ARTICLE IN PRESS

INTEGRATION, the VLSI journal xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

INTEGRATION, the VLSI journal

journal homepage: www.elsevier.com/locate/vlsi

Exact analyses for locking range in injection-locked frequency dividers

Armin Mohammadjany, Ali Reza Hazeri*, Hossein Miar-Naimi

Department of Electrical and Computer Engineering, Babol Noshirvani University of Technology, Babol, Mazandaran, 47148-71167, Iran

ARTICLE INFO

Index Terms:
Frequency dividers
Injection locking
Injection pulling
LC oscillators
Quadrature oscillators

ABSTRACT

In this paper, new equations are introduced for the locking rang of the injected locked LC frequency divider by the tail current. The injection current at the source is analyzed and replaced by two equivalent injection currents at drains. Then, two new simple closed-form equations are derived for the locking range. Geometrical interpretations lead to more clear and accurate results, rather than what considered in previously published works. To evaluate the accuracy of the proposed equations, different simulations and experiments have been performed. Results show a good conformance among simulation, experimental and analytical results.

1. Introduction

oscillators are essential blocks in the most of the electronic circuits especially in the Phase-Locked Loops (PLLs). According to the load, they are classified into many types such as LC, for example, cross-coupled and RC for instance ring oscillators. Another classification is on the basis of the injection signal. The oscillator not injected by external signals is called the free-running oscillator and one injected by external signals is well-known as the injected oscillator. The free-running oscillators have been investigated in many published papers for analyzing oscillation frequency, amplitude, phase noise and jitter [1–10]. When an external is injected into an oscillator, two phenomena (locking and pulling case) occur on the basis of both strength and oscillation frequency of the injected signal. Provided that the strength and oscillation frequency difference of the injected signal and transistor's current are in suitable values i.e. they satisfy the locking condition, the output oscillation frequency of the oscillator is the same as the oscillation frequency, sub-harmonic or super-harmonic of the injected signal. The injected oscillators have been studied in many papers [5,14–34]. They have been investigated in two classes. The first one is for enhancing the locking range employing various configurations such as combining inductors in series or parallel with injection mixer to improve its transconductance, dual injection to improve voltage and current injection paths, body biasing, harmonic suppression and distributed injection to distribute the injection signals in LC-ladder networks in Refs. [11–13]. The second one is for analyzing the performance of the injected oscillators such as locking range, pulling phenomenon and phase noise [5,14–33]. The first harmonic injection signal has been analyzed by Adler and pulling and locking phenomena were investigated for LC oscillators [14]. Then the Adler's equation for the locking range has been improved by Refs. [16–18]. In Refs. [16,17], generalized Adler's equation for the locking range has been obtained by some geometrical interpretations. In Refs. [19,20], for strong injection signals, some equations have been reported by employing differential equations for pulling phenomena. Also, a multi-injection signal case has been presented in Ref. [17]. Another analyzing for getting the locking range has been proposed by the averaging method which obtains Adler's equation again in Ref. [21]. The mentioned references have been introduced for LC oscillators. Also, some papers have been introduced for the ring oscillators [5,22–25]. In Ref. [5], comprehensive investigations about pulling and locking phenomena have been accomplished for the ring oscillators. One another method which can be used for all kinds of oscillators has been proposed by the perturbation projection vector (PPV) [26]. In order to analyze the sub-harmonic ($\omega_{inj} \approx \omega_0/N$) and super-harmonic ($\omega_{inj} \approx N\omega_0$ called the frequency divider) injected oscillators, few papers have been published. In Refs. [27–29], two general models have been introduced. In Ref. [27], an adder has been inserted before a nonlinear block in the given model. However, it is not suitable when oscillator behaves like mixers for the injection signal such as injected cross-coupled oscillators by injecting from the tail current source. For improving [27], multiplier blocks have been replaced [28,29]. However, this method needs SPICE pre-processing for obtaining some parameters dependent on the saturation voltage (V_{SAT}) of the cross-coupled pair and used in the locking range [29]. In Ref. [30], the injection-locked frequency dividers have been studied by phase-domain macromodels. However, the phase-domain macromodel needs tedious pre-processing and time-consuming for getting the PPV. For the second harmonic case (divide-by-2) as shown in Fig. 1, an injected signal has been applied to the tail current source of the cross-coupled oscillator; then, the injected signal was considered as an equivalent

