A 5.3 GHz Phase Shift Tuned I/Q LC Oscillator with 1.1 GHz Tuning Range

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Abstract — **In this paper phase shift tuning of a 5.3 GHz quadrature LC oscillator is investigated. By varying the phase shift of the circuits that couple two LC oscillator stages, a 1.1 GHz tuning range is achieved. Dependency of tuning range and phase noise on the quality factor of the LC resonators is explored on the behavioral level. Expressions are given for the tuning range and an effective quality factor, as a function of the resonator quality, its phase shift and its resonance frequency. The oscillator is realized in a mainstream 30 GHzf_T BiCMOS process and dissipates 45 mW (nominal) with 2.7 V supply voltage. The dependency of the tuning range on the resonator quality is measured by varying the quality factor of a varactor incorporated in the LC resonators of the I/Q oscillator. Measured $\mathscr{L}$(2MHz) is -108 dBc/Hz at 5.6 GHz.**

I. INTRODUCTION

LC oscillators especially are used in applications where low power, in combination with a low phase-noise-to-carrier-ratio $\mathscr{L}(f_m)$ are of high importance. Examples of such systems are wireless communication standards like bluetooth and GSM, which typically require a $\mathscr{L}(2\,\text{MHz})$ (for the receiver) of around -116 dBc/Hz and -137 dBc/Hz, respectively, while dissipating only several tens of milliwatts. In contrast to these systems, oscillators for optical transceiver functions, such as data clock recovery (DCR), have less stringent phase noise requirements. For example, for a 10 Gb/s DCR an oscillator with a $\mathscr{L}(2\,\text{MHz})$ of -95 dBc/Hz is sufficient [1]. When low power is of importance (for example to have a higher level of integration in a cheap IC package with a high thermal resistance) use of an quadrature (I/Q) LC oscillator can be advantageous. It allows construction of efficient DCR architectures [1], and has a low power dissipation compared to ring oscillators. The penalty compared to ring oscillators is a larger chip area, since inductor area often dominates the total active chip area.

In this paper the trade-off between tuning range and phase noise (quality factor) in a 5.3 GHz I/Q LC oscillator is investigated. Although phase shifted tuning in I/Q LC oscillators has been utilized [2, 3], a clear qualitative and quantitative investigation into this tuning method was lacking. The analysis in this paper fills this void using behavioral modeling complemented by a realized 5.3 GHz oscillator with 1.1 GHz tuning range. The I/Q oscillator meets the phase noise requirements for (half-rate) DCR circuits for the SONET/SDH 10 Gb/s standard (OC-192/STM-64) [1].

II. LC OSCILLATOR TUNING

Table 1 presents a qualitative comparison of the various tuning methods that can be used to vary the frequency of LC oscillators.

Tuning method	Tuning	Phase noise	Complexity
Varactor	-	+	+
Band-switching	+	+	-
Osc. switching	+	+	-
Active tuning	+	-	+/-
Phase shift tuning	+/-	-/+	+/-

Table 1. A qualitative comparison of LC oscillator tuning methods.

The tuning range of integrated LC oscillators with only varactor-tuning (e.g a PN-type varactor [4] or MOS varactor [4]) is always problematic (when taking process spread into account). On the other hand, the tuning method is simple and its passive nature makes it a low noise method. Especially at high frequencies parasitics make it difficult to achieve more than 20% tuning range. Band-switching, division of the total tuning range into several bands for example by switching capacitors, yields a larger tuning range at the cost of an increased complexity [5]. Because the switched capacitors and the varactor that is used for tuning within a frequency band are passive, the phase noise performance of band-switched LC oscillators can be good. In the case of oscillator switching, the tuning range is also divided into frequency bands, but each band is covered by one oscillator [6]. Two disadvantages of this method are the large chip area (multiple inductors) and the need of a multiplexer-function that selects one of the oscillator outputs. An example of active tuning is the use of impedance converters [7]. Large tuning ranges can be achieved, but the active devices that realize the variable capacitance for this tuning method in general cause unacceptable phase noise performance degradation. The last tuning method in Table 1, phase shift tuning, is less common and is investigated in the next section. We will see that the tuning range can be small or large and depends on the quality factor of the LC resonator and the amount of resonator phase shift. Also, we will see that a large tuning range comes at the cost of a decreased phase noise performance.

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III. Phase Shift Tuning In An I/Q LC Oscillator

The properties of phase shift tuning in LC oscillators will be investigated using the behavioral model of an N-stage LC oscillator that is presented in Fig. 1. This model is valid for $N \geq 2$. However, the presented calculations are also valid for a single-stage LC oscillator model (i.e. the model with a box around it in Fig. 1) with a phase shifter included in the feedback loop.

