A 248–262 GHz InP HBT VCO with Interesting Tuning Behavior

Jongwon Yun, Namhyung Kim, Daekeun Yoon, Hyunchul Kim, Sanggeun Jeon, *Member, IEEE*, and Jae-Sung Rieh, *Senior Member, IEEE*

***Abstract*—A fundamental-mode common-base voltage-controlled oscillator (VCO) based on 250-nm InP heterojunction bipolar transistor (HBT) technology is reported. The VCO, which employs varactors implemented by connecting the base and emitter of npn transistors as tuning components, shows a tuning range of 247.8–262.2 GHz. The output power is greater than 0 dBm over the entire tuning range, and dissipated dc power is around 85 mW. An unexpected tuning behavior was observed, which was shown to arise from the internal parasitic base inductance of the transistors used for varactors in this work.**

***Index Terms*—Frequency control, heterojunction bipolar transistors (HBT), voltage-controlled oscillators (VCO).**

I. Introduction

THE demand for frequency bands beyond 100 GHz increases in many scientific fields and applications including imaging, broadband communication, radio astronomy, bio-chemical detection, military applications, and so forth. One of the major issues in the system implementation in this high frequency regime is the availability of high performance signal sources. Primary requirement for the signal sources is the high output power, which is highly desired in many applications to achieve large signal strength at the receiving modules. Another favored aspect for high frequency signal sources is the tunability of oscillation frequency, for which voltage controlled oscillators (VCOs) are widely used. VCOs are applied for various systems that need frequency selection and tuning such as multi-channel receivers and phase-locked loops (PLLs). For VCOs, varactors are typically adopted as the major frequency tuning component. With Si CMOS or BiCMOS technologies, accumulation-mode MOS varactors are favored for their relatively large tuning range. For bipolar-only technologies, p-n junction varactors, typically composed of the base-collector (B-C) junction of a bipolar transistor, are often used, but its tuning range is generally not as wide as that of MOS varactors. This work reports an unexpected but interesting large tuning behavior exhibited by a p-n junction varactor made of the B-C junction of an InP HBT, which is used for a VCO operating around fundamental frequency of 250 GHz.

Manuscript received March 04, 2014; revised May 04, 2014; accepted May 08, 2014. Date of publication June 03, 2014; date of current version August 05, 2014. This work was supported by the NRF grant funded by the Korea government (MEST) (2012R1A2A1A01005584) and IDEC.

The authors are with the School of Electrical Engineering, Korea University, Seoul 136-713, Korea (e-mail: jsrieh@korea.ac.kr).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LMWC.2014.2324753

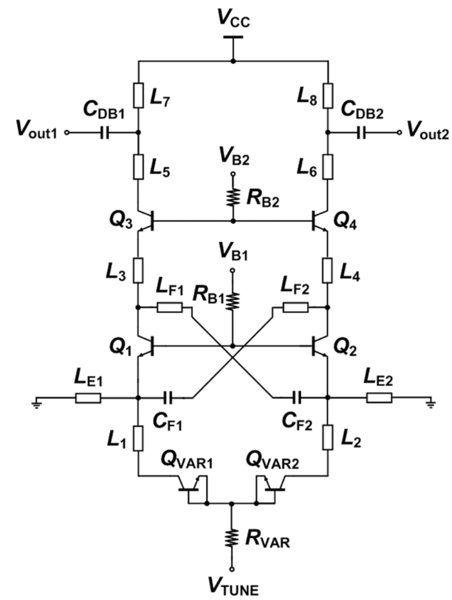


Fig. 1. Schematic of the proposed VCO.

II. Circuit Design and Measurement

The schematic of the VCO proposed in this work is shown in Fig. 1. The core of the VCO is basically two CB amplifiers composed of Q1 and Q2, where their emitters and collectors are cross-connected to each other. This approach is in contrast to the conventional approach where CE amplifiers are adopted with bases and emitters cross-connected. It can be shown that CB stages are less affected by the base-collector capacitance C_{BC}, thus leading to larger MAG (Maximum Available Gain) and higher operation frequency when applied for amplifiers and cross-coupled oscillators, respectively. The output buffer of the VCO is also based on CB topology to boost the gain and thus the output power of the oscillation signal. A pair of varactors is employed for frequency tuning, which are made of tunable collector-base junction capacitance formed by connecting the base and emitter of a HBT.

