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# Integrated GHz Voltage-Controlled Oscillators in a 47GHz SiGe Process

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## Abstract

In this work, two radio frequency (RF) voltage-controlled oscillators (VCOs) are evaluated to determine feasibility for use in a high data rate wireless LAN. Designs are presented for a Colpitts oscillator and a differential L-C oscillator operating at 10GHz. The circuits are to be fabricated in a 3.3V 47GHz  $f_T$  SiGe BiCMOS process, pushing the limits of the technology. Simulated phase noises of -95.0dBc/Hz for the Colpitts VCO implementation and -87.7dBc/Hz for the differential oscillator at offsets of 1MHz from the carrier are observed.

## 1. Introduction

The radio frequency integrated circuit (RFIC) research group at TR Labs is building a high data rate wireless LAN. Accurate modelling of the transistors and spiral inductors at RF frequencies is critical to the project success. The frequency at which a transistor provides unity current gain,  $f_T$ , limits the operating capabilities in integrated circuit design. In fact, designs beyond  $\frac{1}{10}f_T$  are not trivial. In this work two 10GHz L-C voltage-controlled oscillators (VCOs) are designed and simulated to determine their feasibility for use in the high data rate wireless LAN (Fig. 1). The VCOs are contained within the frequency synthesizer block in a transceiver, and two quadrature VCO signals are required.

## 2. Spiral Inductor Modelling

The goal of modelling spiral inductors is to get an accurate broadband model which reflects the actual layout, and which is compatible with all the necessary simulations. One method of obtaining a broadband model for the spiral is to extract s-parameters from the layout using an electromagnetic (EM) simulator. The s-parameter data would

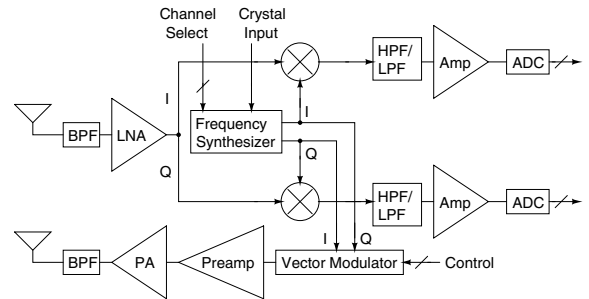


Figure 1. Wireless LAN Remote Terminal

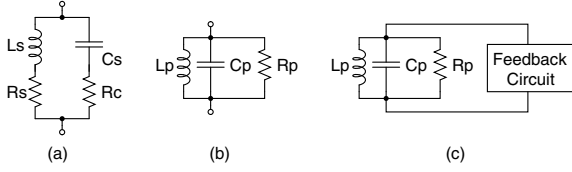
then replace the inductor within a circuit simulator. Another method of obtaining a broadband model is to extract a lumped-element equivalent circuit.

In this project, inductor modelling utilized two main software tools: Analysis and Simulation of Spiral Inductors and Transformers for ICs (ASITIC [13]) and Agilent's 2.5D Momentum EM simulator. ASITIC was used to generate preliminary optimized spiral inductor dimensions. ASITIC results for inductance and self-resonant frequency were confirmed using the Momentum simulator from within Agilent's Advanced Design System (ADS) software environment. Generally ASITIC reported optimistic quality factors compared to Momentum for similar spiral inductor configurations.

For the oscillator topologies presented in this work, a spiral inductor,  $L_s$ , is placed in parallel with a tunable capacitor,  $C_s$  (Fig. 2 (a)). An equivalent parallel RLC network may be obtained (Fig. 2 (b)) which provides insightful parameters  $L_p$ ,  $C_p$ ,  $R_p$ . If a feedback network provides slightly more energy than that lost due to the resistance,  $R_p$  in the parallel tank, then oscillation will occur (Fig. 2 (c)).

The oscillation frequency,  $f_{osc}$ , may be easily predicted as,  $f_{osc} = \frac{1}{2\pi\sqrt{L_p \cdot C_p}}$ . The quality factor,  $Q$ , of the LC-tank

circuit is  $Q = R_p \sqrt{\frac{C_p}{L_p}}$ . The impedance of the L-C tank at resonance is  $R_p$ .



