# Design and Scaling of SiGe BiCMOS VCOs Above 100GHz

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*Abstract* — **This paper presents a comparison of 100 GHz Colpitts VCOs fabricated in two generations of SiGe BiCMOS technology, with MOS and HBT varactors and with integrated inductors. Based on a study of the optimal biasing conditions for minimum phase noise, it is shown that VCOs can be used to monitor the noise performance of the SiGe HBTs at mm-waves. Measurements and simulations show a 104 GHz VCO operating from 2.5 V with phase noise of -101.3 dBc/Hz at 1 MHz offset, which delivers +2.7 dBm of differential output power at 25ºC, with operation up to 125ºC.**

*Index terms* — **Millimeter-wave circuits, phase-noise, SiGe BiCMOS technology, voltage-controlled oscillators, W-band.**

## I. Introduction

The latest SiGe processes with $f_T/f_{MAX}$ above 150 GHz [1-6] allow them to compete directly with III-V technologies for applications in the W-band (75-110 GHz). Many W-band radar transceivers and communications circuits require a phase-locked loop, in which the VCO [7] and the frequency divider are critical components. Fig. 1 compares the phase noises of state-of-the-art W-band SiGe and CMOS VCOs [8]-[13] along with those presented in this paper.

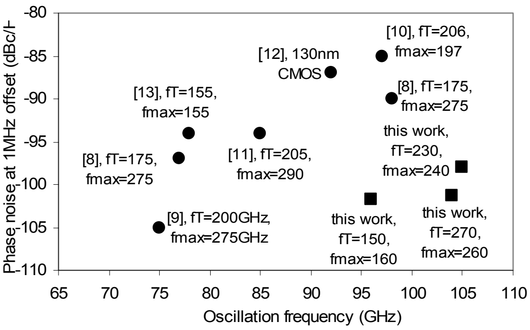


Fig. 1. Phase noise of state-of-the-art SiGe HBT and CMOS W-band VCOs (inc. process $f_T/f_{MAX}$).

As the level of integration in W-band circuits increases, high yield processes must be developed, and circuit scaling between successive SiGe technology generations must be understood. Key process monitor circuits are required to investigate both issues. Given the complexity and variability of noise parameter measurements above 50 GHz, Colpitts oscillators can be employed to monitor the phase noise at W-band in much the same way as ring oscillators are used as process speed monitors.

This paper presents a Colpitts oscillator topology with compact layout, suitable for low-voltage, low-phase noise oscillators in the W-band, and explores the impact of technology scaling on VCO performance.

## II. VCO Topology

The differential Colpitts topology [7] is a common choice for low-phase noise, mm-wave VCOs [8]-[11], [13], [14]. Fig. 2 shows the schematic of our SiGe BiCMOS implementation of this topology.

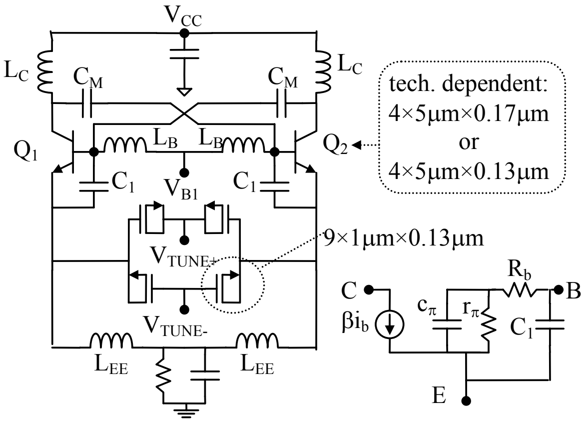


Fig. 2. Colpitts oscillator schematic.