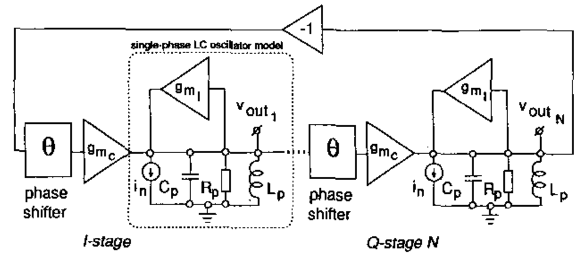

Figure 1. Behavioral model of an N-stage LC oscillator with phase shifters.

The model in Fig. 1 consists of N identical stages. Each stage consists of a phase shifter with phase shift θ, a coupling transconductance g_{mc} and a single-phase LC oscillator. All losses are lumped in the parallel resistor R_p and noise current source i_n models all noise generated in one section. The ratio between the transconductances g_{mc} and g_{ml} determines whether the N oscillator sections are weakly or strongly coupled. If g_{mc}/g_{ml} is too small multiple (undesired) oscillations may occur [8]. For a two-stage (I/Q) LC oscillator weak coupling will result in an increased phase error between the I and Q outputs [9].

The unloaded quality factor of each LC resonator in Fig. 1 can be written as

$$Q_p = R_p\sqrt{\frac{C_p}{L_p}}. \quad (1)$$

In order to get insight into the properties of phase shift tuning in LC oscillators, we need to derive the oscillation frequency of the discussed oscillator model. For the general case of an N-stage LC oscillator, its oscillation frequency, ω_{NLC}, can be expressed as [10]

$$\omega_{NLC} = \frac{-\tan(\pm180^\circ/N-\theta)}{2Q_p}\cdot\omega_{LC} + \frac{\sqrt{4Q_p^2+\tan^2(\pm180^\circ/N-\theta)}}{2Q_p}\cdot\omega_{LC}, \quad (2)$$

with $\omega_{LC} = (\sqrt{L_pC_p})^{-1}$.

Equation 2 points out that the frequency of an N-stage LC oscillator can be varied by changing ω_{LC} (conventional tuning by changing L_p or C_p) or by changing phase shift θ: phase shift tuning.

In Fig. 2, eq. (2) divided by ω_{LC} is plotted for three resonator quality factors and for $N = 2$. For $N = 2$ the resonator phase shift is zero when is $\theta = -90^\circ$ and at this point ω_{NLC}/ω_{LC} is unity and independent of Q_p. The resonator phase characteristic versus frequency has a moderate slope for low Q_p. This results in a significant normalized tuning range when θ is varied, as can be seen in Fig. 2. Because the slope of the resonator phase characteristic versus frequency is steep for high quality factors (e.g. $Q_p = 10$), the variation of ω_{NLC}/ω_{LC} versus θ will be small in this case.

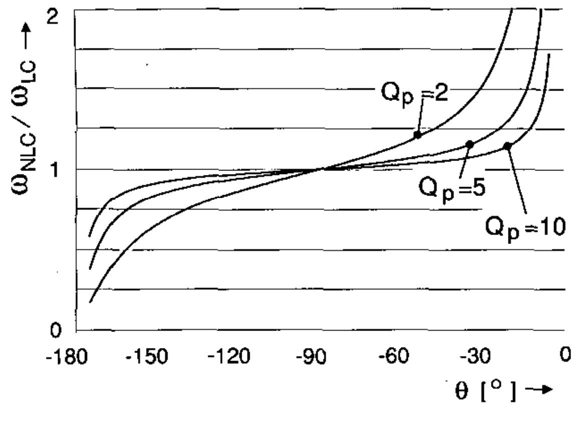

Figure 2. Normalized frequency ω_{NLC}/ω_{LC} of an I/Q LC oscillator versus phase-shift θ, for Q_p is 2, 5 and 10.

$\mathcal{L}(f_m)$ is in practice inversely proportional to Q_p^3 or to Q_p^2, depending whether the resonator noise is dominant or the active device noise is dominant, respectively [10]. For the N-stage LC oscillator model from Fig. 1 an effective quality factor can be derived [11]

$$Q_{NLC} \approx N\,Q_p\cos(\pm180^\circ/N-\theta). \quad (3)$$

Obviously, a lower Q_p will yield a lower $\mathcal{L}(f_m)$ because Q_{NLC} will be lower. In addition, (3) points out that phase shift tuning for large θ also results in a severe phase noise penalty. For example, for $\theta = 60^\circ$ Q_{NLC} is only half of its maximum value of NQ_p. In summary, (2) and (3) make clear that phase shift tuning can be large for relatively low quality factors and that for any quality factor a large variation of θ significantly reduces the achievable $\mathcal{L}(f_m)$. However, small frequency variations are almost without phase noise penalty (the cosine in (3) is close to unity), which makes phase shift tuning a viable option for a fine tune method for an LC oscillator.