**Figure 2. L-C Tank (a) Finite Quality Factors (b) Equivalent RLC-Tank (c) Practical L-C Oscillator**

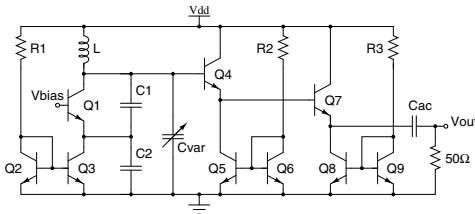
Table 1 compares the characteristics of the inductors used for the oscillator designs, where  $Q$  is the quality factor,  $R_s$  is the series resistance,  $L_s$  is the series inductance,  $n$  is the number of turns and  $f_{SR}$  is the self-resonant frequency. These parameters were extracted from Momentum at 10GHz.

**Table 1. Simulated Inductor Quality Factor**

	HP Momentum				
	$Q$	$R_s$ ( $\Omega$ )	$L_s$ (nH)	$n$	$f_{SR}$ (GHz)
Colpitts	13.44	3.05	0.65	1.25	>40
Differential	10.23	2.47	0.40	1.25	>40

### 3. Oscillator Circuit Implementation

A buffered single-ended Colpitts VCO is shown in Fig. 3. This oscillator topology utilizes positive feedback from the collector to the emitter of Q1 and has been investigated extensively [9], [7]. A two-stage emitter-follower buffer circuit (Q4,Q7) drives the off chip 50 $\Omega$  load. The dual-stage buffers are required because the transistor current gains are significantly reduced beyond  $\frac{1}{10}f_T$ . Voltage biasing resistors R1, R2, and R3 allow for precise tail current control.

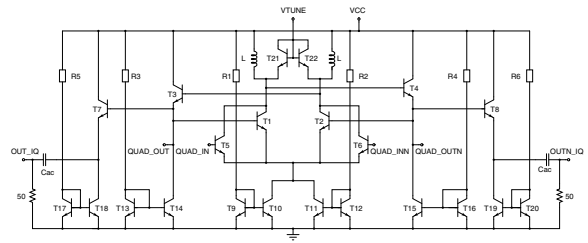


**Figure 3. Single-Ended Colpitts VCO**

It has been shown that the Impulse Sensitivity Function (ISF) for a Colpitts oscillator is superior to various other

oscillator topologies [10]. As a result, phase noise in this circuit is expected to be low. The phase-noise performance for the Colpitts oscillator may be optimized by adjusting the feedback factor  $\propto \frac{C1}{C1+C2}$ . Quadrature signal generation may be implemented using an RC-CR phase shifting network, as required.

Another possible VCO architecture is shown in Fig. 4. This differential L-C VCO generates two anti-phase signals. Quadrature signals may be obtained by connecting a second identical VCO to switching transistors T5 and T6. This circuit has been realized in an 85GHz  $f_T$  process [3], and is investigated in this work for feasibility at 10GHz in a 47GHz  $f_T$  process. Dual emitter-followers are used to drive the off chip 50 $\Omega$  load.



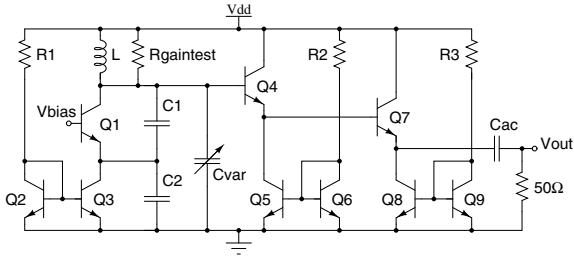
**Figure 4. Differential VCO with Quadrature Parallel Switching Transistors**

