Figure 7 Simulated and measured results

PCLs, shunt stubs, and unit lines have been modified to count for the fringing capacitance and discontinuity effects [10]. The filter shown in Figure 6 is fabricated on a substrate with a relative dielectric constant of 3.38, a loss tangent of 0.0025, and a thickness of 0.8 mm. The filter is rigorously modeled by emulator IE3D [12]. All final characteristic impedances of transmission-lines are obtained by using an optimization process [13]. The simulation results of designed filter performance of pass band with 21% (2.48 GHz) and 10% (5.25 GHz) for duroid substrate. The bandwidths of each passband are highly matched with the desirable values for the filter. The insertion losses of the filter are about 0.731 and 1.403 dB at the frequences of 2.532 and 5.32 GHz, respectively.

The measurements are performed with a HP8510C network analyzer. The measured and simulated performances shown in Figure 7 are well matched. From the experimental results, the 3 dB bandwidths are about 20 and 10% for the frequency of 2.45 and 5.25 GHz, respectively. The insertion loss is about 0.831 dB for the frequency of 2.38 GHz and 1.873 dB for the frequency of 5.216 GHz. The proposed filter has attractive features, including wide bandwidth, low insertion loss, smaller size, and easy mass production.

6. CONCLUSIONS

In this investigation, a mapping method to find the system function of a dualband filter in the *z*-domain by discrete-time domain techniques as well as by chain-scattering matrices of various transmission-lines is developed. By cascading a band-pass filter and a band-stop filter, a dualband filter with the desired bandwidth and low insertion loss is realized. We derive the chain scattering parameters of various microstrip lines and apply the transfer function of transmission lines to design the dual band filter. The validity of the proposed method has been confirmed through the design, simulation, and measurement of dual-band bandpass filter at 2.45–5.25 GHz on duroid substrates. Our design results of the dualband filter is not only easy implementation but also unlimited application to the mentioned bands. It is sensible that many other circuits developed in the digital signal process can also be implemented by using our nonuniform transmission-line method for microwave applications.

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LOW-PHASE-NOISE TRANSFORMER-BASED TOP-SERIES QVCO USING GaInP/GaAs HBT TECHNOLOGY

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ABSTRACT: *The fully integrated GaInP/GaAs heterojunction bipolar transistor, 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 QVCO at 4.1 GHz has phase noise of −120 dBc/Hz at 1 MHz offset frequency, output power of 2 dBm and the figure of merit −178 dBc/Hz. © 2006 Wiley Periodicals, Inc. Microwave Opt Technol Lett 49: 215–218, 2007; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.22067*

1. 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 selfresonance 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, 6.4, 13.5, and 22.3 GHz, respectively [3–6]. 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 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 poly phase 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
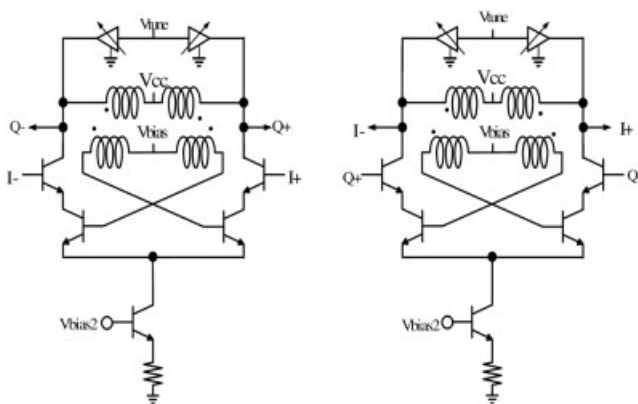
Figure 1 The schematic of the transformer-based top-series GaInP/GaAs HBT quadrature VCO
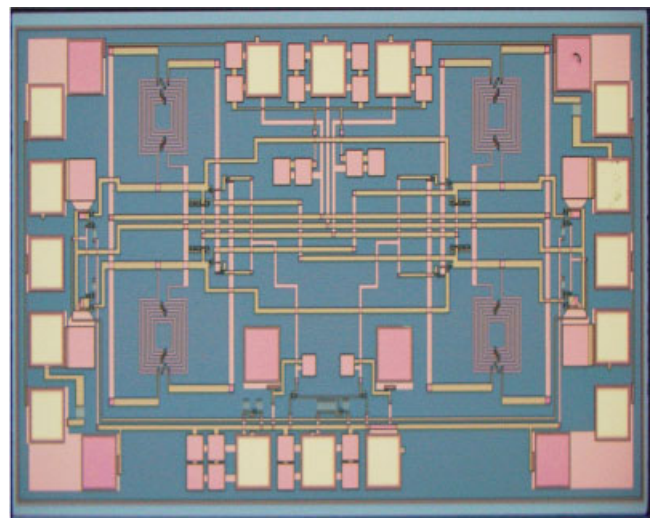

