Quadrature Generation Techniques in CMOS Relaxation Oscillators

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***Abstract*—Shunt and series-coupling techniques for quadrature generation are applied to CMOS relaxation oscillators. The 2.4GHz quadrature oscillators are designed and simulated in a UMC 0.18µm CMOS process. The shunt-coupled oscillator consumes a current of 12mA from a supply of 1.8V and achieves a phase noise of -99.4dBc/Hz @ 1MHz offset. The series-coupled oscillator consumes a current of 16mA from the 1.8V supply and achieves a phase noise of -98.3dBc/Hz @ 1MHz offset. For a systematic mismatch of 1%, the quadrature phase error of the shunt-coupled and series-coupled circuits are 0.55° and 0.1° respectively.**

I. Introduction

CMOS quadrature oscillators are now widely used in transceivers for wireless and wired communications. Specifically, quadrature LO signals are used in wireless systems for image-rejection or in down-conversion and recovery of the I & Q components of the received signal [1], [2]. This obviates the need for bulky and lossy external filters, as well as the extra power consumption required for driving 50Ω impedances.

The commonly employed techniques for quadrature generation in IC implementations are:

1) A differential VCO followed by an RC-CR polyphase filter: Buffers are required to drive the low impedances found at the input of the filter. Quadrature phase error is limited by R and C matching. At higher frequencies, capacitive parasitics become comparable to the filter capacitance, affecting basic operation and matching.

2) A differential VCO running at twice the desired operating frequency followed by a divide-by-2 circuit: Design of relaxation oscillators is more challenging at higher frequencies, but increase in inductor Q could potentially save power in LC-VCO's. The power consumed in the frequency divider becomes significant.

3) Four-stage ring oscillators: Each stage contributes 90° phase shift in the ring. Taps at diametrically opposite points produce quadrature outputs.

4) Quadrature VCO's: These are potentially more power efficient at high frequencies. Several techniques have been proposed to lock two identical LC-VCO's in quadrature [1], [3], [4]. However, only a few topologies of quadrature relaxation oscillators (QRXO's) are found in the literature [5], [6].

It has been noted previously that when two LC oscillators are coupled, their phase noise could increase. This is because, for the typical LC-VCO topologies, noise is injected at the zero crossings, when the oscillators are most sensitive. This is however, not the case with QRXO's, where the phase noise actually improves through coupling [7]. Moreover, device and component mismatches affect quadrature phase error to a lesser extent in relaxation oscillators compared with LC-VCO's. Finally, relaxation oscillators have the additional advantage of larger tuning range compared with LC-VCO's, which is useful in the context of multi-band transceivers.

In this work, we present two alternative methods to realise CMOS QRXO's using shunt-coupling and series-coupling between two identical oscillators. These are inspired by similar techniques used to couple LC-VCO's in quadrature. The QRXO's are designed in a UMC 0.18µm CMOS process with a power supply of 1.8V. The nominal frequency of operation of the oscillators is 2.4GHz.

Section II describes the quadrature coupling techniques investigated in this paper. Section III discusses the design aspects of the circuit topologies, and presents detailed simulation results for each. The paper is summarized and concluded in section IV.

II. Quadrature Relaxation Oscillators

A relaxation oscillator is constructed by simply cascading an integrator with a Schmitt-trigger in a feedback loop, with the Schmitt-trigger controlling the sign of the integration constant. This yields a triangular waveform at the output of the integrator and a square waveform at the Schmitt-trigger output. The CMOS relaxation oscillator circuit, shown in Fig. 1(a), implements the Schmitt-trigger using a cross-coupled NMOS pair with resistive loads, with a capacitor between the sources of the transistors acting as the integrator. Owing to the simplicity of the circuit and lack of PMOS transistors which have larger parasitics, it is suitable for operation at RF frequencies.