#### 3.1. Loop Gain Ratio

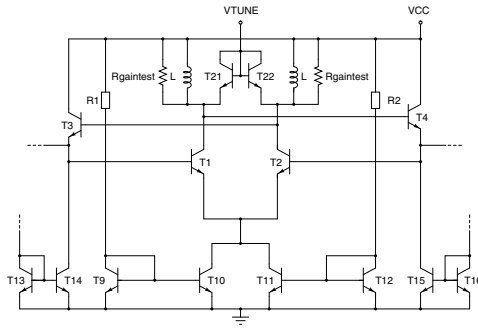
For both oscillators, it is critical that the loop gain is sufficient to ensure oscillation. A commonly used rule of thumb for loop gain ratio for an oscillator is:  $G_{design} \geq 3 \cdot G_{min}$ . A quick test for determining the loop gain ratio may be performed through the addition of a resistance in parallel with the L-C tank,  $R_{gaintest}$  as shown in Fig. 5 for the Colpitts implementation and in Fig. 6 for the differential VCO. In this case, the equivalent pretest L-C tank resistance  $R_p$  is reduced to  $R_{ploaded} = R_p \parallel R_{gaintest}$ . Therefore the quality factor,  $Q$ , of the L-C tank will be reduced. As the gain of the Colpitts amplifier,  $G_{loop}$ , will be linearly dependent ( $G_{loop} = g_m \cdot R_p \cdot \text{some\_constant}$ ) on the  $R_p$  of the L-C tank, this is an effective way of decreasing the simulated loop gain of the amplifier. Similarly, for the differential oscillator,  $G_{loop} \propto R_p$ . The  $R_{gaintest}$  will then be decreased (decreasing the L-C tank  $Q$ ) until transient simulation shows that the oscillator barely starts up - any additional decrease in  $R_{gaintest}$  will result in failure of oscillator start up. Then  $R_{ploaded} = R_{pmin}$ , and the loop gain ratio,  $LGR$ , is

$$LGR = \frac{R_p}{R_{pmin}} = \frac{R_p}{R_p \parallel R_{gaintestmin}} \quad (1)$$

$$\text{Therefore, } R_{gaintest\ min} = \frac{R_p}{LGR - 1} \quad (2)$$



**Figure 5. Loop Gain Ratio Test Circuit for Colpitts Oscillator**



**Figure 6. Loop Gain Ratio Test Circuit for Differential VCO Core**

For a loop gain ratio of 3,

$$R_{gaintest\ min} = \frac{R_p}{3 - 1} = \frac{R_p}{2} \quad (3)$$

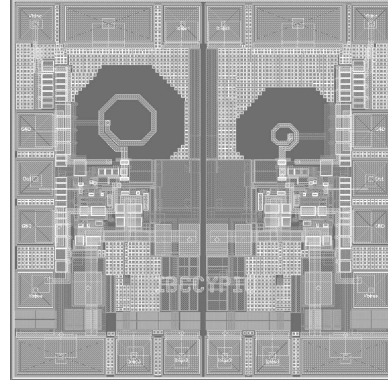
When this minimum resistance is placed in parallel with the L-C tank, the oscillator must still start up. If the oscillator fails to start up circuit parameters, such as bias currents, must be modified.

#### 4. Oscillator Layout

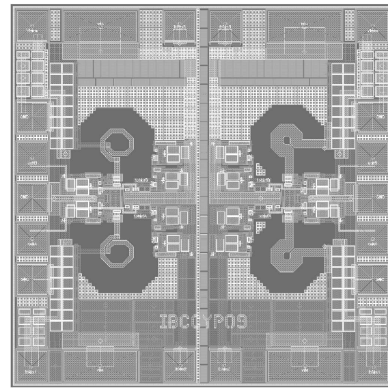
The VCOs were designed for fabrication in IBM's SiGe 5AM 47GHz  $f_T$  process. The SiGe 5AM process utilizes a thick analog metal (AM) layer, above a thick oxide layer which improves the performance of spiral inductors. Two Colpitts oscillators were designed for two different frequencies (10GHz and 17GHz). The two Colpitts oscillators had combined layout dimensions of  $1200\mu m \times 1200\mu m$

(Fig. 7). In addition to the Colpitts oscillators, two differential oscillators were also designed for two different frequencies (10GHz and 17GHz). The two differential VCOs combined layouts consumed  $1400\mu m \times 1400\mu m$  of silicon as shown in Fig. 8.

