A Ku Band InGaP/GaAs HBT MMIC VCO with a Balanced and a Differential Topologies

Dong-Hyun Baek, Jeong-Geun Kim, and Songcheol Hong
Dept. EECS, Korea Advanced Institute of Science and Technology (KAIST)
373-1, Guseong-dong, Yuseong-gu, Daejeon, 305-701, Republic of Korea

Abstract **— Two fully integrated voltage controlled oscillators (VCO) with low phase noise are presented. The VCOs are realized on a commercially available InGaP/GaAs hetero-junction bipolar transistor (HBT) technology with an f_T of 30 GHz. The circuits are based on the balanced common base Colpitts topology and the capacitively coupled differential topology. To improve the quality factor of LC tank, 70-ohm microstrip line is incorporated as an inductor with a varactor. The balanced VCO provides single ended output power of 0 dBm and a phase noise of -90.5 dBc/Hz at 100 kHz offset from a carrier frequency 13.5 GHz. The differential VCO has single ended output power of -1.5 dBm and -88 dBc/Hz at 100 kHz offset from a carrier frequency of 12.2 GHz. The balanced and the differential VCO achieves very low F.O.M of -180.7 and -177.6 dBc/Hz.**

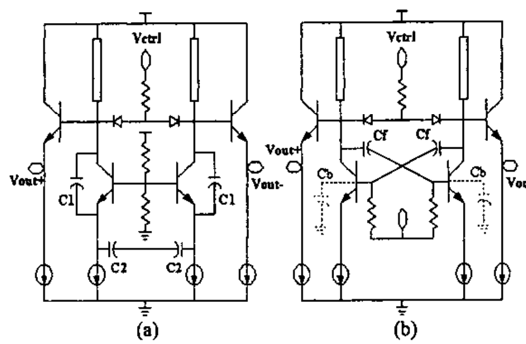

Fig. 1. The schematic circuits of Ku band (a) balanced and (b) differential VCOs.

I. Introduction

Recently the explosion of wireless and optical communication market demands more frequency bandwidth, that pushes the operation frequency up to Ku band in areas of satellite communication, wireless LAN and LMDS [1]-[2]. The VCO is the most important building block in communication transceivers as a part of the frequency synthesizer.

The design considerations of VCO are the phase noise, the tuning range, the output power and the chip size. The LC tank circuit determines the phase noise performance of VCO and the negative resistance cell provides the power to compensate the loss in tank circuits. In mm wave regimes, widely adapted is the Colpitts type negative resistance cell that provides single output. In the frequency synthesizer, the differential outputs are needed to drive the prescaler or the frequency multiplier, to solve this problem recently the balanced VCOs employing two Colpitts structures are published [3]-[4]. In the low GHz regimes, however the differential topology is generally used in Si technology (CMOS, Si BJT, SiGe HBT) [5]-[6].

To measure the topological difference, the Ku band VCOs based on two different negative resistance cells are explored. The one is the balanced common base Colpitts topology. The other is the capacitively coupled differential topology. In this paper the design and the results of the two VCOs are presented. Especially the microstrip line is used as an inductor to increase the quality factor (Q) of LC tank. And the VCO performances are compared to the ever-reported VCOs.

II. Circuit Designs

The VCOs consist of a LC tank, a pair of emitter follower buffers and a negative resistance cell. The schematic circuits are illustrated for both configurations in Fig. 1. Two VCOs differ in their implementation of the negative resistance cell.

An inductor is the primary phase noise-limiting component in LC tuned VCO. In spite of the low quality factor, the spiral inductor is preferred due to its low chip area. However, as the operation frequency increases the required inductance decreases so that over 10 GHz, the short length microstrip line can provide the needed inductance for the oscillation. The advantage of microstrip line over the inductor is its higher quality factor. In GaAs substrate, the conductive loss of the metal layer dominates. The microstrip line has higher quality factor compared to monolithically integrated spiral inductor since it has a wider metal width, leading to low metal loss resultantly.

Conventionally, the length of transmission-line resonator is designed to be a quarter of wavelength that is too large to be applied even in 10 GHz regimes. In these VCO designs, the resonator consists of short length microstrip transmission line and the varactor. The line length and the characteristic impedance have been carefully optimized. The effective inductance of microstrip line is 0.35 nH that is about 1/16 λ_0 at 14 GHz

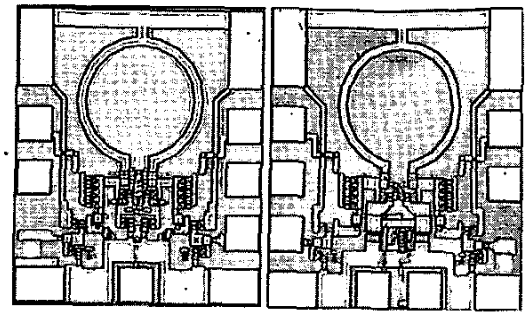

Fig. 2. The microphotographs of (a) the balanced and (b) the differential VCOs. The dimensions are 0.7 x 0.82 mm^2 in each VCOs.

and the simulated quality factor of the microstrip transmission line using 2.5 D microwave simulator, Momentum, is more than 45 which is 2 or 3 times higher than the spiral inductor.

