Low Phase Noise LC Oscillators

C.Huang, L.C.N de Vreede, A.Akhnoukh and J.N.Burghartz
Laboratory of High-Frequency Technology and Components (HiTeC), DIMES
P.O. Box 5031, 2600 GA Delft, the Netherlands
Phone: +31 (0)15 2785 042 Fax: +31 (0)15 2623 271
E-mail: c.huang@ewi.tudelft.nl

Abstract—**In this paper, the main contributions of phase noise in LC oscillators are identified based on the use of a nonlinear phase noise model. Several methods are applied to improve phase noise by reducing these noise contributors. As experimental verification, two 1.2GHz oscillators have been implemented in the TU Delft DIMES04 HRS (High Resistivity Silicon) technology, which achieve -122.17dBc/Hz at 1MHz offset, taking 3.5mA from a 3-V supply.**

Keywords—**Oscillators; phase noise**

I. INTRODUCTION

As both wireless and optical communications systems move towards high-data-rate applications, low-phase-noise high-frequency oscillators are important circuit blocks. In wired and wireless communication terminals, the receiver front-end selects, amplifies and converts the desired high-frequency signal to baseband. Inversely, the transmitter front-end converts an analog baseband signal to a suitable high-frequency signal that can be transmitted over the wired or wireless channel. In these RF transceivers, the bit error rate (BER) characteristic is dependent on a phase noise of the VCO. Although relaxation and ring oscillators are attractive from the standpoint of circuit integration, LC oscillators are still the only reliable way to meet such noise performances [1]. In recent years, a millimeter-wave utilization has been studied and developed for short distance radar systems and high-speed data communication systems. In these systems, the ability to detect different targets at the same time is also dependent on the phase noise characteristic of the VCO [2]-[4].

This paper is organized as follows: In section 2, the contributors of phase noise in LC oscillators are summarized based on the use of a nonlinear phase noise model. This model has been verified using envelope simulator of Agilent's ADS (Advanced Design System) as well as Cadence spice simulations. In section 3, several methods are described to improve phase noise and two 1.2GHz LC oscillators are designed to validate the theory. In section 4, the measured results are depicted followed by conclusions.

II. MAIN PHASE NOISE CONTRIBUTOR

In most circuits, the best noise single sideband-to-carrier ratio (SSCR) is achieved when the transconductor is driven well beyond the range of linear operation. For this condition, Samori's nonlinear phase noise model [1] is a suitable tool to identify the main phase noise contributors.

The noise sources of an LC oscillator in shown in Figure 1. According to Samori's nonlinear phase noise theory, the transconductance of a cross-coupled pair of transistors operates as a hard limiter and its Fourier spectrum features infinite terms given by $(-1)^n \delta(\omega - 2n\omega_0) g_{ot} / 2$. Consequently, the noise components, folded within the filter resonator bandwidth, are the ones close to odd harmonic frequencies. While, the noise generated in the tail current source is delivered to the tank via the switching transconductance and therefore only even harmonic components will be folded within the bandwidth of the loop filter. However, the low frequency noise in the tail current source only contributes to the amplitude noise of the oscillator and is therefore of less interest. So, in the tail current source, the noise at 2nd harmonic frequency is the main contributor of phase noise.

The ADS envelope simulator can be applied to distinguish the main contributions of phase noise. Disturbing signal sources with small amplitudes around different band frequencies were inserted into the oscillator respectively and the corresponding FM or PM responses are observed at the output. The simulation results prove the validity of Samori's theory and the main contributors are listed below in decreasing order of importance.

1. The noise of tail current source around second harmonic frequency;
2. In-band collector current noise of the cross coupled transistors;
3. White noise due to base resistance of cross coupled transistors;
4. In-band noise of the tank.

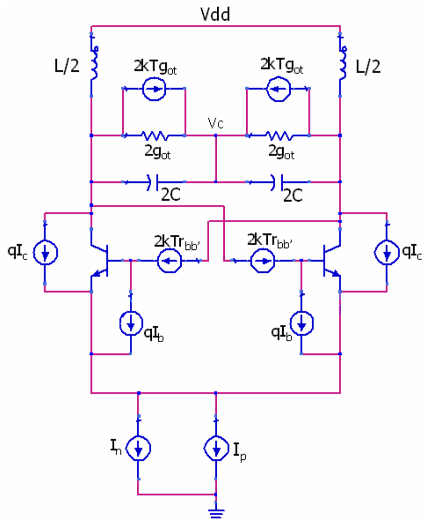

Figure 1. LC oscillator with its noise sources

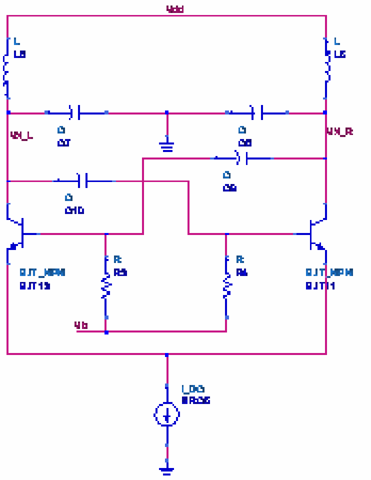

Figure 2. Base and collector uncoupling with capacitor [5]