In an effort to reduce phase noise and to simplify layout, which is critical at 100 GHz, the cascode is replaced by a single-transistor topology. A MiM capacitor ($C_1$) in parallel with $c_\pi$ improves negative resistance and reduces phase noise by shunting the base resistance ($R_B$). Negative Miller capacitors ($C_M$) are placed at the BC junctions to cancel the effect of the $C_{BC}$. Finally, fully differential tuning with MOS varactors is used for better supply noise rejection. This also reduces the modulation of the varactor capacitance ($C_{VAR}$) by the tank voltage, which helps to suppress the maximum in phase noise at the center of the tuning range seen in other VCOs [13]. The varactor layouts are optimized for high-Q [13]. Wherever possible, spiral inductors are used in place of transmission lines to achieve a compact layout.

## III. VCO Design Methodology

The VCO shown in Fig. 2 was designed and fabricated in a SiGe BiCMOS process with $f_T/f_{MAX}$ of 150/160 GHz (referred to as "BiCMOS9" [1]), and two SiGe HBT processes with $f_T/f_{MAX}$ of 230/300 GHz and 270/260GHz (referred to as "BipX" and "BipXF" respectively [2]). The technologies have identical back-ends and HBT layouts (except for the emitter window, see Fig. 2), which allows investigation of the effects of

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SiGe technology scaling on mm-wave VCO performance.

Because MOSFETs are not yet available in BipX and BipXF, two versions of the VCO were designed, one with the differential MOS varactor tuning illustrated in Fig. 2, and another with single ended HBT varactors. Apart from varactors and emitter width, *the VCOs are otherwise identical in design and layout,* which allows measurement results from both VCOs to be compared directly.

The oscillation frequency ($f_{osc}$) of the VCO is given by (1), and was designed to be 100 GHz. Note that $C_M$ is chosen to remove the $C\mu$ contribution to $C_{EFF}$.

$$f_{osc} = \frac{1}{2\pi\sqrt{L_B C_{EFF}}} \qquad C_{EFF} = C_\mu + \frac{C_{VAR}\left(C_1 + C_\pi\right)}{C_{VAR} + C_1 + C_\pi} \qquad (1)$$

The negative resistance provided by $Q_1$, given by (2), must be large enough to overcome losses in the tank.

$$R_{NEG} = R_B + \frac{\omega_{osc} L_B}{Q_{L_B}} + \frac{1}{\omega_{osc} Q_{C_{VAR}} C_{VAR}} - \frac{g_m}{\omega_{osc}^2 C_\pi C_{VAR}} \qquad (2)$$

At 100 GHz, the finite Q of the varactor ($C_{VAR}$) and base inductor ($L_B$) add substantial losses to the tank. Therefore, as illustrated in Fig. 3, $C_1$ should be chosen to maximize the negative resistance at the desired $f_{osc}$.

Low phase noise is an important specification in radar applications [9]. In [13] and [14], it was shown that to minimize phase noise in a mm-wave VCO, $Q_1$ should be biased at the optimum $NF_{MIN}$ current density. However, in the W-band, the correlation between base and collector noise currents pushes the optimum $NF_{MIN}$ current density closer to the peak $f_T/f_{MAX}$ current density [15]. Therefore, the VCOs were designed with $Q_1/Q_2$ biased at peak $f_T/f_{MAX}$ current density.

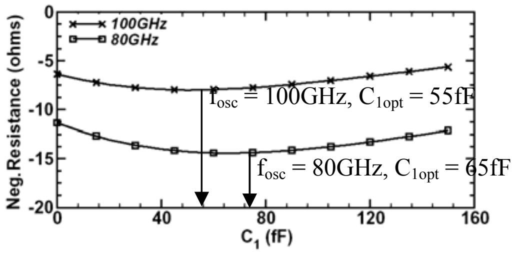


Fig. 3. Simulation to find optimum value of $C_1$.

## IV. Experimental Results

A die microphotograph of the VCO is shown in Fig. 4. The VCO occupies 300μm × 400 μm including all DC pads (not shown). The die area is smaller than other W-band SiGe VCOs [8], [9], [11] because inductors are used in place of transmission lines. The VCO consumes 140 mW from a 2.5 V supply, which to the authors' knowledge is the lowest supply voltage published for a W-band VCO in SiGe BiCMOS technology.

