A Low-Voltage Low-Noise Superharmonic Quadrature Oscillator

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***Abstract*— A qualitative analysis of the large-signal operation of cross-connected LC oscillators at steady state is presented. It provides a physically understandable picture of the amplitude stabilization in these oscillators. Based on the insights gained from the mechanism of operation, a new low-noise, low-voltage (V_{dd} as low as 0.6 V) quadrature oscillator utilizing the superharmonic coupling is proposed and verified with simulation. The same coupling scheme can be extended to multiphase signal generation.**

***Index terms*—Low-noise, low-voltage, quadrature oscillators, multiphase oscillators, superharmonic coupling, negative resistance oscillators, describing functions.**

I. INTRODUCTION

Because of their low phase noise, LC-tank oscillators are an indispensable part of many radio-frequency (RF) circuits [1,2]. The cross-connected LC oscillators have become popular in the RF integrated circuits due to their ease of implementation and low power consumption [3]. Three different versions of this type of oscillator are shown in Figure 1. Because of their symmetric topology, these circuits generate two output signals with equal amplitude and opposite phase, which are suitable as inputs to circuits with differential inputs such as the Gilbert cell mixers.

Cross-connected oscillators are also used as the core building block in many quadrature oscillators [4-8]. Quadrature voltage controlled oscillator (QVCO) has applications in direct conversion receiver and transmitter systems [3]. In the QVCOs made of cross-connected oscillators, two identical cross-connected VCOs are coupled to each other and based on their mechanism of operation can be categorized into two main groups. The operation of the first group is based on injection of the first harmonic from each oscillator to the other [4], and the second group operates based on injection of the second harmonics [5-8].

In this paper a new scheme of coupling two cross-connected LC VCOs via their second harmonics is presented which makes the low values of the supply voltage possible. In the proposed coupling method no extra element is added to the core VCOs and hence, no extra power consumption and noise are added to the circuit.

In the next section the large-signal operation of the cross-connected oscillators is discussed. There has already been a large-signal analysis of a cross-connected oscillator [9], but the analysis here presents a negative resistance model of the oscillator as an alternative to the positive feed back system model in [9]. The presence of the even harmonic signals at common mode nodes (indicated as **a** and **b** in Figure 1) is well known and will be reviewed here. While the second harmonics are all needed to explain the operation of the proposed QVCO, and the mechanism of amplitude stabilization in the core VCO is not the main focus of this paper, the latter will be discussed in some detail as we believe this model, although qualitative, provides a physically tangible explanation for the amplitude stabilization in the circuit. In section 3, first, a review of some of the superharmonic coupling-based QVCOs is provided, and then the new coupling method is explained and simulation results are presented. Finally, section 4 provides a summary of the important results.

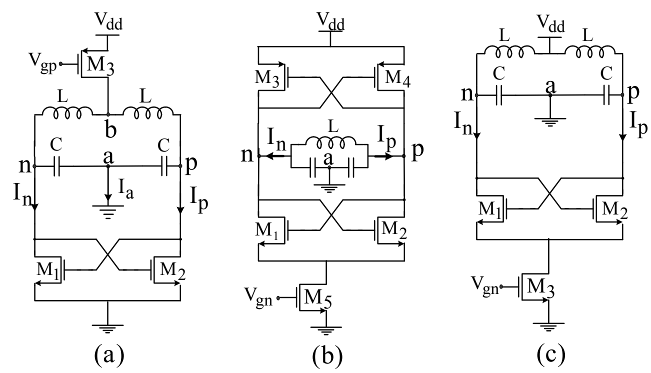


Figure 1. Three different configurations of cross-connected oscillator.

