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Multi-Phase Injection Locked 3-Stage Ring VCO

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ABSTRACT

Multi-Phase injection locked 3-stage ring VCO has been presented in this paper. The circuit consists of free running ring oscillator operating at 4.6GHz and a ring VCO operating at 4.2GHz. Upon injection of the VCO signal, both the oscillators are displaced from their center frequency and are locked onto a new frequency of 4.4GHz, which is the average of their respective frequencies. Generation of new frequencies from existing frequencies has many advantages in modern RF applications.

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INTRODUCTION

The principle of Voltage Controlled Oscillator (VCO) is that the frequency of oscillation can be controlled by an input voltage. Figure 1 shows the relation between control voltage and oscillating frequency. Generally, the control voltage is applied to the gate terminal of the device. Since the gate voltage (V_g) affects the drain current (I_d) of the device, in other words the gate voltage affects the trans-conductance (g_m) of the device which in turn affects the frequency of operation as can be seen from equation (1).

$$F_{osc} = \frac{g_m}{2\Pi C_{gs}} \quad (1)$$

where g_m is the trans-conductance of the device and C_{gs} is the gate capacitance of the device.

An Injection locked differential ring VCO has been presented in (Maran *et al*., 2013). An injection locked frequency multiplier has been presented in (Nourifumi, 2011). In this paper, 3 stage Multi-Phase Injection locked ring VCO is presented. There are two separate ring oscillators operating at two different frequencies F1 and F2. One of the oscillators is voltage controlled. With the concept of current injection, it can be seen that the setup is working at another frequency F3. Injection is also provided in multi-phase so as to reduce phase noise errors and also to establish strong injection pulling. Extensive work on injection locking and pulling has been done by (Behzad Razavi, 2004).

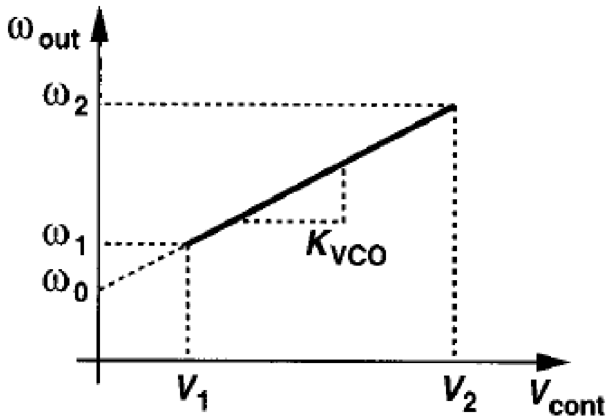

Fig. 1: Frequency variation with Voltage

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Overview of the Differential Ring VCO Topology:

The 3 stage ring oscillators consist of 3 stages of delay cells and the proper phase is provided by them so as to obtain the Barkhausen's criteria for oscillation. The Barkhausen's criteria for oscillation are as follows,

i. Total Phase shift = 360º or 2nπ
ii. Loop gain > 1

The complete 3-stage ring oscillator and a single delay cell at transistor level is shown in Figure 2. The delay cell consists of CMOS differential stage with NMOS tail and PMOS load. The control voltage, V_{bias1}, is given as the gate voltage of the NMOS tail transistor. Since the tail current source determines the current I_d through the differential branches of the delay cell, it can be seen that the control voltage determines the current I_d and hence the frequency of oscillation. Each stage consists of a delay unit and hence 3 stage ring oscillator consists of 3 delay units.

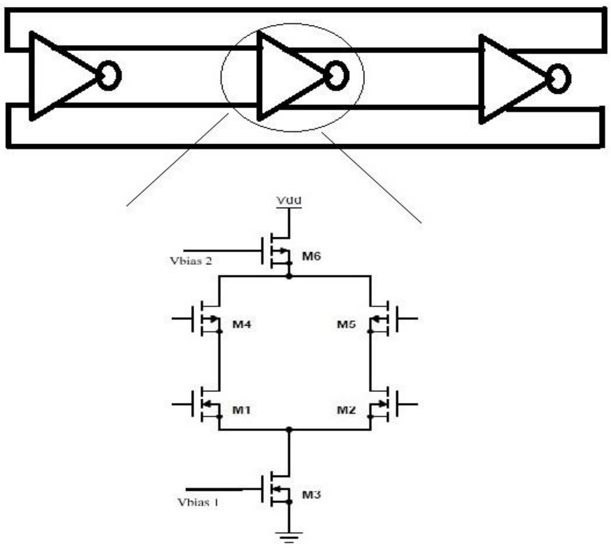

Fig. 2: 3-stage ring oscillator with differential feedback

A. CMOS inverter:

The objective of each of the stages is to provide an inversion of the input. Along with positive feedback, the system works as an oscillator, whose frequency can be controlled by the voltage applied to the gate of the NMOS tail current source in each stage. The inversion can be obtained by using a single PMOS or NMOS device. However, CMOS inverter has the added advantage of rail to rail swing which is a desired parameter in sub-micron process for faithful reproduction of signals.