The base-collector junction capacitance of HBT is used as a variable capacitor for frequency tuning, whose quality factor is more than 15. This relative low quality factor of the varactor limits overall phase noise performance of VCOs.

A. Balanced VCO

In the balanced VCO, two common base Colpitts VCOs are synchronized through the base terminals and the capacitors, C_2 between emitters in Fig 1(a). The balanced VCO operates differentially so that the virtual ground forms at base terminals and at the node between capacitors, C_2. Therefore each half circuit of VCO behaves like as single Colpitts oscillator. MIM capacitor C_1 and C_2 generate the negative resistance at each collector. When a small signal BJT model that excludes the collector-base capacitor (C_μ) and the output resistance (r_0) is taken into account, the half circuit of the balanced VCO provides a negative resistance, $-R_{neg}$, which compensates the loss of LC tank.

$$R_{neg} \approx -\frac{g_m + j\omega(C_1 + C_1 + C_\pi)}{\omega^2 C_1(C_2 + C_\pi) - j\omega \frac{1}{r_\pi} C_1} \quad (1)$$

The negative resistance is optimized to achieve low noise performance and high output power by adjusting the capacitance of C_1 and C_2. In the design if C_1 or C_2 were changed for the frequency tuning the negative resistance would be also varied, that would cause the variation of the voltage swing in the VCO core. Unlike the previous designs in [3]-[4], the tuning varactors are placed between two collectors to maintain the constant negative resistance. As a result, the VCO achieves a constant output power over full tuning range.

TABLE I
SUMMARY OF PERFORMANCES FOR THE BALANCED AND THE DIFFERENTIAL VCOS

VCO	Balanced	Differential
Frequency (GHz)	12.71-13.54	11.71-12.28
Bias (V)	3 V	3 V
Output power (dBm)	~0 (single out)	~-1.5(single out)
I_{core} & I_{buffer} (mA)	~ 12, 12 each	16,12 each
P_{diss} in core (mW)	36	48
Phase noise @100 kHz	-90.5 dBc/Hz	-88 dBc/Hz
Phase noise @1 MHz	-113.8 dBc/Hz	-111.8 dBc/Hz
Tuning range (MHz)	800	600
F.O.M (dB)	-180.7	-176.6
Size of chip (mm^2)	0.7 X 0.82	0.7 X 0.82

B. Differential VCO

A differential topology with cross-coupled feedback is used to realize the VCO as shown Fig.1 (b). The core voltage is fed backed to the base of a differential pair through the feedback capacitor, C_f. The negative resistance of $-2n/g_m$ compensates energy loss in LC resonator to sustain stable oscillation. n is the fraction of voltage fed back to the base of differential pair, that is determined by the ratio of a feedback capacitance, C_f and a base parasitic capacitance, C_b. To maximize the voltage swing in the resonator, the capacitively coupled differential structure is used among the several types of feedback methods. The feedback capacitor is optimized for ensuring the transistor not saturated and high output power.

III. Technology

The presented VCOs are fabricated using a commercially available InGaP/GaAs HBT technology, which offers the NPN HBTs with an f_T of 30 GHz and an f_{MAX} of 45 GHz, respectively. A turn-on voltage of HBT is 1.3 V. The current density of HBTs is 0.2mA/μm^2. The technology provides a nitride MIM capacitor and a TaN register and 2 metal layers, of which thickness are 1 μm and 1.3 μm. The microstrip lines are implemented connecting two metal layers. 60 μm^2 emitter size transistors are used in the core circuits and the emitter follower buffers. The wafer is thinned to 100 μm with backside metal. Fig. 2 shows the photographs of the fabricated VCOs.

In the simulation Gummel-Poon based large signal model including self-heating effects are used [7].

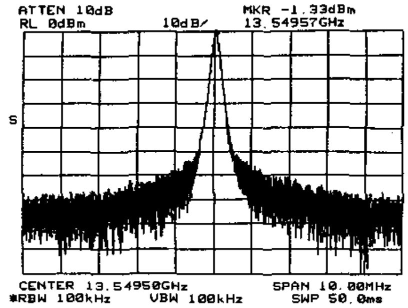

Fig. 3. The Balanced VCO output spectrum over 10 MHz span at 13.55 GHz. The measurement loss is not included.

