4-GHz Low-Phase-Noise Transformer-Based Top-Series GaInP/GaAs HBT QVCO

C. C. Meng, S. C. Tseng, Y. W. Chang, J. Y. Su and G. W. Huang*

Department of Communication Engineering, National Chiao Tung University, Hsin-Chu, Taiwan, R.O.C.
*National Nano Device Laboratories, Hsin-Chu, Taiwan, R.O.C.

Abstract — **The fully integrated GaInP/GaAs heterojunction bipolar transistor (HBT) transformer-based top-series quadrature voltage controlled oscillator (QVCO) is demonstrated at 4 GHz. The transformers on the semi-insulating GaAs substrate possess good electrical properties at high frequencies. The quadrature VCO at 4.1 GHz has phase noise of -120 dBc/Hz at 1MHz offset frequency, output power of 2 dBm and the figure of merit (FOM) -178 dBc/Hz.**

Index Terms — **GaInP/GaAs heterojunction bipolar transistor (HBT), top-series coupling, quadrature voltage controlled oscillator (QVCO), transformer, phase noise.**

I. Introduction

An excellent voltage controlled oscillator is essential for the heterodyne or homodyne transceivers. The device low-frequency noise and the quality factor of the LC tank are the main design factors for a low-phase-noise VCO. The GaInP/GaAs heterojunction bipolar technology has low flicker noise due to the absence of DX center trap in the GaInP material and the device passivation ledge over the extrinsic base surface [1][2]. In addition, low base resistance results in low thermal noise thanks to high base doping. Besides, the semi-insulating substrate enhances the quality factor and self-resonance frequency of the LC tank when compared with the silicon-based substrate. Some low-phase-noise differential GaInP/GaAs HBT oscillators were reported at 4.4 GHz, 6.4 GHz, 13.5 GHz, and 22.3 GHz, respectively [3][4][5][6]. For these reasons, a low-phase-noise VCO can be designed in the GaInP/GaAs HBT process [7][8].

The complexity and integration of radio frequency integrated circuits are increasing. Local oscillators with quadrature outputs are prerequisite in the the direct-conversion and very low-IF wireless architectures. However, there is not too much work for GaInP/GaAs HBT circuits along the direction of quadrature VCOs. Thus, it is our motivation to demonstrate the GaInP/GaAs HBT quadrature VCOs.

Four methods of the quadrature VCO design were offered as follows, a ring-based oscillator, a differential oscillator by a polyphase filter, a differential oscillator followed by a divide-by-two (or divide-by-four) prescaler and a coupling-based oscillator. Though an oscillator with transistors connected in a ring form produces quadrature signals with wide tuning range, this architecture is not main stream for a quadrature VCO due to the poor phase noise performance [9]. A differential oscillator followed by the polyphase filter can generate quadrature signals [10]. However, a high power oscillator is needed and the phase noise degradation occurs because of the loss of the poly phase filter. Moreover, the quadrature accuracy depends on the accuracy of the RC components and thus is difficult to achieve in the IC fabrication process. An oscillator with a divide-by-two circuit needs oscillator working at twice of the desired frequency and thus is difficult to realize at the high frequencies. Besides, the divide-by-two circuit needs to have a truly 50% duty cycle. The truly 50% duty cycle requirement for the divider can be alleviated for the case of an oscillator with the divide-by-four circuit but an oscillator with four times of the desired frequency is needed.

The last approach is that two differential LC oscillators coupling to each other generate quadrature outputs. The coupling mechanism can occur at the fundamental tone of the desired frequency such as parallel cross-coupling, top-series coupling and bottom-series coupling, or at its harmonics, for instance, the superharmonic coupling. The parallel cross-coupling scheme between two differential LC oscillators was employed to obtain the quadrature oscillator [11]. However, the phase noise of this cross-coupling quadrature VCO degrades compared with one differential VCO because the coupling circuit shifts the oscillation frequency from the tank resonant frequency of the individual differential LC oscillator. The quality factor decreases at the off-resonant frequency and thus the phase noise increases. Sometimes complicated phase shifters are employed to isolate the coupling and thus improve the phase noise [12][13] at the cost of higher power consumption. The superharmonic-coupled oscillator can obtain accurate quadrature signals without phase noise degradation from the constituent differential LC-tank VCOs [14]. Top-series-coupling and bottom-series coupling schemes between two differential oscillators have also been employed to relax the trade-offs between phase noise and phase accuracy [15]. Transformer-based VCOs are demonstrated in CMOS and SiGe HBT technologies [16][17][18][19][20][21][22]. The GaAs semi-insulating substrate results in a high self-resonant frequency for the transformer. In this paper, we report the first low-phase-noise transformer-based top-series GaInP/GaAs HBT quadrature VCO at 4 GHz to the best of our knowledge.