Fig. 5 illustrates a spectral plot of phase noise at 1MHz offset for the 104 GHz BipX VCO, and Fig. 6 shows the output power and phase noise of all three VCOs over the tuning range. The measured phase noises of -101.6 dBc/Hz at 1MHz offset for the 96 GHz BiCMOS9 VCO with MOS varactor, and -101.3 dBc/Hz for the 104 GHz BipX VCO with HBT varactor are records for SiGe VCOs above 80 GHz. Table 1 summarizes the performance of all fabricated VCOs, with probe, adapter, DC-blocking capacitor, and cable losses de-embedded.

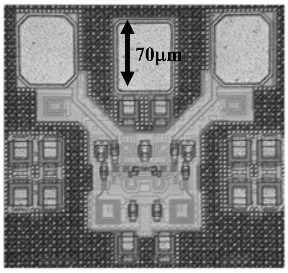


Fig. 4. 104 GHz VCO microphotograph.

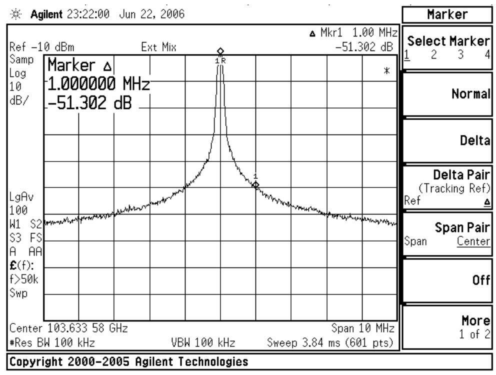


Fig. 5. Averaged spectral plot of phase noise in 104 GHz BipXF VCO with HBT varactor.

TABLE 1: SUMMARY OF VCO PERFORMANCE

| | BiCMOS9, MOS var. | BiCMOS9, HBT var. | BipX, HBT var. | BipXF, HBT var. |
|---|---|---|---|---|
| Differential Pout (dBm) | +0.7 sim. +5.5 | -1.3 sim. -1.15 | +2.7 +6.5 | +2.5 |
| SSB PN @ 1MHz (dBc/Hz) | -101.6 | -80 | -98 | -101.3 |
| Osc. Freq. (GHz) | 96 sim. 96 | 100 sim. 100 | 106 sim. 108 | 104 |

Measurement results indicate that, in the 150/160 GHz BiCMOS technology, the VCO with MOS varactor achieves 14 dB lower phase noise than the one with junction varactor, demonstrating that MOFETs, not just HBTs, are required to optimize the phase noise of W-band SiGe VCOs. Interestingly, The VCO center frequency is practically immune to the change in technology. Although the transistor $f_T$ and $f_{MAX}$ improve by 40%, the VCO center frequency changes by only 6%. Clearly, accurate design and modeling of passive components has a greater effect on the center frequency than the transistor itself. So long as back-end-of-line geometry remains unchanged, mm-wave circuits can be ported quickly between successive generations of SiGe technology, mitigating some of the cost of moving to the next technology node.

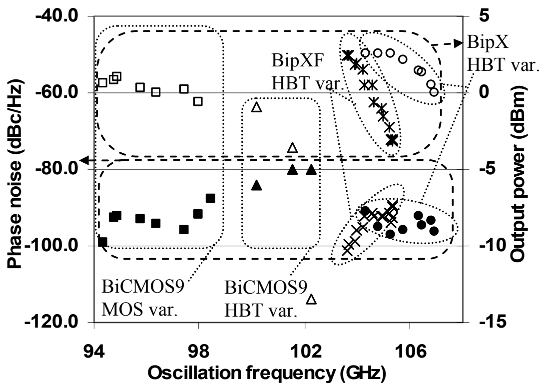


Fig. 6. Phase noise versus oscillation frequency.