Figure 2 Photo of the transformer-based top-series GaInP/GaAs HBT quadrature VCO. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

from the tank resonant frequency of the individual differential LC oscillator. The quality factor decreases at the offresonant 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 [16–18]. The GaAs semi-insulating substrate results in a high selfresonant frequency for the transformer. In this article, 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.

2. 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 Figure 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 Figure 1 are used in each output to avoid the loading effect when the quadrature oscillator is connected to the 50 Ω measurement system.

The die photo of the GaInP/GaAs HBT top-series quadrature VCO is shown in Figure 2. The die size is 2×1 mm^2 and symmetry is kept in the layout for better performance. The 2 μm GaInP/GaAs HBT device has the peak F_t of 40 GHz and F_{max} of 50 GHz. HBT devices of 2×9 um^2 are used for the emitter-follower buffers and varactor diodes. The rest of HBT devices in Figure 1 are 2×4 μm^2. The symmetric transformers are formed by two interconnect metal layers. The turn ratio is 4:3. The
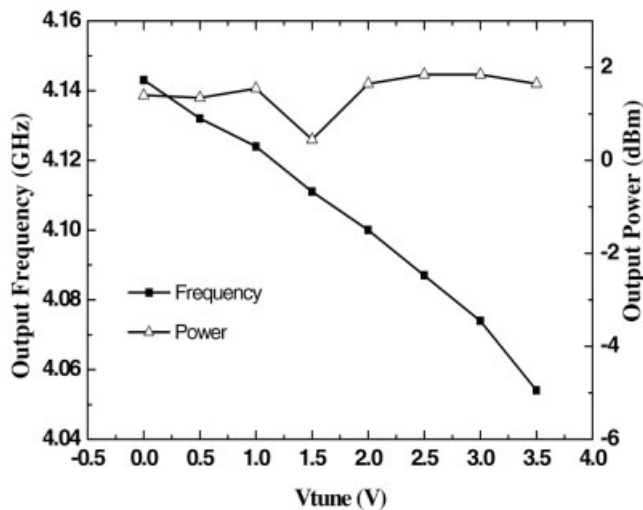
Figure 3 Output power and frequency as a function of the tuning voltage for the top-series GaInP/GaAs HBT quadrature VCO

transformer performance is much better than the transformer on Si substrate, thanks to the semi-insulating GaAs substrate.

3. MEASUREMENT RESULTS

The output power and frequency versus the tuning voltage are shown in Figure 3. The output power stays around 2 dBm while the output frequency varies from 4.14 to 4.05 GHz when tuning voltage changes from 0 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 Figure 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.

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

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

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]. Our GaInP/GaAs HBT quadrature oscillator here has FOM of −178 dBc/Hz.

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 Figure 5 by the real time oscilloscope to evaluate the quadarture accuracy. The error in quadrature accuracy is 2° under the ±2° phase accuracy measurement [19] 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].