IV. I/Q Oscillator Design

In order to demonstrate the influence of Q_p on the tuning range that can be obtained with phase shift tuning and verify the tuning behavior predicted by (2), a 5.3 GHz I/Q LC oscillator has been realized with phase shifters. The circuit diagram of one of the two LC oscillator stages with phase shifters (the implementation of a stage from Fig. 1) is shown in Fig. 3. The circuit is based on the design presented in [11] (the resonator layout is reused to save design time). Phase shift θ is implemented by the parasitic phase shift of the coupling transistors (with tail current I_{couple}) and the emitter followers (with bias current I_{buf}). The cross-coupled pair implements a negative resistance and is used to set (with tail current I_{level}) the voltage swing across the resonator.

The tuning behavior predicted by (2) as a function of θ can only be verified for different Q_p values if we have integrated a method to vary the resonator quality factor. Variation of Q_p is taken care of by the varactors shown in Fig. 3. The varactors are very small and this results in only a minor frequency change when the reverse voltage across the varactors is changed from 0 V to 2.7 V (i.e around 4.3% relative tuning range [11]). However, this variation in tuning voltage V_{tune} results in a significant variation of the total resonator quality factor around 5 GHz: see Table 2. The series

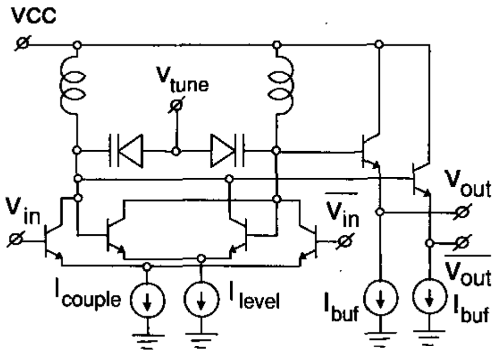

Figure 3. Circuit diagram a stage of the I/Q LC oscillator.

V_{tune} [V]	Q_p at 5 GHz
0	8
1.35	6.5
2.7	3

Table 2. Simulated unloaded resonator quality factor.

resistance of the (PN-type) varactor is the highest for zero reverse bias voltage (V_{tune} is 2.7 V). When the reverse voltage across the varactor is increased, its depletion region reduces and hence its series resistance. For example for $V_{tune} = 0$ V (maximum varactor reverse voltage) the simulated quality factor is 8 at 5 GHz. Table 2 shows that we can change the resonator quality factor between 3 and 8, and hence we can change the tuning range (see (2)), when we realize the 5.3 GHz I/Q LC oscillator.

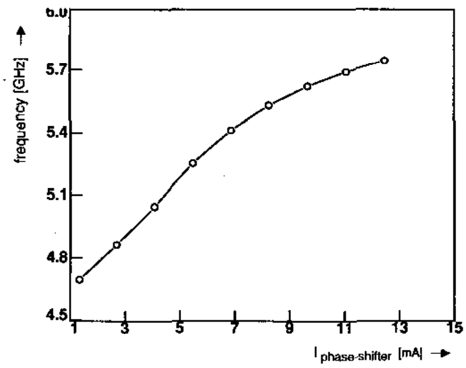

Figure 4. Simulated frequency versus $I_{phase-shifter}$ for V_{tune} is 2.7 V ($Q_p \approx 3$).

In Fig. 4 the simulated oscillation frequency versus $I_{phase-shifter}$ ($= I_{couple} + I_{buf}$; these currents are varied simultaneously) for V_{tune} is 2.7 V is plotted. For this tuning voltage the frequency variation is the largest (Q_p is the lowest). Increase of $I_{phase-shifter}$ lowers θ because the bandwidth of the transistors initially becomes higher when $I_{phase-shifter}$ is increased. When $I_{phase-shifter}$ reaches the peak-f_T current value of the coupling and buffer transistors, the phase shift is no longer a function of $I_{phase-shifter}$. The result is that the tuning characteristic saturates for $I_{phase-shifter}$ beyond 9 mA (see Fig. 4).

Simulated $\mathscr{L}$(2MHz) (with SpectreRF) varies between -104 dBc/Hz and -112 dBc/Hz across the tuning range for V_{tune} is 2.7 V.

V. Experimental Results

Fig. 5 shows the micro-graph of the realized 5.3 GHz I/Q ring oscillator. The active chip area is 1450μm times 2280μm. The power dissipation of the VCO core is 45 mW with a 2.7 V supply voltage.