The VCO is fabricated in Teledyne 250-nm InP HBT technology. The die photo of the circuit is shown in Fig. 2. The chip size is $518 \times 527\ \mu\text{m}^2$ including dc and RF pads. Fig. 3 shows the phase noise of the VCO measured at 258 GHz with a setup including an external mixer for down-conversion. The phase noise measurement was challenging and the measured value varied over tests. It roughly fell in the range of -84.2 to -92.9 dBc/Hz at 10 MHz offset, while a typical case with a value of -87.8 dBc/Hz is presented here. Also shown in Fig. 3 as an inset is a typical output spectrum of the circuit. The output power was obtained from a separate test setup that employs an

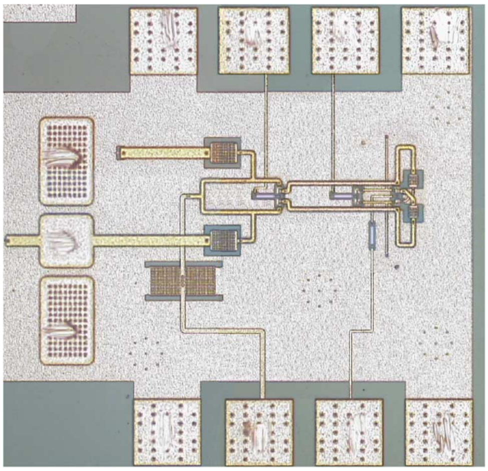


Fig. 2. Photo of the fabricated VCO. ($\mathrm{Area} = 518 \times 527\ \mu\mathrm{m}^2$ including pads).

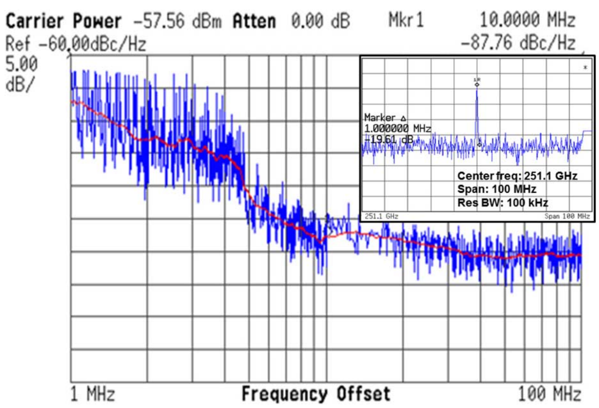


Fig. 3. Measured phase noise of the VCO and output spectrum (inset).

Erickson PM4 calorimeter, which allows a direct power measurement without down-conversion. Fig. 4 shows the oscillation frequency and output power of the VCO as a function of tuning voltage. The measured probe loss of 3.8 dB was compensated in the plot. As the plot indicates, the VCO maintains output power well beyond 0 dBm (up to 2.9 dBm) over the entire tuning range of 247.8–262.2 GHz (14.4 GHz). It is noted that the VCO was designed differential but the measurement was carried out in a single-ended configuration with one of the output nodes terminated with 50 Ω, while the presented data are as measured. The power consumption of the VCO was around 85 mW over the entire tuning range.

The observed tuning profile displayed in Fig. 4 is rather unexpected in that the oscillation frequency shows a sharp increase as V_{TUNE} enters the deep positive region. With negative V_{TUNE}, the varactor diode, which is basically the B-C junction capacitance of a transistor, is reverse-biased and exhibits expected trend: gradually decreasing oscillation frequency with increasing (more positive) V_{TUNE} as the junction capacitance increases. With positive V_{TUNE}, the varactor diode will be now forward-biased, and a further increase of V_{TUNE} is expected to continuously increase the junction capacitance and thus further reduce the oscillation frequency. The measurement, however, shows a rather abrupt increase in the oscillation frequency as V_{TUNE} becomes larger than 0.4 V. An analysis to explain the observed behavior is made and discussed in the next section.

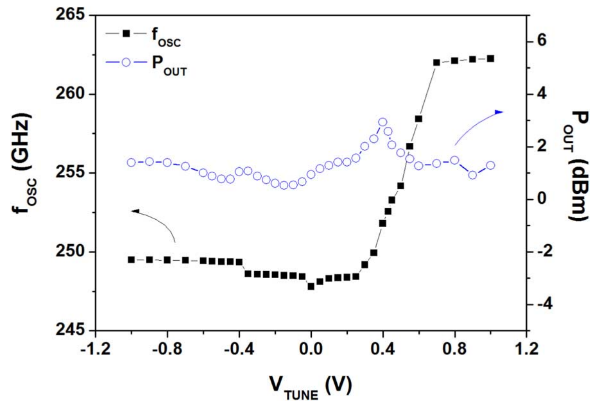


Fig. 4. Measured oscillation frequency and output power shown as a function of tuning voltage.