II. Circuit Design

Figure 1 shows the schematic of the transformer-based top-series quadrature VCO using GaInP/GaAs HBT technology. In the top-series quadrature VCO, a cascode device is employed to couple the two transformer-based differential VCOs. The differential VCO as shown in Fig. 1 consists of a cross-coupled differential pair for the negative resistance generation, two symmetric transformers, and two diode-connected transistors as varactors. 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 transformers. Thus, the collector can be biased at a higher voltage for a larger voltage swing in order to reduce phase noise. Emitter-follower buffers not shown in Fig. 1 are used in each output to avoid the loading effect when the quadrature oscillator is connected to the 50 Ω measurement system.

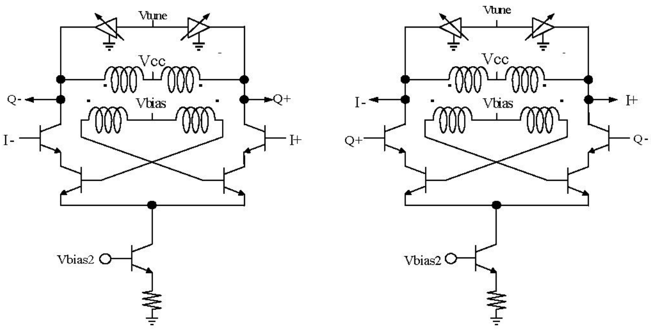

Fig. 1. The schematic of the transformer-based top-series GaInP/GaAs HBT quadrature VCO.

The die photo of the GaInP/GaAs HBT top-series quadrature VCO is shown in Fig. 2. The die size is 2x1 mm^2 and symmetry is kept in the layout for better performance. The 2 um GaInP/GaAs HBT device has the peak F_t of 40 GHz and F_{max} of 50 GHz. HBT devices of 2x9 um^2 are used for the emitter-follower buffers and varactor diodes. The rest of HBT devices in Fig. 1 are 2x4 um^2. The symmetric transformers are formed by two interconnect metal layers. The turn ratio is 4:3. The transformer performance is much better than the transformer on Si substrate, thanks to the semi-insulating GaAs substrate.

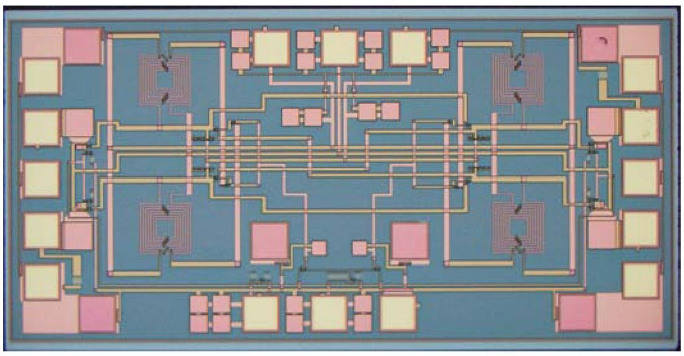

Fig. 2. Photo of the transformer-based top-series GaInP/GaAs HBT quadrature VCO.

III. Measurement Results

The output power and frequency versus the tuning voltage are shown in Fig. 3. The output power stays around 2 dBm while the output frequency varies from 4.14 GHz to 4.05 GHz when tuning voltage changes from 0 V to 3.5 V. The quadrature VCO has a tuning range of 90 MHz and a VCO tuning constant, KVCO, 25.4 MHz/V. The core current consumption is 5.1 mA, buffer current consumption is 15.5 mA, power supply voltage V_{cc} is 5 V and the base voltage V_{bias} is 2 V. Phase noise is measured by Agilent E5052A signal source analyzer and the phase noise spectrum is shown in Fig. 4. The transformer-based GaInP/GaAs HBT quadrature VCO has the phase noise of -120 dBc/Hz at 1 MHz offset frequency when the oscillation frequency is 4.1 GHz and output power is 2 dBm.

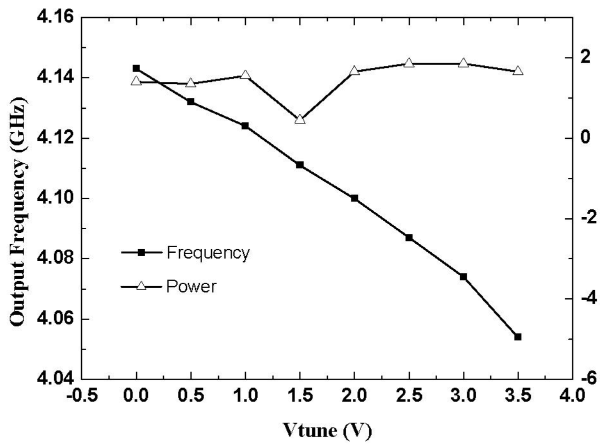

Fig. 3. Output power and frequency as a function of the tuning voltage for the top-series GaInP/GaAs HBT quadrature VCO.