The most significant difference between the oscillators of a given configuration (Colpitts or differential), was the design of a different inductor with a peak  $Q$  occurring at approximately the oscillation frequency.



**Figure 7. Two Colpitts VCO Layouts**



**Figure 8. Two Differential VCO Layouts**

#### 5. Results

The Colpitts and differential oscillators were tested to start up over process corner variations and with transistor mismatch in Monte Carlo simulations (Fig. 9). The two oscillators are compared based on a variety of metrics which include: tuning range, phase noise, and output signal power. These comparison metrics are discussed in the following sections.

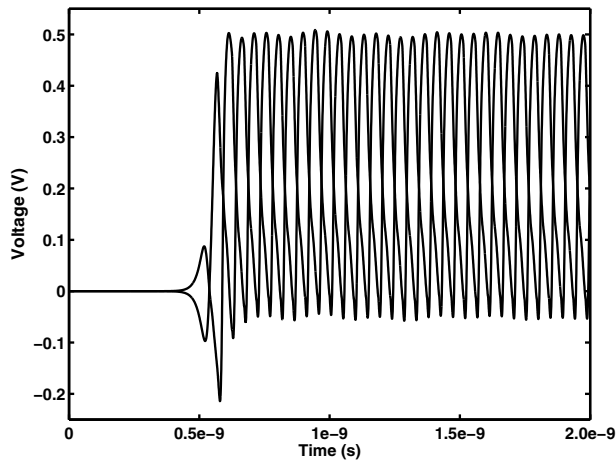


Figure 9. Differential VCO Start up Transient

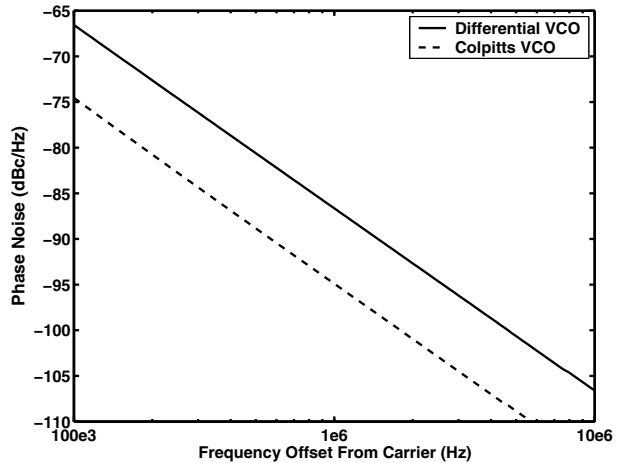


Figure 10. Simulated VCO Phase Noise

### 5.1. Oscillation Frequency and Tuning Range

The tuning ranges for the oscillator designs are summarized in Table 2.

Table 2. VCO Simulated Tuning Range

	Colpitts	Differential
$f_{min}$ {GHz}	9.80	9.23
$f_{max}$ {GHz}	10.21	10.12
Tuning Range {MHz}	410	890

### 5.2. Phase Noise

Phase noise is a figure of merit for an oscillator which describes its spectral purity. Cadence's SpectreRF simulator was used for phase noise simulations. SpectreRF calculates oscillator phase noise using an approach similar to that for solving linear time-varying (LTV) models, utilizing piece-wise polynomials to determine noise contributions for arbitrary waveforms [1]. Phase noise results for the two oscillator implementations are shown in Fig. 10 and specific values are given in Table 3 for the common comparison frequencies of 600kHz and 1MHz offsets from the carrier.

Table 3. VCO Simulated Phase Noise

Offset {MHz}	Colpitts Phase Noise {dBc/Hz}	Differential Phase Noise {dBc/Hz}
0.6	-90.6	-83.33
1.0	-95.0	-87.72

A phase noise figure of merit (FOM) useful for comparison of oscillator implementations can be written as

$$FOM = \left( \frac{\omega_0}{\omega_m} \right)^2 \cdot \frac{1}{\mathcal{L}(\omega_m) \cdot V_{DD} \cdot I} \quad (4)$$

where  $\omega_0$  is the radian carrier oscillation frequency,  $\omega_m$  is a frequency offset from the carrier,  $\mathcal{L}(\omega_m)$  is the phase noise at an offset of  $\omega_m$  from the carrier,  $V_{DD}$  is the DC voltage supply, and  $I$  is the DC current drawn by the differential oscillator core. This FOM was originally proposed in [5] and further discussions may be found in [4].

