Multiphase Signal Generation Using Capacitive Coupling of LC-VCOs

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***Abstract*—A method for multiphase signal generation by means of coupling several identical cross-connected LC-VCOs via capacitors is presented. An analysis is presented which shows that there is a 180/N degrees phase difference between the outputs when N identical oscillators are coupled to each other. Since there is no noise and power consumption introduced by the coupling capacitors, the circuit has a better phase noise performance and lower total power consumption than other similar multiphase oscillators. Simulation results for the oscillator designed with a 0.18 μm CMOS technology are presented and compared with another similar multiphase oscillator.**

I. INTRODUCTION

In high-speed communication systems, multiphase VCOs are used in clock and data recovery (CDR) systems for phase detection [1-4], and also they can be used in demultiplexer block [1]. Various topologies have been proposed for multiphase signal generation [2-7]. In [2] a three-stage, and in [3] a four-stage differential ring oscillators were used to generate multiphase signals with 60^o and 45^o phase differences, respectively. Ring VCOs have a large tuning range compared to LC oscillators; however, they suffer from a poor phase noise performance. In [4], four differential LC ring oscillators are connected in a loop forming a four-stage LC ring oscillator, in order to generate 45^o phase difference between the outputs. However, as highlighted in [7], since each of the LC oscillators operate away from the resonance frequency of their LC tanks, degradation in phase noise will result.

In [5] a method for multiphase signal generation is proposed which is basically Rofougaran's technique for quadrature signal generation [8], generalized to multiphase generation. In this configuration, N identical cross-connected LC oscillators were coupled to each other via coupling transistors in a loop. In that circuit N-1 of the oscillators are connected to each other *in-phase*, and the last one is connected to the first oscillator in the loop in an *anti-phase* manner, resulting in a 180/N degrees phase differences between any two consecutive outputs.

Multiphase VCOs in [6] and [7] have utilized the *in phase-anti phase* scheme of connection (similar to what used in [5]) to couple several identical cross-connected LC oscillators to each other. In [6] coplanar striplines and varactors together form the resonant circuit of each of the oscillators, and at the same time the striplines play the role of the coupling devices among the oscillators as well. Using striplines as coupling devices imposes the constraint that the cross-connected pairs of transistors in each of the oscillators must be complementary pairs, i.e. a stack of cross-connected NMOSFET pair and a cross-connected PMOSFET pair. One issue with the use of the complementary pairs as the active element in each cross-connected oscillator is that the power supply should be at least as high as the sum of the threshold voltage of N and PMOSFETs. In [7] inductors are used as coupling devices to generate a phase difference of 45^o. In this circuit also complementary pairs of cross-connected transistors must be used as the active elements (unless, possibly, the mutual inductance of the inductors is used as the means of coupling the oscillators). In both [6] and [7] the oscillation frequency decreases in reverse proportion to the number of cross-connected oscillators.

In this paper, capacitive coupling of cross-connected LC VCOs is proposed for multiphase signal generation as an alternative to the inductive coupling of oscillators described in [7]. In the proposed circuit, N identical cross-connected LC oscillators are connected to each other via capacitors following the *in phase-anti phase* scheme of connection. However, capacitors as compared to transistors used in [5] as coupling devices, have the advantage of not adding any extra power consumption and noise to the original circuits. Also, as will be explained in the next section, the proposed circuit eliminates the need that the cross-connected transistor pairs be complementary; a single pair of NMOSFETs (or PMOSFETs) can be used as the active element of each of the oscillators, hence allowing a larger reduction of the power supply voltage. Also, the dependence of frequency of oscillation to the number of oscillators can be made less than what is observed in [6] and [7].

In section II the circuit description and analysis will be presented. Simulation results for a circuit designed with a

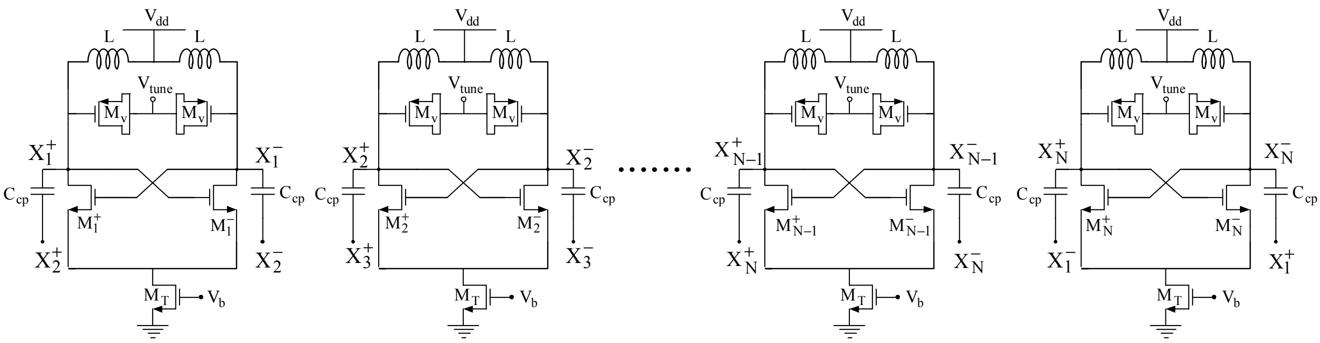

Figure 1. proposed multiphase VCO

0.18μm CMOS technology are presented in section III, and section IV is the conclusion.

