4-GHz Fully Monolithic SiGe HBT QVCO Using Superharmonic Coupling Topology

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Abstract—This paper demonstrates a 4-GHz monolithic SiGe heterojunction bipolar transistor (HBT) quadrature voltage controlled oscillator (QVCO) using superharmonic coupling topology. The quadrature VCO at 4.17 GHz has phase noise of -116 dBc/Hz at 1MHz offset frequency, output power of -6 dBm and the figure of merit (FOM) -179 dBc/Hz. The core current consumption is 3.2 mA at 3V supply voltage. The die size is about 1.4 mm × 1.2 mm.

Index Terms—**phase noise, quadrature voltage controlled oscillator (QVCO), SiGe heterojunction bipolar transistor (HBT), transformer, superharmonic coupling.**

I. Introduction

A quadrature VCO is indispensable in today's complex radio systems such as direct conversion and low-IF architectures to reduce the off-chip components. Three approaches are commonly used to generate quadrature oscillating signals. The first approach is a differential oscillator followed by a divider with the modulus of two or four. The output phase as well as oscillation frequency of an oscillator is divided by a divider to create quadrature signals. Not only the divide-by-two circuit needs to have a truly 50% duty cycle to trim the output even harmonics, but also the oscillator with a divide-by-two circuit works at twice of the desired frequency. Although the divide-by-four circuit can replace the divide-by-two and relax the truly 50% duty-cycle requirement, the oscillation frequency should be four times of the desired frequency. The oscillation frequency of this approach is much higher than the desired and the oscillator is tough to realize at the high frequency regime.

The second approach is a differential oscillator followed by a polyphase filter. The polyphase filter is employed as a quadrature generator and the oscillation frequency is the same as the desired. The oscillator of this approach is designed more easily then the previously mentioned. Nevertheless, a high power oscillator is demanded and the phase noise degradation occurs due to the loss of the poly phase filter. Moreover, the quadrature accuracy is dependent of the precision and reliability of the RC components and hence is difficult to achieve in the IC fabrication process.

The third approach is the parallel cross-coupling scheme between two differential LC oscillators [1]. One big issue of this approach is that the cross-coupling scheme swerves the oscillation frequency from the tank resonant frequency of the single differential LC oscillator. The phase noise increases with the quality factor decreasing at the off-resonant frequency. Higher phase noise hence appears in this quadrature VCO in comparison with a differential VCO. In other words, accurate quadrature phase and low phase noise can not be achieved at the same time. In order to lower the phase noise, complicated phase shifters are proposed to avoid disturbing the tank at the cost of higher power consumption [2][3]. Top-series-coupling and bottom-series coupling schemes between two differential oscillators have also been utilized to relax the trade-offs between phase noise and phase accuracy [4].

The superharmonic injection locking method can be utilized at the emitter of the cross-coupled common emitter pair of the differential VCO to control the oscillation frequency as well as phase [5]. Similarly, the superharmonic coupling scheme employs the concept of controling the signals of the cross-coupled common emitters of two differential VCOs to obtain quadrature oscillating signals [6][7]. At the cross-coupled common emitters, only even harmonics can appear and they are coupled through a transformer connected as shown in Fig. 1. Consequently, the opposite phase waveforms at the common emitter points of the two VCOs are generated at twice of the VCO oscillation frequency. Two differential VCOs hence obtain the quadrature differential output signals. Thanks to the consistency between the oscillation frequency and the LC tank resonant frequency, the superharmonic-coupled scheme can achieve accurate quadrature oscillation without phase noise degradation from the constituent differential LC-tank VCOs. A transformer is employed for superharmonic coupling because no extra source of noise is introduced and it is suitable for low voltage applications. In addition, transformers have better quality factors than the constituent inductors have.

Low-phase-noise transformer-based VCOs are proposed in CMOS and SiGe HBT technologies [8]-[15] while some high frequency VCOs are demonstrated in GaInP/GaAs HBT process [16]-[22]. However, not too much work has been done along the direction of the superharmonic-coupled SiGe HBT QVCOs. In this paper, we report the low-phase-noise SiGe HBT superharmonic coupled quadrature VCO at 4 GHz.

II. Circuit Design

The superharmonic coupled quadrature VCO using SiGe HBT technology is designed and shown in Fig. 1. Transformers are employed in the superharmonic coupled quadrature VCO to couple the two individual LC tank differential VCOs. The differential VCO as shown in Fig. 1 is composed of a cross-coupled differential pair for the negative resistance generation, two inductors, and two diode-connected transistors as varactors. The technique of capacitive coupling feedback is utilized in the cross-coupled differential pair and emitter-base junctions are used for the varactors. Separate bias voltages for both bases and collectors of the cross-coupled differential pair can be applied through the capacitive voltage divider. Thus, the collector can be biased at a higher voltage for a larger voltage swing in order to reduce phase noise. The output buffers not shown in Fig. 1 are emitter-followers and they are applied to keep the oscillator away from the loading effect in the 50Ω measurement system.

