THE DESIGN OF 2.4-GHZ CMOS LC-TANK OSCILLATORS

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ABSTRACT

This paper presents the design of two 2.4-GHz oscillators, targeting a 0.18µm CMOS process from XFAB. Based on the devices available at the technology of choice, we compare the performance of two basic oscillator topologies: the Colpitts Oscillator and the cross-coupled oscillator, and present the results obtained with those topologies. It is shown that while the Colpitts oscillator presents the better phase-noise performance (-101dBc/Hz @100kHz) and smaller die area, its start-up condition requires a supply current of at least 3mA (compared to 75µA for the cross-coupled topology). We thus considered to implement both solutions as a mean to have a low-area or a low-power solution.

1. INTRODUCTION

Oscillators are found in all modern communication systems and instrumentation applications, to provide signal sources for frequency conversion and carrier generation.

They can be classified into two groups: the relaxation oscillators, which generally present poor phase-noise performance and are thus rarely used in high-performance transceivers; and harmonic oscillators, capable of producing a near-sinusoidal signal with good phase-noise and high spectral purity. This type of oscillator is usually built around an LC resonant tank.

In this paper we make a comparison between two topologies of harmonic oscillators: the Colpitts Oscillator and the Cross-Coupled Oscillator, both implemented in a 0.18µm CMOS process from XFAB. For comparing the different architectures, we observed the start-up conditions, power consumption and phase-noise levels.

2. BASICS CONCEPTS OF OSCILLATORS

Basically, an oscillator generates a periodic signal, converting DC power to a sinusoidal steady-state signal. This system can generate a periodic signal with a specified or controllable frequency.

Oscillators can be viewed as feedback circuits. The basic structure of a sinusoidal oscillator consists of an amplifier and a selective frequency network connected in a positive feedback loop. Fig. 1 shows the block diagram of the system with positive feedback.

The equation that transcribes the voltage transfer function in Fig.1 can be written as

$$H(j\omega)=A(j\omega)/[1-A(j\omega)Z(j\omega)] \quad (1)$$

where $A(j\omega)Z(j\omega)$ is the open-loop gain of the system [1]. When the denominator becomes zero at a particular frequency, it will be possible to achieve a non-zero output voltage for a zero input voltage, this is an oscillator. In addition, we must guarantee that the phase of the open-loop gain be equal to zero or multiple of 360º. These conditions are known as the Barkhausen criterion, and for oscillations to startup, we must guarantee $|A(j\omega)Z(j\omega)| > 1$.

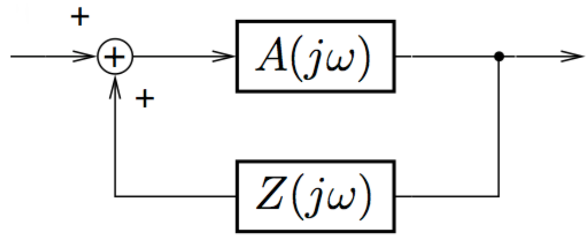

Fig. 1. Block diagram of a positive feedback system.

One of the main performance characteristics of an oscillator is its phase-noise level, which manifests itself as random fluctuations in the zero crossings of the signal. As depicted in Fig. 2, an ideal oscillator would present only a single spectral component. However, due to noise intrinsic to its components or fluctuations in power supply, the actual oscillator presents power distributed over a range around the central (carrier) frequency.

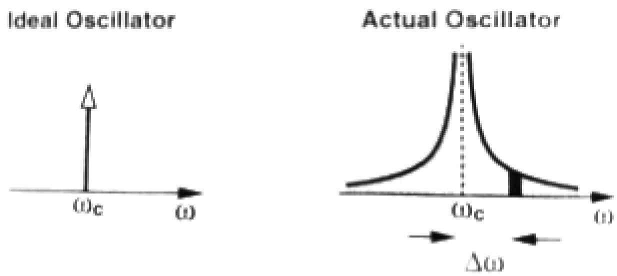

Fig. 2. Spectrum of ideal and actual oscillators [2].

To quantify phase noise, it is necessary to consider a unit bandwidth at an offset Δ_ω with respect to ω_0, calculate the noise power in this bandwidth, and divide the result by the oscillation frequency power, as shown in the equation bellow:

$$L\{\Delta\omega\}=10*\log[P_{sideband}(\omega_0 + \Delta\omega, 1Hz)/P_{carrier}] \quad (2)$$

where L{Δω} is the phase noise measured at Δω from carrier, ω0 is the carrier, $P_{sideband}(\omega_0 + \Delta\omega, 1Hz)$ is the sideband power calculated in a bandwidth of 1Hz at Δω offset from carrier and $P_{carrier}$ is the power of the carrier.

