A Highly Efficient 0.2 THz Varactor-Less VCO with -7 dBm Output Power in 130nm SiGe

Pei-Yuan Chiang¹, Omeed Momeni^{1,2}, and Payam Heydari¹

¹Nanoscale Communication IC (NCIC) Lab, University of California, Irvine, CA, 92697, USA

²University of California, Davis, CA, 95616, USA

Abstract — A highly efficient push-push voltage controlled oscillator (VCO) with a new varactor-less-based frequency-tuning topology for terahertz (THz) frequencies is presented. The tuning technique is based on a variable inductance seen at the emitter node of a base degenerated transistor. Fabricated in a 130nm SiGe BiCMOS process, the VCO achieves a tuning range of 3.5% and output power of -7.2 dBm at 201.5GHz. The VCO consumes 30mW of DC power, resulting in a record-breaking power efficiency of 0.6%. To demonstrate the functionality of the tuning technique, three other VCO prototypes at different oscillation frequencies, including one operating at 222.7~229 GHz range, have been implemented.

Index Terms — Voltage controlled oscillator (VCO), Colpitts oscillator, Clapp oscillator, varactor-less tuning, inductive tuning, sub-millimeter wave, terahertz (THz).

I. INTRODUCTION

THz and millimeter-wave (mm-wave) frequency range presents great promise for non-invasive active and passive imaging, chemicals and biological spectroscopy, as well as high data rate communications and short-range radars. The first step towards realization of a THz system capable of transmitting or detecting a THz wave is to be able to design a high-power, tunable and efficient signal source. Traditionally, a THz signal source is composed of a tunable low frequency signal source, a chain of Schottky diode multipliers, and amplifiers in compound semiconductors [1]. Despite their limited cutoff frequency and break down voltage, recent advances in silicon-based transistors have made them potential candidates for implementation of highly integrated THz radiators and detectors. As a feasibility study, high power and high frequency oscillators have recently been demonstrated in silicon [2], [3]. However, having a power efficient tunable signal source deems necessary for many practical applications. A conventional and widely used way of controlling the oscillation frequency is to implement varactors in an LC oscillator. The Q factor and C_{max}/C_{min} ratio of varactors and resonators degrade at mm-wave and THz frequencies, reducing the output power, power efficiency and tuning range. Furthermore, the loss of the varactor significantly changes across the tuning range, resulting in dramatic variation in output power. On the other hand, inductors become smaller in size and present higher Q factor at these frequencies. Therefore,

inductively tuned oscillators can achieve wider tuning range, higher and relatively constant output power across the band at mm-wave and THz frequencies.

In this paper, an inductive tuning technology has been developed, implemented and verified in four VCOs at different frequencies, including 198~205GHz, 209~215GHz, 218~225GHz, and 223~229GHz. The VCO operating at 198~205GHz has an output power of -7.2~-7.75dBm and a minimal DC power of 30mW. The tuning range is 3.5% and the power efficiency is 0.6%. To the best of authors' knowledge, this work presents the highest frequency inductively-tuned oscillators with the highest power efficiency among silicon-based VCOs.

Fig. 1. The schematic of the proposed varactor-less VCO.

II. CIRCUIT DESIGN

Colpitts and Clapp topologies are proved to achieve higher maximum oscillation frequency than a cross-coupled pair counterpart [4] due to a non-unity gain feedback loop realized using the tapped capacitor resonator. Moreover, the Colpitts and Clapp oscillator phase noise is a function of capacitive division ratio [5], making it more flexible to design lower phase noise circuit. Finally, the dominant base-emitter parasitic capacitor is

absorbed as part of the capacitive feedback network. With capacitive loading at the emitter node, a negative resistance can be seen at the base terminal, which compensate for the LC tank's loss. The tank inductor in a Colpitts oscillator is placed in the base terminals of the active devices, as shown in Fig. 1. Here, the absence of passive losses in the main signal path to the 50Ω load will help maximize the output power. Therefore, the differential Clapp oscillator is a great candidate for high power signal generation at mm-wave and THz frequencies.

Fig. 1 shows the schematic of the proposed VCO. The capacitors C_1 and C_2 form a capacitive feedback around the base-emitter terminals of the transistor. The real part of the impedance seen at the base terminals of T_1 and T_2 will thus be frequency-dependent and negative. This negative real part compensates for the loss of the passive components. Once oscillating, a strong second harmonic signal can be extracted at any common-mode node of the oscillator. In Fig. 1, the 2nd harmonic is extracted from collectors in order to achieve higher output power. The primary reason is that the major portion of the 2nd harmonic current generated by transistors T_1 and T_2 will flow to their collector nodes, while for the other common-mode nodes, the inherent current division will degrade the output power.

The inductor L_C models the interconnection from collectors to RF pads and is considered as part of the output matching network, as well. The common-mode node between C_2 's is grounded to improve output matching at 2nd harmonic. With a bias-T directly implemented on a GSG waveguide probe, DC supply voltage can be applied directly into the circuit, while the signal can be brought out to measurement equipment, which is modeled as a 50Ω resistor.