II. The Circuit Description and Analysis

The schematic of the proposed multiphase VCO is shown in Fig. 1. In the circuit N identical cross-connected LC VCOs are coupled to each other via coupling capacitors C_{cp}. PMOSFETs denoted by M_v are used as varactors. The oscillation amplitude is controlled via the gate biasing V_b of the tail transistors M_T.

In order to show that there is 180/N degrees phase difference between the output waveforms, the KCL at the drains of the cross-connected transistors, $X^+_{1,2,\ldots n}$ can be considered. Following a similar method of analysis to what used in [9], it can be assumed that at steady state the loss in the LC tank of each of the LC oscillators is canceled by the negative resistance created by the cross-connected transistor pairs. Therefore at each of the output nodes only capacitances and an inductor remain. Ignoring the effect of parasitic capacitances of the cross-connected transistors, the KCL equations at $X^+_{1,2,\ldots n}$ nodes are:

$$\begin{cases} (-\omega^{-2}L^{-1}+C_{\text{var}}+2C_{cp})V_{X_1^+}-C_{cp}V_{X_2^+}-C_{cp}V_{X_N^-}=0 \\ (-\omega^{-2}L^{-1}+C_{\text{var}}+2C_{cp})V_{X_2^+}-C_{cp}V_{X_1^+}-C_{cp}V_{X_3^+}=0 \\ (-\omega^{-2}L^{-1}+C_{\text{var}}+2C_{cp})V_{X_3^+}-C_{cp}V_{X_2^+}-C_{cp}V_{X_4^+}=0 \\ \vdots \\ (-\omega^{-2}L^{-1}+C_{\text{var}}+2C_{cp})V_{X_{N-1}^+}-C_{cp}V_{X_N^+}-C_{cp}V_{X_{N-2}^+}=0 \\ (-\omega^{-2}L^{-1}+C_{\text{var}}+2C_{cp})V_{X_N^+}-C_{cp}V_{X_{N-1}^+}-C_{cp}V_{X_1^-}=0 \end{cases} \quad (1)$$

in which C_{var} is the capacitance of MOS varactors M_v. By denoting $\frac{(-\omega^{-2}L^{-1}+C_{cp}+C_{\text{var}})}{C_{cp}}$ as A, and considering that $V_{X_i^+}=-V_{X_i^-}$, all above equations in (1) can be rewritten as:

$$\begin{cases} AV_{X_1^+}=V_{X_2^+}-V_{X_N^+} \\ AV_{X_2^+}=V_{X_1^+}+V_{X_3^+} \\ AV_{X_3^+}=V_{X_2^+}+V_{X_4^+} \\ \vdots \\ AV_{X_{N-1}^+}=V_{X_{N-2}^+}+V_{X_N^+} \\ AV_{X_N^+}=-V_{X_1^+}+V_{X_{N-1}^+} \end{cases} \quad (2)$$

Since all differential oscillators in Fig. 1 are identical, all potentials at drain nodes of cross-connected transistors can be assumed to have the same amplitude. These potentials can be denoted by phasor notation as $V_{x_i^+}=Ve^{j\varphi_i}$, *i=1,2,…,n*, so the oscillation amplitude at drain nodes $X^+_{1,2,\ldots n}$ from equation (2) can be written as:

$$\begin{cases} \left|V_{X_1^+}\right|=\frac{V}{|A|}\sqrt{2-2\cos(\varphi_N-\varphi_2)} \\ \left|V_{X_2^+}\right|=\frac{V}{|A|}\sqrt{2+2\cos(\varphi_3-\varphi_1)} \\ \left|V_{X_3^+}\right|=\frac{V}{|A|}\sqrt{2+2\cos(\varphi_4-\varphi_2)} \\ \vdots \\ \left|V_{X_{N-1}^+}\right|=\frac{V}{|A|}\sqrt{2+2\cos(\varphi_N-\varphi_{N-2})} \\ \left|V_{X_N^+}\right|=\frac{V}{|A|}\sqrt{2-2\cos(\varphi_{N-1}-\varphi_1)} \end{cases} \quad (3)$$

