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A 10 GHz low phase-noise CMOS voltage-controlled oscillator using dual-transformer technology

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Abstract

A novel low phase-noise differential Colpitts VCO by using transformer feedback technology is presented in this paper. This work demonstrates a simple differential topology with dual-transformer approach to reduce phase-noise at low DC power consumption. A symmetrical circuit layout can be realized easily by transformers and a commonly cross-coupled structure is not adopted herein because cross couple feedback path is also a serious parasitic effect more at 10 GHz operation. Therefore, dual-transformers provide a compact feedback path and DC feed path simultaneously. Consuming a DC power of 8 mW in the VCO core, the circuit exhibits a phase-noise of −115 dBc/Hz at offset frequency of 1-MHz and the figure of merit value is −184.1 dBc.
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Keywords: VCO; Colpitts; CMOS; Low phase-noise; Transformer

1. Introduction

Recently, many approaches have been taken to improve the performance of integrated voltage-controlled oscillators (VCOs) in microwave integrated circuit designs [1–3]. In recent proposed oscillator structures, cross-coupled oscillators have been widely adopted by circuit designers due to their ease for implementation, relaxed start-up condition and differential operation. However, in cross-coupled oscillators, the noise generation by active devices occurs when the oscillator is quite sensitive to perturbations [4], worsening the phase-noise especially at very high-frequency operation. On the other hand, the single-ended Colpitts oscillator has superior cyclostationary noise properties and can hence potentially achieve lower phase-noise [5,6]. Furthermore, it also shows a higher output voltage swing and higher energy transfer efficiency than those of NMOS cross-coupled oscillator for a given bias current, which will further enhance its phase-noise. Despite these advantages, the single-ended structure is not commonly used today due to their higher required gain for reliable start-up and single-ended nature that makes them more sensitive to parameter variations and common-mode noise sources, such as substrate and supply noise. Therefore, a commonly used differential oscillator is preferred over a single-ended one due to the start-up issues and a low-noise fully differential output. Also, the tail current transistor in VCO core is replaced by on-chip inductors in many recent publications to reduce noise contribution [7]. However, adopting the on-chip inductors and coupling two identical half Colpitts oscillators without using a cross-coupled structure, a more symmetrical circuit layout can be accomplished. This paper presents a simple and easily accomplished oscillator topology that improves the phase-noise performance by cyclostationary noise alignment. Therefore, an enhanced phase-noise performance can be obtained through these advantages.

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2. Proposed VCO topology

The circuit schematic of the proposed VCO is shown in Fig. 1. In order to reduce the excess noise contribution from the active current source, the on-chip inductors replacing the transistor was adopted as tail current source in our VCO core [8]. For an enhanced voltage swing under a low supply voltage, the capacitive-feedback technique is employed [9]. A differential output can be obtained via coupling the two identical Colpitts oscillators and sharing their source-to-ground capacitors C_2. Since the center node where both C_2 capacitors are connected together is a differential virtual ground, the original operation of the oscillators remains unchanged when the two sides oscillate 180° out of phase. The differential operation will be guaranteed if the center node is left floating and is not grounded. Consequently, the output swing of the VCO is enhanced and lead to a superior close-in phase-noise. Since the varactors are employed in the source terminals of the transistors, a more effective controlled mechanism of the tank resonance is presented. Therefore, a reasonable frequency tuning range can be achieved even with a reduced voltage range for the controlled signal V_{ctrl}. To further investigate the proposed VCO, detailed circuit analysis is provided as follows.