II. REVIEW OF THE LARGE-SIGNAL OPERATION OF THE CROSS-CONNECTED LC OSCILLATORS

To investigate the superharmonic QVCOs, the strength of the second harmonics utilized for injection locking, were varied by varying the oscillation amplitude V_{amp}: the higher the amplitude, the larger the second harmonics. V_{amp} itself can be controlled by the amount of loss (which for now is modeled as a resistor R_{loss} between nodes **n** and **p**) in the LC tank. The higher the loss (i.e. the lower the R_{loss}), the smaller the oscillation amplitude. At high loss values, the oscillation amplitude is proportional to the R_{loss}. As R_{loss} increases, the proportionality of V_{amp} and R_{loss} disappears and V_{amp} becomes constant. Commonly, this is explained by stating that oscillator has entered the "voltage-limited regime" [10] and V_{amp} is limited by some voltage, e.g. V_{dd}. It is observed, however, that when R_{loss} is large, the potentials at nodes **n** and **p** can exceed V_{dd}, e.g. as large as 4 V with V_{dd}=1.8 V for the circuits in Figure 1(a). Therefore, before discussing the new QVCO, an analysis of the core VCO is presented here which provides a more accurate explanation of the amplitude stabilization. This analysis explains the steady-state operation of the circuits based on the balance between the energy generated by the cross-connected MOSFETs, and the energy dissipated in the LC tank. The operation of the oscillator shown in Figure 1 (a) is explained, and the other two circuits in Figure 1 can be analyzed in a similar way. In all simulations, the transistor models were taken from a foundry-based 0.18 µm CMOS technology.

Assuming sinusoidal oscillation at steady state, the voltage at nodes **n** and **p** will be $V_n=V_{dc}+V_{amp}\sin\omega t$ and $V_p=V_{dc}-V_{amp}\sin\omega t$, respectively. Considering the symmetry of the circuit, it can be said that the currents I_n and I_p have periodic waveforms with frequency ω, with one lagging the other one half a period. Due to the non-linearity of the NMOSFETs, I_n and I_p can be written as Fourier series:

$$I_n(t) = I_0 + I_{1s}\sin\omega t + I_{1c}\cos\omega t + I_{2s}\sin 2\omega t + I_{2c}\cos 2\omega t + \dots \quad (1)$$

$$I_{p(t)} = I_0 + I_{1s}\sin\omega(t-\frac{T}{2}) + I_{1c}\cos\omega(t-\frac{T}{2}) + I_{2s}\sin 2\omega(t-\frac{T}{2}) + I_{2c}\cos 2\omega(t-\frac{T}{2}) + \dots \quad (2)$$

where $T=2\pi/\omega$. It is seen that the odd harmonics in I_n and I_p are in opposite phase and therefore, the presence or lack of a connection from node **a** to ground, and also the presence or lack of a connection from node **b** to the drain of PMOSFET, are irrelevant for odd harmonics. The even harmonics, in contrast, are in phase and flow to ground via the connection of the node **a** to ground and, to a lesser extent, through the drain of the PMOSFET. In fact, as simulation results (to be presented shortly) show, the current flowing from the node **a** to ground does have a strong content of second harmonics. Also, for the purpose of this analysis it is assumed that the capacitors have negligible impedance against the higher order harmonics of I_n and I_p, i.e. the resonant circuit has a high quality factor, which is usually the case of interest. As a result, all higher harmonics (even and odd) pass through the capacitors without significantly affecting V_n and V_p. Therefore, the only component which will be important in the process of generation or dissipation of power in the cross-connected pair of NMOSFETs and also in the resonant circuit, is the fundamental tone in I_n and I_p and all the higher harmonics can be ignored energy-wise.

With these considerations, an equivalent circuit can be formed for the oscillator as follows. Since the higher harmonics in I_n and I_p are ignored, the connections of the node **a** to ground and the node **b** to the drain of the PMOSFET can be removed and the circuit can be represented with a parallel connection of a capacitor, an inductor, the loss resistance R_{loss}, and a nonlinear elements R_{nnl} (*nnl* standing for **n**egative **n**on-**l**inear) which represents the cross-connected pair of NMOSFETs. This representation of an oscillator is known as the negative resistance model. Using this model, it can be argued that after oscillation starts in the circuit, its amplitude grows up to the point where there is a balance between the power generated in R_{nnl} and the power dissipated in R_{loss}. At this point the resistance R_{nnl} and R_{loss} effectively cancel each other and the oscillator behaves like a lossless LC tank which oscillates with constant amplitude indefinitely. Therefore, to complete the description of the model, a way of characterizing the nonlinear behavior of R_{nnl} is required which relates the first harmonic of its current to the oscillation amplitude. This is adequately done with G_{eff} defined as:

$$G_{eff} = \frac{I_{1s}}{2V_{amp}} \quad (3)$$

G_{eff} is called the describing function [11] of the cross-connected NMOSFETs and its value depends on the shape of the waveform of I_n and I_p, and therefore on the oscillation amplitude V_{amp}. In Figure 2 (a) the waveforms of I_n for several values of V_{amp} are shown. Variation of G_{eff} versus V_{amp} is also shown in Figure 2 (b). It is seen that for small oscillation amplitudes, the waveforms I_n (and I_p) are very close to sinusoidal, and as the amplitude increases, they become significantly distorted. Eventually amplitude stabilizes at V_{amp} for which G_{eff} is equal to $1/R_{loss}$. It can be stated that the shape of the I_n and I_p and their dependence on V_{amp} translate into an amplitude-limiting mechanism in this circuit.

The large-signal operation of the oscillators in Figure 1 (b) and (c) is analyzed in a similar way and similar results for I_n and I_p and their describing functions are obtained (not shown here).

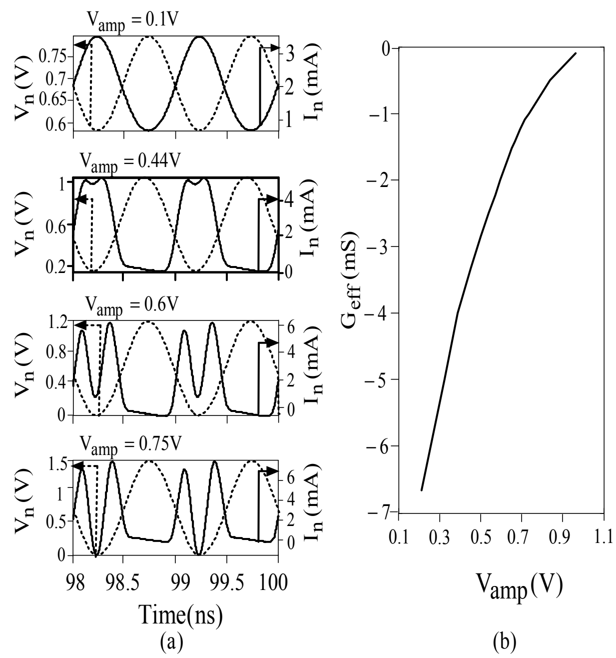


Figure 2. (a) The simulated current I_n for the circuit of Fig. 1(a) for several values of V_{amp}. (b) The effective linear conductance G_{eff} versus V_{amp} for the circuit of Fig. 1(a). $(W/L)_{M1,2}$=40µm/0.18µm, (W_p/L_p)=150µm/0.18µm, C=25pF, L=1nH, V_{dd}=1.8V, V_{gp}=1 V.

As explained in the next section, the node **a** of the oscillators in Figure 1 has the main role in the operation of the proposed QVCO. The waveform of the current flowing from node **a** to ground, I_a, for the circuit of Figure 1 (a) is shown in Figure 3. It can be seen that it contains a strong second harmonic content. This can be utilized in the generation of the quadrature signals, as is explained next.

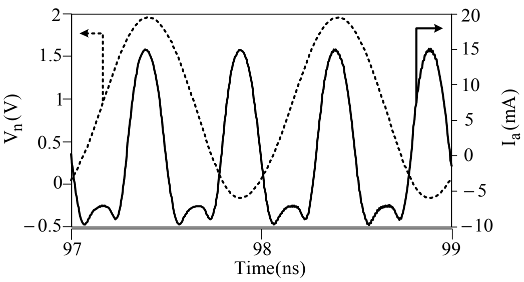


Figure 3. The waveforms of the current flowing from node **a** to ground, I_a, and the voltage at node **n** for the oscillator in Figure 1 (a). The same parameters as those in Fig. (2) were used for the simulation.

III. QUADRATURE SIGNAL GENERATION BASED ON SECOND HARMONIC COUPLING

Some of the reported QVCOs which operate based on the second harmonic coupling of two identical cross-connected LC oscillators are reviewed here.