As discussed in Section I, varactor loss is the main bottleneck to the VCO's performance at THz frequencies. The inductive tuning, on the other hand, is amenable to frequency scaling towards THz regime. This is because, as the oscillation frequency of the LC oscillators increases, the passive components, and in particular, inductance values is scaled down quadratically, leading to a similar decrease in the effective size of inductors. Smaller inductors with higher quality factors and stronger mutual couplings can readily be realized in a silicon process.

The frequency tuning in the VCO of Fig. 1 is achieved using an inductive tuning circuit comprised of transistors T_3 - T_4 , the series RL network R_{BB} - L_{BB} , mutually coupled inductors L_{EE} and L_B , and a tail current transistor T_5 which is externally controlled using V_{tune} .

Fig. 2(a) shows the equivalent circuit explaining the tuning mechanism. The driving point impedance looking into the emitter of T_3 (and T_4) is modeled using an RL network R_{T1} - R_{T2} - L_T [6]. The L_{BB} 's inductance value is

designed to guarantee a negative series resistance R_{T2} near the fundamental oscillation frequency ω_0 . This will, in turn, boost the quality factor of the equivalent variable inductor L_T . This inductance is a function of the transistor's transconductance g_m , and therefore, can be controlled and varied by V_{tune} (i.e., by changing the DC current of T_3 and T_4). To avoid generation of the second oscillation, R_{BB} and L_{BB} are designed carefully to ensure that the real-part of driving point impedance Z_T remains positive.

Fig. 2(b) demonstrates the simulated equivalent inductance seen from the emitter of T_3 (or T_4) with respect to emitter current of T_3 (or T_4). Using the tuning mechanism, the effective inductance varies from 30- to 70-pH, when emitter current varies from 10- to 1-mA.

Fig. 2. (a) the equivalent circuit model for tuning mechanism, (b) the effective inductance seen from emitter of T_3 (or T_4)

III. EXPERIMENTAL RESULTS

The proposed VCO was fabricated in a 130nm SiGe BiCMOS technology. All of the transformers and inductors were designed in the two top metals with the bottom metal being used as a ground plain, shielding the whole circuit from the lossy substrate.

Fig. 3. Die photograph of the varactor-less VCO where the chip size is 250×290 μm² excluding the pad ring.

Fig. 3 shows the chip photograph of 201.5GHz VCO with chip area of 250×290 μm² excluding the pad ring. All the elements and routing lines have been placed symmetrically in order to minimize mismatch and improve overall performance.

Fig. 4. Test setup for measuring (a) output power and (b) oscillation frequency.

Fig. 5. The IF tone is shown on spectrum analyzer after a 201.6GHz signal was down-converted by a harmonic mixer with harmonic number of 11 and LO frequency of 18.3GHz.

Fig. 6. The measured output power and oscillation frequency of 200GHz VCO.

The 200GHz frequency and power measurement setups were configured as shown in Fig. 4(a) and (b). In Fig. 4(a), a GGB WR5 GSG probe with bias T, an Agilent E4407 spectrum analyzer, a Pacific Millimeter GM harmonic mixer and MD4A diplexer are used to verify the oscillation frequency. Fig. 5 shows the down-converted 201.6GHz signal when an LO signal of 18.3GHz and a harmonic number of 11 is utilized. Due to the narrow IF bandwidth of the diplexer compared to the tuning range of the VCO, the LO frequency needs to be adjusted with respect to the tuning voltage of the VCO. To accurately measure the output power, a direct power measurement setup was used, as shown in Fig. 4(b). The WR5 waveguide of the GSG probe is converted to a WR10, and then connected to an Erickson PM4 power meter. The measured output power levels need to be calibrated for the loss of probe, waveguide extension, and taper by 3.25dB.

Fig. 7. The measured output power and oscillation frequency of 212GHz VCO.

Fig. 8. The measured oscillation frequency of 220GHz and 227GHz VCOs.

Fig. 6 shows the measured oscillation frequency and output power of the 200GHz VCO with respect to the tuning voltage, V_{tune} . By controlling V_{tune} from 0.5V to 1.5V, the oscillation frequency is varied from 198GHz to 205GHz, resulting in a tuning range of 3.5%. The measured output power is -7.2dBm with less than 0.5dB variation across the band.

TABLE I
VCO PERFORMANCE COMPARISON

	This Work	This Work	[7]	[8]	[9]	[10]	[11]	[12]
Frequency (GHz)	212	201.5	161.1	184.2	277.6	196.5	139	290
Tuning Range	2.8%	3.5%	4.7%	2%	1.5%	1.5%	0.09%	4.5%
Output Power(dBm)	-7.1	-7.2	-15	-11	-20	-16	-19	-1.2*
DC Power (mW)	30 (min.)	30 (min.)	46.5	95	132	29	9.6	325
Power Efficiency	0.65%	0.64%	0.068%	0.084%	0.0076%	0.087%	0.13%	0.23%
Technology	130nm SiGe	130nm SiGe	250nm SiGe	130nm SiGe	130nm SiGe	90nm CMOS	90nm CMOS	65nm CMOS

* Power combination of four cross-coupled oscillators.