The figure of merit (FOM) is widely used in the comparison of VCOs and is defined as

$$FOM = L(\Delta f) - 20\log(\frac{f_0}{\Delta f}) + 10\log(\frac{P_{dc}}{1\text{mW}}) \quad (1)$$

where Δf (Hz) is the offset frequency, f_0 (Hz) is the oscillating frequency, $L(\Delta f)$ (dBc/Hz) is the measured phase noise at the offset frequency, and P_{dc} (W) is the dc power dissipation of the core VCO [4][21]. Our GaInP/GaAs HBT quadrature oscillator here has FOM of -178 dBc/Hz.

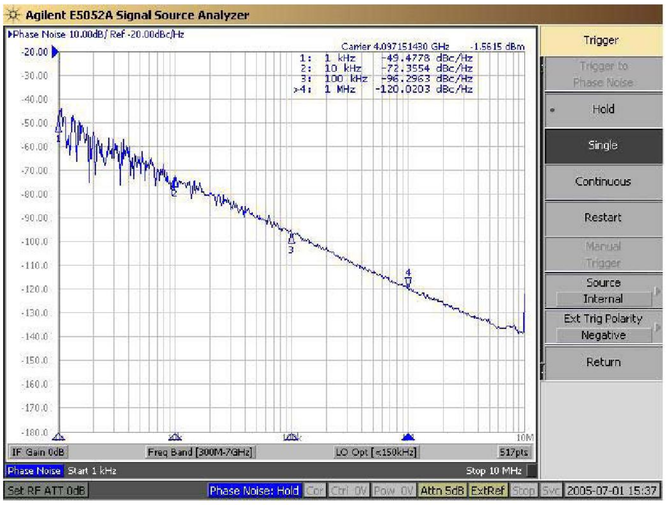

Fig. 4. The phase noise spectrum of the transformer-based top-series GaInP/GaAs HBT quadrature VCO. The phase noise is -120 dBc/Hz at 1 MHz offset frequency when the oscillation frequency is 4.1 GHz.

Both the I and Q outputs of the quadrature VCO have the same performance. The output waveforms for both I/Q channels are shown in Fig. 5 by the real time oscilloscope to evaluate the quadarture accuracy. The error in quadrature accuracy is 2° under the ±2° phase accuracy measurement [23] and is limited by the time delay calibration in our measurement. If necessary, an embedded single sideband upconverter can be employed to measure quadrature phase accuracy with a high resolution based on the image rejection ratio [15].

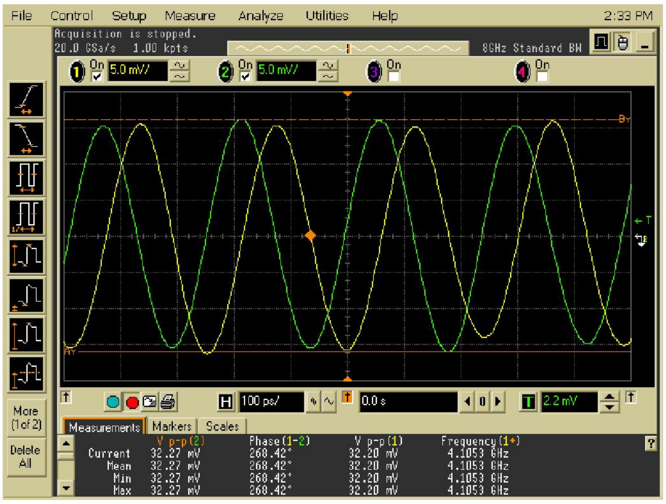

Fig. 5. The time-domain I/Q channel waveforms of the transformer-based top-series GaInP/GaAs HBT quadrature VCO.

IV. Conclusions

The paper presents a low-phase-noise GaInP/GaAs HBT quadrature VCO with the FOM of -178 dBc/Hz. The quadrature VCO at 4.1 GHz has the phase noise of -120 dBc/Hz at 1MHz offset frequency and the output power of 2 dBm. The low phase noise comes from the excellent low-frequency noise properties of the GaInP/GaAs HBT device and the high quality coupling transformers employed in this work.

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