In the QVCO proposed in [5], two VCOs similar to the one in Figure 1 (c) are coupled via the drains and gates of the current sources of each VCO. The drain of the current source (or equivalently, the common source of the cross-connected NMOSFET pairs) in each oscillator is a node which has even harmonics, and as described in [5] is an "ideal node" for injecting second harmonic from one oscillator to the other. The natural mode of operation in the two coupled oscillators is in such a way that the second harmonics in one has 180^o phase difference with that of the other one, which this is equivalent to 90^o phase difference between the output signals of the two oscillators.

The second harmonics present at common mode nodes had been utilized in [6,7] as well, in which integrated transformer networks were used to couple the common source of the cross-connected pairs of one oscillator to that of the other oscillator. Compared to the circuit in [5], however, the QVCOs in [6,7] have the disadvantage of using on-chip inductors which occupy large chip area.

In a recently reported QVCO, a single capacitor which is placed between the common mode nodes of each of the cross-connected oscillators has been used as the coupling device [8]. Compared to the QVCO's in [5-7], this circuit has

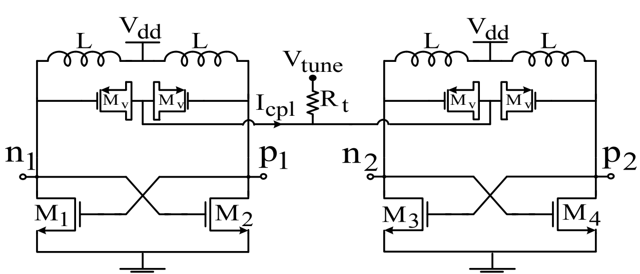


Figure 4. Schematic of the proposed QVCO.

the advantage that the coupling capacitor does not add any noise and extra power consumption to the circuit.

Even a simpler design of the superharmonic-based QVCO is to replace the coupling capacitor in [8] with a direct connection of the two common mode nodes [12]. Although the main focus of the work in [12] was the first harmonic coupling of the two cross-connected LC oscillators, the generation of quadrature signal using a direct connection of the common mode nodes (i.e. the drain of the current source NMOSFETs in the two cross-connected LC oscillators) is briefly mentioned and confirmed with simulation.

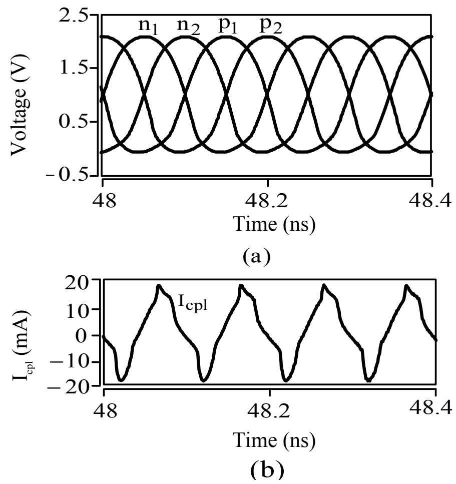
Considering the operation of the QVCOs mentioned above, and the operation of the cross-connected LC VCOs explained in the last section, a QVCO circuit is proposed by directly connecting the nodes **a** (see Figure 1) of two identical cross-connected LC VCOs. Simulations show that quadrature outputs result, with any of the VCOs in Figure 1 as the core VCO, and for both CMOS and the BJT versions.

An implementation of the proposed QVCO is shown in Figure 4. The PMOSFETs M_v (with body connected to V_{dd}) are used as varactors in the LC tank. R_t is used to prevent a virtual ground at node **a**. The simulated output waveforms are shown in Figure 5 (a) and the current flowing through the direct connection of the two LC VCOs are shown in Figure 5 (b). The loss in the LC tank was modeled with resistors in series with inductors with a value of 1 Ω/nH of inductance [13]. Since no extra element is added to the core LC VCOs, no extra power consumption and noise are added to the circuit. The circuit draws a total of 6 mA from the 1 Volt supply and its frequency can be tuned from 4.5 GHz to 5 GHz. The good phase noise performance of this circuit can be seen in Figure 6 where a comparison of the simulated phase noise of the proposed circuit and the simulated phase noise of the QVCO in [5] is shown. Also, a comparison of the simulated phase noise of the core VCO with that of the QVCO (not shown here), indicates no clear effect of the proposed coupling scheme on the phase noise of the circuit.