* Corresponding author. Tel.: +98 9188338697.
E-mail addresses: a.mohammadjany@stu.nit.ac.ir (A. Mohammadjany), alirezahazeri@stu.nit.ac.ir (A.R. Hazeri), h_miare@nit.ac.ir (H. Miar-Naimi).

https://doi.org/10.1016/j.vlsi.2018.05.012
Received 8 September 2017; Received in revised form 29 April 2018; Accepted 26 May 2018
0167-9260/

Please cite this article as: Mohammadjany, A., INTEGRATION, the VLSI journal (2018), https://doi.org/10.1016/j.vlsi.2018.05.012

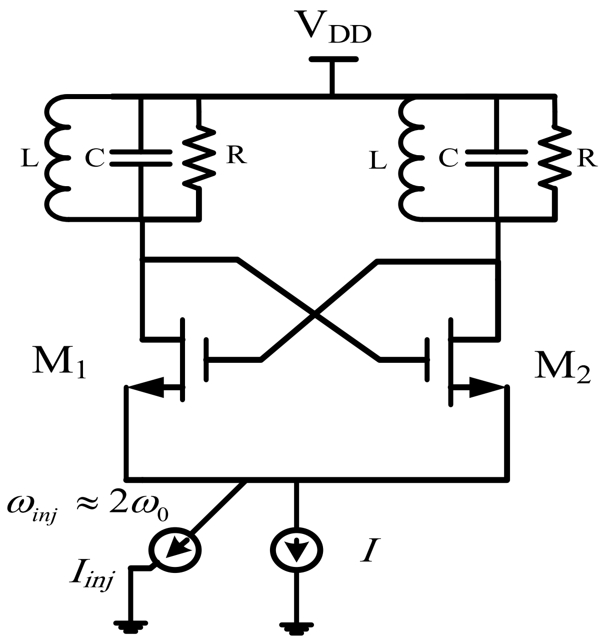

Fig. 1. A simple ILFD with the injection from the tail current source.

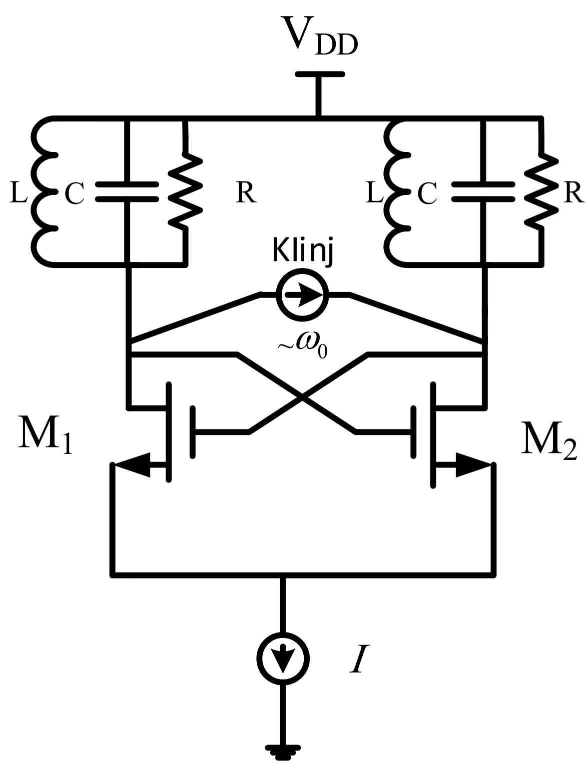

Fig. 2. The equivalent injection currents of Fig. 1, $K = 2/\pi$.

