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Design and optimization of the ring oscillator based injection locked frequency dividers

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ABSTRACT

In this paper, the large signal operation of the ring oscillator based injection locked frequency divider is analyzed considering the trade-offs among the operating frequency, locking range and power consumption. A large signal model is used to reveal several key findings such as voltage-limited locking ranges and asymmetry between the upper and lower locking bands. They are applied to the optimize the dividers maintaining a good balance among design considerations. Several prototypes, including the divide-by-2 with 3 and 5 stages of inverters, divide-by-3 and divide-by-5, are implemented in a standard 0.18 μm CMOS technology to verify the operation under a large injected signal. As an extension, dual-modulus prescalers are further designed by the integration of switches for different ways of signal mixing. Measurements results show the proposed divide-by-2/3 unit and a divide-by-8/9 with this unit are able to work up to 8 GHz and 4.0 GHz with maximum power consumption of 0.7 mW and 1.5 mW respectively.

1. Introduction

The trend toward high frequency and broadband digital communication has increased a great demand for high-speed on-chip clocks at GHz ranges. The high-speed frequency divider is a key block in such clock systems such as the phase locked loop (PLL) [1–6]. The dual-modulus prescaler is the most challenging one among all kinds of frequency divider designs for the highest operating frequency in the system while the variable division ratios are required. In addition, low power consumption is still highly desired since battery time is always a key consideration in nowadays portable applications. The injection locked frequency divider (ILFD), for its ultra-high operating frequency and low power consumption, has been celebrated an ideal candidate for high-speed frequency dividers and many ILFDs optimized with wide range, high frequency and low power consumption have been reported recently [6–13]. Unlike a LC tank based ILFD with narrow range about 10% around the operating frequency, 100% bandwidth is achievable by using a low quality factor ring oscillator (RO) [14–16], making the solution most attractive at GHz ranges. Unfortunately, several issues still remain in the RO based ILFD. Firstly, the theoretical analysis of ILFD is mainly based on a small injected signal while the divider actually works with a large input signal which is common in a VLSI system [10,11,14,17]. In the absence of a large signal model, proper optimization important design parameters in ILFDs is impractical. Moreover, the ILFD is conventionally designed with a fixed division ratio instead of dual or multi modulus which is highly desired in a PLL. Several ILFDs with variable division ratios have been demonstrated in literature [18–23]. However, most of them are based on the injection locking at different order of harmonics instead of the fundamental one. Different division ratios are actually working at different input ranges, which is not the right desire in a dual-modulus prescaler of the PLL. In this paper, a large signal model of ILFD is proposed to solve the first issue. The model and simulations reveal some key trade-offs in ILFD with the large signal input followed by a detailed design procedure of the ILFD with a tail current injection. These findings are then extended to the design of ILFD with dual-modulus operation. By constructing different paths of signal injection and the compensation of propagation delay, prescalers with similar working range at different modulus are hence achievable. Compared with conventional designs, the proposed ILFDs provide maximum flexibility in system integration with low power consumption and wide locking ranges.

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2. Theoretical analysis, simulation and design considerations of ring oscillator based ILFD

The operating frequency and power consumption are the most important considerations in the design of high-speed frequency prescalers. By sacrificing the operating bandwidth, the power consumption of the ILFD is much lower than that of the digital frequency divider. The concept of ILFD is based on the oscillation at the harmonics of the input frequency [9]. It consists of an injector (e.g. a Mixer) and a frequency selective block. The input signal is injected into the mixer, then mixed with the divider's output signal, hence produces a certain order of harmonic of the two signals. The frequency selective block filters out undesired harmonics while keeping the desired frequency equal to f_{in}/N, while the division ratio N is based on the characteristic of frequency selective block. To design an high performance ILFD, the optimization of key parameters, such as power consumption, self-oscillating frequency and locking range require detail investigation from physical model ot the circuit. In Ref. [9], a unify model on the ILFD is addressed based on harmonic balance method. In Ref. [16], the analysis of locking range is based on phasor relationship. However, all the literature works are limited to small input signal. In real scenario, where the injected signal is near rail-to-rail at VLSI circuits, these models need to be considered in a large signal condition.

2.1. Locking range of ring oscillator with a large signal input

A ring oscillator will sustain a stable oscillation as long as the circuit satisfies the Barkhausen criteria, where loop gain $\gg 1$ and the total loop phase amount the integer multiple of 2π. A ring oscillator consists of odd number of inverters with a positive feedback or even number of differential inverter stages with a cross-connected feedback. Fig. 1 shows a simplified N stage ring oscillator circuit. The loop gain requirement can be achieved by adjusting the gain of each stage, while the loop phase is contributed by the phase shift of $-\frac{\pi}{N}$ from load R_L and C_L at each output stage [16].

The self-oscillating frequency f_o is determined by the total RC delay in the ring. When an additional signal I_{inj} with a frequency f_{inj} at the vicinity of f_o is injected in to the circuit, the circuit oscillating frequency drifts from f_o. Consequently, phase shift of ϕ and θ are added at the injected stage and output load respectively. This phase condition is shown in Fig. 2.

