downward and eventually approaches $-\pi/-180°$. Within the region between $\frac{\pi}{2}/90°$ and $-\frac{\pi}{2}/-90°$, plane waves are reflected in-phase, rather than out-of-phase.

Next, we removed the FSS-layer to examine its influence on the antenna-system. Although this shifted the resonance frequency, it was still within the desired range (860−960 MHz), and the input impedance also remained within the acceptable range (Fig. 23); consequently, it should be possible to shrink the size of the antenna by a factor of 1.05. We note from Figure 24 that the directivity shows some minor (around 1.2) differences in the range between 900 and 950 MHz.

By comparing the input impedance (Fig. 25) of the antenna composite, we observe that there is a resonance type of behavior that may be attributed to the FSS-layer, which has its own resonance in this range. The inclusion of the FSS-layer yields a higher level of delivered power (~94%) but the bandwidth is slightly smaller in this case as may be seen from Figure 25. This could be attributed to the relatively narrow frequency range in which we have the AMC behavior.

In addition, we found that, in general, while using an AMC shift, the input impedance characteristics shift toward a lower frequency; hence, we can decrease the size of the antenna, though only slightly (5–10%). However, designing the antenna/FSS composite for maximum delivered power is quite difficult because its input impedance as well as the ratio between the real and imaginary parts of this impedance is very sensitive to any change in the antenna length.

This leads us to conclude that the gain improvement we realized to the RFID system by using an AMC-structure is at best marginal, and more research is needed to fully analyze the complex behavior of the metamaterials for RFID applications.

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C-BAND FULLY INTEGRATED SiGe HBT SUPERHARMONIC QVCO

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ABSTRACT: *This paper demonstrates a 4-GHz monolithic SiGe heterojunction bipolar transistor quadrature voltage-controlled oscillator (QVCO) using superharmonic coupling topology. The QVCO at 4.17 GHz has phase noise of −116 dBc/Hz at 1 MHz offset frequency, output power of −6 dBm, and the figure of merit −179 dBc/Hz. The core current consumption is 3.2 mA at 3 V supply voltage. The die size is about 1.4 mm × 1.2 mm.* © 2007 Wiley Periodicals, Inc. Microwave Opt Technol Lett 49: 867–869, 2007; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.22256

Key words: *phase noise; quadrature voltage-controlled oscillator (QVCO); SiGe heterojunction bipolar transistor (HBT); transformer; superharmonic coupling*

1. INTRODUCTION

A quadrature voltage-controlled oscillator (QVCO) 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 than 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 QVCO in comparison with a differential VCO. In other words, accurate quadrature phase and low phase noise cannot be achieved at the same time. To lower the phase noise, complicated phase shifters are proposed to avoid disturbing the tank at the cost of higher power consumption [2]. 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 [3].

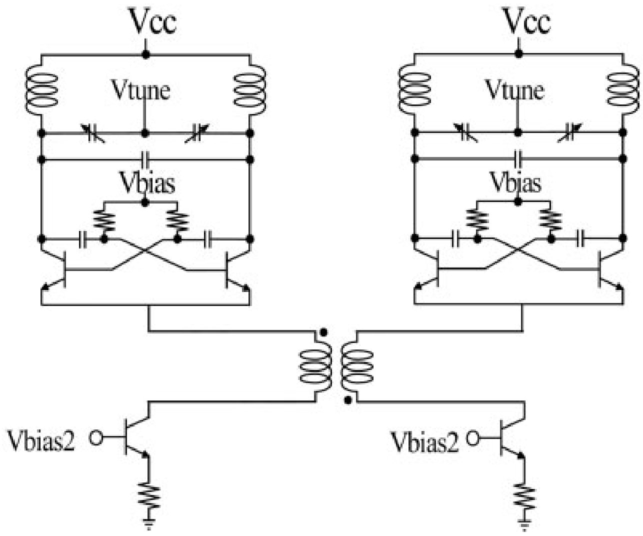

Figure 1 Schematic of the superharmonic coupled SiGe HBT QVCO

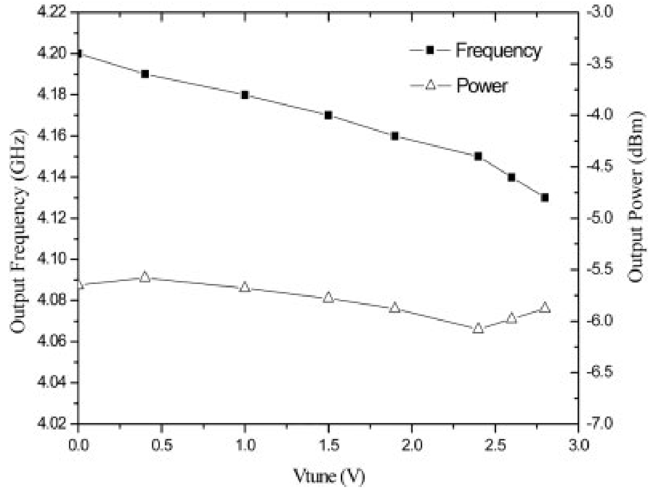

Figure 3 Output power and frequency as a function of the tuning voltage for the superharmonic-coupled SiGe HBT QVCO

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 [4]. Similarly, the superharmonic coupling scheme employs the concept of controlling the signals of the cross-coupled common emitters of two differential VCOs to obtain quadrature oscillating signals [5, 6]. At the cross-coupled common emitters, only even harmonics can appear and they are coupled through a transformer connected as shown in Figure 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-coupling 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. Besides, the micromachining technique can be used to enhance the quality factor of passive components on silicon substrate and then to improve the phase noise of VCOs [7, 8].

