4.9-GHz Low-Phase-Noise Transformer-Based Superharmonic-Coupled GaInP/GaAs HBT QVCO

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***Abstract*—The low-phase-noise GaInP/GaAs heterojunction bipolar transistor (HBT) quadrature voltage controlled oscillator (QVCO) using transformer-based superharmonic coupling topology is demonstrated for the first time. The fully integrated QVCO at 4.87 GHz has phase noise of −131 dBc/Hz at 1-MHz offset frequency, output power of −4 dBm and the figure of merit (FOM) −198 dBc/Hz. The state-of-the-art phase noise FOM is attributed to the superior GaInP/GaAs HBT low-frequency device noise and the high quality transformer formed on the GaAs semi-insulating substrate.**

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

I. Introduction

A QUADRATURE voltage controlled oscillator (QVCO) is a necessity in the direct conversion and very low-intermediate frequency (IF) wireless architectures in order to achieve a fully integrated transceiver. In general, there are three ways to generate quadrature signals—a differential oscillator followed by a divide-by-two circuit, a differential oscillator followed by a polyphase filter, and coupling between two differential oscillators. A differential oscillator with a divide-by-two circuit is difficult to achieve in the high frequency regime because an oscillator and a truly 50% duty cycle divide-by-two circuit at twice of the desired frequency are needed. The polyphase filter can generate quadrature signals from a differential oscillator but the quadrature accuracy depends on the accuracy of the RC components. Many-section polyphase filters are needed to tolerate the component variations in the integrated circuit (IC) fabrication process and thus a high power oscillator is needed to compensate the loss of the polyphase filter. However, the phase noise degradation due to loss is still inevitable. The cross-coupling schemes such as parallel coupling, top-series coupling, and bottom series coupling between two differential LC oscillators have been employed to obtain the quadrature oscillators [1], [2]. The QVCOs formed by these coupling mechanisms exhibit higher phase-noise FOM than the constituent differential VCO does. In other words, there exist trade-offs between quadrature phase accuracy and phase noise because these coupling circuits shift the oscillation frequency from the tank LC resonant frequency. The quality factor decreases at the off-resonant frequency and thus degrades the phase-noise FOM. Complicated phase shifters are employed to isolate the coupling for better phase noise [3] at the cost of higher power consumption.

The superharmonic coupling scheme does not change the oscillation frequency from the LC tank resonant frequency and thus accurate quadrature signals can be obtained without phase noise degradation [4], [5]. If a transformer is used for the superharmonic coupling, no extra source of noise is introduced. However, the coupling transformer must function well at twice of the oscillation frequency. Fortunately, the GaAs semi-insulating substrate results in a high self-resonant frequency for the transformer. The transformer-coupling plays a role in this QVCO not only on providing separate biasing for the bases and collectors of the cross-coupled differential pair to enlarge the output swings in the individual VCO for the phase noise reduction but also on superharmonic coupling to generate quadrature output phases without phase noise degradation. The device low-frequency noise also affects the oscillator phase noise. The low base resistance of the GaInP/GaAs HBT device reduces the thermal noise significantly. The device passivation ledge over the extrinsic base surface and the absence of DX trap center in the GaInP material suppress the 1/f low-frequency device noise [6]. Low-phase-noise differential GaInP/GaAs HBT oscillators were demonstrated at 4.4 GHz, 6.4 GHz, and 13.5 GHz with the phase noise −117.8 dBc/Hz (1-MHz offset), −112 dBc/Hz (100-kHz offset) and −113.8 dBc/Hz (1-MHz offset), respectively [7]–[9]. A parallel-coupled GaInP/GaAs HBT QVCO was demonstrated at 5.4 GHz with the phase noise of −127 dBc/Hz at 1-MHz offset [10]. A reflection-type GaInP/GaAs HBT oscillator was demonstrated at 33 GHz with −87 dBc/Hz (100-kHz offset) [11]. The push–push GaInP/GaAs VCO has been demonstrated at 76 GHz with the phase noise of −102 dBc/Hz at 1-MHz offset [12]. Transformers also have better quality factors than inductors. Low-phase-noise transformer-based VCOs are demonstrated in CMOS technologies [13], [14]. In this letter, we report the first low-phase-noise transformer-based superharmonic-coupled GaInP/GaAs HBT quadrature VCO around 5 GHz to the best of our knowledge.