III. METHODS FOR PHASE NOISE IMPROVEMENT & CIRCUIT DESIGN

A. *Methods for Phase Noise Improvements*

1. A high Q-factor inductor

In LC oscillators, the resonator acts as a bandpass filter to reject undesired noise components. If a higher Q-factor inductor is applied in the tank, a narrower "shirt" around the carrier can be expected, which results in a better phase noise. Since all the noise components are folded around the carrier they will be suppressed by a higher Q-factor resonator, this method is most efficient compared with other phase noise improvement methods. In the meanwhile, a higher Q-factor inductor indicates a smaller in-band noise of the tank, which leads to a lower phase noise.

2. Increase the core current

Normally, phase noise is characterized by the ratio of phase noise power compared to the signal power. In general, larger signal can be achieved by increasing the core current at the cost of larger power consumption. The output voltage swing of LC oscillator is limited by the saturation conditions of the cross-coupled transistors. When this saturation condition is met, a further increase of the core current will have no effect. For this reason, also the saturation condition of the transistor core needs to be optimized. One topology [5] (see Figure 2) was reported for this purpose and increases the output voltage swing of the LC oscillator by uncoupling the steady voltages of collector and base

3. LC Filtering Technique

To reduce the contribution of second harmonic noise in the tail current source to the phase noise of the oscillator, a filtering technique [6] can be applied. As shown in Figure 3, a large capacitor is placed in parallel with the tail current source to short noise frequencies around $2\omega_0$. To raise the impedance, an inductor is inserted between the tail current source and common mode point of the switching transistor pair.

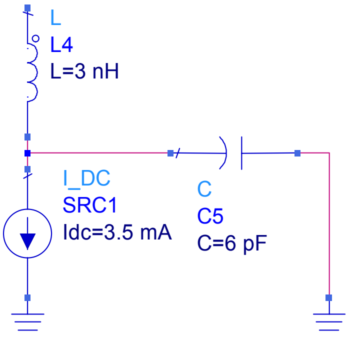

Figure 3. Tail-biased oscillator with noise filter

4. Increasing the area of cross-coupled transistor

The noise due to the base resistance of cross-coupled transistors is converted into phase noise by the spectrum folding mechanism described by Samori's nonlinear phase model. If the area of cross-coupled transistors is increased, the base resistance is reduced, consequently, yielding a smaller voltage noise source and correspondingly a lower phase noise.

B. *Circuit Design*

Based on the guidelines given above, a 1.2GHz LC oscillator has been designed and its schematic is shown in

Figure 4. An emitter follower is applied as the output stage of the oscillator in order to decouple the oscillator core. In this oscillator, the area of the cross-coupled transistors has been optimized for low base resistance while maintaining a high output voltage swing for the given current budget (Ic=3.5mA). In the tail current source, an LC filter is applied and the Q factors of inductors used in the tank and LC filter are optimized using a physics based concentric-ring model [7] of a spiral inductor. The metal thickness of the inductor is 3μm and the simulated Q-factor of the tank inductor is 13.4.

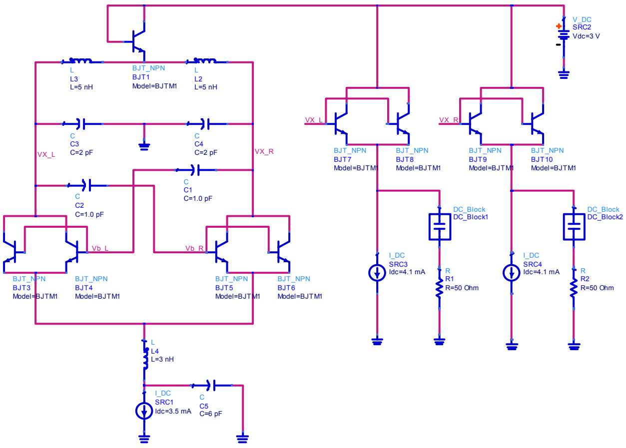

Figure 4. Schematic of LC oscillator

With or without LC filter in the tail	Core Current (mA)	Oscillation Frequency (GHz)	Phase Noise at 1MHz (dBc/Hz)
With	3.5	1.2	-127.9
Without	3.5	1.2	-125