3. OSCILLATOR TOPOLOGIES

We considered two oscillator topologies: the Colpitts and the Cross-coupled. The basic idea behind these oscillators is to combine a resonator with an active device. Just a resonator will not oscillate because the circuit has inherent losses. Even if an electric pulse was applied, the circuit would not sustain oscillations because the energy stored would be gradually dissipated in the equivalent parallel resistor (R_P, see Figs. 3 and 4) representing the losses on the inductor. Therefore, it is essential an active device to replenish the energy lost in every cycle [2],[4].

3.1 The Cross-coupled Oscillator

The Cross-Coupled oscillator (see Fig. 3), is the most common LC-tank oscillator configuration for realization in CMOS technology.

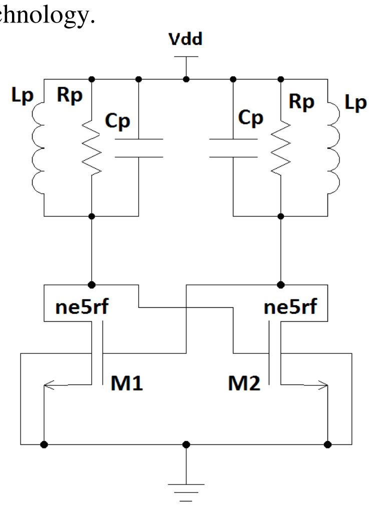

Fig. 3. A Cross-Coupled Oscillator [3].

At resonance, the total phase shift around the loop is equal to zero because each stage contributes to 180º at the resonant frequency. Then, if $g_{m1}R_P g_{m2}R_P \geq 1$, the circuit oscillates (g_m is the small-signal transconductance of the transistors).

3.2 The Colpitts Oscillator

The Colpitts Oscillator uses a combination of an inductance (L) with a pair of capacitors for frequency determination, and a voltage divider made by two capacitors in series, as shown in Fig. 4. The circuit of Fig. 4 has zero phase margins at the resonance frequency, ω_0 of the tank formed by L_P, C_1 and C_2, which is given by:

$$\omega_0 = 1/\sqrt{(LC_{eq})}, \quad C_{eq1} = C_1 || C_2 \qquad (3)$$

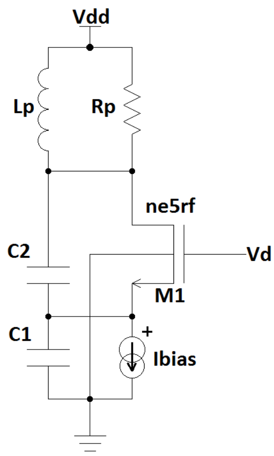

Fig. 4. Colpitts Oscillator.[3]

Further analysis of the Colpitts structure also shows that the condition gm ≥ $4/R_P$ is required to provide a sufficient gain for oscillation, and the minimum is when the ratio of C1 e C2 is equal to 1 [3]. Thus, the Colpitts oscillator will generally require a larger transistor (when compared to a Cross-coupled solution) to guarantee oscillation. This becomes especially critical if the inductor suffers from a low Quality Factor (Q_L).

4. SIMULATION RESULTS

The Cross-Coupled oscillator was implemented using two distinct bias schemes: the circuit in Fig. 3, identified as "Cross A" in Figs. 5 and 6; or by replacing the ground in Fig. 3 by a current source to ensure better stability of the operation pont: this modified circuit is identified as "Cross B" in Figs. 5 and 6. The circuit identified as "Colpitts" in Figs. 5 and 6 is designed as the circuit of the Fig. 4.

The XFAB CMOS process used [5] provides inductors of 2nH and 3.8nH. The choice of the inductor aimed at reducing the die area, since the inductor occupies a large area as compared to other components. For both topologies, the lower value of inductance requires an equivalent capacitance of 2.19pF for a resonant frequency of 2.4GHz. However, taking into account the parasitic effects of each circuit and considering that we must have an output that will be connected to a load of 50 Ohms, the equivalent capacitance value varied for each type of oscillator: 1.69pF for the Cross-coupled, 1.66pF for the Colpitts.

We started by comparing the simulation results of the open-loop gain (small-signal analysis in the frequency domain) with the harmonic balance analysis, a type of analysis in time and frequency domains to obtain highly accurate steady-state solution of a nonlinear circuit. As a matter of fact, the simulation results of the open-loop gain depend on the simulation configuration: it can serve as a first guess for determining the components which define the frequency of oscillation, but may give inconsistent startup conditions. We thus compared the startup conditions obtained from the open-loop gain analysis against those obtained from the harmonic-balance analysis.