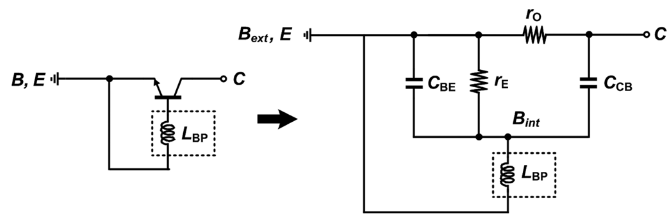


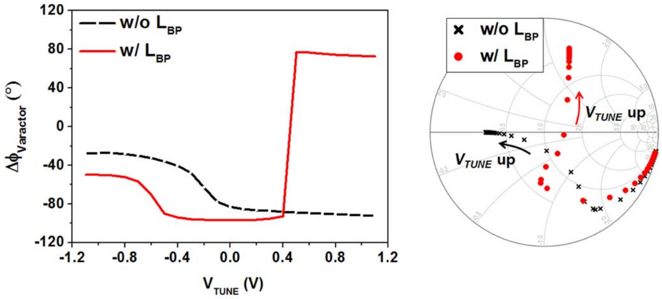
Fig. 5. Varactor equivalent model with parasitic base inductance included.

III. Discussion on Tuning Behavior

The measured tuning behavior can be explained in terms of the effect caused by the internal parasitic base inductance of the transistors. The effects of the internal parasitic base inductance have been reported for amplifiers that are based on CB configuration [1], [2], causing impedance mismatch and/or unsought oscillation. In many cases, the internal parasitic base inductance is not fully reflected in the device model offered in the process design kit (PDK), leading to design-measurement discrepancy. It is a natural conjecture that such situation can also be applied to the oscillator in this work that employs the CB configuration.

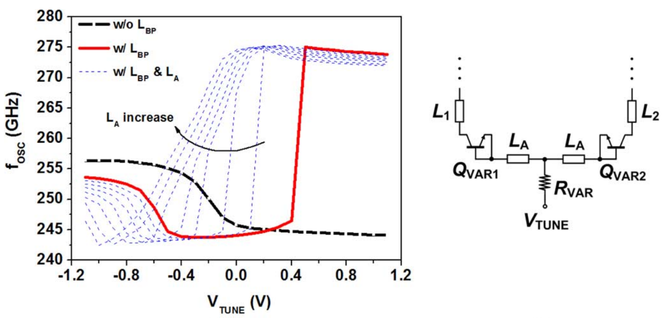
A series of circuit simulations have been carried out to investigate the detailed cause of the observed odd behavior. As a first step, to verify the general effect of the base inductance, the VCO was simulated again with additional base inductance added to the transistors included in the circuit, assuming the internal parasitic base inductance is not included in the device model provided by PDK. The simulation closely matched the measurement with the added base inductance of 7 pH, which showed oscillation frequency around 250 GHz with $V_{\mathrm{TUNE}} = 0\ \mathrm{V}$. This frequency is significantly different from the original simulation without the base inductance that showed oscillation frequency around 300 GHz. The result strongly suggests that the insertion of the base inductance is a necessity for correct prediction of circuit performance and the needed inductance is around 7 pH.

Next, we proceeded to investigate the effect of internal parasitic base inductance on the characteristics of a varactor. The selected value of the base inductance (7 pH) was inserted between the intrinsic and extrinsic base nodes as shown in Fig. 5, assuming the inductance L_{BP} is an internal component. As the impedance of the varactor changes with V_{TUNE}, the phase shift across the varactor immersed in the circuit ($\Delta\phi_{\mathrm{varactor}}$) also varies. It is obvious from Fig. 6(a) that the phase shift shows an abrupt increase around $V_{\mathrm{TUNE}} = 0.4\ \mathrm{V}$. This is in sharp contrast to the case without L_{BP}, also shown in the plot, where no



(a) (b)

Fig. 6. (a) Simulated phase shift across a varactor immersed in the circuit over V_{TUNE} variation (oscillation frequency varies with V_{TUNE}). (b) Simulated trace of the impedance of an isolated varactor over V_{TUNE} variation at fixed frequency of 250 GHz.



(a) (b)

Fig. 7. (a) Simulated oscillation frequency of the VCO with and without parasitic base inductance L_{BP}. Also shown is the simulated effect of the additional anode inductance L_{A} to reduce the slope. (b) Part of the VCO that shows the added inductance L_{A}.