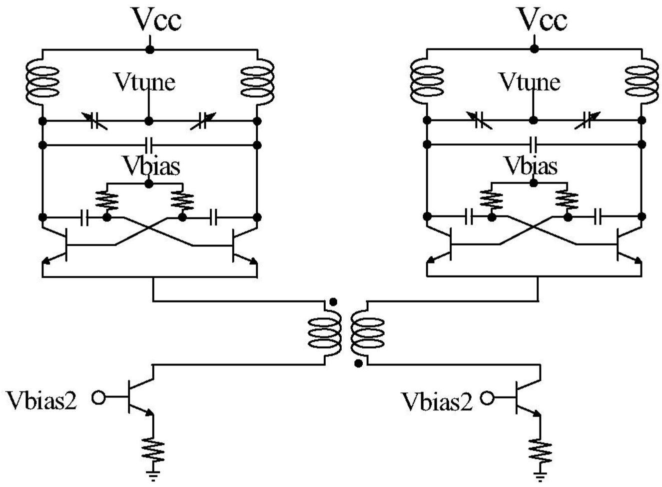

Fig. 1. Schematic of the superharmonic coupled SiGe HBT quadrature VCO.

III. MEASUREMENT RESULTS

Figure 2 displays the die photo of the superharmonic coupled SiGe HBT quadrature VCO and the entire chip size including probing pads is about 1.4 mm × 1.2 mm. The 0.35 um SiGe HBT device has the peak F_t of 67 GHz. The layout keeps symmetry and two differential LC VCOs maintain identical for better performance. The symmetric transformers are formed by two top interconnect metal layers and possess good symmetry for the high quality factor at high frequencies. At the power supply voltage, V_{cc}, of 3 V and the base voltage, V_{bias}, of 2 V, the core current consumption is about 3.2 mA and output buffer current consumption is 33.9 mA.

Figure 3 represents the output power and oscillation frequency with respect to the tuning voltage. This quadrature oscillator has the output power of around -6 dBm and the output frequency decreases from 4.2 GHz to 4.13 GHz when tuning voltage increases from 0 V to 2.7 V. The tuning range is about 70 MHz and a VCO tuning constant, KVCO, is 26 MHz/V.

Figure 4 shows the phase noise spectrum which is measured by Agilent E5052A signal source analyzer. At the oscillation frequency of 4.17 GHz, the superharmonic coupled SiGe HBT quadrature VCO has the phase noise of -116 dBc/Hz at 1 MHz offset frequency. The FOM of an oscillator is defined as follows.

$$FOM = 10\log\left[\left(\frac{\omega_o}{\Delta\omega}\right)^2 \frac{1}{L\{\Delta\omega\} \times V_{DD} \times I_{DD}}\right] \quad (1)$$

where ω_o is the center frequency, $\Delta\omega$ is the frequency offset, $L\{\Delta\omega\}$ is the phase noise at $\Delta\omega$, V_{DD} is the supply voltage and I_{DD} is the supply current. Our SiGe HBT quadrature oscillator here has FOM of -179 dBc/Hz. Our results are better than the superharmonic-coupled SiGe QVCO in reference [7], thanks to the high quality transformer used here. The phase noise keeps almost constant in the tuning range. Both the I- and Q-channel outputs have the same performance.

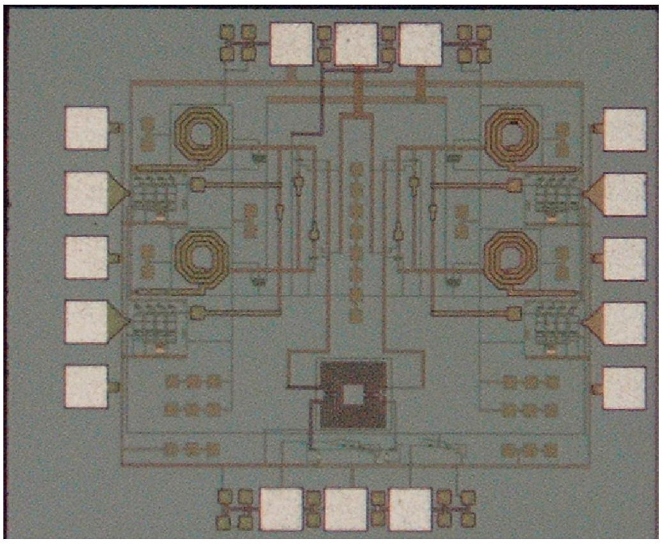

Fig. 2. Photo of the superharmonic-coupled SiGe HBT quadrature VCO.

