modeled using the full voltage-controlled Ebers-Moll bipolar junction transistor model. Section IV extends the approach discussed in Section III to a differential Colpitts oscillator. This structure is then used as the basis for the improved multiphase oscillator. The section shows the subtle difference between this structure and the cross-coupled oscillator. Section V introduces the modified multiphase oscillator with analysis to predict the oscillation amplitude and frequency. This is verified through a MATLAB simulation of the describing differential equation, which can be done either in the time domain or in the frequency domain, using a numerical harmonic balance procedure. The time domain approach tends to generate less accurate solutions and is more computationally expensive. Section VI provides a brief discussion on the phase noise of the oscillator. Finally the multiphase oscillator is analyzed. A general simulation program with integrated circuit emphasis (SPICE) solution is also compared in order to verify the analysis. A new oscillator structure is introduced with current locking to enable the generation of quadrature oscillations. The structure takes advantage of the noise-shaping characteristics of the Colpitts oscillator but relaxes the start-up requirements associated with the structure. The result is a multiphase oscillator with reduced power consumption and improved phase noise performance.

## 2. Oscillator performance

The phase noise of an oscillator can be improved without difficulty by increasing the amplitude of the oscillating voltage and the power associated with the first harmonic, or by improving the quality factor of the tank circuit. These methods are well noted [14]. There are limitations to both of these approaches and it is useful to define a performance metric for the oscillator. The figure of merit (FOM) is defined as follows:

$$\mathrm{FOM} = L(\Delta f) - 20\log\left(\frac{f_0}{\Delta f}\right) + 10\log\left(\frac{P_{DC}}{1\mathrm{mW}}\right) \tag{1}$$

where $L(\Delta f)$ is the phase noise at a $\Delta f$ offset frequency in dBc/Hz, $f_0$ is the oscillation frequency and $P_{DC}$ is the steady state power consumption of the circuit in Watts (1). From (1) it is clear that there are two ways to improve the FOM: improve the phase noise *or* decrease the power consumption of the oscillator. Phase noise has been shown to be stationary and to have increasing variance with time. The total power of the circuit is defined by (2).

$$P_{tot} = \sum_{i=1}^{\infty} |X_i|^2 \tag{2}$$

where $X_i$ are the Fourier components of the oscillator's stable limit cycle in volts squared relative to a 1 Ω load. The phase noise is then given as:

$$L(\Delta f) = 10\log_{10}\left(\frac{S_{ss}(f_0 + \Delta f)}{2|X_1|^2}\right), \tag{3}$$

and $S_{ss}(f_0 + \Delta f)$ is the power spectral density in W/Hz, at a frequency offset of $\Delta f$ Hz. The result of (1) and (2) is that phase noise can be reduced by decreasing the total number of harmonics within the system. The total energy of the system is limited and the summation of all the components must be equal to the steady state power consumption. To identify methods of reducing phase noise one needs to analyze how noise perturbations are translated into phase noise in an autonomous system. Eqs. (4) and (5) give one a basis to begin analyzing phase noise and identify methods that can be used to reduce phase noise. The phase noise of a circuit with stationary noise sources is then approximately:

$$L(\Delta f) \approx 10\log_{10}\left(\frac{f_0^2 c}{\pi^2 f_0^4 c^2 + \Delta f^2}\right), \tag{4}$$

for small $c$, $0 \le \Delta f << f_0$ and

$$c_i = \frac{1}{T}\int_0^T v_1^T(\tau)B(x_s(\tau))B^T(x_s(\tau))v_1(\tau)d\tau, \tag{5}$$

where $c_i$ is the function that describes a noise source $i$ and $c$ is the sum of all the noise source contributions. Eq. (5) is the projection of the noise, assumed stationary, described by $B(x_s(\tau))$ and a function of $x_s(\tau)$ onto the trajectory of the specific node of the system without the presence of noise. It then describes how the noise source is translated into phase noise. The FOM can therefore be improved by reducing the constants, $c_i$. This can be achieved in two ways, by manipulating the manner in which noise is translated into phase noise or by reducing noise within the system. Initially it was shown that to calculate the phase noise of an oscillator, the noise at each node should be projected in the relative state space to the node of interest to predict phase noise. A description of calculating phase noise is given in [1]. The theory is then later expanded to show that only a single variable in the state space is required to obtain the relevant perturbation projection vector (PPV) [15]. The tank current is equivalent to the first derivative of the tank voltage and can be seen as a function of the rate of change of phase. This enables noise sources that are in the form of current perturbations to be directly analyzed, with the PPV being the tangent of the limit cycle. This corresponds directly with the idea of an impulse sensitivity function introduced [7]. The assumption is that the noise is a wide sense stationary variable. The case of colored noise sources is considered in [10]. An interesting analysis, which is conducted in [16], is similar to the method presented here. In this work a lower-order active device is included as the restorative element for the lossy tank circuit and enables subtle differences to be included. In [16], the active device is removed from the model and approximated with an ideal switch, which is mathematically tractable. The currents from the ideal switches are then injected into a tank circuit as impulses and the PPV is calculated exactly under the listed assumptions. The ideal switch tends to approximate the cross-coupled transistors as the gain of the active transistor is taken in the limit to infinity, although this is only true for the basic configuration. This yields results that agree with “intuitive” selection of the oscillator structure. The results highlight a few important aspects. The optimum difference between the eigenvectors representing the current and voltage of the tank circuit is ½π. This then results in the sensitivity of noise-to-phase-noise conversion being minimized when the voltage and current are out of phase and the voltage is at a maximum. This corresponds directly with the Colpitts oscillator where the current injection is out of phase with the oscillation voltage. Secondly, the coefficient describing the PPV onto the current variable in the state space is given as:

$$\frac{1}{F} = \sqrt{\frac{L}{C}}\sqrt{1 + \frac{1}{(2Q)^2}}, \tag{6}$$

where $F$ describes how the components of the tank circuit will contribute to the PPV of the noise current sources. The interesting result here is the fact that an increased $Q$ will improve phase noise, as stated before. The ratio of $C$ to $L$ will also influence phase noise. Finally, by considering the slow transients of the system, the manifold can be analyzed and the shape of the PPV relative to specific state variables in the slow manifold can be manipulated to improve phase noise.