II. Circuit Design

Fig. 1 shows the schematic of the transformer-based superharmonic QVCO using GaInP/GaAs HBT technology. In the

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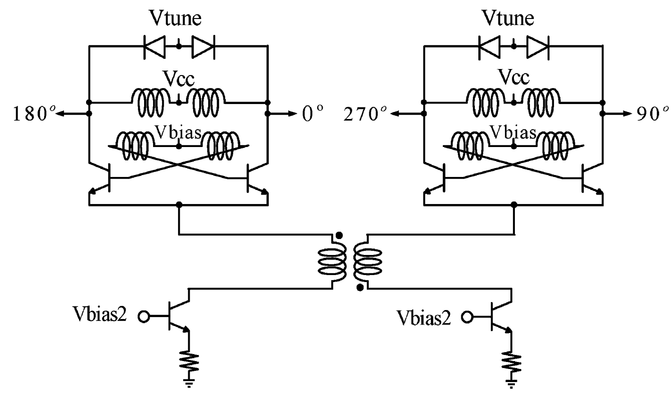

Fig. 1. Schematic of the transformer-based superharmonic-coupled GaInP/GaAs HBT QVCO.

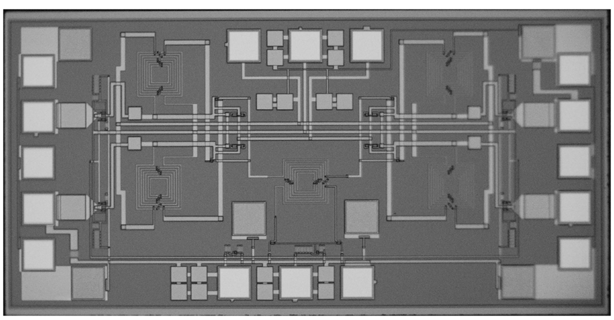

Fig. 2. Photo of the transformer-based superharmonic-coupled GaInP/GaAs HBT QVCO.

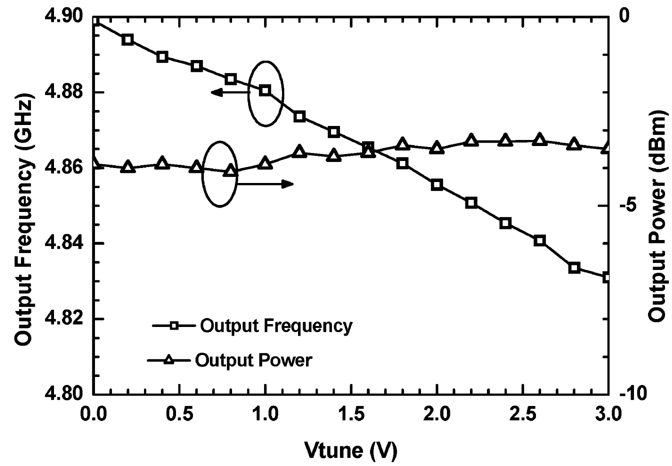

Fig. 3. Output power and frequency as a function of the tuning voltage for the superharmonic-coupled GaInP/GaAs HBT QVCO.

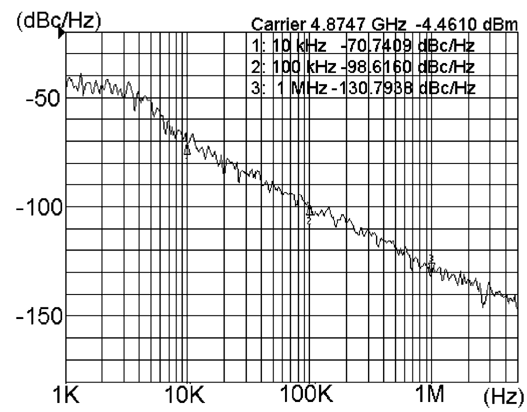

Fig. 4. Phase noise spectrum of the transformer-based superharmonic-coupled GaInP/GaAs HBT QVCO.

superharmonic-coupled QVCO, a symmetric transformer is employed to couple the two transformer-based differential VCOs. A cross-coupled differential pair, two symmetric transformers, and two diode-connected transistors as varactors form the differential VCO in Fig. 1. The cross-coupled differential pairs provide the negative resistance for oscillation and emitter-base junctions are used for the varactors. The superharmonic coupling scheme is employed to generate the differential quadrature signals [4]. Only even harmonics can appear at the emitters of the cross-coupled common emitter pair of each differential VCO. The common-mode even-order harmonics are coupled through a transformer by connecting the common emitter points of two differential VCOs as shown in Fig. 1. Thus, the waveforms at the common emitter points of the two differential VCOs are out of phase at twice of the VCO oscillation frequency. Thus, the output signals of two differential VCOs are in differential quadrature.

Fig. 2 shows the photo of the GaInP/GaAs HBT superharmonic-coupled QVCO. The cross-coupled HBT devices in Fig. 1 are single-finger 2×4 μm^2, varactor diodes are two-finger 3×12 μm^2 and the rest HBT devices are single-finger 2×9 μm^2. The layout is symmetrical and the die size is 2×1 mm^2 [10]. The symmetric transformers are formed by two interconnect metal layers.