Fig. 5 shows a comparison between the open-loop gain as a function of the bias current for the 3 circuits implemented. Ideally, for a gain greater than 0dB, oscillations should start. As can be seen, the Cross-Coupled oscillators showed potential startup at lower values of bias current, as compared to the Colpitts oscillator.

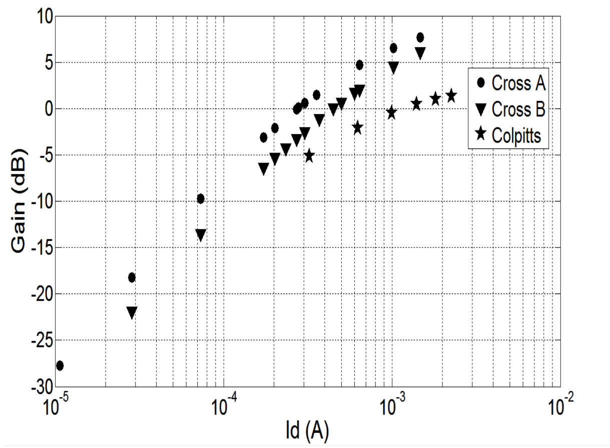

Fig. 5. Gain (dB) X Bias Current (ID)

We then simulated the phase-noise of each circuit, considering an offset of 100KHz from the carrier. The results are shown in Fig. 6.

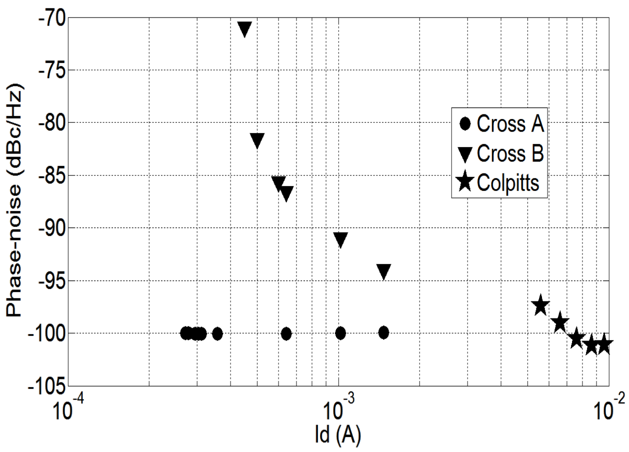

Fig. 6. Phase-noise (dBc/Hz) versus Bias Current (ID)

5. DISCUSSION

The Colpitts and Cross-Coupled oscillators achieved steady-state frequency around 2.4GHz. The first, the Colpitts oscillator, presented oscillation for bias currents of at least 5.1mA. The Cross-Coupled oscillators showed oscillations with much smaller bias currents.

The Cross-Coupled biased with a current source ("Cross B" in Figs. 5 and 6) oscillated for bias currents greater than 450µA, while the circuit in Fig. 3 ("Cross A" in Figs. 5 and 6) oscillated for bias currents greater than 90µA.

During the analysis of phase noise (Fig. 6), it was observed that the Cross-Coupled Oscillator biased with DC voltage ("Cross A") showed a more stable (in terms of bias current) phase noise level, because even with a current variation, between 270µA and 1.5mA, the phase noise remained very close to –100dBc/Hz @100kHz offset. The Cross-Coupled Oscillator biased with a current source ("Cross B") presented a phase noise level which varied greatly, between -81dBc/Hz and -94dBc/Hz for bias currents of 450µA and 1.5mA respectively. Finally, the Colpitts oscillator, with bias currents ranging from 5.1mA to 9.63mA, showed a phase noise level ranging from -97.2dBc/Hz to -101.08dBc/Hz.

6. CONCLUSION

Taking into consideration all simulation results, we decided to proceed on the layout of two oscillators using components of the CMOS XFAB technology of choice.

The first one, the Cross-Coupled Oscillator shown in Fig. 7, is composed of an equivalent capacitance of 1.69pF and an inductor of 2nH. The circuit draws 645µA from a 1V supply and presents a phase noise level of -100dBc/Hz @100kHz offset. The final layout is shown in Fig. 8, designed targeting symmetry properties. The output is coupled to a 50Ω load by a low-value capacitor (100fF), to avoid loosing too much oscillation energy. The circuit occupies an area of 565µm x 845µm.