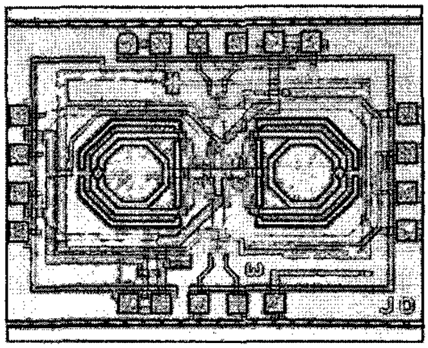

Figure 5. Micro-graph of the I/Q LC oscillator.

The measured tuning characteristic versus $I_{phase-shifter}$ for 10 values of V_{tune} (and thus for Q_p varying between 8 and 3) is shown in Fig. V. The tuning characteristic is similar to the shape predicted in Fig. 2, for low $I_{phase-shifter}$ currents. As mentioned, for high $I_{phase-shifter}$ the transistor phase shift is no longer a function of its biasing current and the tuning characteristics saturate.

In Fig. 7 the power spectrum of the I/Q LC oscillator is shown at 5.6 GHz. At this frequency the measured $\mathscr{L}$(2MHz) is better than -108 dBc/Hz.

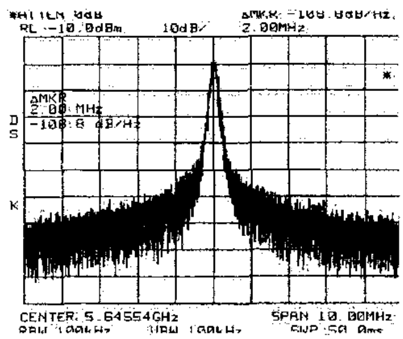

Figure 7. Power spectrum of the I/Q LC oscillator at 5.6 GHz.

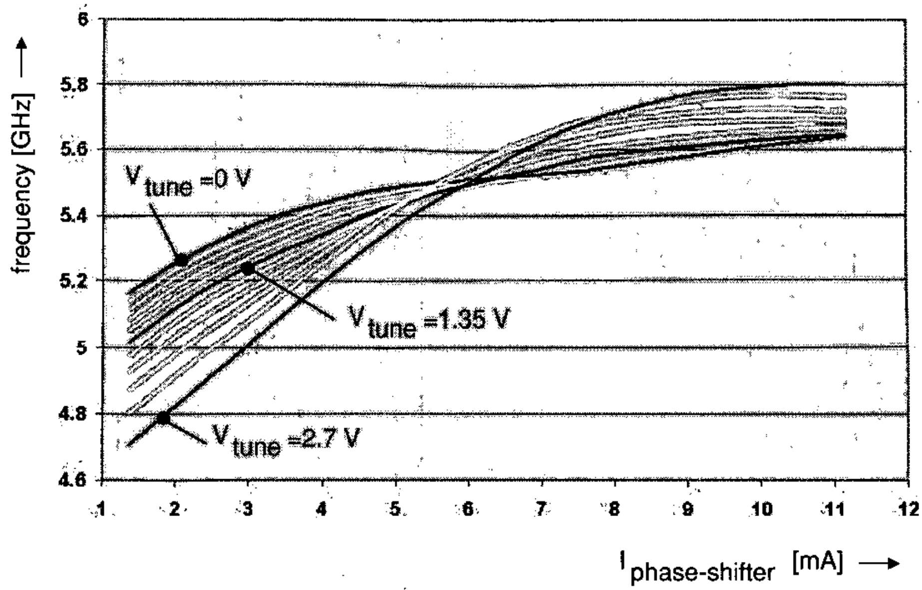

Figure 6. Measured oscillation frequency versus $I_{phase-shifter}$ for 10 values of V_{tune} between 0 V and 2.7 V.

VI. Conclusions

LC oscillators can be tuned by varying the LC resonator phase shift, for example by means of phase shifters in the oscillator feedback loop. Phase shift tuning and its effect on the phase noise in multi-phase LC oscillators have been studied qualitatively and quantitatively. For low LC resonator quality factors Q_p (e.g. 3-5), phase shift tuning be used to achieve a large tuning range without the use of varactors. This has been demonstrated with a realized 5.3 GHz I/Q LC oscillator achieving 1.1 GHz tuning range. This oscillator has been realized in a 30 GHz f_T mainstream BiCMOS technology. Measured $\mathcal{L}(2\text{MHz})$ is better than -108 dBc/Hz at 5.6 GHz. Nominal power dissipation of the I/Q VCO core is 45 mW. Because the effective quality factor of an multi-phase N-stage LC oscillator can be written as NQ_p times the cosine of the resonator phase shift, there is a clear trade-off between achievable $\mathcal{L}(f_m)$ and tuning range for phase shift tuned LC oscillators.

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