TABLE I
FUNDAMENTAL OSCILLATORS OPERATING AT H-BAND AND HIGHER

Ref	Tech.	Freq. (GHz)	Peak P_{OUT} (dBm)	P_{DC} (mW)	Eff. (%)	P.N. @10 MHz (dBc/Hz)
[3]	250 nm InP HBT	573.1	-19.2	76-115	0.01	-
[3]	250 nm InP HBT	267.4	-2.1	76-115	0.65	-102.4
[4]	35 nm InP HEMT	330	-5.7	15.9	1.7	-
[5]	120 nm SiGe HBT	218-245	-3.6	54	0.81	-98
[6]	32 nm CMOS	234-248	-7	13	1.5	-
This	250 nm InP HBT	247.8-262.2	2.9	85	2.29	-87.8

drastic change in the phase shift is observed. In order to better explain the behavior difference between the two cases, the trace of the impedance over V_{TUNE} variation for an isolated varactor is drawn on the Smith Chart for each case [Fig. 6(b)]. Without L_{BP}, the varactor remains capacitive over the entire range of V_{TUNE}. With L_{BP}, on the other hand, the varactor enters the inductive regime when V_{TUNE} reaches around 0.4 V. This can be explained by the fact that the oscillation frequency of the VCO at this tuning voltage just exceeds the self-resonance frequency (SRF) of the varactor if L_{BP} is included, leading to the varactor behaving as an inductor instead of a capacitor. When L_{BP} is absent, SRF is expected to be sufficiently larger than the oscillation frequency for the tuning voltage range considered, enforcing the varactor to safely remain in the capacitive regime. It is noted that the forward-biasing of this varactor with V_{TUNE} does not lead to a significant dc current rise, since the voltage drop across R_{VAR} (Fig. 1) increases with increasing dc current, limiting the actual voltage across the varactor.

As a final step, the VCO was simulated for a wide range of tuning voltage and the oscillation frequency was plotted against V_{TUNE}. Fig. 7 exhibits the simulated tuning behavior of the VCO with and without L_{BP}. The tuning profile shows a reasonable agreement with the measurement in terms of the trend of the oscillation frequency. The results support the idea that the unexpected tuning behavior of the VCO can be attributed to the internal parasitic inductance residing at the base of the transistor.

Although a wide tuning range was obtained as a result of the base parasitic inductance, the oscillation frequency rises rather rapidly with V_{TUNE}, which may prevent some applications. As a method to reduce the slope, additional inductance can be added at the varactor anode. Fig. 7 shows the location of the added anode inductance L_{A} and its effect of the tuning behavior. It is clearly shown that the slope is reduced with increasing L_{A}, a behavior that can be utilized for practical applications. The output power remains roughly the same with the addition of L_{A}.

Table I shows the performance comparison of the VCO with previously reported oscillator results [3]–[6]. It is obvious that the present circuit shows excellent output power and DC-to-RF efficiency. It is also noted that there have been multiplier-based sources reported near this band with comparable performance.

IV. CONCLUSION

A fundamental-mode CB VCO operating near 250 GHz is demonstrated based on InP HBT technology. Output power over 0 dBm was achieved over a tuning range of 247.8–262.2 GHz and a phase noise of -87.8 dBc/Hz at 10 MHz offset. The VCO exhibited an interesting tuning behavior, which turned out to arise from the internal parasitic base inductance of transistors used for the varactors in this work. A method to reduce the slope of the oscillation frequency vs V_{TUNE} was also suggested.

REFERENCES

[1] Z. Griffith, M. Urteaga, P. Rowell, R. Pierson, and M. Field, "Multi-finger 250 nm InP HBTs for 220 GHz mm-wave power," in *Proc. Int. Conf. Indium Phosphide Related Mater.*, Aug. 2012, pp. 204–207.
[2] Y. Mao, K. Schmalz, J. Borngraber, and J. C. Scheytt, "245-GHz LNA, Mixer, Subharmonic Receiver in SiGe Technology," *IEEE Trans. Microw. Theory Tech.*, vol. 60, no. 12, pp. 3823–3833, Dec. 2012.
[3] M. Seo, M. Urteaga, J. Hacker, A. Young, Z. Grifith, V. Jain, R. Pierson, P. Rowell, A. Skalare, A. Peralta, R. Lin, D. Pukala, and M. Rodwell, "InP HBT IC technology for terahertz frequencies: Fundamental oscillators up to 0.57 THz," *IEEE J. Solid-State Circuits*, vol. 46, no. 10, pp. 2203–2214, Oct. 2011.
[4] V. Radisic, L. Samoska, W. R. Deal, X. B. Mei, W. Yoshida, and P. H. Liu *et al.*, "A 330-GHz MMIC oscillator module," in *IEEE MTT-S Int. Dig.*, Jun. 2008, pp. 395–398.
[5] S. P. Voinigescu, A. Tomkins, E. Dacquay, P. Chevalier, J. Hasch, A. Chantre, and B. Sautreuil, "A Study of SiGe HBT Signal Sources in the 220–330-GHz Range," *IEEE J. Solid-State Circuits*, vol. 48, no. 9, pp. 2011–2021, Sep. 2013.
[6] N. Landsberg and E. Socher, "A 234–248 GHz Power Efficient Fundamental VCO using 32 nm CMOS SOI Technology," in *IEEE MTT-S Int. Dig.*, Jun. 2013, pp. 1–3.