The magnitude of all potentials at the gates of cross-connected transistors are equal to each other, hence from (3) we have:

$$\begin{cases} \left|V_{X_1^+}\right| = \left|V_{X_2^+}\right| & \Rightarrow \pi \pm (\varphi_N - \varphi_2) = 2k\pi \pm (\varphi_3 - \varphi_1) \\ \left|V_{X_2^+}\right| = \left|V_{X_3^+}\right| & \Rightarrow \varphi_3 - \varphi_1 = 2k\pi \pm (\varphi_4 - \varphi_2) \\ \left|V_{X_3^+}\right| = \left|V_{X_4^+}\right| & \Rightarrow \varphi_4 - \varphi_2 = 2k\pi \pm (\varphi_5 - \varphi_3) \\ \vdots & \\ \left|V_{X_{N-2}^+}\right| = \left|V_{X_{N-1}^+}\right| & \Rightarrow \varphi_{N-1} - \varphi_{N-3} = 2k\pi \pm (\varphi_N - \varphi_{N-2}) \\ \left|V_{X_{N-1}^+}\right| = \left|V_{X_N^+}\right| & \Rightarrow \varphi_N - \varphi_{N-2} = 2k\pi \pm (\pi \pm (\varphi_{N-1} - \varphi_1)) \end{cases} \quad (4)$$

From (4), it can be seen that:

$$(\varphi_3 - \varphi_1) = (\varphi_4 - \varphi_2) = \ldots = (\varphi_{N-2} - \varphi_N)$$

and

$$(\varphi_2 - \varphi_1) = (\varphi_3 - \varphi_2) = \ldots = (\varphi_{N-1} - \varphi_N).$$

Defining Δ_1 as $(\varphi_i - \varphi_{i-2})$, i=3,4,...,n and Δ_2 as $(\varphi_i - \varphi_{i-1})$, i=2,3,...,n, following can be written:

$$\begin{cases} \Delta_1 = 2\Delta_2 \\ \varphi_i = 2k\pi + \varphi_1 \pm (i-1)\Delta_2 \quad i = 2,3,\ldots, N \quad \Rightarrow \Delta_2 = \dfrac{\pi}{N} \\ \varphi_N - \varphi_{N-2} = 2k\pi \pm (\pi \pm (\varphi_{N-1} - \varphi_1)) \end{cases} \quad (5)$$

Therefore, any two consecutive outputs have 180/N degrees phase difference with each other.

It should be mentioned that this circuit does not generate quadrature signals when N=2. This can be explained by observing that when two oscillators are coupled according to the proposed method, neither of the oscillators injects any odd harmonic signal to the other oscillator.

In this topology capacitances C_{cp} are used as coupling devices so they do not add any noise sources and power consumption to the circuit. However, they contribute to the total capacitance of the LC tank, which in turn affects the oscillation frequency. To investigate the effect of coupling capacitances on the oscillation frequency, the KCL at X_1^+ is considered:

$$\begin{aligned} & j\omega C_{cp}(Ve^{j\varphi_1} - Ve^{j(\varphi_1 + \frac{\pi}{N})}) + j\omega C_{var} Ve^{j\varphi_1} \\ & + j\omega C_{cp}(Ve^{j\varphi_1} + Ve^{j(\varphi_1 + \frac{(N-1)\pi}{N})}) + \frac{Ve^{j\varphi_1}}{j\omega L} = 0 \end{aligned} \quad (6)$$

By setting the imaginary parts at the two sides of (6) equal to each other, oscillation frequency is calculated as:

$$\omega^2 = \frac{1}{L\left(C_{var} + 2C_{cp}(1 - \cos\frac{\pi}{N})\right)} \quad (7)$$

As can be seen from (7) the oscillation frequency is a function of the number of oscillators, N. In the case where N is equal to 1, the oscillation frequency is $\frac{1}{\sqrt{L(C_{var} + 2C_{cp})}}$. An observation here is that when N increases, the oscillation frequency increases and it approaches $\frac{1}{\sqrt{LC_{var}}}$ for large values of N, so the effect of coupling capacitors on the oscillation frequency decreases.

It is worth mentioning that for low values of C_{cp} it seems that the coupling between different cross-connected LC-VCOs is decreased, and gradual lowering of the C_{cp} eventually should result in a loss of multiphase signal generation. In the above analysis of multiphase operation of the circuit, however, no restriction is placed on the value of C_{cp}, implying that C_{cp} can be reduced without limit. Simulation results confirm that for values of C_{cp} as low as 5 fF, and the values of L=1 nH and C_{var}=730 fF resulting an oscillation frequency of about 5.88GHz, the circuit continues to generate multiphase signals. Therefore, the restriction on how small the values of C_{cp} can be chosen comes from the practicality of having matched capacitors when C_{cp}s are very small.