It should be emphasized that in this circuit there is no need for the NMOSFET current source at the bottom and therefore it was eliminated, whereas in the other QVCOs mentioned before, presence of this current source is essential for providing a common mode node. Therefore, the circuit in Figure 4 is capable of operating at lower voltage supplies [14] compared to the QVCOs mentioned. Simulation shows that circuit can operate with V_{dd} as low as 0.6V.

To investigate the loading effect of the external circuits on the QVCO on its quadrature operation, capacitors as large as 10 pF were placed between the 4 output nodes and the ground. These capacitors attenuate the second harmonics at node **a** in the core VCOs, but it is observed that circuit maintains its quadrature operation.

Another interesting observation is the possibility of generating multiphase signals by extending the proposed coupling scheme to several core VCOs. The cases of 3 and 4 coupled VCOs were tested. While the CMOS version of the circuit did not generate multiphase signals for some particular values of some of the circuit parameter such as varactor dimensions, the BJT version did generate multiphase in a robust manner.



Simulated waveforms of the proposed QVCO. (a) The output voltages, (b) The coupling current flowing from one oscillator to the other. $(W/L)_{M1-4}$=20µm/0.18µm, $(W/L)_{Mv}$=500µm/0.36µm, R_l=1kΩ, L=1nH, V_{dd}=1V.

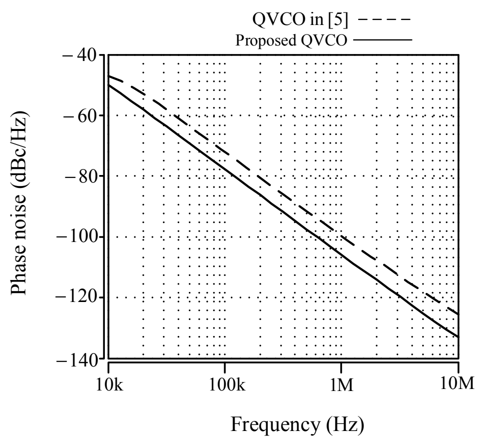


Figure 5. Comparison of the simulated phase noise of the proposed QVCO and the QVCO in [5]. For this simulation, both circuits oscillate at the same frequency of 5 GHz with the same power consumption.

IV. CONCLUSION

A large-signal analysis of the cross-connected LC oscillators was presented first. The oscillator was modeled as the parallel connection of a capacitor, an inductor, a linear resistor (representing loss), and a negative nonlinear resistor. It was assumed that the LC tank has high Q and therefore, the voltage across the nonlinear resistor is sinusoidal. To explain the mechanism of amplitude stabilization, the nonlinear resistor is replaced with its describing function, which is a *linear* negative resistor and its absolute value increases as the oscillation amplitude increases. The model relates the steady-state amplitude to the nonlinear behavior of the transistors in the circuit and does not need to resort to mechanism of clipping of a waveform by the supply voltage [10], which usually is not the case. It is emphasized that the purpose of the model (to the extent presented here) is only to give a physically understandable picture of the operation of the circuit. The key for a quantitative model is the efficient calculation of the describing function with V_{dd} and transistors dimensions as variables. This will be done in another work.

Based on the insight gained from this analysis, a new coupling scheme for the quadrature signal generation was proposed. In this QVCO two identical cross-connected LC VCOs are coupled using the second harmonic of their current at the node between the two capacitors in each LC tank. The two oscillators are connected directly, and therefore no extra power consumption and noise sources are added to the core circuit, which results in a good phase noise performance. Since there is only one transistor between the V_{dd} and ground, the circuit can be used for low voltage applications. The same coupling scheme can be extended for generation of the multiphase signals as well.

To our knowledge the proposed method allows the lowest supply voltage for the superharmonic coupling of two cross-connected LC oscillators for quadrature and multiphase signal generation.

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