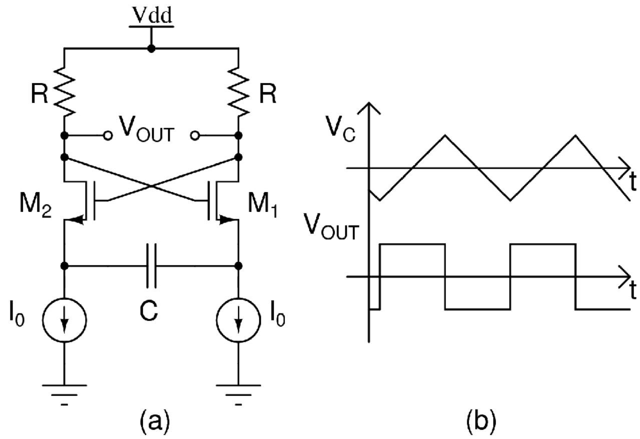

Figure 1. (a) CMOS Relaxation Oscillator (b) Typical Waveforms

It has previously been shown that cross-connection of two relaxation oscillators through a pair of soft-limiters connected to the respective integrator outputs results in quadrature oscillations [7]. This is due to the fact that the output of each integrator is 90° out-of-phase with that of the respective oscillator, as shown in Fig. 1(b) above. Thus, each limiter triggers the other oscillator in such a way that the resulting pair of signals are in quadrature.

It is also possible to lock two relaxation oscillators in quadrature by designing the coupling to inhibit the basic Schmitt-trigger functionality when the two sets of signals are in-phase or out-of-phase. This effectively breaks the oscillator feedback loops in these two states. Therefore, when the two oscillators start up at different (random) phases, their in-phase (0°) or out-of-phase (180°) oscillation components soon die out naturally, leaving behind only the quadrature component. Two such coupling techniques are described in this work.

A. Shunt-coupling

The shunt-coupled QRXO topology is shown in Fig. 2. This technique is quite popular with LC-oscillators [3], but has now been applied to relaxation oscillators in this work. To analyse circuit operation, we will assume that the coupling transistors are the same size as the Schmitt-trigger devices. Suppose the two oscillations are perfectly in-phase with each other. The Schmitt-trigger relies on the positive feedback from V_I^- and V_I^+ to the gates of M_1 and M_2, respectively. This is however impeded by the coupling through M_5 and M_6 (note the signal phases at the gates of pairs of transistors M_1 and M_5 and M_2 and M_6). M_5 and M_6 act as diode-connected transistors in this state. Thus, the coupling path from $QRXO_Q$ to $QRXO_I$ through M_5 and M_6 acts to obstruct the proper operation of the Schmitt-trigger made up of M_1 and M_2. $QRXO_I$ ceases to oscillate, and its output nodes are pulled up to V_{DD}. Coupling transistors M_7 and M_8 are now strongly turned on and they 'steal' current from the Schmitt-trigger of $QRXO_Q$, and $QRXO_Q$ too shuts down. When the two oscillations are out-of-phase with each other, the same process applies in reverse, and $QRXO_Q$ and $QRXO_I$ cease to oscillate, in that order. Thus, the oscillations in the system stabilise to a state where the two outputs synchronise exactly in quadrature.

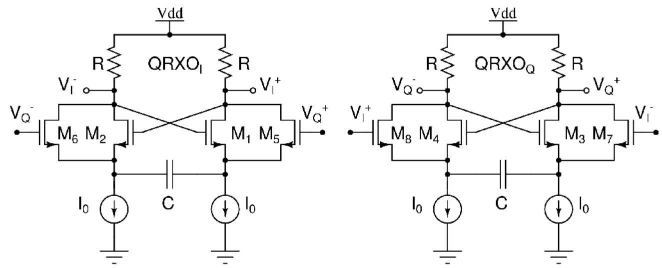

Figure 2. Shunt-coupled CMOS Relaxation Oscillator

B. Series-coupling

The series-coupled QRXO topology is illustrated in Fig. 3, where the quadrature coupling mechanism is similar to that of the LC-VCO in [4]. The voltage waveforms across the capacitors of the two oscillators are in quadrature with the respective outputs. The analysis proceeds in a similar manner as with the shunt-coupling case. Suppose the two oscillations are perfectly in-phase or out-of-phase with each other. Consider the gate-source voltages of the coupling devices $M_{5\text{-}8}$. Each of these transistors is turned on during only part of the oscillation cycle, because their gate and source voltage waveforms are in quadrature. The operation of Schmitt-triggers $M_{1\text{-}2}$ and $M_{3\text{-}4}$ is thus inhibited in this state. Thus, the oscillations in the system stabilise to a state where the two oscillator outputs are in quadrature.