To meet the Barkhausen criteria, the total loop phase condition in injection locking should satisfy:

$$N \times \theta + \phi = \pi \tag{1}$$

The relationship between θ and ϕ is then given by:

$$\theta = \frac{\pi - \phi}{N} \tag{2}$$

From Fig. 2, the relationships among different current signal is described as:

$$|I_{osc}|\sin\phi = |I_{inj}|\sin(\alpha - \phi) = |I_{inj}|(\sin\alpha\cos\phi - \cos\alpha\sin\phi) \tag{3}$$

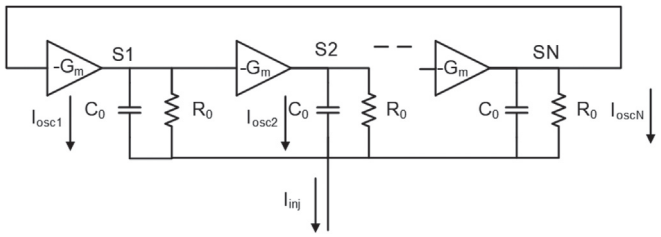

Fig. 1. A N-stage ring oscillator based ILFD.

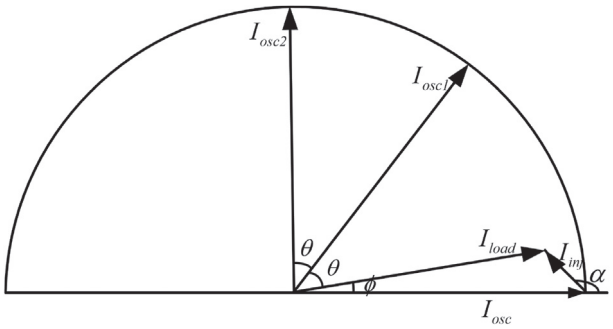

Fig. 2. Phasor in the N-stage ring oscillator based ILFD.

which is re-written as:

$$\frac{\sin\phi}{\cos\phi} = \frac{|I_{inj}|\sin\alpha}{|I_{osc}| + |I_{inj}|\cos\alpha} \tag{4}$$

by applying the partial differentiation, we have

$$\frac{1}{\cos^2\phi}\frac{d\phi}{d\alpha} = \frac{|I_{inj}||I_{osc}|\cos\alpha + |I_{inj}|^2}{(|I_{osc}| + |I_{inj}|\cos\alpha)^2} \tag{5}$$

which can be re-written as:

$$\frac{d\phi}{d\alpha} = \frac{|I_{inj}||I_{osc}|\cos\alpha + |I_{inj}|^2}{|I_{osc}|^2 + |I_{inj}|^2 + 2|I_{osc}||I_{inj}|\cos\alpha} \tag{6}$$

when $\frac{d\phi}{d\alpha} = 0$, which leads to $\alpha = \pi - \arccos(\frac{|I_{inj}|}{|I_{osc}|})$, namely $|I_{inj}| \perp |I_{load}|$, hence

$$|\phi_{max}| = \arctan\frac{|I_{inj}|\sqrt{|I_{osc}|^2 - |I_{inj}|^2}}{|I_{osc}|^2 + |I_{inj}|\sqrt{|I_{osc}|^2 - |I_{inj}|^2}} \tag{7}$$

In the RC network of output load in each stage, we have $\arctan(2\pi RCf_o) = \frac{\pi}{N}$ and $\arctan(2\pi RCf_{inj}) = \frac{\pi}{N} + \theta$, hence we have

$$\arctan\left(\frac{f_{inj}}{f_o}\tan\frac{\pi}{N}\right) = \frac{\pi}{N} + \theta \tag{8}$$

Let

$$f(f_{inj}) = \arctan\left(\frac{f_{inj}}{f_o}\tan\frac{\pi}{N}\right) \tag{9}$$

Using Taylor series in the vicinity of f_o, we have

$$f(f_{inj}) = \frac{\pi}{N} + \frac{\tan\frac{\pi}{N}}{\tan^2\frac{\pi}{N} + 1}\frac{f_{inj} - f_o}{f_o} + \cdots \tag{10}$$

In case of $f_{inj} < f_o$, $\theta < \frac{\pi}{N}$, and $\phi > 0$, we have

$$\frac{\pi}{N} + \frac{\tan\frac{\pi}{N}}{\tan^2\frac{\pi}{N} + 1}\frac{f_{inj} - f_o}{f_o} \geq \theta_{min} = \frac{\pi - |\phi_{max}|}{N} \tag{11}$$

Hence we have

$$\frac{f_{inj} - f_o}{f_o} \geq \frac{\tan^2\frac{\pi}{N} + 1}{\tan\frac{\pi}{N}}\frac{-|\phi_{max}|}{N} \tag{12}$$

Otherwise, for $f_{inj} > f_o$, $\theta > \frac{\pi}{N}$, and $\phi < 0$, we have

$$\frac{\pi}{N} + \frac{\tan\frac{\pi}{N}}{\tan^2\frac{\pi}{N} + 1}\frac{f_{inj} - f_o}{f_o} \leq \theta_{max} = \frac{\pi + |\phi_{max}|}{N} \tag{13}$$

we have