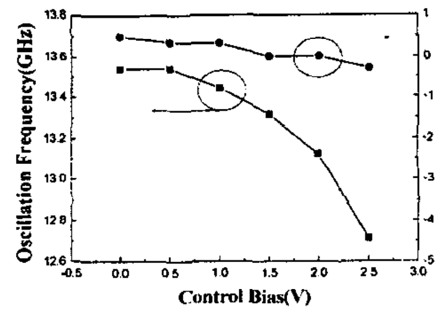

Fig. 5. The oscillation frequency and the output power of the balanced VCO as a function of varactor control bias.

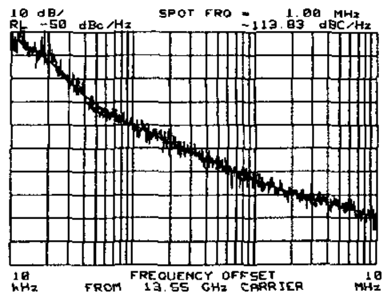

Fig. 4. Phase noise measurements of the balanced VCO between 10 kHz and 10 MHz offset. The balanced VCO shows phase noise of −88, −113.8 dBc/Hz @ 100 kHz, 1 MHz offset.

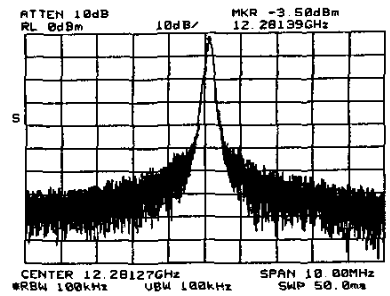

Fig. 6. The differential VCO output spectrum over 10 MHz span at 12.28 GHz. The measurement loss is not included.

IV. MEASUREMENTS RESULT AND DISCUSSION

The test of VCOs was carried out on on-wafer. The output spectrums and the phase noise performance were obtained from HP8764E spectrum analyzer and the phase noise measurement kit. Single ended measurements were performed on the one of the differential outputs while the other is terminated to 50 ohm on the chip. The VCOs were measured using the GSG probes from 3 V supply. The loss of measurement setup is about 2 dB at 13 GHz. The measurement results are summarized TABLE I.

Fig. 3 shows an output spectrum of the balanced VCO, which shows clear spectral purity without any spurious signal. A free running frequency of 13.55GHz is achieved at 3 V supply and V_{ctrl} of 0V. It provides high output power of 0 dBm with the core current of 12 mA and the buffer current of 12 mA. The core current is controlled by the external bias and is optimized for the low phase noise performance. The measured output phase noise is −90.5 and −113.8 dBc/Hz at 100 kHz and 1 MHz offset as shown in Fig. 4. Fig. 5 illustrates the oscillation frequency and the output power with the varactor control bias from 0 to 2.5 V. The power variation is less than 1dB within a tunable range of 850 MHz from 12.7 to 13.55 GHz.

Fig. 6 depicts an output spectrum of the differential VCO that provides an output power of about −1.5 dBm. The oscillation frequency is ~12.25 GHz. The differential core consumes more currents in the core circuits than that of the balanced VCO. However, it shows 2 ~ 3 dB inferior phase noise of −88 and −111.8 dBc/Hz at 100 kHz and 1 MHz offset as shown in Fig. 7.

The two types of Ku band VCOs show low phase noise performances. For comparison, the phase noise performances of other VCOs realized on the different technologies are plotted in Fig. 8. Some data are extrapolated to 100 kHz using -20 dB/decade formula. The phase noise performance of the balanced and the differential VCO show top-level characteristics.

They are advantageous in respect to not only the phase noise but also low power consumption. As a measure for comparison with VCOs in different frequency band, different power consumption and a phase noise, the following figure of merit has been proposed [5].