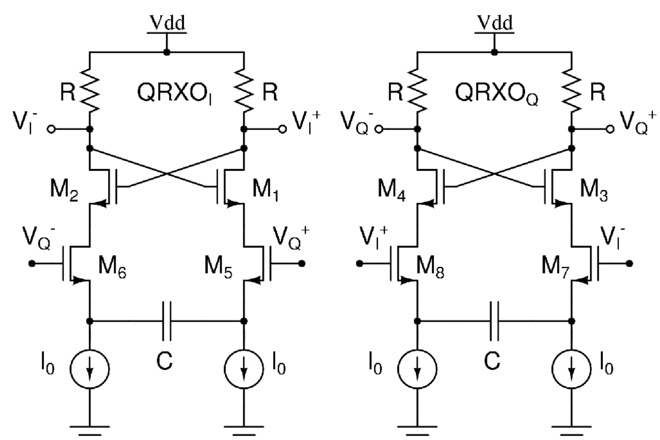

Figure 3. Series-coupled CMOS Relaxation Oscillator

In the above circuit, since the nominal bias points of V_I^+, V_I^-, V_Q^+ and V_Q^- are the same, coupling devices $M_{5\text{-}8}$ operate in the triode region. To allow reliable oscillations with good quadrature coupling, the sizes of $M_{5\text{-}8}$ need to be significantly larger than those of $M_{1\text{-}4}$. However, large coupling devices also add substantial parasitic capacitance across the primary capacitor C, altering circuit operation.

III. Circuit Design and Simulation Results

This section covers the design aspects and simulation results with respect to each quadrature oscillator described previously. The shunt-coupled and series-coupled oscillators are designed and simulated in Spectre, in a UMC 0.18µm CMOS process. All circuits operate from a power supply of 1.8V.

The basic differential relaxation oscillator is designed for single-ended bias current I_0 = 3mA, with Schmitt-trigger devices $M_{1\text{-}4}$ = 100µm X 0.25µm. A prior implementation reported in the literature [7] uses a current of $(0.67)\cdot I_0$ = 2mA in the quadrature cross-coupling path. However, both techniques reported in this work avoid the need for explicit current biasing of the coupling path, which could potentially save up to 25% of the total current. The load resistance R and integrator capacitance C are set to 100Ω and 460fF respectively.

A. *Shunt-coupled QRXO*

In this architecture, basic circuit operation is minimally impacted by adding quadrature coupling, as long as the coupling devices are kept relatively small. The sizes of $M_{1\text{-}4}$ and single-ended bias current I_0 are set to be the same as those in the basic differential oscillator. Therefore, the primary design parameter of interest in the quadrature version is the size of the coupling devices $M_{5\text{-}8}$. Very large coupling devices alter the oscillation frequency, while very small devices exhibit weak quadrature coupling as well as higher flicker noise (i.e. worse phase noise). In the present design, the optimum size of $M_{5\text{-}8}$ was set to 36µm X 0.65µm. The simulated differential waveforms at the output of the quadrature oscillator are shown in Fig. 4. The frequency of oscillation is 2.37GHz. The oscillator circuit consumes a total current of 12mA.

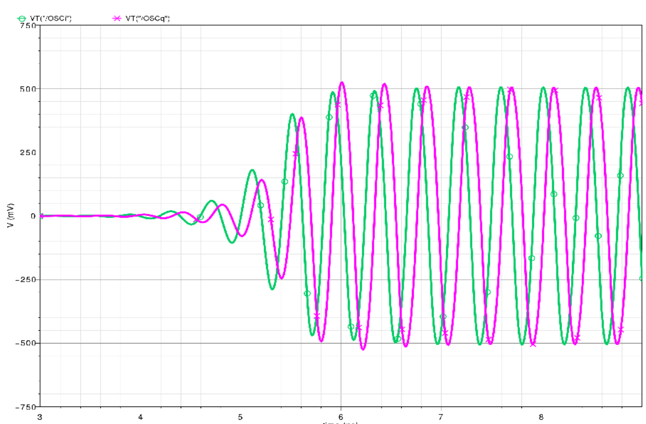

Figure 4. Differential Quadrature Output Waveforms of the Shunt-coupled Oscillator

A systematic 1% mismatch applied between the primary active devices in the I and Q sections of the oscillator produces a quadrature phase error of approximately 0.55°, which is comparable with that for previously implemented topologies.