Substituting the SpectreRF determined phase noise value allows the normalized FOM for the oscillators to be determined, as shown in Table 4. Comparisons with previously published bipolar results are also included for comparison.

Table 4. VCO Simulated FOM

VCO Implementation	FOM {dB}
Soyuer [15]	174.5
Colpitts (This Work)	161.9
Nguyen [12]	154.7
Differential (This Work)	151.6

### 5.3. Output Signal Power

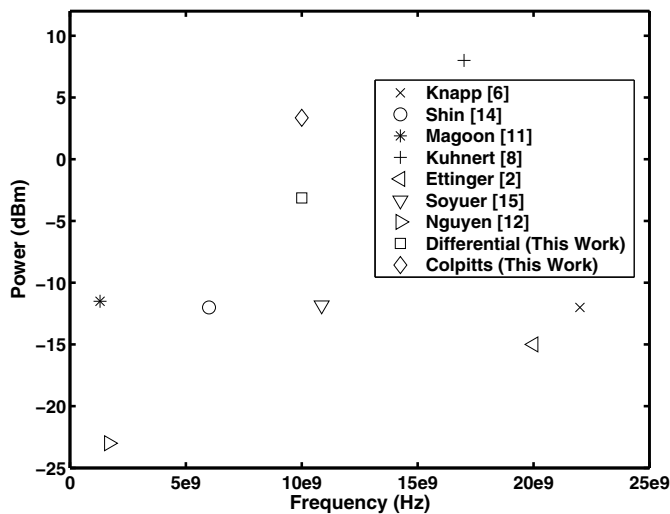
VCOs are often used in transceivers to drive the local oscillator (LO) input for mixers. VCOs also provide frequency inputs to dividers in the frequency synthesizer. The conversion gain of a mixer may be improved with larger LO signal swings, therefore, it is important to maximize the amplitude of the output oscillation signal. Of course phase

noise generally also improves with increased signal swing. The circuits were designed for maximum signal swing without compromising power consumption.

The output signal powers of the two VCO implementations are shown in Table 5. Output signal powers for various implementations are compared to [2], [6], [8], [11], [14] in Fig. 11.

**Table 5. VCO Simulated Output Signal Power**

	Colpitts	Differential
$P_{out}@f_{min}$ {dBm}	3.35	-3.13
$P_{out}@f_{max}$ {dBm}	2.67	-3.41



**Figure 11. VCO Output Signal Powers**

## 6. System Specifications

The performances of the two voltage-controlled oscillators have been compared with the system specifications (Table 6). For each specification both oscillators exceeded the system requirements. The Colpitts implementation performed well in terms of phase noise and output power but had limited tuning range. In contrast, the differential implementation had a larger tuning range and more limited margins on the other metrics.

## 7. Conclusions

Two integrated RF voltage-controlled oscillator designs were described. The integrated circuits were designed to oscillate at 10GHz with a second set of designs targeted to 17GHz, and are to be fabricated in a 47GHz silicon germanium bipolar process. It was found that both designs are

**Table 6. Performance Summary**

	Spec.	Colpitts	Differential
10GHz Operation	10GHz	Yes	Yes
Tuning Range {MHz}	$\geq 400$	410	890
Phase Noise at 1 MHz offset {dBc/Hz}	$\leq -85.0$	-95.0	-87.7
$P_{out}$ {dBm}	$\geq -5.0$	2.67 (min)	-3.41 (min)

feasible at an operating frequency of  $\frac{1}{3} f_T$  without consuming excessive power.

## 8. Acknowledgements

This research was supported by the Natural Sciences and Engineering Research Council of Canada, TRILabs, iCORE, and the Canadian Microelectronics Corporation.

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