B. Differential stage over single-ended:

The advantage of differential stage over a single-ended stage is a known feature (Ruiii Wu *et al*., 2011). Differential CMOS inverter stages are used. This overcomes several shortcomings of the single ended stages. For instance, differential stage will provide better voltage swing than the single ended stages. Also, differential stages have the advantage of superior Common Mode Rejection Ratio (CMRR) and better noise performance. Use of single ended stages strictly warrants that the feedback be given out of phase to the first stage i.e. odd number of stages is necessary. But with differential stages, the feedback can be cross coupled to the first stage i.e. even number of stages is also possible. Though the transistor count is doubled for a differential stage, the superior noise performance, CMRR and better voltage swing of the differential setup overpowers the shortcomings of a single ended stage.

Multi-Phase Frequency Injection:

The multi-phase frequency injection schematic is shown in Figure 3. The ring oscillator is free running at 4.6GHz and the ring VCO for injection control is running at 4.2GHz is connected to the differential nets of another ring oscillator. The differential nets are tied together in phase. Injection locking can be achieved by injecting current at a single node. Here, current is injected at both the differential nodes and also at multi-phases of the ring oscillator. Typically the nets are the drains of the CMOS device. Refer fig. 3. There are totally 3 stages and 6 nodes, two for each stage, being connected to provide multi-phase injection to the ring oscillator. Since the total phase shift around the loop is 360º, the phase is divided among the 6 nodes equally to 60º each. Since the currents vary in both the oscillators, the frequencies also vary proportionately. To achieve equilibrium, current stealing occurs from the oscillator with higher frequency (free running) and gets injected into oscillator with lower frequency (ring VCO). Now, the oscillator with lower frequency experiences more current and its frequency increases. Thus, current injection and current stealing takes place and an equilibrium state is achieved with equal currents flowing in both the ring oscillators and an intermediate frequency ω_3 is obtained which is approximately the average of the initial frequencies ω_1 & ω_2. Let I_1 and I_2 be the currents in the two ring structures.

$$I_1 = A \sin \omega_1 t \quad (2)$$

$$I_2 = A \sin \omega_2 t \quad (3)$$

$$I_3 = I_1 + I_2 \quad (4)$$

using trigonometric identities and simplifying, we get

$$I_3 = A\left[\sin\left(\frac{\omega_1 + \omega_2}{2}\right)t + \sin\left(\frac{\omega_1 - \omega_2}{2}\right)t\right] \quad (5)$$

From the above equation, we can see that the resulting current I_3 has the frequency component which is the average of ω_1 and ω_2. Injection is done in multi-phase so as to reduce the phase errors and stronger locking of frequency to a new value.

The multi-phase injection provides strong locking and also helps in reducing the phase noise. Phase noise of <20 dB was obtained in a simple injection locked VCO (Maran *et al*., 2013). With multi-phase injection locking, we can achieve greater phase noise performance. Better the phase noise performance, better the spectral purity. The ability to synthesize multiple frequencies in an on-chip circuit with good spectral purity is an added advantage in today's IC design. The method described in this paper proves more than useful in synthesizing multiple frequencies and can also be used for other analog operations in the chip with greater accuracy and performance.