The VCO phase noise was also measured as a function of HBT bias current density. Shown in Fig. 7 are the averaged phase noise and output power measurements for four BipX VCOs. The minimum in phase noise corresponds to the peak $f_T/f_{MAX}$ current density. It confirms the shift to higher current densities of the $NF_{MIN}$ current density as frequency increases. The transistor noise figure was obtained from Y parameter measurements, as in [15], with a noise transit time of 0.3 ps. Note that $NF_{MINn}$ @ 65 GHz is only 1.7 dB, the lowest reported for a SiGe HBT at this frequency.

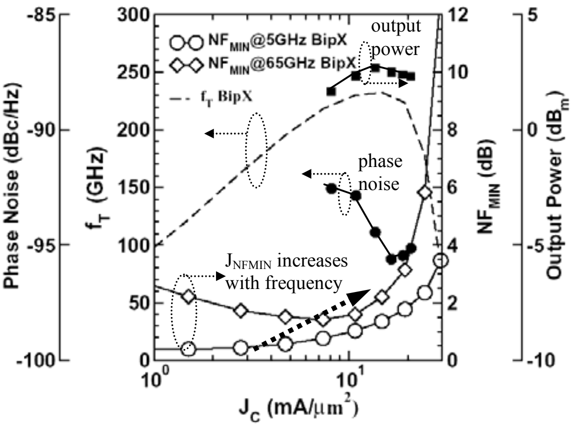


Fig. 7. Measured minimum phase noise is at measured peak $f_T/f_{MAX}$ current density.

Shown in Fig. 8 are simulated and measured tuning characteristics of the VCOs with HBT varactors. The BipX VCO displays 2.5 GHz of tuning range up to 125ºC. The tuning is linear enough to allow frequency modulation of the VCO output by applying a triangular wave to the tuning input – a modulation technique commonly employed in FMCW radar systems. The resulting spectrum obtained at 100ºC using the BipX HBT varactor VCO, is shown in Fig. 9.

Fig. 10 compiles the measured output power across the tuning range at 25ºC, 70ºC, and 125ºC. The BiCMOS9 VCO with MOS varactor oscillates up to 70ºC and the BiCMOS9 VCO with HBT varactor operates up to 50ºC. In contrast, the BipX oscillator functions up to at least 125ºC.

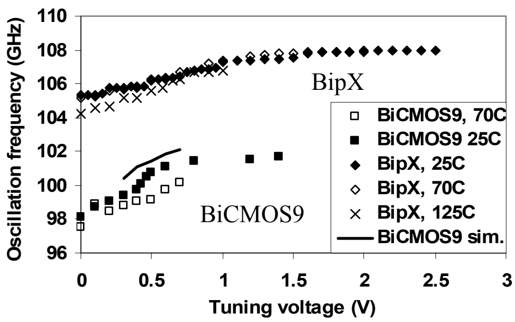


Fig. 8. Tuning characteristics across temperature for HBT varactor VCOs in BipX and BiCMOS9.

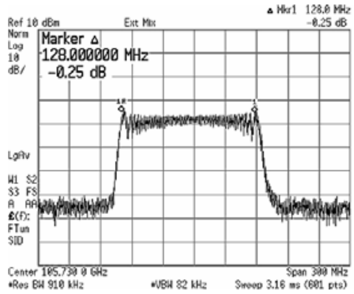


Fig. 9. Frequency modulation of BipX VCO output.

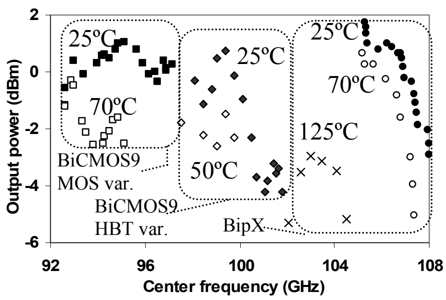


Fig. 10. $P_{out}$ versus $f_{osc}$ at 25ºC, 70ºC, and 125ºC.