2.1. Startup conditions

In order to derive the startup conditions and the oscillation frequency, the equivalent half-circuit of the proposed VCO is shown in Fig. 2, where R_1 and R_2 represent the losses of the on-chip inductors L_1 and L_2, respectively. Note that the losses of inductors are typically modeled as a series resistance. In the equivalent circuit, the narrowband approximation is employed to simplify the analysis, and the shunt resistance R_1 and R_2 can be estimated by

$$R_1 \approx \omega^2 L_1^2 / R_{s1} \tag{1}$$

$$R_2 \approx \omega^2 L_2^2 / R_{s2} \tag{2}$$

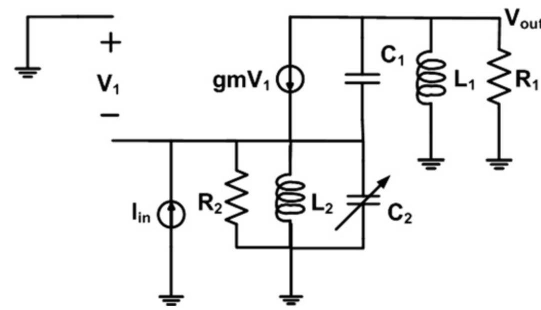

Fig. 2. Simplified half-circuit model of the proposed VCO.

where R_{s1} and R_{s2} are the equivalent series resistances of L_1 and L_2, respectively. Besides, the transistor parasitic capacitances, which are much smaller than the values of C_1 and C_2, are neglected. From the small-signal analysis, the transfer function between V_{out} and I_{in} is given by

$$\frac{V_{out}}{I_{in}} = \frac{s^2 L_1 L_2 R_1 R_2 (g_m + sC_1)}{a_4 s^4 + a_3 s^3 + a_2 s^2 + a_1 s + a_0} \tag{3}$$

where

a_0: $R_1 R_2$
a_1: $g_m R_1 R_2 L_2 + R_1 L_1 + R_2 L_1$
a_2: $L_1 L_2 (1 + g_m R_2) + R_1 R_2 (L_1 C_1 + L_2 C_1 + L_2 C_2)$
$\approx R_1 R_2 (L_1 C_1 + L_2 C_1 + L_2 C_2)$
a_3: $L_1 L_2 (R_2 C_1 + R_1 C_1 + R_2 C_2)$
a_4: $R_1 R_2 L_1 L_2 C_1 C_2$

The circuit oscillates if the close–loop transfer function goes to infinity at an imaginary value of s, $s_R = j\omega_R$. Consequently, both the real and imaginary parts of the denominator must drop to zero at this frequency

$$L_1 L_2 R_1 R_2 C_1 C_2 \omega_R^4 - R_1 R_2 (L_1 C_1 + L_2 C_1 + L_2 C_2) \omega_R^2 + R_1 R_2 = 0 \tag{4}$$

$$L_1 L_2 (R_1 C_1 + R_2 C_2 + R_2 C_1) \omega_R^3 + (g_m L_1 R_1 R_2 + R_1 L_2 + R_2 L_1) \omega_R = 0 \tag{5}$$

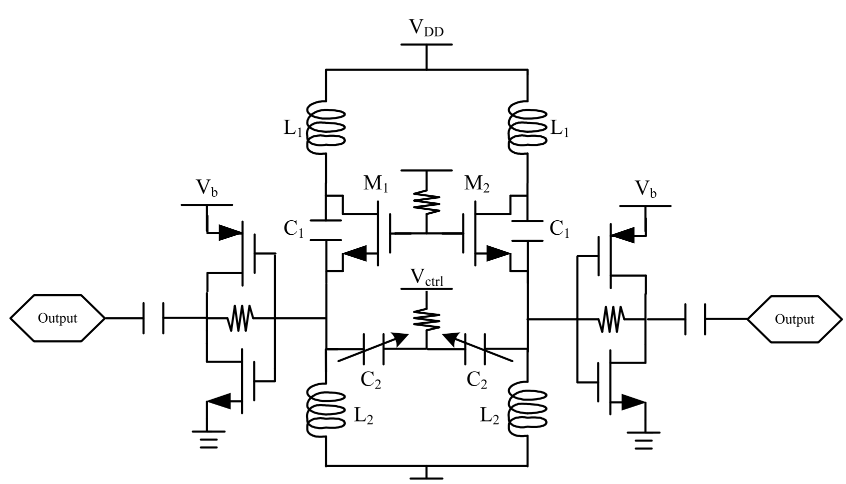

Fig. 1. Schematic of the proposed VCO topology.

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