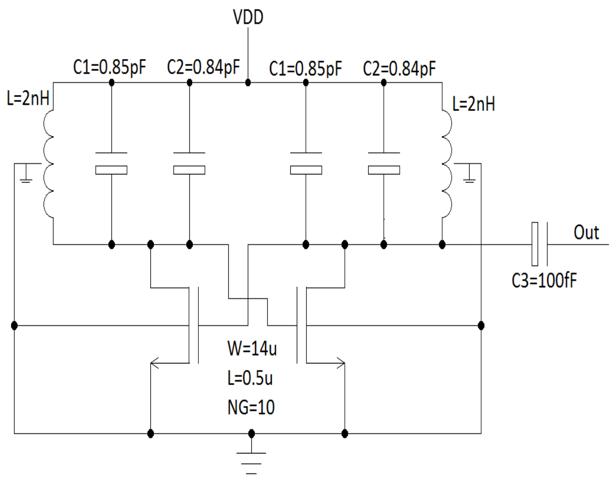

Fig. 7. 2.4GHz Cross-Coupled Oscillator

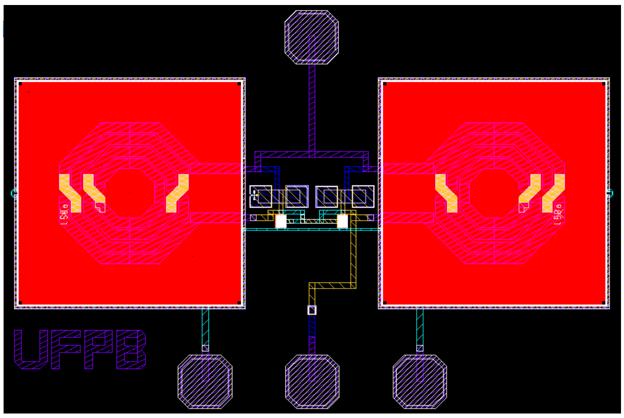

Fig. 8. Layout of the Cross-Coupled Oscillator.

The second circuit is the Colpitts Oscillator shown in Fig. 9, implemented with an equivalent capacitance of 1.66pF and an inductor of 2nH. The circuit draws 9.63mA from a 3V supply and presents a phase-noise level of -101dBc/Hz @100kHz offset. The final layout is shown in Fig. 10. The circuit occupies an area of 590µm x 420µm, which is roughly half of the die area required by the Cross-Coupled solution (the photos are not in scale).

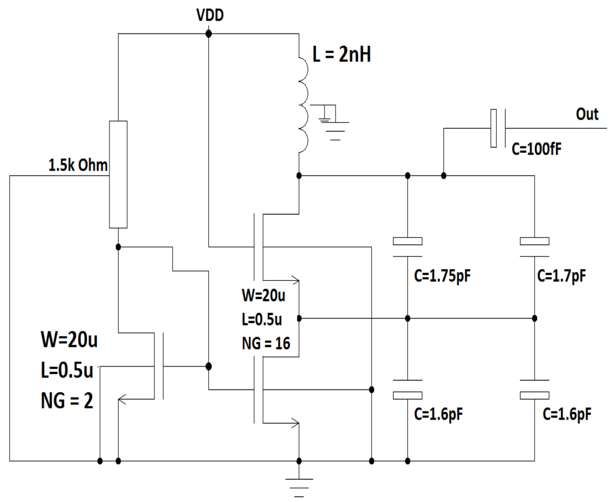

Fig. 9. 2.4GHz Colpitts Oscillator

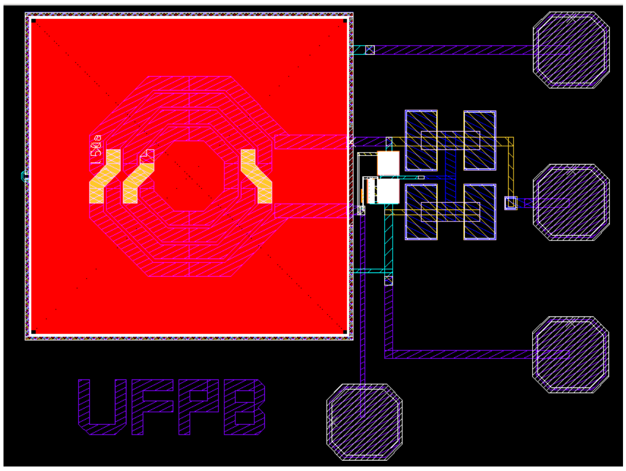

Fig. 10. Layout of the Colpitts Oscillator.

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