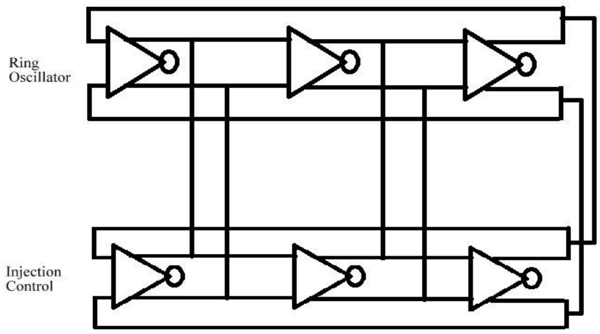

Fig. 3: Multi-Phase 3 stage ring VCO

Results:

The proposed circuit was designed using Cadence Design Suite and simulated using Virtuoso platform from the same using GPDK 180nm CMOS process technology. The circuit is shown in figure 4. Table 1 shows the design parameters of the transistors in a single delay unit. The spectrum for the ring oscillator and ring VCO operating at 4.6GHz and 4.2GHz respectively are shown in figure 5 and figure 6. The spectrum of locked frequency 4.4GHz is shown in figure 7. Table 2 outlines the results.

Table 1: Design Values

Name	$M_{1,2,4,5,7,8,19,20,21,22,23,24}$	$M_{10,11,13,14,16,17,25,26,27,28,29,30}$	$M_{3,6,9}$	$M_{12,15,18,31,32,33}$
Length	180nm	180nm	180nm	180nm
Width	400nm	1.08um	800nm	2.16um

Table 2: Results Summary

Free Running Frequency of Ring Oscillator (F1)	4.6 GHz
Injection Frequency of Ring VCO (F2)	4.2 GHz
Output Frequency (F3)	4.4 GHz
Control Voltage of VCO	1.8V
Phase Noise	~25 dB