Table 1. ADS Simulation Results

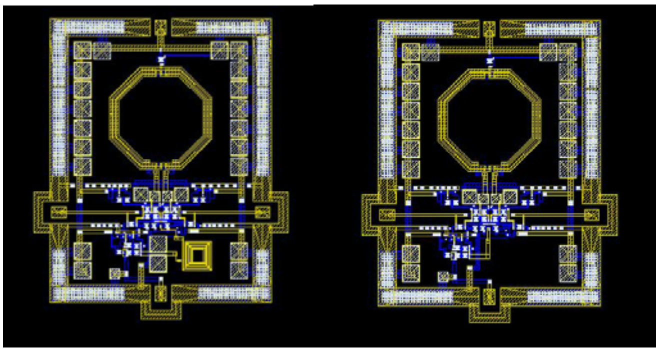

Figure 5. Layouts of the 1.2GHz oscillators (The left one with LC filter in the tail; while the right one without LC filter in the tail)

For comparison and verification of Samori's theory, an identical LC oscillator without LC filter in the tail is also designed and processed. The ADS simulation results are listed in Table 1, which indicates that the LC filtering technique in the tail improves the phase noise by 2.9dBc/Hz at 1MHz offset frequency.

These two 1.2GHz oscillators are implemented in the DIMES 04 HRS (High Resistivity Silicon) technology with a substrate resistivity of 4000 and a fT of 15GHz. The layouts are shown in Figure 5, both with a total area of 1250μm by 1580μm.

IV. EXPERIMENTAL RESULTS

A HP 8565E spectrum analyzer is applied for the phase noise measurement. The test setup is shown in Figure 6. The single-ended measurement results are listed in Table 2, which indicate that the phase noise is indeed improved by 1.3dBc/Hz at 1MHz with the LC filter in the tail and its phase noise plot is shown in Figure 7.

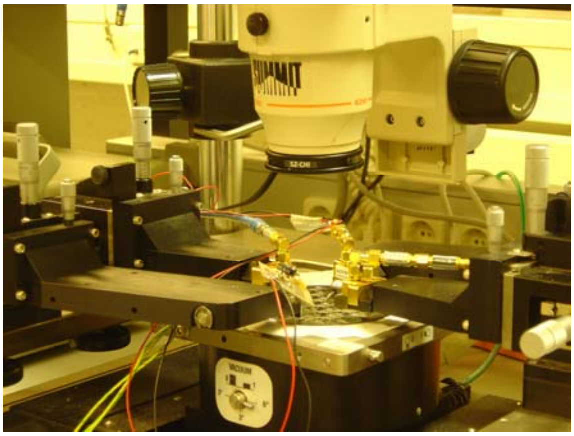

Figure 6. Measurement environment

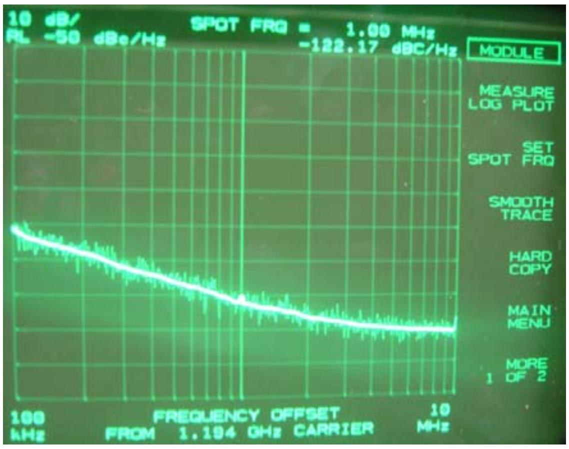

Figure 7. Measured phase noise plot of the 1.2GHz oscillator with LC filter in the tail

With or without LC filter in the tail	Core Current (mA)	Oscillation Frequency (GHz)	Phase Noise at 1MHz (dBc/Hz)
With	3.5	1.2	-122.17
Without	3.5	1.2	-120.87

Table 2. Measurement Results

V. CONCLUSIONS

Based on Samori's nonlinear phase noise model, design techniques which are focused on phase noise reduction have been applied in the design of two BJT based oscillators. The 1.2GHz oscillators are processed within DIMES 04 high resistivity technology (substrate resistivity=4000 $\Omega \cdot cm$; f_T =15GHz). The experiments confirm Samori's phase noise theory. The oscillator with the LC filter in the tail achieves -122.17dBc/Hz at 1MHz offset, taking roughly 3.5mA from a 3-V supply, which is 3.8dBc/Hz away from the phase noise record at 1.2GHz [8] which was achieved in a more advanced transistor technology (f_T=25GHz)

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