The phase noise of the quadrature oscillator is plotted in Fig. 5. The spot phase noise at a 1MHz offset from the centre frequency is -99.4dBc/Hz @ 1MHz offset. The primary contributors to spot noise at the above offset are resistor thermal noise (24%), coupling device flicker noise (21%) and Schmitt-trigger device drain thermal noise (18%).

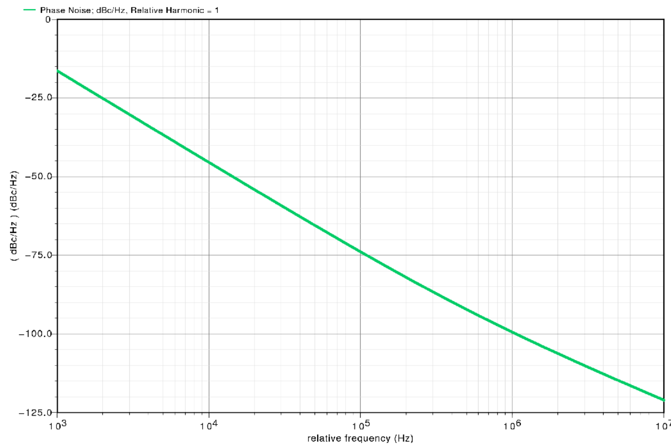

Figure 5. Phase Noise of the Shunt-coupled Quadrature Oscillator

It is well-known that the strength of coupling of quadrature oscillators is inversely proportional to the quadrature phase error, i.e., as the oscillators are coupled more tightly, the quadrature error decreases and vice versa. Figure 6 illustrates this by plotting the quadrature phase error against the size of the coupling devices for the shunt-coupled topology with a systematic 1% mismatch between I and Q sections. The phase error reduces with increase in coupling device width until a particular point and then flattens out, indicating fairly strong coupling beyond that. The corresponding change in oscillation frequency is also plotted in Fig. 6.

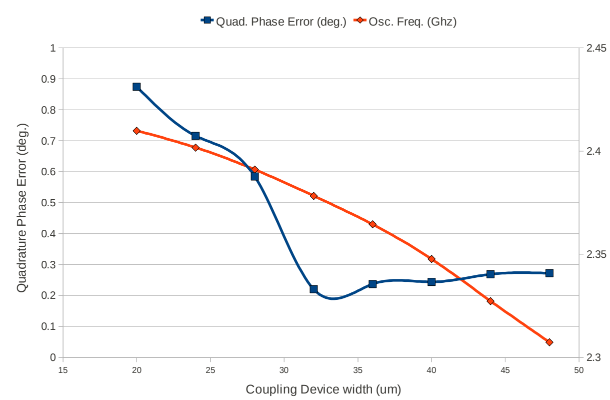

Figure 6. Frequency and Quadrature Error versus coupling strength for Shunt-coupling

B. *Series-coupled QRXO*

In the series-coupled QRXO topology, basic operation of the oscillator circuit is altered by quadrature coupling, because degeneration of transistors $M_{1\text{-}4}$ with the coupling devices $M_{5\text{-}8}$ degrades Schmitt-trigger performance. To ensure reliable startup, the single-ended bias current I_0 is increased to 4mA, while the sizes of $M_{1\text{-}4}$ are kept the same at 100µm X 0.25µm. $M_{5\text{-}8}$ are required to be much larger than those in the shunt-coupled case, but their flicker noise does not directly add to the output. The optimum device size of $M_{5\text{-}8}$ = 200µm X 0.18µm. The simulated differential waveforms at the output of the quadrature oscillator are shown in Fig. 7. The frequency of oscillation is 2.37GHz, and the oscillator circuit consumes a total current of 16mA.