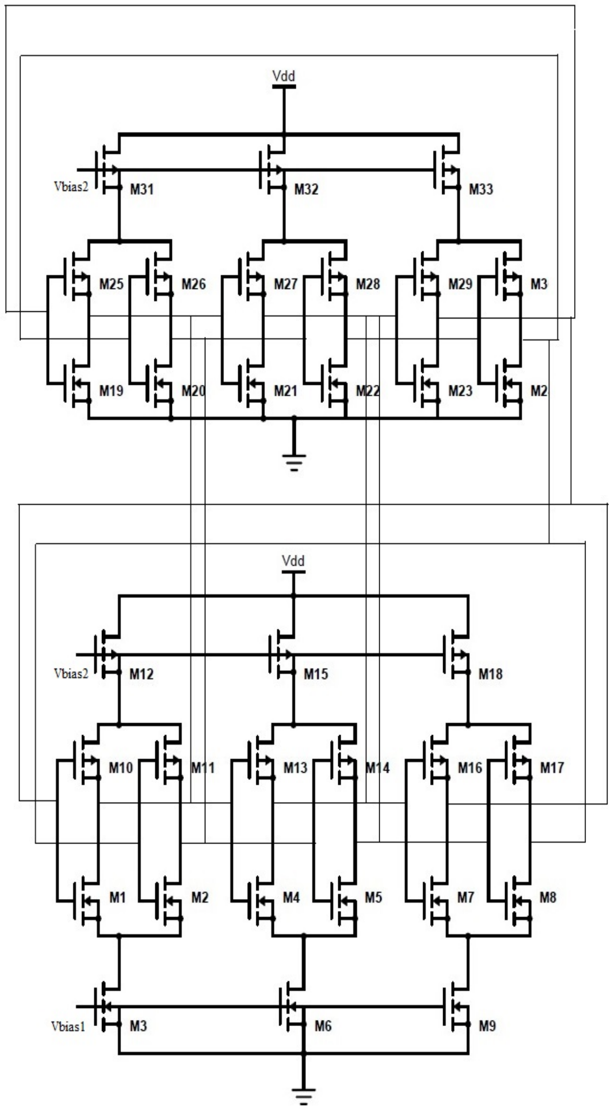

Fig. 4: Circuit Schematic in Cadence Design Suite

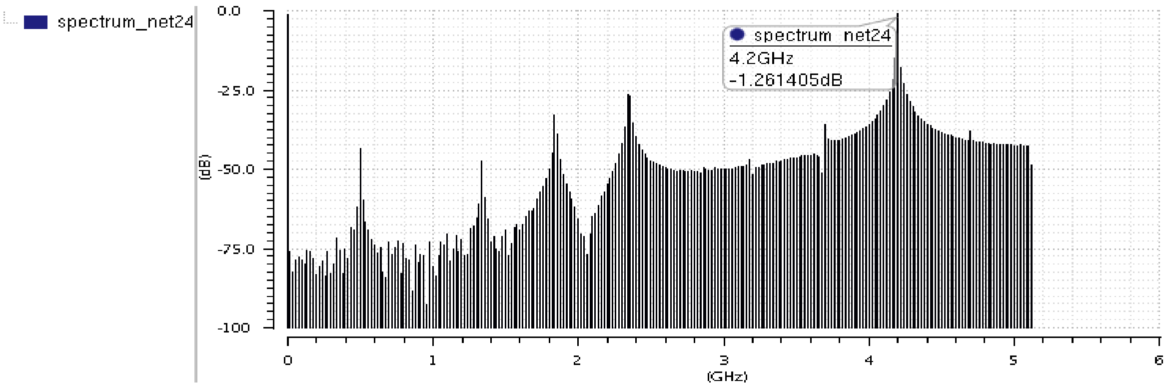

Fig. 5: Spectrum of ring VCO running at 4.2GHz

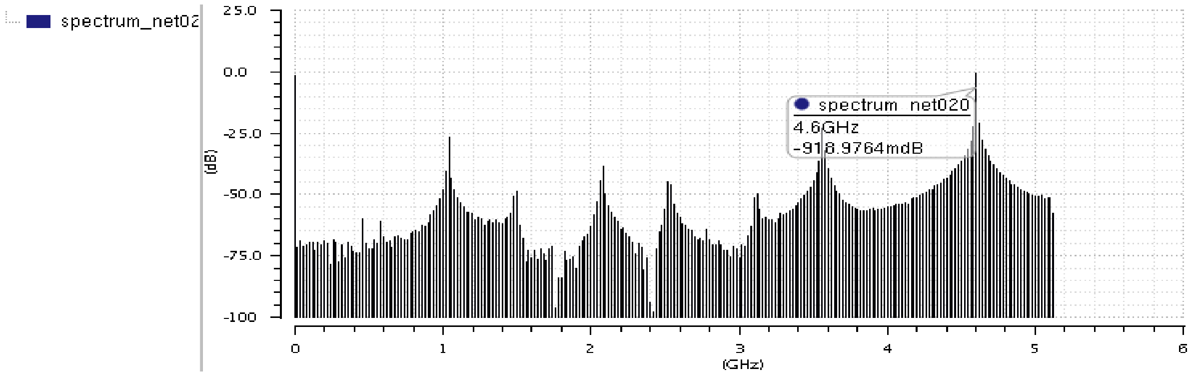

Fig. 6: Spectrum of free running ring VCO at 46GHz

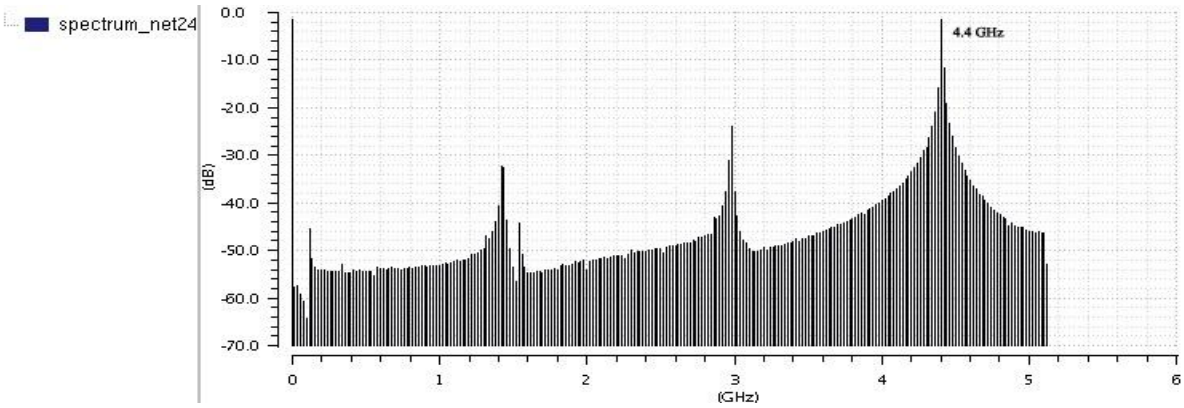

Fig. 7: Spectrum after injection locking at 4.4GHz

Conclusion:

Thus, the work presented in this paper can act as a robust methodology to be implemented on an integrated RF chip. By using the control voltage the VCO can be tuned to wide variety of frequencies along with the inherent free running frequency. The advantage of the circuit presented in this paper can be exploited by other components such as Phase Locked Loop (PLL), Mixer etc.

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