To gauge the impact of process variations on VCO performance, the mm-wave and DC characteristics of both BiCMOS9 VCOs were collected from 60 dice from 4 different wafers. Tables 2 and 3 summarize the results for the MOS varactor and HBT varactor VCOs, respectively. Of the 120 VCOs tested, 4 had significantly below average performance, and another 2 VCOs failed to oscillate. Those VCOs are not included in the averages given.

To further characterize the VCOs over process variations, in Fig. 11 we have plotted measured output power versus oscillation frequency for 1 die on each of the 4 wafers, beside simulation results. A 2 dB variation in output power between BiCMOS9 VCOs on different wafers is illustrated. Note however that the tuning range and center frequency remain constant over the wafers.

Fig. 12 reproduces wafer maps of oscillation frequency and phase noise as functions of location for BipX VCOs. Both plots show that dice at the center of the wafer perform better than dice on the edges.

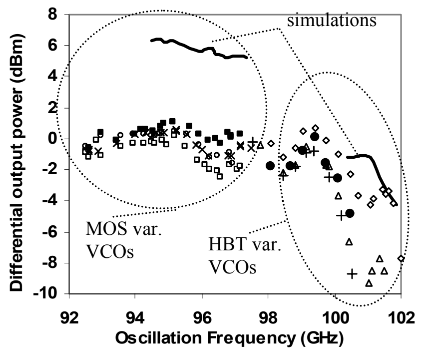


Fig. 11. Output power versus oscillation frequency for BiCMOS9 VCOs on different wafers.

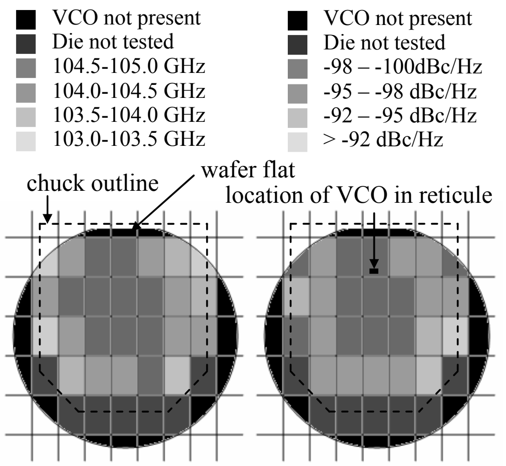


Fig. 12. BipX wafer maps of oscillation frequency (left) and phase noise at 1 MHz offset (right).

TABLE 2: SUMMARY OF BICMOS9 MOS VAR. VCOS.

| Wafer | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Center freq. (GHz) | 94.7 | 94.9 | 94.9 | 95.0 |
| Tuning range (GHz) | 4.6 | 4.6 | 4.6 | 4.6 |
| Output power (dBm) | 0.2 | 0.7 | 0.6 | 0.8 |
| DC power (mW) | 133.8 | 133.2 | 137.3 | 132.6 |

TABLE 3: SUMMARY OF BICMOS9 HBT VAR. VCOS.

| Wafer | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Center freq. (GHz) | 99.6 | 100.5 | 100.1 | 100.5 |
| Tuning range (GHz) | 3.4 | 3.6 | 3.6 | 3.7 |
| Output power (dBm) | -1.1 | -1 | -1.4 | -0.9 |
| DC power (mW) | 133.0 | 133.0 | 136.2 | 132.8 |

## V. CONCLUSIONS

W-band low-voltage VCOs have been presented with record phase noise for SiGe VCOs above 80 GHz. Experimental results indicate that transistors in W-band VCOs should be biased at peak $f_T/f_{MAX}$ to minimize phase noise because $NF_{MIN}$ current density approaches peak $f_T/f_{MAX}$ current density in the W-band. Additionally, MOS varactors are shown to be superior to HBT varactors for achieving low phase noise. Furthermore, while VCO performance improves when SiGe technology is scaled, the oscillation frequency – determined by passive components – is insensitive to scaling. Wafer mapping and temperature data show that SiGe HBTs with over 200 GHz $f_T/f_{MAX}$ are required to obtain production-quality W-band VCOs.

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