After this paper was submitted to be considered for publication, we became aware of another recent work in which the idea of capacitive coupling for multiphase signal generation has been used [10]. In [10] series varactors are used both as tuning elements of the LC tank and as a means for coupling oscillators. In our work an alternative analysis of the frequency of oscillation and also, an analysis of the multiphase operation of the circuit are presented.

III. SIMULATION RESULTS

The multiphase VCO in Fig. 1 with 4 stages designed with a 0.18µm CMOS technology. The dimensions of transistors and circuit parameter values are shown in table I. Substrates of the varactors PMOSFETs are connected to the highest potential in the circuit to achieve a wide tuning range [11]. For the purpose of this simulation the ohmic loss of the inductors is modeled with a series resistance of 1 ohm per each nH of inductance [12]. The simulated waveforms of this circuit are shown in Fig. 2. As can be seen, the output potentials have 45^o phase difference with each other. Fig. 3 shows a comparison of the simulated phase noise of this work with the simulated phase noise of the multiphase VCO in [5] for 4 stages at the same frequency and the same power consumption. The proposed multiphase VCO has a phase noise of -132 dBc/Hz at 3 MHz offset frequency from the center frequency of 5 GHz, which is an improvement of about 19 dBc/Hz compared to that of the multiphase VCO in [5]. The performance parameters of the multiphase VCO with 4 stages is summarized in table II. The figure of merit (*FOM*) is calculated as [13]:

$$FOM = 10\ \log(S_{SSB}(\frac{\Delta f}{f_0})^2 P_{VCO}) \qquad (8)$$

in which S_{SSB} is the single-sideband phase noise, f_o is the oscillation frequency, Δf is the offset frequency and P_{VCO} is the total power consumption in mW.

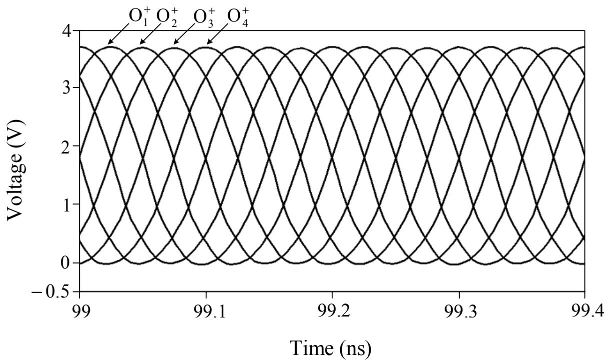

Figure 2. Simulated outputs of the proposed multiphase VCO.

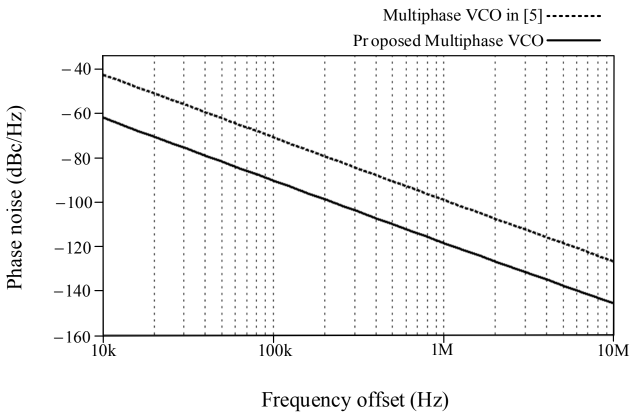

Figure 3. Simulated phase noise of the propose oscillator with that of [5]. Phase noise simulation was done with HSPICE-RF.

TABLE I. MULTIPHASE VCO PARAMETER VALUES

M_{1-4}	40µm/0.18µm
M_T	150µm/0.36µm
M_v	200µm/0.36µm
C_{cp}	0.5pF
V_{dd}	1.8 V
V_b	0.8 V
L	1nH

TABLE II. SIMULATION RESULTS OF MULTIPHASE VCO

Multiphase VCO performances	4stages
Frequency	5 GHz
Tuning range	4.8 ~ 5.2 GHz
Power dissipation[mW]	36
Phase noise [dBc/Hz}	-132[@3MHz]
FOM[dBc]	-180.87

IV. CONCLUSION

A new method for multiphase signal generation is proposed. In this multiphase VCO, *N* identical cross-connected oscillators are connected in a ring structure via capacitors as coupling devices. Capacitors do not add any power consumption and noise sources and therefore, do not degrade the phase noise performance. To show the multiphase operation of the circuit a linear analysis was presented. This analysis shows that the oscillation frequency is a function of the number of stages and increases as the number of oscillators increases. The proposed circuit was designed with a 0.18µm CMOS technology and simulation results were presented.

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