Fig. 7 shows the performance of a 212GHz VCO prototype, which was designed using the same topology. The tuning range is from 209GHz to 215GHz with -7.1dBm output power.

Both VCOs consume a DC power of 30~57mW with respect to V_{tune} . As shown in Fig. 8, two additional VCOs were implemented for 210GHz and 220GHz. The measured tuning range is 6GHz, when the maximum oscillation frequency extends to 229GHz. Due to the bandwidth limitation of WR5 waveguide (170GHz~220GHz), the output power of these two VCOs can not be measured accurately. Table I shows the performance comparison with prior work. The proposed VCOs show the highest power efficiency, a high output power and a wide tuning range compared to the state of the art in silicon-based VCOs.

IV. CONCLUSION

A varactor-less push-push VCO topology has been presented for mm-wave and THz frequency bands. Four VCOs with different frequencies have been implemented to show the feasibility of the proposed approach. The maximum tuning range is 3.5% and highest oscillation frequency is 229GHz. An outperform power efficiency can be achieved with output power of -7.2dBm.

ACKNOWLEDGMENT

The authors thank Prof. Gabriel Rebeiz of UCSD for providing access to the 200GHz measurement facility and Mehmet Uzunkol for help in measurement. They also acknowledge TowerJazz Semiconductor for chip fabrication. Technical support from Sonnet Software is highly appreciated.

REFERENCES

- [1] T. W. Crow, W. L. Bishop, D. W. Porterfield, J. L. Hesler, and R. M. Weikle, "Opening the THz window with integrated diode circuits," *IEEE J. Solid-State Circuits*, vol. 40, no. 10, pp. 2104–2110, Oct. 2005.
- [2] O. Momeni, and E. Afshari, "High Power Terahertz and Millimeter-Wave Oscillator Design: A Systematic Approach," *IEEE J. Solid-State Circuits*, vol. 46, no. 3, pp. 583–297, Mar. 2011.
- [3] B. Razavi, "A 300-GHz Fundamental Oscillator in 65-nm CMOS Technology," *IEEE J. Solid-State Circuits*, vol. 46, no. 4, pp. 894–903, April 2011.
- [4] C.-C. Wang, Z. Chen, and P. Heydari, "W-Band Silicon-Based Frequency Synthesizers Using Injection-Locked and Harmonic Triplers," *IEEE Trans. Microw. Theory Tech.*, vol. 60, no. 5, pp. 1307–1320, May 2012.
- [5] V. Jain, B. Javid, and P. Heydari, "A BiCMOS dual-band millimeterwave frequency synthesizer for automotive radars," *IEEE J. Solid-State Circuits*, vol. 44, no. 8, pp. 2100–2113, Aug. 2009.
- [6] B. Razavi, *Design of Analog CMOS Integrated Circuits*, pp. 181–182, McGraw-Hill, 2001.
- [7] Y. Zhao, B. Heinemann, and U.R. Pfeiffer, "Fundamental Mode Colpitts VCOs at 115 and 165-GHz," *2010 IEEE Bipolar/BiCMOS Circuits and Tech. Meeting*, pp. 33–36, 2011.
- [8] H. Rücker, B. Heinemann, W. Winkler, R. Barth, J. Borngräber, J. Drews, G. G. Fischer, A. Fox, T. Grabolla, U. Haak, D. Knoll, F. Korndörfer, A. Mai, S. Marschmeyer, P. Schley, D. Schmidt, J. Schmidt, K. Schulz, B. Tillack, D. Wolansky, and Y. Yamamoto, "A 0.13μm SiGe BiCMOS technology featuring f_T/f_{max} of 240/330 GHz and gate delays below 3 ps," *IEEE J. Solid-State Circuits*, vol. 45, no. 9, Sep. 2010.
- [9] R. Wanner, R. Lachnert, G. R. Olbrich, and P. Russer, "A SiGe monolithically integrated 278 GHz push-push oscillator," in *2007 MTT-S Int. Microwave Symp. Dig.*, Jun. 2007, pp. 333–336.
- [10] H.Y. Chang, H. Wang, "A 98/196 GHz low phase noise voltage controlled oscillator with a mode selector using a 90 nm CMOS process," *IEEE Microw. and Wireless Compon. Lett.*, vol.19, no.3, Mar. 2009.
- [11] E. Seok, D. Shim, C. Mao, R. Han, S. Sankaran, C. Cao, W. Knap, and K. K. O, "Progress and challenges towards terahertz CMOS integrated circuits," *IEEE J. Solid-State Circuits*, vol. 45, no. 8, pp. 1554–1564, Aug. 2010.
- [12] Y.M. Tousi, O. Momeni, and E. Afshari, "A 283-to-296GHz VCO with 0.76mW Peak Output Power in 65nm CMOS," *IEEE Int. Solid-State Circuits Conf. Dig. Tech. Papers*, pp. 286–288, Feb. 2011.