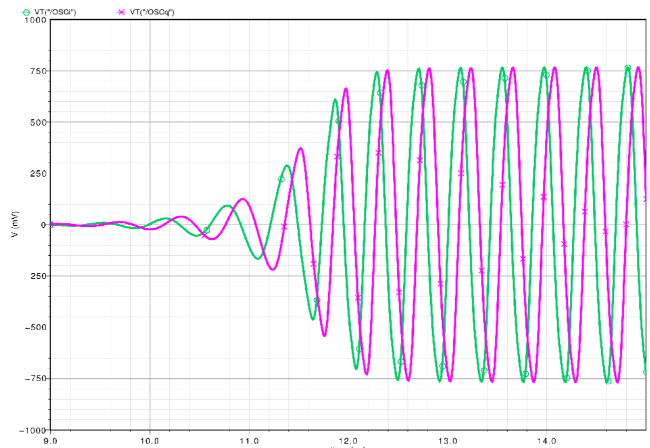

Figure 7. Differential Quadrature Output Waveforms of the Series-coupled Oscillator

The phase noise of $QRXO_2$ is plotted in Fig. 8. The spot phase noise at a 1MHz offset from the centre frequency is -98.3dBc/Hz. The Schmitt-trigger devices $M_{1\text{-}4}$ are the primary contributors to phase noise at a 1MHz frequency offset in the form of flicker noise (70%). The design trade-offs to improve phase noise are much more stringent in this case: increase in device width impacts oscillation frequency while increase in device length reduces loop gain as well, and impairs startup. However, one positive effect of having large $M_{5\text{-}8}$ devices is very tight coupling between the I and Q sections of the oscillator. The quadrature phase error for a 1% systematic mismatch in primary active devices is 0.1°, which is much less than that of the shunt-coupled topology. Fig. 9 depicts the variation in phase error with quadrature coupling strength.

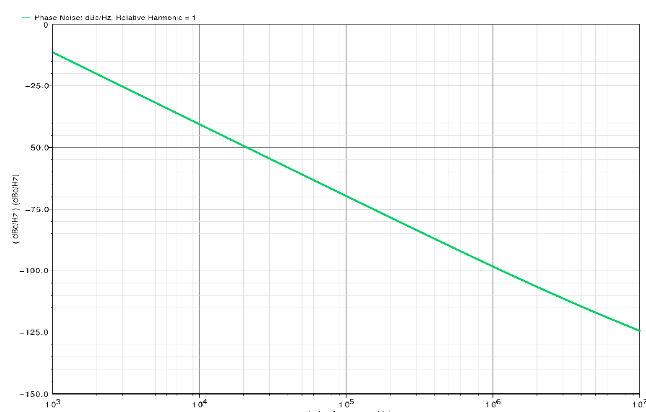

Figure 8. Phase Noise of the Series-coupled Quadrature Oscillator

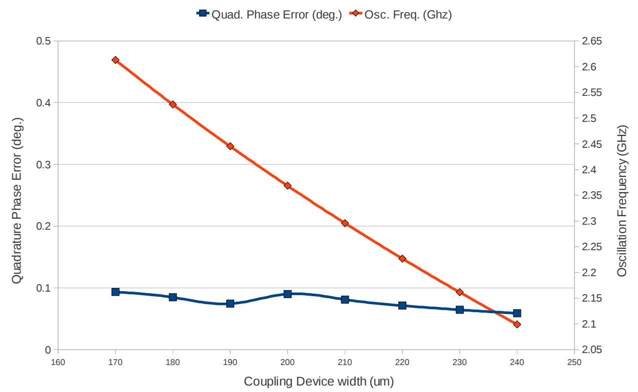

Figure 9. Frequency and Quadrature Error versus coupling strength for Series-coupling

IV. Conclusions

Two quadrature relaxation oscillator circuit topologies have been investigated based on shunt-coupling and series-coupling between two identical oscillators. Both circuits were designed in a UMC 0.18µm CMOS process for an oscillation frequency of 2.4GHz. The shunt-coupled and series-coupled oscillators consume currents of 12mA and 16mA respectively, from a 1.8V power supply. The shunt-coupled technique allows significant current savings by avoiding the need for biasing of the quadrature cross-coupling path, while the series-coupled technique exhibits low quadrature phase error for a given mismatch.

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