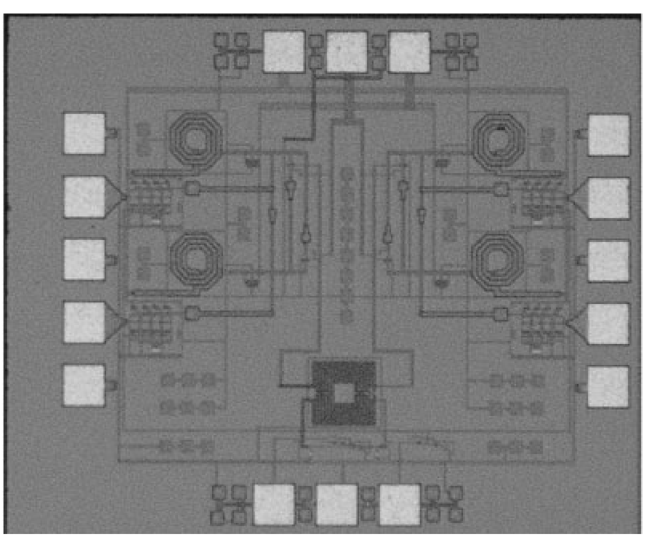

Figure 2 Photo of the superharmonic-coupled SiGe HBT QVCO

Low-phase noise transformer-based VCOs are proposed in the CMOS technology [9, 10]. However, not too much work has been done along the direction of the superharmonic-coupled SiGe heterojunction bipolar transistor (HBT) QVCOs. In this paper, we report the low-phase-noise SiGe HBT superharmonic-coupled QVCO at 4 GHz.

2. CIRCUIT DESIGN

The superharmonic-coupled QVCO using SiGe HBT technology is designed and shown in Figure 1. Transformers are employed in the superharmonic-coupled QVCO to couple the two individual LC tank differential VCOs. The differential VCO as shown in Figure 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 Figure 1 are emitter-followers and they are applied to keep the oscillator away from the loading effect in the 50 Ω measurement system.

3. EXPERIMENTAL RESULTS

Figure 2 displays the die photo of the superharmonic coupled SiGe HBT QVCO and the entire chip size including probing pads is about 1.4 mm × 1.2 mm. The 0.35 μm 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 about −6 dBm and the output frequency

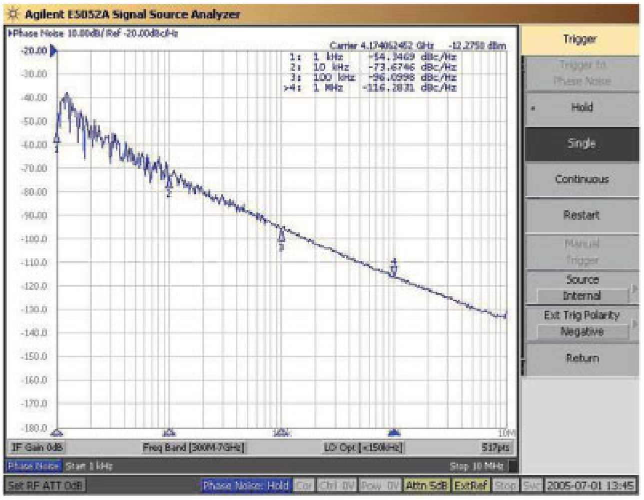

Figure 4 Phase noise spectrum of the superharmonic-coupled SiGe HBT QVCO. The phase noise is −116 dBc/Hz at 1 MHz offset frequency when the oscillation frequency is 4.17 GHz. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

decreases from 4.2 to 4.13 GHz when tuning voltage increases from 0 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 that is measured by Agilent E5052A signal source analyzer. At the oscillation frequency of 4.17 GHz, the superharmonic coupled SiGe HBT QVCO has the phase noise of −116 dBc/Hz at 1 MHz offset frequency. The figure of merit (FOM) of an oscillator is defined as follows:

$$\mathrm{FOM} = 10\log\left[\left(\frac{\omega_0}{\Delta\omega}\right)^2 \frac{1}{L\{\Delta\omega\} \times V_{\mathrm{DD}} \times I_{\mathrm{DD}}}\right], \quad (1)$$

where ω_0 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 [6]; 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.

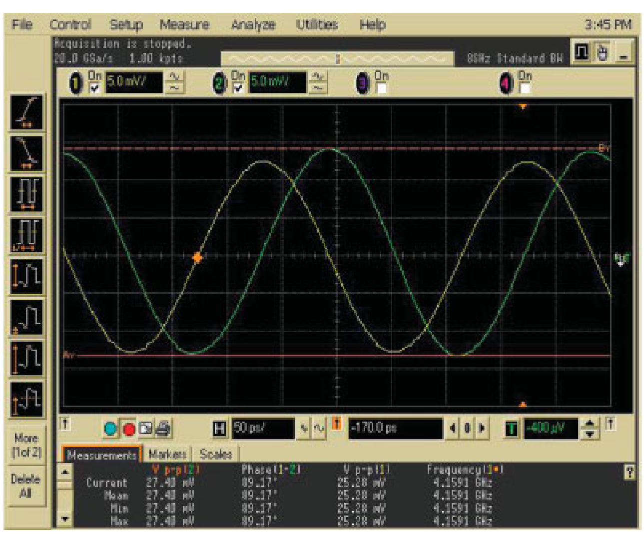

Figure 5 Time-domain I/Q channel waveforms of the superharmonic-coupled SiGe HBT QVCO.[Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

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

4. DISCUSSIONS AND CONCLUSIONS

The low-phase-noise transformer-based SiGe HBT QVCO is demonstrated in this paper. The QVCO at 4.17 GHz has the phase noise of −116 dBc/Hz at 1 MHz 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.

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