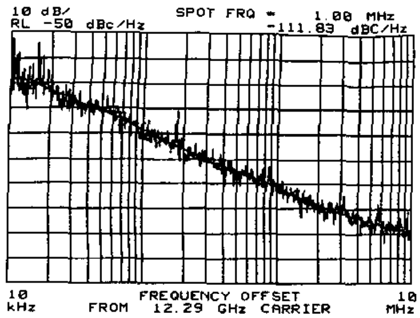

Fig. 7. Phase noise measurements of the differential VCO from 10 kHz to 10 MHz offset frequency. The balanced VCO shows phase noise of −90, −111.8 dBc/Hz @ 100 kHz, 1 MHz offset.

$$F.O.M = \mathcal{L}_{meas}(f_{Offset}) - 20\cdot\log(f_{osc}/f_{Offset}) + 10\cdot\log(P_{diss}/1\,mW) \qquad (2)$$

Where $\mathcal{L}_{meas}$ is the phase noise measured off the offset, f_{offset} at the oscillation frequency, f_{osc}, and P_{diss} is the power consumption in the VCO core. The balanced VCO shows very low F.O.M of −181 dB/Hz. It is better or comparable to the state of art VCOs implemented on CMOS or SiGe HBT technologies as shown Fig. 9. And the F.O.M of the differential VCO is −176.6 dB/Hz.

V. CONCLUSION

Ku band VCOs based on the balanced topology and the differential topology have been demonstrated using the InGaP/GaAs HBT technology. Both VCOs has shown low phase noise performance with an aid of high Q microstrip line inductor in small chip area. The balanced topology is better in the phase noise and the output power. The phase noise performance and F.O.M are better or comparable to ever-reported VCOs in all types of technologies (CMOS, BJT, FET, HBT and HEMT).

ACKNOWLEDGEMENT

The authors wish to acknowledge Teltron inc. for providing an opportunity of the chip fabrication. This work was partly supported by KOSEF under the ERC program through the MINT research center at Dongguk University.

REFERENCE

[1] B. H. Klepser, M. Scholz, and W. Klein, "A 10GHz SiGe BiCMOS Phase-Locked-Loop Frequency Synthesizer", *IEEE Custom integrated circuits conf.*, pp 567-570, 2001.

[2] J. Portilla, M. L. Fuente, J. P. Pascual, and E. Artal, "Low-Noise Monolithic Ku-Band VCO Using Pseudomorphic HEMT Technology," *IEEE Microwave Guided Wave Lett.*, vol. 7,(11), pp 380-382. Nov. 1999.

[3] J. W. M. Rogers, J. A. Macedo, and C. Plett, "The Effect of Varactor Nonlinearity on the Phase Noise of Completely Integrated VCOs," *IEEE J. Solid-State Circuits.*, vol. 35, (9), pp 1360-1366. Sept. 2000.

[4] S. P. Voinigescu, D. Marchesan, and M. A. Copeland, "A Family of Monolithic Inductor-Varactor SiGe-HBT VCOs For 20 GHz to 30 GHz LMDS and Fiber Optic Receiver Application," *IEEE RFIC symp.*, pp 173-176, 2000.

[5] H. Jacobsson, S. Gevorgian, M. Mokhtari, C. Hedenass, B. Hansson, T. Lewin, H. Berg, W. Rabe, and A. Schuppen, "Low-Phase-Noise Low-Power IC VCOs for 5-8GHz Wireless Applications," *IEEE trans. Microwave Theory Tech.*, vol.48, (12), pp 2533-2539, Dec. 2000.

[6] A. Hajimiri and T.Lee. "Design issues in CMOS differential LC oscillators," IEEE J. Solid-State Circuits, vol. 34, pp.717-724, May 1999.

[7] Hyun-Min Park, Sangsoo Ko, and Songcheol Hong, "An isothermal Gummel-Poon model parameter extraction of HBT for self-heating effects using pulsed measurements," in *Proceedings of the 9th GAAS*, 2001, pp. 159-162.

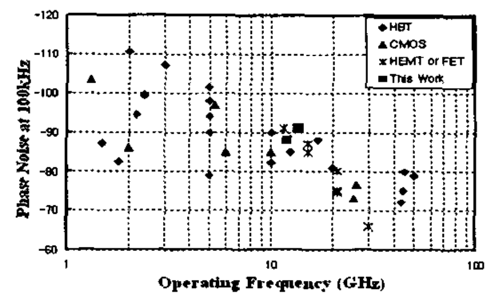

Fig. 8. Comparison of phase noise at 100 kHz offset with the other VCOs in literatures.

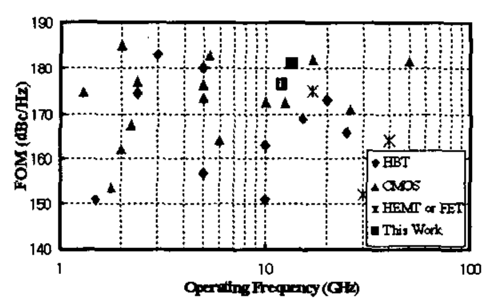

Fig. 9. F.O.M comparison with ever-reported VCOs. The balanced and differential VCOs exploiting microstrip line inductor show −181 and -176 dBc/Hz