4. CONCLUSIONS

This article 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 1 MHz 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.
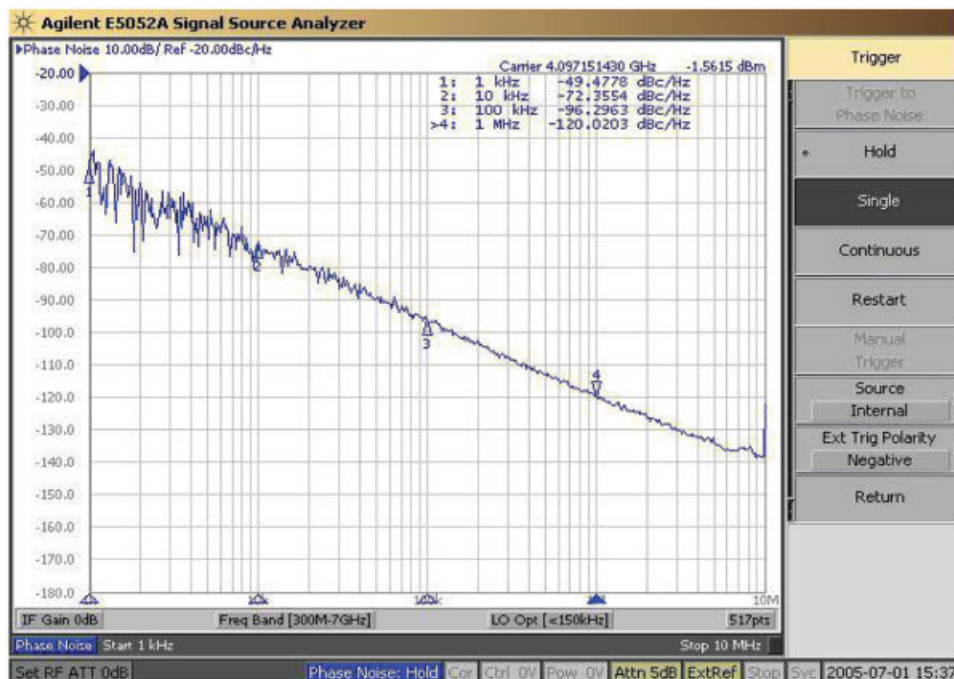
Figure 4 The phase noise spectrum of the transformer-based top-series GaInP/GaAs HBT quadrature VCO. The phase noise is −120 dBc/Hz at 1 MHz offset frequency when the oscillation frequency is 4.1 GHz. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]
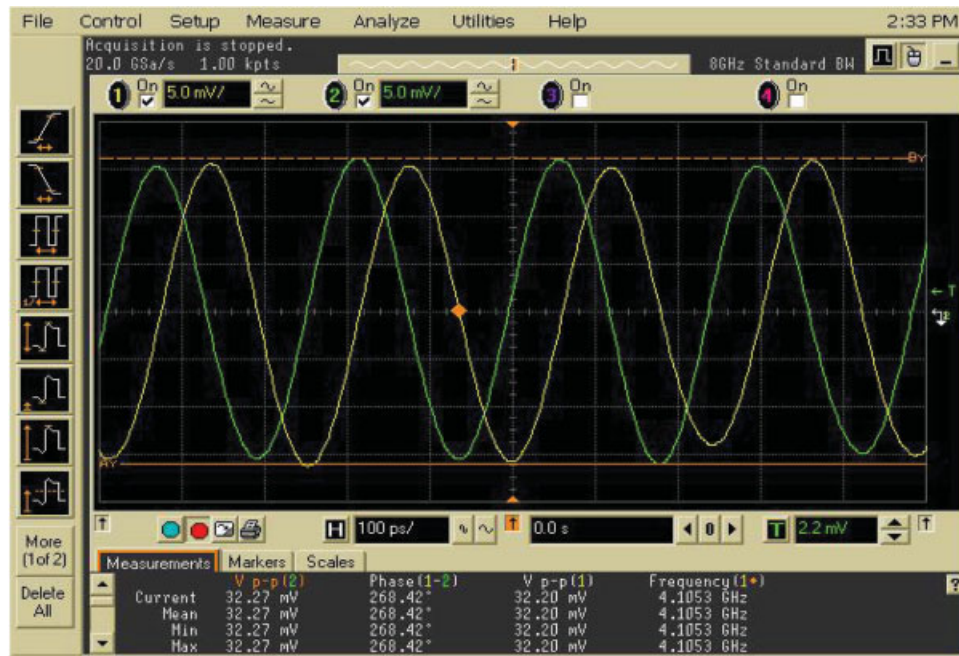
Figure 5 The time-domain I/Q channel waveforms of the transformer-based top-series GaInP/GaAs HBT quadrature VCO. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

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