injection signal at drains which is $2/\pi$ times of the amplitude current and half oscillation frequency of the injected signal as portrayed in Fig. 2 [16]. Hence, the locking range was achieved such as the first harmonic one. Since this locking range was referred to output ports, the locking range referred to the tail current source is two times than the first harmonic one [16]. This locking range has been acquired by a little different analysis in Ref. [18]. In Refs. [31–33], by employing the averaging method, asymptotic analysis, or slowly-varying amplitude and phase analysis, the second harmonic case has been reported when the injection signal was directly applied to output ports, called direct Injection Locked-Frequency Divider (ILFD), of the cross-coupled oscillator. In Ref. [31], the locking range equation has been obtained for ILFD by applying the injection signal to the tail current source. Nonetheless, it is dependent on the circuit parameters and needs pre-processing by simulators to obtain some features of the oscillator leading it to a non-closed-form equation especially in the short-channel devices. Also, ILFD injected by the tail current source has been studied by the numerical bifurcation analysis using continuation software such as AUTO [34]. One another application of the injection signal is in implementing the quadrature oscillators [17,35]. From the above, it follows that a comprehensive exact analytical method to predict the locking range for divide-by-2 has been not available when the injection signal is applied in the tail current source yet. The exact locking range is the most significant evaluation measure of the ILFD. Having closed-form, simple and accurate enough equation for the locking range without pre-processing makes the design procedure easy.

In this paper, the injection signal at the tail current source is equivalently replaced by two different injection currents at the drains. Then, the locking range is calculated employing multi-injection analysis. The proposed equations for the locking range are closed-form equations and exacter and simpler than the previous works. The rest of the paper is as follow, in Section 2, the proposed analytical approach is introduced and two closed-form equations are derived for the locking range. In Section 3, the proposed analyses are evaluated using simulations in both typical quadratic level 1 CMOS and TSMC 0.18 µm CMOS process technology. In Section 4, experimental results are presented from a hybrid circuit. Finally, conclusions are expressed in Section 5.

2. Proposed analysis of ILFD

Consider the LC oscillator shown in Fig. 3. When the oscillator oscillates with the large enough amplitude (the condition that holds in practical applications) the cross-coupled transistors act as current switches which switch the tail current between two drain terminals. So drain currents flowing in the LC tanks can be represented by the tail current multiplied by a periodic square waveform. Using the Fourier series theory, the periodic square waveform can be represented by the sum of a sine wave and its harmonics as follows:

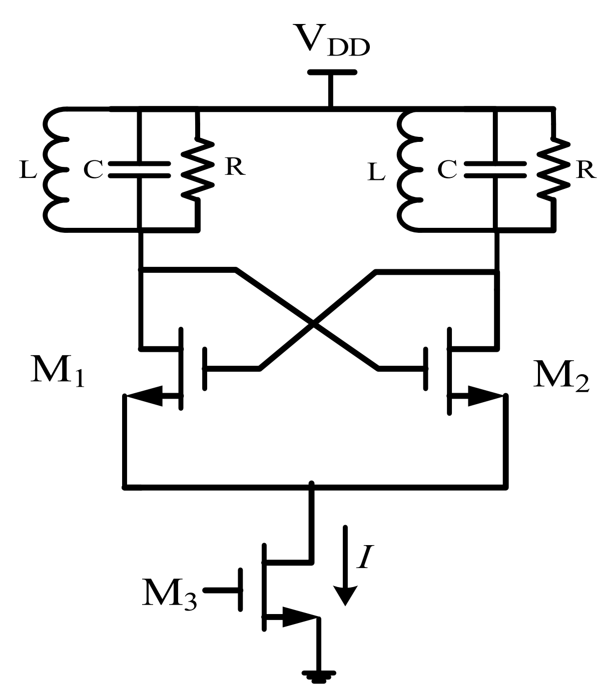

Fig. 3. Typical cross-coupled LC oscillator.