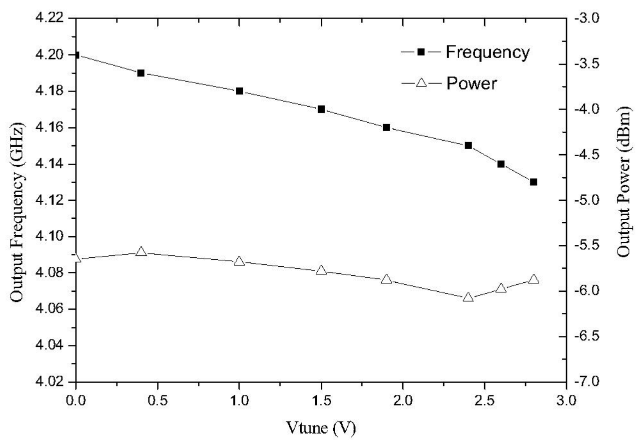

Fig. 3. Output power and frequency as a function of the tuning voltage for the superharmonic coupled SiGe HBT quadrature VCO.

The quadrature accuracy is evaluated by the real time oscilloscope and the I- and Q-channel output waveforms are displayed in Fig. 5. Due to the limitation by the time delay calibration in our measurement, the measured phase error in quadrature accuracy is less than 2°.

IV. CONCLUSIONS

The low-phase-noise transformer-based SiGe HBT quadrature VCO is demonstrated in this paper. The quadrature VCO at 4.17 GHz has the phase noise of -116 dBc/Hz at 1MHz offset frequency and output power of -6 dBm. The FOM is about -179 dBc/Hz. The low phase noise comes from the excellent low-frequency noise properties of the SiGe HBT device and the high quality coupling transformers employed in this work.

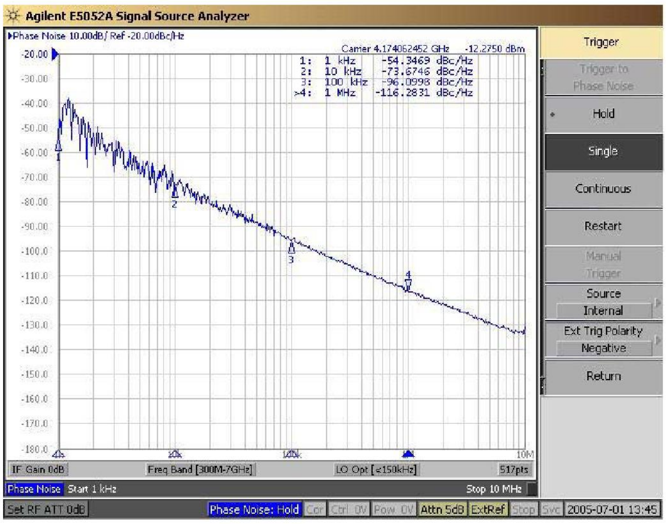

Fig. 4. Phase noise spectrum of the superharmonic coupled SiGe HBT quadrature VCO. The phase noise is -116 dBc/Hz at 1 MHz offset frequency when the oscillation frequency is 4.17 GHz.

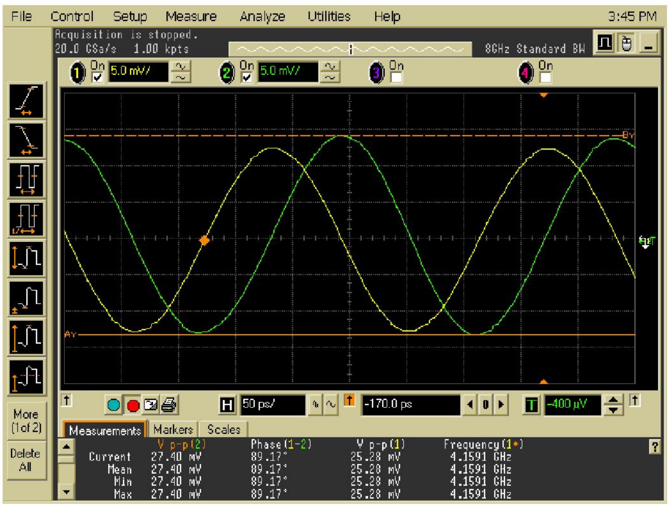

Fig. 5. Time-domain I/Q channel waveforms of the superharmonic coupled SiGe HBT quadrature VCO.

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