III. Measurement Results

The output frequency and power as a function of the tuning voltage are shown in Fig. 3. The output frequency ranges from 4.9 GHz to 4.83 GHz when the tuning voltage varies from 0 V to 3 V. The tuning range is 70 MHz and the tuning constant, KVCO, is 23 MHz/V. The output power is about -4 dBm, the core current consumption is 1.6 mA, the buffer current consumption is 22.4 mA, the power supply voltage, $V_{\rm cc}$, is 3 V and the base voltage, $V_{\rm bias}$, is 2 V. The phase noise spectrum measured is shown in Fig. 4. The transformer-based superharmonic-coupled GaInP/GaAs HBT QVCO has the phase noise of -131 dBc/Hz at 1-MHz offset frequency when the oscillation frequency is 4.87 GHz and output power is -4 dBm. Both the I-channel output and Q-channel output of the QVCO have the same performance. The phase noise stays almost the same in the tuning range. The quality factor of passive components and the noise of devices influence phase noise strongly in a VCO. The semi-insulating substrate enhances the self-resonant frequency and quality factor of transformer while the GaInP/GaAs HBT devices have low thermal and flicker noise. Both low-noise components are employed to improve phase noise in this QVCO.

Phase accuracy is measured by the real-time oscilloscope and measurement is performed by on-wafer probing. The phase error resulting from cables must be calibrated based on a precise differential balun and compensated by phase shifters. The phase error is about 2° under the ±2° phase accuracy measurement [5]. If a better resolution on phase accuracy is required, an on-chip single sideband upconverter is needed in

TABLE I
COMPARISON OF THE PHASE NOISE PERFORMANCES FOR MONOLITHIC VCO IN 1–20-GHZ BAND

Technology and Reference	Supply (V)	Frequency (GHz)	Power Consumption (mW)	Phase Noise (offset)	FOM (dBc/Hz)
CMOS QVCO [1]	1.3	2.27	20.8	-140 dBc/Hz (3MHz)	-184
CMOS QVCO [2]	2	1.8	50	-140 dBc/Hz (3MHz)	-179
CMOS QVCO [3]	2	1.57	21.2	-133.5 dBc/Hz (600kHz)	-187
CMOS QVCO [4]	2.5	5.2	22	-124 dBc/Hz (1MHz)	-185
SiGe HBT QVCO [5]	5	5.92	14	-105.8 dBc/Hz (1MHZ)	-170
GaInP/GaAs HBT DVCO [7]	3.5	4.24	14	-117.8 dBc/Hz (1MHz)	-179
GaInP/GaAs HBT DVCO [8]	3	13.13	36.4	-113.8 dBc/Hz (1MHz)	-181
GaInP/GaAs HBT DVCO [9]	5.25	6.4	173.3	-112 dBc/Hz (100kHz)	-186
SiGe HBT DVCO [9]	3.2	5	64	-109 dBc/Hz (100kHz)	-185
GaInP/GaAs HBT QVCO [10]	4	5.38	12.8	-127 dBc/Hz (1MHz)	-191
CMOS QVCO [13]	3	7.96	24	-117 dBc/Hz (1MHz)	-181
CMOS DVCO [14]	0.5	3.8	0.57	-119 dBc/Hz (1MHz)	-193
GaInP/GaAs HBT QVCO [This Work]	3	4.87	4.8	-131 dBc/Hz (1MHz)	-198

the circuit to obtain quadrature phase accuracy according to the image rejection ratio [2].

Table I summarizes the state-of-the-art results of the fully integrated VCOs in the range of 1–20 GHz for all kinds of semiconductor technologies. The commonly used FOM [1]–[5], [7]–[10], [13], [14] for oscillator comparison is also shown in Table I. The FOM of our GaInP/GaAs HBT superharmonic-coupled QVCO shows a record of −198 dBc/Hz and is much better than the FOMs of CMOS superharmonic-coupled QVCO [4] and SiGe superharmonic-coupled QVCO [5]. As expected, the superharmonic-coupled GaInP/GaAs HBT QVCO here has better FOM than the parallel-coupled GaInP/GaAs HBT QVCO has [10]. The FOM of our oscillator is also the best FOM ever reported among all the monolithic VCOs to the best of our knowledge.

IV. CONCLUSION

The letter presents the low-phase-noise superharmonic-coupled GaInP/GaAs HBT QVCO with the state-of-the-art FOM −198 dBc/Hz. The QVCO at 4.87 GHz has the phase noise of −131 dBc/Hz at 1-MHz offset frequency and output power of −4 dBm. The low base resistance, the passivation ledge and the absence of DX trap center of the GaInP/GaAs HBT device make the low-frequency device noise insignificant and reduce the phase noise. The superharmonic coupling topology preserves the low-phase-noise property of the constituent differential VCOs when the high quality coupling transformers formed on the GaAs semi-insulating substrate is provided.

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